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# GROWTH OF JUVENILE CHINOOK SALMON, (ONCORHYNCHUS TSHAWYTSCHA), ACCLIMATED TO CYCLING AND CONSTANT TEMPERATURES: APPLICATION TO AN ENVIRONMENTAL IMPACT ASSESSMENT

by

Nancy Louise Knight

B.Sc., Simon Fraser University, 1979

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# ABSTRACT

The purpose of this project was to increase the understanding of the effect of cycling temperatures on growth of juvenile chinook salmon, (Oncorhynchus tshawytscha), and to investigate the implications of this information in environmental impact assessment. Growth rates of juvenile chinook salmon were examined under three constant and three cycling temperature regimes, and two rations. The constant temperatures, 13°C, 16°C and 19°C, corresponded to the means of the cycling regimes which had amplitudes of ±2°C. The two rations were 12% and 7% of dry body weight per day. Growth of juvenile chinook salmon acclimated to cycling temperatures was greater than or equal to their growth when acclimated to the constant mean temperatures. The difference in growth rates between the two thermal regimes was larger when the mean acclimation temperature was below the optimum metabolic temperature.

A simulation model was used to investigate the magnitude and direction of any difference that might occur in estimation of fry weight if a growth function based on cycling rather than constant temperatures was used. The difference was small when mean temperatures were high. At lower mean temperatures, estimates of fry weights based on cycling temperatures were 10% larger than estimates based on constant temperatures. This difference could have implications in fisheries management and environmental impact assessment.

The model was extended to a preliminary impact assessment of the Kemano Completion Project, (KCP), on summer growth of juvenile chinook salmon in the Upper Nechako River. If post-KCP temperatures in the Upper Nechako River were similar to those assumed in the model, an increase in fry weight from pre-KCP conditions could occur.

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# TABLE OF CONTENTS

Approval ....................ii

ABSTRACT ....................iii

Acknowledgements ....................v

List of Tables ....................vii

List of Figures ....................viii

I. INTRODUCTION ....................1

II. MATERIALS AND METHODS ....................7

Experimental ....................7

Simulation Model ....................13

III. RESULTS ....................23

Experimental ....................23

Simulation Model ....................28

IV. DISCUSSION ....................32

LITERATURE CITED ....................48

APPENDIX I ....................52

A. Model Documentation ....................52

B. Tables Presenting Supplementary Data and Results ..55

C. Method for Construction of Growth Function for Model ....................58

D. Method for Adjustment of Growth Rates as a Function of Size ....................62

# LIST OF TABLES

TABLE PAGE

1 Experimental Design, showing temperature treatments, rations received and feeding techniques .......... 9

2 The eight thermal regimes in the Nechako River explored in the simulation model .......... 16

3 The eight distributions of juvenile chinook salmon in the Nechako River assumed in the simulation model .......... 16

4 Juvenile chinook salmon growth rates, (%wet weight/day), and results of a hypothesis test .......... 25

5 Predicted average fry weight (grams) under cycling and constant temperatures for the eight thermal regimes .......... 30

6 Predicted average fry weight, (grams), for four of the juvenile chinook salmon distributions and eight thermal regimes:cycling and constant growth function results .......... 31

B1 Temperatures assumed in the model for each thermal regime during the summer for each location .......... 55

B2 Initial and final average weights, and growth rates of juvenile chinook salmon under daily cycling and constant temperatures at two rations .......... 56

B3 Dry weight increase, dry weight of food consumed, and gross conversion efficiency of juvenile chinook salmon under daily cycling and constant temperatures at two ration levels .......... 57

# LIST OF FIGURES

FIGURE PAGE

1 Kemano Completion Project Location Map ................ 4

2 Semi-sinusoidal Temperature Pattern .................. 11

3 Growth rates of juvenile chinook salmon acclimated to cycling and constant temperatures and fed 12% and 7% rations ................................. 26

4 Gross conversion efficiencies of juvenile chinook salmon acclimated to cycling and constant temperatures and fed 12% and 7% rations .......... 27

5 Predicted growth rates of juvenile chinook salmon acclimated to cycling and constant temperatures at 50% of satiation ration .......... 43

# I. INTRODUCTION

Water resources have many different uses. Allocation between competing uses relies, in part, on environmental impact assessment. Risk and uncertainty may play large roles in the allocation process if the knowledge required to accurately predict impacts is incomplete. Environmental scientists work to clarify the scientific questions and thereby assist in determining a sensible use of our resources.

In British Columbia, two uses that often compete in the water allocation process are hydroelectric power generation and fish habitat maintenance. Hydroelectric projects can alter downstream temperatures, an important component of fish habitat. Changes in temperature regimes may influence the growth rates of fish living in the altered environment.

Estimates of the effect of temperature changes on fish growth have implicitly assumed that growth under constant temperatures is representative of growth under daily cycling temperatures, as long as the constant temperature is equal to the mean of the cycle. The assumption is based on the belief that fish under cycling temperatures acclimate to the cycle's mean. This has permitted the results of laboratory studies of fish growth at constant temperatures to be applied to field situations where water temperatures cycle daily.

Recent studies indicate that this assumption may not be warranted (Hokanson et al. 1977, Biette and Geen 1980, Cox and

Coutant 1981, Spigarelli et al. 1982). The forerunner to these recent investigations was an hypothesis advanced by McLaren (1963) to explain the selective advantage of the daily vertical migrations of zooplankton between warm surface and cool subsurface waters. He hypothesized that a metabolic advantage resulted from this behaviour because the food ingested in the warm surface waters was metabolized at lower temperatures in subsurface waters. Therefore, the growth and reproductive capabilities of migratory zooplankton were enhanced compared to those of non-migratory zooplankton. Other scientists tested this hypothesis with fish growth in stratified lakes (Brett 1971, Biette 1978), and in waters receiving thermal effluents (Hokanson et al. 1977, Cox and Coutant 1981). At low temperatures, these authors found higher growth rates under cycling temperatures than under constant temperatures equal to the cycle's mean or extremes.

The studies that found higher growth rates under cycling temperatures have involved large cycle amplitudes, which may not be found in rivers. Yet, it is possible that the application of fish growth studies at constant temperatures to fish growth in rivers may produce an error in estimation of growth rates. The purpose of this project was:

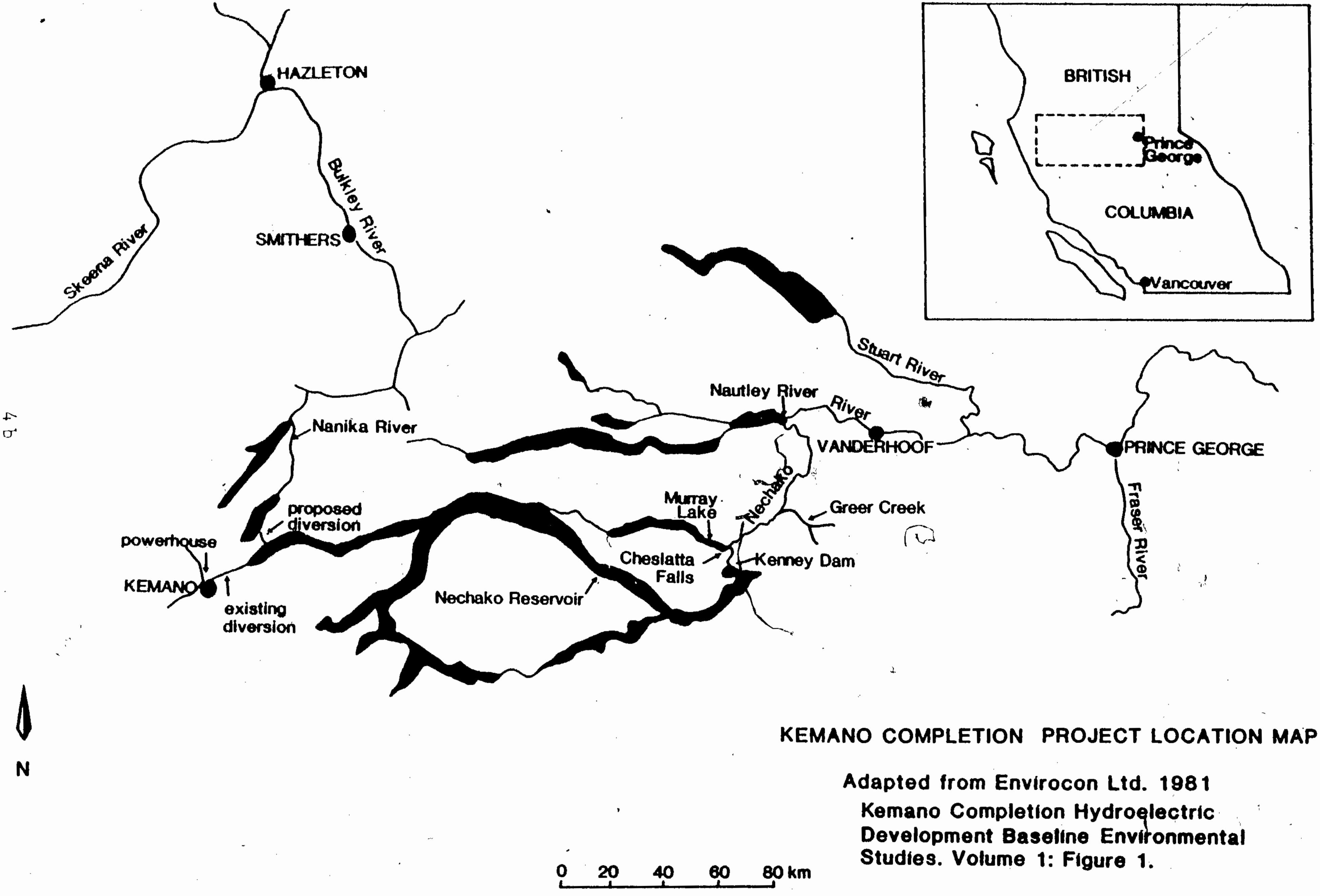
1. to test whether juvenile chinook salmon, (Oncorhynchus tshawytscha), grow faster when acclimated to a cycling temperature rather than a constant temperature, when the constant temperature is equal to the mean of the cycle; and,

2. to investigate the implications of the experimental results in environmental impact assessment.

The need for this study arose because of a hydroelectric development proposal in central British Columbia, the Aluminum Company of Canada's, (ALCAN), Kemano Completion Project, (KCP). ALCAN was granted a water license by the B.C. government in 1950 for the use of all water in the Upper Nechako and Nanika Rivers, (Fig. 1), as a source of low-cost, assured-supply hydroelectricity for aluminum smelting. Part of this potential was developed in the early 1950s. In the late 1970s ALCAN began to investigate possibilities of developing the remainder. The resulting KCP proposal would reduce mean annual flows in the Upper Nechako River, and if cooling water was not provided, lowered flows could be accompanied by higher summer water temperatures. Higher water temperatures, particularly near the Stuart River confluence, could be harmful to salmon species in the Nechako River (International Pacific Salmon Fisheries Commission 1983).

