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MEMORANDUM

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

FROM: **Jonathan Abell, Ph.D., E.P., Bogdan Caradima, Ph.D., and Adam Lewis, M.Sc., R.P.Bio, Ecofish Research Ltd.**

DATE: **January 9, 2023**

FILE: **1316-09**

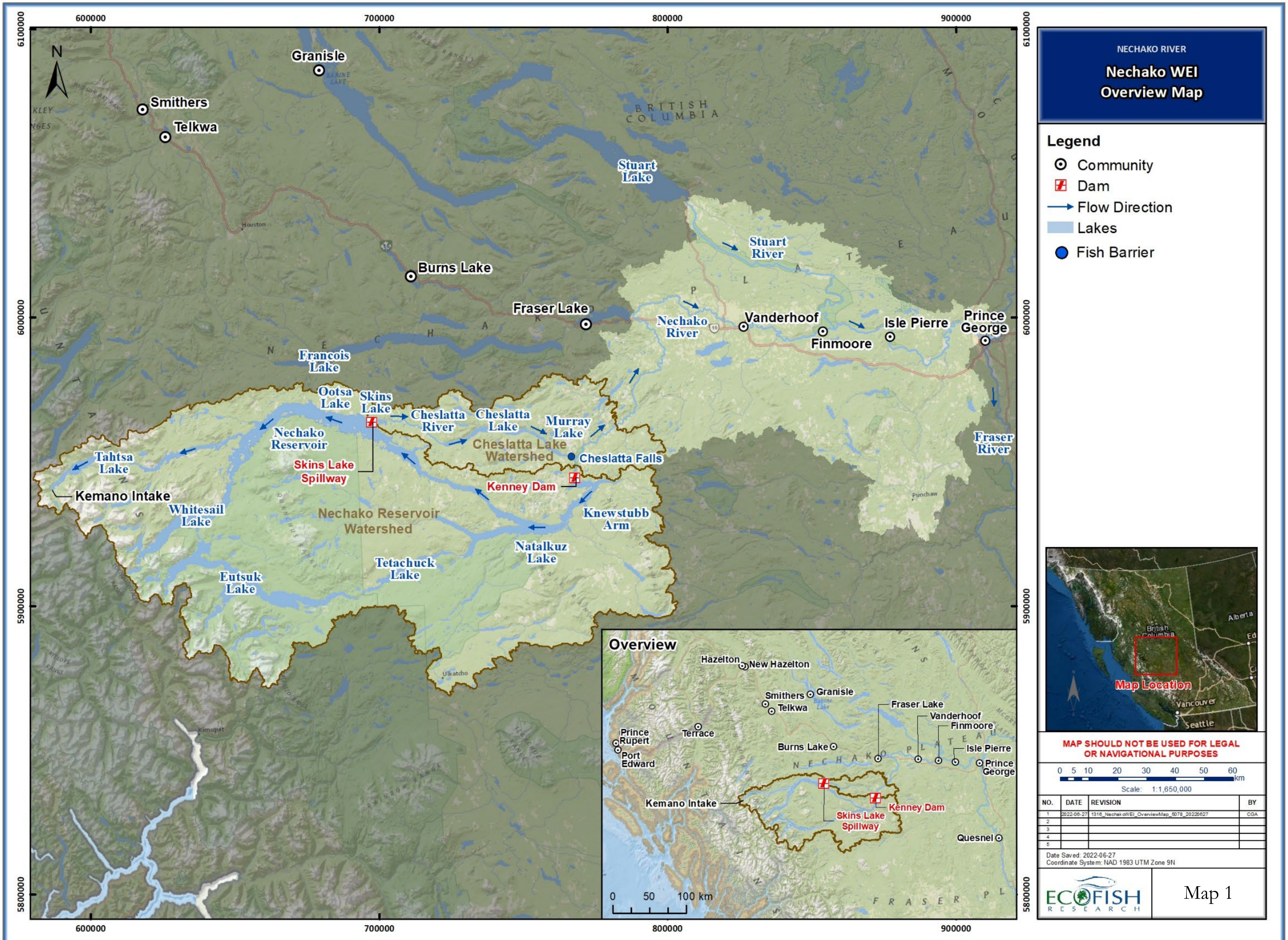
RE: Issue #11, 12, 14 – Nechako Reservoir Productivity

1. INTRODUCTION

During Main Table and Technical Working Group meetings of the Nechako Water Engagement initiative (WEI), concerns were raised about potential effects of Rio Tinto Alcan operations on aquatic productivity in Nechako Reservoir. The Technical Working Group asked Ecofish Research Ltd. (Ecofish) to prepare a technical memo to review this topic and develop recommendations for consideration by the WEI. Specifically, the following three issues were identified as priorities for evaluation:

- Issue #11: potential effects of changes in reservoir water levels (i.e., elevation) on primary and secondary productivity of periphyton, macrophytes, and macroinvertebrates in the reservoir;
- Issue #12: potential effects of changes in reservoir flushing on plankton productivity; and
- Issue #14: potential effects of changes in reservoir flushing on reservoir water temperature and thermocline.

This memo provides a review of the potential impacts of changes to water levels and reservoir outflow discharge on the aquatic productivity of Nechako Reservoir (Map 1). Recommendations are provided regarding potential performance measures to evaluate the effects of alternate flow management scenarios.



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2. BACKGROUND

2.1. Nechako Hydroelectric System

The Nechako Reservoir is located approximately 200 km west of Prince George, BC 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), flooding a chain of six major lake and river systems (Ootsa, Whitesail, Knewstubb, Tetachuck, Natalkuz, and Tahtsa; ~420 km total length; see Map 1). The remainder of this sub-section provides an overview of the hydrology of Nechako Reservoir. Further details regarding the hydrology of the Nechako watershed are provided in a separate Ecofish memo that focuses on hydrology (Beel *et al.* 2022).

Nechako Reservoir has a surface area of ~910 km^2 with a normal annual drawdown range of ~ 3 m (10'); annual minimum reservoir levels occur in late spring and annual maximum levels water occur in late summer. Water levels in Nechako Reservoir vary among years, but they generally follow a similar seasonal trend (Figure 1A). Based on data from 1987 – 2021, the annual range in reservoir level varied from 0.32 m to 3.33 m, with a median annual range of 1.87 m (Figure 1B). Generally, reservoir levels increase rapidly in spring (April – May) and peak in summer, reaching a mean maximum of 852.74 m in ~July, before steadily declining during the fall through to the following spring to minimum levels (mean minimum = 850.94 m) in ~April – July, prior to freshet (Figure 1A).

There are two outflows from the reservoir (Map 1). On Tahtsa Lake, an intake to the Kemano hydroelectric station diverts ~70% of the annual reservoir inflow 16 km west into the Kemano River watershed. The Skins Lake Spillway on Ootsa Lake diverts the remaining flow (~60 m^3/s mean annual discharge) from the surface of the lake ~80 km through the Cheslatta watershed, before discharging into the Nechako River at Cheslatta Falls (Map 1). There is no discharge facility at the Kenney Dam.

While the discharge at the Kemano station intake has remained relatively stable within each year during 1987 – 2018, the discharge from Skins Lake Spillway varies seasonally. Relative to the fall and winter (September – March), flows at Skins Lake Spillway are generally higher during the growing season (April – September), with an average growing season discharge of ~100 m^3/s[1] and mean maximum flows during July and August (Figure 2). Discharge during individual years can vary substantially from the longer-term average condition shown in Figure 2, highlighting the potential for rapid changes in discharge during the growing season.

