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

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Abstract

Since the early 1980's 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 in an attempt to prevent temperature from exceeding a specified threshold of 20 °C downstream during a period when spawning migrations of sockeye salmon (*Oncorhynchus nerka*) are in the Nechako River. Since the inception of the program this threshold has been exceeded only rarely but an independent analysis of the variables that influence water temperature in the Nechako watershed and are used to manage 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 threshold. Furthermore, during most summers, the Nechako River provided a cooling influence to input from the Stuart River tributary in a downstream reach that is used by the majority of the migrating sockeye salmon. Water temperature has a modest influence on pre-spawning mortality (up to 22% of the variability) suggesting that attempts to reduce 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, water quality, reservoir management, pre-spawning mortality, environmental flows

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 ecosystem function. Referred to as environmental flows (Acreman and Dunbar 2004), these strategies generally promote a paradigm based on the maintenance of natural hydrologic variation (Richter and Thomas 2007; Enders et al. 2009). Recently, scientific dialogue has evolved to consider water quality objectives, most notably temperature, as well as water quantity in flow allocation planning (Olden and Naiman 2010). The use of environmental flows to mitigate thermal impacts from dams has received attention in the past. Releases from the Dworshak Reservoir, Idaho, reduce summer water temperatures in the lower Snake River for Chinook salmon *(Oncorhynchus tshawytscha)* 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). Similarly, a summer temperature management plan (STMP) in the Nechako River watershed (Figure 1) that was initiated in 1981 to release epilimnetic water to cool downstream temperatures during a period critical to returning sockeye salmon *(Oncorhynchus nerka)* (NFCP 2005) is the subject of this paper. However, management releases designed to address a temperature objective frequently violate natural flow patterns, and can create water use conflicts among other interest groups (Gu et al. 1998; Sinokrot and Gulliver 2000). In the Nechako watershed, the release of large volumes from a reservoir in the summer (Figure 2) must be justified because they come at the expense of broader management goals that include water diversion for power generation and irrigation, and the maintenance of a natural hydrograph to preserve additional biological values (NFCP 2005, Macdonald et al. 2007).

Potentially harmful temperature thresholds can be avoided 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). A review of additional examples and techniques has been prepared by Olden and Naiman (2010). The large volumes of reservoir water released through the Kenney Dam (Figure 1) to control Nechako River summer temperatures could be reduced, but only through development of temperature control capabilities to access hypolimnetic water. The water saved could be released at other times, providing a more natural hydrograph, and broadening water management options (Figure 2). Currently, water release capabilities do not exist at the Kenney Dam as water enters the Nechako by way of the Cheslatta watershed from the Skins Lake Spillway (Figure 1). Cost estimates for this capability exceed 200 million dollars but the concerns of many Nechako stakeholders (Bouillon 2004; Macdonald et al. 2007), and the ability to actively manage habitat for a wider list of biota such as the endangered white sturgeon (*Acipenser transmontanus*) (COSEWIC 2003; McAdam et al. 2005), may provide justification. However, remaining below the legislated STMP threshold temperature at Finmoore in the middle Nechako (Figure 1) with lower water volumes using a cold water release technology will likely have temperature implications in the lower Nechako watershed below its confluence with the Stuart River during summer sockeye salmon returns.

Summer temperatures are particularly relevant for returning sockeye salmon. The Early Stuart population spends three to four days migrating up the lower Nechako River between early July and early August (Macdonald et al. 2007) and then enters the Stuart River (Figure 1). Temperatures can exceed 22°C during this period and are the warmest they will experience during their normal four year lifecycle. Temperatures have gradually increased since the middle of the last century (Figure 3). Historic salmon run size exceeded 200,000 fish but has undergone an 84% decline in the last 15 years despite a reduction in harvest rate (Cass et al. 2006). Temperatures exceeding 20°C can be lethal for salmon (Brett 1952; Bouck et al. 1975); create impediments to migration (Cooper and Henry 1962; Major and Mighell 1966; Keefer et al. 2004; Salinger and Anderson 2006); reduce swimming performance by depleting energy and promoting exhaustion (Gilhousen 1980; Rand and Hinch 1998); elicit immunosuppression, disease development and parasitic infection (Anderson 1990; Schreck et al. 2001; St-Hilaire 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). Migration temperatures bordering 20°C and infection severity have been cited as causes for egg retention in salmon from many stocks that successfully reach the spawning grounds but die before spawning (pre-spawn mortality - PSM) (Gilhousen 1990; Traxler et al. 1998; 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 (Macdonald et al. 2000a). The availability of sufficient data to examine the relationship between migration temperature and the spawning success of Early Stuart sockeye salmon provides an opportunity to test the presumed temperature control benefits of the current STMP, or future temperature control initiatives, against the program's biological objectives.

There are many cases where water-use plans, once adopted, are not effectively evaluated (Lewis and Mitchell 1995). Evaluations of the objectives may be hampered by poorly defined assessment criteria, or by the failure of the objectives themselves, when met, to provide meaningful societal benefit (Larkin 1984; Castleberry et al. 1996). This paper has three objectives. As a first objective, it assesses the efficacy of a water-use plan that has a focus on water quality issues. The plan uses environmental flows released in the upper Nechako River to avoid a temperature threshold of 20°C at Finmoore during a defined period in the summer (NFCP 2005). While the temperature has remained below the threshold most days since the inception of the STMP in 1981, the relative contributions of the variables responsible for its efficacy have not been tested empirically. As a second objective, this paper assesses the ability of the STMP to moderate temperatures in the Nechako River below Finmoore, and the confluence of a major tributary, the Stuart River (Figure 1). The Stuart and the lower Nechako rivers are migration corridors for the Early Stuart sockeye salmon run. Examination of the degree to which this run may be influenced by upstream environmental flow objectives is the paper's third objective.

2. Materials and Methods

2.1 Study Area

The Nechako River in the interior plateau of British Columbia drains an area of approximately 47,200 km^2 and accounts for the northwestern 20% of the Fraser basin. Its two major tributaries, the Nautley and the Stuart, approximately double the Nechako water volume (Figure 1). 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). Winter precipitation generally falls as snow which results in snowmelt-generated hydrographic peaks in the late spring in the unregulated tributaries of the Nechako (Figure 2).

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 275 km from its confluence with the Fraser River at Prince George. Once filled in 1956, they began diverting the majority of the water out of the watershed for hydropower at Kemano (Figure 1). The remaining water was released from the surface via a flow control through the Skins Lake Spillway (SLS) to the Cheslatta system to provide for conservation of fisheries resources in the Nechako River. Initially these released flows were highly variable but following a court injunction in 1980, Alcan began releasing base flows (30 m^3/s at Cheslatta Falls) in the fall and winter for the benefit of Chinook salmon and additional summer 'cooling flows' (STMP) for the benefit of migrating sockeye salmon in the Nechako River between the Stuart River and Nautley River confluences (NFCP 2005; Macdonald et al. 2007). The summer flows have created an unnatural annual hydrographic maximum in the summer (Figure 2). The STMP is based on computer modeled water temperature responses to anticipated meteorological conditions in the watershed between July 10th and August 20th, and is preceded with spring/early summer baseflows of 53 m^3/sec. It has resulted in a mean daily release of 158 to 335 m^3/s from the surface of the Nechako Reservoir through the Skins Lake Spillway from 1981-2006, with flows never less than 15 m^3/s at any time. The daily temperature threshold at Finmoore of 20°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, this location doesn't consider one of the largest sockeye runs in the Nechako, the Early Stuarts, which are found below Finmoore in a Nechako reach influenced by the Stuart River.