ALCAN is committed to sharing use of the water in the Nechako River with fish (ALCAN 1982), and has planned to add cooling water to the Nechako River's flow. This cooling water, provided in July and August, would maintain downstream water temperatures below safety limits suggested by the International Pacific Salmon Fisheries Commission, (IPSFC), and the Department of Fisheries and Oceans, (DFO). ALCAN has proposed to build a cold-water release facility in the existing Kenney Dam, and to

Figure 1: Kemano Completion Project Location Map



KEMANO COMPLETION PROJECT LOCATION MAP

Adapted from Envirocon Ltd. 1981
Kemano Completion Hydroelectric
Development Baseline Environmental
Studies. Volume 1: Figure 1.

mix flows from this source with the warm surface waters of Murray Lake to produce 10°C source water discharged at 1100 cubic feet per second, (cfs), (DFO 1984). In years of average sunshine, ALCAN believed this cooling water would restrict water temperatures in July and August near the Stuart River confluence to less than 18°C. However, the 10°C source water would depress temperatures in the Upper Nechako River.

Juvenile chinook salmon could be affected by the addition of cooling water to the Nechako River. Adults spawn in rivers during the fall. Fry emerge from the gravel in April and May and rear in freshwater for periods varying from three months to a full year before migrating to sea. Adult chinook salmon spend three to five years in the ocean before returning to spawn. The freshwater rearing period may be important in determining juvenile and adult survival rates. Chinook salmon use the Upper Nechako River for spawning and rearing and the growth of the rearing juveniles could be affected by the cooler water temperatures.

A study by Brett et al. (1982) was used to estimate the impact of proposed temperature changes on growth of juvenile chinook salmon. That study was based on fish acclimated to constant temperatures and fed satiation rations. Application of their results requires the implicit assumption that growth is equivalent under constant and cycling temperatures. Consequently, predictions of the impact of temperature changes in the Upper Nechako River on growth rates of juvenile chinook salmon could be incorrect. This project was directed towards assessing the direction and magnitude of any error. In addition, a preliminary assessment of the effect of various, post-KCP temperature regimes on the growth of juvenile chinook salmon was undertaken.

# II. MATERIALS AND METHODS

## Experimental

Three groups of juvenile chinook salmon were obtained from the Capilano River Salmon Hatchery on January 23, February 28, and April 19 of 1984. All groups were from the same stock of Capilano chinook salmon. Each group was acclimated to a different mean temperature; 13°C, 16°C, and 19°C respectively. Half of each group was kept under a constant temperature equal to the mean temperatures above, the other half was kept under a daily temperature regime which cycled ±2°C around the mean.

The mean weight of the juvenile salmon was determined. Only fish within ±1 standard deviation of the mean weight were used in the experiments. The objective was to reduce the competitive edge in feeding engendered by large size differences (Brett 1979) and so reduce depensatory growth, characterized by increasing variance in fish weights over time.

Forty fish were placed in each of eight 80-liter aquaria. Each aquarium held 60 liters of dechlorinated water, 40 liters of which were replaced with fresh water every Monday, Wednesday, and Friday mornings. Aquaria were cleaned every morning of the week and once on weekends. The aquaria were aerated constantly and held under a 12L:12D photoperiod at Simon Fraser University.

Salmon in four of the aquaria received a 12% ration daily, and in the other four they received a 7% ration daily, calculated on a dry weight basis. The actual ration provided to the fish was slightly less than 12% and 7% because the food weights were calculated at the beginning of the ten-day sampling period and were not adjusted for assumed fish growth during that period. The temperature treatments and rations provided are presented in Table 1.

Two of the four aquaria at each ration were exposed to constant temperatures and two to cycling temperatures. Cycling temperatures were achieved by heating the water with time-controlled, 50-watt aquarium heaters which produced a semi-sinusoidal temperature pattern (Fig. 2). Thermograph recordings and daily spot-checks showed that the cycling pattern was reasonably constant, (within ±0.5°C), during and among the experiments. Constant temperatures were also achieved through the use of aquarium heaters, which kept temperatures within ±0.5°C of the desired temperatures.

The fish were held for four days in the aquaria before beginning the experiment. The average weight of the juvenile salmon at the beginning of each experiment was:

experiment 1 - 0.824 g ( $\sigma$=0.053 g);
experiment 2 - 1.249 g ( $\sigma$=0.035 g); and,
experiment 3 - 0.806 g ( $\sigma$=0.037 g).

Fish were fed Oregon Moist pellets, which were kept frozen and weighed out fresh daily. Records were kept of mortalities

Table 1 - Experimental Design, showing temperature treatments, ration levels, and feeding regimes.

| Expt | Treatment | Temp (C) | Ration (%) | Actual Ration (%) | Feeding Regime |
|---|---|---|---|---|---|
| 1 | 1 | 11-15 | 12 | 10.35 | 1 |
| | 2 | 13 | 12 | 10.35 | 1 |
| | 3 | 11-15 | 7 | 6.6 | 1 |
| | 4 | 13 | 7 | 6.6 | 1 |
| 2 | 1 | 14-18 | 12 | 10.0 | 1 |
| | 2 | 16 | 12 | 10.0 | 1 |
| | 3 | 14-18 | 7 | 6.1 | 2 |
| | 4 | 16 | 7 | 6.1 | 2 |
| 3 | 1 | 17-21 | 12 | 11.35 | 2 |
| | 2 | 19 | 12 | 11.35 | 2 |
| | 3 | 17-21 | 7 | 6.6 | 2 |
| | 4 | 19 | 7 | 6.6 | 2 |

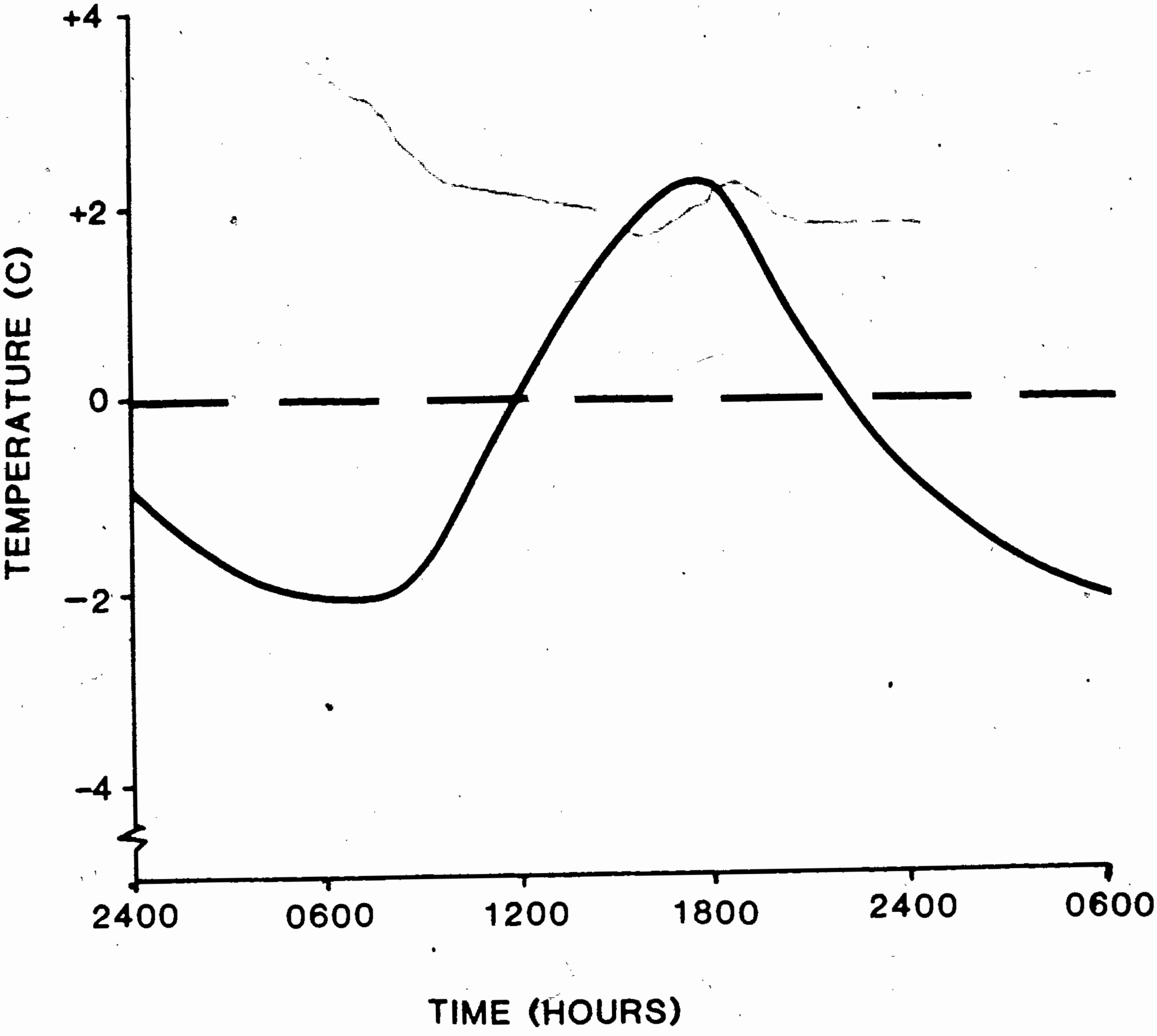
where: feeding regime 1 indicates single ration feeding 6 days/week; and, feeding regime 2 indicates double ration feeding every other day.

and the food provided was immediately adjusted. On average, total mortalities were less than 10% of the population, or approximately 0.3% per day.

Two feeding techniques were employed. If the ration was sufficient for all fish to have a reasonable opportunity to feed, the fish were fed 6 days per week between 1700 and 1800 hours. If the ration was insufficient for all fish to have a reasonable opportunity to feed, the fish were fed double rations every other day, also between 1700 and 1800 hours. The latter feeding technique was an attempt to reduce the depensatory growth that occurs in fish growth studies. I assumed that this change in feeding regime between experiments did not influence the growth rates, and so did not limit comparison of the results.

Neilson and Geen (1985) and Shelbourn et al. (1973) have studied the effects of different feeding regimes on salmonid growth rates. Neilson and Geen's findings indicated that, at low rations, juvenile chinook salmon fed once per day would grow faster than when fed twice per day. The change in feeding regime may have biased the results from the experiments using a 7% ration. At this ration, the growth rates in experiment 1, (13°C mean temperature), could be lower than they would have been if the fish had been fed on the same regime as in the other two experiments. Shelbourn et al. (1973), studying the growth of sockeye salmon fry, compared the effect of continuous satiation feeding for 15 hours per day versus three, half-hour satiation

Figure 2: Semi-sinusoidal Temperature Pattern


+4
+2
0
-2
-4
TEMPERATURE (C)
2400
0600
1200
1800
2400
0600
TIME (HOURS)

feedings per day. They found that the all-day feeding regime resulted in significantly higher growth rates than the three times per day regime. This evidence suggests that growth studies involving discreet feeding might underestimate growth rates in nature where feeding may be more continuous.

The experimental duration was 28 days. Approximately 15 fish were randomly sampled from each aquarium on day 1, 10, 20, and 28 of each experiment. They were anaesthetized and their weights and lengths recorded to the nearest 0.01 g and 0.1 cm respectively. The fish were weighed in a tared, water-filled container, and then replaced into their original aquarium. Dry weights of the fish and food were determined at the beginning and end of each experiment.