[1] Average daily discharge at Skins Lake Spillway (gauge 08JA013) during May through October 1987–2019 is 102 m^3/s.

Figure 1. **Plots showing (A) daily reservoir water levels in Nechako Reservoir coloured by year (1987 – 2021), and (B) the distribution of the annual range in reservoir water levels (1987 – 2021) as a standard box plot.**

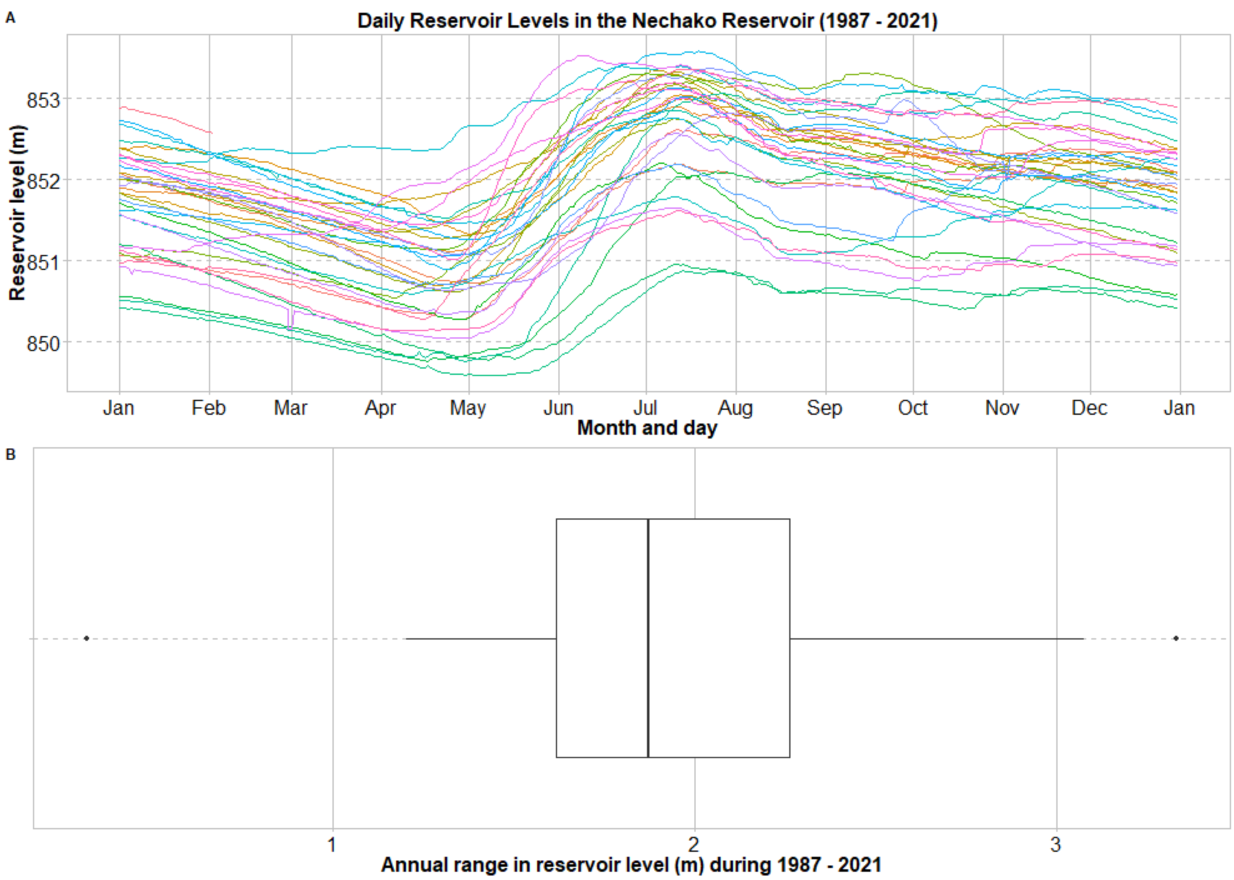
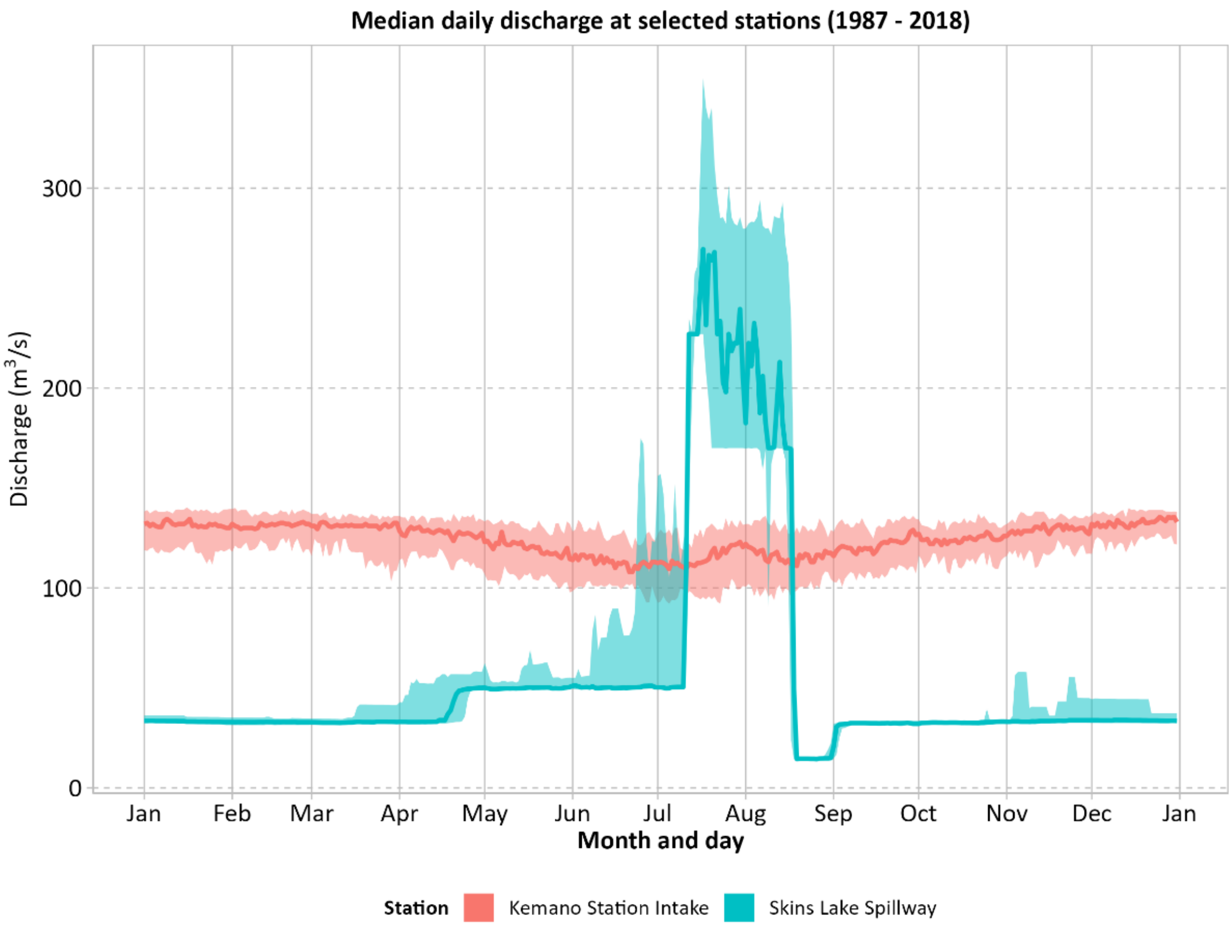


