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Limnological and Fisheries Assessment
of Sockeye Salmon (*Oncorhynchus nerka*)
Production in the Laura Lake System

by
S. G. Honnold and J. A. Edmundson

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Alaska Department of Fish & Game
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ABSTRACT

Before 1950, the migration of anadromous fish into the Laura Lake system was prevented by natural barriers. In the early 1950's fishways were installed in the lake outlet and sockeye salmon (*Oncorhynchus nerka*) eggs were planted in order to expand spawning habitat and enhance sockeye production. Egg plants were discontinued by 1956, but during the 1970's, the U.S. Forest Service (USFS) and the Alaska Department of Fish and Game (ADF&G) continued fishway improvements, as a result, a significant sockeye run developed. Sockeye total returns (escapement and harvest) reached nearly 52,000 in 1980; however, since then sockeye salmon production in the Laura Lake system has significantly declined. Concern over declining sockeye production prompted the ADF&G, in cooperation with the Kodiak Regional Aquaculture Association (KRAA), to initiate fishery and limnological investigations of the Laura Lake system. Fish surveys revealed a spawning area that is underutilized by the current number of spawners. In addition, limnology studies show that existing zooplankton biomass levels are very low, and not sufficient to sustain increasing juvenile recruitment through higher escapements or fry stocking. That is, too few spawners and a low forage base are currently limiting sockeye production in this system. Thus, we recommend a nutrient enrichment project in Laura Lake in conjunction with balanced fry recruitment to increase the amount of forage (zooplankton) and rearing capacity for sockeye juveniles.

INTRODUCTION

The Laura Lake system comprises three lakes: Laura, Paul's, and Gretchen lakes which are located on the northern end of Afognak Island. The Laura Lake system originally supported few sockeye salmon *(Oncorhynchus nerka)*. Barriers (cataracts and falls) between Paul's and Laura lakes, and between Laura and Gretchen lakes frequently limited sockeye returns to less than 2,000. In 1952, fishways were constructed by Waterways Construction, under contract by the Alaska Department of Fisheries (ADF), to enable returning adults to ascend the barriers (Figure 1). During 1951-1955, the ADF conducted sockeye egg plants in Gretchen Creek, the major drainage into Laura Lake, in order to enhance sockeye production. By 1958, 7,400 adults returned to the Laura Lake system to spawn in previously unused habitat. In 1959, a 9 m steeppass was installed by ADF&G at the original fishpass site, and in 1964 a 27 m steeppass was installed at the highest barrier between Paul's and Laura lakes (Honnold 1990). During 1972-1976, the USFS and ADF&G continued fishway improvements at both locations including additional steeppasses, resting pools, and low water diversion structures. As a result, sockeye salmon spawning habitat has expanded and a significant run has developed.

Recent sockeye salmon returns (escapement and harvest) for this system have been as high as 51,653 (1980), and as low as 3,250 (1991). However, the runs have declined since the mid-1980's, and from 1985-1992 averaged 11,800. The minimum escapement goal for sockeye salmon set by the ADF&G, Commercial Fisheries Division is 20,000, with 40,000 the desired escapement. Minimum escapements for this system have been achieved in only seven of the past 23 years, indicating that the return per spawner ratio has been poor. The commercial fishery contribution from the Laura Lake system has resulted in a sockeye harvest of less than 10,000 in all but three years since 1969, and recently (1988-1992) has been less than 2,000 fish. As a result, the ADF&G, Kodiak Regional Planning Team, and the KRAA considered the Laura Lake system as a high priority for sockeye enhancement.

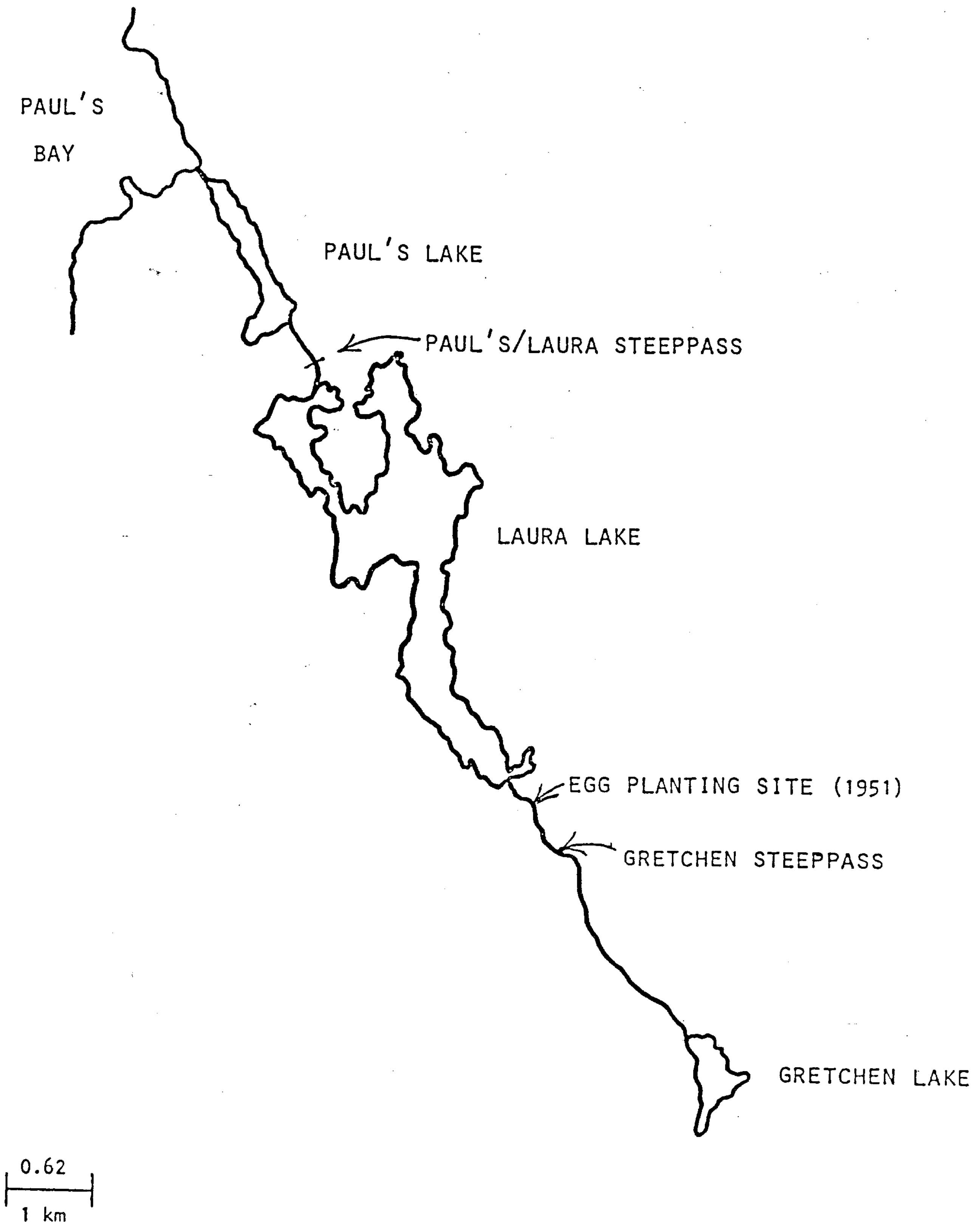

Figure 1. Laura Lake system showing locations of Paul's, Laura, and Gretchen lakes, the steeppasses, and the original egg planting site.

In 1990, the ADF&G, Division of Fisheries Rehabilitation, Enhancement, and Development (FRED), in cooperation with KRAA, began fisheries and limnological investigations of the Laura Lake system. In 1992, juvenile fish sampling (trapping) was conducted at lower Paul's Creek, downstream of Laura Lake, the largest of the three lakes. In 1991 hydroacoustic surveys were initiated at Laura Lake to determine the population and distribution of rearing fish, and the spawning area in Gretchen and Paul's creeks was evaluated. The purpose of this report is to summarize the results of fisheries and limnological investigations relative to the assessment of current sockeye salmon production. In addition, we estimate the potential production of sockeye salmon and recommend an enhancement strategy appropriate for the Laura Lake system.

Description of Study Area -- Laura, Paul's and Gretchen lakes (58° 23'N, 152° 18' W) are located on the north end of Afognak Island 65 km north of the city of Kodiak (Figure 2). Gretchen Lake is drained by Gretchen Creek which flows into Laura Lake. The outlet of Laura Lake is referred to as Paul's Creek which flows into Paul's Lake. Paul's Lake empties into Perenosa Bay via a short (<0.5 km) outlet stream. Laura Lake is 5.0 km long, up to 2.0 km wide, and has a total surface area of 4.2 km^2 (Figure 3). Paul's Lake (Figure 4) and Gretchen Lake (Figure 5) are much smaller with surface areas of 0.6 km^2 and 0.3 km^2, respectively. The mean depth of Laura Lake is 12 m and the maximum depth is ~33 m. Paul's Lake has an average depth of 11 m and the deepest point is ~21 m, whereas Gretchen Lake is quite shallow with a mean depth of only 4.5 m and a maximum depth of 15 m. The total lake volumes of Laura, Paul's and Gretchen lakes is 50.5, 6.9, and 1.4 $x10^6$ m^3, respectively. Finally, annual precipitation on northern Afognak Island averages 155 cm (Dugdale and Dugdale 1961; Anonymous 1979), and the lake-water residence times are estimated to be 1.2, 0.93, and 0.10 yr, respectively in Laura, Paul's and Gretchen lakes.

Sockeye salmon begin migrating into the Laura Lake system in late May and continue entering the system until September. These fish spawn from early August to early October. The early-run component spawn in Gretchen Creek, the major spawning area, and the late run fish spawn along the lake shores of both Laura and Paul's lakes. In

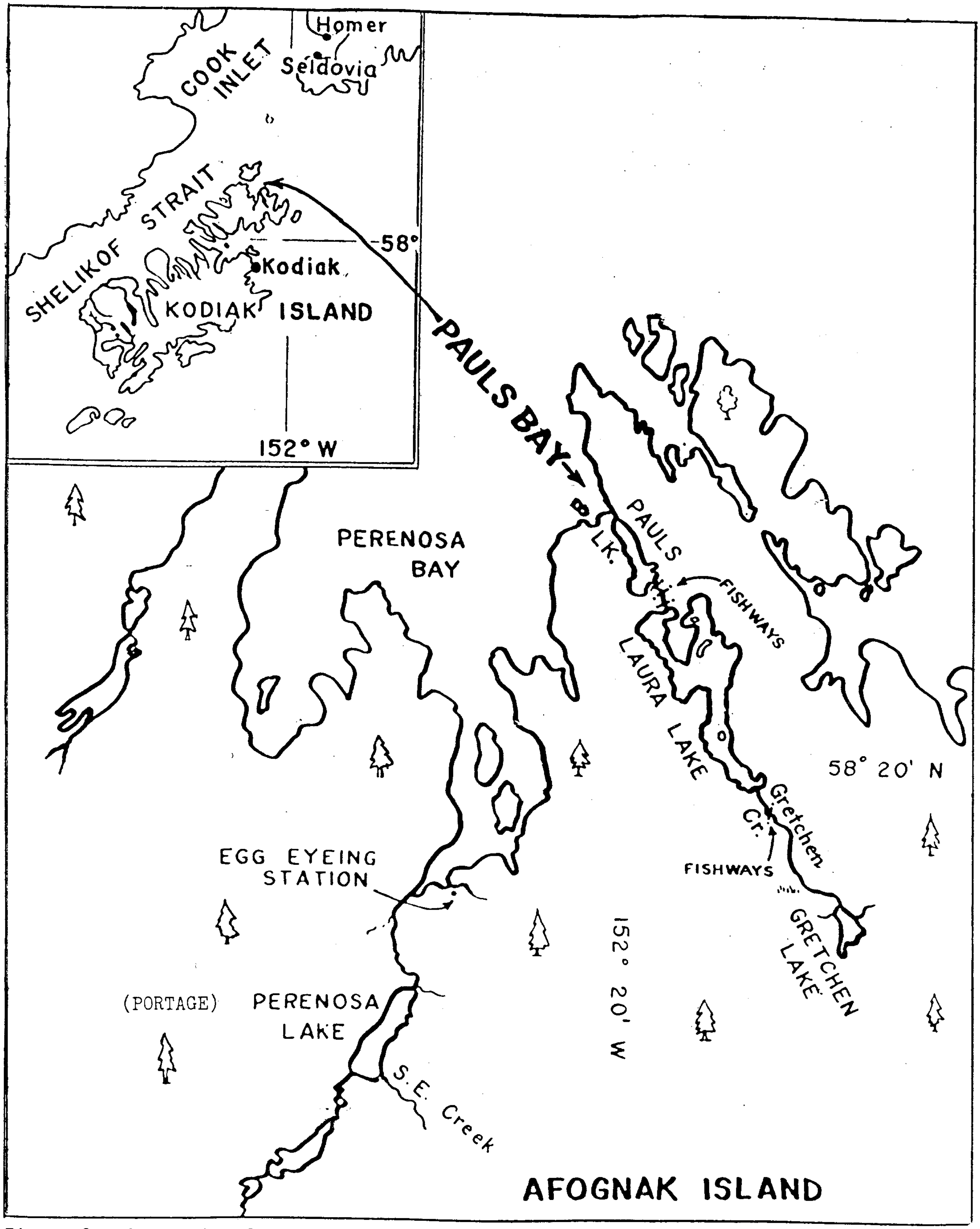

Figure 2. Geographic location of Paul's, Laura, and Gretchen lakes on Afognak Island.

