# FRED Reports

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and Potential for Sockeye Salmon
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J. A. Edmundson, G. B. Kyle, and T. Balland

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April 1992

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**ABSTRACT**

Sockeye salmon (*Oncorhynchus nerka*) returns to the English Bay Lake system have declined in recent years prompting the closure of commercial fishing on this stock. Despite the closures, annual escapements into the English Bay Lakes were much lower than expected; and as a result, a fry stocking program was initiated in 1990. Because this system has a rapid flushing rate, primary and secondary production are very low. Stocking of juvenile sockeye fry above the capacity of the system to produce sufficient forage (zooplankton) could result in a complete collapse of the zooplankton community. Under existing forage conditions, the English Bay Lakes produces slightly above threshold sized age-1 smolts, indicating rearing conditions near capacity. In addition, the low densities and small sizes of zooplankton coupled with the small size of smolts suggest intense competition for food. Through balancing of juvenile recruitment (from both wild production and hatchery stocking) with the forage base, a sustainable level of smolt production, and ultimately, a consistent total return ranging between 15,000 and 20,000 adults can be achieved. As an alternative to fry stocking, a pre-smolt stocking project should be considered for this system as it would have minimum impact on the zooplankton community (relative to fry out-plants), yet produce a larger return of adults than the lake could produce naturally or from fry plants given the low freshwater productivity.

## INTRODUCTION

Historically, the English Bay Lakes were a significant producer of sockeye salmon in the Port Graham subdistrict of the Lower Cook Inlet commercial fishing management area. In recent years, sockeye salmon production in this system has declined; and as a result, commercial fishing closures were implemented in 1985 to increase escapements. Even with a reduction in commercial fishing, subsequent sockeye escapements into the English Bay Lake system did not increase, and still remain below historical levels. In order to increase production, a juvenile sockeye fry stocking program was initiated in 1990. Limnological studies initiated in 1988, indicated that the English Bay Lakes are nutrient poor (oligotrophic) and primary and secondary production was low. As zooplankton biomass is the primary forage for rearing sockeye juveniles, excessive fry stocking coupled with natural recruitment will result in intense planktivory (over-grazing) which further acts to reduce rearing efficiency for ensuing broods (Kyle et al. 1988; Koenings and Kyle 1991). Thus, juvenile sockeye growth and survival depends on balancing fry recruitment levels with sufficient quantity and quality of forage (zooplankton).

In general, lake productivity depends largely on an adequate nutrient supply (Vollenweider 1976; Schindler 1978; Smith 1979). For example, fish yield is related to nutrients through trophic level or food-web linkages (Foerster 1968; Brocksen et al. 1970; Hanson and Leggett 1982; Koenings et al. 1989). In sockeye nursery lakes, the decomposition of adult carcasses provides an important source of nutrients (Foerster 1968; Donaldson 1967) that are essential for algal growth. Over the past 30 years, annual escapements into the English Bay Lakes have varied widely; however, recent escapements (1985-1990) are only ~60% of the historical average. Thus, we surmise that the amount of nutrients from carcasses has been reduced from what it once was, and has further decreased fertility of the lakes in the English Bay watershed.

The amount of nitrogen and phosphorus entering the system (nutrient loading) is also a function of morphometry (Rawson 1953; Northcote and Larkin 1956; Sakamoto 1966; Oglesby 1977). In particular, because of dilution, large deep lakes are less susceptible to a buildup of nutrients compared to small shallow lakes. A fast flushing rate (short hydraulic residence time) tends to counteract nutrient loading as exemplified in the classic study of Cameron Lake (Dillon 1975), and can wash algal cells directly out of the system through the outlet, thereby lowering primary production (Uttormark and Hutchins 1985). The English Bay Lakes have a large drainage area to surface area ratio (90:1), which results in a very rapid flushing rate. Thus, these lakes are characteristic of a low productive system. This report examines sockeye salmon production in the English Bay Lakes and characterizes current productivity relative to the potential for enhancement.

