The Efficacy of Reservoir Flow Regulation for Moderating Migration Temperature for Sockeye Salmon in the Nechako Watershed

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ABSTRACT

Since the early eighties a water temperature management program has been in existence on the Nechako River system in central British Columbia, Canada. The program releases water based on anticipated meteorological conditions to meet a summer temperature target downstream and benefit spawning migrations of sockeye salmon in the Nechako River. Since the inception of the program the temperature target has been exceeded only rarely but an independent analysis of the role played by the water releases has not occurred. Increasing demand for water at other times of year and a desire to restore a more natural hydrograph to the river to meet other ecological demands has impelled this analysis. A principal component analysis that examined the factors contributing to river temperature demonstrated that the summer controlled flow releases accounted for 24% of the temperature variability and were likely a factor in maintaining compliance to the program's temperature target. Furthermore, during most summers, the Nechako River was cooler than the Stuart River, providing a cooling influence in the reach downstream of the target location, the reach used by the majority of migrating sockeye salmon. Nechako water temperature influences pre-spawning mortality (30.4% of variability) suggesting that attempts to moderate summer water temperatures through releases in the upper Nechako watershed can mitigate against poor spawning success of sockeye populations that migrate through the lower reaches of the system.

KEY WORDS: salmon migration, water withdrawal, water temperature impacts, reservoir management, pre-spawning mortality

1. INTRODUCTION

The regulation of river flow and the impoundment of water have often been in conflict with ecological values (Ward and Stanford 1987; Dynesuis and Nilsson 1994). This conflict has led to management schemes that seek mitigation strategies to allow water use development while conserving natural values. However, after a water use plan has been adopted there have been very few cases where the plan's efficacy has been evaluated relative to the original objectives (Lewis and Mitchell 1995). Evaluations of the objectives are frequently hampered by poorly defined assessment criteria or the objectives themselves may be questioned as having no influence on the productive capacity of a particular fish species (Larkin 1984; Castleberry *et al*. 1996). A summer water management plan in the Nechako River watershed (Figure 1) was designed in 1981 to release water to moderate water temperatures during a period critical to sockeye salmon migration. It provides a unique opportunity to test the efficacy of a water use plan to mitigate temperature while assessing the overall purpose of temperature control to benefit sockeye salmon. Both the efficacy and the overall objective of this plan need to be justified because the release of large volumes from a reservoir in the summer comes at the expense of broader management goals that include power generation, irrigation and the maintenance of a natural hydrograph to preserve additional biological values.

In 1951, the Aluminium Company of Canada (later Alcan Inc.) began construction of the Kenney Dam on the Nechako River to create the Nechako Reservoir, and in 1956 began diverting water out of the watershed for hydropower at Kemano (Figure 1). Since 1978, the majority of available water has been used for power generation. The remaining water is released from the reservoir via a flow control spillway constructed on Skins Lake called Skins Lake Spillway (SLS). These controlled releases from SLS through the Cheslatta system to the Nechako River provide for conservation of fisheries resources downstream. Initially these released flows were highly variable but following a court injunction in 1980, Alcan began releasing year-round base flows (30 cms at Cheslatta Falls) for the benefit of Chinook salmon (*Oncorhynchus tshwaytscha*) and additional summer 'cooling flows' for the benefit of migrating sockeye salmon (*O. nerka*) in the Nechako River between Stuart River and Nautley River confluences (NFCP 2005; Macdonald *et al.* 2007) (Figure 2). The summer water release, now referred to as the Summer Temperature Management Program (STMP) is based on computer modelled water temperature responses to anticipated meteorological conditions in the watershed between July 10th and August 20th. It has resulted in a mean daily release from 158 to 335 cms, from the surface of the Nechako Reservoir through the Skins Lake Spillway from 1981-2006. The temperature target at Finmoore of 20^{o}C ((Figure 1; NFCP 2005), a limit considered the highest daily mean temperature safe for migrating adult sockeye at the time of STMP initiation (IPSFC 1979), is only rarely exceeded. However a test of the efficacy of water release to moderate downstream temperature has not occurred. The first goal of this paper is to examine the efficacy of these releases; validation of the model on which the STMP is based is the subject of a future publication.