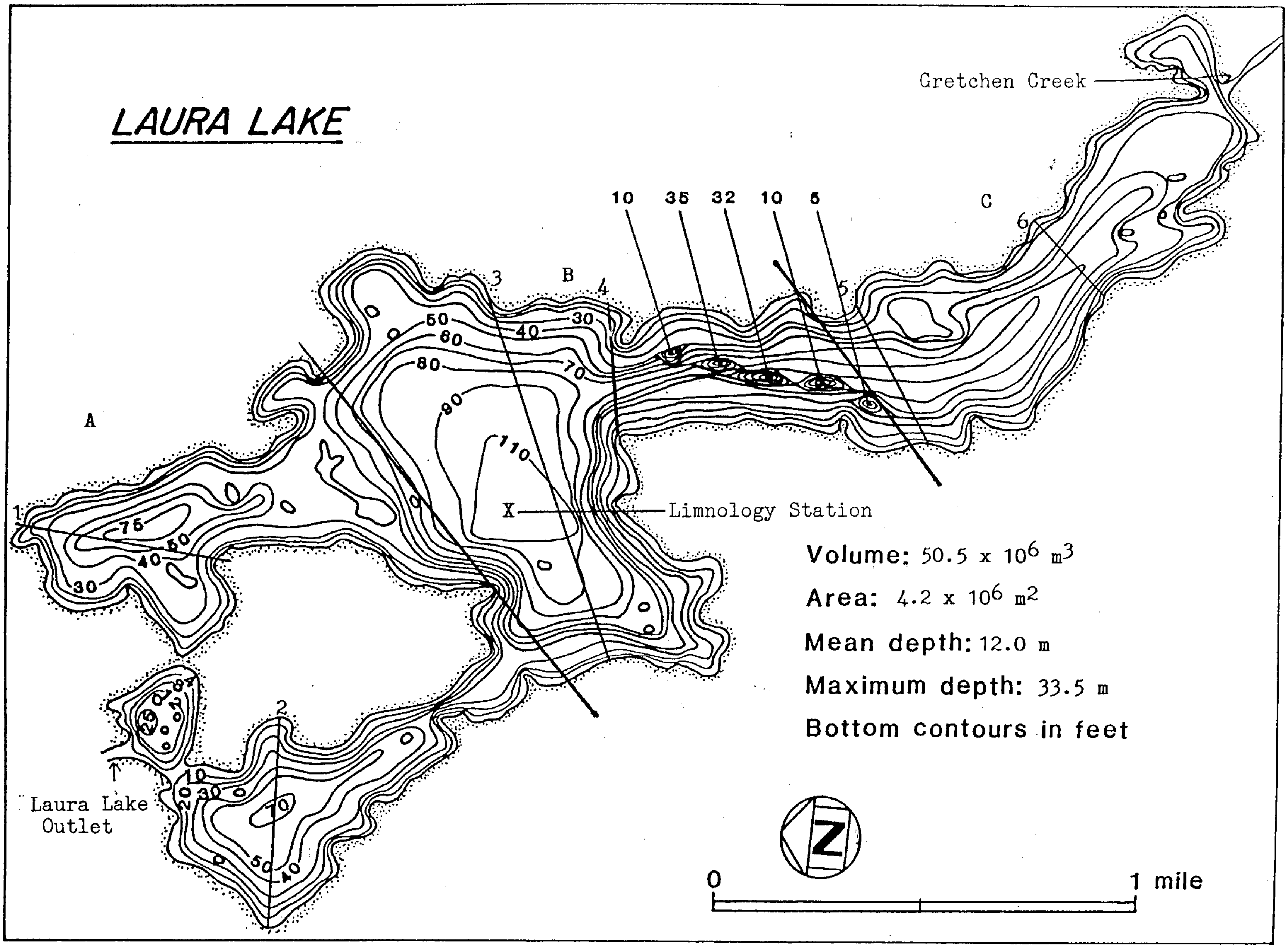

Figure 3. Morphometric map of Laura Lake showing location of the limnological sampling station, hydroacoustic areas (A-C) and transects (1-6), and the major spawning area (Gretchen Creek).

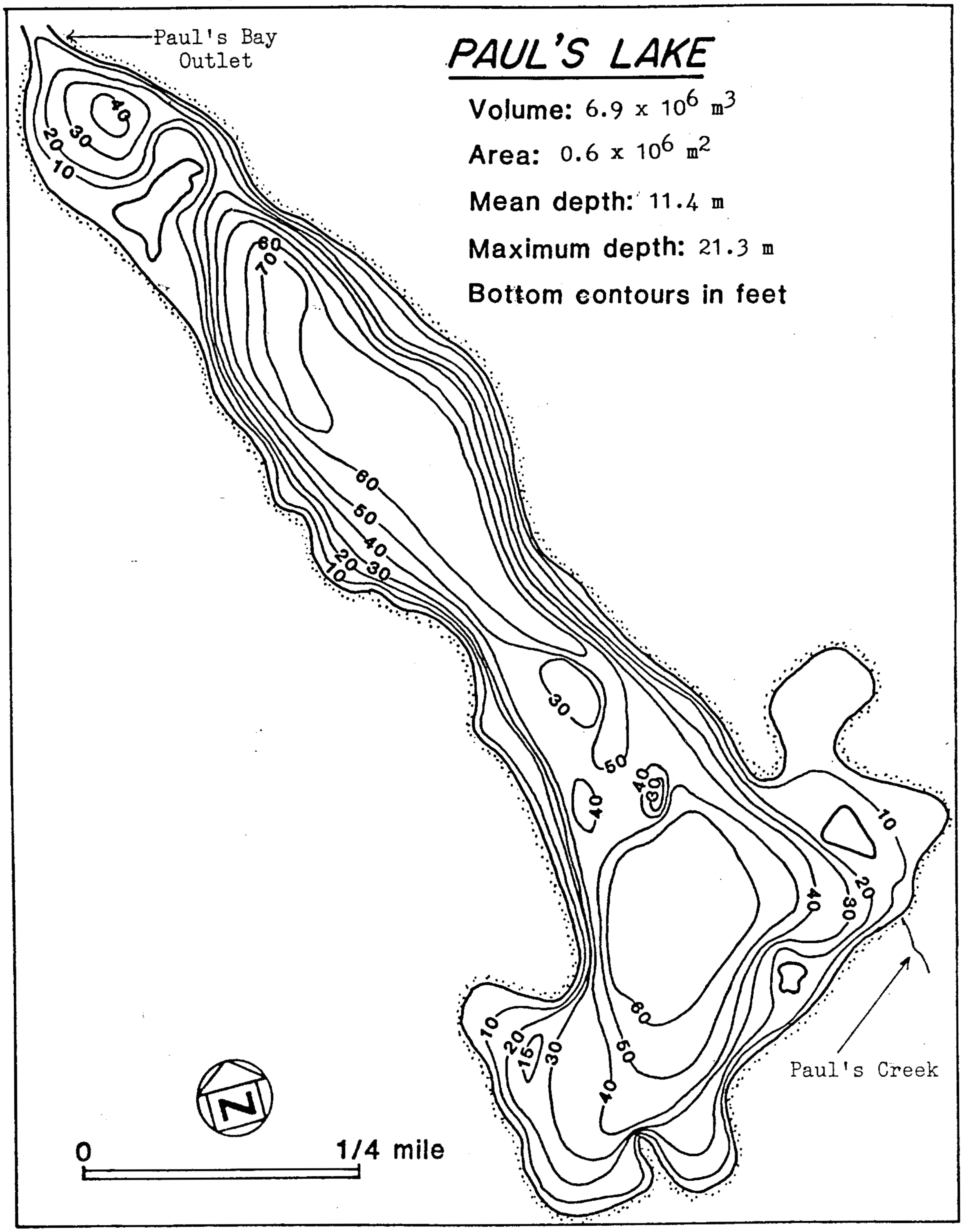

Figure 4. Morphometric map of Paul's Lake.

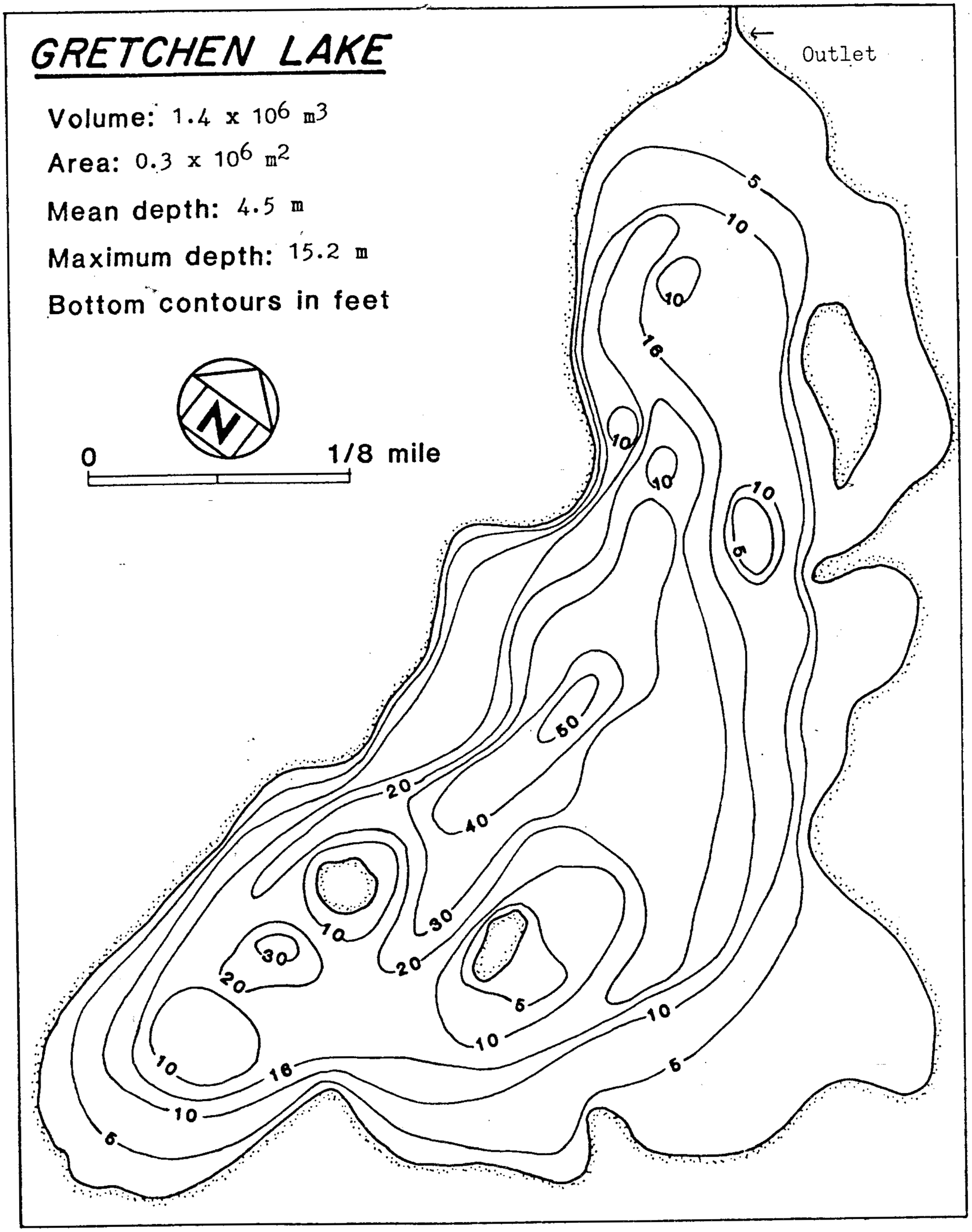

Figure 5. Morphometric map of Gretchen Lake.

addition to sockeye salmon, other fish within the Laura Lake system include: pink salmon (*Oncorhynchus gorbuscha*), coho salmon (*Oncorhynchus kisutch*), rainbow or steelhead trout (*Oncorhynchus mykiss*), Dolly Varden char (*Salvelinus malma*), three spine stickleback (*Gasterosteus aculeatus*), and freshwater sculpin (*Cottus aleuticus*).

METHODS AND MATERIALS

Fishery Assessment

Sockeye Egg Plants -- In 1951, 84,000 sockeye eggs were collected from Southeast Portage Creek brood stock and planted in lower Gretchen Creek (Figure 1). Additional eggs, including Karluk Lake stock, were collected and transported to Port Williams on Shuyak Island for incubation (Appendix Table 1). After these eggs reached the eyed egg stage, they were planted in Gretchen Creek. In 1952, 352,000 eyed eggs from Portage and Karluk brood stocks were planted at Gretchen Creek, and egg plants continued during 1953-1955 with only Portage sockeye stock being utilized. The peak number of eggs planted was 552,000 in 1953.