2.2 Data Collection and Locations

Prince George airport was the source of meteorological data (air temperature, cloud cover, solar radiation, dew point) collected daily since the inception of the STMP (1980) and Fort St James for earlier air temperatures (Table 1, Figure 1). Since the 1950's summer water temperature and flow data have been collected continuously with chart recorders or more recently on hourly intervals with electronic dataloggers from many locations throughout the Fraser watershed. Models of Nechako flow on temperature used Finmoore, the headwaters of the Stuart River and Isle Pierre as the primary sources of water temperature (°C) data and Skins Lake Spillway, Vanderhoof and the headwaters of the Stuart River as the primary sources of flow (m^3/sec) data. Data from several alternative sites (i.e. Vanderhoof and two locations on the Stuart River) were available to confirm data quality or extrapolate to fill data gaps at nearby sites. Historic temperature and river flow trends used to illustrate migration conditions at other locations were made with data collected daily since the early 1950's from coastal light stations at Amphitrite Pt. and Entrance Island, and within the Fraser watershed at Hells Gate and their spawning grounds at Forfar Creek, a freshwater migration distance of 1155 km (Table 1, Figure 1).

To measure the implication of these conditions on Early Stuart sockeye spawning migrations (objective 3), annual estimates of spawning success were accessed. These have been conducted on systematic basis since 1938 for many major Fraser River sockeye salmon populations, by IPFSC (1938-1986) and more recently by DFO (Gilhousen 1990; Schubert and Fanos 1997). Annual spawning success is calculated based on the proportion of females that have completely extruded their eggs following spawning during carcass dissections (Gilhousen 1990). During the 3- to 4-week spawning period carcasses are examined every third or fourth day from all creeks used for spawning with an attempt to examine ≥ 10% of the total carcases from the population. These data were made available by T. Cone (DFO Science Branch). Pre-spawn mortality, also referred to as egg retention (Quinn et al. 2007), is the proportion of female carcasses on the spawning grounds that have retained most of their eggs. This concept can also be expressed as spawning success which is the proportion of carcasses counted where the majority of eggs have been released.

2.3 Data Analysis/Models

The current STMP strategy of increasing flows in response to modeled 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. An ANCOVA comparing air temperature as a predictor of maximum mean daily water temperature at

Finmoore during the STMP period (July 20th to August 20th) in the years before and after its initiation provided a visual estimate of the efficacy of the STMP (objective 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) was a more thorough test of this assumption. Anticipated correlation among the predictor variables was examined with a principal components analysis (PCA) as was the possibility for autocorrelation among the daily records with a Durbin-Watson test (Draper and Smith 1981). 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 (objective 1) and avoids the statistical violation of predictor independence (Green 1979):

$$T_{Finmoore}=a+b_1PC1+b_2PC2+b_3PC3+b_4PC4 \qquad (1)$$

Strength of the variable loadings on principal 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, over several years (NFCP 2005).

Subsequently, a regression model was developed using the most influential factors from the preceding analysis as predictors to estimate mean temperature responses at Finmoore, each year (1981-2002), during the management period (eqn. 2). The daily response to actual flow and air temperature, and to two reduced Nechako flow simulations were used to estimate mean water temperature during the management period. The two reduced flow simulations, 15 and 53 m^3/sec at Skins Lake were based on the minimum daily release during the STMP, and the base-flow release before the STMP respectively (NFCP 2005). These simulated flows bracket the actual annual mean SLS releases excluding releases during the STMP (37.7 m^3/sec) (NFCP 2005). Flow 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).

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

Graphical analysis was used to make annual comparisons of mean Finmoore water temperature predictions during the management period as influenced by the three flow management regimes. Predictions of the frequency at which the mean daily temperature of 20°C at Finmoore was exceeded during the management period were also graphed.

We also estimated the influence of flow control on temperatures at Isle Pierre, located below the confluence with the Stuart River and in the main migration corridor used by sockeye salmon (objective 2). To do so, we developed a mass balance equation that combined the effects of water temperature (T) and flow (Q) of the Nechako (at Finmoore) and Stuart rivers:

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

This equation assumes the Stuart and Nechako rivers mix completely and their temperatures and flows have exclusive influence on temperatures below the confluence. The actual mean daily volume of water at Finmoore during the control period, and a reduced volume based on constant flow from SLS of 53 m^3/sec provided two sets of Isle Pierre temperature simulations, one with and one without an STMP. During approximately half the years since 1953, actual Isle Pierre temperatures were available to regress against the corresponding simulations to confirm the equation's reliability (Table 1).

Water temperatures and river flow regimes experienced by returning sockeye salmon at numerous locations, including the spawning grounds, were examined as possible correlates of spawning success (objective 3). Annual escapement to Gluskie, Forfar and Kynoch creeks (as an estimate of migration density, Quinn et al. 2007) was also considered but proved to be inconsequential as a predictor of PSM and was dropped from further analysis. At each location a mean was calculated from daily mean temperature or flow collected during a 16-day period centered on the median date the migrating fish passed the location. A matrix of Pearson correlation coefficients (r) was produced to examine the correlation among temperature, flow and spawning success by location. Included were pair-wise probabilities corrected for multiple comparisons ($P<0.05$). Water temperature was regressed as a predictor against 51 years of spawning success data (1953 to 2004) to estimate the relative influence of water temperature on spawning success at each location. Regression equations with coefficients of determination (R^2), plots and mean temperatures were produced for each location to illustrate the results.

3. Results

Over 90% of the variation among the predictor variables was described by the first three principal components, with the meteorological variables air temperature (PC1) and humidity (PC2) providing the greatest amount of the information in the environmental matrix (Table 2). The positive (albeit weak) correlation between lagged daily flows from the Skins facility and the meteorological variables on the first PC is confirmation that summer operation of the Skins Spillway was based on meteorological forecasts – water was released as conditions became warmer. Following reservoir completion, air temperature has had an influence on water temperature above the Stuart confluence (ANCOVA $p<0.01$) both before and after the implementation of the STMP (Figure 4). More importantly, removal of the correlation between flow and the meteorological variables on which the releases were based (PC3 describing 24 % of the variation), provided evidence that the daily operation of the Skins Spillway had an influence on Finmoore water temperature that was second only to air temperature (Multiple regression $p<0.01$, Table 3). This provided credence to the efficacy of the STMP protocol (objective 1) which has prevented temperatures from exceeding 20^{o}C at Finmoore most days, most years (NFCP 2005). Temporal autocorrelation was detected among daily records (Durbin-Watson $p<0.01$), but a re-analysis with annual means of the regression parameters during the STMP replacing daily records, and the inclusion of year as a parameter to address a time-ordered linear trend in the residuals during the STMP (Neter et al. 1985), confirmed the dependence of water temperature on both air temperature and strategic water releases from the SLS. Also, high solar radiation during days with low humidity (Table 2, PC2) had a positive influence on Finmoore water temperature (Table 3).

Based on the results of the preceding PCA and regression analyses, both air temperature and water flow were proposed as predictor variables to model Finmoore daily mean summer water temperature between 1981 and 2002, at the actual and two reduced SLS flow simulations (Table 4). Humidity was omitted as a predictor to simplify the model. When actual SLS flows were reduced to 53 m^3/sec (spring base release) or 15 m^3/sec (minimum release during the STMP period), Finmoore's mean water temperature was predicted to increase by 0.50 ^oC ($range_{81-02}$ = 0.34-0.94 ^oC) or 0.62 ^oC ($range_{81-02}$ = 0.47-1.06 ^oC) on average during the STMP respectively (Figure 5). Even with these temperature increases, mean summer temperature predictions during the STMP remained below the 20^{o}C threshold in the Nechako above the confluence with the Stuart River (Figure 5), but the mean number of days the threshold was exceeded rose from 1.05 days to 3.32 or 4.41 days depending on the amount of water volume reduction.