Release of large volumes of water from reservoirs have been used in many jurisdictions to moderate water temperature downstream. Releases from the Dworshak Reservoir, Idaho, cool summer water temperatures in the lower Snake River for Chinook smolts and returning adults (Clabough *et al.* 2006). Introducing minimum flow regimes in the Platte River, Idaho, has been proposed as a method to mitigate against temperature peaks during summer low flow periods (Gu *et al.* 1998) and to preserve habitat values associated with eight endangered fish species and hundreds of migratory birds (Gu et al 1999). However, management releases frequently violate the natural flow paradigm which promotes the management of flow regimes with consideration to natural hydrologic variation (Enders et al. 2009), and can create water use conflicts among other interest groups (Gu *et al*. 1998; Sinokrot and Gulliver 2000). Temperature targets can be met with less water if the releases incorporate cooler deep water as demonstrated in the River Haddeo, UK (Webb and Walling 1997) and the Flathead River, Montana (Stanford and Hauer 1992). In the Nechako watershed, recent consideration of the broader concerns of many Nechako stakeholder groups (Bouillon 2004; Macdonald *et al.* 2007) may allow the reduction of summer reservoir flow releases contingent on the development of cold water release capabilities at the Kenney Dam (Figure 1). Cost estimates for this capability exceed 200 million dollars but improved water temperature control may broaden water management options (e.g. release volumes and timing) and enable a more active management of a wider list of biota such as the endangered white sturgeon (*Acipenser transmontanus*) (COSEWIC 2003; McAdam *et al.* 2005). However, the achievement of the current STMP target temperature at Finmoore in the middle Nechako with lower water volumes will likely have temperature implications in the lower Nechako watershed below its confluence with the Stuart River during summer sockeye salmon migrations. Therefore a second goal of this study was to examine the ability of the STMP to influence water temperature in the summer in the lower-Nechako River below its confluence with the Stuart River and below the STMP target location at Finmoore.

Summer temperatures are particularly relevant during sockeye salmon migrations. The Early Stuarts and a smaller run to the Nadina River, enter the Fraser River in early July and are in the lower Nechako River between July 8th to August 9th (Macdonald *et al.* 2007), when temperatures are at an annual high. These temperatures are the warmest they will experience during their normal four year lifecycle (Figure. 3). The Nadina run proceeds past Finmoore into the middle reach of the Nechako River, while the Early Stuart run enters the Stuart watershed (Figure 1). The Early Stuart run has had historic runs in excess of 200,000 fish but has experienced an 84% decline in the last 15 years despite a reduction in harvest rate (Cass *et al.* 2006). During the three or four days that sockeye salmon spend in the lower Nechako River, they are frequently exposed to daily mean temperature in excess of 20°C. These temperatures, have been cited as lethal thresholds for salmon (Brett 1952; Bouck *et al.* 1975), creating impediments to migration (Cooper and Henry 1962; Major and Mighell 1966; Keefer *et al.* 2004; Salinger and Anderson 2006), reducing swimming performance by depleting energy and promoting exhaustion (Gilhousen 1980; Rand and Hinch 1998), eliciting immunosuppression and disease development (Anderson 1990; Schreck *et al.* 2001), and have led to large losses to the Early Stuart run during their freshwater return (Macdonald *et al.* 2000a and b; Cooke *et al.* 2004). Also the incidence, development rate and virulence of bacterial and parasitic infection in salmon are positively associated with temperature (Williams 1973; Williams *et al.* 1977). This includes the myxosporean parasite *Parvicapsula minibicornus,* a contributing factor to freshwater en route loss of Fraser sockeye (St-

Hilaire *et al.* 2001). Migration temperatures bordering 20°C and infection severity has been cited as a cause for reduced spawning success (pre-spawn mortality, PSM) in many salmonid stocks (Gilhousen 1990; Traxler *et al.* 1998; Macdonald *et al.* 2000a; Quinn *et al.* 2007). Among upper Fraser River sockeye salmon, PSM is generally 10% but can reach and exceed 40% during warm years particularly in the early runs (supplementary figure 1). The availability of sufficient data to examine the relationship between temperature and the spawning success of Early Stuart sockeye salmon provides an opportunity to relate the potential temperature benefits of the current reservoir flow release program, the STMP, or future temperate control initiatives, to a biologically relevant criterion. This is the studies' third goal.

This paper describes the STMP, a water use plan that was designed 30 years ago to moderate summer temperatures in compensation for water lost to 50 years of hydroelectric generation. Our ability to gauge the plan's influence in terms sockeye salmon migration success is considered only after an analysis ensures that the release of large quantities of water has been effectively moderating temperatures at sites downstream during the variety of conditions encountered during three decades of summers. The goals of this paper can be described with three hypotheses to be tested in the following order:

1. The STMP has had no effect on Nechako River water temperature at Finmoore.
2. Annual water volumes associated with the STMP have no influence on water temperature below Finmoore and the Stuart-Nechako confluence, in the lower Nechako River.