Before the growth rates could be statistically compared, several steps were necessary. First, replicate weight data were pooled because logistic constraints required that the number of treatment replicates and the sample sizes be small. A t-test, comparing mean weights of replicate samples, was used to determine if the data could be pooled, and in all cases it was possible. Second, natural logarithms of the weight data were regressed against time. The slope of each regression line gave an estimate of the instantaneous growth rate of the juvenile chinook salmon. Gross conversion efficiencies, (GCE), were determined for each experiment using the equation:

$$GCE=100 \times \frac{((\text{total growth (dry. wt.)}))}{(\text{total food consumption(dry wt.)})}$$

## Simulation Model

A simulation model was constructed to investigate the potential implications of the experimental results in impact assessment. The model, based on the KCP and addition of cooling water to the Nechako River, simulated the deterministic freshwater growth of juvenile chinook salmon from time of emergence, late April, until the end of August. For the purpose of this project the Upper Nechako River was defined as the stretch of river between Cheslatta Falls and Vanderhoof (Fig. 1). Chinook salmon spawn along this part of the river, with the heaviest concentration of spawners located near Cheslatta Falls (Envirocon 1981b). Three locations along the Upper Nechako River were chosen for study because the temperature of the water changes as it travels downstream. They were Greer Creek, Nautley River, and Vanderhoof. The model simulated chinook salmon growth during the summer at each of these locations, and then averaged the three weights.

The model had two major components; average monthly temperatures in the Upper Nechako River from May to August, and a mathematical representation of juvenile chinook salmon growth rates at various temperatures.

In the first component separate functions described the estimated temperature pattern from May to August at each location on the Upper Nechako River for eight different thermal regimes. The first thermal regime was an estimate of the long-term, average water temperatures and reflects temperatures in the Upper Nechako River from 1950 to the present. The data were obtained from Envirocon's (1981b)[1] baseline reports, and this case was represented by Case 1 (Table 2). The actual temperatures used in the model can be found in Appendix IB, Table B1. Predictions of post-KCP thermal regimes in the Nechako River were not available from ALCAN or Envirocon Ltd., and so the information for the seven remaining thermal regimes was obtained from a variety of other sources which are outlined below.

The second, third, and fourth thermal regimes were estimates of post-KCP water temperatures and were drawn from Figure 22 in DFO's discussion paper of KCP (DFO 1984). This figure gave predicted temperatures at various locations along the Upper Nechako, assuming a source water temperature of 10°C, a flow rate of 1100 cfs, and three climatic conditions, hot, average, and cold. Temperatures from this figure were used for three post-KCP thermal regimes, Case 2, 3, and 4 (Table 2).

---

[1] Envirocon Ltd. was ALCAN's environmental consultant on the KCP proposal.

The four remaining thermal regimes postulated two colder source water temperatures, 8°C and 6°C, combined with two flow rates, 1100 cfs and a flow rate between 500 and 1100 cfs. The effects of these thermal regimes were simulated because of suggestions by IPSFC (1983) that the proposed 10°C source water would still allow too many days annually when water temperature in the Nechako River at the Stuart River confluence would exceed 20°C, and that the long term average water temperatures in July and August at this point would be shifted from 16.9°C to 19.2°C. These conditions would be unsatisfactory to IPSFC, and so a source water temperature colder than 10°C or a higher discharge of the 10°C source water might be required. The provision of additional cooling water would represent lost power production to ALCAN, and so colder source water temperatures were postulated even though it might not be possible to obtain such cold water from behind the Kenney Dam in the summer. For the cases where a flow rate of 1100 cfs was postulated, predictions of downstream temperatures were based on the average climate temperature profile in Figure 22 of the DFO (1984) report. For the cases that postulated a lower flow rate, it was assumed that most of the effect of cold source water was lost when the warmer Nautley River entered the Nechako River. Consequently there was a large increase in water temperature at this point. A general outline of the thermal regimes considered is presented in Table 2. The actual temperature patterns assumed in the model are presented in Appendix IB, Table B1.

Table 2 - The eight thermal regimes in the Nechako River explored in the simulation model.

| Case | KCP | Climate | Flow Rate | Source Water Temperature |
|---|---|---|---|---|
| 1 | no | average | 1100 cfs | 10C |
| 2 | yes | average | 1100 cfs | 10C |
| 3 | yes | hot | 1100 cfs | 10C |
| 4 | yes | cold | 1100 cfs | 10C |
| 5 | yes | average | 1100 cfs | 8C |
| 6 | yes | average | low | 8C |
| 7 | yes | average | 1100 cfs | 6C |
| 8 | yes | average | low | 6C |

where KCP represents the Kemano Completion Project.

Table 3 - The eight distributions of juvenile chinook in the upper Nechako River assumed for the simulation model.

| Case | Proportional Distribution by Area<br>a | <br>b | <br>c |
|---|---|---|---|
| 1 | .80 | .10 | .10 |
| 2 | .50 | .25 | .25 |
| 3 | .25 | .50 | .25 |
| 4 | .25 | .25 | .50 |
| 5 | .15 | .30 | .55 |
| 6 | .10 | .20 | .70 |
| 7 | .05 | .15 | .80 |
| 8 | .05 | .05 | .90 |

where a = the area near the Greer Creek confluence with the Nechako River;
b = the area near the Nautley Creek confluence with the Nechako River;
c = the area near Vanderhoof on the Nechako River.

The second model component was a mathematical description of the growth rates of juvenile chinook salmon at various temperatures. The growth function was assumed to represent the growth capabilities of a 0.82 gram chinook salmon feeding at 50% of satiation. It was derived from data generated in the experimental portion of this project combined with information from Brett et al. (1982). Third order polynomial growth functions were fit to data from cycling and constant temperatures. The addition of the third term in the polynomial did not improve the fit statistically but provided a curve that was closer to the shape of the growth-ration-temperature relationship described for sockeye salmon (Brett et al. 1969) and for chinook salmon (Brett et al. 1982). The equations used in the model were:

1. $G=0.215+(0.207xT)+(0.0229xT^2)-(0.0016xT^3)$
2. $G=0.057+(0.256xT)+(0.0139xT^2)-(0.0012xT^3)$

where G is instantaneous growth rate and T is temperature. Equation 1 predicts growth under daily cycling temperatures and equation 2 predicts growth under constant temperatures. For details of how the growth functions were constructed, see Appendix IC.

The potential maximum growth rate of fish decreases as size increases (Brett 1979, Brett and Shelbourn 1975). In the model, the growth functions assume a size of 0.82 grams. Consequently, the growth rate predicted for a given temperature had to be adjusted for the size of the fish before using it to calculate the weight gained in any time period. Brett and Shelbourn (1975) presented an equation that described the maximum potential growth rate of fish at different sizes, and this equation was the basis of the growth rate adjustments made in the model. For a complete discussion of this adjustment process, see Appendix ID.

The variable in the model chosen to provide an indication of the impacts of altered thermal regimes was the predicted average weight of the chinook salmon fry in the Upper Nechako River at the end of August. Other possible indicators, such as fry abundance, were not modelled because reliable information about the effect of temperature shifts on freshwater survival was lacking. Analyses were conducted to explore two objectives:

1. to determine the magnitude and direction of any difference in predicted size caused by using growth functions based on cycling versus constant temperatures; and,
2. to explore the potential effect of KCP on summer growth of juvenile chinook salmon.

Sensitivity analyses were conducted to determine how the model's predictions regarding the second objective varied with the juvenile distribution pattern in the Upper Nechako River. Envirocon (1981b) suggested that up to 90% of the fry population may migrate out of the Upper Nechako River in late June or early July. This was based on beach seine catches taken in the summers of 1979 and 1980 which may have underestimated the size of the rearing population (DFO 1984). Beach seines sample habitat close to the river banks and exclude the faster flowing, mid-river habitat preferred by older chinook salmon juveniles. DFO (1984) reported further studies by Envirocon on downstream migration of chinook salmon fry that estimated that 30% of the population leaves the Upper Nechako River by the end of June. Russell et al. (1983) estimated that, in 1980, 35% of the fry population had migrated downstream by late June. It is unknown where the remaining juveniles rear in the Upper Nechako River. As there is uncertainty regarding the size and location of the rearing population during the summer in the Upper Nechako River, the model tested different distributions of a hypothetical population of 100 fry, and averaged the weights predicted at the three locations to give one indicator value. Eight different distributions were explored in the model, each having a proportion of the population located around one of the three locations described earlier (Table 3). It was assumed that no further changes in these distributions occurred. Russell et al. (1983) and Envirocon (1981b) reported minor downstream migrations of juvenile chinook salmon from the Upper Nechako River during July and August.

The model was narrow in scope, focussing only on the relationship between water temperature and growth of juvenile chinook salmon. Consequently, many factors were omitted and several assumptions were made. First, I assumed that juvenile chinook salmon obtained an average ration equal to 50% of satiation during the summer, both before and after KCP. Benthic invertebrates and drift organisms are the major components of the diet of juvenile chinook salmon (DFO 1984, Russell et al. 1983). Several authors have reported a decrease in diversity of benthic invertebrate species accompanied by an increase in the density of remaining species downstream of impoundments releasing cold, hypolimnetic, nutrient-rich water (Helsenhoff 1971, Spence and Hynes 1971, Ward and Stanford 1979). The assumption of similar feeding levels pre- and post-KCP would be reasonable if juvenile chinook salmon are opportunistic feeders, as indicated by Russell et al. (1983), and so easily able to switch food preferences, and if the changes in species composition resulted in no net loss of caloric content in the available food. The assumption of maintenance of an average feeding level during the summer would be reasonable if fish abundance in the Upper Nechako River paralleled the abundance of food organisms. This may not be true before the June outmigration but may hold afterwards. Growth in May and June may thus be slightly overestimated, but this overestimation would be common to all analyses.

Second, I assumed that changes in the thermal regime of the river had little effect on the behaviour or individual fitness of juvenile chinook salmon. It is possible that an increase in growth would improve individual fitness, which might be reflected in other characteristics such as a higher survival rate. However, these relationships are difficult to estimate v

numerically and were not addressed in the model.

Third, I assumed that any change in rearing habitat resulting from changes in flow rates from 500 cfs to 1100 cfs was of no consequence to juvenile chinook salmon. Two of the eight postulated thermal regimes, Cases 6 and 8 (Table 2), assumed a flow rate between 500 and 1100 cfs, and to be comparable to regimes with flow rates of 1100 cfs, the available habitat had to be similar so the results would not be confounded by crowding and behavioural interactions. Holden (1979) noted that dewatering is one of the important and immediate fish habitat changes resulting from dams, but Envirocon (1981b) predicted no major change in available habitat in the Upper Nechako River for flow rates between 500 cfs and 1000 cfs. Flow rates greater than 1500 cfs produced a loss of habitat. Therefore, this assumption is reasonable.

Fourth, I assumed that the potential maximum growth rate of chinook salmon from the Capilano River was the same as chinook salmon from the Nechako River. Brett et al. (1982) found significant differences between the potential maximum growth rates of two different stocks of chinook salmon. This may influence how accurately the model predicts the size of chinook salmon fry in the Nechako River.