**Study Site Description** -- The English Bay Lake system (59° 20' N, 151° 45' W) is a chain of five small lakes located ~40 km southwest of the City of Homer at an elevation of 12 m (Figure 1). Only the two larger lakes within the English Bay watershed were investigated. English Bay Lake 2 has a surface area of 0.70 x $10^6$ $m^2$ (150 acres), a mean lake depth of 10.9 m, a maximum depth of 25.9 m and a total volume of 7.6 x $10^6$ $m^3$ (Figure 2). English Bay Lake 3, which drains into lake 2, has a surface area of 0.72 x $10^6$ $m^2$ (166 acres), a mean lake depth of 14.7 m, a maximum depth of 29 m, and a total volume of 10.6 x $10^6$ $m^3$ (Figure 3). Mean annual precipitation is an estimated 300 cm (Anonymous 1979), and as the watershed area encompasses 63 $km^2$, the hydraulic residence time (the time it takes for the total volume of water to be replaced) is ~15 days for lake 2 and 35 days for lake 3. Total annual outflow of lake 2 is more than 20 times greater than its volume and the outflow of lake 3 is nearly 10 times its volume.

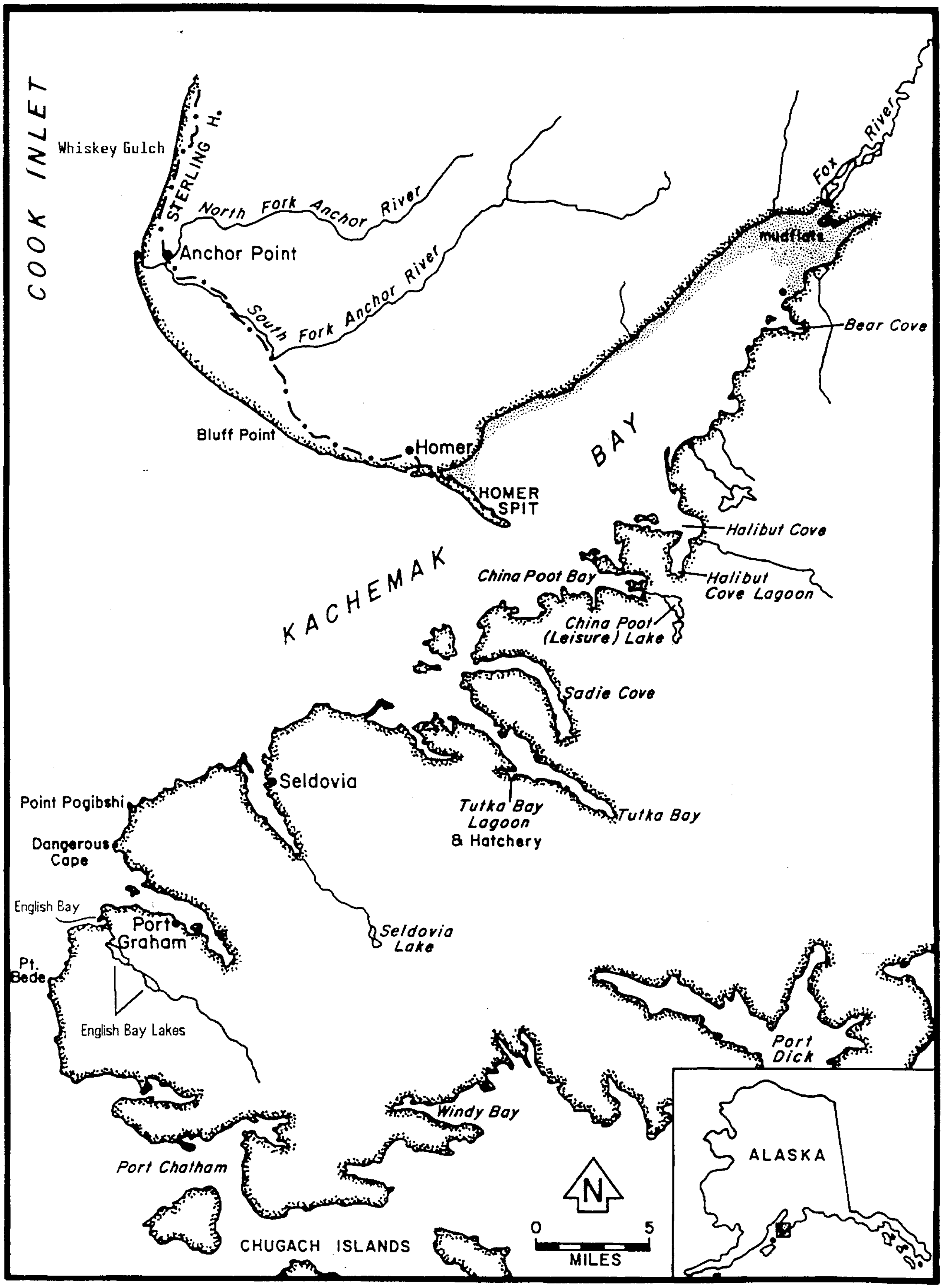


Figure 1. Geographic location of the English Bay Lakes in lower Cook Inlet.