Below the confluence a mixing model (eqn. 3) that integrated the temperatures and volumes of the Stuart and Nechako rivers provided reliable predictions of the actual water temperature at Isle Pierre ($p<0.05$, $R^2=0.79$). 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 confluence and at Isle Pierre (approx. 30km) where the actual temperatures were collected. The mixing model predicted an increase in lower Nechako River temperature most years (<1.0^{o}C), as a consequence of reducing the actual STMP flow from the Skins Lake Spillway to 53 m^3/sec (positive deviations, Figure 6). This was best demonstrated during the warmest summer observed (i.e. 1998) particularly during the three week period centered on annual peak migration timing of Early Stuart sockeye. The actual STMP was much less influential when meteorological conditions were more benign (e.g. 1995), but nearly always had a cooling influence at the confluence with the Stuart River during most days of most summers (objective 2).

Temperature exposure during spawning migration explained up to 22% of the annual variation in Early Stuart salmon spawning success, but this relationship was more reliable at locations in the upper portion of the watershed as fish neared the end of their migration (objective 3; Figure 7). The temperatures experienced tended to increase with increasing migration distance. For instance, the Nechako and Stuart watersheds had means for the period that exceeded 18 and 22 ^{o}C respectively and were the warmest temperatures the fish experienced until reaching the spawning grounds, where mean seasonal temperatures rarely exceeded 12 ^{o}C (Figures 3 and 7). Hence, correlations between 50+ years of pre-spawn mortality data and both temperature and flow were greater in the upper watershed but were not necessarily associated with the warmest locations (Figure 8). Furthermore, correlation in both temperature and flow occurred among many locations along the migration corridor (Table 5) suggesting annual meteorological influences are common across locations and work on large geographical scales. There was also a watershed-wide indication that years with lower flow had warmer temperatures.

4. Discussion

The STMP is the only component of the Nechako Fisheries Conservation Program directed at the protection and conservation of sockeye salmon (NFCP 2005). When the STMP temperature was established, there was no requirement to assess its efficacy, beyond the realization that temperatures rarely exceeded the threshold. Epilimnetic releases have actually increased summer temperature thresholds in other coldwater systems (Lessard and Hayes 2003), so increased STMP flow could conceivably be a disadvantage to sockeye salmon migrating through the Nechako. 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 another incentive (NFCP 2005). Mean daily water temperature in the Nechako River above the confluence of the Stuart has rarely exceeded the 20°C during the STMP period (NFCP 2005) despite a 1.5°C increase in water temperature in the last five decades in the Fraser watershed (Morrison et al. 2002; Patterson and Hague 2007, Martins et al. 2011). Similar trends have 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 m^3/sec 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. On a broader scale, this process may be partially responsible for the negative correlations in the annual flow-temperature relationship at locations throughout the watershed. Flow maintenance regulations 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 $b < 1$ (Foreman et al. 1997). Thus an increase in river flow is accompanied by a slower increase in surface area exposed to the atmosphere and is therefore less responsive to the warming effects from atmospheric input (Ward 1982). Water temperature is also a function of heat load divided by discharge (Hockey et al. 1982; Poole and Bergman 2001); both relationships are likely responsible for the success of the STMP in meeting the temperature threshold at Finmoore.

Numerous studies have shown both epi- and hypolimnetic reservoir drawdown to reduce downstream temperatures in the summer (Finlayson et al. 1994; Paller and Saul 1996; Flodmark et al. 2004; Olden and Naiman 2010). During most of the years examined, STMP releases into the Nechako River helped to moderate the Stuart River water temperatures, improving conditions for sockeye salmon in one of the warmest portions of their migration path (IPSFC 1979). Thus the STMP has supported upper Fraser river sockeye recovery goals. However, a proposal exists to construct a cold water release facility at the Kenney Dam to allow the temperature threshold of 20^oC at Finmoore to be met with lower release volumes. If the facility were built the Nechako River would have less thermal capacity to cool downstream migration routes (which tend to have summer temperatures > 20^oC) unless it were managed to maintain or increase flows with cooler water and temperature threshold goals were based on conditions below the Stuart confluence. Cold water releases could also depress summer and increase winter thermographs adjacent to the reservoir outlet, as reported at many other locations (reviewed in Olden and Naiman 2010), with possible dramatic ecosystem impacts in the upper Nechako (Donaldson et al. 2008).

As the influence of global climate change becomes more evident in the Fraser basin, with an anticipated decline in the survival of Fraser sockeye stocks (Martins et al. 2011), models that support the incorporation of temperature goals into water use plans may be fundamental to our ability to address the broader concerns of many stakeholder groups while meeting fishery management objectives. However, Olden and Naiman (2010) when considering broader ecosystem issues beyond the management of a fishery, are less hopeful. They cite operational complexities and difficulties predicting direct and indirect climate impacts to the entire ecosystem as limitations to our ability to address climate change impacts with water use plans. These limitations are exemplified in this paper. While the STMP provides an example of reservoir management to provide environmental flows for a more natural thermal regime, it does so at the expense of the system's natural hydrology. Nonetheless, in the face of multiple stakeholder demands and climate challenges, both flow and temperature, and possibly additional water quality parameters, must be considered simultaneously when designing water use plans (Olden and Naiman 2010).

The relationships between the Early Stuart sockeye salmon spawning success and the aquatic conditions in the upper Fraser watershed are consistent with evidence that temperatures bordering on 22°C are beyond that which migrating sockeye salmon can endure (Brett 1952; Eliason et al. 2011), are known to avoid (Hyatt et al. 2003; Quinn et al. 1997) and are thought to impair reproductive success (Williams et al. 1977; Gilhousen 1990; Traxler et al. 1998; Macdonald et al. 2000a; Quinn et al. 2007). This relationship may provide a predictive mechanism to equate water temperature management schemes to migration habitat quality and sockeye salmon fitness. With the models (i.e. Figure 7) it is possible to estimate annual spawner loss attributed to PSM as a function of the predicted mean temperature in the Stuart, during migration, with and without the STMP. Without the STMP, the largest numerical losses were estimated at nearly 4000 fish in 1989, or the largest proportional losses at 1.8% of the run in 1998 (Macdonald et al. unpublished data). However, this modeling approach has many limitations. If used predictively, a combined estimate of the errors associated with the influence of modeling the STMP, integrating Stuart River conditions and modeling their combined influence on PSM would be required before practical implementation. More dauntingly, this approach implies that temperatures in the upper watershed alone influence PSM despite evidence of strong annual correlations among daily stressors (both temperature and flow) at many migration/spawning locations in the watershed. It assumes that localized acute exposure to elevated temperature is a reliable determinant of PSM. However, literature evidence suggests that stressors act additively from chronic exposure over a large geographical area, by increasing susceptibility to disease (Gilhousen 1990; Fagerlund et al. 1995). This may explain why the PSM-temperature relationship is strongest on the spawning grounds where despite a respite from earlier high temperatures, the prolonged exposure during much of the freshwater migration is partially responsible for a predetermined physiological conclusion. Currently, 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 additional predictor variables, of greater duration and possibly complexity, is necessary to better understand the origin of pre-spawning mortality.

