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A Review of the Limnology and Sockeye Salmon Ecology of Babine Lake

by

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Westwater Research Centre
The University of British Columbia
in cooperation with
B.C. Ministry of Forests
Forest Service, Prince Rupert Forest Region

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PREFACE

In response to a pine beetle infestation in the forests of Morrison Arm region of Babine Lake, Houston Forests Products Co. and the B.C. Forest Service decided to accelerate logging plans in an attempt to halt the spread of the parasite and salvage the infested timber. A transportation system was proposed that would involve dumping, storage, towing and dewatering of logs. The Department of Fisheries and Oceans reviewed the proposal and gave its conditional approval provided that a three year study be undertaken to determine the effects of log transportation on the fish habitats and populations of Babine Lake, with emphasis on sockeye salmon. The Westwater Research Centre agreed to undertake the project as the next stage in the development of its research on forestry-fishery interactions (Dorcey, McPhee and Sydneysmith, 1980; Levy, Northcote and Barr, 1982).

The research is supported as a project under Section 88.2 of the B.C. Forest Act and is provided to the University as a grant from Houston Forest Products Co. Additional funding for component studies is provided by a GREAT Award from the B.C. Science Council, Youth Employment Program funds to the University and an NSERC grant to Dr. Hall.

An Advisory Committee has been established to advise on the design of the research and its revision as results are produced. The members of the Committee are: A.H.J. Dorcey (Westwater) Chairman, T.G. Northcote (Westwater-Forestry), P.T. Ogawa (Houston Forest Products Co.), S. MacPherson (Eurocan Pulp and Paper Co.), D.J. Rowse, W.E. Johnson, and T. Turnbull (Fisheries and Oceans), M. Whately (B.C. Ministry of Environment), B.D. Downie, J.W. Schwab, and G.Stahl (B.C. Forest Service), and M. Newman (Vancouver Aquarium).

The research program proposed by Westwater is being carried out in three phases. Phase I (1983 - 1984) was pre-impact environmental assessment of existing conditions and fish utilization of areas that Houston Forest Products (HFP) would use for log handling and storage in subsequent years. Phase II (1984 - 1985) was a paired comparison study of water quality conditions and fish utilization at several historical and active log handling sites on the lake. Phase III (1985 - 1986) is a post-impact assessment of the HFP log transportation sites designed to evaluate changes in the environment and fish utilization after two years of forestry development.

After a review of the Phase I results, the Advisory Committee strongly recommended that controlled perturbation experiments be conducted in experimental enclosures during the second and third years of the project. The research is currently being undertaken by two UBC graduate students.

This literature review was undertaken at the beginning of the project to draw together the results of the varied and extensive research that has been undertaken on the limnology and sockeye ecology of Babine Lake. A workshop that brought together many of these researchers (List in Appendix 1) was also used to supplement this information.

At this date the first two phases of the project have been completed. The results of the project will be published by Westwater following the conclusion of Phase III.

Kenneth J.Hall
Project Director

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This research was supported as a project under Section 88.2 of the B.C. Forest Act and was provided to the University of British Columbia as a grant from Houston Forest Products Co.

A draft of this manuscript was reviewed by B. Downie and J. Schwab of the B.C. Forest Service in Smithers, W.E. Johnson, H. Smith and J. Stockner of the Department of Fisheries and Oceans, and T.G. Northcote, Institute of Animal Resource Ecology, University of British Columbia. B. Downie and J. Schwab provided information on forest harvesting activities in the Babine watershed. W.E. Johnson and H. Smith provided reports that were not available in the published literature.

We would like to thank I. Yesaki for drafting figures and A. Moroz, D. Nickull, and J. Pladsen for typing the manuscript.

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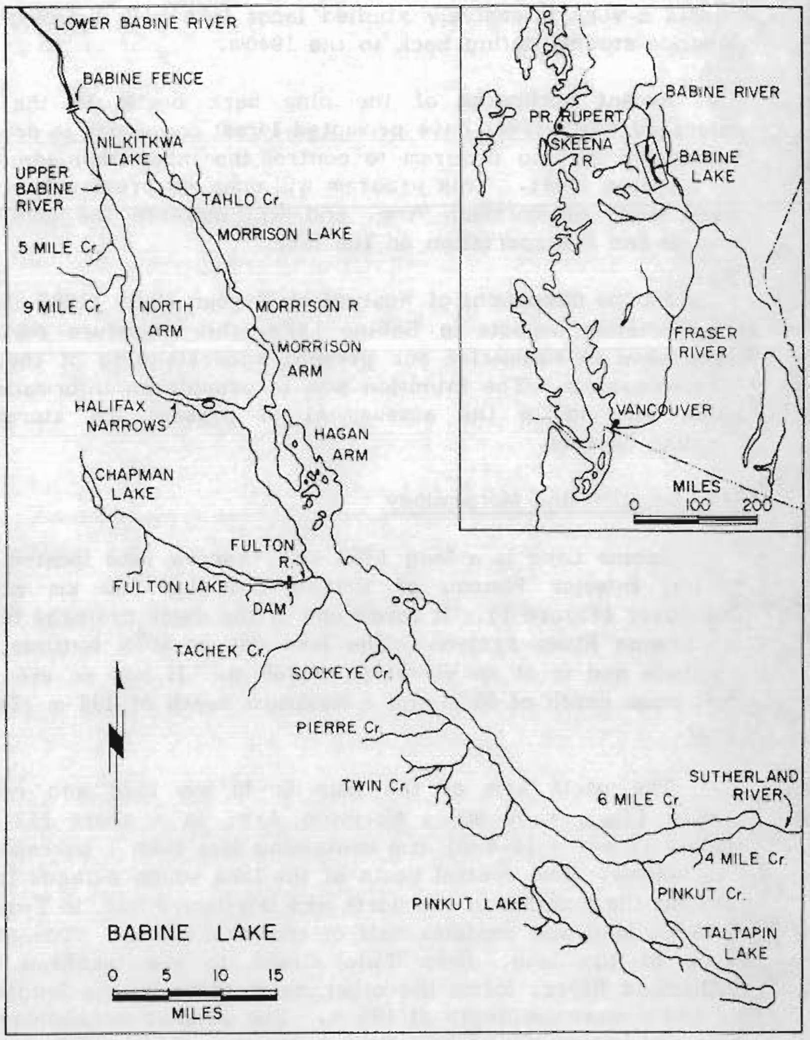

Figure 1. Location and morphology of Babine Lake (from West, 1978).

The Babine Lake watershed has an area of approximately 10,000 km². The watershed contains four main sub-basins. They include the Morrison, Fulton, Pinkut and Sutherland watersheds which drain 5.8, 21.1, 13.3, and 13.1% of the Babine watershed respectively (Figure 2). The rest of the Babine watershed boundary (46.6%) is very close to the lake. In these areas numerous small creeks, many with intermittent flow, discharge directly into Babine Lake.

Climate

The climate is typical of the central interior plateau of British Columbia. Winter temperatures are cold with an average of -15°C for the winter months, but periods of -40°C are common. The lake is usually covered with ice from December to May. The temperatures in summer vary from 8° to 27°C. The area gets about 50 cm of precipitation a year including 2.5 - 3 m of snow between October and May. The total precipitation is higher in the north basin since the mountains are closer to the lake which causes a higher percent of cloud cover when compared to the more open terrain south of Topley Landing. This protection in the north basin and Morrison Arm makes these areas of the lake less windy (Stockner and Shortreed, 1974). The wind tends to blow in the direction of the long axis of the lake (Withler et al., 1949).

Geology and Mining

The terrain around the lake has relatively low relief with the higher mountains in the watershed 700-1000 meters above the lake surface. Several areas are dominated by gently rolling terrain dissected by small streams flowing to the lake. Stockner and Shortreed (1974) have summarized the main bedrock geology of the Babine watershed.

> "In the vicinity of the lake the oldest rocks, highly contorted and metamorphosed cherts, argillites and marbles of the Upper Palaeozoic Cache Creek Group, occur around Boling Point and on the south side of the lake. To the north exposed rocks range in age from Upper Triassic to Tertiary, and reveal a complex history of sedimentation, erosion, intermediate to acidic volcanicity, and plutonism. Scattered and sometimes economic copper deposits are locally associated with Plutonic rocks. Pleistocene glacial and postglacial tills and drift now cover much of the area."

Large scale copper mining began in the area of Hagan Arm in the mid 1960's. Granisle Copper Limited operated an open pit mine

I.

INTRODUCTION

Babine Lake is the largest natural lake in the province of British Columbia. The lake is one of the major sockeye salmon producers in the province, and presently 90 percent of the Skeena River sockeye originate in tributaries surrounding the lake. The lake is a very intensively studied large lake with limnological and fisheries studies dating back to the 1940's.

Recent outbreaks of the pine bark beetle in the Babine watershed (1979-1981) have prompted forest companies to propose an accelerated logging program to control the infestation and harvest the diseased trees. This program will open up previously unlogged areas, such as Morrison Arm, and will increase the level of log storage and transportation on the lake.

As one component of Westwater's 3-year study (1983-85) of log transportation impacts in Babine Lake, this literature review was undertaken to summarize our present understanding of the Babine Lake ecosystem. The intention was to provide an information base which will aid in the assessment of present log storage and handling impacts.

Lake Location and Morphology

Babine Lake is a long (150 km), narrow lake located on the Central Interior Plateau of British Columbia 580 km north of Vancouver (Figure 1). It forms one of the major drainage basins in the Skeena River system. The lake lies at 55°N latitude, 123°W longitude and is at an elevation of 708 m. It has an area of 490 km^2, mean depth of 55 m and a maximum depth of 186 m (Johnson, 1965).

The north arm of the lake is 40 km long and relatively shallow (Z_{max} = 36 m). Morrison Arm, is a short (13.4 km), shallow ($Z_{av.}$ = 11.4 m) arm containing less than 1 percent of the lake volume. The central basin of the lake which extends from Old Fort, at the junction of the north and Morrison Arms, to Twin Creek is 65 km long and contains half of the lake volume. The southern reach of the lake, from Twin Creek to the lakehead at the Sutherland River, forms the other major basin with a length of 45 km and a maximum depth of 186 m. The detailed morphology of the arms and basins of the lake have been presented by Johnson (1965).

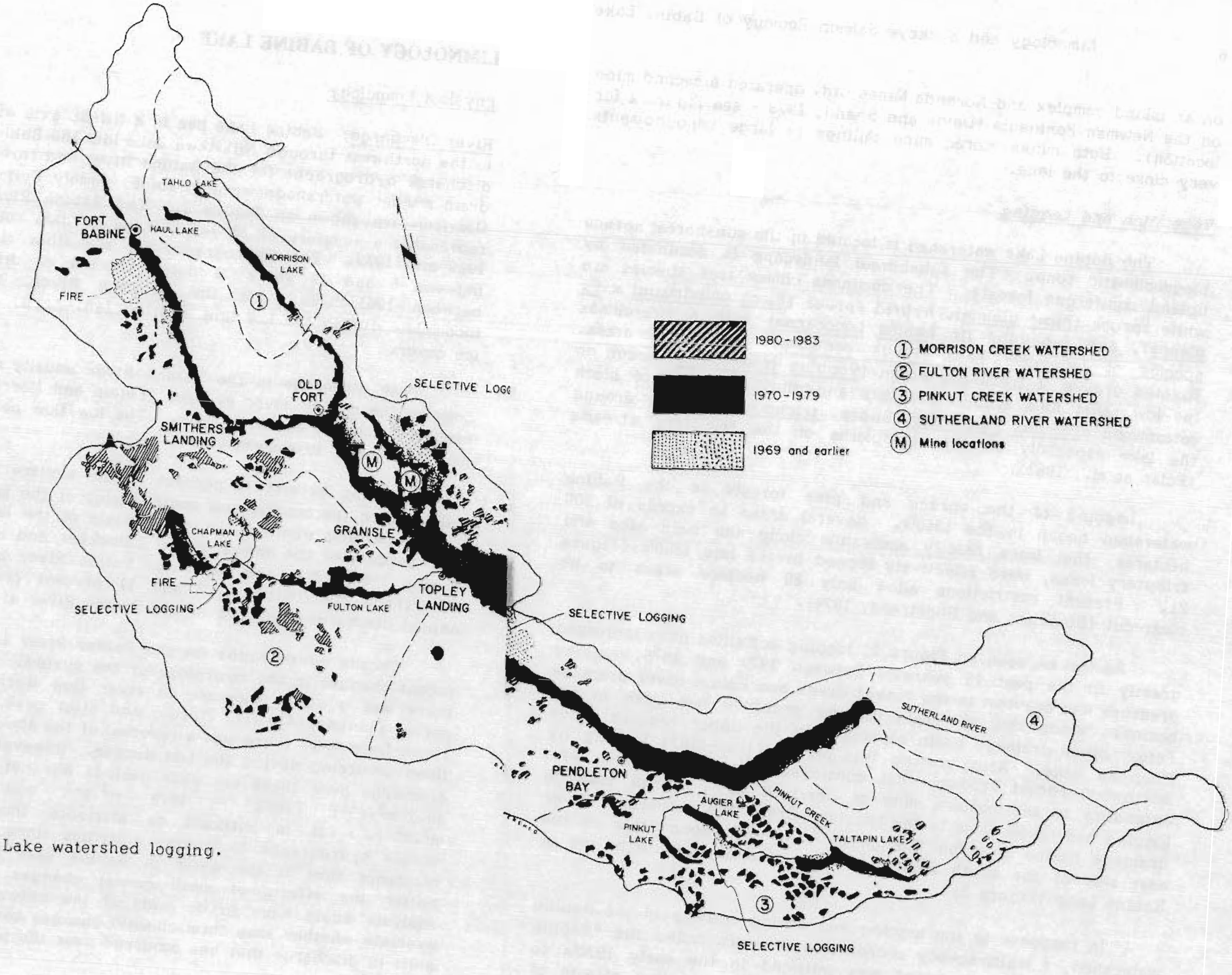

Figure 2. Babine Lake watershed logging.
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on an island complex and Noranda Mines Ltd. operated a second mine on the Newman Peninsula (Davis and Shand, 1978 - see Figure 2 for location). Both mines stored mine tailings in large impoundments very close to the lake.

Vegetation and Logging

The Babine Lake watershed is located in the sub-boreal spruce biogeoclimatic zone. The sub-boreal landscape is dominated by upland coniferous forests. The dominant climax tree species are white spruce (*Picea glauca*), hybrid spruce (*Picea engelmanni* x *P. glauca*), and subalpine fir (*Abies lasiocarpa*) with a fire-climax species of lodgepole pine (*Pinus contorta*) in many areas. Isolated groves of trembling aspen (*Populus tremuloides*) occur on the low relief hills around the lake and alluvial forests of black cottonwood (*Populus balsamifera* subsp. *trichocarpa*) occur around the lake especially on the floodplains of the tributary streams (Pojar et al., 1982).

Logging of the spruce and pine forests in the Babine watershed began in the 1950's. Several areas in excess of 200 hectares, that were readily accessible along the main lake and tributary lakes, were selectively logged in the late 1960's (Figure 2). Present restrictions allow only 80 hectare areas to be clear-cut (Stockner and Shortreed, 1974).

As can be seen on Figure 2, logging activities have increased greatly in the past 15 years. Between 1970 and 1979, logging pressure was heaviest in the Pinkut Creek and Fulton River drainage basins. Since 1980 the main logging pressure has been in the Fulton River drainage basin especially in the upper reaches above Chapman Lake. Also, during this period (1980-1983) logging by Northwood Forest Products has continued adjacent to Hagan Arm extending to the eastern side of Morrison Arm. Until 1983 no logging had taken place in the Morrison Creek and Sutherland River drainage basins or along the narrow watershed boundaries on the east side of the south basin and east side of the north arm of Babine Lake (Figure 2).