Adult Surveys and Sampling -- Aerial and foot surveys of the Laura Lake system were conducted by ADF&G from 1969 to 1981, and peak counts were doubled (Barrett *et al.* 1984) to estimate sockeye escapements. Beginning in 1982, Commercial Fisheries Division (CFD) of ADF&G enumerated escapements by using a weir placed at the outlet of Paul's Lake (Figure 4). In addition, during 1976-1991 FRED personnel conducted foot surveys of Gretchen Creek to determine peak spawning numbers and spawner distribution. In 1990 and 1991, the CFD collected peak escapement samples by beach seining near the inlet of Paul's Lake. Scales were taken from 423 and 457 sockeye, respectively, acetate impressions were made, and ages were determined using a microfiche projector. In 1955-1957 age information was collected in the same manner (Stockley 1958). Finally, historical escapements for Perenosa sockeye systems (Portage and Paul's/Laura) were proportioned to estimate the historical contribution of

Paul's/Laura Lake sockeye salmon commercially caught in the Perenosa Bay sections (251-82 and 251-83) of the Afognak fishing district.

Spawning Habitat Evaluation -- The available spawning habitat above and below barriered areas in Gretchen and Paul's Creeks (Figure 1) was measured and evaluated to estimate the number of sockeye salmon that could be supported. Two transects were randomly selected in each section of the stream and the cross-sectional area was measured. The distance between each transect on each bank was measured, thus giving rectangular dimensions. The dimensions of the two banks, as well as the two transects, were averaged. The resulting average dimension of width and length were multiplied to estimate the total area (m^2) of the spawning section. The total useable spawning habitat was determined by estimating the percentage of usable spawning habitat in each survey section, and multiplying by the estimated total area. Useable spawning habitat was defined as flows of approximately 0.5 m sec^{-1}, water depth of 0.3-0.5 m, gravel size of 6-150 mm with $<25\%$ by volume of the gravel ≤ 6 mm, and minimal compactness (Chambers *et al.* 1955). The lakeshore spawning area of Laura and Paul's lakes was estimated based on the following assumptions/techniques: 1) spawning area was limited to a depth of 3.1 m; 2) the 3.1 m shoreline area was determined by planimetry of established morphometric map; and 3) approximately 1.0% of the shoreline spawning area has useable spawning area (based on observations of spawning activity in 1992) as defined above.

Hydroacoustic/Townet Surveys -- Fall hydroacoustic surveys were conducted 27 August 1991 and 02 October 1992 to estimate the number and distribution of juvenile fish (sockeye salmon fry) rearing in Laura Lake. Surveys consisted of collecting (recording) hydroacoustic data along six transects orthogonal to the longitudinal axis of Laura Lake (Figure 3). Transects were selected randomly from representative areas (basins). The number of transects was based on the size of the lake and number of delineated areas. The lake was divided into three equal areas (A-C) and two transects per area were selected. Data were recorded once along each transect, and the survey was continued until all transects were completed. All surveys were conducted at night, when juvenile salmon are distributed in the upper to middle part of the water column (Narver 1970; McDonald 1973; Eggers 1978; Simpson *et al.* 1981; Nunnallee 1983; Burczynski and Johnson 1986; Levy 1987).

A 4.9-m Achilles raft powered by a 30-hp outboard engine was utilized for the surveys. Survey speed along each transect was maintained at 1.5 m sec^{-1} and monitored by the use of a portable Marsh-McBirney flow meter. Transect direction was maintained by compass bearings and by the use of flashing strobe lights at one end of each transect. A BioSonics® model 105 echosounder with a model-171 tape recorder interface system with 6/15° dual-beam transducer was used. Fish signals were recorded electronically using a Sony digital audio tape recorder (Model TCD-D10), and on chart paper using a BioSonics model 115 recorder. The specific instrumentation for data acquisition is described by Honnold (1993). Analysis of the recorded hydroacoustic tapes was conducted by BioSonics, Inc. using procedures described by Kyle (1990) and Honnold (1993).

Identification of fish species from the acoustic target data was accomplished by using a 2 x 2 m townet (Gjernes 1979). Tows were conducted for 7 to 14 min along the axis of the lake. Species composition and abundance were recorded for each tow, and samples were preserved in 10% formalin. Townet samples were used to estimate juvenile sockeye compositions, and populations for the hydroacoustic estimates. All captured sockeye juveniles were sampled for age, length, weight, and condition coefficient.

Smolt Sampling -- Sockeye salmon smolts were collected and sampled for age, weight, and length in 1992. Smolts were collected using a fyke net placed in Paul's Creek near the inlet to Paul's Lake (Figure 4). Smolts were anesthetized in a tricaine methanesulfonate (MS-222) solution, measured for length (nearest 1.0 mm), weight (0.1 g), and calculated for the condition coefficient (Bagenal 1978). In addition, a scale smear was taken from each fish, placed on a glass slide, and ages were determined using

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a microfiche projector. Original samples (1953-1957) were collected by fyke trapping inPaul's Creek near the outlet of Laura Lake.

Limnological Sampling -- Limnological surveys of Laura Lake were conducted three times in 1990, five times in 1991, and four times in 1992. Transportation to and from Laura Lake was provided by a float-equipped aircraft and sampling was conducted after mooring to a permanent station (Figure 3). For each survey, light penetration, temperature, and dissolved oxygen profiles were recorded, and both water quality and biological (phytoplankton and zooplankton) samples were collected. All samples were sent to the Limnology Laboratory in Soldotna for analysis. No limnological surveys were conducted at Paul's or Gretchen lakes.

Physical Features -- Light penetration was measures using a Protomatic or International Light submarine photometer at 0.5-m increments to a depth of 5 m, and at subsequent 1-m increments to a depth equivalent to 1% of the sub-surface light level. The euphotic zone depth (EZD), defined as the depth at which 1% of the subsurface light (photosynthetically available radiation [400-700 nm) penetrates (Schindler 1971), was calculated as the y-intercept derived by regressing depth against the natural logarithm (ln) of the percent subsurface light. Water clarity was measured with a 20-cm Secchi disk by recording the depth at which the disk disappeared from view. Lake temperature profiles and dissolved oxygen levels were measured using a YSI model 57 temperature/dissolved oxygen analyzer at 1-m increments from the surface to the lake bottom (~35 m).

Water Quality -- Lake water samples were collected from the 1-m stratum (epilimnion) and hypolimnion (25-35 m) using a non-metallic Van Dorn sampler. Approximately eight liters of water were collected from each depth, stored in pre-cleaned translucent carboys, transported to Kodiak, and then filtered and/or preserved for laboratory analysis. Filtered and unfiltered samples were: 1) refrigerated for general tests and metals; 2) frozen for total nitrogen and phosphorus analyses; and 3) filtered through a Whatman GFF glass-fiber filter for analysis of dissolved nutrients and stored in pre-cleaned polybottles and sent to the Limnology Laboratory for analysis (Koenings *et al.* 1987).

Phytoplankton -- Samples for the analysis of chlorophyll *a* (chl *a*) were prepared by filtering 1-2 L of lake water through a Whatman 4.25-cm GFF glass-fiber filter to which 1-2 ml of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in individual plexislides for later analysis.

Zooplankton -- Replicate 30-35 m vertical zooplankton hauls were taken using a 0.2-m diameter, 153-μ mesh, conical net. The net was pulled manually at a constant 1 m sec^{-1}, rinsed prior to removing the organisms, and the specimens were preserved in neutralized 10% formalin (Koenings *et al.* 1987).

Morphometry and Water Residence Time -- Bottom profiles were recorded at Laura, Paul's and Gretchen lakes with a fathometer along numerous transects, and used to develop bathymetric maps. The area of each depth strata was determined with a polar planimeter, and the lake volume (V) was computed by summation of successive strata (Hutchinson 1957):

$$z = V/A_L$$

Where: z = lake mean depth (m)

V = lake volume (x 10^6 m^3)

A_L = lake surface area (x 10^6 m^2)

The theoretical water residence time was calculated using the following formula (Koenings *et al.* 1987):

$$T_w \text{ (yr)} = V/TLO$$

Where: T_w = theoretical water residence time (years)

V = total lake volume (x 10^6 m^3)

TLO = total lake outflow (x 10^6 m^3 yr^{-1})

Laboratory Analysis

General Water Quality -- Water samples were analyzed for the following parameters as detailed by Koenings *et al.* (1987). Conductivity (temperature compensated to 25°C) was measured with a YSI model-32 conductance meter, and the pH was measured with a Corning model-399A specific ion meter. Alkalinity levels were determined by acid titration (0.02 N H_2SO_4) to pH 4.5 (AHPA 1985). Turbidity, expressed as nephelometric turbidity units (NTU), was measured with a HF model-DRT100 turbidimeter, and color (Pt units) was determined on filtered samples by measuring the spectrophotometric absorbance at 400 nm and converting to equivalent platinum cobalt (Pt) units. Calcium and magnesium were determined from separate EDTA (0.01 N) titrations after Golterman (1969), and total iron was analyzed by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion after Strickland and Parsons (1972).

Nutrients -- Filterable reactive phosphorus (FRP) was analyzed by the molybdate-blue/ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich *et al.* (1975). Total phosphorus was determined by FRP procedure, after persulfate digestion. Estimates of yearly phosphorus loading in Laura Lake were calculated after Vollenweider (1976):

Surface specific loading:

$$Lp(mgP\ m^{-2}\ yr^{-1}) = \frac{[P]^{sp} \times \bar{z}(1 + \sqrt{T_w})}{T_w}$$

Surface critical loading:

$$Lc(mgP\ m^{-2}\ yr^{-1}) = \frac{10\ mgP\ m^{-3} \times \bar{z}(1 + \sqrt{T_w})}{T_w}$$

Permissible supplemental P (mg m^{-2} yr^{-1}) loading = $L_c \bullet 90\% - L_p$

Where: $[P]^{sp}$ = spring overturn period total P (mg m^{-3})

z = mean depth (m)

T_w = water resident time (yr)

10 mgP m^{-3} = lower critical phosphorous level.

Nitrate and nitrite (NO_3 + NO_2) were determined as nitrite after cadmium reduction and diazotization with sulfanilamide, and total ammonia was determined using the phenylhypochlorite methodology after Stainton *et al.* (1977). Total Kjeldahl nitrogen (TKN) was determined as total ammonia following sulfuric acid block digestion (Crowther *et al.* 1980), and total nitrogen was calculated as the sum of TKN and NO_3 + NO_2. Finally, reactive silicon was determined using the method of ascorbic acid reduction to molybdenum-blue after Stainton *et al.* (1977).

Phytoplankton -- Algal standing crop was estimated by the algal pigment chlorophyll a (chl *a*). Chl *a* was extracted after homogenizing glass-fiber filters in 90% acetone using a tissue grinder and pestle. Chl *a* concentrations (corrected for inactive phaeophytin) were determined using the fluorometric procedure of Strickland and Parsons (1972). The low-strength acid addition recommended by Riemann (1978) was used to estimate phaeophytin.

Zooplankton -- Identification of *Daphnia* followed Brooks (1957), *Bosmina* after Pennak (1978), and the copepods after both Wilson (1959) and Yeatman (1959). Enumeration consisted of counting triplicate 1-ml subsamples taken with a Hansen-Stempel pipette in a 1-ml Sedgewick-Rafter counting chamber. Zooplankton body sizes were obtained by measuring the length to the nearest 0.01 mm of at least 10 individuals along a transect in each 1-ml subsample (Koenings *et al.* 1987). Finally, zooplankton biomass, weighted by organism density, was estimated from species-specific regressions between zooplankter body length and dry weight (Koenings *et al.* 1987).

RESULTS AND DISCUSSION

Fish Assessment

Sockeye Escapement and Total Run -- Since 1969, adult escapements into the Laura Lake system (via Paul's Lake) ranged from a high of nearly 52,000 in 1980 to a low of ~3,200 in 1991, and averaged ~18,200 (Table 1). During 1969-1979, escapements averaged 11,500, increased three-fold during 1980-1984 and averaged 28,900; but since 1985 escapements have decreased and averaged 11,800. The Commercial Fisheries Division of ADF&G has set a desired escapement goal of 40,000 and a minimum of 20,000 (Barrett *et al.* 1990). Since 1970, the commercial harvest ranged from a maximum of 19,463 in 1981 to a low of two in 1992 (Table 1). Commercial harvest records were not available during 1970-1974, 1977, and 1989. The mean historic harvest estimate for this system is 2,551, but in the last three years harvests have declined significantly, averaging only 120. Chapman (1986) indicates that a fishing exploitation rate of approximately 60% is optimum for Alaska sockeye salmon stocks. In contrast, the average exploitation rate of the Laura Lake sockeye run is only 15%. Finally, since 1981 the subsistence harvest averaged 131 sockeye. The peak subsistence harvest of 207 occurred in 1989, but decreased ~50% to 118 in 1992. Thus, escapement and harvest estimates indicate that total returns to this system have been cyclic and in recent years declining.

Fishpass Performance -- As with other Kodiak Island sockeye stocks, stream spawners comprise the early portion of the run. Spawning surveys at Gretchen Creek revealed that the number of sockeye spawners in this creek compared to the total escapement varied from 90.4% (1980) to 7.1% (1982), which may indicate variable use of the fishpass at the barrier falls (Table 2). This is further illustrated by the variable proportion of spawners above (52-84%) and below (16-48%) the fishpass. It is known that at high escapements in nearby Waterfall Creek, pink salmon migrate further upstream with increased usage of the fishpass (Honnold 1990). This trend may also occur with sockeye salmon at Gretchen Creek as evidenced in 1980 and 1981 when escapements were higher and a larger proportion of spawners (83.7% and 73.4%, respectively) occurred above the

Table 1. Adult sockeye salmon escapement, commercial harvest, and total return for Paul's and Portage lakes, 1968-1992.