Lastly, I assumed that water temperatures in the Upper Nechako River cycled an average of ±2°C around the mean from May to August, and that this amplitude was constant along the entire length of the Upper Nechako River. Envirocon (1981b) provided some support for this assumption, however, it may have overestimated the amplitude in the Upper Nechako River below the Nautley River confluence, where discharge is greater. This might result in overestimation of growth rates at Vanderhoof when using the growth function based on cycling temperatures.

# III. RESULTS

## Experimental

Table 4 presents the calculated growth rates of juvenile chinook salmon acclimated to cycling and constant temperatures for the three mean temperatures examined in this study. The probability values indicate that growth under cycling temperatures was significantly greater than growth under constant temperatures on one occasion; in experiment 1 at the 7% ration. This assumes that the significance level in the statistical test is 0.05. When one considers the small number of replicates, the small sample sizes, and the large variance in the data, it may be reasonable to choose a higher alpha level, 0.10, to evaluate the results of the statistical comparisons. At $\alpha=0.10$, growth under cycling temperatures was significantly greater that growth under constant temperatures on three occasions; experiment 1 at the 7% ration, experiment 1 at the 12% ration, and experiment 2 at the 12% ration. There was no significant difference between growth rates under the other three temperature/ration combinations. The relationship between growth rate and temperature is graphically presented in Figure 3. The average initial weight, average final weight, and growth rate for the juvenile chinook salmon at each mean temperature are presented in Appendix IB, Table B2.

It is worth noting some trends in the growth rate data. First, for fish fed the 12% ration, growth rates under both cycling and constant temperatures were high, near 3.10% wet weight per day, at 13°C and 16°C, and declined to approximately 1.60% wet weight per day at 19°C (Fig. 3). For fish fed the 7% ration, growth rates were moderate at 13°C and 16°C under both cycling and constant temperatures, around 1.6% wet weight per day and declined to approximately 1.1% wet weight per day at 19°C (Fig. 3). Second, the difference in growth rates under cycling and constant temperatures was larger at lower temperatures than at higher temperatures. At the 12% ration, growth rate differences at 13°C and 16°C were larger, but at 19°C the difference was much smaller. At the [illegible]% ration, the growth rate difference, large at 13°C, was almost nonexistent at 16° and 19°C.

The gross conversion efficiency, (GCE), data are presented graphically in Figure 4. The GCE of juvenile chinook salmon acclimated to cycling temperatures was greater than the GCE of those acclimated to constant temperatures. At both rations, the difference in GCE between the daily cycling and constant temperatures lessened as the temperature rose, becoming almost equal at 19°C, particularly at the 7% ration. Statistical comparison of GCE's was not possible because the fish in each aquarium were fed as a unit and so no measure of individual variation in food consumption was possible.

Table 4 - Juvenile chinook salmon growth rates, (% wet weight per day), and results of hypothesis test where:
$H_0$: Growth rate under cycling temperatures is less than or equal to growth rate under constant temperatures vs.
$H_1$: Growth rate under cycling temperatures is greater than growth rate under constant temperatures.

| Ration Level | Mean Temperature | Specific Growth Rates G(Cycle) | G(Const) | Probability |
|---|---|---|---|---|
| EXPT 1 | | | | |
| 7% | 13C | 1.81 | 1.36 | 0.0293 |
| 12% | 13C | 3.20 | 2.90 | 0.0933 |
| EXPT 2 | | | | |
| 7% | 16C | 1.67 | 1.61 | 0.3879 |
| 12% | 16C | 3.10 | 2.75 | 0.0885 |
| EXPT 3 | | | | |
| 7% | 19C | 1.12 | 1.13 | 0.4850 |
| 12% | 19C | 1.69 | 1.53 | 0.3215 |

Figure 3: Growth rates of juvenile chinook salmon acclimated to cycling and constant temperatures and fed 12% and 7% rations. Points represent average values ± 1 S.D.

——— represents 12%, cycling temperature data,  
- - - - - represents 12%, constant temperature data,  
·········· represents 7%, cycling temperature data, and  
—— —— represents 7%, constant temperature data.

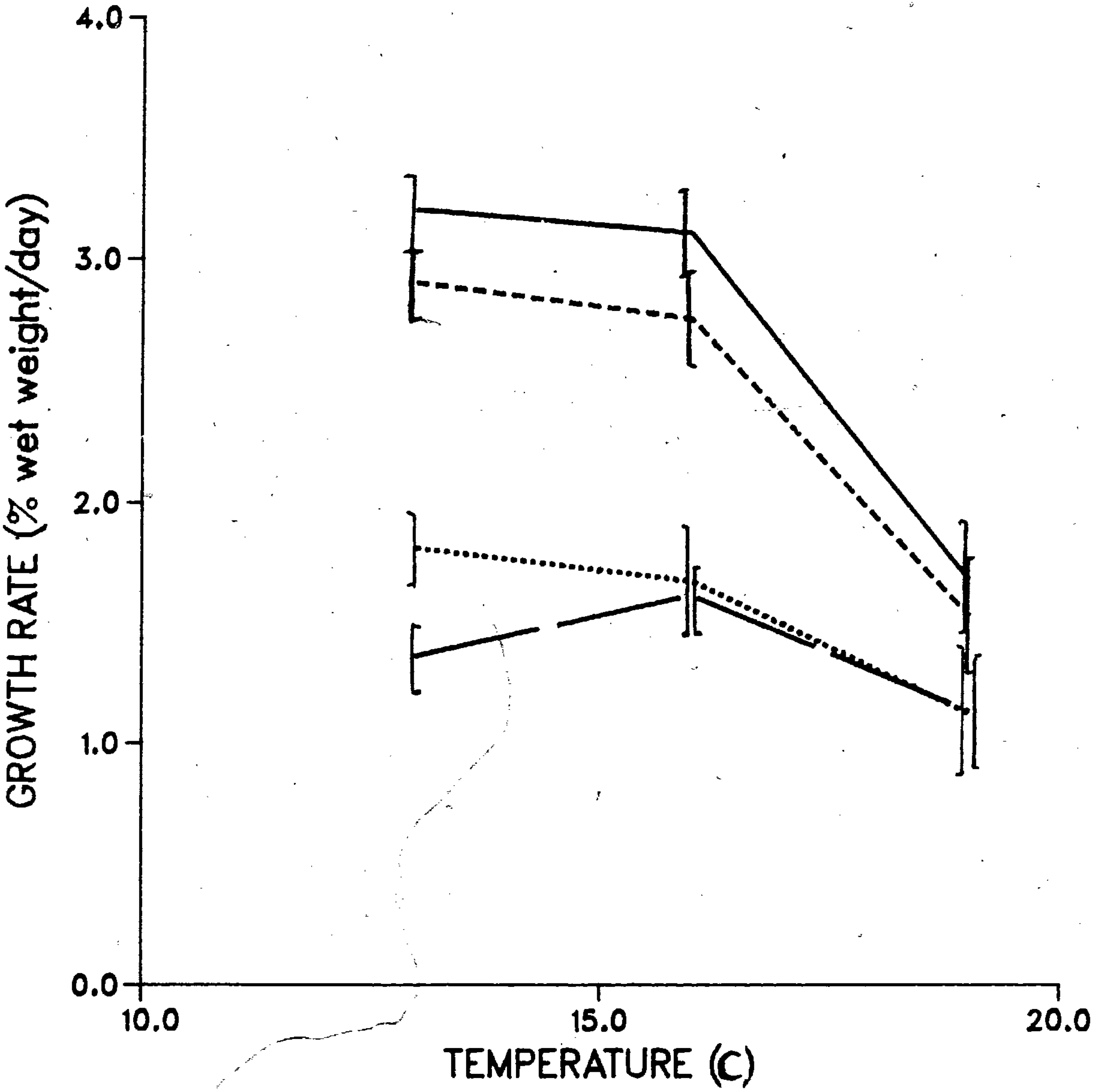
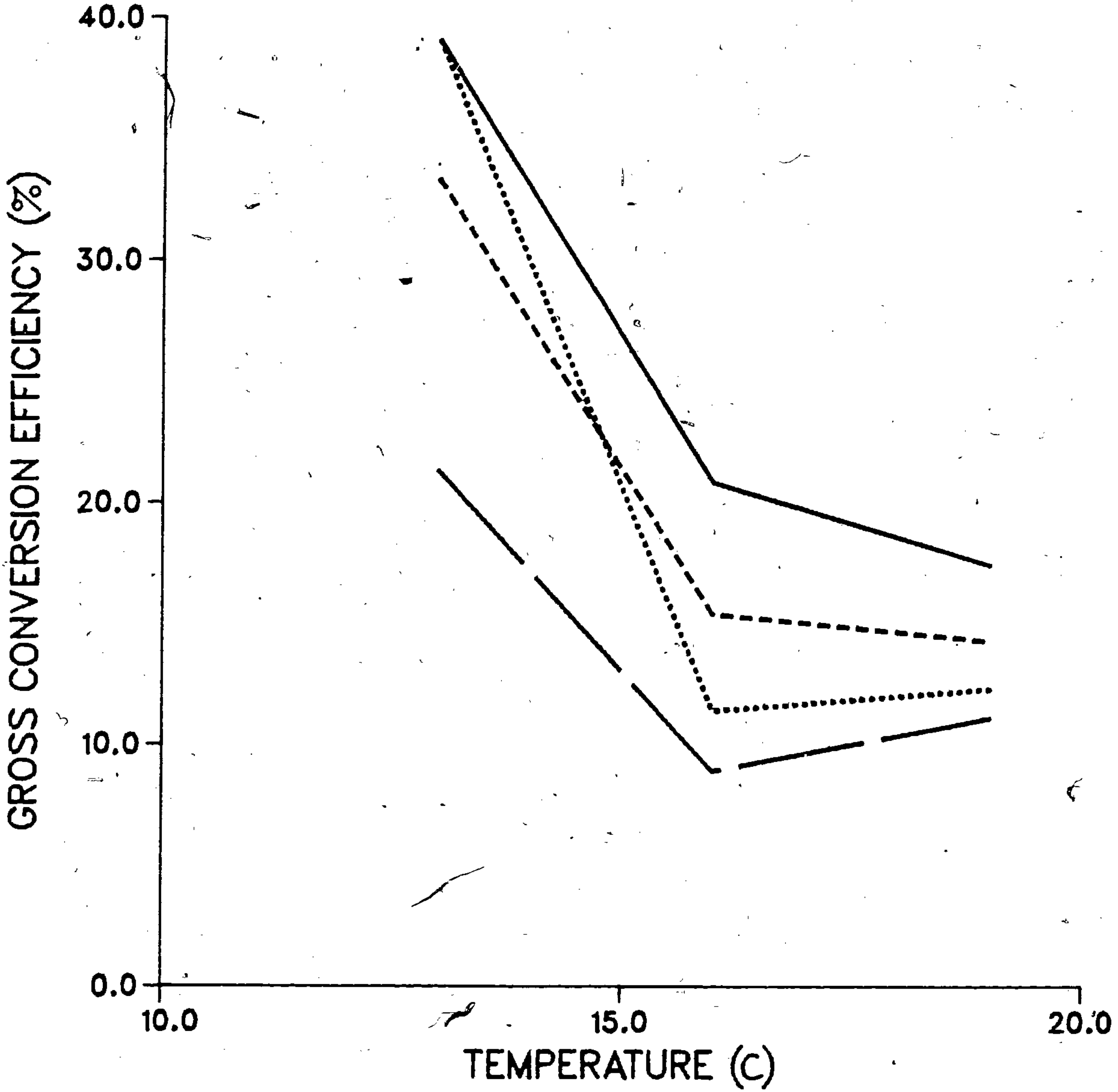

4.0
3.0
2.0
1.0
0.0
GROWTH RATE (% wet weight/day)
10.0
15.0
20.0
TEMPERATURE (C)

Figure 4: Gross conversion efficiencies of juvenile chinook salmon acclimated to cycling and constant temperatures and fed 12% and 7% rations.