3. Sockeye salmon spawning success bears no relation to temperatures at selected locations during their migration from coastal locations to their spawning ground.

2. MATERIALS and METHODS

2.1 Study Area

The Nechako River is located in the northern portion of the interior plateau of British Columbia. The Nechako and its tributaries drain an area of approximately 47,200 km^2 which accounts for approximately 20% of the Fraser basin. Since the construction of the Kenney Dam, the Nechako River has been regulated by releases from the reservoir through Skins Lake spillway, Cheslatta Lake, River and Falls (Figure. 1). During the 275 km passage from Cheslatta Falls to join the Fraser River at Prince George, the volume of the Nechako is approximately doubled by two watersheds. First the Nautley River, draining the Fraser and Francois lakes system, and then the Stuart River, draining Stuart and associated lakes in the most northerly portion of the Fraser River watershed. The watershed is situated in the subboreal spruce biogeoclimatic zone, and during the key months of July and August has a mean precipitation of $\approx$ 45 mm and a mean air temperature of $\approx$16 ^{o}C (as recorded at the Vanderhoof Airport since 1950). In this time period precipitation has declined and temperature has risen (Morrison *et al.* 2002). Winter precipitation generally falls as snow which results in snow-melt generated hydrographic peaks in the late spring in the unregulated tributaries of the Nechako (Figure. 2).

2.2 Data Collection Locations

The most reliable source of meteorological data (air temperature, cloud cover, solar radiation, dew point) since the inception of the STMP (1980) has come from the Prince George airport (World Meteorological Organization ID 71896) (Figure 1). Since the 1950’s summer water temperature and flow data have been collected continuously with chart recorders (e.g. Wexlers) or more recently on hourly intervals with electronic dataloggers (e.g. Vemco’s) from many locations throughout the Fraser watershed. Locations most consistently collected and useful were the Nechako at Finmoore and Isle Pierre, and the headwater of the Stuart River for temperature (C^{o}), and the Nechako River at the Skins Spillway and Vanderhoof, and the headwater of the Stuart River for discharge (cubic metres/sec = cms) (Figure 1). Tests of the efficacy of the STMP (hypothesis 1) were based on Finmoore temperatures and flows from the Skins spillway, while Isle Pierre (Figure 1) and the Stuart River data were necessary to examine the influence of the STMP on downstream temperatures (hypothesis 2). Temperature collection from the Nechako at Vanderhoof and two locations on the Stuart River nearer to the confluence with the Nechako River, were used for confirmation and occasional extrapolation to nearby sites in cases where data was absent from the primary sites or data quality was in question.

Plots of historic temperature trends (Figure 3) and estimates of their influence on Early Stuart sockeye spawning migrations (hypothesis 3) were made with data collected since the early 1950’s from coastal light stations at Amphitrite Pt. and Entrance Island, and within the Fraser watershed at Hells Gate, Nechako and Stuart rivers, and on their spawning grounds at Forfar Creek; a freshwater migration distance of 1100 km (Figure 1). At each location an annual mean was calculated from daily mean temperatures collected during a 16 day period centred on the median date the migrating fish passed the location. A continuous record of Nechako River observations were not available from Isle Pierre but were from Finmoore, which is located above the Nechako River's confluence with the Stuart River. Finmoore has been the site of the STMP temperature regulation target and is influenced by the Nechako flow regulation to a greater degree than is the Early Stuart migration path downstream, below the confluence. Almost all earlier data were collected with paper chart recorders but with the advent of electronic dataloggers data collection and management was greatly simplified. Macdonald *et al.* (2007) provides a full description of data sources.