	Escapement		Harvest		Total Return	
Year	**Portage**	**Paul's**	**Portage**	**Paul's**	**Portage**	**Paul's**
1968	282	nd	nd	nd	nd	nd
1969	1,000	12,000	nd	nd	nd	nd
1970	8,000	4,000	0	0	8,000	4,000
1971	0	8,000	0	0	0	8,000
1972	13,000	7,500	0	0	13,000	7,500
1973	4,000	12,000	0	0	4,000	12,000
1974	600	10,500	0	0	600	10,500
1975	10,480	17,000	16	26	10,496	17,026
1976	10,000	20,000	140	280	10,140	20,280
1977	24,948	6,650	0	0	24,948	6,650
1978	3,200	20,043	854	5,346	4,054	25,389
1979	15,400	8,415	8,083	4,417	23,483	12,832
1980	4,200	50,933	54	660	4,254	51,653
1981	11,822	21,806	10,552	19,463	22,374	41,269
1982	17,926	18,574	11,246	11,652	29,172	30,226
1983	3,600	20,625	771	4,415	4,371	25,040
1984	3,000	32,659	502	5,463	3,502	38,122
1985	6,400	14,941	628	1,467	7,028	16,408
1986	0	5,402	0	3,281	0	8,683
1987	1,000	13,122	34	442	1,034	13,564
1988	0	22,794	0	1,388	0	24,182
1989	850	12,605	0	0	850	12,605
1990	3,670	14,510	88	347	3,758	14,857
1991	5,466	3,237	22	13	5,488	3,250
1992	6,045	8,033	2	2	6,047	8,035
Mean	**6,196**	**15,225**	**1,434**	**2,551**	**8,113**	**17,916**

nd indicates no data
0 indicates none observed

Table 2. Peak live counts and sockeye escapement estimates derived from surveys above and below the fish pass (FP) at Gretchen Creek, 1960-1991.

	Live Count					Escapement	
Date	Above FP	Percent	Below FP	Percent	Total	Gretchen Creek	Total
??/??/60	nd	nd	nd	nd	3,500	7,000	nd
09/11/76	479	52.3	437	47.7	916	1,832	20,000
08/18/80	19,300	83.7	3,770	16.3	23,070	46,140	50,993
08/25/81	1,850	73.4	670	26.6	2,520	5,040	21,806
08/31/82	394	59.5	268	40.5	662	1,324	18,574
08/28/91	566	66.1	290	33.9	856	1,712	3,237

nd indicates no data

fishpass. Since the majority of useable spawning habitat occurs in the upper reaches of Gretchen Creek, the fishpass is essential for sustaining the Laura Lake sockeye run. The Gretchen Creek fishpass has a grade of 25% (Honnold 1990); however, Blackett (1987) reported that $\leq$ 22% grade is optimum for sockeye passage, as evidenced by the successful Frazer Lake fish pass. In addition, the Frazer fish pass utilizes a diversion weir to lead salmon to the fishpass entrance, preventing sockeye from congregating below the falls. These modifications may be necessary for the Gretchen Creek fishpass to improve passage of adult salmon.

Adult Age Composition -- During 1990-1991, sockeye returns to the Laura Lake system were comprised primarily of six-year old fish (Table 3). Specifically, 32.6% were age-2.3 and 7.6% were age-1.4. Four-year old fish were the next dominant age class (31.9%) with 15.4% age-1.2 and 16.5% age-2.1. Five-year old fish comprised 23% of the return with 16.4% age-1.3 and 6.6% age-2.2. Very few (4.3%) three-year old (age-1.1) fish returned. In contrast, the dominant age class of the 1955-1957 returns was age-1.2 (60.5%).

Spawning Area Estimate -- Gretchen Creek has a usable spawning area of 15,765 m^2 and Paul's Creek has an additional 4,786 m^2, for a total spawning area of 20,552 m^2 (Appendix Table 2). Based on an optimum spawning density of 1 female per 2.0 m^2 (Burgner *et al.* 1969), Gretchen Creek could support 7,883 females, and Paul's Creek could support 2,393 females. The desired escapement at a 50:50 sex ratio would equate to 15,765 for Gretchen Creek and 4,786 for Paul's Creek, for a system total of 20,552 stream spawners. In addition, the useable lakeshore spawning area in Laura and Paul's lakes was estimated to be 4,900 m^2 and 1,000 m^2, respectively. This equates to 2,950 females or a total of 5,900 lakeshore spawners. Gretchen Lake spawning area was not assessed since spawners have not been observed utilizing lakeshore habitat and therefore is assumed to be negligible. Based on the combined usable tributary and lake-shore spawning areas the total area is capable of supporting an estimated 26,500 sockeye. Thus, the desired escapement goal of 40,000 is high compared to the number of spawners the system can support.

Table 3. Percent age composition of Paul's Bay sockeye escapement samples, 1955-1957 and 1990-1991.

Year	Sample size (n)	Age Class 1.1	1.2	2.1	1.3	2.2	1.4	2.3	2.4	3.3
1955	58	12.1	72.4	13.8	0.0	0.0	0.0	1.7	0.0	0.0
1956	87	2.3	78.2	1.1	4.6	13.8	0.0	0.0	0.0	0.0
1957	230	27.8	30.9	2.2	27.8	8.3	0.0	3.0	0.0	0.0
Mean		**14.1**	**60.5**	**5.7**	**10.8**	**7.4**	**0.0**	**1.6**	**0.0**	**0.0**
1990	423	0.5	23.6	0.2	32.4	10.6	0.9	31.0	0.5	0.2
1991	457	8.1	7.2	32.8	0.4	2.6	14.2	34.1	0.4	0.0
Mean		**4.3**	**15.4**	**16.5**	**16.4**	**6.6**	**7.6**	**32.6**	**0.5**	**0.1**

Note: 1990 sample data unavailable; sample age composition applied to total escapement.

Juvenile Population Estimates, Distribution, and Size -- The hydroacoustic survey conducted 27 August 1991 in Laura Lake revealed a total fish population estimate of 1,111,551 ± 377,237 (Table 4). The population for the northern-most basin of Laura Lake, represented by area A (Figure 3), was an estimated ~420,000 compared to 336,000 and 356,000 in areas B and C, respectively. The 02 October 1992 survey revealed a somewhat higher population estimate of 1,783,451 ± 389,651 (Table 5). Of the total population, ~1,000,000 fish were distributed in area B compared to 123,000 and 339,000 in areas A and C, respectively. For both surveys, the largest proportion of fish were distributed in the top depth intervals, indicating near-surface orientation at night and limited deep rearing, in potentially sub-optimal temperatures (Tables 6 and 7).

On 11 October 1991, 83 sockeye salmon juveniles were caught in the townet which represented 15.3% of the total catch, thus the juvenile sockeye population for the 1991 survey was an estimated 169,830 ± 57,683. (Table 8). The remainder (84.7%) of the catch comprised 459 stickleback (Appendix Table 3). Of the juvenile salmon collected, 68.4% were age-0 and 31.6% were age-1 fingerlings (Table 9). The mean weight, length, and condition coefficient (K) of age-0 fish was 1.6 g, 52.8 mm, and 1.07 K. respectively; whereas, age-1 sockeye averaged 2.8 g, 63.7 mm, and 1.05. In comparison, 78 juvenile sockeye were caught during the 03 October 1992 townet survey representing 10% of the total catch which equates to a sockeye population estimate of 178,000 ± 38,707. The remainder of this catch (90%) comprised 702 sticklebacks (Appendix Table 4). Of the sockeye captured, 81.2% were age-0, 17.4% were age-1, and 1.4% were age-2 fingerlings. Age-0 sockeye averaged 1.8 g in weight, 53.3 mm in length, and had a condition coefficient 1.14. Age-1 sockeye averaged 3.2 g, 66..6 mm, and had a K value of 1.07. Finally, age-2 sockeye averaged 3.9 g, 71 mm, and had a K value of 1.09.

Smolt Size and Age Composition -- A total of 3,016 sockeye smolts were captured in Paul's Creek during 10-12 June 1992. Of the 253 smolt sampled, 74.7% were age-1 and 25.3% were age-2 (Table 10). Age-1 smolts were relatively small averaging 69.9 mm in length and 2.6 g in weight, while the age-2 smolts averaged 76.3 mm and 3.3 g. The

Table 4. Densities and poulation estimates of juvenile fish rearing in Laura Lake by transect from the 27 August 1991 hydroacoustic survey.

Transect	Mean density (no./1000 m^2)	Area (x1000 m^2) Transect	Total	Weighted density (no./1000 m^2)	Variance	Population	Variance
1	308	882					
2	199	749	1,631	258	2.94E+03	420,256	7.80E+09
3	223	1,088					
4	218	423	1,511	222	7.03E+00	335,694	1.60E+07
5	146	611					
6	421	633	1,244	286	1.89E+04	355,602	2.90E+10
Total			**4,386**			**1,111,551**	**3.70E+10**

95% confidence limits = 377, 237

Table 5. Densities and poulation estimates of juvenile fish rearing in Laura Lake by transect from the 02 October 1992. hydroacoustic survey.

Transect	Mean density (no./1000 m^2)	Area (x1000 m^2) Transect	Area (x1000 m^2) Total	Weighted density (no./1000 m^2)	Variance	Population	Variance
1	275	758					
2	582	369	1,127	376	2.08E+04	423,160	2.60E+10
3	514	1,417					
4	413	709	2,126	481	2.30E+03	1,021,660	1.00E+10
5	399	607					
6	285	339	946	358	2.97E+03	338,631	2.70E+09
Total			**4,199**			**1,783,451**	3.95E+10

95% confidence limits = 389,651

Table 6. Density of fish (no./m^3) by depth and one-third sections along the 6 hydroacoustic transects on Laura Lake, 27 August 1991.

		Depth Interval (m)							
Transect	**Section**	**2-4**	**4-8**	**8-13**	**13-18**	**18-27**	**27-36**	**36-45**	**45-54**
	SW	19.6	23.3	6.2	0.0	0.0	0.0	0.0	0.0
1	M	54.0	29.5	14.0	1.9	0.0	0.0	0.0	0.0
	NE	70.0	57.7	16.0	0.6	0.0	0.0	0.0	0.0
	S	19.3	11.0	5.7	1.1	0.1	0.2	0.0	0.0
2	M	14.0	16.5	15.1	6.2	0.6	0.7	0.0	0.0
	N	15.7	23.6	19.2	6.9	1.2	0.3	0.1	0.0
	NE	26.4	16.7	18.8	4.6	0.5	0.0	0.0	0.0
3	M	38.8	12.0	18.1	4.1	1.2	1.6	0.1	0.0
	SW	38.4	12.0	4.9	2.7	0.4	0.0	0.0	0.0
	SW	18.1	19.6	5.5	13.0	2.0	0.4	0.2	0.0
4	M	18.1	6.0	3.4	13.5	1.4	1.0	0.6	0.0
	NE	24.8	4.7	14.9	15.8	1.1	1.7	0.0	0.0
	NE	31.6	6.3	4.3	0.5	0.0	0.0	0.0	0.0
5	M	50.1	12.5	6.4	1.5	0.0	0.0	0.0	0.5
	SW	19.4	9.7	9.6	2.0	0.0	0.0	0.0	0.0
	SW	84.7	60.8	8.5	2.5	1.9	0.0	0.0	0.0
6	M	169.3	21.2	9.7	4.1	1.9	0.0	0.0	0.0
	NE	63.5	26.5	4.8	2.5	0.0	0.0	0.0	0.0
Total		775.8	369.6	185.1	83.5	12.3	5.9	1.0	0.5
Percent		**54.1**	**25.8**	**12.9**	**5.8**	**0.9**	**0.4**	**0.1**	**0.0**

SW = southwest, M = middle, NE = northeast, S = south, and N = north

Table 7. Density of fish (no./m^3) by depth and one-third sections along the 6 hydroacoustic transects on Laura Lake, 02 October 1992.

		Depth Interval (m)							
Transect	**Section**	**2-4**	**4-8**	**8-13**	**13-18**	**18-27**	**27-36**	**36-45**	**45-54**
	SW	51.4	23.1	2.9	7.6	4.9	0.0	0.0	0.0
1	M	66.9	12.9	7.6	9.2	5.2	0.0	0.0	0.0
	NE	30.6	20.4	2.3	11.9	0.3	0.0	0.0	0.0
	W	94.8	36.9	2.4	0.8	0.0	0.0	0.0	0.0
2	M	231.7	50.0	3.6	3.3	7.8	0.0	0.0	0.0
	E	168.5	63.2	4.8	2.5	0.0	0.0	0.0	0.0
	SW	33.2	53.9	29.7	7.3	4.7	0.0	0.0	0.0
3	M	52.5	58.8	18.3	3.9	3.4	0.1	0.0	0.0
	NE	65.0	50.8	23.5	2.9	3.1	0.0	0.0	0.0
	E	116.1	42.9	10.7	3.4	2.8	0.0	0.0	0.0
4	M	55.3	60.8	18.3	8.1	2.6	0.0	0.0	0.0
	W	5.4	23.1	9.3	4.2	0.5	0.0	0.0	0.0
	SW	41.9	40.2	14.4	9.2	3.7	0.0	0.0	0.0
5	M	34.9	62.9	15.2	0.0	0.0	0.0	0.0	0.5
	NE	38.7	44.2	25.2	3.9	0.0	0.0	0.0	0.0
	NE	104.8	40.7	6.7	0.0	0.0	0.0	0.0	0.0
6	M	46.6	20.4	5.3	9.0	2.4	0.0	0.0	0.0
	SW	11.3	36.6	2.6	0.0	0.0	0.0	0.0	0.0
Total		1249.6	741.8	202.8	87.2	41.4	0.1	0.0	0.5
Percent		**53.8**	**31.9**	**8.7**	**3.7**	**1.8**	**0.0**	**0.0**	**0.0**

SW = southwest, M = middle, NE = northeast, E = east, and W = west

Table 8. Total fish population and juvenile sockeye salmon estimates from townet surveys, 11 October 1991 and 03 October 1992 at Laura Lake.