In response to the logging and mining activity in the Babine watershed, a multi-agency coordinated program called the "Babine Watershed Change Program" was initiated in the early 1970's to review and collect baseline environmental data so that effects of environmental change on salmonids could be properly assessed (Smith, 1973, 1975, 1976). The program inititated several studies to provide a base line of the physical, chemical, and biological conditions of Babine Lake.

II.

LIMNOLOGY OF BABINE LAKE

Physical Limnology

River Discharge: Babine Lake lies in a NW-SE axis with the outflow to the northwest through Nilkitkwa Lake into the Babine River. The discharge hydrographs for the Babine River and three rivers which drain smaller watersheds within Babine, namely Fulton, Pinkut and Morrison are shown on Figure 3. The Babine River hydrograph represents a summary of 38 years of gauge data collected between 1929 and 1979. The hydrographs for the other rivers represent between 6 and 19 years of data collected at different periods between 1961-1979. For the Morrison River, the data were incomplete during the low flow months (Jan.-April) when there was ice cover.

Peak discharge in the Babine River usually occurs in June. Some of the smaller river systems (Fulton and Morrison) have their highest discharge earlier in May. The low flow period is in March and April prior to snowmelt.

Between 60 and 70 percent of the surface inflow to Babine Lake enters the central and south basins of the lake southward of Topley Landing whereas the north basin of the lake receives only 5-10 percent of the annual inflow (Stockner and Shortreed, 1974). During 1967, 1968, and 1969, the Fulton River and Pinkut Creek watersheds contributed 27.7 and 11 percent respectively of the annual discharge measured in the Babine River at Fort Babine.

Decade hydrographs for the Babine River (Figure 4) indicate recent changes in the hydrology of the system. During the 1970's there was a slight increase in river flow during the ice cover period (January-April). During and after peak discharge periods (June-December) there was a reversal of the above trend with lower flows occurring during the last decade. However, the mean annual discharge over these ten year periods has not changed (1950's - 49.5 $m^3.s^{-1}$, 1960's - 49.9 $m^3.s^{-1}$ and 1970's - 49.7 m^3,s^{-1}). It is difficult to attribute these shifts in the decade hydrographs to logging activities since the relatively long residence time of the water in Babine Lake (17.8 years) would buffer the effects of small runoff changes. Also a detailed analysis would have to be made of the meteorological records to evaluate whether long term climatic changes could have caused the shift in discharge that has occurred over the past 30 years.

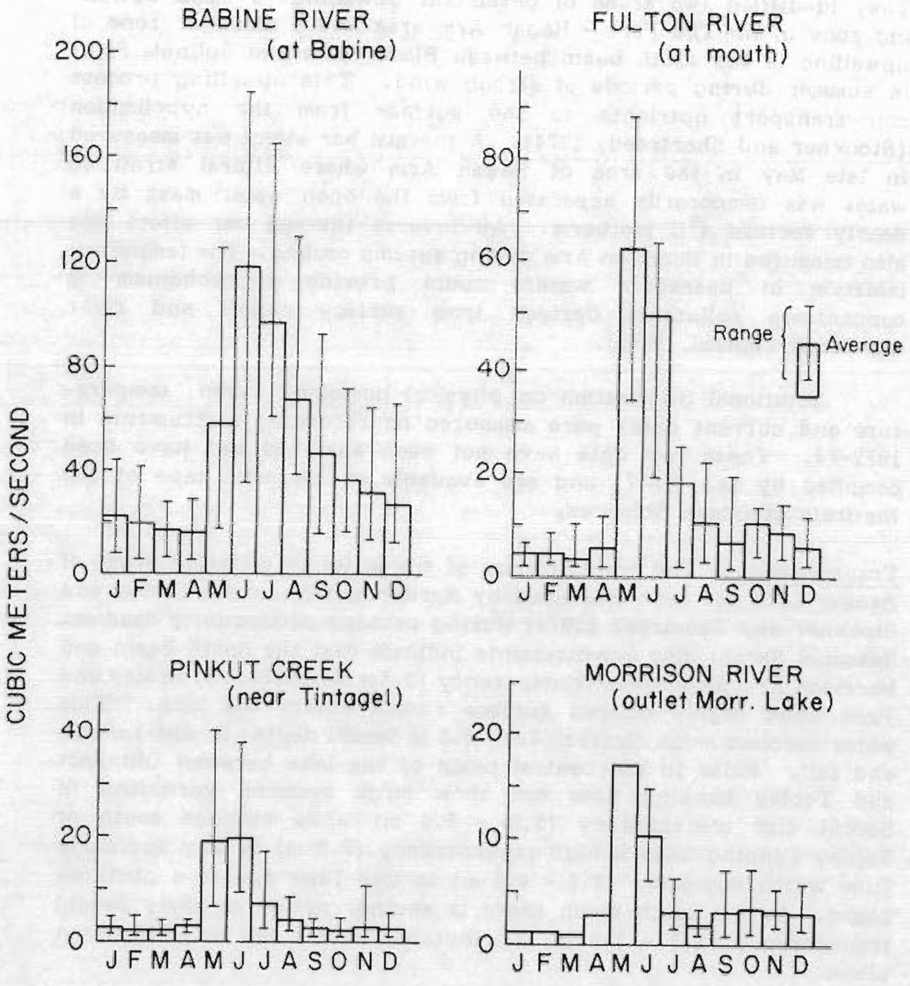

Figure 3. Discharge of Babine River and Selected Sub-Basin Tributaries (data from Environment Canada, 1979).

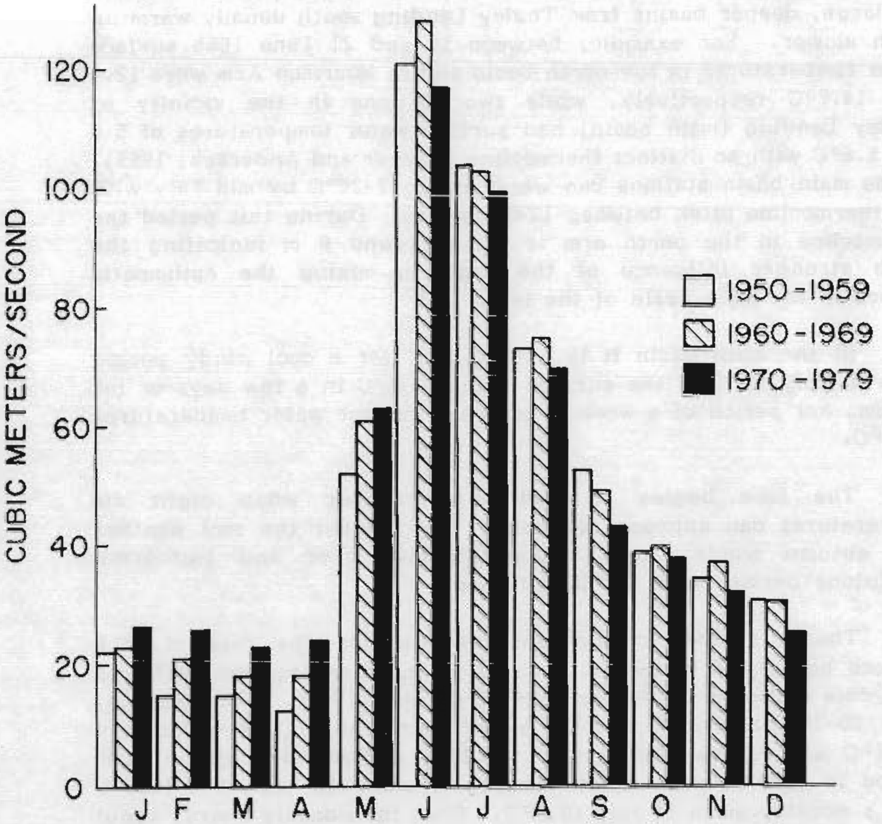

Figure 4. Decade Hydrographs for the Babine River.

Temperature: The seasonal temperature patterns in Babine Lake are presented in limnological studies by Narver and Andersen (1969) and Stockner and Shortreed (1978). After the ice leaves in early May the water usually warms very rapidly especially in Morrison Arm where surface temperatures can be 15-17°C in early June. By this time such narrow, relatively shallow basins are well stratified with a pronounced thermocline between 3 and 5 meters. In contrast the large, deeper basins from Topley Landing south usually warm up much slower. For example, between 18 and 21 June 1966 surface water temperatures in the north basin and in Morrison Arm were 12.8 and 14.7°C respectively, while two stations in the vicinity of Topley Landing (main basin) had surface water temperatures of 5.0 and 8.6°C with no distinct thermocline (Narver and Andersen, 1969). These main basin stations can warm up to 17-20°C by mid July with the thermocline often between 12-15 meters. During this period the thermocline in the north arm is often around 8 m indicating the much stronger influence of the wind in mixing the epilimnetic waters in the main basin of the lake.

In the main basin it is not unusual for a cool windy period even in July to drop the surface waters 5-6°C in a few days or for a calm, hot period of a week to increase surface water temperatures 8-10°C.

The lake begins to cool in September when night air temperatures can approach freezing. By October the cool weather and autumn winds have turned the lake over and isothermal conditions persist until the lake freezes.

There is often considerable variation in the rate of lake surface heating in different years as is indicated by the 1967 and 1968 data collected by Narver and Andersen (1969). For example, from 20-25 June 1967 surface water temperatures were between 18-21°C with a mean for June of 17.2°C, whereas during the same period in 1968 surface water temperatures varied from 9.5-13.5°C with a monthly mean of only 10.9°C. Thus the monthly energy input to these surface waters was approximately a third higher in 1967 when the mean monthly insolation was compared to June of 1968.

Farmer and Spearing (1975) made detailed vertical temperature measurements in Babine Lake in 1972-73. They made 153 north-south transects down to the lake and conducted several transverse profiles to derive isothermal plots of the lake during the ice free period. This information allowed them to identify important physical processes such as upwelling, thermal bars and mixing which could influence plankton distribution and productivity in the lake. They identified two areas of persistent upwelling: a small upwelling zone in the Old Fort - Hagan Arm area and a stronger zone of upwelling in the south basin between Black Point and Boling's Point in summer during periods of strong wind. This upwelling process can transport nutrients to the surface from the hypolimnion (Stockner and Shortreed, 1974). A thermal bar effect was measured in late May in the area of Hagan Arm where littoral stratified water was temporarily separated from the open water mass by a nearly vertical 4°C isotherm. An inverse thermal bar effect was also measured in Morrison Arm during autumn cooling. The temporary isolation of nearshore waters could provide a mechanism to concentrate pollutants derived from surface runoff and river discharge (Wetzel, 1975).

Additional information on physical limnology (wind, temperature and current data) were measured on recording instruments in 1972-74. These raw data have not been analyzed but have been compiled by Lee (1977) and are available on magnetic tape at the Institute of Ocean Sciences.

Transparency: The transparency of the water in different areas of Babine Lake has been measured by Narver and Andersen (1968) and Stockner and Shortreed (1974) during primary productivity studies. Seasonal Secchi disc measurements indicate that the north basin and Morrison Arm have lower transparency (2.5m Secchi depth) in May and June when highly colored surface runoff enters the lake. This water becomes much clearer (6.0 - 6.5 m Secchi depth) in mid-summer and fall. Water in the central basin of the lake between Old Fort and Topley Landing does not show large seasonal variations in Secchi disc transparency (5.0 - 6.0 m) while stations south of Topley Landing have a high transparency (7.0 m) in May and early June which decreases (4.0 - 4.5 m) in late June due to a plankton bloom. In the south basin there is another period of lower Secchi transparency (4.5 - 5.0 m) attributable to the fall phytoplankton bloom.

Log handling activities in littoral areas of the lake could potentially affect the water transparency if there was suspension of bottom sediments or if poor water circulation caused the concentration of colored tannin materials leached from bark to build up.

Chemical Limnology

Babine Lake has been classified as a dystrophic, oligotrophic lake (Stockner, 1975; Stockner and Shortreed, 1974). A dystrophic lake is characterized as a body of water which is stained with a yellow-brown color attributable to humic substances most often derived from leaching of terrestrial organic matter and bog drainage. An oligotrophic lake is characterized as a nutrient poor body of water with relatively low phytoplankton productivity that maintains oxygen in the hypolimnion throughout the summer. The chemical data that have been collected on Babine Lake provides some support for the oligotrophic classification however, the lake is not highly colored when compared to many dystrophic lakes found in north temperate boggy environments.

General Water Chemistry: The color in Babine Lake varies from 10 to 25 mgPt.l^{-1} and different reaches of the lake show some seasonal variation in color as a result of river systems (Fulton and Morrison) which receive water from bogs and marshy areas in their watersheds. Spring runoff from these rivers often contains 3-4 times as much color (60 color units, Stockner and Shortreed, 1974) when compared to average lake color values (Table 1).

The average general chemical characteristics of Babine Lake water are presented in Table 1. These data are average values for 3 sampling periods namely May, July and October. The complete data set presented by Stockner and Shortreed (1978) show very little seasonal variation for most of these quality parameters.

The pH is very close to neutrality (7.0). The alkalinity of the water (35-37 mg$CaCO_3$.l^{-1}) indicates that it is not highly buffered which might result in a slight increase in pH due to photosynthesis in the trophogenic zone during periods of higher phytoplankton activity. The dissolved solids content of the lake is between 60 and 63 mg.l^{-1}. From the information available on the major cations and anion in the water (Table 1), it is apparent that calcium and the carbonate-bicarbonate anions (alkalinity) predominate with smaller contributions from sodium, magnesium and sulphate. A cation/anion balance of the analytical data presented by Stockner and Shortreed (1978) indicate that their major ion analysis was very complete and one would not expect to find any other major dissolved inorganic constituents in the water. The difference between the total residue and dissolved residue indicates a very low level of suspended solids, namely 2-4 mg.l^{-1}. These low levels of suspended solids are verified by low turbidity in the water, usually <1 F.T.U.

There is very little spatial variation in general chemical characteristics of the mid lake samples collected by Stockner and Shortreed at 5 different stations in Babine Lake. They never had a station in Morrison Arm which should be the first area to show any quality differences attributable to surface runoff since Morrison

Table 1. General chemical characteristics of Babine Lake [1]

Chemical Parameter	Station 1	2	3	4	5
pH	7.6	7.6	7.7	7.7	7.6
Specific Conductivity (uS.cm^{-1})- at 25°C	76	78	77	78	79
Turbidity (F.T.U.)	3.0	0.4	0.4	0.4	0.6
Color (mg Pt.l^{-1})	20	17	15	15	18
Total Residue (105°C)	63	65	62	63	66
Dissol. Residue (105°C)	61	63	60	61	63
Total Alkalinity (mg $CaCO_3$.l^{-1})	35.3	36.1	36.4	36.2	36.9
Chloride	<0.5	<0.5	<0.5	0.6	<0.5
Sulphate	<5.0	<5.0	<5.0	<5.0	<5.0
Sodium	2.0	2.0	2.0	2.0	2.1
Potassium	0.5	0.6	0.6	0.6	0.6
Calcium	10.3	10.3	10.3	10.2	10.5
Magnesium	2.5	2.5	2.5	2.4	2.7

[1] Values taken from Stockner and Shortreed (1978) and represent average values for three sampling dates (May, July and Oct. 1976). The 5 stations are spaced from the north arm of the lake (Stn. 1) to Pinkut Creek area in the south basin (Stn. 5). All values in mg.l^{-1} unless indicated.