Figure 2. **Median daily discharge during 1987 – 2018 (solid lines) and the 25th and 75th quantiles of the daily discharge (transparent ribbons) at the Skins Lake Spillway and Kemano station intake.**



2.2. Limnology of Nechako Reservoir

Nechako Reservoir is oligotrophic (i.e., nutrient poor) with a steep bathymetric transition between the littoral and pelagic zone (Perrin 2021). The reservoir thalweg is ~40–80 m deep, with the deepest areas in Knewstubb Lake close to Kenney Dam and shallower areas present in the Narrows that connect Knewstubb Lake to Natalkuz Lake where a sill is present at 812 masl (Lawrence *et al.* 2007). Water clarity is high: Perrin *et al.* (1997) report a mean Secchi depth of 6.2 m (n = 22 from 11 sites), equating to an estimated euphotic depth of 12.4 m.

Information about the physical limnology of Nechako is limited, although information has been obtained via modelling studies of the feasibility of a cold water release at Kenney Dam

(James *et al.* 1991; Lawrence *et al.* 2007). Field data collected from Knewstubb Lake and Ootsa Lake in 2022 (Regehr and Kurtz 2022) show that the basins are well-mixed during the winter months and a thermocline typically begins to form in early June (Lawrence *et al.* 2007; Winsby *et al.* 1997[2]). By August, thermal stratification generally becomes well-established, with the thermocline approximately 20 m – 25 m deep and temperatures range approximately 14ºC – 20ºC in the epilimnion, which overlies a metalimnion, below which is the hypolimnion where temperatures range approximately 4ºC – 10ºC (Lawrence *et al.* 2007).

The littoral zone has relatively sparse macrophyte communities (due to fluctuations in reservoir levels; Perrin, 2021), although submerged timber is abundant and provides valuable habitat for fish and benthic communities, including periphyton and invertebrates (Northcote and Atagi 1997). Sampling of littoral benthos in the reservoir has identified a community composed mainly of chironomids (Orthocladiinae, Tanytarsini, Chironomini, Tanypodinae, and Diamesinea), a lower abundance of ostracods, oligochaetes and nematode worms, and trace abundance of mayflies (Ephemeroptera), caddisflies (Tricoptera), gastropods, bivalves (Pelecypoda) and water mites (Hydracarina) (Perrin *et al.* 1997).

Nechako Reservoir is recorded to contain four species of salmonids (Rainbow Trout, Kokanee Salmon, Mountain Whitefish, and Pygmy Whitefish), at least two species of sculpin (Prickly Sculpin and Slimy Sculpin), four species of sucker (Bridgelip Sucker, Largescale Sucker, Longnose Sucker, and White Sucker), three species of minnow (Northern Pikeminnow, Lake Chub, and Brassy Minnow), along with one ling (family: Lotidae) species (Burbot) and one sturgeon species (White Sturgeon) (Table 1).

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[2] Thus, these observations alone indicate a monomictic mixing regime; however, considering the latitude (53°N; Lewis 1983), and the observation that the Nechako River can freeze in cold winters (Faulkner and Ennevor 1999), inverse temperature stratification (i.e., a dimictic regime) presumably occurs in at least some parts of the reservoir during cold winter periods.

Table 1. Summary of fish species observed in the Nechako Reservoir, Murray-Cheslatta River, and the Nechako River.

Family	Common Name	Scientific Name[1]	Geographic Region		
			Nechako Reservoir	Cheslatta Watershed	Nechako River
Burbots	Burbot	*Lota lota*	X	X	X
Lampreys	Pacific Lamprey	*Entosphenus tridentatus*	-	-	X
Minnows	Brassy Minnow	*Hybognathus hankinsoni*	X[2]	-	X
	Lake Chub	*Couesius plumbeus*	X[3]	X	X
	Leopard Dace	*Rhinichthys falcatus*	-	-	X
	Longnose Dace	*Rhinichthys cataractae*	-	X	X
	Northern Pikeminnow	*Ptychocheilus oregonensis*	X	X	X
	Peamouth Chub	*Mylocheilus caurinus*	-	X	X
	Redside Shiner	*Richardsonius balteatus*	-	X	X
Salmonids	Bull Trout	*Salvelinus confluentus*	-	-[4]	X
	Kokanee	*Oncorhynchus nerka*	X	X	-[5]
	Lake Trout	*Salvelinus namaycush*	-	X	-[5]
	Lake Whitefish	*Coregonus clupeaformis*	-	X	-
	Mountain Whitefish	*Prosopium williamsoni*	X	X	X
	Umam	*Prosopium* sp.	X[6]	X[6]	
	Rainbow Trout	*Oncorhynchus mykiss*	X	X	X
Sculpins	Prickly Sculpin	*Cottus asper*	X	-	X
	Sculpins	*Cottus spp.*		X	
	Slimy Sculpin	*Cottus cognatus*	X[3]	-	X
Suckers	Bridgelip sucker	*Catostomus columbianus*	X	-	X
	Largescale Sucker	*Catostomus macrocheilus*	X	X	X
	Longnose Sucker	*Catostomus catostomus*	X	X	X
	White Sucker	*Catostomus commersonii*	X[3]	-	X

"-" indicates no records of species presence in region.

[1] Species presence sourced from: Ableson 1985; Envirocon 1989; Triton 2000a, 2000b, 2000c; Hamilton and Schmidt 2005; NFCP 2005; Triton 2005; Hagen and Decker 2011; BC MOE 2021a, 2021b; Robertson, pers. comm. 2021.

[2] Observations in Skins Lake Spillway plunge pool indicate species could be entrained from Nechako Reservoir (Triton 2005).

[3] Species observed in tributaries of the Nechako River (Triton 2000a, 2000b, 2005) and could potentially use Nechako Reservoir lacustrine habitats.

[6] Species' taxonomic classification is unclear. This fish is important to the Cheslatta Carrier Nation, and it is unclear if the rough translation ("pygmy" whitefish; Triton 2008) relates to a common translation (i.e., "small" whitefish) or refers to *Prosopium coulterii*. The Nation is undertaking ongoing work to better understand whitefish populations in the basin (Triton 2008; Robertson, pers. comm. 2021).

[7] Sculpins in this system are only identified to the genus level.

2.3. Water Quality Sampling, 2022

To collect supplementary information relevant to reservoir productivity, Ecofish completed sampling at two sites in spring (May 31 – June 1) and four sites in summer (July 26 – 28) 2022. Four sites were sampled in basins of Nechako Reservoir – namely, Knewstubb Lake, Ootsa Lake (one site sampled on both trips), Whitesail Lake, Tahtsa Lake – and one site was sampled at a tributary (ER1) to Nechako Reservoir. Sampling was conducted opportunistically while crews were collecting information regarding other issues, although the data nonetheless provided valuable information about reservoir productivity to supplement existing background information. Details of methods and all results are provided in a separate memo (Regehr and Kurtz 2022); pertinent details regarding reservoir productivity are summarized below.