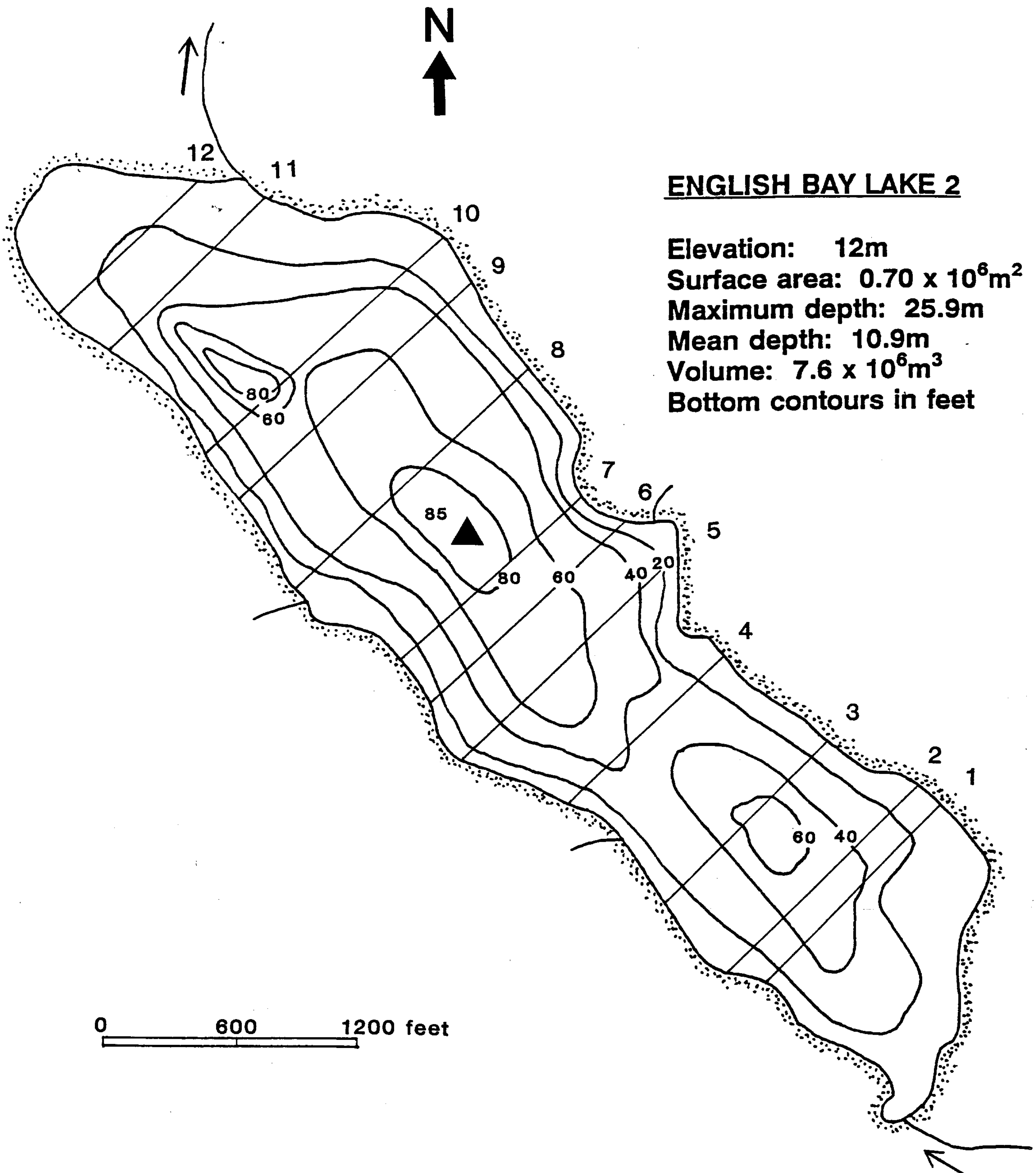


Figure 2. Morphometric map of English Bay Lake 2 showing the location of the limnological sampling station and the hydroacoustic survey transects.