Arm has a relatively small volume compared to other basins and reaches of the lake.

Data collected from Morrison Lake which empties into Morrison Arm shows a lower total alkalinity (25 $mgCaCO_3.l^{-1}$) and lower total dissolved solids (57 $mg.l^{-1}$) than found in the main basins of Babine Lake (Narver, 1967).

Log storage and handling activities in the shallow bay and shore areas will probably have little effect upon the general chemical characteristics of the pelagic areas of Babine Lake. Where circulation in shallow areas is poor there is a potential for local increases in water color due to bark leachates. Since most of these colored leachates are weak acids they could consume some alkalinity and possibly lower the pH since the water of Babine Lake is poorly buffered. Increases in the turbidity or suspended solids could occur in shallow areas due to log dumping and handling especially where there are fine organic sediments. However, one would expect these turbidity changes to be sporadic and difficult to detect unless detailed sampling was conducted while these activities were taking place.

Nutrients: The nutrient levels in Babine Lake are presented in Table 2. There was very little temporal or spatial variation in these nutrient measurements. Other data collected by Smith and Davidson (MS, 1974 - reported by Stockner and Shortreed, 1974) during 1972-1973 also show very little temporal (June, July and Sept.) or spatial variation in nutrient concentrations and are very similar to the 1976 levels measured by Stockner and Shortreed. Some of the nutrient measurements, especially dissolved and total phosphate are very close to the detection limits of the techniques so it is possible that some changes are occurring below these detection levels. Earlier nutrient data collected in 1963 and 1969 show some lower values for nitrate and phosphate in the north arm and Morrison Arm with generally some higher values in the southern areas (Stephens et al., 1969). These higher levels may be a result of the upwelling from the hypolimnetic regions which occurs during summer storms in these areas (Farmer, MS 1973).

The nutrient concentrations in Babine Lake support the oligotrophic classification it has been given. Sawyer (1952) in a study of several lakes in Wisconsin indicated that inorganic phosphorus and inorganic nitrogen concentrations had to be 0.01 $mg.l^{-1}$ and 0.30 $mg.l^{-1}$ respectively or larger before algal blooms were considered a nuisance and the lake is in an eutrophic state. An estimate of a phosphorus budget for Babine

Table 2. Nutrients in Babine Lake [1]

Nutrient	Station 1	2	3	4	5
Dissolved P	<.003	<.003	<.003	<.003	<.003
Total P	.005	.005	.005	.005	.006
Dissolved N (NO_3^- + NO_2^-)	.07	.08	.08	.08	.08
Total Kjelkhal N	.19	.17	.20	.16	.15
Total N	.23	.25	.24	.24	.34
Reactive SiO_2	4.2	4.2	4.3	4.4	4.6
Total Org. C	8.0	8.0	8.0	7.0	7.0

[1] Values taken from Stockner and Shortreed (1978) and represent average values for 3 sampling dates (May, July and October 1976). stations are the same as in Table 1. All values are in $mg.l^{-1}$.

Lake relative to the mean depth/residence time places the trophic state of Babine Lake in the oligotrophic region while Nilkitkwa Lake, with its very short residence time, is close to the mesotrophic classification (Stockner and Shortreed, 1978).

A comparison of nutrient concentrations to the ratios of C:N:P essential for healthy algal growth indicates that phosphorus is most likely the limiting nutrient in Babine Lake. Although there appears to be some decrease in silicate concentrations during the fall diatom bloom in the southern region of the lake it does not go below the 0.5 $mg.l^{-1}$ considered limiting for diatom growth (Stockner and Shortreed, 1978).

Log handling activities that result in sediment suspension could cause release of nutrients. This nutrient release would be more significant if excessive deposits of wood debris result in highly anoxic sediments. For example, these conditions can reduce iron which could cause phosphorus release if it is bound as ferric phosphate in the sediments.

Trace Metals: With the exception of copper, iron and zinc, most trace metal concentrations were near or less than the detection limit of the analytical technique (Table 3). The slightly higher average levels for Cd, Cu, Pb and Zn at Station 5 are attributable to higher concentrations found in the sample collected in May and may be attributable to spring runoff since this lakewater sample contained the highest conductivity and dissolved solids of all samples collected during the study (Stockner and Shortreed, 1976). Also, Pinkut Creek is near this station and the creek water is usually higher than the lake in dissolved and suspended solids.

Copper mining in the area of Hagan Arm has raised concern over trace metal contamination from tailings impoundments. Stockner and Shortreed (1978) monitored the water quality at stations adjacent to the mining areas. The trace metal levels measured in these areas were not significantly different than levels found at other stations in the lake. Due to the presence of sulphide ores in the watershed there was also concern that mining and logging activities could expose these minerals to air with the resultant oxidation of sulphide to produce acid which could leach elements such as copper and zinc from the rock and contaminate the lake. In a comprehensive study by Strasdine and Razzell (1974), 45 rock samples from the watershed, especially from areas of mining, logging and road construction, were analyzed for their acid consuming potential. Most of the rock material was not extremely easy to acidify so the authors concluded that there was no leaching hazard from this oxidation process.

Table 3. Trace metals in Babine Lake [1]

Metal	Station				
	1	2	3	4	5
Cadmium	<0.5	0.5	<0.5	<0.5	1.6
Copper	3.6	4	3.6	3.6	9.6
Iron	100	100	<100	100	100
Lead	2	<1	2	<1	3
Molybdenum	<0.5	<0.5	<0.5	<0.5	<0.5
Zinc	<5	<5	9	6	20

[1] Values taken from Stockner and Shortreed (1978) and represent average values for 3 sampling dates (May, July and October 1976). Stations are the same as in Table 1. All values are in $ug.l^{-1}$.

As mentioned previously, if anoxic sediments are created by wood debris deposits, the reducing conditions could release iron into the water. Tannin materials that are leached from bark have a potential to complex and mobilize trace metals. However, these materials would have to be concentrated in areas of mineralization before there would be a concern with metal toxicity.

Tributary Water Quality: The water quality of three rivers which discharge to Babine Lake, namely Pinkut, Fulton and Morrison was investigated during the lake monitoring program of Stockner and Shortreed (1978). These rivers contain higher levels of suspended solids, organic matter and color than is present in the main lake stations. This is attributable to the transport of allochthonous organic matter made up of decomposing terrestrial plant material and the brown stain of humic-like substances that leach from forest litter and bogs in these watersheds. The alkalinity of Pinkut Creek was similar to Babine Lake while Morrison and Fulton Rivers have lower alkalinities (26.5-34 $mgCaCO_3.l^{-1}$). The concentration of other cations and anions in these rivers is very similar to levels found in Babine Lake indicating no large differences in the geochemistry of these tributary watersheds.

Sediments: The chemical composition of ten sediment cores (40 cm depth) collected from deep-water regions at ten stations in Babine Lake were investigated by Stockner and Smith (1974). They measured the vertical distribution of organic matter, carbon, total phosphorus, copper and zinc to investigate regional differences and determine if recent watershed activities (mining and logging) could be detected in recent sediments. With the exception of zinc, they found higher levels of all measured constituents in the lake sediments collected north of the Fulton River (Table 4). The concentrations of organic carbon and total phosphorus were higher in the surface sediments (0-4.5 cm) than in the deeper sediments (5.0-40 cm). The surface sediments from the Morrison Arm core contained very high organic carbon levels (i.e. 7.51% compared to an average of 4.28% for all cores) which provides additional evidence for the more dystrophic nature of this arm when compared to other reaches of the lake. Surface layers of sediment from the core collected from Hagan Arm near Granisle Copper Mine site contained high copper concentrations, an indication of possible leakage from the tailing impoundment.

Phytoplankton, Chlorophyll and Primary Production

Phytoplankton and primary production studies in Babine Lake were conducted by Narver and Andersen (1968) during 1966-67, by

Table 4. Sediment Characteristics of Babine Lake [1]

Area	Organic C (%)	Total P ($mg.g^{-1}$)	Cu ($ug.g^{-1}$)	Zn ($ug.g^{-1}$)
North Region (Fort Babine to Fulton R.)	4.29	2.47	66	139
South Region (Fulton R. to Pinkut Cr.)	2.98	2.40	34	141

[1] Data from Stockner and Smith (1974).

Stockner and Shortreed (1974) in 1973, and by Stockner and Shortreed (1978) from 1974 to 1978.

Phytoplankton: The four year study period of Stockner and Shortreed (1978) provides an indication of spatial and seasonal distribution of the relative volumes of different groups of phytoplankton in Babine Lake. The Bacillariophyceae (diatoms) usually constitute the largest volume of phytoplankton with smaller contributions from Cyanophyta (blue-greens) and Chrysophyceae. A different seasonal and temporal pattern of phytoplankton emerges if a comparison is made by numbers with the smaller blue-green algae often dominating the larger diatoms (Stockner and Shortreed, 1974). When phytoplankton volumes are integrated over the year there is considerable annual variation in different basins. For example, a south basin station opposite Pierre Creek contained 5 times the phytoplankton found at the Morrison Arm station and there were 3 times more phytoplankton at the southern most station (south of Pinkut Creek) compared to the station in the north arm during 1973.

Phytoplankton succession shows a spring bloom dominated by diatoms which is usually higher in the northern reaches of the lake (down to Granisle). A fall bloom of diatoms also occurs but it does not usually reach spring levels and it is more prevalent in the southern reaches of the lake. Species enumeration between May and October in 1973 indicated that *Rhizosolenia longiseta* and *Cyclotella stelligera* were the main diatoms associated with the spring algal bloom while the fall bloom at stations south of Topley Landing was dominated by the diatoms *Tabellaria fenestrata* and *Fragilaria* spp. (Stockner and Shortreed, 1974). These authors also provide a complete species list of the algae identified during this period and show the major species found in different zones of the lake.

Chlorophyll: Chlorophyll *a* measurements, which represent an estimate of phytoplankton biomass, were made at 10 stations sampled at approximately two week intervals between May and October in 1973 (Stockner and Shortreed, 1974). Table 5 summarizes the chlorophyll *a* concentrations in four areas of the lake during four periods between May and October. A plankton bloom in late spring occurred throughout the lake with chlorophyll *a* levels between 20-60 mg.m^{-2}. This was followed by a period of mid-summer lows where chlorophyll *a* dropped to values between 3-11 mg.m^{-2}. There was a resurgence of the phytoplankton biomass in the late summer and early fall when the chlorophyll *a* increased to levels between 16-46 mg.m^{-2}. This early fall plankton bloom was most prominent in the south basin of the lake.

Table 5: Chlorophyll *a* Levels in Babine Lake (1)

Period	Area of Lake			
	North Arm	Morrison Arm	Central Basin	South Basin
Early May	10.5	11.2	4.3 - 13.5	2.6 - 11.6
Mid-Late June	20.0	35.5	18.1 - 46.4	40.9 - 63.2
Mid-Summer	11.0	9.7	3.0 - 11.8	6.2 - 9.6
Early Fall	24.3	16.7	19.4 - 34.9	24.2 - 46.3

(1) All values in mg.m^{-2}, samples taken at 1, 3, 5, and 20 m and concentrations integrated over depth profile. (Stockner and Shortreed, 1974).

Table 6: Primary Productivity in Babine Lake (1)

Period	Area of Lake			
	North Arm	Morrison Arm	Central Basin	South Basin
Early May	96.3	117.4	103.3 - 163.7	48.0 - 123.7
Mid-Late June	174.2	497.7	245.8 - 378.2	200.2 - 330.8
Mid-Summer	146.1	111.5	148.2 - 158.7	111.1 - 148.2
Early Fall	68.6	124.7	134.2 - 301.1	188.2 - 319.7

(1) All values in $mgC.m^{-2}.d^{-1}$, samples taken at 0, 1, 2, 3, 5, 10, 20 and 30 m and concentrations integrated over depth profile (Stockner and Shortreed, 1974).

Primary Productivity: The average daily rate of primary production was 122 $mgC.m^{-2}.d^{-1}$ during the ice free period in 1973 (Stockner and Shortreed, 1974). This varied from a mean of 100 $mgC.m^{-2}.d^{-1}$ in the northern half of the lake (5 stations north of the Fulton River) to a mean of 145 $mgC.m^{-2}.d^{-1}$ in the southern half of the lake (5 stations south of the Fulton River). Higher productivity in the central and south basins of the lake was attributable to the fall diatom bloom when productivity exceeded 300 $mgC.m^{-2}.d^{-1}$ (Table 6). During this period, the productivity in the north arm and Morrison Arm was quite low (60-125 $gC.m^{-2}.d^{-1}$).

Measurements made during subsequent years (1974 - 1978) during spring and fall sampling periods showed a primary production rate as low as 43 $mgC.m^{-2}.d^{-1}$ at a station south of the Old Fort to a value as high as 511 $mgC.m^{-2}\cdot d^{-1}$ in the north arm station in the spring (Stockner and Shortreed, 1978). Earlier studies by Narver (1967) had indicated a range of 8-41 mg $C.m^{-2}$ for 4 hour incubation periods which was reported by Stockner and Shortreed (1974) as an estimated average of 55 $mgC.m^{-2}\cdot d^{-1}$. They attributed this much lower primary productivity rate to differences in methodology since nutrient concentrations appeared to have changed very little between 1966 and 1973.

Primary production on an annual basis was 33 $gC.m^{-2}$ with a mean of 27 $gC.m^{-2}$ for the 5 north stations and 40 g $C.m^{-2}$ for the 5 south stations (Stockner and Shortreed, 1974).

Extensive log storage in shallow areas could block out some solar radiation which might reduce primary productivity. Colored leachates can reduce the water transparency and have an effect upon primary productivity. Tannins from bark can also bind to proteins and could cause inhibition of some enzyme systems which affect both microbial and phytoplankton metabolic processes. It would probably require conditions of very poor water circulation for extended periods of time before water quality conditions would deteriorate sufficiently to affect the phytoplankton population.

Trophic Status: Based on the 1973 primary productivity measurements which were the most complete, Babine Lake ranks as one of the more productive large lakes in British Columbia. It is more productive than Okanogan Lake, more than 10 times as productive as Great Central Lake, but less productive than Kootenay Lake and the smaller eutrophic lakes in the Okanagan basin (Stockner and Shortreed, 1974). A comparison of primary production in Babine

Lake to several well characterized lakes in Europe places Babine between the oligotrophic (30-100 mgC.m^{-2}.d^{-1}) and the natural eutrophic (300-1000 mgC.m^{-2}.d^{-1}) classification of these European lakes.

If the trophic status of Babine Lake is evaluated across several trophic state indicators it appears that Babine Lake best fits the oligotrophic classification. Babine Lake has an average primary productivity of 122 mgC.m^{-2}.d^{-1}, a range of chlorophyll *a* levels from 1.2-2.9 mg.m^{-3}, 5-6 ug.l^{-1} total phosphorus and 230-340 ug.l^{-1} total nitrogen. These trophic state indicators are similar to the range of values measured in several oligotrophic lakes, namely, primary productivity 50-300 mgC.m^{-2}.d^{-1}, chlorophyll *a* 0.3-3.0 mg.m^{-3}, total phosphorus 1-5 ug.l^{-1} and total nitrogen 1-250 ug.l^{-1} (Likens, 1975).