The vertical profile data showed that during late May/early June (May 31–June 1), water temperatures in Whitesail Lake (WS1) were approximately 3.7°C and near-constant at different depths, whereas thermal stratification was present in Ootsa Lake, with temperatures of 8°C or higher at depths of ~ 5 m and temperatures declining to ~ 6°C at a depth of ~10 m. In late July (July 26–28), water temperatures were generally warmer than earlier in the season, with water temperatures warmer in Knewstubb Lake (surface temperature ~ 20°C) than in Tahtsa Lake (surface temperature ~ 13°C). Thermal stratification was observed in both basins in late July. These findings are generally consistent with those of other studies, namely that thermal stratification does not become well-established until the summer months, with the thermocline depth progressively becoming deeper as the summer stratified season progresses (Lawrence *et al.* 2007; Winsby *et al.* 1997). Vertical profiles of dissolved oxygen showed well-oxygenated conditions with vertical variations that were consistent with stratification patterns evident in water temperature data. The available dissolved oxygen did not show evidence of hypolimnetic oxygen consumption, indicative of unproductive conditions.

Secchi depth measurements in Ootsa Lake (5.9 m), Knewstubb Lake (5.1 m and 5.3 m), and Tahtsa Lake (6.3 m) were similar to those measured during earlier field studies. For instance, a mean Secchi depth of 6.2 m was measured at selected locations (n = 22 from 11 site locations) in the reservoir, with an estimated euphotic zone depth of 12.4 m (Perrin *et al.* 1997). These Secchi depth measurements reflect moderately high water clarity, indicative of oligotrophic conditions (Carlson 1977).

Concentrations of chlorophyll *a* (mean 0.00105 mg/L ± SD 0.000691 mg/L), total nitrogen (mean 0.159 mg/L ± SD 0.069 mg/L), and total phosphorus (mean 0.011 mg/L ± SD 0.0020 mg/L) in the reservoir were consistent with an oligotrophic trophic status (Carlson 1977; CCME 2004).

3. METHODS

3.1. Background Review

To identify potential pathways for reservoir management (i.e., changes in reservoir level and flushing) to affect the productivity of Nechako Reservoir, we reviewed literature regarding the effects of flow management operations on aquatic productivity generally (e.g., Furey *et al.* 2004, 2006; Zohary and Ostrovsky 2011), in addition to relevant studies that characterized physical processes and biological communities in Nechako Reservoir (Lawrence *et al.* 2007; Northcote and Atagi 1997). Studies considered included field and modelling studies of the thermal regime of the reservoir (e.g., Lawrence *et al.* 2007), analyses of the effects of reservoir levels on primary productivity (Lucas *et al.* 2009; Perrin 2021), and a similar study of the impacts of water management on the productivity of the downstream Cheslatta watershed (Stockner 2006).

3.2. Water Residence Time Calculations

Water residence time was calculated for the reservoir as a whole and for individual basins to inform assessment of the potential for changes to water residence time (the inverse of flushing rate) to affect reservoir productivity. The calculations were based on historical data regarding reservoir levels, outflow discharge, and basin volume.

Discharge data for Skins Lake Spillway were obtained from Water Survey of Canada, whereas discharge data for the Kemano station outflow were obtained from Rio Tinto. Volume estimates were obtained using GIS analysis of a digital elevation model that was developed based on bathymetry data originally collected by Triton Environmental Consultants and a contour map developed in 1946 – 1947, assuming that reservoir level was 852 masl, which was the mean annual reservoir level during 2000–2020 (data provided by Rio Tinto).

The contour map only included topographic features above the water surface elevation of lakes and rivers that existed in 1946 – 1947, prior to the impoundment of Nechako Reservoir. Consequently, the estimated volumes of the reservoir and its basins are likely biased low, and separate volume estimates for Tahtsa Lake and Tetachuck Lake could not be obtained. However, due to the large volume of the reservoir relative to the volumes of the pre-existing lakes, this issue is assumed to be a minor source of error, consistent with similar assumptions made in previous studies of the reservoir (Lawrence *et al.* 2007; Perrin 2021).

The residence time (years) of water in a waterbody is defined as the mean duration of time that a parcel of water remains in a waterbody, and was calculated as:

$$Residence\ time = V/Q_{out}$$

where V (m^3) is the volume of the waterbody and Q_{out} (m^3/year) is the outflow (i.e., discharge) from the reservoir. Water residence times were estimated separately for the entire reservoir, as well as four main basins (Ootsa, Knewstubb, Whitesail, and Natalkuz Lake). Furthermore, water residence times were calculated separately on an annual basis and also for the growing season, which was assumed to be May to October inclusive (Stockner 2006). Annual water residence time was calculated based on the full volume of the reservoir basins, whereas the growing season water residence time was calculated based on the estimated volume of the epilimnion, i.e., the surface mixed layer present during the summer stratified period. The depth of the epilimnion was assumed to be 20 m based on Lawrence *et al.* (2007). Water residence time was calculated based on the mean total discharge observed during 2000–2018, with discharge data for only May through October used for the growing season water residence time calculations. To understand how changes to reservoir outflow could potentially affect water residence time, scenarios comprising an increase or decrease in discharge of up to 50% were simulated in 5% increments.

4. RESULTS

4.1. Overview of Potential Pathways of Effect

Key mechanisms by which Skins Lake Spillway and Kemano Hydroelectric Project operations could potentially affect aquatic productivity in the Nechako Reservoir are summarized as follows:

1. Changes in reservoir water levels can affect habitat quantity;
2. Changes in the timing, frequency, or magnitude of reservoir water level fluctuations can affect productivity of riparian and littoral habitats due to inundation and dewatering of these habitats;
3. Changes to reservoir outflows can change the water residence time of the reservoir, influencing flushing of planktonic biomass and nutrient retention; and
4. Changes in reservoir volume and water residence time can influence thermal stability and associated stratification processes, potentially affecting aquatic productivity.

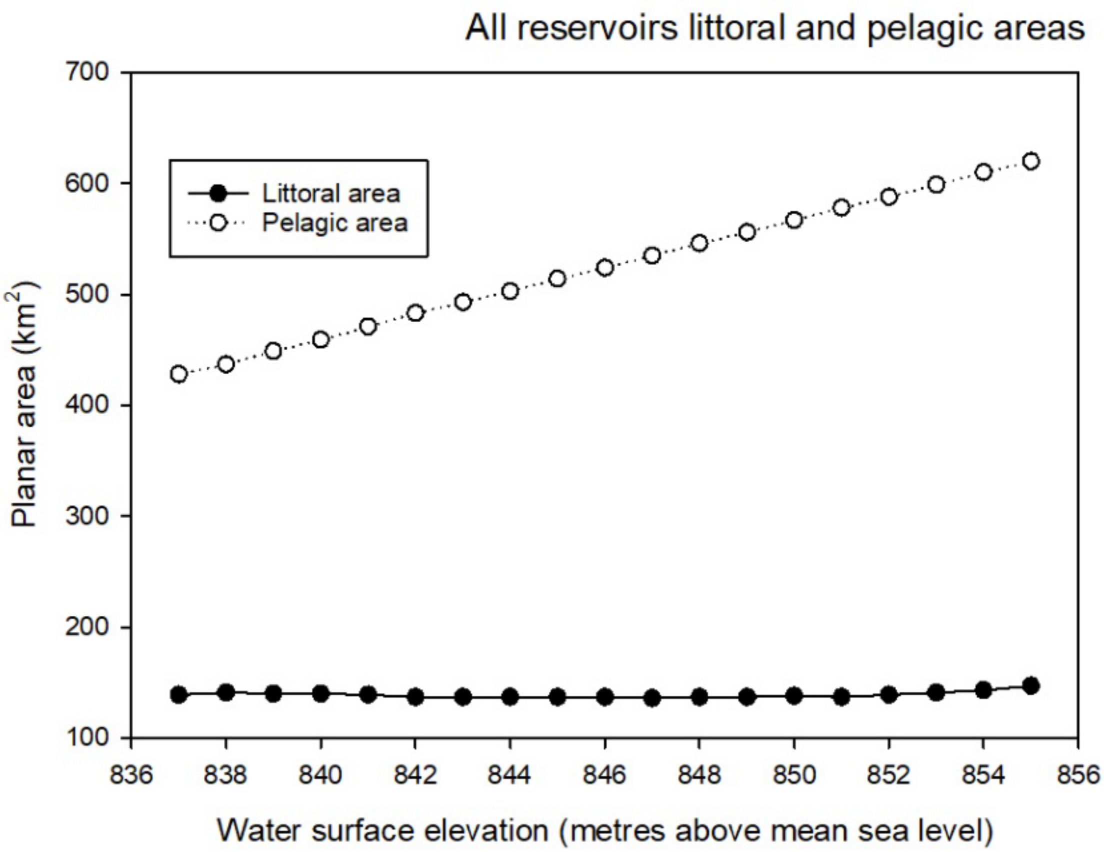
Each of these four mechanisms is described separately in further detail in the sub-sections below.