——— represents 12%, cycling temperature data,  
- - - - - represents 12%, constant temperature data,  
········· represents 7%, cycling temperature data, and  
— — — represents 7%, constant temperature data.


40.0
30.0
20.0
10.0
0.0
GROSS CONVERSION EFFICIENCY (%)
10.0
15.0
20.0
TEMPERATURE (C)

## Simulation Model

Table 5 presents the fry weights predicted by the model for growth functions based on cycling and constant temperatures, G(Cycle) and G(Const) respectively. These results were used to address the first objective of the modelling exercise, to determine what difference one might expect in predicted size caused by using growth functions based on cycling or constant temperatures. Under thermal regime 1, there was a 2% difference in the predicted fry weight. This regime reflected long-term, average temperatures in the Nechako River (Case 1, Table 2). The other thermal regimes, Cases 2 through 8, represented possible post-KCP Nechako River temperatures, and the difference in predicted fry weight increased to approximately 10% of predicted weight. The model results presented in Table 5 assumed one juvenile distribution pattern, $(JDP)_1$, Case 1 (Table 3). This JDP assumed that the largest proportion of the population was located near Greer Creek. When the JDP was changed in the model to one that had the largest proportion of the population located near Vanderhoof, Case 8 (Table 3), the difference in predicted fry weights caused by the use of different growth functions was reduced to 7% (Table 6).

Table 6 presents the predicted fry weights at the end of August under the eight thermal regimes, four of the JDPs considered, and both growth functions. These results were used to address the second objective of the modelling exercise, to explore the potential effect of KCP on summer growth of juvenile chinook salmon. Under the average current thermal regime, Case 1, the predicted fry weight was approximately 4.70 grams. The model predicted larger fry weights for the other thermal regimes, indicating an increase in growth rates after KCP. The amount of the increase varied with the thermal regime considered and the JDP assumed. In general, larger increases were predicted assuming thermal regimes 5, 8, and 4, and smaller increases predicted assuming regimes 6 and 3. Specifically, assuming JDP 1 and G(Cycle), the predicted fry weight under thermal regime 5, 7.84 grams, represents an approximate 68% increase in weight from 4.60 grams. The predicted weight under thermal regime 7, 6.04 grams, represents an approximate 30% increase in weight.

There were some general trends in the simulation model results. First, the JDP assumed in the model determined the relative positions of the thermal regimes regarding the rank order of the predicted weights. For example, simulations that assumed thermal regime 7 and JDP 1 predicted the smallest fry weight. Simulations that assumed thermal regime 7 and JDP 8 predicted the fourth largest fry weight. Second, the variance in the predicted weights between thermal regimes increased as the large proportion of the population was shifted downstream. For example, the difference between the largest and smallest fry weight predicted for thermal regimes 2 through 8, assuming JDP 1, was 1.80 grams. This difference was increased to 2.74 grams by assuming JDP 8.

Table 5 - Predicted average fry weight (grams) using cycling and constant growth functions for the eight thermal regimes and juvenile distribution pattern 1.

| Thermal Regime (Case) | Predicted Average Fry Weight (g) G(Cycle) | G(Const) | Difference |
|---|---|---|---|
| 1 | 4.66 | 4.74 | -.08 |
| 2 | 7.45 | 6.76 | .69 |
| 3 | 7.49 | 6.86 | .63 |
| 4 | 7.36 | 6.65 | .71 |
| 5 | 7.84 | 7.19 | .65 |
| 6 | 7.17 | 6.52 | .65 |
| 7 | 6.04 | 5.49 | .55 |
| 8 | 7.45 | 6.93 | .52 |

Table 6 - Predicted average fry weights (grams) for four juvenile chinook salmon distributions, eight thermal regimes and two growth functions.

| THERMAL REGIME | JUVENILE DISTRIBUTIONS | | | |
|---|---|---|---|---|
| | 1 | 3 | 4 | 8 |
| G(Cycle) Simulations | | | | |
| 1 | 4.66 | 4.25 | 4.02 | 3.56 |
| 2 | 7.45 | 7.43 | 7.23 | 6.96 |
| 3 | 7.50 | 6.81 | 6.24 | 5.60 |
| 4 | 7.36 | 7.52 | 7.61 | 7.71 |
| 5 | 7.84 | 8.20 | 8.20 | 8.34 |
| 6 | 7.17 | 7.34 | 7.15 | 6.94 |
| 7 | 6.04 | 6.93 | 7.09 | 7.62 |
| 8 | 7.45 | 7.62 | 7.62 | 7.68 |
| G(Const) Simulations | | | | |
| 1 | 4.74 | 4.41 | 4.22 | 3.85 |
| 2 | 6.76 | 6.82 | 6.69 | 6.53 |
| 3 | 6.86 | 6.40 | 5.99 | 5.52 |
| 4 | 6.65 | 6.81 | 6.90 | 7.00 |
| 5 | 7.19 | 7.54 | 7.54 | 7.66 |
| 6 | 6.52 | 6.74 | 6.61 | 6.52 |
| 7 | 5.49 | 6.28 | 6.43 | 6.91 |
| 8 | 6.93 | 7.14 | 7.14 | 7.21 |

where thermal regimes 1 through 8 are those of Table 2, and the juvenile distributions are from Table 3.

# IV. DISCUSSION

The experimental work was conducted to determine if the assumption of equivalent growth under cycling and constant temperatures was reasonable when studying juvenile chinook salmon. In my experiments, the growth rates of juvenile chinook salmon, acclimated to cycling temperatures were greater than or equal to their growth rates when acclimated to the cycle's mean temperature. At both rations, as the mean temperature under examination increased, the difference between growth rates of fish under cycling and constant temperatures decreased. This indicated that the assumption of equivalent growth may not be reasonable at low temperatures.

My observation of faster fish growth under low cycling temperatures was consistent with the findings of other studies. Biette and Geen (1980) studied the growth of juvenile sockeye salmon, <u>O. nerka</u>, fed several rations under one cycling temperature regime and a constant temperature approximately equal to the cycle's mean. They found juvenile sockeye salmon grew significantly faster under the cycling temperature regime when fed restricted rations. At satiation feeding, they grew faster under the constant temperature. Spigarelli et al. (1982) reported that brown trout, <u>Salmo trutta</u>, fed to satiation grew faster under a cycling thermal regime than a constant temperature approximately equal to the cycle's mean. Hokanson et al. (1977) studied the growth of rainbow trout, <u>S. gairdneri</u>, under several cycling temperature regimes and a series of constant temperatures. They concluded that rainbow trout grew faster under cycling temperatures compared to constant temperatures when these temperatures were low. Cox and Coutant (1981) studied growth of juvenile striped bass, (Morone saxatilis), at several rations, three cycling temperature regimes and three constant temperatures. They found cycling temperatures enhanced growth at low temperatures.

At high temperatures my results were not in agreement with the findings of other studies. My results suggested there would be little difference between growth rates of fish under cycling compared to constant temperatures. The results of Hokanson et al. (1977) and Cox and Coutant (1981) suggested that growth would be depressed under cycling temperature regimes when the cycle's mean temperature was high.

Spigarelli et al. (1982), reviewing the work of Hokanson et al. (1977), suggested that a depression of growth rates under high cycling temperatures could results from the cycle's mean being higher than the metabolic optimum. To examine my results from this perspective, I first had to identify the optimum metabolic temperature at each ration. The optimum metabolic temperature can be defined as the temperature, for any given ration, that produces the maximum growth rate (Brett 1979). Brett et al. (1969) observed that this optimum shifted down as ration decreased and referred to this pattern as the temperature shunt phenomenon. My results provided a rough estimate of the optimum metabolic temperature of juvenile chinook salmon at each ration. At the 12% ration, the growth rates suggested that the optimum may be between 13°C and 16°C. At the 7% ration, growth rates suggested an optimum near 13°C (Fig. 3). The suggestion of the latter optimum is strengthened by the possibility that the growth rates at 13°C were biased downwards from their true values because of the feeding régime employed.

Brett et al. (1982) studied the growth of juvenile chinook salmon fed satiation rations at a number of constant temperatures and determined that 19°C was the optimum metabolic temperature under those conditions. They deduced that the optimum temperature at 60% of satiation feeding would be 15°C. My results compared favourably with these because the 12% ration in my experiments roughly corresponded to an average feeding level of 50% of satiation, and the 7% ration to 30% of satiation. There is a potential difficulty in directly comparing my results to Brett et al. (1982) because the two studies were conducted in different seasons. There may be a seasonal shift in the metabolic optimum that would complicate or confound comparison. Yet, my results suggested optimum temperatures that would be in the ranges expected according to the temperature shunt phenomenon and the findings of Brett et al. (1982).

In my experiments, 19°C was above the optimum metabolic temperature at the 12% ration and growth under cycling and constant temperatures was not different (Table 4). At the 7% ration 16°C and 19°C were above the optimum temperature and growth under cycling and constant temperatures was not different (Table 4). So, my experimental results are not in complete agreement with those of studies that have specifically examined temperatures above the metabolic optimum (Hokanson et al. 1977, Cox and Coutant 1981). One difference in experimental design that might explain the contradictory observations is the amplitude of the cycling temperature regimes in each study. My cycling temperature regimes had amplitudes of ±2°C around the mean temperature, whereas Hokanson et al. (1977) and Cox and Coutant (1981) used amplitudes of ±3.6°C and ±4.0°C respectively.

Spigarelli et al. (1982) suggested that some knowledge of amplitude effects might be important in understanding how cycling temperatures affect fish growth. Different cycle amplitudes might cause varying physiological outcomes because the fish may, in effect, be acclimating to a temperature between the mean and maximum of the cycle (Hokanson et al. (1977), Houston 1982). Fish exposed to a wide cycle amplitude would acclimate to a higher temperature than fish exposed to a narrower cycle centred around the same mean temperature. Above the metabolic optimum, where growth rates decline with increasing temperature, fish exposed to a wide compared to a narrow temperature cycle might grow more slowly. Further, narrower cycle amplitudes might make differentiation between growth under cycling and constant temperatures more difficult because the acclimation temperatures would be closer. This could explain why my results indicated little difference between growth rates under cycling and constant temperatures once above the metabolic optimum while Hokanson et al. (1977) and Cox and Coutant (1981) found depressed growth rates under cycling temperatures. These observations could lead one to hypothesize that the size of the cycle amplitude is correlated with the size of the growth rate difference that would be observed between cycling and constant temperature regimes. Some support for this hypothesis can be found in Threader and Houston (1983) who observed that rainbow trout had varying thermal tolerances when acclimated to different cycle amplitudes.