The stratigraphy of diatom frustules preserved in sediment cores provides a useful indicator of historic conditions and causes for change in lakes. Usually, centric diatoms are more common in oligotrophic lakes while pennate (araphidine) diatoms are more common in a eutrophic lake (Wetzel, 1975). Thus an assessment of A/C ratios of diatoms in sediment cores provides one indicator of the trophic status of a lake and changes that have occurred. Oligotrophic lakes are considered to have an A/C ratio of <1, mesotrophic from 1-2 and eutrophic lakes >2. The values of A/C ratios (averaged for the total core) taken from ten stations on Babine Lake were all less than 1 except for a station near Old Fort with a value of 1.75. The overall average for all cores was 0.58 again indicative of an oligotrophic status for Babine Lake (Stockner, 1975). The A/C ratios for diatoms in the water column were higher than in sediment cores for the southern stations due to an underestimation of *Melosira italica* (a centric diatom) and an overestimate of *Fragillaria* spp. (an araphidine diatom). Fragile diatoms like *Rhizosolenia* which ranked between second and fourth in abundance in the water were not found in cores an indication of possible errors in relating sediment A/C ratios to past conditions in the water.

Zooplankton

Zooplankton populations are of interest because they serve as the predominant food of juvenile sockeye in Babine Lake. The distribution, abundance and seasonal patterns of zooplankton occurrence strongly influence the growth and survival of juvenile sockeye during their nursery year (Foerster, 1968).

The most intensive zooplankton sampling has been carried out by Johnson (1964, 1965). The following species have been identified in Babine Lake samples:

Cyclops scutifer Sars
Cyclops bicuspidatus thomasi S.A. Forbes
Diaptomus ashlandi Marsh
Diaptomus pribilofensis Juday and Muttkowski
Epischura nevadensis Lilljeborg
Heterocope septentrionalis Juday and Muttkowski
Bosmina coregoni longispina Leydig
Daphnia longispina hyalina Leydig, var. *microcephala* Sars
Daphnia galeata galeata Sars
Daphnia longiremis Sars
Holopedium gibberum Zaddech
Leptodora kindtii Focke
Polyphemus pediculus Linne

Analysis of zooplankton standing crops (Johnson, 1964) showed that mean dry weights of zooplankton increased with mean depth and mean flushing times in different lake basins. A negative relationship between zooplankton dry weight and sockeye fry density suggested a fish cropping effect on zooplankton.

Other zooplankton investigations at Babine Lake (Narver, 1970; McDonald, 1973; Rankin, 1977) have been carried simultaneously with sockeye fry sampling in order to analyze fish-zooplankton interactions. During Narver's (1970) study, the diel vertical migration patterns of zooplankton in Babine Lake were described. Only *Bosmina coregoni* and *Heterocope septentrionalis* migrated vertically, the former species moving into surface waters by day, and the latter species moving upwards at night. Most of the zooplankton were found in relatively shallow depths, between 9m and the surface.

A comprehensive analysis of the long-term changes in Babine lake zooplankton associated with the 3 - 4 fold increase in sockeye fry loading following construction of spawning channels was undertaken by Rankin (1977). Comparisons were made between zooplankton collections obtained in the years 1958-62 (pre-enhancement) and in 1973 and 1974 (post-enhancement). The results indicated a recent decrease in zooplankton biomass, on the order of 65% in some areas, although the results were confounded by large variations between the 1973 and 1974 samples. Decreases were most apparent in large body-sized zooplankters eg. *Cyclops*, *Diaptomus*, and *Daphnia*, the former 2 genera showing decreases of 50%, and the latter, a decrease of 80% in some areas. Rankin (1977) attributed these changes to the selective removal of these species by the increased number of juvenile sockeye foraging in the pelagic zone of Babine Lake. Contrary to expectations, there was not much change in *Heterocope* (a large calanoid) or *Bosmina* (a small cladoceran) abundance. It is perhaps significant that these are the 2 genera which migrate vertically on a diel basis in Babine Lake (Narver, 1970).

III.

JUVENILE SOCKEYE IN BABINE LAKE

A large majority of the fish-related studies at Babine Lake focus on sockeye salmon. While sockeye are of prime importance economically, they are but one species in the fish community of Babine Lake which is comprised of at least 4 salmonids (sockeye salmon, coho salmon, rainbow trout, lake char), 3 coregonids (lake whitefish, Rocky Mountain whitefish, pygmy whitefish), 4 cyprinids (peamouth chub, squawfish, redside shiner, longnose dace), 2 catostomids (largescale sucker, longnose sucker), 1 cottid (prickly sculpin) and 1 gadid (burbot).

Egg-to-Fry Mortality

The mortality of sockeye salmon during their years of stream, lake, estuary and ocean life has immense practical importance. When management can intervene to reduce mortality during a specific life history stage, benefits may be realized by commercial fisheries. Lake fertilization (Stockner, 1979) and predator control (Foerster and Ricker, 1942) are two examples of enhancement techniques which successfully reduce sockeye mortality rates at specific life history stages.

A hypothetical mortality schedule for Babine Lake sockeye was suggested by Johnson (1965). From an average female fecundity of 3200, if one assumes an equal sex ratio, a total mortality rate of 99.9375% results in a stable population which just reproduces itself. The following shows Johnson's hypothetical mortality schedule:

3200	- eggs
-2650	(80% loss during spawning, incubation, emergence and entry into the lake)
640	- fry entering lake
- 576	(90% loss during lake residence)
64	- smolts migrating from lake
- 62	(96.88% loss during ocean life, including downstream migration and fishing)
2	- spawning adults

While the actual mortality rates of Babine sockeye depart from the hypothetical values (eg. fry - smolt, see p. 41), the hypothetical schedule shows the correct order of magnitude for mortality loss at different life history stages. Mortality is greatest between the egg and fry stages.

Egg-to-fry mortality rates in Six Mile Creek, which flows into the southeastern end of Babine Lake, have been estimated by Withler (1952). From a knowledge of: 1) the number of spawning females, 2) the egg retention rate in spawned females, 3) the proportion of dead and living eggs and alevins revealed by excavation of redds, and 4) the numbers of fry migrating down the creek the following spring, Withler estimated a total egg-to-fry mortality of 85%. Most losses occurred during the eyed stage between October and February and were attributed to freezing of the redds.

Mean egg-to-fry mortality values of 51.4-79.2% in different areas of the Fulton spawning channel, and 83% in the Fulton River have been measured by Ginetz (1972; Table IX). Most egg mortality was thought to occur at the earlier stages of egg development, during the period from egg deposition to the pre-eyed stage. In the Fulton spawning channel, the major mortality factor was mechanical disturbance which resulted from superimposition of redds when adult spawner densities were high, and wave spawning occurred (Ginetz, 1972).

Fry Distribution and Abundance

The understanding of where sockeye fry occur in Babine Lake, and how many there are, has evolved with the development of fish sampling methods which permit the analysis of fry distribution and abundance patterns. The earliest fry sampling conducted in Babine Lake (Johnson, 1956) relied on a fine-meshed conical net that was towed in surface waters behind 2 boats. The maximum fishing success with this method was achieved during evening twilight periods in the first few minutes of darkness.

Very intensive surface water (upper 15 m) sampling throughout Babine Lake has been carried out with a 150 x 10 fathom purse seine fished off a 10.7 m aluminum hull drum seiner (Scarsbrook and McDonald, 1970). Purse seining was carried out in 1966-68 (Scarsbrook and McDonald, 1970), 1971 (Scarsbrook and McDonald, 1972), 1972 (Scarsbrook and McDonald, 1973), 1973 (Scarsbrook and McDonald, 1975) and in 1977 (Scarsbrook et al., 1978). Sockeye fry abundance estimates based on seine catches have been recently summarized by McDonald and Hume (1984; Table 1). The results document a three- to four-fold increase in lake populations of juvenile sockeye following establishment of the Pinkut and Fulton spawning channels.

Fry in deeper waters of Babine Lake have been sampled by means of trawl nets, usually operated in conjunction with an echosounder. Andersen and Narver (1968) describe the use of an Isaacs-Kidd trawl operated behind a specially designed trawling barge and developed for studies on diel vertical migration of sockeye fry (Narver, 1970). McDonald and Scarsbrook (1970) also used an Issacs-Kidd trawl (6' x 8' mouth dimension, 15' length) capable of fishing down to 59 m. A portable trawl (2m x 2m mouth dimensions, 7.5 m length) capable of operating below 50 m has been designed by Gjernes (1979) for use in sockeye salmon lake fertilization evaluation programs, and this system was successfully operated in surface waters of Babine Lake during 1983 by the Dept. of Fisheries and Oceans, Prince Rupert (Orr, in preparation).

The most recent approach for analysing Babine Lake sockeye fry distribution and abundance relies on echosounder traces to provide population density estimates (Mathisen and Smith, 1982). Results of this hydroacoustic survey carried out in October, 1975, indicated a total population of 48.5 million fry, about 20% higher than the 38.8 million (± 1.6 million) smolts which emigrated from Babine Lake in May and June, 1976. Further information on the use of echosounders for estimates of juvenile sockeye abundance in lakes is given in Mathisen et al. (1977).

Sockeye fry are unequally distributed within Babine Lake (Johnson, 1956; 1958; 1961). During 3 years of study (1955-1957) Johnson found that sockeye fry were concentrated in Babine's northern basin and in Nilkitkwa Lake. Moreover, there was an inverse relationship between mean sockeye body sizes and population density - larger fish occurring in areas of low density, and smaller fish occurring in regions of high density (e.g. northern basin, Nilkitkwa Lake). Johnson's observations are consistent with a limited dispersal by fry from their natal spawning grounds and a density dependent relationship between fry growth and abundance. The observation of underutilized lake nursery areas in the main and south basins of the lake led to the construction and development of spawning channels on the Fulton and Pinkut Rivers. The intent was to produce fry which would utilize the main and south basins of Babine Lake as a nursery area.

Most fry from the spawning channels appear to spend their year of juvenile lake residency in the main and southern basins of Babine Lake. Fry marking studies (Coburn and McDonald, 1972, 1973) have established the lake distribution patterns of both wild and channel produced Fulton River fish. Both shore observations and recaptures of marked fish in purse seines (McDonald, 1969) suggest an initial southward movement by Fulton River fish at the rate of about 1 $km.day^{-1}$ following lake entry in June. Later in the summer, the fish move northward into the main basin of Babine Lake. The absence of marked fish in northern basin purse seines in October (McDonald, 1969) suggests only a limited dispersal by Fulton River fish into the northern basin during their first summer of lake residence. Fulton River fry movements were successfully simulated by Simms and Larkin (1977) by assuming 1) between May 25 - July 12, 90% of the fry have a 10:90 bias toward southward movement and 10% move at random; 2) between July 13 - Aug. 28, 50% have a 90:10 bias for northward movement and 50% move at random,; and 3) between Aug. 29 - Oct. 12, 100% move at random.

Feeding Ecology

As in other sockeye lakes, zooplankton are the predominant food of juvenile sockeye in Babine Lake during their nursery year. Stomach analyses by Narver (1970), McDonald (1973) and Rankin (1977) indicate both spatial and temporal differences in food acquisition by underyearling sockeye. Factors controlling these differences are not well understood.

Narver (1970) compared juvenile sockeye feeding off Nine Mile Creek (northern basin) with those feeding off Pierre Creek (main basin). While *Heterocope septentrionalis*, *Daphnia longispina* and *Bosmina coregoni* were predominant food of sockeye off Nine Mile Creek, adult insects (mainly Homoptera and Diptera) supplanted the former 3 zooplanters as the predominant food off Pierre Creek. Stomach analyses of main basin fry by McDonald (1973) also indicated the importance of *Daphnia* and *Heterocope* in the diet, as well as *Diaptomus*. Rankin's (1977) analysis showed that *Cyclops* were also eaten, especially in the northern part of the main arm.

Sockeye fry feeding habits shift over time. Seasonally, between July and September, the importance of *Heterocope* in the diet decreases, while the importance of *Bosmina* and especially *Daphnia* increases (Narver, 1970; McDonald, 1973). By October, sockeye fry shift back to feeding on *Heterocope* (McDonald, 1973). Rankin (1977) has suggested that due to the higher sockeye fry numbers in Babine Lake following spawning channel construction, and increases in predation pressure, changes have occurred in the zooplankton community. Sockeye fry stomachs analyzed by Rankin had substantially higher amounts of *Diaptomus* and *Cyclops* than previous fry specimens analyzed by McDonald (1973).

Diel differences in sockeye feeding have been well-analyzed by Narver (1970). While day-time feeding on *Heterocope* occurred, especially during mid-summer, other zooplankton were acquired primarily during dusk and dawn feeding episodes near the surface. On a clear night in August having a full moon, nocturnal feeding occurred and zooplankton food was present in fry stomachs through the night.

The previous feeding studies indicate that juvenile sockeye acquire prey selectivity in Babine Lake. Ivlev electivity indices (Ivlev, 1961) calculated by Narver (1970) based on lake fry and zooplankton samples, and also by Rankin (1977) for laboratory feeding trials, indicate that sockeye do not acquire prey in proportion to their abundance in the environment. Factors in addition to prey density e.g. prey size, visibility and behaviour, appear to influence the feeding of juvenile sockeye in Babine Lake.

A study on the effect of starvation on subsequent sockeye fry mortality and growth (Bilton and Robins, 1973) suggests that fry in Babine Lake can withstand an initial 2 week (at a low temperature) period without substantial mortality from starvation. Beyond 2 weeks starvation, mortality rates become significant and fry growth is retarded.

Fry Production Characteristics

By simultaneously estimating sockeye fry and zooplankton biomass in seven different basins of the Babine-Nilkitkwa lake system, Johnson (1961) was able to establish 1) an assymptotic relationship between sockeye growth rate and zooplankton biomass (Figure 5) and 2) an inverse relationship between zooplankton biomass and sockeye biomass (Figure 6). These relationships suggest that the mean growth rate of juvenile sockeye is a simple function of the mean zooplankton biomass during the mid-June to mid-October sockeye growth period, and secondly, that juvenile sockeye exert a controlling influence on the biomass of zooplankton in Babine Lake. Brocksen et al. (1970) have interpreted Johnson's results as evidence for a density-dependent production relationship. When sockeye increase in biomass, food density (zooplankton) decreases causing a reduction in sockeye growth.

Brocksen et al. (1970) have suggested theoretical relationships of fish growth and production to biomass (Figure 7) and have recalculated Johnson's (1961) data to fit this model (Figure 8). The data fit the theoretical curve very closely, although data

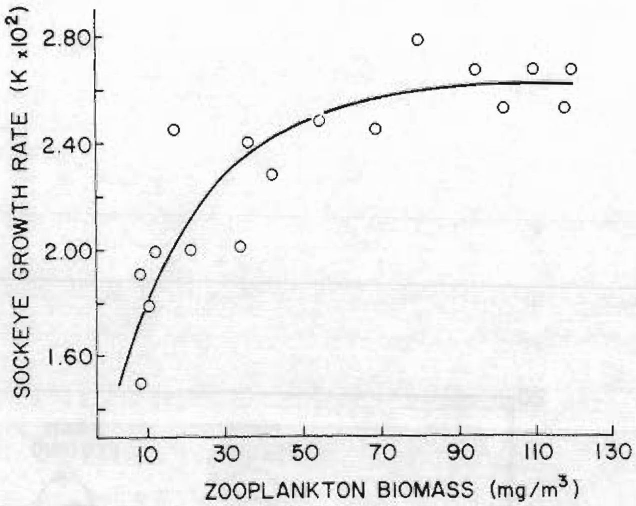

Figure 5. Relationship between sockeye growth rate and zooplankton biomass in Babine Lake (from Johnson, 1961).