Date	Number of tows	Duration of tows (min)	Sockeye Catch			Total Population		Sockeye Population	
			number	CPUE	Percent	number (x 10^6)	95% C. I. (x 10^6)	number	95% C. I.
11-Oct-91	5	58	83	1.43	15.3	1.11	0.38	169,830	57,683
03-Oct-92	6	69	78	1.13	10.0	1.78	0.39	178,000	38,707

CPUE = catch per unit effort
C. I. = confidence interval

Table 9. Age, size, and condition coefficient of juvenile sockeye salmon collected by townetting 11 October 1991 and 03 October 1992 in Laura Lake.

Sample date	Number sampled	Age	% Age	Mean weight (g)	Mean length (mm)	Condition coefficient (K)
11-Oct-91	39	0	68.4	1.6	52.8	1.07
	18	1	31.6	2.8	63.7	1.05
03-Oct-92	56	0	81.2	1.8	53.3	1.14
	12	1	17.4	3.2	66.6	1.07
	1	2	1.4	3.9	71.1	1.09

Table 10. Summary of smolt trapping data collected from 1953-1957 and number, age, size, and condition coefficient of sockeye salmon smolts collected in the fyke trap in Paul's Creek, 10-12 June 1992.

Year	Number	Age	% Age	Weight (g)	Length (mm)	Condition coefficient (K)
1953	1,238	1	100.0	nd	132.5	na
	0	2	0.0	na	na	na
	0	3	0.0	na	na	na
1954	8,702	1	82.5	nd	nd	nd
	1,842	2	17.5	nd	nd	nd
	0	3	0.0	na	na	na
1955	936	1	31.5	nd	nd	nd
	1,853	2	62.3	nd	nd	nd
	184	3	6.2	nd	nd	nd
1956	nd	1	86.1	nd	nd	nd
	nd	2	3.0	nd	nd	nd
	nd	3	10.9	nd	nd	nd
1957	226	1	69.8	nd	nd	nd
	66	2	20.4	nd	nd	nd
	32	3	9.9	nd	nd	nd
1992	189	1	74.7	2.6	69.9	0.75
	64	2	25.3	3.3	76.3	0.75
	0	3	0.0	na	na	na

nd = no data, na = not available

Source: Stockley (unpublished field notes, 1953) condition coefficient for both age-1 and age-2 smolts was 0.75 K. The size of Laura Lake smolts (age-1) are near threshold size (60 mm; 2 g) and may indicate rearing limitation (Koenings and Burkett 1987). Specifically, the current forage base (zooplankton) may not be sufficient to produce larger smolts (4-5 g) capable of greater marine survival (Koenings *et al.* 1993). However, it has been documented that Afognak Island sockeye smolt are generally smaller than other Kodiak Island systems (White *et al.* 1990). The peak smolt migration occurred in the second week of June as evidenced by the high catch-per-unit effort (287 fish hr^{-1}) during fyke trapping (Appendix Table 5). Stockley (unpublished field notes, 1953) also reported that smolt migration at Laura Lake occurred from mid-May to early July and peaked in mid-June.

Limnological Assessment

Light Penetration -- During 1990-1992, the euphotic zone depth (EZD) in Laura Lake ranged from 7.1-14.6 m and averaged 10.0 m (Table 11). Thus, the euphotic volume (EV) is an estimated 42 x 10^6 m^3 (EV x surface area) or 42 EV units, and comprised ~83% of the total volume. Secchi disk (SD) transparency ranged from 3.3 to 5.3 m, and averaged 4.4 m. The mean EZD/SD ratio equalled 2.2 which is consistent for other Alaska clearwater lakes (Koenings and Edmundson 1991).

Temperature and Dissolved Oxygen -- In Laura Lake, a thermocline usually formed in June and persisted well into September (Figure 6). The lake heats as a homogenous unit to a depth of ~12 m, and surface temperatures reached as high as 15° C in July and August. The depth of the thermocline or mixing depth was within the photic zone. For most of the season, dissolved oxygen (DO) concentrations ranged between 10-12 mg L^{-1} (90 - >100% saturation) at all depths; however, in mid-August 1992 and September 1990, DO concentrations fell to as low as 6.0 mg L^{-1} (46% saturation) and 8.0 mg L^{-1} (85%), respectively, near the bottom of the lake (~30 m). These concentrations are not unusual considering the high surface temperatures in July (15° C), and the formation of a stable thermocline. These DO levels are well within limits acceptable for salmonids (Davies *et al.* 1979).

Table 11. Euphotic zone depth (EZD), Secchi disk (SD) transparency, and EZD/SD ratio by sample date in Laura Lake, 1990-1992.

Date	EZD (m)	SD transparency (m)	EZD/SD
05/14/90	8.1	5.3	1.5
07/12/90	10.7	4.8	2.2
09/17/90	9.6	4.8	2.0
Mean	**9.5**	**4.9**	**1.9**
05/17/91	10.4	3.3	3.2
06/12/91	10.3	4.8	2.1
08/01/91	14.6	5.3	2.8
09/19/91	11.1	3.3	3.4
11/06/91	7.2	3.8	1.9
Mean	**10.7**	**4.1**	**2.6**
05/22/92	11.6	3.8	3.1
06/24/92	8.3	5	1.7
08/17/92	7.1	4.3	1.7
09/30/92	11.1	nd	--
Mean	**9.5**	**4.3**	**2.2**

nd = no data

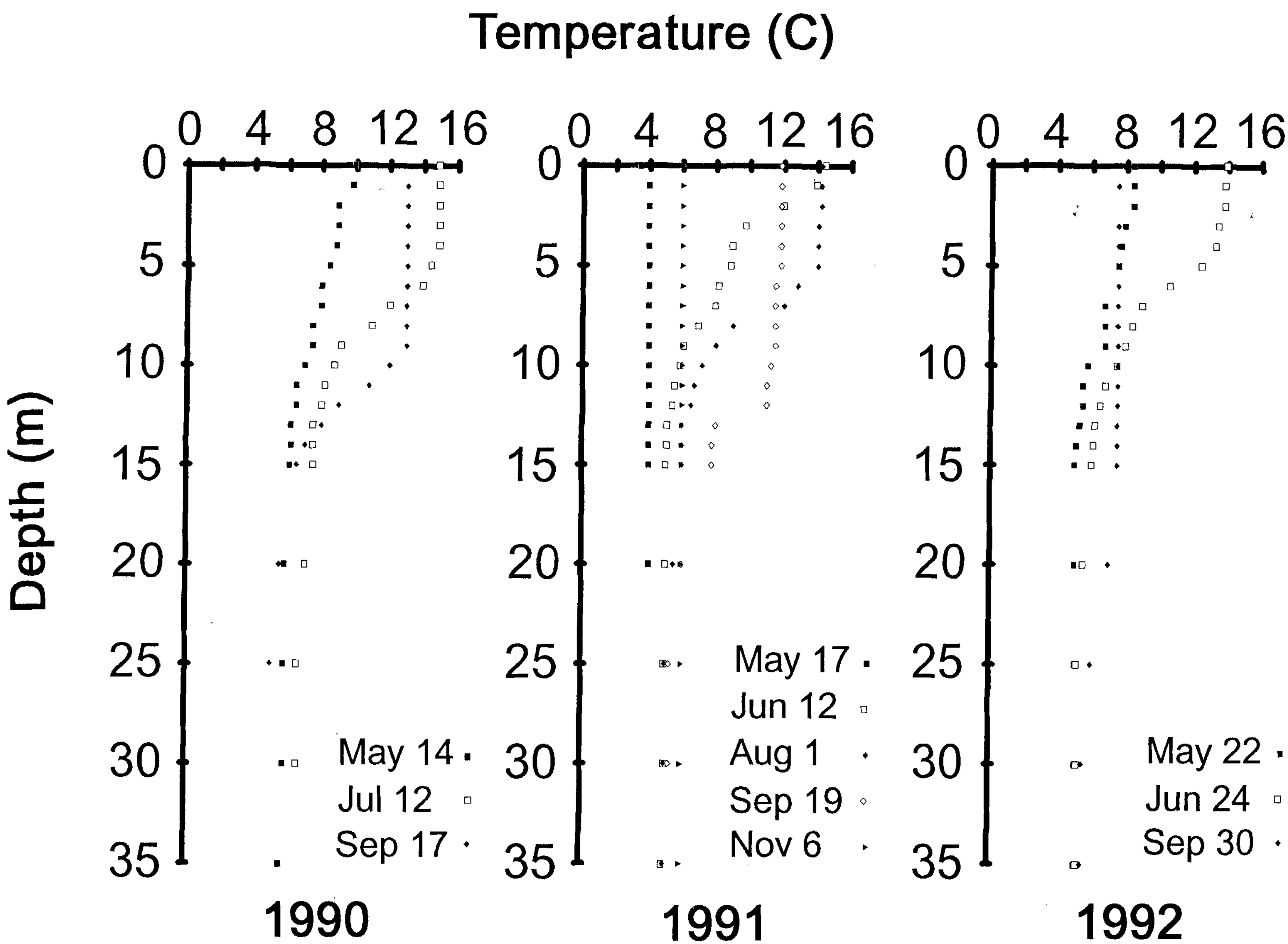

Figure 6. Seasonal temperature profiles in Laura Lake, 1990-1992.

General Water Quality -- Laura Lake is a relatively soft-water system as evidenced by conductivities ranging between 60 and 76 μmhos cm^{-1} and an averaged of 68 μmhos cm^{-1} (Table 12). The pH varied between 6.2 and 7.2 units, and alkalinity ranged between 6 and 14 mg L^{-1} (as $CaCO_3$), which indicates a very low inorganic carbon reserve (Wetzel 1975). Turbidity levels ranged from 0.3 to 1.4 NTU and color averaged 16.5 Pt units, which characterizes Laura Lake as a clearwater system, but at times may exhibit a slight stain (Koenings and Edmundson 1991). Calcium and magnesium concentrations ranged from 2.6-7.1 and 0.1-2.3 mg L^{-1} respectively, and are within the general range for Alaska lakes. Iron levels ranged from 37-126 μg L^{-1}, and averaged 65 μg L^{-1}, which is slightly above concentrations (< 20 μg L^{-1}) considered typical for clearwater lakes under chemical equilibria (Stumm and Lee 1960).

Nutrients -- Inorganic nitrogen levels within the epilimnion (1 m) of Laura Lake were very low (Table 12). For example, nitrate + nitrite levels averaged 7 μg L^{-1} and were highest in the spring (~25 μg L^{-1}), but decreased to below the limit of analytical detection (<3 μg L^{-1}) during the summer. In contrast, hypolimnetic concentrations of nitrate + nitrite remained relatively consistent throughout the growing season and averaged 29 μg L^{-1}. This is a typical cycle in many lakes as inorganic nitrogen within the surface layers is assimilated by increased phytoplankton growth (Hutchinson 1957). Similarly, total ammonia levels were lower in the epilimnion compared to the hypolimnion averaging 7 and 12 μg L^{1}, respectively. Hypolimnetic concentrations of ammonia were highest in July and August reaching ~25 μg L^{-1} and were attributed to excretion by spawners and decaying salmon. Total Kjeldahl nitrogen levels exhibited little variation within a season or by depth and averaged 95 μg L^{-1}, which indicates relatively low algal biomass (Wetzel 1975).

Phosphorus (P) is most often the nutrient limiting primary production (Vollenweider 1976; Schindler 1978; Smith 1979) and has been tied to fish yield through food-chain linkages (Forester 1968; Hansen and Leggett 1982). Total phosphorus (TP) concentrations within the epilimnion of Laura Lake ranged from 3.0-10.7 μg L^{-1} and averaged 4.7 μg L^{-1}, indicating a highly oligotrophic condition (Table 12). Based on a

Table 12. General water-quality parameters, metals, nutrient concentrations, and algal pigments within the 1-m stratum (epilimnion) and hypolimnion of Laura Lake, 1990-1992.