2.3 Data Analysis/Models

The current STMP strategy of increasing flows in response to modelled predictions of warming Nechako water temperature at Finmoore assumes that water temperature is a function of both meteorological conditions in the watershed and the volume of water released from the surface of the Nechako reservoir (hypothesis 1). A regression of the daily mean Nechako water temperature at Finmoore in response to all potential and available predictors, including meteorological variables (i.e. daily mean air temperature, solar radiation and dew point) and the mean daily Nechako water volume released from the Skins Lake Spillway (SLS) is a test of this assumption. However, considering that SLS water releases are frequently based on anticipated meteorological conditions, the predictor variables in this model are very likely to be correlated thus violating a statistical assumption of regression (Draper and Smith 1981); an assumption that is particularly important when using multiple regression to judge the significance of individual variables (Green 1979). The potential for correlation among predictor variables was examined with a principle components analysis (PCA) for the years 1981-2002 during the STMP period (July 20th to August 20th). A regression using the resulting PCA scores, which are uncorrelated transformations of the original predictor variables, provides a test of the efficacy of the current STMP policy and avoids the statistical violation of predictor independence (Green 1979)(eqn. 1):

$$T_{Finmoore} = a + b_1 PCI + b_2 PCII + b_3 PCIII + b_4 PCIV \quad (1)$$

Strength of the variable loadings on principle components combined with the regression results provided a measure of the relative influence of each original variable on Nechako water temperature at Finmoore. For the analysis the Skins spillway flow variable was lagged by four days to account for the travel time of water between Skins Lake and Finmoore in the summer. The lag calculation was confirmed with a temporal analysis of the correlation between upper and lower watershed water volumes. Subsequently, with an understanding of the factors that influence Nechako water temperatures gained from the preceding analysis, a regression model was developed to compare annual Nechako thermographs at Finmoore associated with actual and two reduced Nechako flow management simulations from Skins Lake (eqn. 2). The two reduced flow simulations, 15 and 53 cms., were based on the minimum daily release during the STMP and the base-flow release respectively (NFCP 2005). Discharge with the travel-time lag, was expressed at Finmoore (Nechako*Q*) rather than SLS to allow for annual variation in tributary flow between the SLS and Finmoore (e.g. the Nautley River).

$$T_{Finmoore} = a + b_1 NechakoQ + b_2 AirTemp \quad (2)$$

Graphical analysis was used to make annual comparisons of mean Nechako water temperature predictions at Finmoore during the STMP period and to compare the influence of the three flow management regimes.

Predictions of daily water temperature deviations downstream of Finmoore, below the confluence of the Nechako and the Stuart rivers that would result from reduced water releases (hypothesis 2), were based on a calculation of the combined effects of water temperature (T°C) and volume (V) of both systems (eqn. 3):

$$T_{below\ confluence} = \left(V_{Finmoore} T_{Finmoore} + T_{Stuart} V_{Stuart}\right) / V_{below\ confluence} \qquad (3)$$

This equation shows that Nechako water passing Finmoore will reduce temperatures in the lower-Nechako during the Early Stuart migration period if it is cooler than the Stuart River. This moderation will decline with declining Nechako water volume (simulated as 53cms from SLS) and/or decreased temperature difference. We demonstrate this relationship by comparing our calculated values to actual lower-Nechako River temperature data from July and August, during the years it was available from Isle Pierre.

Temperatures approaching 22°C, a critical temperature beyond which migrating sockeye salmon can not endure (Brett 1952) and are known to avoid (Hyatt *et al.* 2003; Quinn *et al.* 1997), were measured in the mid-Nechako, Stuart and Fraser rivers in coincidence with Early Stuart sockeye salmon migration timing. The Pearson correlation coefficients (r) among these temperatures, their associated water volumes, and temperatures at several other Early Stuart migration locations were examined, and the likelihood they had an influence on Early Stuart sockeye spawning success was appraised (hypothesis 3; $p<0.05$). Annual spawning success is calculated based on the proportion of females that have completely extruded their eggs during carcass dissections on the spawning grounds (Gilhousen 1990) and was made available by T. Cone (DFO Science Branch). Pre-spawn mortality, also referred to as egg retention, is the inverse of spawning success (Quinn *et al.* 2007).

3. RESULTS

Since 1981, water volume released from the Skins Lake spillway during the STMP period has been larger during warm summers, as estimated from air temperature at the Prince George airport (Supplementary Figure 2). However, this relationship was weakened as a result of several years during which above average snow pack volumes during the previous winter/spring necessitated summer forced spills for dam safety reasons, unrelated to summer temperature (e.g. 1997, in Macdonald 2000b, 1985 and 1992, and 1996, in NFCP 2005). From this relationship it was apparent that 1995 and 1998 defined particularly cool or warm years when relatively minor or major STMP release responses occurred respectively.