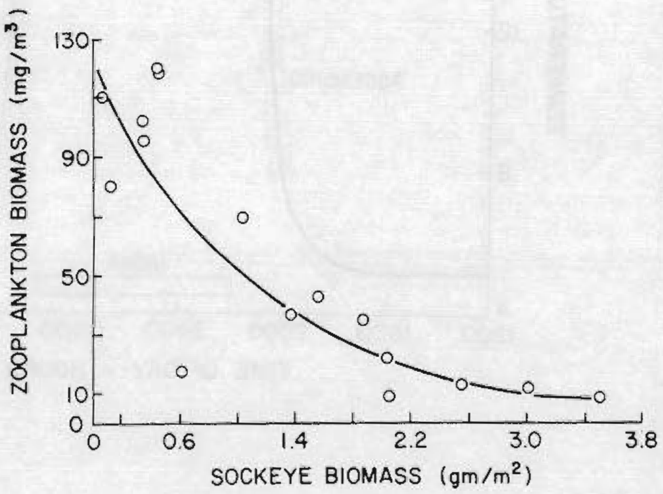

Figure 6. Relationship between zooplankton biomass and sockeye biomass in Babine Lake (from Johnson, 1961).

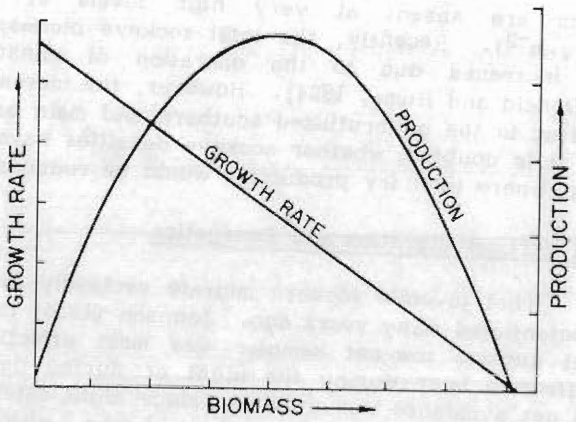

Figure 7. Theoretical relationships of fish growth and production to biomass (from Brocksen et al., 1970).

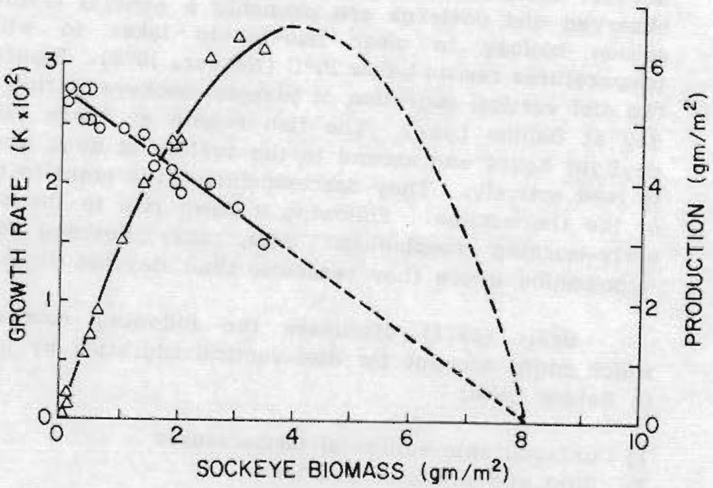

Figure 8. Relationship of sockeye growth and production to sockeye biomass in Babine Lake (from Brocksen et al., 1970).

points are absent at very high levels of sockeye biomass (>4 g.m^{-2}). Recently, the total sockeye biomass in Babine Lake has increased due to the operation of enhancement facilities (McDonald and Hume, 1984). However, the increase in biomass was realized in the underutilized southern and main basins of the lake, and it is doubtful whether sockeye densities have increased to the point where total fry production would be reduced.

Diel Vertical Migration and Energetics

That juvenile sockeye migrate vertically in Babine Lake was substantiated many years ago. Johnson (1956) reported that a two boat surface tow-net sampler was most effective at dusk, and ineffective later during the night or during daylight. Differential net avoidance was unlikely (since night catches were low) and the pattern of catches is consistent with a diel vertical migration.

Since Johnson's early work, studies have been specifically designed to compare day and night fry catches in purse seines, Isaacs-Kidd midwater trawls, and echo sounders (Andersen and Narver, 1968; McDonald, 1969; Narver, 1970; McDonald, 1973). The observed diel patterns are probably a general feature of sockeye salmon biology in clear non-turbid lakes in which epilimnial temperatures remain below 20°C (Narver, 1970). Figure 9 summarizes the diel vertical migration of juvenile sockeye during a mid-summer day at Babine Lake. The fish remain at depth (30-45m) during daylight hours and ascend to the surface at dusk where they begin to feed actively. They descend during the night to the upper level of the thermocline. Following a dawn rise to the surface and an early-morning zooplankton meal, they descend back into the hypolimnion where they reassume their daytime depth.

Brett (1971) discusses the following relevant hypotheses which might account for diel vertical migration by juvenile sockeye in Babine Lake:

1) unfavourable epilimnial temperatures
2) light and predator avoidance
3) response to prey
4) bioenergetic hypothesis

The first hypothesis (unfavourable epilimnial temperatures) was dismissed because surface waters at Babine rarely rise above 18°C, and are always tolerable by juvenile sockeye. Predator avoidance at Babine is unlikely because of its scant predator population

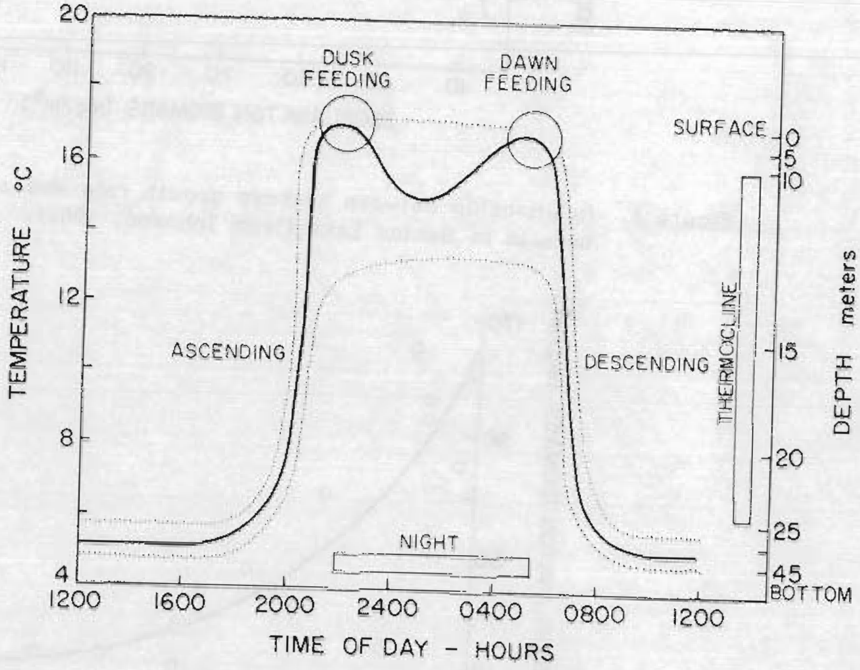

Figure 9. Diel vertical migration of juvenile sockeye in Babine Lake (from Brett, 1971)

(Narver, 1970) and light avoidance was dismissed by Brett because diel vertical movements are evident only when thermal stratification develops in the lake. At the time of the fall overturn light levels continue to fluctuate on a diel basis, yet the vertical movements by juvenile sockeye disappear. Support for the third hypothesis was weak and Brett suggests that remaining in the surface waters would maintain sockeye fry in closer relation with the predominant zooplankton biomass.

The bioenergetic hypothesis was first suggested by McLaren (1963) to explain the diel vertical migration behaviour of zooplankton. McLaren maintained that growth conversion efficiency would be improved for zooplankton that conduct systematic vertical migrations in thermally stratified waters by feeding in warm surface waters and digesting in colder deeper waters. A critical requirement for the bioenergetic hypothesis to explain sockeye diel vertical behaviour in Babine Lake is for food-limiting conditions to prevail. Because observed sockeye growth rates were lower than the maximum possible at both average and surface temperatures this condition was satisfied (Brett, 1971). Since the metabolic rate that juvenile sockeye experience in the cooler hypolimnion is reduced from that in the epilimnion, Brett concluded that vertical migration by juvenile sockeye would result in "maximizing growth through the selective pressure of bioenergetic efficiency."

Support for the bioenergetic hypothesis as an explanation for the observed diel vertical migrations by sockeye has been provided in a series of experiments by Biette and Geen (1980A, 1980B). Growth rates of sockeye fry held under cyclic temperature conditions (similar to those experienced by a vertically migrating fish) were higher than growth rates of fish maintained at constant low (6.2°C) or constant high (15.9°C) temperatures. This conclusion was true only when food rations were submaximal, conditions which likely prevail in Babine Lake (Biette and Geen, 1980A). The mechanism whereby juvenile sockeye under cyclic temperatures grow more rapidly than at a constant temperature is due to higher respiration rates at constant high temperatures, and greater rates of defecation and excretion at low temperatures (Biette and Geen, 1980B).

While these experiments support bioenergetics as an explanation for diel vertical migration in juvenile sockeye salmon, critical testing of the bioenergetic hypothesis will be carried out as a focus of future Ph.D research by D. Levy at the University of B.C.

Horizontal Migrations

Studies on horizontal migrations by juvenile sockeye at Babine Lake have been carried out on recently-emerged fry moving into the lake, and on smolts just prior to their emigration from the lake. Mark-recapture studies provide information on within-lake movements.

The timing and behaviour of sockeye fry moving into Babine Lake from both the Upper and Lower Babine River, as well as the Fulton River, is described by McCart (1967). McCart compared the movements and size frequencies of two different classes of migrating fry -- those that moved upstream, and those that moved downstream, from a spawning site into the lake. In the Upper Babine River upstream migrants were larger than downstream migrants, but Lower Babine River fry showed no such size differences. Clarke and Smith (1972) estimated that 7.5 million fry from the Lower Babine River (18% of the fry produced from the Lower Babine River spawning ground) moved downstream past the counting fence during 1966 and were believed to perish shortly thereafter. Suggestions for minimizing this loss include directing fry with leads to reach the shore sooner, and providing baffles to reduce current velocities (Clarke and Smith, 1972).

Once in Babine Lake, sockeye fry are observed in littoral areas for several weeks (McDonald, 1969) after which time they take up a pelagic existence. Capture of fry in beach seines through July and as late as Aug. 4, 1965 (McCart, 1967) suggests that juvenile sockeye can utilize the littoral zone for a considerable period.

The significance of this initial period of littoral residency in Babine Lake is not well understood, and is the subject of current research by the Westwater Research Centre (1983-1985).

Movements of marked Fulton River sockeye fry indicate an initial southward motion in June at a swimming speed of 1 km.day^{-1}, followed by a northern movement putting most fish opposite the Fulton River by fall (McDonald, 1969). In the north arm of Babine Lake, McCart (1967) has observed a direct relationship between the mean length of fry and the distance from the Babine River, reflecting a dispersal of fry from a single source (Babine River) and fry growth during the dispersal period.

In early May of most years, immediately following ice break-up, schools of sockeye smolts begin a directed migration to the outlet of Babine Lake. The migration behaviour of sockeye smolts in Babine Lake has been intensively studied by Johnson and Groot (1963), Groot and Wiley (1965), Groot (1965; 1972) and Simpson (1979).

Early studies of smolt migration in Babine Lake (Johnson and Groot, 1963; Groot, 1965) compared the migration behaviour and characteristics of animals from several areas of the lake: Sandspit, Morrison River, Halifax Narrows, and at the outlet of Nilkitkwa Lake. Migrating schools were observed directly, smolts were tagged and recaptured, and orientation tests in specially designed observation chambers were carried out. These migration studies established that sockeye smolts migrate at a rate of 5-8 km per day, and that most migration takes place near dusk. Rates of travel increased through the month of May (associated with a strengthening migration drive) and were more rapid during periods of sunshine. Orientation studies showed that the preferred direction correlated with the compass direction of the shortest route through the lake to the outlet. Morrison River smolts showed a changing directional preference over time which corresponded well with their necessity to migrate first in a southerly direction, and later in a northwesterly direction, in order to reach the outlet of Babine Lake. Laboratory studies by Simpson (1979) confirmed the changing directional preference of Morrison River smolts from south to northwest, clockwise, at the rate of 3.0° per day.

A technological advancement for the analysis of smolt movements in Babine Lake was made by Groot and Wiley (1965) and Groot (1972) who used time-lapse photography of sonar observations for studying smolt movements. These studies suggested peak smolt migrations at dawn and dusk, and directional preferences consistent with a directed migration to the lake outlet. Anomalies in migration direction, noted for Morrison smolts near the entrance to Morrison Arm, were also observed indicating that migration to the lake outlet involves a certain amount of back-tracking.

Parasitology

Parasitological examinations of migrating smolts obtained at the outlet of Babine Lake have identified the cestode Eubothrium salvelini and the nematode Philonema oncorhynchi to be the 2 major parasites infecting juvenile sockeye salmon in Babine Lake (Dombroski, 1955). During two years of study, the following infection rates were measured:

	1952	1953
n	1654	1234
% infected by E. salvelini	27%	31%
% infected by P. oncorhynchi	12%	11%
% infected by both E. salvelini and P. oncorhynchi	6%	7%
% uninfected	55%	51%

Whereas smolts infected by cestodes were significantly smaller than uninfected animals, nematode-infected smolts showed no such growth depression, and in fact were significantly larger than the uninfected animals. The faster growth of animals infected by nematodes was attributed to either (1) higher feeding rates of larger smolts causing a higher infection by nematodes (obtained via intermediate hosts which serve as sockeye food items) or (2) higher temperatures which promote rapid smolt growth also promoting a higher infection rate.

Smith (1973) reported the E. salvelini infection frequency in outmigrating smolts of Babine Lake over a 20 year period between 1952-1971. Infection rate by this cestode varied between a low of 12% in 1970 to a high of 46% in 1960. Smolts which migrated later during the spring showed a generally higher infection rate than those which migrated out of the lake early. Parasite load in fry was relatively stable by midsummer and persisted until the animals migrated out of Babine Lake as smolts the following spring. Smith suggested that the stable incidence was related to a midsummer feeding shift from cyclopoid copepods, the intermediate host of E. salvelini, to cladocerans, effectively preventing additional infections through the late summer-winter period. During two years of study (1966 and 1967), migrating smolts infected by E. salvelini were significantly smaller than uninfected animals and would be expected to show lower marine survival rates (Ricker, 1962; Foerster, 1968). Laboratory observations (Smith and Margolis, 1970) suggested that the swimming performance of sockeye smolts was reduced by E. salvelini infection, a factor which would promote higher marine mortality.

In an attempt to better understand the life cycle of E. salvelini, Boyce (1974) artificially infected the following species of copepods with E. salvelini eggs:

Cyclops scutifer
Cyclops bicuspidatus thomasi
Cyclops vernalis

Macrocyclops fuscus
Diaptomus novemdecimus
Diaptomus oregonensis
Diaptomus sp.
Epischura nevadensis

The 3 Cyclops species were the only ones to become readily infected, and the infection rate was shown to be size-dependent, with larger copepods (>400u prosome length) more prone to becoming infected. During the experiments, a 75% infection incidence was generally achieved after an 8-24 h exposure of adult Cyclops sp. to high densities of cestode eggs. Out of 179 sockeye fry which fed upon infected Cyclops sp., 70 animals (39%) became infected by E. salvelini. Susceptibility to infection was inversely related to fry size, with smallest fry showing the highest (60%) infection rates. Boyce suggests that this is due either to
(1) smaller pyloric caecae in small fish enhancing the ability of the parasite to attach itself to the gut wall or,
(2) incomplete development of the immune system in smaller fish.