4.2. Changes to Reservoir Habitat Quantity

Fluctuations in reservoir water levels change reservoir volume and thus aquatic habitat quantity. Reductions in reservoir water level intrinsically reduce aquatic habitat quantity although, depending on reservoir morphometry, impacts of water level changes may vary between littoral (nearshore/shallow) and pelagic (offshore/deep) habitats.

The potential effects of reservoir operations on the productivity of Nechako Reservoir due to direct changes to habitat quantity were considered for the WEI by Perrin (2021), as summarized in a presentation by Ecofish to the WEI Technical Working Group on January 19, 2022. Specifically, Perrin (2021) estimated the impacts of fluctuating water levels on (1) the area and volume of the littoral and pelagic zones, and (2) the total primary productivity within these zones. A key result was that the quantity of littoral habitat (assumed to be habitat <13 m deep) in Nechako Reservoir is insensitive to changes in water levels, whereas the area of pelagic habitat (>13 m deep) increased linearly with increasing reservoir water levels (Perrin 2021; Figure 3). Changes in the abundance of pelagic habitat were estimated to cause proportional changes in the biomass of zooplankton available to support aquatic productivity (Perrin 2021), including zooplanktivorous fishes such as kokanee. Implications of these key results for reservoir management and associated uncertainties are described by Perrin (2021).

Figure 3. Change in pelagic and littoral areas over a range of water surface elevations in Nechako Reservoir. Tahtsa Lake and Tetachuck Lake were omitted from analysis due to insufficient bathymetric data. Reproduced from Perrin (2021).



4.3. Inundation/Dewatering of Littoral/Riparian Habitats

Reservoir level fluctuations can affect productivity due to unnatural cycles of wetting and drying in riparian and littoral habitats, which cause declines in riparian and aquatic plant biomass due to desiccation and disturbance within drawdown zones (Wilcox and Meeker 1991; Furey *et al.* 2004; Turner *et al.* 2005). Such impacts are frequently considered during water use planning in BC watersheds where changes to reservoir operations have potential to change water levels in reservoirs (Krogh *et al.* 2019; d'Entremont *et al.* 2020; Miller and Hawkes 2020).

Under the current operating regime, a mitigating factor is that the annual drawdown range of Nechako Reservoir is relatively low: the median annual reservoir level range is ~1.9 m with annual range < 2.4 m during >75% of years (Figure 1). By contrast, the drawdown range is in the order of tens of metres in several reservoirs in BC where adverse effects to nearshore productivity is a recognized management issue (Table 2). Accordingly, although vegetation is generally absent or sparse in the drawdown zone of Nechako Reservoir, the drawdown zone is narrow, with flood-tolerant vegetation such as willow and emergent herbaceous species present in areas (Figure 4), as noted during the spring and summer 2022 field trips – see Regehr and Kurtz (2022) and photographs therein for further details of shoreline vegetation characteristics at Nechako Reservoir. Changes to reservoir management that increase the range of water level fluctuations or otherwise increase hydrological disturbance in nearshore areas (e.g., by increasing the frequency of water level fluctuations) have potential to adversely affect productivity of plants and invertebrates in riparian and littoral habitats.

Table 2. Drawdown ranges in a sample of lakes/reservoirs (including control lakes) where the effects of water level fluctuations on nearshore productivity have been studied.

Waterbody	Drawdown Range (m)	Comments	Reference
Arrow Lakes Reservoir, BC	21.46	Based on normal operating ranges. Impacts to shoreline vegetation are a management issue; revegetation studies are ongoing.	Miller and Hawkes (2020)
Kinbasket Reservoir, BC	46.97		
Williston Reservoir, BC	29.9	Based on normal operating ranges. Impacts to shoreline vegetation are a management issue.	BC Hydro (2007); d'Entremont *et al*. (2020)
Upper Campbell Reservoir, BC	8.5	Based on min./max. operating levels. Studies have been undertaken to inform management of riparian/littoral impacts	BC Hydro (2012); Krogh *et al*. (2018)
Lower Campbell Reservoir, BC	4.3		
Sooke Reservoir, BC	4.5	May–Sept, 2000	Furey *et al.* (2004)
Shawnigan Lake, BC	0.6	Unregulated control lake; May–Sept, 2000	
Rainy Lake, MN, USA	1.9	Unregulated condition, annual mean	Wilcox and Meeker (1990)
	1.1	Regulated condition, annual mean	
Namakan Lake, MN, USA	1.8	Unregulated condition, annual mean	
	2.7	Regulated condition, annual mean	
Lake 226, ON	~2–3	Experimental treatments over three years	Turner *et al.* (2005)
Kamsloops Lake	5.0	Unregulated; large natural drawdown range	ILEC (2022)

Figure 4. Inundated vegetation (shrubs and emergent plants) along the margins of the reservoir shoreline at the southern end of a bay at the south side of Knewstubb Lake, July 28, 2022. Photograph reproduced from Regehr and Kurtz (2022), which presents additional photographs that further show the range of shoreline habitats at Nechako Reservoir.

4.4. Hydraulic Flushing and Pelagic Productivity

4.4.1. Water Residence Time

Phytoplankton (suspended algae) form the foundation of the pelagic food web in lakes. Phytoplankton are grazed by zooplankton (suspended invertebrates), which in turn are prey for planktivorous fish. In the epilimnion, phytoplankton growth rates are often highest in spring (i.e., the "spring bloom"), when surface temperatures increase, and nutrient concentrations are elevated following vertical mixing (Kalff 2002).

Increasing outflows from a reservoir can reduce water residence time, leading to "transport losses" of planktonic biomass and nutrients that are flushed from the system (Lucas *et al.* 2009). Small reservoirs and reservoirs with high outflows (relative to their volume) are particularly vulnerable to flushing effects and can become net exporters of nutrients and biomass, leading to a decline in trophic status (e.g., Dickman 1969). High flushing rates have been identified as a cause of reduced productivity in lakes in the Cheslatta watershed (Stockner and Slaney 2006).