Date	Depth (m)	Specific conductance (umhos/cm)	pH (Units)	Alkalinity (mg/L)	Turbidity (NTU)	Color (Pt units)	Calcium (mg/L)	Magnesium (mg/L)	Iron (ug/L)	Total-P (ug/L P)	Total filter-able-P (ug/L P)	Filterable reactive-P (ug/L P)	Total Kjel-dahl nitrogen (ug/L N)	Ammonia (ug/L N)	Nitrate+ nitrite (ug/L N)	N:P atom ratio	Reactive silicon (ug/L Si)	Chloro-phyll a (ug/L)	Phaeo-phytin a (ug/L)
05/14/90	1	74	6.9	11.0	0.6	17	2.6	1.5	82	3.0	2.4	1.9	114.4	5.5	14.5	95	1790	0.48	0.29
05/14/90	30	74	6.9	12.0	0.6	15	3.5	2.3	88	2.1	2.1	1.7	93.7	7.0	25.2	125	1869	0.30	0.16
07/12/90	1	71	7.2	10.0	1.0	13	7.1	<0.3	48	4.8	2.2	1.7	126.0	4.2	<4.0	62	1964	0.64	0.40
07/12/90	30	74	6.8	10.5	0.4	18	6.2	<0.3	60	2.0	5.1	3.1	103.9	12.7	29.5	148	2128	0.29	0.22
09/17/90	1	71	6.9	12.0	0.5	13	3.6	1.4	40	3.9	2.6	1.3	134.8	4.0	<4.0	76	1754	1.27	0.42
09/17/90	27	76	6.6	12.0	0.3	13	4.6	1.4	40	2.8	1.6	1.4	106.7	14.7	35.9	113	1953	0.21	0.22
05/17/91	1	71	6.9	14.0	0.6	23	3.8	0.9	104	4.4	2.0	1.3	78.0	8.8	28.3	53	1880	0.88	0.27
05/17/91	25	71	6.8	12.0	0.6	20	4.0	1.5	106	4.3	2.4	1.5	65.7	6.8	28.3	48	1880	1.01	0.24
06/12/91	1	68	7.0	11.5	0.5	18	3.8	1.7	74	3.9	2.1	1.5	67.2	6.8	<4.0	39	1741	0.60	0.26
06/12/91	35	69	6.8	11.0	0.6	22	3.8	1.7	74	4.0	2.6	1.3	71.8	15.0	26.2	54	1814	0.31	0.25
08/01/91	1	68	7.0	8.0	0.6	15	3.7	1.5	37	4.3	1.7	1.4	71.8	9.9	<4.0	39	1627	0.56	0.36
08/01/91	35	72	6.6	8.0	0.4	15	4.7	1.5	51	4.7	2.7	2.1	74.4	25.8	31.9	50	1888	0.14	0.15
09/19/91	1	67	7.0	12.0	1.4	14	3.9	<0.3	46	3.1	4.8	3.2	71.3	8.8	<4.0	54	1513	1.09	0.40
09/19/91	35	70	6.7	12.0	1.0	14	3.9	0.8	42	3.3	2.9	1.4	75.9	16.1	33.5	73	1765	0.30	0.20
11/06/91	1	70	7.0	12.0	1.2	18	4.0	1.4	126	4.6	3.6	2.2	124.5	15.5	17.9	69	1720	0.81	0.30
11/06/91	30	70	7.0	12.0	0.5	33	4.0	1.4	72	3.6	7.1	6.6	126.9	14.5	17.9	89	1776	NA	NA
05/22/92	1	62	6.7	9.0	0.7	14	3.7	1.7	78	4.2	1.8	1.8	98.6	7.0	12.3	58	1961	0.97	0.41
05/22/92	35	63	6.4	9.5	0.6	15	3.7	1.7	90	3.8	1.7	1.7	88.6	8.0	23.1	65	1961	0.80	0.45
06/24/92	1	60	7.0	9.0	0.4	19	3.6	1.5	56	10.7	5.4	4.5	106.2	8.0	NA	--	1762	0.21	0.31
06/24/92	35	63	6.6	10.0	0.4	14	3.6	1.5	68	8.6	2.5	2.3	117.7	5.6	24.6	37	1951	0.50	0.37
08/17/92	1	61	6.5	6.0	0.5	12	4.7	1.3	40	4.8	4.4	4.0	110.9	3.2	NA	--	1515	0.92	0.48
08/17/92	34	65	6.2	11.0	0.7	14	4.7	0.7	37	7.9	2.5	2.0	89.4	11.8	37.0	35	1943	0.14	0.21
09/30/92	1	60	6.8	11.0	0.3	15	4.2	0.5	51	4.2	3.2	3.3	85.6	3.2	7.7	49	1590	0.23	0.24
09/30/92	36	64	6.4	10.0	1.0	12	3.3	1.8	38	4.0	2.2	1.7	71.8	10.4	38.5	61	1964	NA	NA

NA = not available

three year average of spring TP levels (3.9 μg L^{-1}) , the surface-specific loading rate is an estimated 82 mg P m^{-2} yr^{-1}, the critical loading rate is 210 mg P m^{-2} yr^{-1}, and the permissible supplemental loading rate is 107 mg P m^{-2} yr^{-1}. Thus, given a surface area of 4.2 km^2, the amount of permissible loading would equate to 449 kg P yr^{-1}. Total filterable (TFP) and filterable reactive phosphorus (FRP) exhibited little variation within a season or by depth averaging 3.0 and 2.3 μg L^{-1}, respectively. FRP or soluble orthophosphate is the fraction of TP considered readily available for algal uptake and it comprised ~33% of TP. Finally, reactive silicon concentrations varied from a low of 1,513 μg L^{-1} to a high of 2,128 μg L^{-1}, and averaged 1,800 μg L^{-1} which is typical of other Alaskan sockeye lakes.

Not only is the amount of nitrogen (N) and phosphorus (P) important to lake productivity, but so are their relative ratios. Specifically, optimal production of favorable green algae and diatoms occurs at a N:P ratio of ~16:1 (Schindler 1978; Smith 1982). In Laura Lake, nutrient ratios within the epilimnion during the open-water period ranged from 23:1 to 95:1 and averaged 55:1, indicating that phosphorus is indeed the primary nutrient limiting phytoplankton production (Table 12).

Phytoplankton -- Chlorophyll *a* (chl *a*) levels, an index of algal biomass, within the epilimnion were nearly twice that of the hypolimnion averaging 0.72 and 0.40 μg L^{-1}, respectively (Table 12). Maximum seasonal concentrations occurred in September of 1990 and 1991, but chl *a* concentrations in 1992 were highest in the spring. Both spring and fall phytoplankton blooms are a common pattern in the seasonal cycle of phytoplankton biomass (Marshall and Peters 1989). Chl *a* concentrations in Laura Lake are considered low, but within the range established for other oligotrophic clearwater lakes of Alaska (Koenings and Edmundson 1991).

Zooplankton Abundance, Size, and Biomass -- The macrozooplankton community of Laura Lake comprises three species of cladocerans and three species of copepods (Table 13). The cladocerans accounted for ~85% of the total macrozooplankton (TMZ) densities and were represented by *Daphnia longiremis*, *Holopedium gibberum*, and *Bosmina*

Table 13. Macrozooplankton densities (number/m^2) and body sizes (mm) by taxa in Laura Lake, 1990-1992.

Date	Bosmina		Daphnia		Holopedium		Cyclops		Diaptomus		Ergasilus		TOTAL
05/14/90	1,178	0.30	796	0.56	96	NA	30,207	0.72	P	NA	P	NA	32,277
07/12/90	22,160	0.31	7,962	0.53	1,858	0.48	7,298	1.06	P	NA	P	NA	39,278
09/17/90	60,111	0.30	21,895	0.49	5,706	0.52	1,194	0.62	P	NA	531	0.58	89,437
Mean	**27,816**	**0.30**	**10,218**	**0.50**	**2,553**	**0.51**	**12,900**	**0.78**	--	--	**177**	**0.58**	**53,664**
05/07/91	239	0.30	1,162	0.58	P	NA	2,691	0.72	P	NA	16	0.92	4,108
06/12/91	3,981	0.33	1,990	0.63	1,327	0.53	29,459	0.93	398	NA	P	NA	37,155
08/01/91	13,800	0.32	7,856	0.51	849	0.51	2,229	1.00	P	0.54	212	0.53	24,946
09/19/91	201,168	0.30	36,093	0.55	10,085	0.49	531	0.76	P	NA	P	0.58	247,877
11/06/91	16,083	0.35	24,363	0.58	398	NA	4,697	0.73	P	NA	P	NA	45,541
Mean	**47,054**	**0.31**	**14,293**	**0.56**	**2,532**	**0.50**	**7,921**	**0.89**	**80**	**0.54**	**46**	**0.56**	**71,925**
05/22/92	908	0.35	1,815	0.52	P	NA	2,468	0.63	P	NA	P	NA	5,191
06/24/92	20,807	0.35	4,352	0.62	955	0.51	10,934	0.97	P	NA	212	NA	37,260
08/17/92	80,255	0.33	17,197	0.54	4,883	0.45	4,034	0.97	P	NA	212	NA	106,581
09/30/92	33,439	0.33	12,314	0.57	1,274	0.52	1,062	0.62	P	NA	212	NA	48,301
Mean	**33,852**	**0.33**	**8,920**	**0.56**	**1,778**	**0.47**	**4,624**	**0.91**	--	--	**159**	--	**49,334**

P = present
NA = not available

longirostris. Whereas, the copepods comprised ~15% and consisted of *Cyclops columbianus*, *Diaptomus pribilofensis*, and *Egrasilus* sp. The seasonal mean total macrozooplankton (TMZ) densities (number m^{-2}) during 1990-1992 averaged 53,600 m^{-2}, 71,900 m^{-2}, and 49,300 m^{-2}, respectively.

The cladocerans were dominated by *Bosmina* which appeared in May and peaked during mid-August to mid-September (Table 13). On a seasonal basis, *Bosmina* populations accounted for ~62% of the TMZ density and averaged 28,800 m^{-2}, 47,050 m^{-2}, and 33,800 m^{-2} during 1990-1992, respectively. Overall, *Bosmina* body sizes averaged 0.31 mm, which is considerably smaller than the minimum threshold size (0.40 mm) for elective feeding by sockeye salmon fry (Koenings and McDaniel 1983; Kyle *et al.* 1988), and suggests excessive foraging by rearing juvenile sockeye. *Daphnia* were the next most numerically dominant cladoceran species followed by *Holopedium* with seasonal mean densities and corresponding body sizes ranging from 8,900-14,300 m^{-2} (0.50-0.56 mm) and 1,800-2,600 m^{-2} (0.47-0.47 mm), respectively. Like *Bosmina*, both *Daphnia* and *Holopedium* populations reached maximum densities during August-September. Of the copepods, *Cyclops* accounted for 24% of the TMZ densities during 1990-1992 averaging 12,900 m^{-2}, 7,900 m^{-2}, and 8,900 m^{-2}, respectively. In contrast to the cladocerans, *Cyclops* densities were highest during May-June and lowest in September. Overall, *Egrasilus* populations were much less abundant and averaged 127 m^{-2}; and *Diaptomus* appeared on only one occasion (June 1991) and in very low numbers (400 m^{-2}). The average body sizes of *Cyclops* and *Egrasilus* were 0.86 and 0.57 mm, respectively. *Diaptomus* were not present in sufficient numbers for measuring purposes.

On a seasonal basis, the TMZ biomass was consistently low, averaging 67, 86, and 62 mg m^{-2}, respectively during 1990-1992 (Table 14). As a group, the cladocerans accounted for ~70% of the TMZ biomass. In particular, *Bosmina* comprised 44% of the biomass, whereas *Daphnia* and *Holopedium* comprised 19% and 7%, respectively. Of the copepods, *Cyclops* comprised 29% of the biomass and both *Egrasilus* and *Diaptomus* each accounted for <1% . The TMZ biomass levels in Laura Lake ranked 21 out of 26 sockeye nursery lakes recently surveyed in the Kodiak area (Table 15).

Table 14. Seasonal mean macrozooplankton biomass (mg/m^2) and percent composition for each taxa in Laura Lake, 1990-1992.

Taxa/Year	1990	1991	1992
Bosmina	23.0	39.0	33.0
	34%	45%	53%
Daphnia	11.0	19.0	12.0
	16%	22%	19%
Holopedium	6.0	5.0	3.0
	9%	6%	5%
Cyclops	27.0	22.0	13.0
	40%	26%	21%
Diaptomus	0.0	0.0	0.0
	0%	0%	0%
Ergasilus	0.2	0.0	0.0
	3%	0%	0%
TOTAL	**67.2**	**86.0**	**62.0**

Table 15. Comparison of total mean weighted macrozooplankton biomass (mg/m^2) for a variety of sockeye nursery lakes in the Kodiak area.

Lake	Rank	Survey Years	Biomass
Red	1	1990-1992	1333
Karluk	2	1980-1992	1085
Jennifer	3	1990	1054
Spiridon	4	1987-1992	1046
Little River	5	1990-1991	865
Upper Station	6	1990-1992	790
Summit	7	1990	697
Hidden	8	1987-1992	529
Crescent	9	1987-1992	401
Horse Marine	10	1992	334
Frazer	11	1987-1992	271
Dry Spruce	12	1991	256
Mush	13	1991	254
Red Fox	14	1990-1992	248
Waterfall	15	1990, 1992	216
Afognak	16	1987-1992	185
Uganik	17	1990-1991	162
Barabra	18	1990-1991	153
Akalura	19	1990-1992	150
Malina	20	1990-1992	126
Laura	**21**	**1990-1992**	**70**
Buskin	22	1990	64
Little Afognak	23	1991-1992	30
Little Kitoi	24	1990-1992	30
Portage	25	1990-1992	30
Goat	26	1991	<1

EVALUATION

Potential Sockeye Salmon Production -- Assuming a 50% fall fry-to-smolt survival and a 20% smolt-to-adult survival, juvenile sockeye population estimates of 170,000 and 178,000 for 1991 and 1992 (Table 8), respectively would be expected to produce approximately 17,000 returning adults. This return size would indicate an increase compared to current returns; however, the estimated spawning capacity (26,500) would be underutilized. Using a 50:50 sex ratio and a fecundity of 2,500 eggs/female, potential egg deposition (PED) would be estimated to be 37 million. Assuming a PED-to-emergent fry survival of from 4% (Drucker 1970) to 10% (Forester 1968; Koenings *et al.* 1987), the predicted fry recruitment would range from 1.5 to 3.7 million juvenile sockeye.