Over 90% of the variation among the predictor variables was described by the first three principle components (PC's), with the meteorological variation (PCI and II) providing the greatest amount of the information in the environmental matrix (Table 1). The correlation between daily flow from the Skins facility and the meteorological variables was confirmed by the variable loadings on the first principle component of the PCA. This suggests that the summer operation of the Skins spillway was based on functional five day meteorological forecasts that promote the release of water as conditions become warmer. The variation in PCI, largely associated with air temperature, had the greatest influence on Finmoore water temperature ($p<0.01$, Table 2). However, the variation in Skins spillway flow, independent of meteorological conditions (PCIII describing 24 % of the variation), had a significant influence on Finmoore water temperature that was second only to air temperature ($p<0.01$, Table 2). This provided credence to the efficacy of the STMP protocol (hypothesis 1). High solar radiation during days with low humidity (Table 1, PCII) had a positive influence on Finmoore water temperature (Table 2) as a result of increased evaporative energy loss and exposure to greater radiant energy.

Based on the combination of the preceding PCA and regression analyses, both air temperature and water discharge were proposed as predictor variables to model Finmoore daily mean water temperatures during specific summers if SLS flows were reduced (Table 3). Humidity was omitted as a predictor to simplify the model. When actual SLS flows were reduced to 53 cms (spring base release) and 15 cms (minimum release during the STMP period) respectively, an annual mean increase in water temperature at Finmoore of 0.38 °C ($range_{81-02}$ = 0.22-0.85 °C) or 0.51 °C ($range_{81-02}$ = 0.34-0.97 °C) resulted (Figure 4). With these reduced water volumes, annual mean summer temperature predictions during the STMP remained below 20°C in the Nechako above the confluence with the Stuart River.

Below the confluence a mixing model (eqn. 3) that integrated the temperatures and volumes of the Stuart and Nechako rivers, adequately predicted the actual water temperature at Isle Pierre (Supplementary Figure 3, $p<0.05$). While the relationship between the actual and predicted temperatures was highly significant the slope was significantly less than one ($b = 0.912$, $a=1.65$, $p<0.05$) suggesting continued meteorological influence occurred on the river water between the site of the prediction at the confluence, and at Isle Pierre where the actual temperatures were collected. The mixing model predicted an increase in lower Nechako River temperatures of nearly 1.0^{o}C most years, as a consequence of reducing the STMP to 53 cms from the Skins Lake Spillway in the upper Nechako (positive deviations, Figure 5). This was particularly likely during the warmest year observed (e.g. 1998 – Supplementary Figure 2) and during the three week periods centred on annual peak migration timing of Early Stuart sockeye. The STMP was much less influential when conditions were more benign (e.g. 1995- Supplementary Figure 2), but nearly always had a moderating influence at the confluence with the Stuart River during most days of most summers (hypothesis 2).

Warm temperature and low flow in the Stuart and Nechako watersheds and temperatures on the spawning grounds were more highly correlated to 50+ years of spawning success data than conditions they were exposed to further downstream or in the ocean (hypothesis 3; Figure 6). Water temperature trended upward during this period. With the exception of the spawning ground, the temperatures experienced increased with advancing migration to the extent that the annual daily maximum temperature in the Stuart River may exceed 22^{0}C during some years (Figure 3). However, correlation in both temperature and flow occurred among many locations along the migration corridor ($p<0.05$ - Table 4) making it difficult to detect a direct causal relationship between the physical conditions at a single migratory location and the ability to spawn successfully.

4. DISCUSSION

The Summer Temperature Management Program (STMP) is the only component of the annual activity of the Nechako Fisheries Conservation Program directed at the protection and conservation of sockeye salmon (NFCP 2005). When the STMP temperature target was established, there was no requirement to assess its efficacy in terms of temperatures realized or benefits to sockeye salmon. In addition to the obvious interest in conducting such an assessment, recent interest in altering water release timing to enhance other species (e.g. sturgeon – Korman and Walters 2001; McAdam *et al.* 2005) provides additional incentive (NFCP 2005). Water temperature in the Nechako River above the confluence of the Stuart has rarely exceeded the 20°C target during the STMP period despite a warming summer temperature trend during the last five decades in the Fraser watershed (Figure 3) (Morrison *et al.* 2002) that has been attributed to climatic drivers in rivers worldwide (Webb *et al*. 2008). However, proof that the expenditure of considerable volumes of water (approximately 15.8 cms annualized average since 1987) actually supports STMP objectives is based on theoretical approaches with mathematical energy balance models (Mitchell *et al.* 1995; Triton 2004). Our study, using empirical data, provided independent support for the conclusions reached with these models; increased water volume retards the rate at which water temperature increases as it proceeds downstream. Minimum flow regimes have been used to mitigate against high summer temperatures in other locations (Gu *et al.* 1998; Sinokrot and Gulliver 2000). Furthermore, in the Platte River, Nebraska, Gu et al. (1999) proposed that flow regulation could be linked to forecasts of meteorological conditions in a manner similar to the STMP. The rate at which water in a river will respond to atmospheric conditions depends, in part, on the ratio of its surface area to its volume. In most rivers there is a non-linear relationship between width and flow in the form of $w = aQ^b$ with b less than 1 (Foreman *et al.* 1997). Thus an increase in river discharge is accompanied with a slower increase in surface area exposed to the atmosphere and is therefore less responsive to the warming effects from atmospheric (Ward 1982) or groundwater input (Webb 1995). As stated by Hockey *et al.* (1982), and Poole and Bergman (2001), water temperature is a function of heat load divided by discharge; a relationship that is likely responsible for the success of the STMP in meeting temperature targets at Finmoore.