Estimates of lake volume (Figure 5) were used to calculate water residence time (Figure 6) to examine the potential for flushing to affect reservoir productivity. At observed water levels (i.e., 849.6 – 853.6 m; 1987 – 2020), the volume of Nechako Reservoir is approximately 17.71 – 20.84 billion m^3, based on analysis of Ootsa, Natalkuz, Whitesail, and Knewstubb basins (listed in order of decreasing volume). At 852 m (i.e., a typical mean annual elevation based on the mean annual reservoir elevation during 2000 – 2020; Figure 1), the estimated reservoir volume is approximately 19.25 billion m^3.

Based on this volume, and a mean total daily outflow from Nechako Reservoir of 227 m^3/s (based on the growing seasons of 2000 – 2018), the estimated water residence time is 980 days (2.7 years) based on the volume of the entire reservoir, or 637 days (1.7 years) based on the volume of the epilimnion, which is most applicable to calculating water residence time in the growing season when the reservoir is stratified and water is withdrawn from the surface mixed layer (Figure 6). Increasing the mean total outflow by 50% to 341.0 m^3/s would reduce the water residence time to 653 days (1.8 years) based on the volume of the entire reservoir, or 425 days (1.2 years) based on the volume of the epilimnion (Figure 6).

In addition to considering the whole reservoir, the dendritic morphometry of the reservoir means it is relevant to also consider hydraulic conditions in individual basins. If outflow were to increase from approximate current conditions (mean outflow = 227 m^3/s) by 50% then annual water residence time in Ootsa Lake would decline from 494 days to 330 days (1.4 years to 0.9 years) based on the whole basin volume, or from 331 days to 221 days based on the volume of the epilimnion (Figure 6). Whitesail and Natalkuz basins are similar in volume and therefore have similar water residence times, with the epilimnetic residence time declining from 133 days to 88 days in Whitesail Lake and from 118 days to 79 days in Natalkuz Lake (Figure 6) under the scenario of 50% increased outflow. Of the four main basins, Knewstubb Lake has the shortest water residence time, e.g., the estimated epilimnetic residence time based on current operations is 48 days, which declines to 32 days for a scenario of 50% higher outflows (Figure 6).

These calculations provide a screening-level analysis to support an initial evaluation of the potential influence of flushing. The analysis made several simplifying assumptions, notably ignoring (1) variability in reservoir inflows, (2) fluctuations in water levels (which affect storage), (3) complications associated with the complex reservoir morphometry, and (4) the unusual feature of two large outflows located at opposite ends of the reservoir. These simplifications limit the accuracy of the water residence time estimates (Monsen *et al.* 2002), although we maintain that the estimates are nonetheless useful to inform the need to consider the issue in further detail during the water use planning process. As discussed in Section 5.3, a three-dimensional hydrodynamic model could be used to better understand physical mixing processes in the reservoir.

Figure 5. Relationship between estimated volume and water level in Nechako Reservoir (red line; all basins combined) and in separate basins. The vertical solid black lines indicate minimum and maximum observed reservoir levels (849.6 – 853.6 m) during 1987 – 2020.

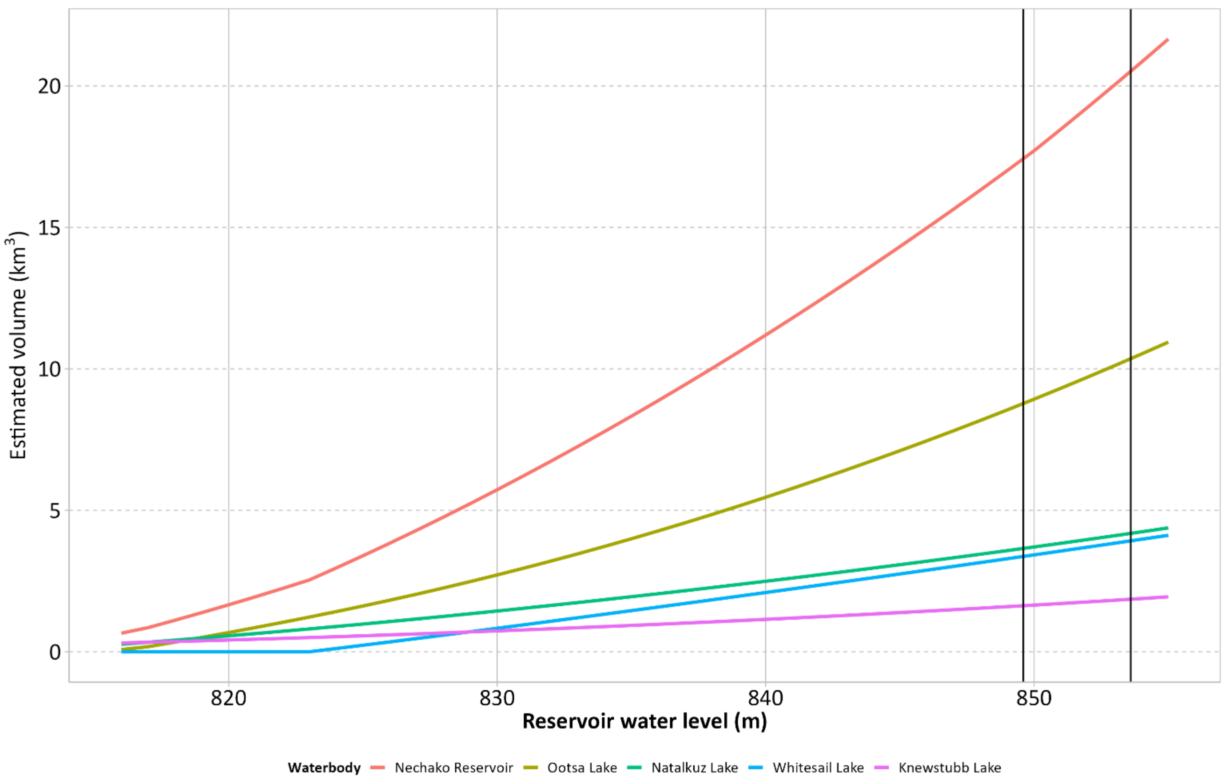
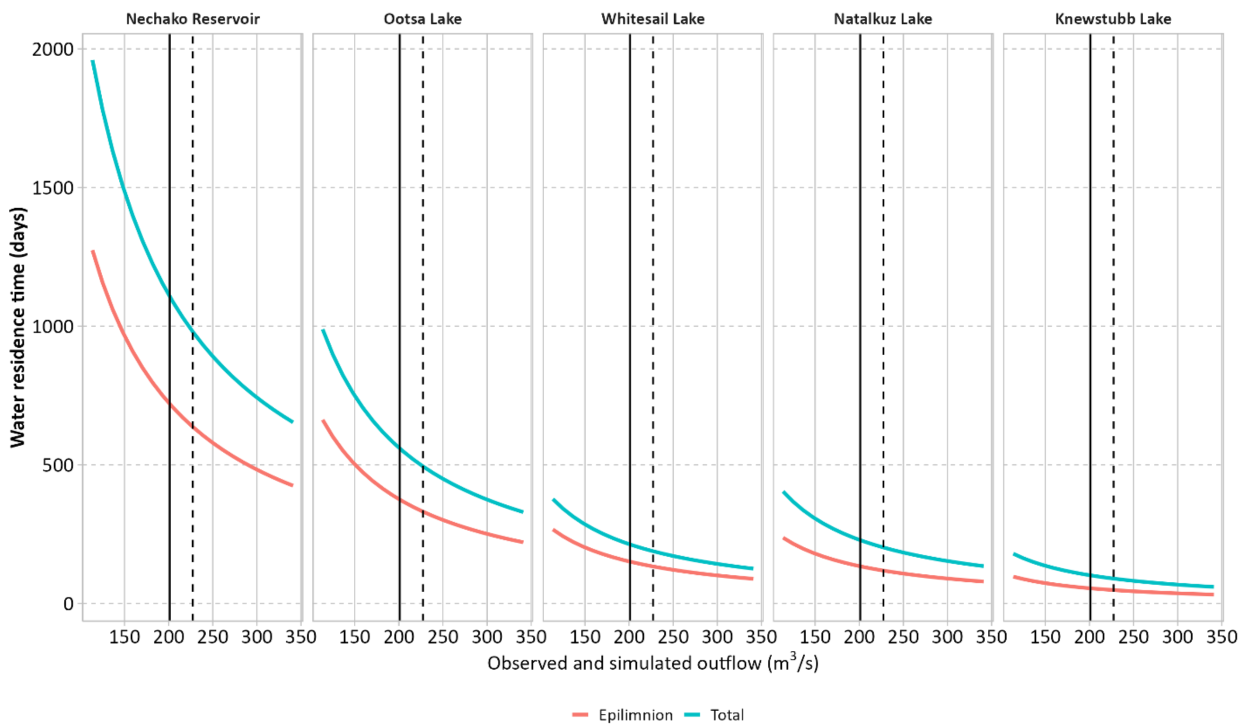