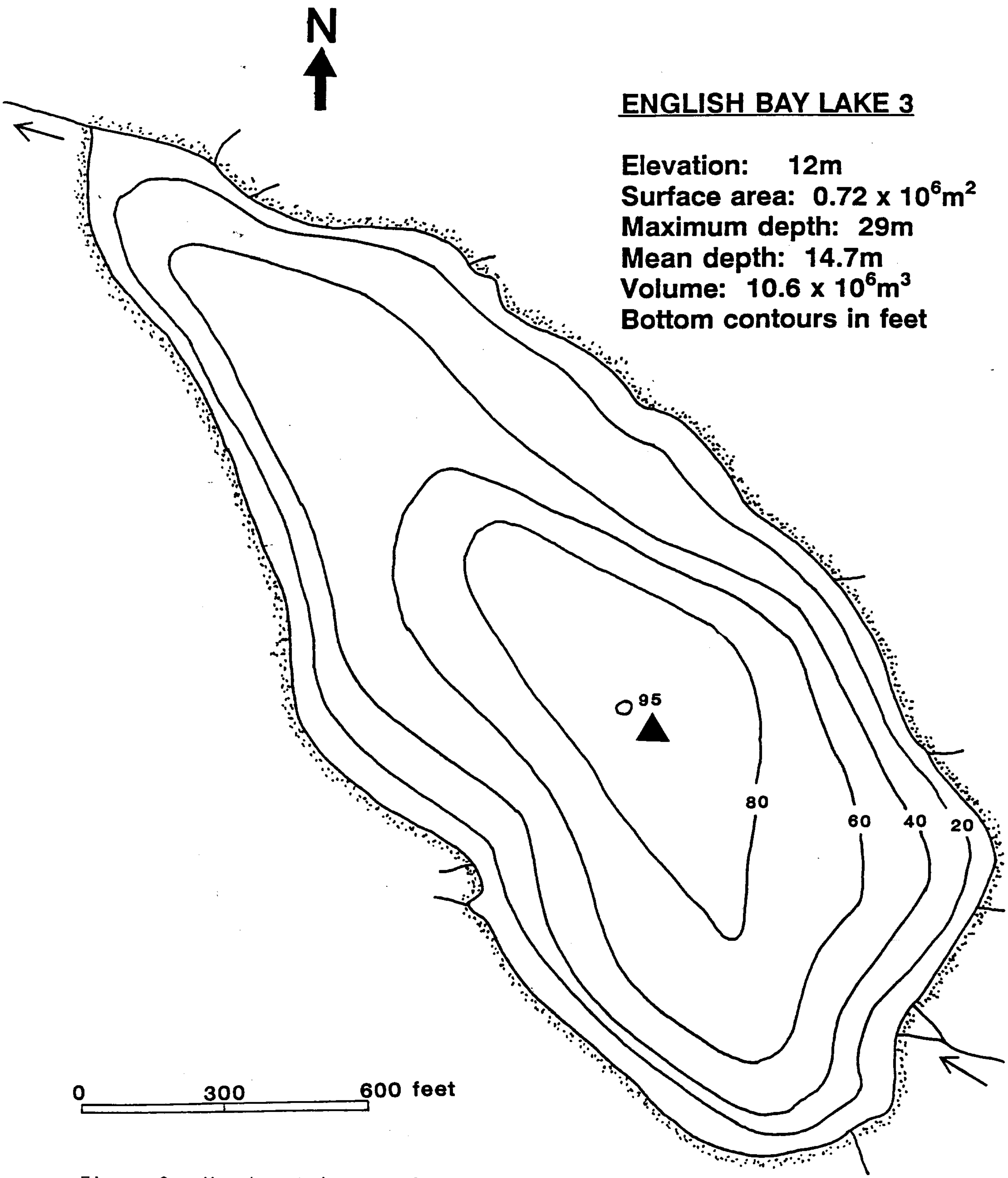


Figure 3. Morphometric map of English Bay Lake 3 showing the location of the limnological sampling station.

## METHODS AND MATERIALS

### Limnological Assessment

**Field Sampling** -- Limnological surveys were conducted at English Bay Lakes during 1988-1991. A single sampling station was located in the deepest part of each lake and sampled at approximately one month intervals from May to October. Water samples were collected from the 1-m stratum and the hypolimnion (~60% of the maximum depth) using a non-metallic, opaque Van Dorn sampler. Eight liters of water were collected from each depth, stored in pre-cleaned polyethylene carboys, transported to Homer, and pre-processed for laboratory analysis.