The experimental work was conducted to determine if the assumption of equivalent growth under cycling and constant temperatures was reasonable when studying juvenile chinook salmon. My results suggest it is probably not reasonable at temperatures below the metabolic optimum where growth is faster under cycling temperatures. For temperatures above the metabolic optimum, the assumption may be reasonable if cycle amplitudes are small. If cycle amplitudes are large, one might expect growth to be lower under cycling compared to constant temperatures. The experimental work would have benefited from a more extensive series of cycling and constant temperatures, and more replication of the treatments. Analysis of the results was difficult because only a rough identification of the optimum metabolic temperature at each ration was possible, and because the variance in the weight data was large.

The simulation model was constructed to explore the implications of the experimental results in environmental impact assessment. Specifically, one objective was to determine whether any difference in predicted fry weight resulted from the use of growth functions based on cycling or constant temperatures. The growth functions used in the model assumed that fish were feeding at 50% of satiation and predicted a metabolic optimum between 13°C and 16°C. The only thermal regime with temperatures greater than 16°C at every location on the Upper Nechako River was Case 1 (Table 2), which was an estimate of the long-term average water temperatures. Fry weights predicted by simulations of the effects of that regime varied little when I used growth functions based on cycling or constant temperatures. The majority of assumed temperatures in the other seven thermal regimes were less than 16°C. When the effects of these regimes were simulated, fry weights predicted using cycling temperature growth functions were 10% larger on average than the weights predicted using constant temperature growth functions.

The identification of differences in predicted fry weights could be important in fisheries management because there are many ways that changes in growth could influence a fish stock's biology. Size may influence survival rates of juvenile fish. Birds and other fish are the major predators of juvenile salmon, and each may have a preferred prey size (Mace 1983, Parker 1971, Patten 1971). Changes in growth rates might influence how long a juvenile salmon will remain within that preferred size range.

Size may also influence ocean survival rates. Bilton et al. (1982), studying coho salmon, found that smolt size and time of release were significant determinants of the number of adults returning, with late releases of large smolts producing high returns. Other studies (Bilton 1978, 1980, Peterman 1982) suggested that large smolts could also lead to an earlier age at maturity, thereby implying a loss of one or more years of ocean growth and a possible loss in yield to the fishery. For example, a 10% increase in smolt weight could lead to a 6% increase in the percentage of age class 4 adults in the returns of Babine Lake sockeye salmon (Peterman 1982). From Bilton's studies of Oregon coho salmon (Bilton ~~1978,~~ 1980) an increase in smolt weight from 10 grams to 11 grams could produce:

1. an increase in jacks from 12% to 18% of the total escapement;
2. an increase in total adult returns, (catch + escapement), from 25% to 27% of smolts released; and,
3. an increase in total adult biomass, (catch + escapement), from 119 million pounds to 133 million pounds.

The predictions from Bilton's work are based on June emigrations of 10 or 11 gram coho salmon smolts, which has not been observed for chinook salmon in the Nechako River, but illustrates the potential biological significance of a 10% difference in smolt weight. In systems that have high variability in, for example smolt returns, this error may not be crucial. But, if temperatures are being used to predict fry or smolt weights, and if the use of growth studies based on constant temperatures caused a significant error in estimation of these weights, the effect on other stock parameters might be incorrectly anticipated.

Fish acclimated to cycling temperatures have exhibited changes in other characteristics that are important in fisheries management. For example, several studies, (Feldmuth et al. 1974, Otto 1974, Threader and Houston 1983), reported that fish acclimated to cycling temperatures exhibited an increase in heat tolerance. Fish acclimated to cycling temperatures were able to withstand higher exposure temperatures than fish acclimated to constant temperatures.

The preceding discussion has shown how accuracy in knowledge of the effect of cycling compared to constant temperatures on fish growth and other factors can affect fisheries management and impact assessment.

The simulation model was also used to assess the potential effect of KCP on summer growth of juvenile chinook salmon in the Upper Nechako River. To determine how well the model simulated conditions in the Upper Nechako River, it's weight predictions were compared to existing data. The model predicted that the average fry weight at the end of August under the current thermal regime was approximately 4.70 grams. This assumed the majority of the juveniles were located near Greer Creek. When compared to existing data of juvenile chinook weights in the Upper Nechako River in September, this appeared to be an underestimate. Brett et al. (1982) reported the average weight of juvenile chinook salmon sampled by DFO in the Nechako River near Cheslatta Falls in early September, 1981 was 6.50 grams (n=50). The weight predicted by the model was different from this observed weight because water temperatures in 1981 were not the same as those assumed in the model (Table B1). When I substituted the mean monthly water temperatures reported by Brett et al. (1982) into the model, it predicted the fry weight at the end of August at Greer Creek was approximately 6.0 grams. This is close to the size reported by Brett et al. (1982). Russell et al.(1983) reported two years of size data for juvenile chinook salmon caught in the Upper Nechako. In 1980, their data suggested that the average size in mid-August was approximately 6 grams. In 1981, they reported data obtained from Envirocon which suggested that fry weights at the beginning of September were approximately 9.2 grams. Although sample sizes in September 1981 were moderate, (average sample size = 16, 14 samples), I do not believe this was an accurate estimate of the weight of juvenile chinook salmon in the Upper Nechako River in early September, and was perhaps caused by sampling error, different sampling locations, or a more favourable environment in 1981.

The model predicted that an increase in the summer growth of juvenile chinook salmon would occur if cooling water was added in July and August to the Nechako River's flow. This result should only be interpreted as preliminary because the growth functions that it is based on were derived from few real data points. At temperatures less than 13°C, the growth curves are extrapolations based on my results and those of Brett et al.(1982) and assumed that the growth advantage observed under cycling temperatures was maintained at mean temperatures less than 13°C. Further investigation to test the validity of this assumption would be desirable. Secondly, the results must be regarded as preliminary because the temperatures used in the model to simulate post-KCP thermal regimes may not accurately represent the actual temperatures in the Upper Nechako River after KCP. ALCAN's predictions were unavailable.

The increase in summer growth of juvenile chinook salmon was predicted when either the cycling or constant temperature growth function was used in the model. This prediction can also be deduced from Brett et al. (1982). According to that study, growth rates in July and August would average 1.33% per day and 1.05% per day at 18°C and 19°C respectively, temperatures that reflect long-term averages in the Nechako River. A reduction of the temperature to 11°C in July and August, which is predicted for the Greer Creek area after KCP, could produce daily growth rates of approximately 1.50%. This is larger than the long-term temperatures would produce yet less than 80% of the potential maximum growth rate, but the current temperatures do not produce growth rates within the 80% range either.

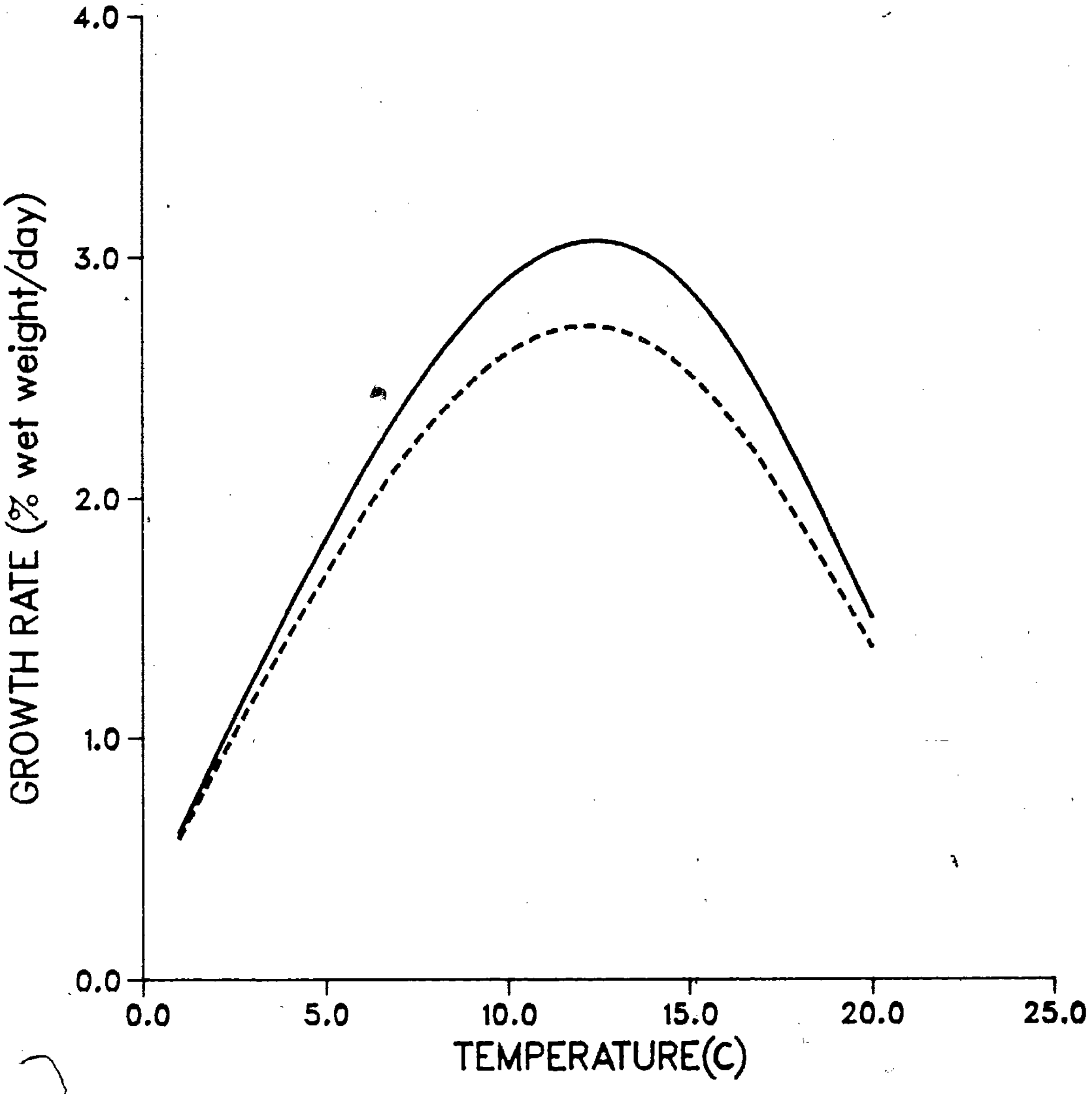
The increase in summer growth, represented by the weight predicted for the end of August, varied with the thermal regime and juvenile distribution pattern, (JDP), assumed in the simulation (Table 6). Predictions of post-KCP fry weights ranged from 5.5 to 8.34 grams. Thermal regimes 5, 4, and 8 consistently predicted larger fry increases; 3 and 6 predicted smaller increases, reflecting the warmer temperatures assumed in thermal regimes 3 and 6. The sensitivity of the predicted weights to JDP suggested that if the bulk of the population was upstream, warmer source water temperatures would produce larger weights than if the bulk of the population was downstream. The opposite of this was the case for cold source water temperatures.