Figure 6. **Estimated water residence times in the Nechako Reservoir and its basins. The vertical black lines indicate the mean annual observed outflows during the entire year (solid line; 201.1 m^3/s) and the growing season (dashed line; 227.4 m^3/s). Water residence times are presented separately based on the total volume of the reservoir/basins and the epilimnion (most relevant to the growing season).**



4.4.2. Plankton Ecology

To evaluate potential effects to reservoir productivity, it is pertinent to consider water residence time in the context of the ecology of plankton, which is an important driver of pelagic productivity. A key point is that this effect pathway is only relevant if flushing is sufficiently high to reduce water residence time to low values that are comparable with the intrinsic growth rates of plankton. It is necessary to consider phytoplankton and zooplankton in the effect pathway. The synthesis of literature below is partly reproduced from an unpublished information sheet developed by Ecofish for a separate water use planning process (Abell and Hatfield 2018).

The maximum intrinsic growth rates of phytoplankton in natural environments (i.e., accounting for losses) are typically of the order of 0.1–1/day (Reynolds 2006 and references therein). This means that increased flushing is not expected to significantly affect phytoplankton productivity unless water residence time is reduced to the order of days to weeks. Based on this assumption, a water residence time of 20 days has been proposed as an appropriate threshold below which flushing has potential to exert a substantial effect on phytoplankton biomass (Hamilton and Dada 2016).

Zooplankton taxa have longer generation times and are therefore more sensitive to flushing effects than phytoplankton. The effect of flushing on zooplankton production is variable but flushing has been demonstrated to exert a biologically significant effect in some systems such as rapidly flushed impoundments. For example, zooplankton biomass increased approximately 19-fold when water residence time was increased from 4 to 338 days in a Newfoundland reservoir (Campbell *et al.* 1997). The relationship between zooplankton production and water residence time is expected to be non-linear, with the effect declining as water residence time increases. Walz and Melker (1998) proposed that lentic plankton communities do not develop at all below water residence times of ~3 days. The authors report relationships between the biomass of zooplankton taxa and water residence time in the range of ~1 day to 53 days for a single lake. Based on these relationships, maximum biomass was achieved at a water residence time of less than 53 days for the majority of taxa, indicating that the biomass of these taxa was insensitive to changes to water residence time when water residence time exceeds 53 days. Exceptions were some copepods, which are important prey for zooplanktivorous fish. A study of 11 waterbodies near Campbell River (BC) showed no positive relationship between zooplankton biomass and growing season water residence time (range = 0.5 to 874 days), with the highest zooplankton biomass measured in small productive lakes with short water residence time (Hocking *et al.* 2017). This result is instructive, although the study made comparisons among (not within) lakes and therefore other limiting factors were not controlled. A similar study in a montane lake in Italy showed that the zooplankton community switched from being dominated by rotifers to being dominated by crustacea above a threshold water residence time of 193 days (Obertegger *et al.* 2007). Crustacean zooplankton taxa are preferred prey for fish and therefore such changes in community composition are relevant to fish productivity.

Based on the studies cited above, the following general inferences can be made:

- Decreasing water residence time to less that ~3 weeks could reduce phytoplankton production;
- Decreasing water residence time to less than several months could reduce production of crustacean zooplankton with long generation times. Biologically significant declines in zooplankton biomass are most likely to occur when water residence time is less than ~2 months;
- Decreasing water residence time to less than ~200 days could cause a shift in the zooplankton community that could potentially adversely affect fish production.

4.4.3. Evaluation

Considering the results of the residence time analysis (Section 4.4.1) in the context of plankton ecology (Section 4.4.2) indicates that Nechako Reservoir productivity is generally insensitive to flushing. For example, even assuming a scenario of a 50% increase in mean outflow, the estimated epilimnetic water residence time is 424 days, which is higher than the indicative thresholds identified in the bullets above at which plankton productivity may potentially be affected, based on studies elsewhere. A qualifier is that horizontal mixing can be limited in reservoirs such as Nechako that have dendritic morphometry (Trolle *et al.* 2014) and therefore it is feasible that large increases in outflow from small basins such as Knewstubb Lake could have localized effects, although the potential influence of such a scenario on overall reservoir productivity is nonetheless expected to be minor.

4.5. Thermal Stability and Stratification

Nechako reservoir thermally stratifies during the summer, with maximum thermocline depth of 20 m – 25 m typically occurring in August (Section 2.2). Thermal stratification in deep reservoirs during the summer creates a surface mixed layer (epilimnion) where pelagic primary productivity is highest and phytoplankton and zooplankton can proliferate, physically isolated from deeper hypolimnetic waters that have cooler temperatures and low light irradiance (Kalff 2002). Changes to reservoir management and separate environmental factors have potential to affect stratification characteristics (Duka *et al.* 2021), potentially affecting pelagic productivity.

Field experiments in Canada have shown that artificial deepening of the thermocline in multi-basin lakes can lead to increases in zooplankton biomass and shifts in zooplankton community composition (Cantin *et al.* 2011; Gauthier *et al.* 2014). Climate change is expected to affect thermocline depth and mixing in reservoirs through changes in wind stress, air temperature, and precipitation (Gauthier *et al.* 2014; Sastri *et al.* 2014).

Key aspects of reservoir operation that may affect thermal stability are changes to the depth of reservoir outflows and changes in reservoir elevation (Monosmith and MacIntyre 2009; Duka *et al.* 2021). Changes to physical water withdrawal infrastructure are not being considered as part of the WEI process; however, changes in reservoir elevation are being considered to support downstream flow scenarios. The stability of stratification is closely related to reservoir depth, with the water column exhibiting greater resistance to mixing (i.e., more stable) in deeper reservoirs (Kalff 2002; Monosmith and MacIntyre 2009). Therefore, management scenarios that result in lower reservoir elevations (i.e., reduced depth) could reduce thermal stability and thereby affect stratification. However, a key mitigating factor is that Nechako Reservoir is deep (maximum depth along the thalweg is ~ 40–80 m; Section 2.2) and therefore reductions in reservoir elevation would need to be large to cause substantive changes to thermal stability. For context, a maximum depth of 10 m is considered a “rule of thumb” to distinguish temperate lakes that stably stratify in the summer from lakes that are potentially polymictic and may therefore mix multiple times through the growing season

(Padisák and Reynolds 2003). Thus, unless scenarios entail particularly large decreases in reservoir elevation (e.g., >10 m), there is expected to be low potential for changes to reservoir management to affect reservoir productivity via this pathway. Hydrodynamic modelling could help to more precisely evaluate the potential effects of management scenarios on the physical limnology of Nechako Reservoir.