5. Conclusions

The Nechako River Summer Temperature Management Plan was designed with the single purpose to reduce water temperature at a single location. Within this narrow assessment criterion it has been an effective strategy, achieving a temperature objective in the middle reach of the Nechako River for nearly a quarter century during a prolonged warming period in the Fraser watershed (objective 1). However, measured against other legitimate criteria the plan has a number of limitations. Achievement of the temperature alone fails to recognize the importance of temperatures further downstream at locations more commonly used by migrating salmon and subject to complex tributary mixing (objective 2). The volume of water released to meet the temperature objective at Finmoore generally has a cooling influence on temperatures further downstream. Consequently, a proposed modification to water release facilities to allow the release of smaller volumes of cooler hypolimnetic water will reduce the Nechako's thermal capacity to cool downstream reaches and be deleterious to migration conditions despite compliance with the current criterion. However, 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 criterion 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. Nevertheless, despite predictive uncertainty with the spawner loss to water regulation relationship, a growing body of knowledge linking loss of sockeye salmon to elevated temperatures places a high priority on actions that impede temperature increase in the upper Fraser watershed, where sockeye salmon experience the warmest conditions of their lives.

6. Acknowledgements

We wish to thank staff of Fisheries and Oceans Canada for providing data and a critical review of the concepts developed in this manuscript. Of particular significance was the insight provided by Mr. Jason Hwang, Mr. Dave Innell, Mr. Byron Nutton and Mr. Ken Smith. Thanks are also extended to Mr. Keith Clarke and Dr. Michael Bradford for providing us with unpublished documents reviewing pertinent literature that assisted us in providing complete coverage of a wide range of flow management topics. Editorial suggestions by Dr. Petticrew and an anonymous reviewer during the publication process were insightful and are appreciated by the authors. Ms. Beth Piercey, Ms. Catherine Dickie and Ms. Dawn Woestenburg assisted with the editing and Mr. John Heinonen provided tireless support during the identification of data sources and the evaluation of their quality. This research was supported by funds from the Habitat and Enhancement Branch, Fisheries and Oceans Canada.

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Tables and Figures

Figure 1: The Nechako watershed with locations of data collection sites (■), water management facilities, salmon spawning sites and migration corridors as modified from NFCP technical data review (2005). The Early Stuart sockeye salmon run spawns north of Stuart Lake and the Stuart River.

Figure 2: Mean daily flow in the Nechako River (at Vanderhoof) during four distinct flow regimes: 1950-52 (Natural Flow); 1953-56, immediately following dam construction (Reservoir Filling); 1957-1982, prior to STMP implementation (Initial Operation); and 1983-2003 during STMP implementation (STMP).

Figure 3: Annual mean temperatures (^{o}C) and historic trends (dashed line) experienced by Early Stuart sockeye since the early 1950's during their return from the Pacific Ocean (Entrance Island), passage through the lower (Hells Gate) and upper (Stuart River) Fraser watershed to their spawning grounds north of Stuart River (Figure 1). Annual maximum temperatures in the Stuart River are presented as individual dots. Nechako temperatures are highly correlated to those in the Stuart (Table 5) and are presented separately as maximum daily means (Figure 4).

Figure 4: Regressions of the influence of Fort St. James air temperature (x-axis) as a predictor of maximum mean daily water temperature (y-axis) at Finmoore between July 10th and August 20th in the years pre-STMP (1957-1982, ◊) and during the STMP (1983-

2003, Δ). Also indicated are the water temperatures during the three years pre-dam construction (1950-1952, ○) and the four years during reservoir filling (1953-1956, □) which were not used in the calculation of the regression plots. Outlying years are also indicated numerically.

Figure 5a): Mean water temperature (^{o}C) at Finmoore during the STMP period as predicted by regressions (Table 4) based on three Finmoore flow (Q) scenarios: actual daily water volumes released from SLS (STMP), the annual spring baseflow used before the initiation of the STMP (53 m^3/sec), and the minimum release flows allowed during the STMP (15 m^3/sec). b) The number of days that mean daily temperature exceeded the 20^{o}C are presented annually for each flow scenario.

Figure 6: Yearly temperature deviations in the lower Nechako River (below the Stuart River confluence), assuming an upstream release of 53 m^3/sec at the Skins Lake spillway. Deviations are estimated for two time periods: the STMP period (July 10th to August 20th), and the period during which Early Stuart sockeye salmon were moving through the lower Nechako system (July early August).

Figure 7: The influence of water temperature on spawning success from 1953 to 2004 during the period Early Stuart sockeye occupy six locations on the migration route. The regression equations, trend lines, coefficients of determination (R^2) and mean temperature for the 51years of record are presented.

Figure 8: Correlations (Table 5) between mean daily temperature(◊) and Early Stuart sockeye spawning success from 1953 to 2004 (□) during the 3 week period the fish migrate past six locations: Amphitrite Pt. and Entrance Isl. (east and west coast of Vancouver Island) and locations measured (km) from of the mouth of the Fraser River to the spawning grounds. A horizontal line is provided above which correlations have p-values that are less than α=0.05 following correction for multiple comparisons (Holm 1979). Spawning ground temperatures are from Forfar Creek in the Stuart drainage.

Table 1: Environmental databases used in this study by location and source. Hourly data or at least daily means in July and August were available from 1950 to 2005 at all locations except Isle Pierre where 26 of the 55 years were created with the mixing model described in the text. Sources include World Meteorological Organization (WMO), Water Survey of Canada (WSC), Fisheries and Oceans Canada (DFO), Institute of Ocean Science (IOS) and Alcan Aluminum Inc. Multiple data sources are linked to a data type with a ‘*’.

Location	**Lat/Long**	**DATA TYPE**			**Data Source**
		Water $T^{0}C$	**Discharge**	**Meteorological**	
P. G. Airport	53^{0} 53’ N 122^{0}40’W	-	-	1953-2007	WMO ID#71896
Fort St. James	54^{o}27’N 124^{o}15’W			1895-present (air temp. only)	WSC 1092970
Skins Spillway	53^{o}42’N 125^{o}42’W		1956-present		NFCP (2005)
Stuart River	54^{0}25’N 124^{0}16’ W	1953-2003*	1929-2007	-	WSC (Station 08JE001); *WSC(53-00) and DFO(00-03)
Isle Pierre	53^{o}57’N 123^{o}14’W	1950, 59-60, 61-73, 76, 81-82, 84, 86-87, 93-94			Compiled by S. Macdonald from Alcan, and DFO
Vanderhoof	54^{0}1’ N 124^{0}0’ W	1969-present	1915-present	1916-present	WSC (Station 08JC001); CMS (5 stations)
Finmoore	53^{0}58’ N 123^{0}37’ W	1953-present	-	-	Alcan (Triton)
Nautley River	54^{0}57’ N 124^{0}36’W	1954-present*	1950-present	-	WSC (Station 08JB003); *DFO
Upper Stuart Spawning Grd. (Forfar Crk.)	55^{0}09’ N 125^{0}42’ W	1938-present	-	-	S. Macdonald unpublished
Hells Gate	49^{0}50’ N 121^{0}26’ W	1941-present	1912-present	-	Compiled by Patterson et al. 2007b
Entrance Island	49^{0}12’ N 123^{0}49’ W	1950-2005	-	-	R. Thompson DFO, IOS, Sidney,B.C.
Amphitrite Point	48^{o}55’N 125^{o}32’W	1950-2005			R. Thompson DFO, IOS, Sidney,B.C.

Table 2: Eigenvector coefficients from a principal component analysis among the daily mean meteorological and SLS water release variables, with a four day lag (Skins 4.0D), during a 32D period (July 20th – August 20th, 1981-2002). The original variables that loaded most heavily on the first three PC's are indicated in bold.

Variable	**PC1**	**PC2**	**PC3**	**PC4**
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 3: The results of a regression to predict daily Finmoore water temperature response to the effects of the variation in meteorological conditions and Skins Lake water releases from July 20th – August 20th, 1981-2002 (n=630 days). The original predictor variables (in brackets) were transformed to PC scores as new uncorrelated variables using the analysis described in Table 2. Variation in Skins Lake water releases as described by PC3 represents water released independent of meteorological forecasts.