It was surprising to find that the model predicted an increase in fry weight when the effects of the four cold source water thermal regimes were simulated, Cases 5, 6, 7, and 8 (Table 2). The model made this prediction when cycling and constant temperature growth functions were used, and when the bulk of the population was located near Greer Creek. This is contrary to what one would predict from Brett et al. (1982) whose work indicated that growth rates at temperatures below 10°C would be lower than at 18°C. Based on that study, growth, and so eventual weight, would be lower under these regimes. The curves used in the model to describe the growth rate - temperature relationship suggest that growth would be greater than or equal to that achieved at 18°C at temperatures as low as 7°C (Fig. 5). This result may be suspect because I have no real data for temperatures less than 13°C, but I also have no reason to believe the growth advantage under cycling temperatures would

Figure 5: Predicted growth rates of juvenile chinook salmon acclimated to cycling and constant temperatures at 50% of satiation ration.

——— represents the cycling temperature growth function, and

- - - - - represents the constant temperature growth function.


4.0
3.0
2.0
1.0
0.0
GROWTH RATE (% wet weight/day)
0.0
5.0
10.0
15.0
20.0
25.0
TEMPERATURE(C)

not be observed at low temperatures as found by Hokanson et al. (1977).

The model's results were important because, assuming that an increase in fry growth and weight is beneficial, they indicated that the addition of cooling water in the summer to the Nechako River could provide benefits to the chinook salmon juveniles rearing there. The temperatures changes could enhance their growth. In addition, the results provided an indication of which thermal regimes might be expected to produce larger or smaller fry, and still satisfy the downstream maximum temperature constraint. The results also indicated the variable importance of JDP to average growth rates achieved by the population; changing JDPs caused a large difference in predicted fry weight only when the temperature profile in the Upper Nechako had substantial differences between the upstream and downstream temperatures.

The model was used to achieve two objectives: to determine the magnitude and direction of any error in weight prediction that might be encountered by using growth functions based on cycling or constant temperatures; and, to attempt to remove some of the uncertainty surrounding the effect of different thermal regimes on juvenile chinook salmon growth. By examining the critical assumptions made in the model, other information needs were identified that might improve the model's predictions and widen its applicability. First, the growth curves used in the model were generated in a 'best-guess' fashion, combining results from these experiments and other studies. It would be desirable to have a series of growth functions for several rations under a more complete range of both constant and cycling temperatures. Second, the model assumed no change in the food available to juvenile chinook salmon. This may not be correct but is crucial in growth rate determinations because ration affects the growth capabilities of fish. Third, the effects of temperature and flow changes on juvenile chinook salmon mortality due to predation or other factors was assumed to be negligible. The model's predictions might be improved if information on these factors could be included. The model's predictions might also be improved from more precision in the temperature component. Perhaps a weekly or biweekly, rather than monthly, estimate of average temperatures would increase the accuracy of the predictions. The model could also be extended in the source water temperature and flow rate combinations considered, with perhaps an estimate of the power production gain or loss associated with each regime.

The KCP proposal presents an opportunity to investigate the environmental impacts of large scale changes in temperatures and flow rates. Experimental manipulation of the thermal regime in the Nechako River could be undertaken. Some scientists support this adaptive approach to environmental management (Holling 1978, Hilborn and Walters 1981). Other scientists, believing adaptive management is not always a feasible alternative (Larkin 1984) recommend long-term observations of ecosystems, and stress the need for both pre- and post-construction evaluations in impact assessment (Lash et al. 1974, Geen 1975). Either adaptive management or post-construction evaluation studies applied to KCP could yield large gains in understanding the impacts of flow and temperature changes on the composition and production of benthic invertebrate species, the growth and survival of juvenile chinook salmon, and perhaps even on stock production parameters.

Scientific information, combined with other basic information, plays a large role in environmental impact assessment, and so is a component of the water allocation process in British Columbia. The information is used early in the process by both proponents and government managers. Proponents use it to evaluate the feasibility of projects and to anticipate problems, and the government uses it to review and assess the project. Accuracy, therefore, is important. Accurate information leads to confidence in impact assessments and the resulting recommendations. Then the tradeoffs in decision-making are pictured more realistically and value judgements about the social acceptability of those tradeoffs are clearer.

This project was directed towards improving the knowledge of growth of juvenile chinook salmon under cycling compared to constant temperatures, and towards investigating the implications of this type of information in environmental impact assessment. Juvenile chinook salmon grew faster under cycling temperatures when the mean of the cycle was less than the optimum metabolic temperature. When the mean was greater than the optimum temperature, there was no difference in growth rates under cycling or constant temperatures. This result suggested that application of growth studies based on constant temperatures would underestimate fry weights at moderate, but not at extreme temperatures. At low temperatures, (≤16°C), predicted fry weights based on cycling temperature growth studies might be 10% larger than those based on constant temperature growth studies. This size difference might be important in fisheries management and impact assessment. The addition of cooling water to the Nechako River could result in an increase in the growth rate of juvenile chinook salmon rearing there, depending on the effects of the thermal changes on other ecosystem components.

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# APPENDIX I

## A. Model Documentation

```
      SUBROUTINE UMODEL(ITIME)
      COMMON AVWT(3),AVWTSM,FLAG
      COMMON GMAX,GRATE(3),I,IFLAG,J,N
      COMMON O,P,Q,R,S,U,V,W
      COMMON PERCNG(3),POPN(3),T,TT,TEMP,TIME,TOT,TPOP
      COMMON XGMAX(3),XGRATE(3),XVEC(4),YVEC11(4),YVEC12(4)
      COMMON YVEC13(4),YVEC21(4),YVEC22(4),YVEC23(4)
      COMMON YVEC31(4),YVEC32(4),YVEC33(4)
      COMMON YVEC41(4),YVEC42(4),YVEC43(4)
      COMMON YVEC51(4),YVEC52(4),YVEC53(4)
      COMMON YVEC61(4),YVEC62(4),YVEC63(4)
      COMMON YVEC71(4),YVEC72(4),YVEC73(4)
      COMMON YVEC81(4),YVEC82(4),YVEC83(4)
C
C     FRY EMERGE IN TWO WEEK PERIOD FROM MID TO LATE APRIL
C     MEAN WEIGHT = 0.40 g
C
C     PROPORTION OF FRY AT EACH LOCATION
C     SET IN DATA FILE
C
      DO 5 I=1,3
      AVWT(I)=0.40
    5 CONTINUE
C
C     CALCULATE THE AVERAGE TEMPERATURE FOR THE MONTH
C     ACCORDING TO LOCATION ON THE UPPER NECHAKO RIVER
C     EIGHT OPTIONS AVAILABLE FOR THERMAL REGIME
C
      DO 20 I=1,3
      DO 10 J=1,4
      TIME=FLOAT(J)
C
      IF(FLAG.EQ.1..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC11,N)
      IF(FLAG.EQ.1..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC12,N)
      IF(FLAG.EQ.1..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC13,N)
C
      IF(FLAG.EQ.2..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC21,N)
      IF(FLAG.EQ.2..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC22,N)
      IF(FLAG.EQ.2..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC23,N)
```

```
C
      IF(FLAG.EQ.3..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC31,N)
      IF(FLAG.EQ.3..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC32,N)
      IF(FLAG.EQ.3..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC33,N)
C
      IF(FLAG.EQ.4..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC41,N)
      IF(FLAG.EQ.4..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC42,N)
      IF(FLAG.EQ.4..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC43,N)
C
      IF(FLAG.EQ.5..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC51,N)
      IF(FLAG.EQ.5..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC52,N)
      IF(FLAG.EQ.5..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC53,N)
C
      IF(FLAG.EQ.6..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC61,N)
      IF(FLAG.EQ.6..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC62,N)
      IF(FLAG.EQ.6..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC63,N)
C
      IF(FLAG.EQ.7..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC71,N)
      IF(FLAG.EQ.7..AND.I.EQ.2) TEMP=SLP(TIME,XVEC,YVEC72,N)
      IF(FLAG.EQ.7..AND.I.EQ.3) TEMP=SLP(TIME,XVEC,YVEC73,N)
C
      IF(FLAG.EQ.8..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC81,N)
      IF(FLAG.EQ.8..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC82,N)
      IF(FLAG.EQ.8..AND.I.EQ.1) TEMP=SLP(TIME,XVEC,YVEC83,N)
C
C
C
C     DETERMINE THE APPROPRIATE GROWTH RATE FOR THE MONTH
C     FROM THE CYCLING OR CONSTANT TEMPERATURE GROWTH FUNCTION
C
C     POWER 3 POLYNOMIAL DESCRIBING CHINOOK GROWTH
C     ALL DERIVED POINTS PLUS MY DATA
C
      IF(IFLAG.EQ.3) GRATE(I)=O+(P*TEMP)+(Q*TEMP**2)-(R*TEMP**3)
      IF(IFLAG.EQ.4) GRATE(I)=S+(U*TEMP)+(V*TEMP**2)-(W*TEMP**3)
C
C     ADJUST THE GROWTH RATE FOR DIFFERENCES IN AVERAGE WEIGHTS
C
      PERCNG(I)=GRATE(I)/GMAX
      XGMAX(I)=EXP((ALOG(5.42))-0.4*ALOG(AVWT(I)))
      XGRATE(I)=PERCNG(I)*XGMAX(I)
C
C     APPLY GROWTH RATE FOR THIRTY DAY PERIOD TO FRY ACCORDING
C     TO THEIR DISTRIBUTION IN THE UPPER NECHAKO RIVER
C
      AVWT(I)=AVWT(I)*((1+(XGRATE(I)/100.))**30.)
   10 CONTINUE
   20 CONTINUE
C
C     DETERMINE THE AVERAGE WEIGHT OF THE FRY POPULATION
C
      DO 26 I=1,3
      T=AVWT(I)*POPN(I)
```

```
      TT=TT+T
      TPOP=TPOP+POPN(I)
   26 CONTINUE
      AVWTSM=TT/TPOP
      RETURN
      END
      SUBROUTINE UINIT
      CALL CMREAD('ALCAN.C ')
      CALL DFAULT('1=ALCAN.D ')
      CALL DFAULT('0=-OUT(LAST+1) ')
      CALL DFAULT('8=-OUT(LAST+1) ')
      RETURN
      END
      FUNCTION SLP(X,XX,YY,N)
      DIMENSION XX(N), YY(N)
      SLP = YY(1)
      IF (X .LT. XX(1)) GO TO 99
      M = N - 1
      DO 10 I = 1, M
      IF (X .GT. XX(I+1)) GO TO 10
      SLP = YY(I)+(YY(I+1)-YY(I))/(XX(I+1)-XX(I))* (X-XX(I))
      GO TO 99
   10 CONTINUE
      SLP = YY(N)
   99 RETURN
```

## B. Tables Presenting Supplementary Data and Results

Table B1 - Temperatures assumed in the model for each thermal regime during the summer at each location.