Toxicology

The presence of two copper mines operating close to the shores of Babine Lake, Granisle Copper and Noranda Bell Copper, has raised concerns about the toxicological effects of copper on juvenile sockeye. A study by Davis and Shand (1978) has shown that no acute toxicity hazard due to copper currently exists in Babine Lake. Their study showed that the acute toxicity (96 hr LC_{50} static bioassay) of dissolved copper to sockeye fry, fingerlings and smolts, varied from 210-240 $ugCu^{++}.l^{-1}$ while lake concentrations of copper ranged from 4-44 $ugCu^{++}.l^{-1}$. The dissolved organic matter in Babine was capable of complexing up to 100 $ugCu^{++}.l^{-1}$ therefore copper was not considered an acute toxicity threat to salmon in the lake.

In a study on yearling coho, Lorz and McPherson (1976) showed that exposure to copper in freshwater (5-30 ug/l) impaired the physiological ability of test animals to tolerate seawater. When seawater challenge tests were repeated on Babine sockeye smolts (Davis and Shand, 1978), some of which had been exposed to copper, there was a strong effect of prior copper exposure on osmoregulatory ability. Pre-exposure to copper at 30 $ugCu^{++}.l^{-1}$ for 44 hours interfered with the salinity tolerance by sockeye smolts. However due to the high complexing capacity of the lake water, Davis and Shand (1978) calculated that copper concentrations in Babine Lake would have to reach 100-150 $ugCu^{++}.l^{-1}$ for this sub-lethal effect to be expressed, many times higher than present concentrations.

Boyce and Behrens Yamada (1977) have demonstrated that Babine sockeye smolts infected by the cestode Eubothrium salvelini, were significantly more susceptible to zinc under laboratory conditions than non-infected smolts. Davis and Shand (1978) obtained contrasting results for copper and found no evidence that Eubothrium infestation affected the acute copper sensitivity of Babine sockeye smolts. There was no obvious explanation as to why cestode infected sockeye smolts proved more susceptible to zinc and did not show an increased sensitivity to copper. Davis and Shand (1978) suggest that study of the synergistic effects of parasitism and toxicity on fish mortality would be a productive area for further research.

Fry-to-Smolt Mortality

Mortality processes of sockeye during their year-long juvenile residency period in Babine Lake have been studied by West (1983) who compared body-otolith relationships of fry and smolts. Higher mortality was found among fish of smaller initial body size at emergence. By comparing back-calculated fork lengths at emergence against otolith lengths for lake samples obtained by tow-net during July, August and September, and for the same year-class when they emigrated from the lake as smolts the following spring, West (1983) concluded that selective mortality against smaller individuals occurred between mid-August and the time of their downstream smolt migration the following spring. Mortality was found to be intense on those sockeye which had emerged at 31mm fork length or smaller. West's hypothesis to account for delayed mortality related to size-at-emergence involves parasitization by the cestode Eubothrium salvelini. Fry which are initially larger would grow out of the size range which is susceptible to infection more quickly than smaller fry which would be more likely to become infected. It should be noted that West's (1983) observations relate to selective mortality and not absolute mortality which undoubtedly decreases as sockeye increase in body size during their year of lake residency. Foerster (1938) presents mark-recapture evidence which shows that sockeye mortality rates in Cultus Lake decrease with increasing stage of lake residency.

Total fry-to-smolt mortality rates for Babine Lake sockeye have been measured in mark-recapture experiments (McDonald and Hume, 1984) and varied between 62.8% and 87.3%.

Smolt Characteristics

An average of 1 million sockeye smolts typically emigrate from Babine Lake every day over a 40-day period between 5 May - 15 June (MacDonald and Smith, 1980). The pattern of emigration is a bi-modal one, with a large peak of smolts emigrating out of the lake in mid-May, and a second one occurring at the end of the first week in June (Figure 10). Recaptures of marked Fulton River fish exclusively during the June peak (McDonald, 1969) provide evidence that Fulton River animals (and probably also Morrison and Pinkut fish) migrate out of the lake in June. Babine River fish, which are concentrated in the northern basin of Babine and Nilkitkwa Lake as underyearling fry (McCart, 1967), probably comprise most of the smolts which emigrate during May.

Smolt sampling at the outlet of Nilkitkwa Lake provides numerical estimates of smolt abundance, as well as qualitative information (e.g. smolt size) useful for predicting returning adult run strength. Attempts at quantifying smolt emigrants by means of mark-recapture experiments date back to the early 1950's (Withler, 1952, 1953). The estimates have been refined through better tagging methods (Jordan and Smith, 1968), improved smolt trapping facilities, and development of appropriate mathematical models (MacDonald and Smith, 1980). Estimates of the late run Babine Lake smolt production from the 1962 to 1974 brood years are shown in Figure 11.

Scale analysis of Babine Lake sockeye smolts (Dombroski, 1952, 1954) indicate that the smolt emigrants are largely 1 lake-year fish, with a small fraction (<2%) spending a two year nursery period in Babine Lake. Examination of smolt gonads suggest a 1:1 sex ratio of males:females in the smolt population. Slight differences in smolt body sizes occurred in different years and also within years (Dombroski, 1954), perhaps reflecting variations in sockeye fry population density between years and also between the different lake basins. Johnson (1961) has documented an inverse relationship between sockeye fry density and growth rate which occurs within Babine Lake.

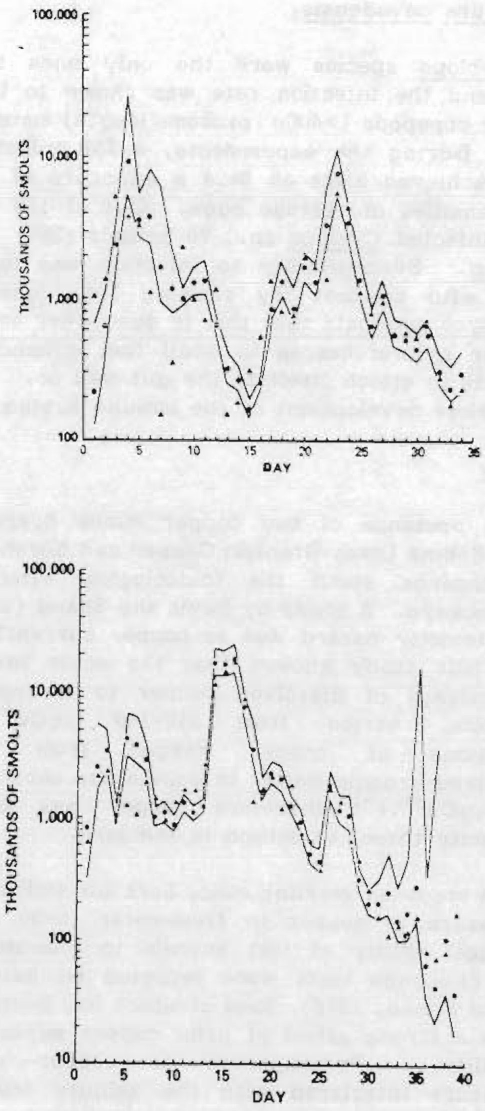

Figure 10. Sockeye smolt migration out of Babine Lake (from MacDonald and Smith, 1980).

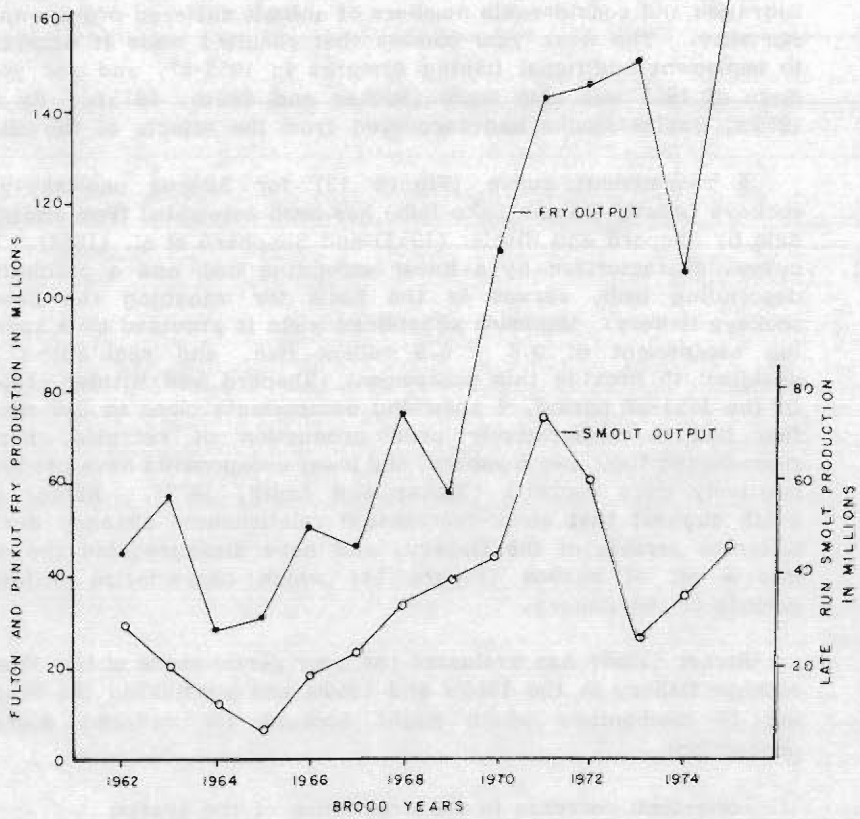

Figure 11. Numbers of Fulton River and Pinkut Creek sockeye fry in relation to the late run Babine Lake smolt production from the 1962 brood years (from West, 1978).

IV.

ADULT SOCKEYE RUNS

Skeena Fishery Production

Babine Lake sockeye stocks are the dominant contributors to the important sockeye salmon fishery which takes place at the mouth of the Skeena River. Depending upon the relative strength of the Rivers Inlet sockeye run, the Skeena River is the second or third largest sockeye producer in British Columbia. The fishery has been operating for over a century. Out of 18 "major" sockeye stocks in the Skeena system [those which had 5000 or more spawners at least once during 1951-62 (Aro and Shepard, 1967)] 12 of the major ones (including the largest) are in the Babine watershed (Ricker and Smith, 1975). Babine stocks contribute to over 90% of the Skeena sockeye catch (Larkin and McDonald, 1968).

The fishery for Skeena sockeye is based largely near the mouth of the Skeena River in the vicinity of Prince Rupert. The fish are captured in drift gillnets, although in recent years, considerable numbers have been obtained by purse-seiners as well as trollers. There is also a significant Indian food fishery in freshwater. Mark-recapture studies between 1944-48 (Aro, 1953) suggested a recapture rate of tagged fish of 27% and 9% in the commercial (inshore) and Indian fisheries respectively. Todd and Larkin (1971) demonstrated that sockeye gillnets in the Skeena fishing area select for relatively large sockeye, except in years (e.g. 1968) when the average sockeye body size is large. Under these conditions, selection is against smaller fish. Due to the nature of the fishery (frequent closures permitting the escape of all fish size-classes), it was concluded that gillnet selectivity probably did not affect the size or age structure of sockeye in the spawning escapement. Skeena sockeye return primarily as 4 and 5 year old adults, although 3 year old "jacks" are also abundant, and 6 year old adults can be present (Godfrey, 1958).

A description of the earlier stages of the Skeena sockeye fishery, from 1877-1948, is provided by Milne (1955). The peak catch of sockeye was realized in 1910 when 187,000 cases of canned salmon were packed, representing a total catch of over 2 million fish. Between 1910-1935 there was a general decline in the catches of about 50%, followed by a period of levelling off between 1935 and 1948 (Figure 12).

During 1951 and 1952, a slide in the Babine River 40 miles downstream of the lake affected the upstream migration of adult

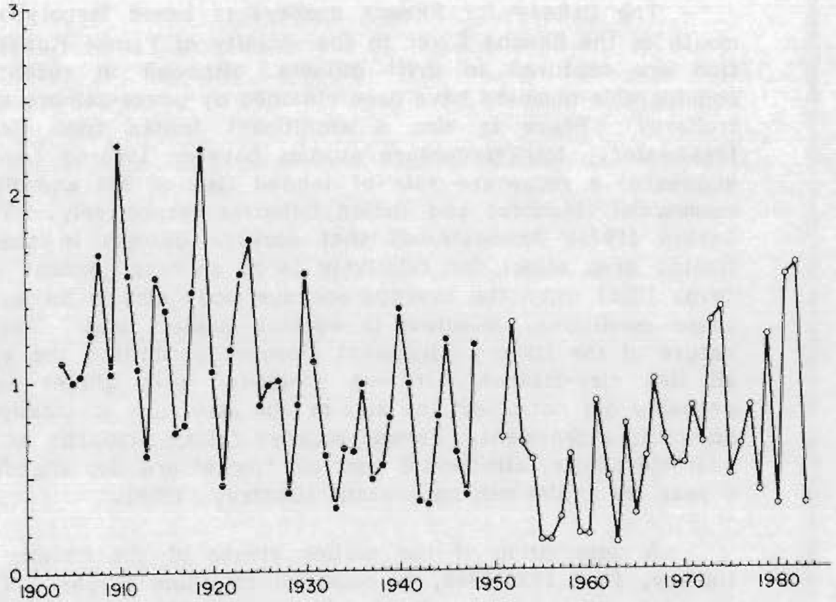

Figure 12. Skeena river commercial sockeye catch between 1904 and 1982. Data from Milne, 1955 (closed circles) and DFO files, Prince Rupert (open circles).

sockeye bound for Babine Lake (Foskett, 1952; Godfrey et al., 1954, 1956). It was possible to assess the degree of damage to the sockeye population by comparing counts made at the Babine counting fence with data collected in previous years (Aro, 1952). Two-thirds of the migrating fish were blocked, many fish delayed their migration and considerable numbers of animals suffered pre-spawning mortality. The weak year-classes that resulted made it necessary to implement additional fishing closures in 1955-57, and the year-class of 1955 was also weak (Ricker and Smith, 1975). By the 1960's, Babine stocks had recovered from the effects of the slide.

A recruitment curve (Figure 13) for Skeena one-lake-year sockeye (mostly Babine Lake fish) has been assembled from empirical data by Shepard and Withler (1958) and Shephard et al. (1964). The curve, characterized by a linear ascending limb and a precipitous descending limb, serves as the basis for managing the Skeena sockeye fishery. Maximum substained yield is provided by a spawning escapement of 0.8 - 0.9 million fish, and regulations are designed to provide this escapement (Shepard and Withler, 1958). In the 1953-67 period, 4 spawning escapements close to 0.9 million fish had a comparatively poor production of recruits, barely reproducing their own numbers, and lower escapements have produced relatively more recruits (Ricker and Smith, 1975). Ricker and Smith suggest that stock-recruitment relationships changed during different periods of the fishery, and have disaggregated the data into a set of curves (Figure 14) which characterize different periods of the fishery.