Predictor	**Coefficients**	**T-Value**	**Probability**	**R^2**	**n-1**
Constant	18.0	368.78	0.000	0.405	629
PC1 (Air Temp ^{o}C)	0.792	20.19	0.000		
PC2 (Low Humidity)	0.0923	2.11	0.035		

PC3 (Skins Lake Q)	-0.193	-3.96	0.000

Table 4: Description of a model (Finmoore T°C = 13.2 – 0.00331 Finmoore Q + 0.346 PG Air T°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 2 and 3.

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 °C	0.346	25.36	0.000	

Table 5: An examination of the correlation among spawning success, temperature (T) and flow (Q) at several locations during the period they are used by the Early Stuart sockeye. Pearson correlation coefficients (r) with significance marked in bold and with an "*" ($p<0.05$) following correction for multiple comparisons (Holm 1979). Analysis includes data from 1953-2004 from sources described by Macdonald et al. (2007).

	Spawning Success	**Spawning Grd. T**	**Stuart T**	**Stuart Q**	**Finmoore T**	**Vanderhoof Q**	**Isle Pierre T**	**Hells Gate T**	**Hells Gate Q**	**Entrance Isl. T**
Spawning Grd. T	**-0.468 ***									
Stuart T.	-0.357	**0.829 ***								
Stuart Q	0.296	-0.398	-0.415							
Finmoore T	-0.304	**0.657 ***	**0.760***	**-0.438 ***						
Vanderhoof Q	0.089	0.001	0.027	0.382	-0.408					
Isle Pierre T	-0.321	**0.770***	**0.919***	-0.411	**0.901***	-0.204				
Hells Gate T	-0.191	0.431	**0.456 ***	**-0.638 ***	0.321	-0.002	0.364			
Hells Gate Q	0.167	-0.378	-0.253	**0.675 ***	-0.293	0.227	-0.245	**-0.754 ***		
Entrance Isl. T	0.013	0.257	0.218	-0.418	0.043	0.163	0.138	**0.774 ***	**-0.617 ***	
Amphitrite Pt. T	-0.241	0.354	0.221	-0.319	0.072	0.184	0.160	**0.582 ***	**-0.543 ***	**0.614 ***

Figure 1

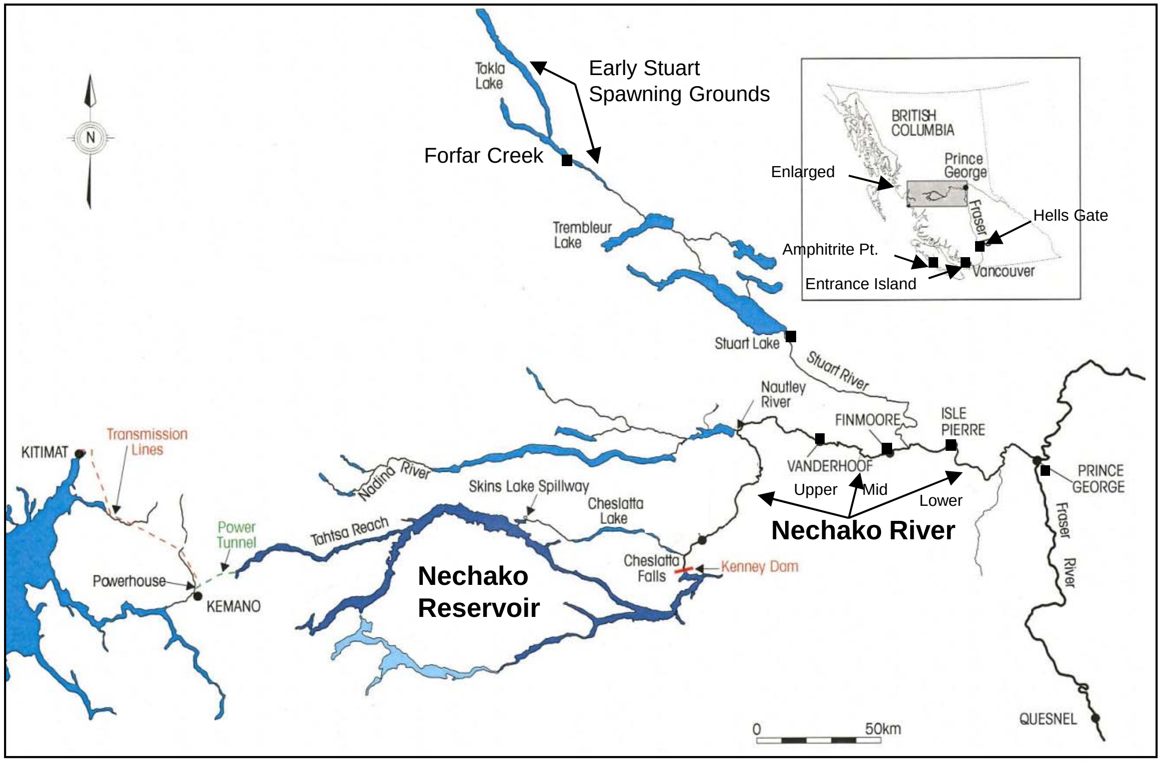
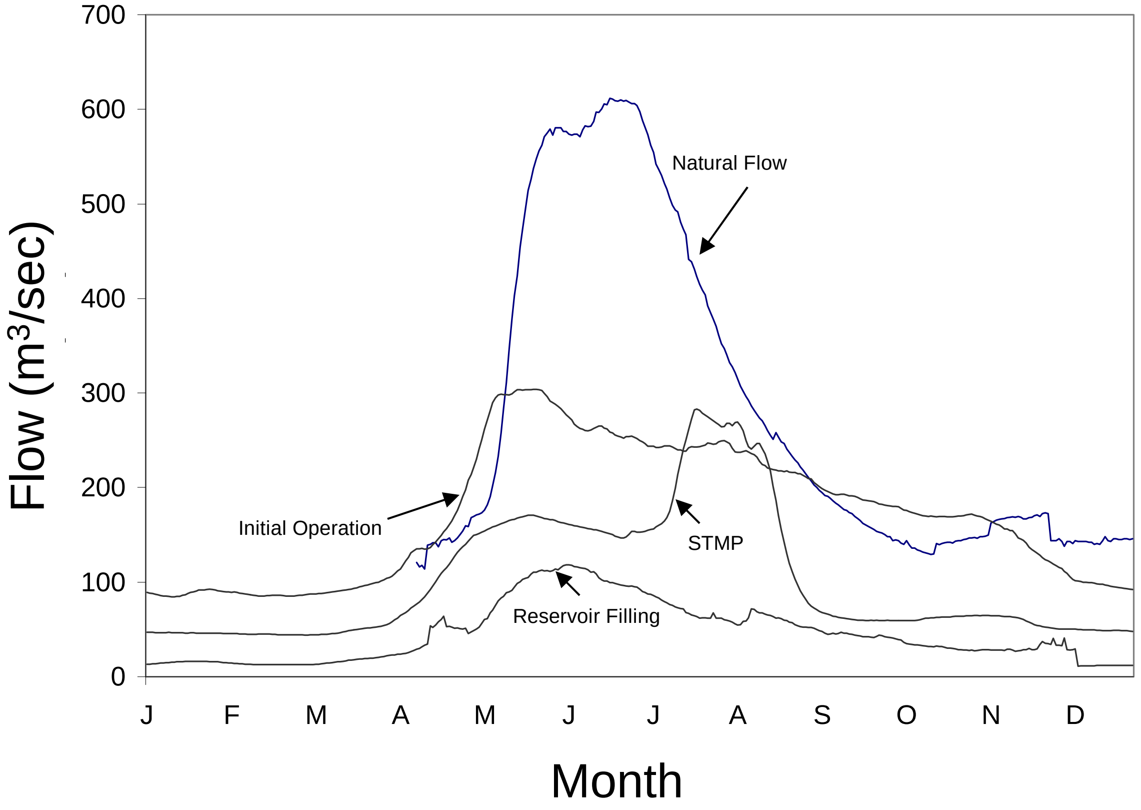
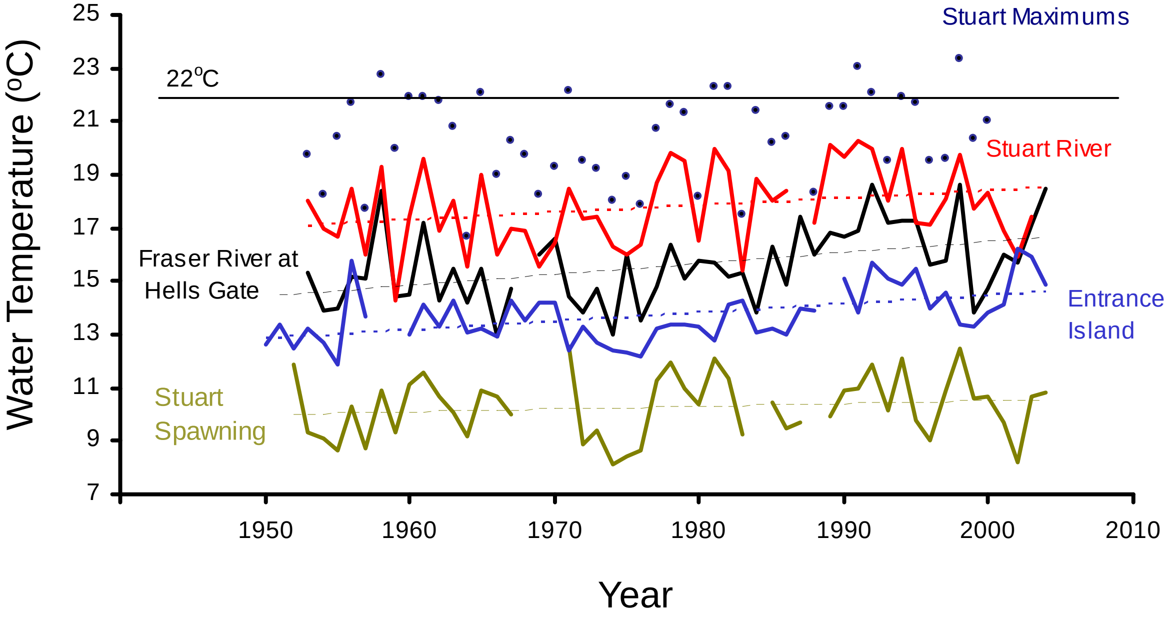