Numerous studies have shown both epi and hypolimnetic reservoir drawdown to reduce down-stream temperatures in the summer (Finlayson *et al.* 1994; Paller and Saul 1996; Flodmark *et al.* 2004). However, in the Nechako this approach to water use planning if it is to benefit Early Stuart sockeye salmon is complicated by the need to consider the combined influence of the volumes and temperatures of both the Nechako and Stuart rivers. During most but not all of the years examined in this study, the Nechako River moderated Stuart River temperatures and thus improved conditions in one of the warmest portions of their migration path (IPSFC 1979). Curtailment of the STMP would reduce the volume of Nechako water in the summer at the confluence and would almost always have a detrimental effect on upper Fraser sockeye recovery goals. Furthermore, if the existing temperature target of 20^{o}C at Finmoore could be met using lower release volumes but at a cooler temperature from proposed changes to the Kenney Dam, lower Nechako temperatures would climb and migration habitat would be less hospitable. Conversely, managed to provide higher flows and/or cooler releases, present or future water control structures could have a positive influence on migration conditions in the upper Fraser. As the influence of global climate change becomes more evident in the Fraser basin, models that support the incorporation of temperature goals into water use plans, are fundamental to our ability to address the broader concerns of many stakeholder groups while meeting fishery management objectives.

The positive correlations between the spawning success of Early Stuart sockeye salmon and the conditions in the Nechako and Stuart rivers are consistent with the evidence and suggest that a temperature exposure process during migration can influence sockeye reproductive success (Gilhousen 1990; Macdonald *et al.* 2000a). This relationship may provide a predictive mechanism to equate water temperature management schemes to migration habitat quality and sockeye fitness. It is possible to estimate annual spawner loss associated with PSM as a function of the STMP water release decisions and Stuart River conditions; without the STMP, losses some years may exceed 4000 fish. However, this modelling approach has many limitations. If used predicatively, a combined estimate of the errors associated with the influence of modelling the STMP, integrating Stuart River conditions and modelling their combined influence on PSM would be required before practical implementation. More daunting, this approach implies that temperatures in the upper watershed alone influence PSM despite evidence of strong annual correlations among daily temperatures at many migration/spawning locations in the watershed. It assumes that localized acute exposure to elevated temperature is a reliable determinant of PSM when literature evidence suggests that stressors act additively from chronic exposure by increasing susceptibility to disease (Gilhousen 1990; Fagerlund *et al.* 1995). At this stage in the investigation we can only speculate that the warmest temperatures encountered during migration, which are found in the Stuart/Nechako corridor, are the most critical for successful spawning and are the most deserving of temperature management. A more thorough analysis of the variance structure in a matrix of possible predictor variables, of greater duration and possibly complexity, is necessary to better understand the origin of pre-spawning mortality. This is required knowledge if we are to ever use controlled water releases from Skins Spillway as a quantitative fishery management tool to compensate for losses to production.