Temperatures were recorded from the surface to the bottom using a YSI® model-57 temperature/dissolved oxygen meter. Dissolved oxygen concentrations were recorded only at the sub-surface level using the above meter or were determined using the standard Winkler procedure (Koenings et al. 1987). Measurements of light penetration (footcandles) were taken with a Protomatic submarine photometer at 0.5-m intervals from the subsurface to a depth of 5 m, and at subsequent depths to the lake bottom or to the depth at which 1% of the subsurface light penetrated. The euphotic zone depth (EZD) or the depth at which 1% of the subsurface light remains (Schindler 1971), was calculated as the y-intercept derived by regressing the natural logarithm of the percent subsurface light. Secchi disk (SD) transparency was determined as the averaged reading derived from lowering and raising a standard 20 cm-diameter, black and white disk.

**General Water Quality** -- Conductivity (temperature compensated to 25°C) was measured (μmhos $cm^{-1}$) using a YSI-model 32 conductance meter, and the pH (units) was measured with an Orion 399A ionanalyzer. Alkalinity (mg $L^{-1}$ as $CaCo_3$) was determined by sulfuric acid (0.02N) titration to a pH of 4.5 (APHA

1985). Turbidity (nephelometric turbidity units or NTU) was determined using a DRT-100 turbidimeter, and color was determined on a filtered sample by measuring the spectrophotometric absorbance at 400 nm and converting to equivalent platinum cobalt (Pt) units (Koenings et al. 1987).

**Metals** -- Calcium and magnesium were determined from separate EDTA (0.01N) titrations after Golterman (1970). Total iron was determined by reduction of ferric iron with hydroxylamine acid during hydrochloric acid digestion (Strickland and Parsons 1972).

**Nutrients** -- Filterable reactive phosphorus or orthophosphate was determined using the molybdenum-blue method (Murphy and Riley 1972) as modified by Eisenreich et al. (1975). Total and total filterable phosphorus analyses utilized the same procedure following acid-persulfate digestion. Estimates of yearly phosphorus (P) loading in English Bay Lake 2 and 3 were calculated after Vollenweider (1976):

Surface specific loading (Lp):

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

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

$\bar{z}$ = mean depth (m)

$t_w$ = water resident time (y)

Total ammonia was determined using the phenylhypochlorite procedure; and nitrate + nitrite were determined as nitrite following cadmium reduction and diazotization with sulfanilamide after Stainton et al. (1977). Total Kjeldahl nitrogen was determined as ammonia after sulfuric acid block digestion (Crowther et al. 1980). Reactive silicon was determined using the ascorbic acid reduction to molybdenum blue methodology after Stainton et al. (1977).

**Phytoplankton** -- Samples for the analysis of the algal pigment chlorophyll a (chl a) were prepared by filtering 0.5 L of lake water through a Whatman 4.5-cm GFF glass-fiber filter to which 1-2 ml of 1 N magnesium carbonate were added prior to completion. Filters were stored frozen in individual plexiglas holders until analyzed. Chl a was extracted from glass-fiber filters after homogenizing the filters in 90% acetone. Chl a concentrations (corrected for inactive phaeophytin) were determined using the fluorometric procedure of Strickland and Parsons (1972) with a dilute acid (0.02N HCL) after Reimann (1978).

**Zooplankton** -- Replicate bottom-to-surface vertical zooplankton tows were taken using a 0.2-m diameter, 153-μm mesh, conical net. The net was pulled at a constant speed (~1 m $s^{-1}$), rinsed prior to removing the organisms, and all specimens were preserved in neutralized 10% formalin. *Daphnia* were identified according to Brooks (1957), *Bosmina* and *Holopedium* after Pennak (1978), and copepods were identified after Wilson (1959) and Yeatman (1959). Zooplankton were enumerated from three separate 1-ml subsamples taken with a Hensen-Stemple pipet and placed in a 1-ml Sedgewick-Rafter counting chamber. Zooplankton body sizes from 30 organisms of each taxa were measured to the nearest 0.01 mm along a transect in each of the 1-ml subsamples using a calibrated ocular micrometer. Zooplankter biomass was estimated from an empirical regression between body length and dry weight, and weighted by organism density (Koenings et al. 1987).