Takla Lake
Early Stuart Spawning Grounds
Forfar Creek
Trembleur Lake
Stuart Lake
Stuart River
BRITISH COLUMBIA
Enlarged
Prince George
Fraser
Hells Gate
Amphitrite Pt.
Entrance Island
Vancouver
N
Nautley River
FINMOORE
ISLE PIERRE
VANDERHOOF
Upper
Mid
Lower
Nechako River
PRINCE GEORGE
Fraser River
KITIMAT
Transmission Lines
Nadina River
Skins Lake Spillway
Cheslatta Lake
Power Tunnel
Tahtsa Reach
Nechako Reservoir
Cheslatta Falls
Kenney Dam
Powerhouse
KEMANO
0
50km
QUESNEL

Figure 2



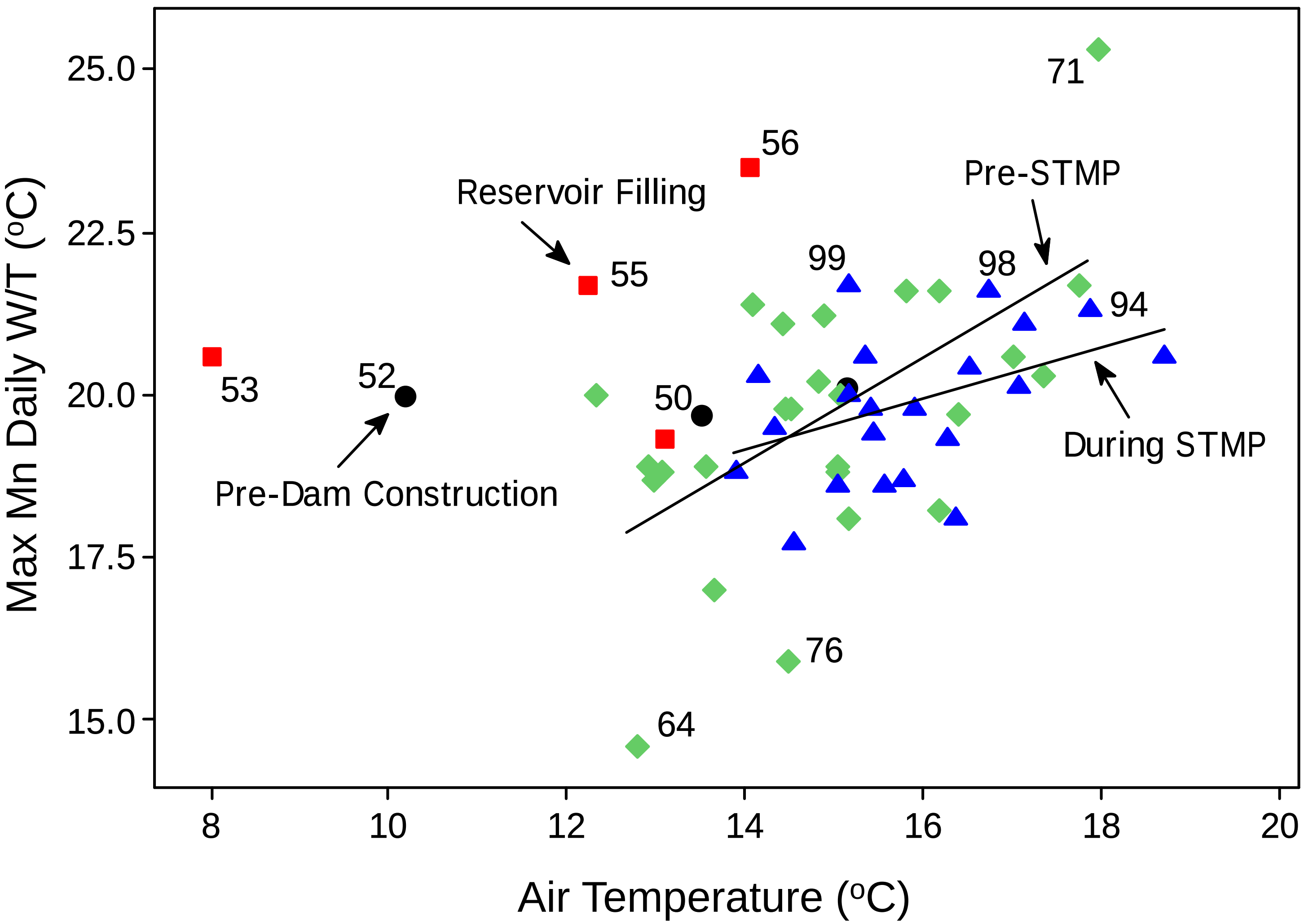
700
600
500
400
300
200
100
0
Flow (m³/sec)
J
F
M
A
M
J
J
A
S
O
N
D
Month
Natural Flow
Initial Operation
STMP
Reservoir Filling

Figure 3



Stuart Maximums
22ºC
Stuart River
Fraser River at
Hells Gate
Entrance
Island
Stuart
Spawning
Water Temperature (ºC)
25
23
21
19
17
15
13
11
9
7
1950
1960
1970
1980
1990
2000
2010
Year