Ricker (1968) has evaluated the poor performance of the Skeena sockeye fishery in the 1950's and 1960's and considered the following 14 mechanisms which might account for reduced sockeye production:

1. Long-term decrease in the production of the system

2. Rapid decline of the smaller Skeena stocks

3. Chance occurrence

4. Decline in spawning success

5. Decrease in fertility of sockeye lakes

6. Deterioration of the ocean environment

7. Different vulnerabilities of different stocks

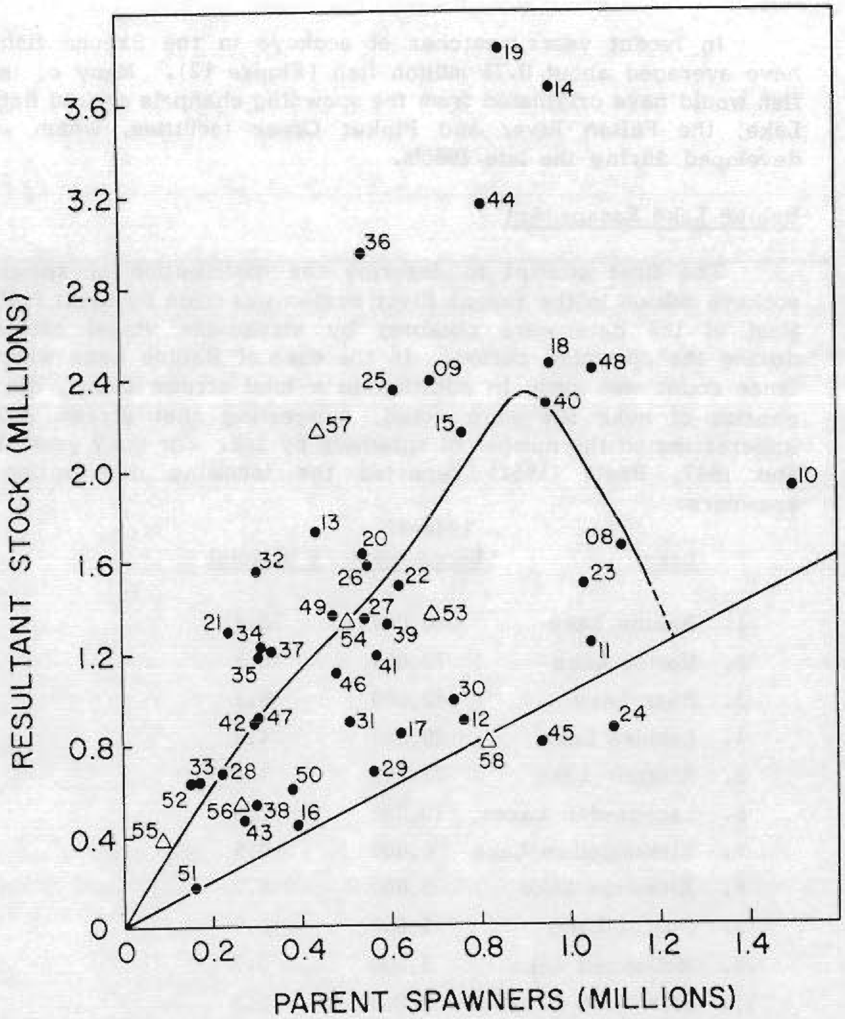

Figure 13. Recruitment curve for Skeena River sockeye (from Shepard et al., 1964).

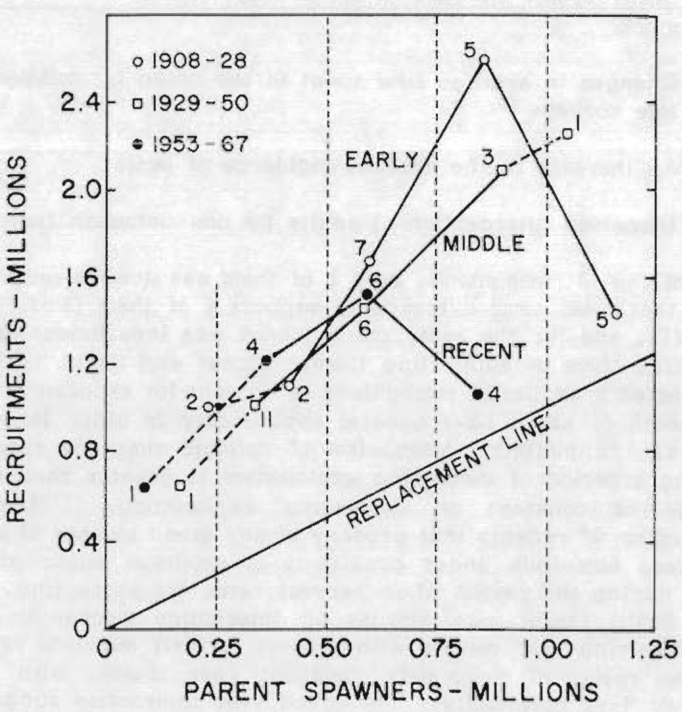

Figure 14. Skeena sockeye stock-recruitment relationships during 3 periods of the fishery (from Ricker and Smith, 1975).

8. Differences in reproductive potential of different stocks
9. Interaction between successive year-classes of the stocks in a given lake
10. Decreased overall spawning success because of unequal utilization of runs migrating at different seasons
11. Unfavourable changes in the average size of the fish in a stock
12. Changes in average time spent in the ocean by commercial-size sockeye
13. An increase in the average incidence of jacks
14. Increased interception of adults by non-Canadian fisheries.

Out of the 14 mechanisms, only 1 of them was deemed unlikely (No. 12), there was some evidence to support 4 of them (Nos. 1, 2, 9, and 11), and for the rest, the evidence was insufficient either for rejecting them or supporting them. Ricker and Smith (1975) have suggested 2 additional mechanisms to account for reduced productivity, both of which have general applicability in other large salmon rivers. "Exploitation Mechanism 1" reflects that the catch taken during a period of increasing exploitation is greater than during a period of constant or decreasing exploitation. "Exploitation Mechanism 2" reflects that progeny of any given number of spawners are less numerous under conditions of maximum sustainable yield than during the period when harvest rates are increasing. Ricker and Smith (1975) also discuss an interaction mechanism between neighbouring year classes with respect to their survival rate which causes cycles of moderately dominant year classes with either a 5-yr or 4-yr periodicity. The brood year interaction suggests that one or more small spawnings are required previous to the successful spawning of a later large year class, and that a large year class somehow depresses the survival of the subsequent smaller ones.

Climatic factors can also affect Skeena sockeye production. Brett (1951) demonstrated a significant positive correlation between precipitation in the spawning months of August and September and subsequent commercial returns of sockeye for the years 1920-1934. Presumably higher precipitation promotes higher egg-to-fry survival.

In recent years, catches of sockeye in the Skeena fishery have averaged about 0.75 million fish (Figure 12). Many of these fish would have originated from the spawning channels around Babine Lake, the Fulton River and Pinkut Creek facilities, which were developed during the late 1960's.

Babine Lake Escapement

The first attempt to describe the distribution of spawning sockeye salmon in the Skeena River system was made by Brett (1952). Most of the data were obtained by streamside visual estimates during the spawning period. In the case of Babine Lake where a fence count was made in addition to a total stream count, discrepancies of over 50% were noted, suggesting that stream counts underestimated the number of spawners by 1/2. For the 2 years 1946 and 1947, Brett (1951) reported the following distribution of spawners:

	Lake	1946-47 Escapement	% of total
1.	Babine Lake	480,000	70.8
2.	Morice Lake	70,000	10.3
3.	Bear Lake	42,000	6.2
4.	Lakelse Lake	29,000	4.3
5.	Alastair Lake	22,000	3.2
6.	Lac-da-dah Lakes	10,000	1.5
7.	Kitsumgallum Lake	6,000	0.9
8.	Kitwanga Lake	5,000	0.7
9.	Sustut Lake	5,000	0.7
10.	McDonnell Lake	5,000	0.7
11.	Slamgeesh Lakes	2,000	0.3
12.	Bulkley Lakes	1,000	0.1
13.	Johnston Lake	1,000	0.1
	TOTAL	678,000	

Due to the recent decline of non-Babine sockeye stocks relative to the Babine stocks (Larkin and McDonald, 1968) and the present operation of 2 major spawning channel facilities around Babine Lake, Babine stocks now probably account for over 90% of the sockeye escapement to the Skeena River system. Recent sockeye escapement data for tributaries of Babine Lake are tabulated in Hancock et al. (1983).

Spawning escapement records for the Babine Lake system are probably the best ones available for any of the major sockeye spawning populations in British Columbia. In 1945-46, a counting fence was constructed on the Lower Babine River, 1.6 km below Nilkitkwa Lake. The fence was completely rebuilt during 1966-1967 and has provided an almost complete record of Babine Lake spawning escapements since 1946 to the present. Summaries of fence counts and related data are provided by Aro (1961), Jordan (1967) and Jordan and Smith (1972). The counts include other species of salmon in addition to sockeye, as well as steelhead.

Attempts have been made by Pritchard (1953A, 1953C) to tag migrating adult sockeye at the Babine Fence and recover the tags on the spawning grounds in order to verify escapement estimates based on visual observations. In two years of study, calculated escapement numbers were roughly double the actual escapement (known from the fence count). Pritchard (1953C) suggests that an increased mortality rate of tagged fish by the Indian fishery, as well as non-reporting of tagged fish captured by this fishery, were responsible for the overestimate of spawning escapement. Recently, higher estimates of escapement have been noted at the counting fence than the sum of the escapements in the various tributaries. McDonald and Hume (1984) suggest that up to 20% of the adult sockeye entering Babine Lake might lake spawn. Part of the discrepancy might also be related to pre-spawning mortality.

Chemical Characteristics

Populations of sockeye from different tributaries in Babine Lake have been examined by x-ray fluorescence spectrometry in order to identify the area of origin of juveniles and adults (Calaprice, 1971). The x-ray spectra which resulted from irradiation of dried tissue samples were analyzed statistically by discriminant function analysis and canonical analysis. Fry and adult samples were collected from the following tributaries:

fry samples	adult samples
Four Mile Cr.	Tachek Cr.
Pinkut Cr.	Sockeye Cr.
Gullwing Cr.	Pierre Cr.
Pierre Cr.	L. Babine R.
L. Babine R.	Pinkut Cr.
U. Babine R.	U. Babine R.
Fulton R.	U. Tahlo R.
	(Adams R.)
	(Cultus L.)
	L. Tahlo R.
	U. Morrison R.
	L. Morrison R.

When known samples were re-classified as to area of origin based on the discriminant function probabilities, the technique resulted in successful classification of 77.4% and 73.1% of fry and adult samples respectively. Both discriminant function and canonical analyses indicated chemical differences between populations, with recognizably distinct animals occurring in different tributaries. Populations within a single tributary e.g. Upper and Lower Babine R. were chemically similar, attributable to the similar freshwater source. Calaprice concluded that sockeye from different tributaries of Babine Lake possessed a "chemoprint", which could be used as a form of natural tag to determine the geographic origin of sockeye captured in the fishery. Apparently, this technique was never adopted as an ongoing sockeye fisheries management strategy.

Adult Migration

The homing migration of adult Babine Lake sockeye salmon spans the distance between the Gulf of Alaska and a spawning stream adjacent to Babine Lake. This migration can be broken into three stages: movements through coastal areas, movements through the Skeena and Babine Rivers as far as the counting fence, and movements from the counting fence through Nilkitkwa and Babine Lakes and into the spawning streams.

Adult sockeye movements through coastal areas have been evaluated through sonic tagging of individuals (Madison et al., 1972) and tagging studies (Aro and McDonald, 1968; Takagi and Smith, 1973). An average sockeye swimming speed of 53 cm/sec was observed in 1969 and 1970 in the vicinity of Dundas Island (Madison et al., 1972). During 1970, most of the 9 animals tracked from Dundas Island headed in the direction of the Skeena River (presumably Babine Lake fish) and averaged 66 cm/sec or approximately 1 body length per second which is metabolically the most efficient swimming speed for sockeye (Brett, cited by Groot et al., in press). Diel patterns were observed (faster swimming and fewer angular course changes during daylight) and no differences in swimming speed were evident when the sonically-tagged animals moved within 2 km of shore.

Aro and McDonald (1968) have summarized tagging and recapture data for Skeena River sockeye and pink salmon that was obtained by the Fisheries Research Board of Canada between 1944 and 1948 as well as between 1955 and 1959. A total of 1983 sockeye tags were recovered at Babine Lake. Babine fish were estimated to have been in the commercial fishing area of the Skeena between June 17 and August 24. Taggings indicated that during June and early July, sockeye in the Skeena fishery were bound for Alastair, Lakelse and Babine Lakes and the Bulkley River. During the latter part of July the run was comprised of mostly Babine Lake and Bulkley River sockeye. In August, most of the sockeye were bound for Babine Lake (Aro and McDonald, 1968).

Migration rates of Babine sockeye in the Skeena and Babine Rivers can be estimated by comparing the occurrence of tagged fish in test nets (fished at the upper boundary of the commercial fishery) with the occurrence of tagged fish at the Babine counting fence. Observations suggest a total travel time of about 3 weeks to cover this distance, although differences have been noted in the median travel times of different segments of the run: early fish = 24.5 days, "middle-run" fish = 14-18 days, and late fish = 21.3 days (Takagi and Smith, 1973).

Fence tagging of sockeye with tag recovery on the spawning grounds permits identification of timing differences between stocks. Smith and Jordan (1973) identified three temporal groups of sockeye returning to Babine Lake (early, middle and late). These were further broken down by Groot et al. (in press) into 4 groups based on time of entry into the lake as follows:

1) An early run from mid-July to mid-August to 9 small streams mainly situated in the southern half of the lake.
2) A run of Morrison River, Tahlo, Grizzly and Pinkut Creek sockeye which pass the counting fence mainly between August 1 and 18.
3) A large run of Fulton River fish passing the fence between August 5 and 30.
4) A late run after August 15 which spawn in the upper and lower Babine River.

Comparisons of tagging results between years indicate remarkably precise adult migration timing from year-to-year (Smith and Jordan, 1973). Because of the observed overlap in run timing of different stocks in the commercial fishery and a difference in their productivity (enhancement stocks being more productive than wild stocks) the present commercial fishery could over-exploit and possibly annihilate wild stocks (Smith and Jordan, 1973). Further, Smith and Jordan (1973) suggest that it may prove impossible to preserve the Morrison River sockeye stock in view of their temporal overlap with Fulton River fish.[1]

Migration rate estimates for adult sockeye moving through Babine Lake have been calculated from tag recovery data by Pritchard (1953B, 1953D). The following are Pritchard's estimates of the number of days on which (1) 50% of tag recoveries occurred at a specific location in Babine Lake and (2) 50% of the fish had died (Day 0 = day of tagging at the Babine Fence):

	Day on which 50% of tag recoveries occurred		Day on which 50% of the fish had died	
	1946	1947	1946	1947
Nilkitkwa Lake	4	6		
Babine River	36	-		
Fort Babine	7	11		
Halifax Landing	6	11		
Old Fort	11	11		
Topley Landing	16	16		
Pendleton Bay	18	18		
Pierre Creek	-	15		
Fifteen Mile Creek	-	30	41	35
Four Mile Creek	-	14	30	32
Morrison Creek	-	36	44	44
Six Mile Creek			33	30
Pendleton Creek			28	27
Twin Creek			26	27
Pierre Creek			37	32
Sockeye Creek			-	23
Tachek Creek			35	23
Fulton River			44	46

Pritchard's data suggest a lake residency time for adult sockeye in Babine Lake of between 15 and 30 days, and perhaps slightly longer

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[1] Problems of overharvesting wild sockeye stocks around Babine Lake create a serious fishery management dilemna. One biological solution would involve reducing commercial fishing pressure at the mouth of the Skeena River and increasing the exploitation of enhancement stocks by a fishery operating within

in the case of Morrison Creek fish. A period of 10-15 days is indicated for passage up the creek and completion of spawning.

Sonic tracking studies on adult sockeye migrating through Babine Lake (Groot et al., 1972; Groot et al., in press) are in agreement with Pritchard's migration rate estimates. Groot et al., (in press) measured an average migration time of 23.7 days for migration of intercepted adults to their spawning stream. Animals displaced from a spawning stream required 9.0 days on average to return to their home stream, although surprisingly, two of the fish displaced from a spawning creek strayed to another one. One Morrison Creek animal released at the entrance to Morrison Arm was recovered 9 days later spawning in Pierre Creek, and one Nine Mile Creek sockeye, following release near Old Fort, was recovered in Tachek Creek 5 days later. Conclusions by Groot et al. (in press) suggest that adult sockeye swim at sufficient velocity and have sufficient time available, once they have entered the lake, to cover the 160 km length of Babine Lake several times prior to spawning. Groot's observations suggest that the straying potential by different sockeye populations (including those from the spawning channels) in Babine Lake could be substantial.