In comparison, Koenings and Burkett (1987) derived a significant relationship between euphotic volume (EV) and sockeye salmon production. Specifically, under rearing limitation maximum fish densities were estimated to be 110,000 fry per EV unit which would produce 23,000 threshold-sized (60 mm; 2.2 g) age-1 smolts. The optimal density of 54,000 fry per EV unit yields fewer, but larger sized smolts (4-5 g) capable of greater marine survival. Given that Laura Lake has 42 EV units, the optimal model predicts that this system can produce 2.3 million fry (42 EV units x 54,000 fry/EV unit) which is consistent with predicted juvenile recruitment (1.5-3.7 million) based on spawning area. If Paul's Lake is included, an additional 0.4 to 0.8 million fry could be supported. Thus, the Laura Lake system could support 2.7 million juvenile sockeye salmon. Further, assuming a 21% spring fry-to-smolt survival, the EV model predicts Laura Lake could produce ~567,000 age-1 smolts. Finally, using a 20% smolt-to-adult survival for optimal sized smolts (Koenings *et al.* 1991), 113,000 adult sockeye salmon would be predicted to return. Run strength in recent years reveals significantly lower returns. Thus, it appears Laura Lake is currently either recruitment (escapement) or forage limited.

A significant relationship has been derived between sockeye smolt biomass and zooplankton biomass, specifically: smolt biomass (kg km^{-2}) = 2.1 x TMZ biomass

(Kyle *et al.* 1993). Given a combined averaged TMZ biomass estimate of 71 mg m^{-2} for Laura Lake, this model would predict a total of 629 kg of smolt which yields 286,000 threshold-sized (2.2 g) smolts or ~140,000 optimal sized (4-5 g) smolts. Using a smolt-to-adult survivorship of 12% for threshold-sized smolts (Koenings and Burkett 1987) and 21% for optimal sized smolts equates to a total return of ~30,000 adult sockeye in both cases. This return approximates the average returns during the mid-1980's, but is ~30% of potential production based on EV (i.e., 113,000). Thus, it appears that sockeye production in Laura Lake is limited by a very low forage base (zooplankton biomass). A technique that has proven effective in increasing a lake's capacity to produce forage is through nutrient enrichment (LeBrassuer 1978; Stockner and Hyatt 1984; Olsson *et al.* 1992; Kyle *et al.* 1993). That is, supplemental nutrient loading (fertilization) can increase primary (phytoplankton) and secondary (zooplankton) production resulting in greater smolt numbers (and sizes) and leading to higher adult returns.

RECOMMENDATIONS

The existing forage base in Laura Lake is not sufficient to support the potential sockeye production based on a fully utilizing spawning area (or euphotic volume). Therefore, we recommend fertilizing Laura Lake in order to increase the amount of forage available for rearing sockeye juveniles. To achieve the desired nutrient levels and maintain optimal N:P ratios for favorable algal growth, we recommend for the first year the application of 22 tons of 20-5-0 (20% nitrogen; 5% P_2O_5) liquid fertilizer to the lake surface. Fertilization should commence in late May to early June and continue through August for a period of ~12 weeks. Approximately 1.9 tons or 350 gal of the product should be applied once per week evenly over the surface of the lake. We also recommend continuing hydroacoustic/townet surveys and qualitative smolt sampling to determine population estimates, sizes, and ages of juvenile sockeye salmon. In addition, limnological sampling should be conducted every three weeks in order to monitor changes in nutrient levels and productivity and to evaluate the effects of lake fertilization. Furthermore, based on available spawning area, the desired escapement goal should not exceed 30,000. Given that current escapements are well below the desired goal, supplemental fry stocking could be conducted in conjunction with lake fertilization. Stocking levels should be determined annually based on the 15 July cumulative escapement. That is, fry stocking will replace decreased production as a result of escapement levels below optimum numbers. Egg take goals, based on 1991 and 1992 escapements, would be approximately 2.4 to 3.0 million eggs (Appendix Table 6).

The Gretchen Creek fishpass should be expanded and improved. Initially, water diversion work and season monitoring during low flow should be expanded to bi-monthly evaluations during July and August. In addition, a diversion weir should be constructed at the base of the barrier falls to direct salmon into the fishpass entrance. Stream surveys should be expanded to determine utilization of upstream spawning area and to determine what changes, if any, are necessary. Finally, fishpass doors should be left in place until sockeye smolt migration is complete (end of June) to eliminate de-scaling and mortality that may occur when smolt wash down the fishpass section.

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REFERENCES

American Public Health Association (AHPA), American Water Works Association and Water Pollution Control Federation. 1985. Standard methods for the examination of water and wastewater. 16th ed. New York, N.Y. 1268 p.

Anonymous. 1979. Water resources atlas. U.S. Forest Service-Region 10. Juneau Alaska. 7 p.

Bagenal, T. B. [ed]. 1978. Methods for assessment of fish production in fresh waters. Third edit., IBP Handbook No. 3, Blackwell Scientific Publ. Ltd. 365 p.

Barrett, B. M., F. M. Thompson, and S. W. Wick. 1984. Adult anadromous fish investigations: May - October, 1984. Report for the Alaska Power Authority. Alaska Department of Fish and Game, Susitna Hydro Aquatic Stocks. Report No. 6. Anchorage, AK.

Barrett, B. M., C. O. Swanton, and P. A. Roche. 1990. An estimate of the 1989 Kodiak management area salmon catch, escapement, and run number had there been a normal fishery without the Exxon Valdez oil spill. Ak. Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K90-35.

Blackett, R. F. 1987. Development and performance of an Alaska steeppass fishway for sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences. Volume 44, No. 1. p. 66-76.

Brooks, J. L. 1957. The systematics of North American *Daphnia*. Mem. Conn. Acad. Arts Sci. 13:1-180.

Burczynski J. J. and R. L. Johnson. 1986. Application of dual-beam acoustic survey techniques to limnetic populations of juvenile sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 43:1776-1788.

Burgner , R. L., C. J. DiCostanzo, R. J. Ellis, G. Y. Harry, Jr., W. L. Hartman, O. E. Kerns, Jr., O. A. Mathisen, and W. F. Royce. 1969. Biological studies and estimates of optimum escapements of sockeye salmon in the major river systems in southwestern Alaska. U. S. Fish. Wild. Serv., Fish Bull. 67(2):405-459.

Chambers, J. S., G. H. Allen, R. T. Presley. 1955. Research relating to the study of spawning grounds in natural areas. *In* W. R. Meehan [ed.] Influence of forest and rangeland management on anadromous fish habitat in the Western United States and Canada. USDA Forest Service. General Technical Report PNW-96.

Chapman, D. W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. American Fisheries Society 115:662-670.

Crowther, J., B. Wright, and W. Wright. 1980. Semi-automated determination of total phosphorus and total Kjeldahl nitrogen in surface waters. Anal. Chem. Acta. 119:313-321.

Davies, J. C., G. I. Bresnick, P. Doudoroff, T.R. Doyle, A. J. Mearns, J. B. Pearce, J. J. Peterka, J. G. Robinson, and D. L. Swanson. 1979. Dissolved oxygen. 169-174. *In* A Review of the EPA Redbook: Quality criteria for water. R. V. Thurston, R. C. Russo, C. M. Felleroff, Jr., T. A. Edsall, and Y. M. Barber, Jr. [eds.] Water Quality Section, American Fisheries Society, Bethesda, MD.

Drucker, B. 1970. Red salmon studies at Karluk Lake, 1968. U. S. Bur. Comm. Fish., Auke Bay Biol. Lab., Admin. Rep. 55 p.

Dugdale, R. C. and V. A. Dugdale. 1961. Sources of phosphorus and nitrogen for lakes on Afognak Island. Limnol. Oceanogr. 6:13-23.

Eggers, D. M. 1978. Limnetic feeding behavior of juvenile sockeye salmon in Lake Washington and predator avoidance. Limnol. Oceanogr. 23:43-53.

Eisenreich, S. J., R. T. Bannerman, and D. E. Armstrong. 1975. A simplified phosphorus analysis technique. Environ. Letters 9:43-53.

Forester, R. E. 1968. The sockeye salmon (*Oncorhynchus nerka*). Fish. Res. Bd. Can. Bull. 162:422 p.

Gjernes, T. 1979. A portable midwater trawling system for use in remote lakes. Dept. Fish and Oceans Tech. Rep. Ser. 10 p.

Golterman, H. L. 1969. Methods for chemical analysis of freshwater. IBP Handbook 8. Blackwell Scientific Publications, Oxford. 166 p.

Hansen, J. M. and W. C. Leggett. 1982. Empirical predictions of fish biomass and yield. Can. J. Fish. Aquat. Sci. 39:257-263.

Honnold, S. G. 1990. Assessment and evaluation of the performance of fish passes located on Afognak Island. Unpublished report. Ak. Department of Fish and Game, Kodiak, Alaska.

Honnold, S. G. 1993. Summary of hydroacoustic and townetting surveys conducted at Red, Akalura and Upper Station Lakes in response to the 1989 Exxon Valdez oil spill 1990 - 1992. AK Dept. of Fish and Game, FRED Division report. In review.

Hutchinson, G. E. 1957. A Treatise on Limnology: Vol. I. Geography, Physics and Chemistry. John Wiley and Sons, New York 1015 p.

Koenings, J. P. and R. D. Burkett. 1987. The production patterns of sockeye salmon (*Oncorhynchus nerka*) smolts relative to temperature regimes, euphotic volume, fry density, and forage base within Alaskan Lakes. *In* H. D. Smith, L. Margolis, and C. C. Woods [eds.] Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish Aqaut. Sci. 96 p.

Koenings, J. P. and J. A. Edmundson. 1991. Secchi disk and photometer estimates of light regimes in Alaskan lakes: effects of yellow color and turbidity. Limnol. Oceanogr. 46:91-105.

Koenings, J. P. and J. McDaniel. 1983. Monsoon and Dickey: Two phosphorus-rich brown-water lakes with little evidence of vertebrate predation pressure on the zooplankton community. Ak. Department of Fish and Game, FRED Division Report Series 21:p.

Koenings, J. P., J. A. Edmundson, G. B. Kyle, and J. M. Edmundson. 1987. Limnology field and laboratory manual: Methods for assessing aquatic production. Ak. Department of Fish and Game, FRED Division Report Series 71:212 p.

Koenings, J. P., G. B. Kyle and J. A. Edmundson. 1988. Density-dependent environmental influences on sockeye salmon (*Oncorhynchus nerka*) fry recruitment and smolt production in Tustumena Lake, Alaska. Unpublished report. Ak. Department of Fish and Game. Soldotna, Alaska.

Koenings, J. P., H. Geiger, and J. Hasbrouck. 1993. Smolt-to-adult survival patterns of sockeye salmon: effects of length and latitude after entering sea. Can. J. fish. Aquat. Sci. 48:xxx-xxx. In review.

Kyle, G. B. 1990. Summary of acoustically-derived population estimates and distributions of juvenile sockeye salmon (*Oncorhynchus nerka*) in 17 nursery lakes of southcentral Alaska, 1982-1987. Ak. Department of Fish and Game. FRED Division Report Series 104:47 p.

Kyle, G. B., J. P. Koenings, and B. M. Barrett. 1988. Density-dependent, trophic level responses to an introduced run of sockeye salmon (*Oncorhynchus nerka*) at Frazer Lake, Kodiak Island, Alaska. Can. J. Fish. Aquat. Sci. 45:856-867.

Kyle, G. B., J. P. Koenings, and J. A. Edmundson. 1993. An overview of Alaska lake-rearing salmon enhancement strategy: nutrient enrichment and juvenile stocking. *In* A. Milner and M. Oswood [eds.] Alaska Freshwaters. *In review*. Springer-Verlag. New York, NY.

LeBrasseur, R. J., C. D. McAllister, W. E. Barraclough, V. O. Kennedy, J. Manzer, D. Robinson and K. Stephens. 1978. Enhancement of sockeye salmon (*Oncorhynchus nerka*) by lake fertilization in Great Central Lake: summary report. J. Fish. Res. Board Can. 35:1580-1596.

Levy, D. A. 1987. Review of the ecological significance of diel vertical migrations by juvenile sockeye salmon (*Oncorhynchus nerka*). p. 44-52. *In* H. D. Smith, L. Margolis, and C. C. Wood [eds.] Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96 p.

Marshall, C. T. and R. H. Peters. 1989. General patterns in the seasonal development of chlorophyll *a* for temperate lakes. Limnol. Oceanogr. 34:856-867.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

McDonald, J. 1973. Diel vertical movements and feeding habits of underyearling sockeye salmon (*Oncorhynchus nerka*), at Babine Lake, B. C. Fish. Res. Bd. Can. Tech. Rep. No. 378. 55 p.