## Fish Assessment

**Sockeye Salmon Escapement** -- Adult sockeye salmon returning to the English Bay Lake system were enumerated by the Commercial Fisheries Division of the ADF&G. Estimated escapements were derived from either peak aerial counts or adjusted aerial counts based on conditions and time of surveys (Bucher and Hammarstrom 1992).

**Fry Stocking** -- In June of 1990, 355,000 hatchery-reared sockeye fry (0.3 g) from the Tutka Bay Hatchery were outplanted in English Bay Lake 3. In June of 1991, 155,000 hatchery fry averaging 0.2 g in weight were released in lake 3. In addition, in 1991 95,000 hatchery sockeye fry that were reared since June in a pen suspended in lake 2 were released in September. These fry averaged 72 mm and 4.7 g at the time of release.

**Hydroacoustic Survey** -- A single hydroacoustic survey was conducted in October of 1988 to estimate the population and distribution of rearing sockeye juveniles. Data were recorded at night along 12 randomly selected transects that were oriented perpendicular to the longitudinal axis of lake 2. The data were collected using a 420-Khz Biosonics 105 echo sounder and recorded in digital format on a Beta cassette recorder, and sent to BioSonics, Inc. for analysis.

**Smolt Sampling** -- Sockeye salmon smolts emigrating from the English Bay Lakes during 1991 were captured using a fyke net. A 15-m wide net with a 1.2 x 1.2 m opening connected to a live box was deployed at the outlet of lake 2. The net spanned ~67% of the width of the outlet and was fished intermittently from 25 May to 14 July 1991. Each day of operation, the trap was fished for a period of from 12 to 24 hours. The sampling program was designed to determine migration timing, and the size and age of emigrating smolts. The capture efficiency of the net was not determined and no estimate of the 1991 smolt outmigration was made. Each sampling day, 30-60 smolts were collected, anesthetized in MS-222, measured for length to the nearest millimeter, and weighed to the nearest 0.1 g. The overall mean length and weight was weighted by the number of smolts outmigrating. A scale smear was affixed to a glass slide and aged using a microfiche projector.

## RESULTS AND DISCUSSION

### Limnological Assessment

**Light Penetration --** English Bay Lakes 2 and 3 exhibited similar light penetration profiles. In general, during 1989-1991 the euphotic zone depth (EZD) was deepest in the spring and early summer and shallowest in the fall (Sept-Oct), as a result of increased precipitation and run-off. On a seasonal basis, the EZD ranged from 16.5-18.2 m in lake 2 and from 13.1- 21.2 m in lake 3 (Table 1). The EZD averaged 17.2 and 15.8 m in lakes 2 and 3, respectively, and the euphotic volumes (EV) are 7.1 x $10^6$ $m^3$ and 9.4 x $10^6$ $m^3$ or 7.1 and 9.4 EV units in lakes 2 and 3, respectively. Secchi disk (SD) transparency followed the same seasonal trends as the EZD, and averaged 7.0 m in lake 2 and 6.9 m in lake 3. The EZD:SD ratios equalled 2.5 and 2.3 for lake 2 and 3, respectively and are consistent with other clearwater Alaskan lakes (Koenings and Edmundson 1991).

**Temperature and Dissolved Oxygen--** Temperature profiles obtained during 1990 and 1991 were used to characterize the thermal structure of the English Bay Lakes. In general, temperatures were considerably warmer in 1990 compared to 1991. That is, in 1990 surface temperatures in both lakes reached nearly 12°C by early June, but were only 7°C at the same time in 1991. In addition, as both lakes are relatively shallow and subjected to frequent wind mixing, the lakes were only weakly stratified. For example, during the summer of 1990 surface temperatures in lake 2 reached 14°C, cooled rapidly between 10 and 15 m to 10°C, and then decreased to 9°C near the bottom. However, by early September the lake was isothermal at ~12°C. Lake 3 exhibited similar profiles except summer temperatures were slightly cooler compared to lake 2 i.e., decreasing from 12°C near the surface to 7°C at the bottom. The lower temperatures in lake 3 are attributed to its greater depth and smaller littoral zone. During 1990-1991, the dissolved oxygen

Table 1. Seasonal changes in euphotic zone depth (EZD) and Secchi disk (SD) depth in English Bay Lake 2 and 3, 1988-1991.