5. CONCLUSIONS

The Nechako River Summer Temperature Management Plan was designed with the single purpose to moderate water temperature at a single target location. Within this narrow assessment criterion it has been an effective strategy, achieving a temperature target objective in the middle reach of the Nechako River for nearly 30 years despite a warming trend in the Fraser watershed. Thus the first hypothesis was rejected. However, measured against other legitimate criteria the plan has a number of limitations. Achievement of the temperature target alone fails to recognize the importance of temperatures further downstream at locations more commonly used by migrating salmon and subject to complex tributary mixing. At present, we can reject the second hypothesis as the volume of water released to meet the target at Finmoore generally has a positive influence on temperatures further downstream. Consequently, a proposed modification to water release facilities to allow the release of smaller volumes of cooler hypolimnetic water may be deleterious to migration conditions despite compliance with the current criterion. Furthermore, the STMP is predicated on large and variable water releases at a time of year when a natural flow paradigm would prescribe a steady decline in the hydrograph and lower flow. Many stakeholders within the watershed suggest that adherence to a criteria based solely on sockeye salmon opposes other watershed values that may benefit from a redistribution of water resources and/or a more natural hydrograph. Water use planning is fraught with these tradeoffs. However, a growing body of knowledge linking loss of sockeye salmon to elevated temperatures prompts the rejection of the third hypothesis and places a high priority on actions that moderate upper Fraser River temperatures, where sockeye salmon experience the warmest conditions of their lives.

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TABLE AND FIGURES

Figure 1: The Nechako watershed with locations of data collection sites (■), water management facilities, salmon spawning sites and migration corridors. The Early Stuart sockeye salmon run spawns north of Stuart Lake and the Stuart River.

Figure 2: Mean daily discharge (cms) in the Nechako River at Vanderhoof during the entire year. Data spans the pre-dam, natural flow period (1950-52), the extreme low flows when the reservoir was filling (1953-1956), the pre-STMP period during initial operation when greater water volume was released but releases where variable (1957-1982), and the present situation typified by more uniform releases of moderate volumes for a 30 day period for STMP cooling purposes (1983-2003).

Figure 3: Annual mean temperatures (^{o}C) and historic trends (dashed line) experienced by the Early Stuart sockeye since the early 1950's during their return from the open Pacific Ocean to their spawning grounds north of Stuart River (Figure 1). Entrance Island is in the Strait of Georgia 30 km. from the mouth of the Fraser River. Hells Gate is a high gradient reach of the Fraser River approximately 200 km upstream from the river mouth. Stuart River mean temperatures are graphed with annual maximum temperatures indicated by individual dots. Data sources are provided in Macdonald et al. (2007).

Figure 4: Predictions of mean annual water temperature (^{o}C) at Finmoore in July and August from 1981 to 2002 using the regression model described in Table 3. Three

Finmoore flow (Q) scenarios were modelled based on water releases from SLS as follows; actual annual STMP flows, the annual base release used before the initiation of the STMP in the spring (53 cms), and the minimum flows allowed during the STMP (15 cms). Reduced flow resulted in warmer water at Finmoore.

Figure 5: Reduced flows from the Skins spillway create positive deviations most years in the annual mean lower Nechako River water temperature, below the confluence of the Stuart River. Reductions were based on the elimination of the STMP flows and the adoption of a baseflow release strategy of 53 cms. Deviations are calculated for the period the STMP was in effect (July 10th – August 20th) and for the briefer period, adjusted for the annual timing of Early Stuart sockeye migrations through the lower Nechako system in July and early August (Table 1).

Figure 6: Correlations (r) between the mean daily temperatures and spawning success (proportion of eggs retained in carcasses) of the Early Stuart sockeye salmon run from 1953 to 2004 (□). Temperatures are those encountered on the west (Amphitrite Pt.) and east coast (Entrance Isl.) of Vancouver Island, and at locations measured (km) from of the mouth of the Fraser River to the spawning grounds. A horizontal line above which correlations have p-values that are less than α=0.05 is provided. A plot of mean temperature during the 3 week period the fish are at each location is also presented (◊). Spawning ground temperatures are from Forfar Creek in the Stuart drainage (Figure 1).

Supplementary Figure 1: Pre-spawn mortality data by year for Early Stuart sockeye salmon as provided by T. Cone DFO Science Branch.

Supplementary Figure 2: A comparison of mean annual Skins Lake water release volume (cms) and mean annual summer temperatures (^{o}C) at Prince George between 1981 and 2002. Three years are indicated during which forced spills occurred beyond those needed to control summer temperature (i.e. 85, 92, 96). A fourth year, 1997, is not shown (15.7^{o}C x 284.2 cms). The equation, p-value and 95% confidence limits are provided for a regression of all years. The R^2 for the relationship was 26.5% but improved to 39.6% ($p<0.004$) when years with forced spills were removed from the regression. Both 1995 and 1998 were chosen as being representative of cool and warm years respectively.