| THERMAL REGIME | AVERAGE MONTHLY TEMPERATURE (C) | | | |
|---|---|---|---|---|
| GREER CREEK | May | June | July | August |
| 1 | 8.5 | 13.5 | 18.0 | 19.0 |
| 2 | 8.5 | 13.5 | 11.0 | 11.0 |
| 3 | 9.0 | 14.0 | 12.0 | 12.0 |
| 4 | 8.0 | 13.0 | 10.8 | 10.8 |
| 5 | 8.5 | 13.5 | 9.0 | 9.0 |
| 6 | 8.5 | 13.5 | 10.0 | 10.0 |
| 7 | 8.5 | 13.5 | 7.0 | 7.0 |
| 8 | 8.5 | 13.5 | 8.0 | 8.0 |
| NAUTLEY RIVER | | | | |
| 1 | 8.5 | 14.0 | 19.0 | 19.0 |
| 2 | 8.5 | 13.5 | 14.0 | 14.0 |
| 3 | 9.0 | 14.5 | 15.8 | 15.8 |
| 4 | 8.0 | 13.5 | 11.8 | 11.8 |
| 5 | 8.5 | 14.0 | 12.0 | 12.0 |
| 6 | 8.5 | 13.5 | 14.0 | 14.0 |
| 7 | 8.5 | 13.5 | 10.0 | 10.0 |
| 8 | 8.5 | 13.5 | 13.0 | 13.0 |
| VANDERHOOF | | | | |
| 1 | 9.0 | 14.5 | 20.0 | 20.0 |
| 2 | 9.0 | 14.5 | 16.0 | 16.0 |
| 3 | 9.5 | 15.0 | 18.0 | 18.0 |
| 4 | 8.5 | 14.0 | 12.8 | 12.8 |
| 5 | 9.0 | 14.5 | 14.0 | 14.0 |
| 6 | 9.0 | 14.5 | 16.0 | 16.0 |
| 7 | 9.0 | 14.5 | 12.0 | 12.0 |
| 8 | 9.0 | 14.5 | 15.0 | 15.0 |

These temperatures were derived according to the method outlined in the Materials and Methods section of this report.

Table B2 - Initial and final average weights, and growth rates of juvenile chinook salmon under daily cycling and constant temperatures at two ration levels.

| | Temp (C) | Initial Weight(g) | Final Weight(g) | Growth Rate(%) | S.D. |
|---|---|---|---|---|---|
| 12% RATION | | | | | |
| EXPT 1 | | | | | |
| | 11-15 | 0.814 | 1.976 | 3.20 | 0.14 |
| | 13 | 0.857 | 1.903 | 2.90 | 0.14 |
| EXPT 2 | | | | | |
| | 14-18 | 1.273 | 2.372 | 3.10 | 0.17 |
| | 16 | 1.269 | 2.175 | 2.75 | 0.19 |
| EXPT 3 | | | | | |
| | 17-21 | 0.848 | 1.411 | 1.69 | 0.23 |
| | 19 | 0.885 | 1.424 | 1.53 | 0.24 |
| 7% RATION | | | | | |
| EXPT 1 | | | | | |
| | 11-15 | 0.764 | 1.275 | 1.81 | 0.15 |
| | 13 | 0.824 | 1.203 | 1.36 | 0.14 |
| EXPT 2 | | | | | |
| | 14-18 | 1.173 | 1.449 | 1.67 | 0.23 |
| | 16 | 1.220 | 1.503 | 1.61 | 0.14 |
| EXPT 3 | | | | | |
| | 17-21 | 0.801 | 1.150 | 1.12 | 0.26 |
| | 19 | 0.758 | 1.067 | 1.13 | 0.23 |

Table B3 - Dry weight increase, dry weight of food consumed, and gross conversion efficiency of juvenile chinook salmon under daily cycling and constant temperatures at two ration levels.

| | Temp (C) | Dry Weight Gained(g) | Dry Weight Food(g) | G.C.E. (%) |
|---|---|---|---|---|
| 12% RATION | | | | |
| EXPT 1 | | | | |
| | 11-15 | 19.35 | 49.43 | 39.2 |
| | 13 | 6.15 | 18.48 | 33.3 |
| EXPT 2 | | | | |
| | 14-18 | 16.19 | 77.95 | 20.8 |
| | 16 | 12.77 | 83.77 | 15.2 |
| EXPT 3 | | | | |
| | 17-21 | 8.71 | 50.07 | 17.4 |
| | 19 | 7.08 | 49.52 | 14.3 |
| 7% RATION | | | | |
| EXPT 1 | | | | |
| | 11-15 | 8.71 | 22.30 | 39.1 |
| | 13 | 1.90 | 8.94 | 21.3 |
| EXPT 2 | | | | |
| | 14-18 | 3.28 | 28.92 | 11.34 |
| | 16 | 2.05 | 17.70 | 11.58 |
| EXPT 3 | | | | |
| | 17-21 | 3.29 | 26.74 | 12.30 |
| | 19 | 2.42 | 21.28 | 11.37 |

## C. Method for Construction of Growth Function for Model

Difficulties were encountered when construction of a growth-temperature relationship was attempted. The major obstacle was lack of data points: only three growth rates were available for each of the cycling and constant temperatures, and they were all in the temperature range of 13°C-19°C. To obtain estimates of growth rates at other temperatures, a literature search was conducted.

There is a dearth of available information reporting growth rates of chinook salmon juveniles at various temperatures and rations. Brett et al. (1982) studied the growth rates of two races of juvenile chinook salmon fed satiation rations at several constant temperatures. The two races were the Nechako River and Quinsam River stocks. Their study concentrated on the upper end of the thermal range of juvenile chinook (16-24°C). Banks et al. (1971) studied the growth of Abernathy fall chinook fed satiation rations, again under several constant temperatures. In this work, the temperatures studied were in the middle of the thermal range of juvenile chinook salmon (10-18.3°C). One can compare the results of these two experiments at two temperatures, 16°C and 19°C[1]. The data chosen from Brett et al. (1982) for comparison were growth rates of the Nechako River stock. After adjustments were made to the growth

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[1] Brett et al. (1982) tested growth at these temperatures exactly, while Banks et al. (1971) tested growth at 15.6°C and 18.3°C.

rates so that a starting size of 0.82 grams was common, the growth rates were;

1. Banks et al. (1971) : 16°C - 4.91%/day ; 19°C - 4.75%/day
2. Brett et al. (1982) : 16°C - 5.12%/day ; 19°C - 5.20%/day

The difference in maximum growth rates could be accounted for simply by stock characteristics. The Nechako River juveniles might have a higher potential maximum growth rate than the Abernathy juveniles.

Direct comparison of the results of this study with those of Banks et al. (1971) or Brett et al. (1982) was not possible because the feeding levels in the studies were different. So, an indirect comparison of my experimental results with those of the other studies was made. The growth rates at the 12% ration levels in this experiment represented 69.4%, 63.1%, and 35.6% of the maximum growth rates in Banks et al. (1971)[2] at temperatures of 12.8°C, 15.6°C, and 18.3°C. This points out the weakness in an assumption made in building the simulation model and so, a possible bias in the model's predictions. The assumption was that the 12% ration growth rates were approximately equal to those that would be achieved at feeding levels equal to 50% satiation. The comparison of my results to Banks et al. (1971) indicated that this was not exactly correct, with possible over- and underestimations of growth rates at low and high temperatures respectively. However, the manner in which the growth curves were constructed probably evened out these

---

[2] Adjusted to a starting size of 0.82 grams.

temperature-specific biases. The growth rates at the 7% ration level in this experiment represent 39.2%, 34.0%, and 23.6% of similarly adjusted maximum growth rate figures reported by Banks et al. (1971).

Brett et al. (1982) derived a growth function for juvenile chinook salmon and, in Figure 8 of their report, generated growth temperature relationships for various levels of satiation feeding. I adjusted these curves to achieve a common size of 0.82 grams and plotted the 12% ration growth rates onto the same graph. The 12% ration growth rates appeared to represent what Brett et al.'s (1982) growth function would predict for 50% of satiation feeding. This size-adjusted growth function was chosen as the basis for estimation of growth rates outside the 13°C to 19°C range. A curve was fit by eye to the available data points, making every effort to have this curve closely resemble the shape of the curves presented in Figure 8 of Brett et al. (1982). Growth rates at 1°C, 5°C, 10°C, and 20°C were estimated from this hand drawn curve. Polynomial functions were then fit to the combinations of estimated and real data points for both the cycling and constant temperatures. A third order polynomial more closely approximated the shape of the desired curve even though the addition of the extra term in the equation did not improve the fit statistically, due to a lact of data points. The growth-temperature functions for the daily cycling and constant temperatures at 12% ration, (50% satiation), were:

1. $G=0.215+(0.207xT)+(0.0229xT^{2})-(0.0016xT^{3})$

2. $G=0.057+(0.256xT)+(0.0139xT^{2})-(0.0012xT^{3})$

where G is instantaneous growth rate and T is temperature. Equation 1 predicts growth under daily cycling temperatures and equation 2 predicts growth under constant temperatures. Figure presents these equations graphically.

## D. Method for Adjustment of Growth Rates as a Function of Size

The growth rates determined through the use of the growth-temperature curve cannot be directly applied to chinook salmon of any size; adjustments for size differences must be made to these estimated rates before using them in the model. This was accomplished in part by using the equation presented in Brett et al. (1969) that allows comparison of growth rates of different sized salmon:

$$\ln(G)=\ln(5.42)-0.41(\ln(W))$$

where G is the maximum instantaneous growth rate and W is the wet weight of the fish in grams.

This equation provides the ~~maximum~~ maximum growth capability of a particular size of salmonid. One can then determine the difference in the maximum potential growth rate between two sizes and then either add or subtract this difference from one of the observed growth rates, which makes the growth rates comparable.

In the model, the growth function is not based on maximum ration levels but 12% ration levels. Therefore, to apply the rationale explained above, it was assumed that the proportion of the maximum growth rate, (Gmax), represented by the growth at the 12% ration at any temperature would be the same for chinook salmon of all sizes, at least during the freshwater portion of their life. For example, the maximum instantaneous growth rate of a 0.82 gram salmon is 0.0579. Under a daily cycling temperature of 15°C ± 2°C, and a ration level of 12%, the predicted instantaneous growth rate, using the growth function based on cycling temperatures, is 0.0330. This represents 57% (0.0330/0.0579) of the maximum growth potential. If, in the simulation, the average weight of the fish is 10 grams when the water temperature is averaging 15°C, then the instantaneous growth rate is determined by multiplying the maximum instantaneous growth rate for a 10 gram salmon, 0.0216, by 0.57. This gives an instantaneous growth rate of 0.0123 which is then used in the model to determine the growth of the fish over the next time period.

This approach is based on the assumption that a 12% ration always produces the same proportion of Gmax, no matter the size of the fish. Clearly, this is not accurate. However, if one assumes that the 12% ration curve is equal to some proportion of satiation, then it is realistic to approach the problem in this manner. After examining the results of Brett et al. (1982) I have concluded that, for the purpose of the model, the 12% ration growth function can be looked upon as an approximation to one assuming 50% satiation feeding. This approach likely underestimates the instantaneous growth rates at higher temperatures and consequently may cause an underestimation of average fry weight when high water temperatures, (>18°C), are simulated. However, the time period over which temperatures greater than 18°C occur is short, and so the influence of this bias is probably slight.