Smolt-to-Adult Mortality

Babine smolt-to-adult mortality rates were estimated by Aro (1951) who fin-clipped migrating smolts and recovered adults in the Skeena gillnet fishery and on Babine spawning grounds for several years. Total smolt-to-adult mortality rates (including fishing mortality) varied between 99.3-99.8%, although these figures are likely overestimates due to the non-recovery of tagged fish. Peterman (1982, Figure 15) shows Babine adult per smolt survival[1] values (the inverse of mortality) as ranging between 1 and 9% for the years 1959-1976, and also presents evidence that Babine smolt-to-adult mortality rates are density dependent. Thus when smolt abundance increases, smolt-to-adult mortality also increases, resulting in lower-than-anticipated adult returns. Ricker (1962) has suggested that most smolt-to-adult mortality occurs shortly after the smolts emigrate from the lake and during their early months of ocean residence. Because of the linear relationship between returns from a single year class in successive years (e.g. age 4 vs. age 3, age 5 vs. age 3) Peterman (1982) confirmed that most of the Babine sockeye smolt-to-adult mortality takes place between the time when smolts emigrate from the lake, and when

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[1] Peterman's adult numbers include both catch and escapement numbers.

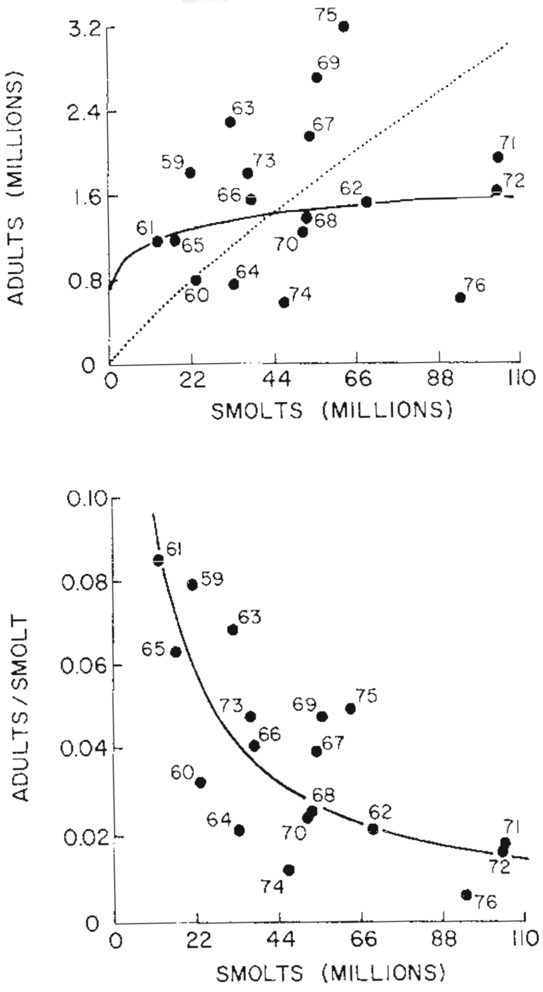

Figure 15. Babine Lake adult sockeye production in relation to smolt output (from Peterman, 1982).

returning jacks from the same brood are enumerated at the Babine fence. This evidence strongly suggests a mortality factor operating on smolts either during their freshwater migration, or else in the estuary of Skeena River.

Enhancement Facilities

Reviews of Babine Lake sockeye enhancement efforts are provided by Ginetz (1977) and West (1978). Enhancement was based on three premises:

(1) the main basin of Babine Lake was underutilized by sockeye fry,

(2) additional fry could be produced by spawning channels and partial flow control, and

(3) fry produced in spawning channels are of comparable quality to naturally-produced fry, and are equally viable to the adult stage.

There are three spawning channel facilities at Babine Lake, two on the Fulton River and one at Pinkut Creek. Both Pinkut and Fulton have partial flow control. The two Fulton River channels (completed in 1965 and 1971) and the Pinkut Creek channel (completed in 1968) produce about 100 million fry annually, mostly from Fulton Channel No. 2. The number of adult spawners which spawned in the facilities between 1965-1977 has averaged 266,000 (West, 1978; Table 2) slightly exceeding expectations. For Skeena sockeye the ratio of catch:escapement is probably slightly greater than 1 in most years (catch:escapement ratio estimated from data in Anon. (1971)). This would imply that Babine enhancement facilities annually produced over 0.25 million adult sockeye in the commercial catch during the period that they have operated.

There is good support for the 3 premises outlined above. Studies in the 1950's (Johnson, 1956, 1958, 1961) verified that the main basin of Babine Lake is underutilized by sockeye fry. The production of fry from the spawning channels has exceeded expectations, although the benefits from partial flow control appear negligible during years of normal precipitation (Ginetz, 1977). Evidence suggests that channel-produced fry are no less viable than naturally-produced fry (Dill, 1970) although slight differences in timing of emergence in the 2 groups occur in some years (Dill, 1970; Paine, 1971). Differences in migration timing were noted by McDonald and Hume (1984) between 1965-67 when wild fry migrated to Babine Lake earlier (by 9-14 days) than channel

fry, giving wild fry a slight size advantage at the time of smolt emigration from the lake. Since 1970, downstream migrations of channel fry have peaked earlier (due possibly to flow control, water temperature, and timing of adult spawning) and channel-produced fish have similar smolt body sizes as wild fish (McDonald and Hume, 1984).

Overall smolt numbers have increased as a result of the 3 spawning channels in Babine Lake (Figure 11). The increase in smolt numbers went from a pre-enhancement average of 30.1 million to a post-enhancement average of 68.2 million, an increase of 2.3 times (McDonald and Hume, 1984).

The success of any salmon enhancement program is ultimately related to the number of returning adults, and in the case of the Babine enhancement facilities, adult returns have been lower than expected. This was first noted by Peterman (1982) who established that smolt-to-adult mortality rates for Babine sockeye are density dependent -- enhanced numbers of smolts suffer higher post-lake mortality. Secondly, there is a marked difference in odd:even year mortality rates which Peterman suggests is an interaction with the even-year pink runs along the north coast. Peterman hypothesizes that pink fry in odd years buffer odd year sockeye smolts against marine predators, or alternatively, might prey upon even year sockeye smolts as returning adults. McDonald and Hume (1984) have disaggregated adult per smolt data into even and odd brood years. These data (Figure 16) clearly indicate a difference in sockeye production for even and odd brood years. McDonald and Hume suggest a strategy to best capitalize on the current even and odd year phenomenon by maintaining or even increasing smolt outputs from odd brood year stocks. Even brood year smolt outputs would be reduced and fishery regulations designed to maintain even brood years at moderate levels.

In future it may be advantageous to consider other forms of sockeye enhancement for Babine Lake. Additional spawning channel facilities (e.g. on the Morrison River) are probably not warranted because of the poor adult returns in relation to the presently high level of smolt output in even-numbered brood years. Lake fertilization (Stockner, 1979) might provide a cost-effective sockeye enhancement technique, especially since underyearling fry are concentrated in the northern basin of the lake (Johnson, 1956, 1958). A possibility exists that selective fertilization of the northern basin of Babine Lake and of Nilkitkwa Lake would result in the enhancement of Upper and Lower Babine River sockeye stocks.

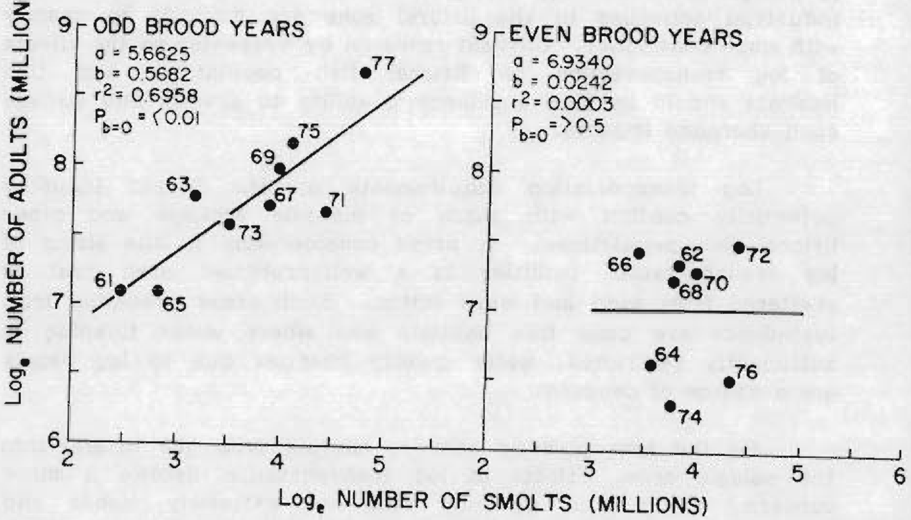

Figure 16. Babine Lake sockeye production in relation to smolt output in odd and even brood years (from McDonald and Hume, 1984).

Reproduction

Most adult sockeye returning to spawning grounds around Babine Lake are animals close to 4 and 5 years of age which migrated to sea in their second year of life (Godfrey, 1958). The two dominant age groups can be referred to as 4_2 and 5_2 fish respectively. While other age classes can be present (e.g. 3_2, 5_3, 6_3) these generally make up less than 10% of the Skeena catch. Since construction of the spawning channels, the frequency of jack males (3_2) in the escapement has increased from 5.9% (pre-channel period) to 10.5% (McDonald and Hume, 1984). Presently, these fish are selectively harvested at the Babine Fence and sold for the benefit of the Fort Babine Indian Band.

Godfrey (1958) compared the age structure of Rivers Inlet and Skeena River sockeye in fishery catches for the period 1912-1954. Patterns in catches over time suggest 5-year and 4-year cycles occurring early and late in the 1912-1954 period respectively. While final size at maturity is strongly controlled by environmental conditions during the latter stages of oceanic life there are indications that age at maturity is heritable. The latter is supported by behavioural observations of sockeye spawning in Four Mile Creek which indicated that adults of a specific size (and similar age) often mate together (Hanson and Smith, 1967).

Female sockeye returning to Babine Lake have a mean fecundity of about 3200 eggs (Withler, 1950) and there is a tendency for larger females to produce larger eggs (Bilton, 1970). Scale analysis of 4_2 and 5_2 fish indicates that juvenile growth in Babine Lake is inversely proportional to age at return (Bilton, 1970, 1971). Fish of age 4_2 had significantly more freshwater circuli on their scales than fish of age 5_2 from the same brood year. Bilton suggests that fish which grow more slowly in Babine Lake are more likely to return as age 5_2 fish than as age 4_2 fish. These large females carrying large eggs produce large, fast-growing offspring which would then return as smaller 4_2 adults. This "hypothesis of alternation of age of return in successive generations" has important management implications but is as yet untested.

Spawning behaviour of adult sockeye in tributaries of Babine Lake is well described by Hanson and Smith (1967) and McCart (1971). Tautz (1970) gives water depth, water velocity and gravel permeability characteristics for sockeye spawning in Four Mile Creek. The behaviour and distribution of sockeye spawning in the Fulton Spawning Channel No. 2 showed a bimodal pattern, with 2 "waves" of fish successively utilizing the same general area of the channel (Tautz, 1977). Superimposition of redds was found to be negligible and the second wave of fish spawned mainly between the previously established redds. Results from a simulation model suggest an optimal spawning area per female in Fulton Spawning Channel No. 2 of 1.6 m^2, greater than the operating level of 1.05 m^2 per female, suggesting a possible over-escapement in the spawning channel.

Examination of sockeye and kokanee (the non-anadromous form of Oncorhynchus nerka) reproductive behaviour revealed that the 2 groups can spawn sympatrically in "early streams" of Babine Lake (McCart, 1970). Temporal and spatial overlap in their use of the same spawning grounds resulted in hybridization occurring under natural conditions. A current study by C. Foote (PhD. Thesis, in progress) is examining sockeye-kokanee interbreeding in Pierre Creek.

V.

CONCLUSIONS

The preceding review reflects that there exists a rich and extensive literature on the limnology and sockeye salmon ecology of Babine Lake. In British Columbia, only one other lake system, Marion Lake, which was the focus of an International Biological Program study (Hall and Hyatt, 1974), has been studied to the same degree as Babine. Unlike the Marion Lake study which concentrated on ecological processes, most studies at Babine have been aimed towards understanding sockeye fisheries production.

The impacts of industrial activities along the Babine shore are most acute in shallow littoral areas. Most of the previous research efforts at Babine have focused largely on stream ecology or pelagic zone limnology and fish ecology. Thus the impacts from industrial activities in the littoral zone are difficult to specify with much confidence. Current research by Westwater on the effects of log transportation on littoral fish populations and fish habitats should improve a manager's ability to predict and manage such shoreline impacts.

Log transportation requirements by the Forest Industry potentially conflict with those of juvenile sockeye and other littoral fish populations. A prime consideration in the siting of log transportation facilities is a well-protected area that is sheltered from wind and wave action. Such areas protected from turbulence are good fish habitats and where water flushing is sufficiently restricted, water quality changes due to log debris are a source of concern.

By the time juvenile sockeye migrate from the littoral into the pelagic zone, effects of log transportation become a minor concern. The fish by this time are extremely mobile and wide-ranging (both vertically and horizontally) and their pelagic environment is sufficiently voluminous that log transportation impacts are likely insignificant.

Siting criteria which would minimize fishery-forestry interaction include locating log transportation facilities away from sockeye spawning streams and enhancement facilities. Under these circumstances, impacts of log transportation on sockeye salmon would be avoided. For example, location of a log dump and storage area in Hagan Arm of Babine Lake would necessarily have negligible influence on Babine sockeye production since few sockeye spawn adjacent to this area and no enhancement facilities are located there.

VI.

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Appendix I: Participants at Babine Lake Workshop - November, 1983

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A.H.J. Dorcey	Westwater Research Centre, UBC
G.H. Geen	Dept. Biological Sciences, SFU
C. Groot	Dept. of Fisheries & Oceans, Vancouver
K.J. Hall	Westwater Research Centre, UBC
J. Hume	Fish & Wildlife Branch, UBC
W.E. Johnson	Dept. of Fisheries & Oceans, Vancouver
R. Kadowaki	Dept. of Fisheries & Oceans, Prince Rupert
C. Lam	Dept. of Fisheries & Oceans, Vancouver
D.A. Levy	Westwater Research Centre, UBC
T.G. Northcote	Westwater & Forestry, UBC
P. Ogawa	Houston Forest Products, Houston
U. Orr	Dept. of Fisheries & Oceans, Prince Rupert
E. Parkinson	Fish & Wildlife Branch, UBC
J. Payne	Dept. of Fisheries & Oceans, Vancouver
H. Smith	Dept. of Fisheries & Oceans, Vancouver
J. Stockner	Dept. of Fisheries & Oceans, West Vancouver
T. Turnbull	Dept. of Fisheries & Oceans, Vancouver
C. West	Dept. of Fisheries & Oceans, Vancouver
I. Williams	Int. Pac. Salmon Fish. Comm., Cultus Lake
I. Yesaki	Westwater Research Centre, UBC

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I. Coastal Resources Management
II. Water Quality Management
III. International River Basin Management
IV. Northern Water Resources Planning and Management

I. Coastal Resources Management Program

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