Supplementary Figure 3: A linear comparison of actual lower Nechako temperatures at Isle Pierre July 10th to August 20th, to those predicted by a calculation that was based on Nechako (Finmoore) and Stuart (Fort St. James) river characteristics (eqn 3). This relationship is highly significant ($p<0.05$, $R^2 = .785$) with an intercept near the origin ($a = 1.65$) but had a slope slightly less than one ($b = 0.912$) suggesting additional river warming occurred downstream of Finmoore and/or Ft St James.

Variable	PCI	PCII	PCIII	PCIV
Skins 4.0D	0.225	-0.191	**0.954**	0.051
PG Air Temp	**0.735**	-0.001	-0.138	-0.664
PG Humidity	0.401	**-0.721**	-0.265	0.500
PG Solar Radiation	0.498	0.667	-0.014	0.554
Proportion	0.402	0.294	0.240	0.064

Table 1: Results of a principle component analysis to describe the information shared among the daily mean meteorological and water release variables during a 30D period (July 20th – August 20th, 1981-2002) when STMP flows from Skins Lake (SLS) were released in response to meteorological forecasts. A four day lag in the flows accounts for the length of time required for the water release response from SLS to reach the temperature target location at Finmoore. Variation associated with the first three components is accounted for primarily by the variables indicated in bold.

Predictor	Coefficients	T-Value	Probability	R^2	n-1
Constant	18.0	368.78	0.000	0.405	629
PCI (Air Temp °C)	0.792	20.19	0.000		
PCII (Low Humidity)	0.0923	2.11	0.035		
PCIII (Skins Lake Q)	-0.193	-3.96	0.000		

Table 2: A table describing the results of the regression of daily Finmoore water temperature response to the effects of the variation in meteorological and Skins Lake water release variables from July 20th – August 20th, 1981-2002 (n=630 days). Predictor

variables were PC scores from the PCA analysis (Table 1), which are transformations of the original variable loadings (in brackets) on each component. Humidity is negatively correlated with solar radiation (Table 1) and positively correlated with dewpoint if temperature remains constant. Variation in Skins Lake water releases as described by PCIII represents water released independent of meteorological forecasts.

Predictor	Coefficient	T-Value	Probability (p value)	n-1
Constant	13.2	59.57	0.000	1097
Finmoore Q	-0.00331	-7.15	0.000	
Air Temp ^{o}C	0.346	25.36	0.000	

Table 3: Description of a model (Finmoore T^{o}C = 13.2 – 0.00331 Finmoore Q + 0.346 PG Air T^{o}C), to predict daily Finmoore water temperature response to both Prince George air temperature and Finmoore water flow ($p<0.05$) from July 7th to August 30th, 1981-2002 (n=1098 days). Predictor variables were chosen based on variable selection results described in Tables 1 and 2.

Temperature (°C)

	Spawning Success	Spawning Grounds T.	Stuart Temperature	Stuart Q	Finmoore Temp.	Vanderhoof Q	Hells Gate Temp.	Hells Gate Q	Entrance Isl. Temp.
Spawning Grd. Temp.	**-0.468 ***								
Stuart Temp.	**-0.357 ***	**0.829 ***							
Stuart Q	**0.296 ***	**-0.398 ***	-0.415						
Finmoore Temp.	**-0.304 ***	**0.657 ***	0.760	**-0.438 ***					
Vanderhoof Q	0.089	0.001	0.027	**0.382 ***	**-0.408 ***				
Hells Gate Temp.	-0.191	**0.431 ***	**0.456 ***	**-0.638 ***	**0.321 ***	-0.002			
Hells Gate Q	0.167	**-0.378 ***	-0.253	**0.675 ***	**-0.293 ***	0.227	**-0.754 ***		
Entrance Isl.Temp.	0.013	0.257	0.218	**-0.418 ***	0.043	0.163	**0.774 ***	**-0.617 ***	
Amphitrite Pt. T.	-0.241	**0.354 ***	0.221	**-0.319 ***	0.072	0.184	**0.582 ***	**-0.543 ***	**0.614 ***

Table 4: An examination of the correlation among spawning success, temperature (T^0C) and flow (Q) at several locations during the period they are used by the Early Stuart sockeye. Pearson correlation coefficients (r) are provided with significant correlations marked in bold and with an "*" ($p<0.05$). Analysis includes data from 1953-2004 from sources described by Macdonald et al. (2007).