Narver, D. W. 1970. Diel vertical movements and feeding of underyearling sockeye salmon and the limnetic zooplankton in Babine Lake, British Columbia. J. Fish. Res. Bd. Canada 27:281-316.

Nunnallee, E. P. 1983. Scaling of an echo integrator using echo counts, and a comparison of acoustic and weir count estimates of a juvenile sockeye salmon population. FA Fish. Res. 300:261-268.

Olsson, H., P. Blomqvist, and H. Olofsson. 1992. Phytoplankton and zooplankton community structure after nutrient additions to the oligotrophic Lake Hecklan, Sweden. Hydrobiologia 243/244: 147-155.

Pennak, R. W. 1978. Fresh-water invertebrates of the United States, 2nd. edition. John Wiley and Sons. New York. 803 p.

Reimann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. Limnol. Oceanogr. 23:1059-1066.

Roelofs, Eugene W. 1964. Further studies of the Afognak Lake system. Alaska Department of Fish and Game. Information Leaflet No. 41. 18 p.

Schindler, D. W. 1971. Light, temperature, and oxygen regimes of selected lakes in the experimental lakes area, Northwestern Ontario. J. Fish. Res. Board Can. 28:157-169.

Schindler, D. W. 1978. Factors regulating phytoplankton production and standing crop in the worlds freshwaters. Limnol. Oceanogr. 24:478-486.

Simpson, K. L., L. Hop Wo, and I. Miki. 1981. Fish surveys of 15 sockeye salmon (*Oncorhynchus nerka*) nursery lakes in British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. No. 1022. 87 p.

Smith, V. H. 1979. Nutrient dependence of primary productivity in lakes. Limnol. Oceanogr. 24:1051-1066.

Smith, V. H. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: an empirical and theoretical analysis. Limnol. Oceanogr. 27:1101-1112.

Stainton, M. P., M. J. Capel, and F. A. J. Armstrong. 1977. The chemical analysis of fresh water, 2nd ed. Fish. Mar. Serv. Misc. Spec. Publ. 25:166 p.

Stockner, J. G. and K. D. Hyatt. 1984. Lake fertilization: state of the art after 7 years of application. Can. J. Fish. Aquat. Sci. 1323:33 p.

Strickland, J. D. H. and T. R. Parsons. 1972. A practical handbook of seawater analyses. Bull. Fish. Res. Board Can. 167:310 p.

Stumm, W. and G. F. Lee. 1960. The chemistry of aqueous iron. Scweizererische Zeitchrift fur Hydrologie revue Suisse d-Hydrologic. 22:295-319.

Vollenweider, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake entrophication. Mem. Ist. Ital. Idrobiol. 33:53-83.

Wetzel, R. G. 1975. Limnology. W. B. Saunders Co., Philadelphia. 743 p.

White, L. E. 1986. Karluk Lake sockeye investigations. AFS-52, Anad. Fish Cons. Act (PL 89-404). 65 p.

White, L. E., G. B. Kyle, J. P. Koenings, and S.G. Honnold. 1990. Limnological and fisheries assessment of sockeye salmon (*Oncorhynchus nerka*) production in Afognak Lake. Ak. Department of Fish and Game, FRED Division report. Number 103.

Wilson, M. S. 1959. Calanoida. p. 738-794. In: W. T. Edmondson [ed.], Freshwater biology, 2nd ed. John Wiley and Sons, New York.

Yeatman, H. C. 1959. Cyclopoida. p. 795-815. In: W. T. Edmondson [ed.], Freshwater biology, 2nd ed. John Wiley and Sons, New York.

Appendix Table 1. History of sockeye egg plants at Gretchen Creek, Afognak Island, 1951-1955.

Plant Year	Date	Number of eggs	Source	Number of eggs planted	Comments
1951	6-Aug	84,050	Portage Lake, SE tributary	84,050	green eggs planted
1951	16-Aug	33,621	Portage Lake, SE tributary	22,000	eyed at Port Williams
1951	30-Aug	107,000	Karluk Lake O'Malley Lake	106,000	eyed at Port Williams
1952	16-26 Aug	nd	Karluk Lake O'Malley Lake Portage Lake, SE tributary	352,000	eyed at Port Williams and Portage station
1953	3-Aug	554,000	Portage Lake, SE tributary	552,000	eyed at Portage station
1954	?	501,000	Portage Lake, SE tributary	488,000	eyed at Portage station
1955	?	nd	Portage Lake, SE tributary	320,000	eyed at Portage station

nd indicates no data

Appendix Table 2. Summary of spawning area parameters, calculations of useable spawning area, and sockeye spawning area capacity for surveys of Gretchen and Paul's creeks.

Length (m)	Width (m)	Useable Area (%)	Useable Area (m^2)	Spawning Capacity
27.4	3.7	60	60	60
43.6	9.1	100	399	399
28.7	7.6	90	196	196
76.2	6.1	80	372	372
70.1	6.1	75	321	321
139.6	6.1	65	553	553
82.3	7.6	65	408	408
58.5	6.1	40	143	143
38.1	4.6	30	52	52
59.7	3.0	10	18	18
Below Gretchen barrier totals:			**2,521**	**2,521**
74.1	4.3	20	63	63
76.5	6.1	75	350	350
61.6	7.6	80	375	375
24.7	6.1	70	105	105
33.8	6.1	75	155	155
52.1	7.6	70	278	278
32.6	6.1	70	139	139
17.7	7.6	75	101	101
36.9	9.1	40	135	135
61.0	7.6	65	302	302
118.3	9.1	80	865	865
115.5	7.6	80	704	704
52.7	7.6	60	241	241
55.5	9.1	80	406	406
120.1	6.1	75	549	549
89.3	7.6	50	340	340
66.8	4.6	70	214	214
66.1	6.1	70	282	282
78.0	6.1	80	381	381
59.4	6.1	65	236	236
82.3	4.6	60	226	226
142.6	6.1	60	522	522
133.8	7.6	40	408	408
135.3	7.6	50	516	516
73.2	6.1	60	268	268
90.2	4.6	40	165	165

continued

Appendix Table 2 (continued). Summary of spawning area parameters, calculations of useable spawning area, and sockeye spawning area capacity for surveys of Gretchen and Paul's creeks.

Length (m)	Width (m)	Useable Area (%)	Useable Area (m^2)	Spawning Capacity
130.1	3.7	35	167	167
140.8	4.6	70	451	451
76.2	3.7	80	223	223
106.7	4.6	90	439	439
82.3	3.7	80	241	241
123.4	4.6	90	508	508
98.8	4.6	90	406	406
62.2	3.7	95	216	216
146.3	4.6	90	602	602
86.0	3.7	70	220	220
130.8	4.3	70	391	391
229.8	4.6	20	210	210
149.4	4.6	25	171	171
148.1	3.7	35	190	190
199.3	6.1	40	486	486
Above Gretchen barrier totals:			**13,244**	**13,244**
9.1	6.1	40	22	22
45.7	7.6	40	139	139
41.1	9.1	40	151	151
57.9	10.7	40	247	247
21.3	9.1	40	78	78
24.4	10.7	40	104	104
48.8	13.7	40	268	268
79.2	10.7	40	338	338
91.4	12.2	40	446	446
32.0	13.7	40	176	176
80.8	9.1	40	295	295
91.4	13.7	40	502	502
61.0	7.6	40	186	186
21.3	22.9	40	195	195
109.7	10.7	40	468	468
79.2	15.2	40	483	483
42.7	15.2	40	260	260
30.5	0.0	40	0	0
12.2	9.1	40	45	45
89.9	10.7	40	384	384
Paul's Creek totals:			**4,786**	**4,786**
Gretchen Creek totals:			**15,765**	**15,765**
Laura system totals:			**20,552**	**20,552**

Appendix Table 3. Results of townet sampling in Laura Lake, 11 October 1991.

Tow	Time		Duration	Sockeye Catch			Stickleback Catch		
	Start	End	(min)	Number	Percent	CPUE	Number	Percent	CPUE
1	20:47	20:55	8	11	14.9	1.4	63	85.1	7.9
2	21:18	21:32	14	17	7.7	1.2	205	92.3	14.6
3	22:20	22:30	10	23	32.4	2.3	48	67.6	4.8
4	23:12	23:25	13	18	18.2	1.4	81	81.8	6.2
5	23:39	23:52	13	14	18.4	1.1	62	81.6	4.8
Total			**58**	**83**	**15.3**	**1.4**	**459**	**84.7**	**7.9**
Mean					**18.3**	**1.5**		**81.7**	**7.7**

CPUE = catch-per-unit- effort

Appendix Table 4. Results of townet sampling in Laura Lake, 03 October 1992.

Tow	Time		Duration	Sockeye Catch			Stickleback Catch		
	Start	End	(min)	Number	Percent	CPUE	Number	Percent	CPUE
1	21:11	21:24	13	2	7.4	0.2	25	92.6	1.9
2	21:38	21:50	12	15	5.8	1.3	245	94.2	20.4
3	22:17	22:30	13	26	15.4	2.0	143	84.6	11.0
4	23:01	23:13	12	15	8.0	1.3	173	92.0	14.4
5	23:38	23:45	7	2	18.2	0.3	9	81.8	1.3
6	00:11	00:24	12	18	14.4	1.5	107	85.6	8.9
Total			**69**	**78**	**10.0**	**1.1**	**702**	**90.0**	**10.2**
Mean					**11.5**	**1.1**		**88.5**	**9.7**

CPUE = catch-per-unit- effort

Appendix Table 5. Results of fyke trapping at Paul's Creek, 10-12 June 1992.

Sample date	Sample period	Total time (hr)	Sockeye		Coho		Other		
			smolt	CPUE	smolt	fry	Sculpin	Stickleback	Dolly Varden
10-Jun	23:45-02:45	4.0	1,313	328.3	208	378	1	1	1
11-Jun	22:00-01:30	3.5	1,093	312.3	106	53	0	0	0
12-Jun	22:00-01:00	3.0	610	203.3	146	38	2	0	1
	Total	**10.5**	**30,165**	**287.2**	**460**	**469**	**3**	**1**	**2**

CPUE = catch-per-unit-effort

Appendix Table 6. Estimation of sockeye fry recruitment based on escapements into Laura Lake.

Optimum Spawners Required	Fry Produced	Escapement Level	Fry Produced	Replacement Fry	Eggs Required	Females Required	Males Required	Total Adults
30,000	2,625,000	29,000	2,537,500	87,500	109,375	44	29	73
30,000	2,625,000	28,000	2,450,000	175,000	218,750	88	58	146
30,000	2,625,000	27,000	2,362,500	262,500	328,125	131	88	219
30,000	2,625,000	26,000	2,275,000	350,000	437,500	175	117	292
30,000	2,625,000	25,000	2,187,500	437,500	546,875	219	146	365
30,000	2,625,000	24,000	2,100,000	525,000	656,250	263	175	438
30,000	2,625,000	23,000	2,012,500	612,500	765,625	306	204	510
30,000	2,625,000	22,000	1,925,000	700,000	875,000	350	233	583
30,000	2,625,000	21,000	1,837,500	787,500	984,375	394	263	656
30,000	2,625,000	20,000	1,750,000	875,000	1,093,750	438	292	729
30,000	2,625,000	19,000	1,662,500	962,500	1,203,125	481	321	802
30,000	2,625,000	18,000	1,575,000	1,050,000	1,312,500	525	350	875
30,000	2,625,000	17,000	1,487,000	1,137,500	1,421,875	569	379	948
30,000	2,625,000	16,000	1,400,000	1,225,000	1,531,250	613	408	1,021
30,000	2,625,000	15,000	1,312,500	1,312,500	1,640,625	656	438	1,094
30,000	2,625,000	14,000	1,225,000	1,400,000	1,750,000	700	467	1,167
30,000	2,625,000	13,000	1,137,500	1,487,500	1,859,375	744	496	1,240
30,000	2,625,000	12,000	1,050,000	1,575,000	1,968,750	788	525	1,313
30,000	2,625,000	11,000	962,500	1,662,500	2,078,125	831	554	1,385
30,000	2,625,000	10,000	875,000	1,750,000	2,187,500	875	583	1,458
30,000	2,625,000	9,000	787,500	1,837,500	2,296,875	919	613	1,531
30,000	2,625,000	8,000	700,000	1,925,000	2,406,250	963	642	1,604
30,000	2,625,000	7,000	612,500	2,012,500	2,515,625	1,006	671	1,677
30,000	2,625,000	6,000	525,000	2,100,000	2,625,000	1,050	700	1,750
30,000	2,625,000	5,000	437,500	2,187,500	2,734,375	1,094	729	1,823
30,000	2,625,000	4,000	350,000	2,275,000	2,843,750	1,138	758	1,896
30,000	2,625,000	3,000	262,500	2,362,500	2,953,125	1,181	788	1,969
30,000	2,625,000	2,000	175,000	2,450,000	3,062,500	1,225	817	2,042
30,000	2,625,000	1,000	87,500	2,537,500	3,171,875	1,269	846	2,115
30,000	2,625,000	0	0	2,625,000	3,281,250	1,313	875	2,188

Assumptions:

1) spawners required to maximize spawning habitat.

2) escapement 50:50 sex ration and 2,500 fecundity.

3) 7% egg deposition to fry survival.

4) two males for every three females for egg takes.

5) 80% egg to fry survival for eggs collected.