Figure 4



Max Mn Daily W/T (°C)
25.0
22.5
20.0
17.5
15.0
Air Temperature (°C)
8
10
12
14
16
18
20
71
56
Reservoir Filling
55
Pre-STMP
99
98
94
53
52
50
During STMP
Pre-Dam Construction
76
64

Figure 5

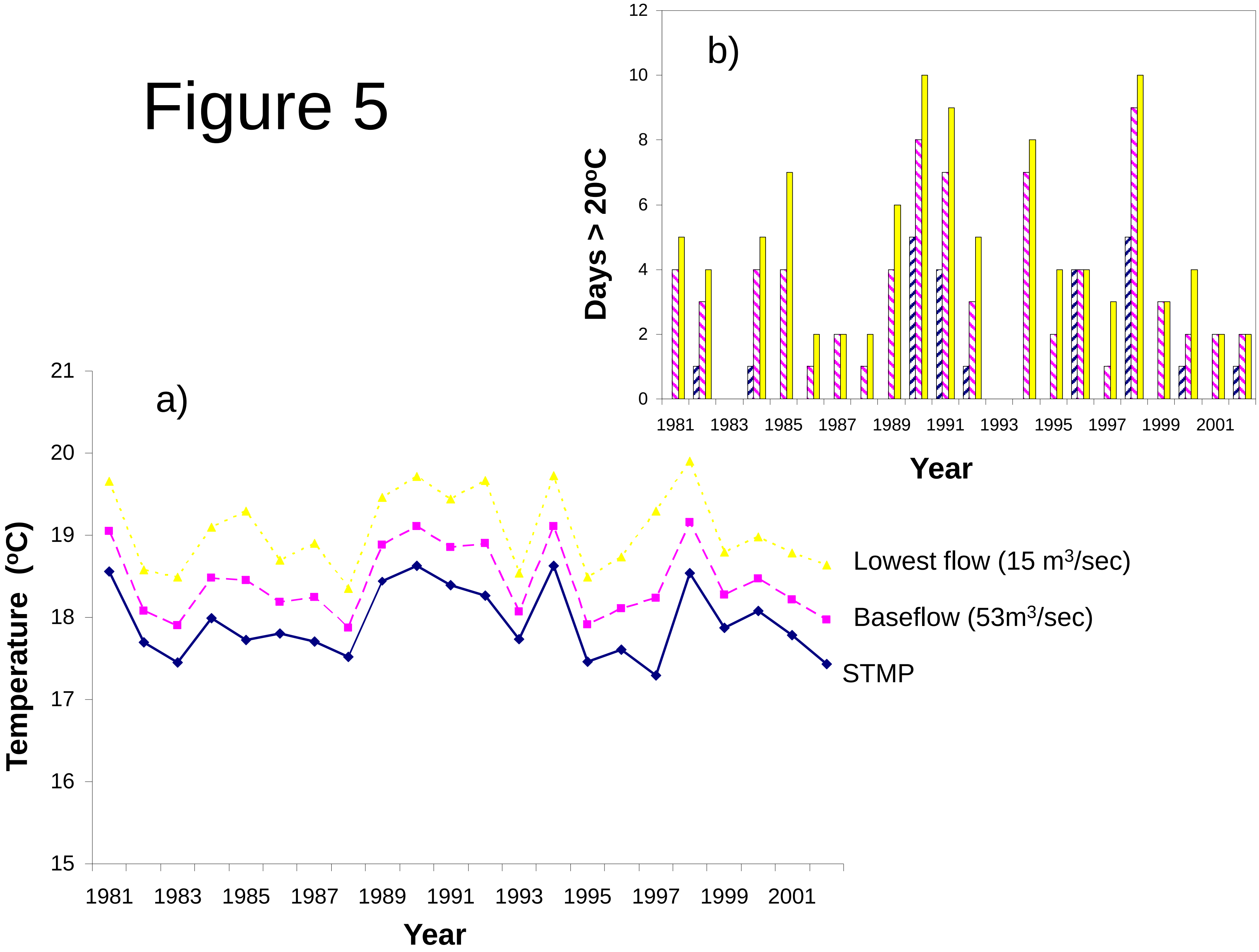
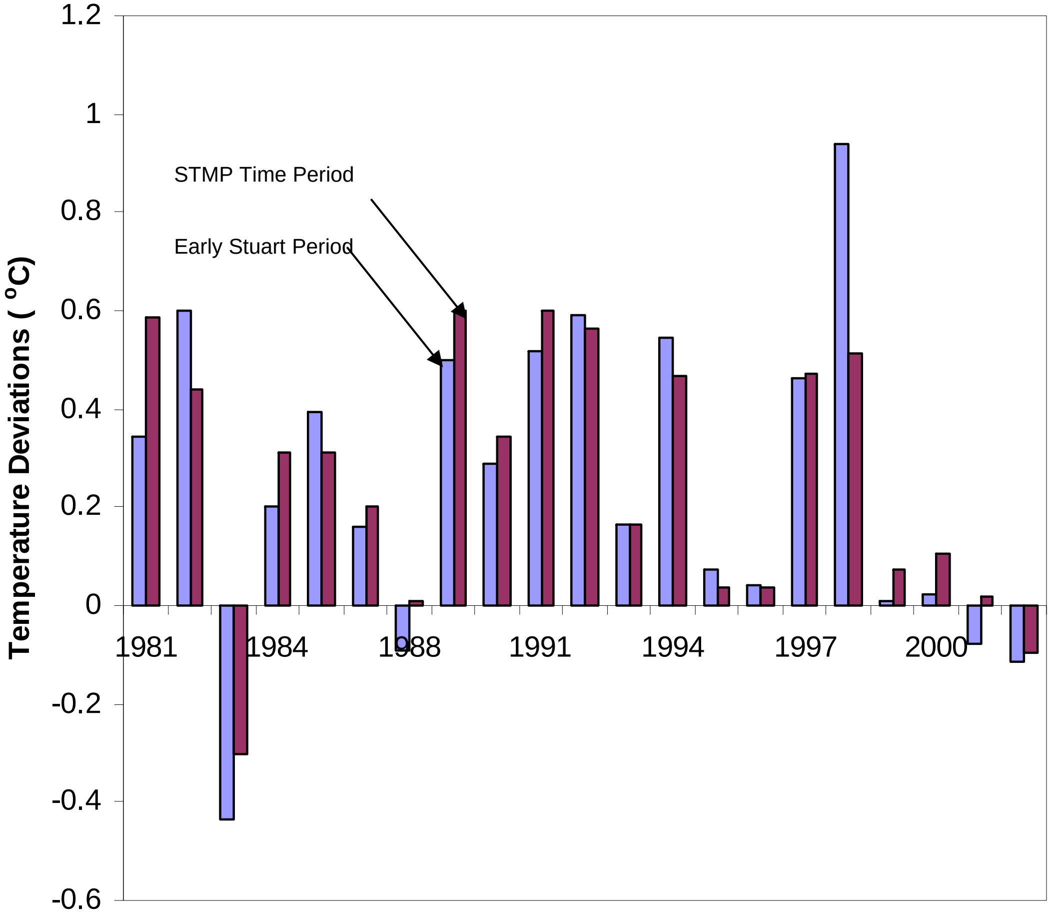

b)
Days > 20ºC
0
2
4
6
8
10
12
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
a)
Temperature (ºC)
15
16
17
18
19
20
21
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
Lowest flow (15 m³/sec)
Baseflow (53m³/sec)
STMP

Figure 6



STMP Time Period
Early Stuart Period
Temperature Deviations (°C)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1981
1984
1988
1991
1994
1997
2000