5. DISCUSSION

5.1. Limiting Factors

A key factor limiting aquatic productivity in Nechako Reservoir is low nutrient concentrations (Section 2.2). Unlike the smaller lakes in the Cheslatta watershed (Stockner and Slaney 2006), flushing is not considered to be an important limiting factor in Nechako Reservoir due to the relatively long water residence time (Section 4.4.1).

5.2. Data Gaps

Information regarding the aquatic ecology of Nechako Reservoir is limited in general and recent (post 2000) data are particularly limited. For example, recent data were generally not identified in relation to plankton communities, macroinvertebrates, littoral habitats, and water chemistry. There is an uncertainty regarding physical processes in the reservoir (e.g., horizontal/vertical mixing, water fluxes between basins). Valuable information regarding physical limnology is provided by Lawrence *et al.* (2007), although their work specifically focused on a hypothetical deep-water withdrawal and the authors noted that computational limitations constrained the scope of hydrodynamic modelling studies that were possible at the time, ~15 years ago. Imam *et al.* (2013; 2020) have since provided additional insights to physical limnology, focused on Knewstubb and Natalkuz lakes.

Despite these limitations, available information was sufficient to evaluate potential performance measured for the WEI to consider (see below), although guidance has been provided regarding how uncertainty could be reduced if desired.

5.3. Potential Performance Measures

Performance measures are metrics for evaluating how changes in hydrological metrics such as flow or reservoir elevation affect a particular interest or issue. We have identified preliminary performance measures for the WEI to consider as part of the structured decision-making process. Additionally, suggestions are provided regarding how preliminary 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 pathway of effect. It is important to recognize that the potential performance measures presented here might be revised, replaced, or ignored depending on the specific needs and interests of the WEI.

Changes to Reservoir Habitat Quantity: Perrin (2021) showed that the quantity of shallower littoral habitat in Nechako Reservoir is insensitive to changes in water levels, whereas the area of deeper pelagic habitat increases linearly with increasing reservoir water levels (Figure 3). Accordingly, PM1 below is proposed for initial consideration by the WEI:

- PM1: Area of pelagic habitat.

PM1 can be calculated based on the linear relationship derived by Perrin (2001), shown in Figure 3. Higher values will represent preferable conditions.

Inundation/Dewatering of Littoral/Riparian Habitats: Changes to reservoir management that increase the range of water level fluctuations or otherwise increase hydrological disturbance in nearshore areas (e.g., by increasing the frequency of water level fluctuations) have potential to adversely affect productivity of plants and invertebrates in riparian and littoral habitats. Under current conditions, the range of water level fluctuations at Nechako Reservoir is relatively low (Figure 1; Table 2); however, changes to reservoir outflows have potential to change this status.

PM2 below is proposed for initial consideration by the WEI:

- PM2: Mean annual range of Nechako Reservoir water level during the growing season.

PM2 will be calculated for each scenario by calculating the mean annual range in water level in Nechako Reservoir during the growing season, assumed to be May through October. Lower values will indicate preferable conditions.

If the WEI seeks a more-detailed approach, modelling that considers an "effective littoral zone" could be considered to better understand the effects of reservoir management on the littoral zone. Notably, work has already been undertaken by Lewis (2001) to describe how such a modelling approach could be applied specifically to Nechako Reservoir. Additionally, modelling approaches have been developed to support water use planning elsewhere in BC to examine the potential effects of reservoir management on riparian productivity (Krogh *et al.* 2019). Such modelling approaches could therefore help to extent PM2 to better evaluate differences among management scenarios, although substantial modelling work and potentially fieldwork would be required to integrate such modelling approaches into the WEI process. The need for such additional studies could be revaluated once potential changes to reservoir management are better understood.

Hydraulic Flushing and Pelagic Productivity: Analysis described in Section 4.4 showed that changes to reservoir management that affect flushing have low potential to affect productivity in Nechako Reservoir because water residence time is long. Accordingly, no performance measure is proposed in relation to this pathway of effect.

Assumptions that were made during this assessment should be evaluated when timeseries of reservoir outflows have been developed for management scenarios to confirm that this pathway of effect remains a low priority for the WEI's consideration. For example, a scenario that entails an extremely high reservoir release during the growing season (e.g., greater than historical peak flows) could theoretically cause an adverse effect to reservoir productivity by flushing plankton and nutrients downstream. Furthermore, as described in Section 4.4.1, the water residence time calculations presented here provide only a screening-level analysis and assumptions such as ignoring non-steady state flow, the complex morphometry, and the presence of two outflows limit the accuracy of the water residence time estimates (Monsen *et al.* 2002). A hydrodynamic model (discussed further below) could be used to provide more accurate water residence time estimates, although the substantial additional effort required may not be warranted based on the screening-level results presented here.

Thermal Stability and Stratification: As described in Section 4.5, changes to reservoir management have potential to affect thermal stratification, potentially affecting pelagic productivity. However, a key mitigating factor is that Nechako Reservoir is deep (maximum depth along the thalweg is ~40-80 m; Section 2.2) and therefore reductions in reservoir elevation would need to be large to cause substantive changes to thermal stability. Currently, it is assumed that changes to thermal stability due to potential changes to reservoir management will generally be within the range of interannual variation that is currently observed due to background variability in factors that include solar radiation, wind speed, and reservoir elevation. Overall, potential effects to reservoir productivity are expected to be minor, challenging to predict precisely, and sensitive to interannual variability in meteorological conditions. Furthermore, there is partial redundancy with PM2 (water level range) because large fluctuations in reservoir elevations are expected to have greater potential to cause changes to thermal stability than small fluctuations. Accordingly, no performance measure is proposed in relation to this pathway of effect.

Assumptions that were made during this assessment should be re-evaluated when timeseries of reservoir elevation and reservoir outflows have been developed for management scenarios to confirm that this pathway of effect remains a low priority for the WEI's consideration. For example, it is assumed that the reservoir will not be drawn below an elevation of 812 masl (drawdown of ~40 m), which is the elevation of the sill that separates Knewstubb Lake and Natalkuz Lake (Lawrence *et al.* 2007). Hydrodynamic modelling could help to more precisely evaluate the potential effects associated with management scenarios on the physical limnology of Nechako Reservoir. Due to the complex morphometry of the reservoir, such a study would require configuring and validating a three-dimensional (rather than a one-dimensional) hydrodynamic model of the reservoir, potentially by building on the work that was initiated by Lawrence *et al.* (2007) and subsequently advanced by Imam *et al.* (2013; 2020), which focused on Knewstubb and Natalkuz lakes.

6. CLOSURE

This memo provides a review of the potential for changes in reservoir management (reservoir outflow and water levels) to affect aquatic productivity in the Nechako Reservoir. Outcomes of the review have been used to develop preliminary performance measures for the WEI to consider, and data gaps have been identified that could be addressed with further study.

Yours truly,

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Disclaimer:

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