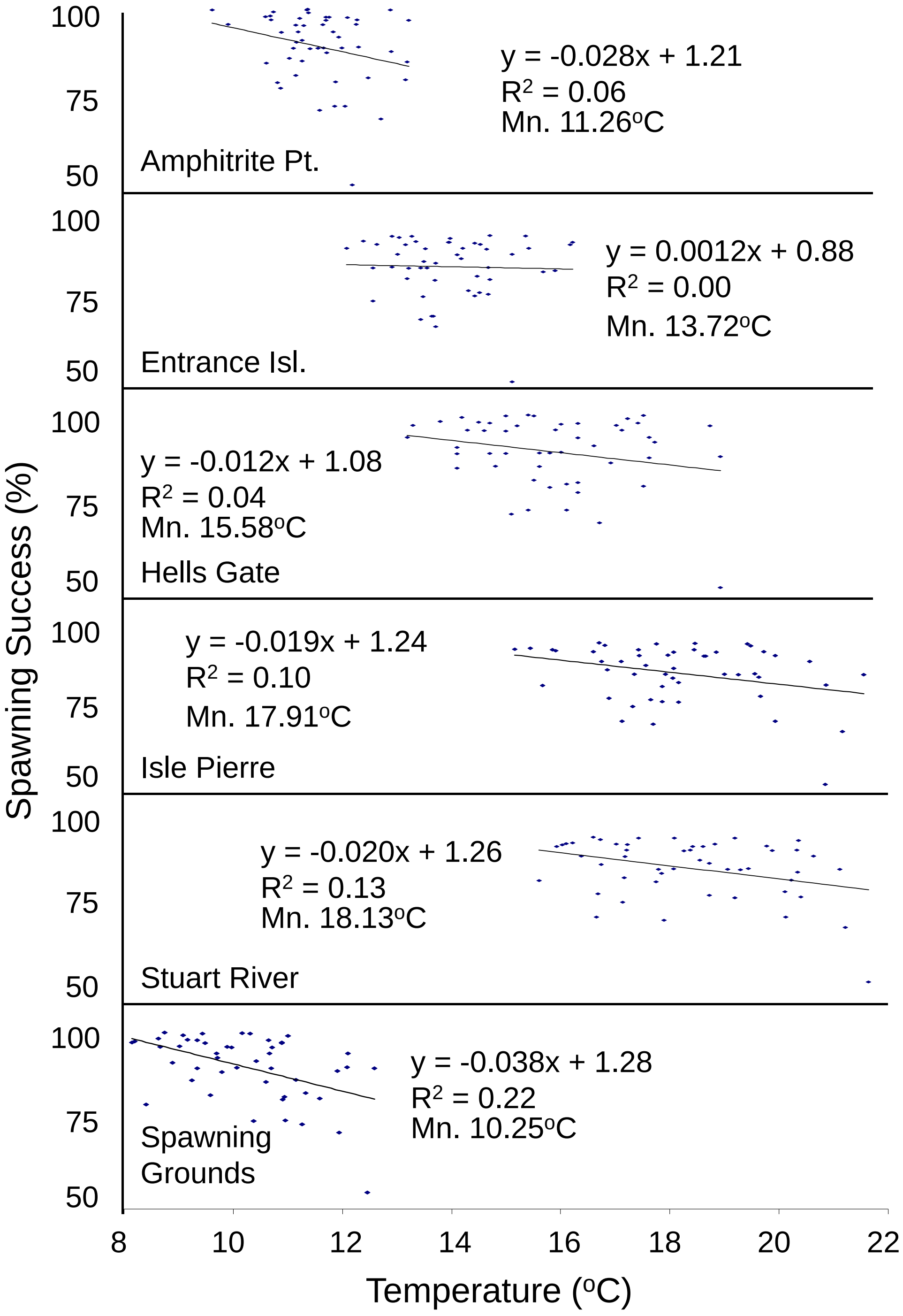
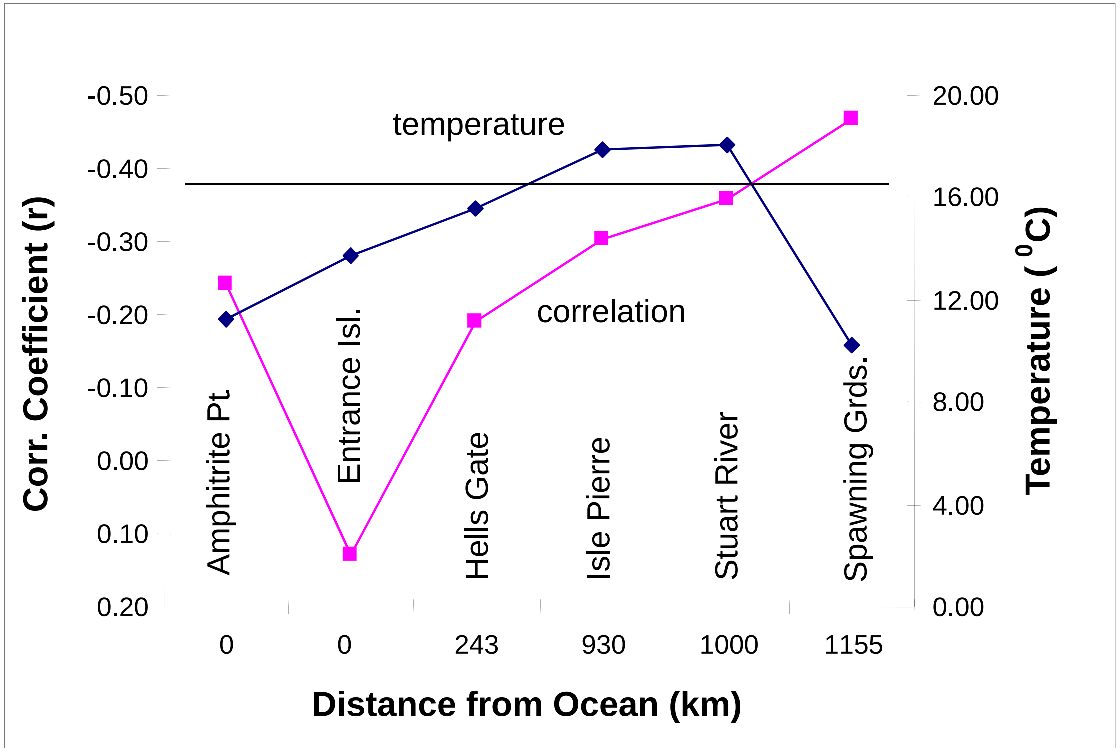

100
75
50
Amphitrite Pt.
y = -0.028x + 1.21
R^2 = 0.06
Mn. 11.26°C
100
75
50
Entrance Isl.
y = 0.0012x + 0.88
R^2 = 0.00
Mn. 13.72°C
100
75
50
y = -0.012x + 1.08
R^2 = 0.04
Mn. 15.58°C
Hells Gate
100
75
50
y = -0.019x + 1.24
R^2 = 0.10
Mn. 17.91°C
Isle Pierre
100
75
50
y = -0.020x + 1.26
R^2 = 0.13
Mn. 18.13°C
Stuart River
100
75
50
y = -0.038x + 1.28
R^2 = 0.22
Mn. 10.25°C
Spawning Grounds
Spawning Success (%)
8
10
12
14
16
18
20
22
Temperature (°C)

Figure 7

Figure 8



temperature
correlation
Corr. Coefficient (r)
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
Temperature (^{0}C)
20.00
16.00
12.00
8.00
4.00
0.00
Amphitrite Pt
Entrance Isl.
Hells Gate
Isle Pierre
Stuart River
Spawning Grds.
0
0
243
930
1000
1155
Distance from Ocean (km)