| | Lake 2 | | Lake 3 | |
|---|---|---|---|---|
| Date | EZD (m) | SD (m) | EZD (m) | SD (m) |
| 07/12/89 | 23.0 | 7.0 | 29.8 | 7.8 |
| 08/16/89 | 20.5 | 9.0 | 23.9 | 11.0 |
| 10/13/89 | 11.1 | 5.0 | 9.9 | 5.0 |
| Mean | 18.2 | 7.0 | 21.2 | 7.9 |
| 05/10/90 | 17.9 | 7.5 | 19.6 | 6.5 |
| 06/08/90 | 12.4 | 6.5 | 9.2 | 7.0 |
| 08/02/90 | 21.9 | 7.5 | 16.1 | 8.0 |
| 09/13/90 | 16.2 | 7.5 | 7.4 | 7.0 |
| Mean | 17.1 | 7.3 | 13.1 | 7.7 |
| 06/06/91 | 17.6 | 5.5 | 15.8 | 4.5 |
| 07/13/91 | 19.0 | 8.0 | 19.8 | 7.5 |
| 09/04/91 | 18.4 | 8.5 | 14.6 | 7.5 |
| 10/09/91 | 10.9 | 5.5 | 7.5 | 4.5 |
| Mean | 16.5 | 6.9 | 14.4 | 6.0 |

(DO) concentrations at the surface ranged from 11.0-13.4 mg $L^{-1}$ (90-115% saturation) in lake 2 and from 8.7-12.8 mg $L^{-1}$ (68-103% saturation) in lake 3.

**General Water Quality** -- General water quality parameters were quite similar in lakes 2 and 3, and exhibited little variation within season or by depth. For ease of comparison, the following analytical results are discussed in terms of seasonal mean values except where noted.

The English Bay Lakes are a moderately hard water system compared to other Alaskan coastal lakes. That is, conductivity, an index of dissolved solids, averaged 67 and 60 μmhos $cm^{-1}$ in lake 2 and 3 (Tables 2 and 3), respectively. Similarly, alkalinity showed little inter-lake variation and ranged from 14-18 mg $L^{-1}$, which indicates a low inorganic carbon supply (Wetzel 1975). In addition, the pH was slightly above neutral ranging from 7.0-7.4 units, and turbidity and color levels were characteristic of a clearwater system (Koenings and Edmundson 1991) and averaged 0.6 NTU and 8 Pt units, respectively.

**Metals** -- Calcium levels in both lakes are average compared to other Alaskan lakes and ranged from 6.3-8.1 mg $L^{-1}$, whereas magnesium concentrations ranging from 0.4-1.3 mg $L^{-1}$ fell slightly below the mean for other Alaskan lakes. In addition, iron concentrations in both lakes are considered typical for a clearwater system (Stumm and Lee 1960), and ranged from 11-46 μg $L^{-1}$ (Tables 2 and 3).

**Nutrient Levels** -- In many lakes, nitrate + nitrite (inorganic nitrogen) levels within the epilimnion decrease sharply during the summer as nitrogen reserves are assimilated by algal growth (Hutchinson 1957; Wetzel 1975; Cole 1979). In contrast, nitrate + nitrite concentrations within the English Bay Lakes remained very high throughout the growing season, ranging from 358-425 μg $L^{-1}$ in lake 2 (Table 2) and from 285-385 μg $L^{-1}$ in lake 3 (Table 3). Reserves of nitrate + nitrite were present throughout the summer in the hypolimnion of both lakes. In contrast, ammonia nitrogen levels were quite low and consistent with depth

Table 2. Range and seasonal mean values for general water quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) of English Bay Lake 2, 1988-1991.

| | | Sample year | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1988 (n = 3) | | 1989 (n = 3) | | 1990 (n = 4) | | 1991 (n = 4) | |
| Parameter | Depth | Range | Mean | Range | Mean | Range | Mean | Range | Mean |
| Conductivity (umhos/cm) | 1m | 57-66 | 62 | 65-75 | 71 | 52-72 | 63 | 64-74 | 71 |
| | hypo | 57-66 | 63 | 62-74 | 70 | 56-73 | 65 | 68-75 | 71 |
| pH (Units) | 1m | 7.1-7.2 | 7.2 | 7.0-7.3 | 7.1 | 7.1-8.0 | 7.4 | 6.9-7.2 | 7.1 |
| | hypo | 7.1-7.3 | 7.2 | 7.1-7.1 | 7.1 | 6.8-7.2 | 7 | 6.8-7.2 | 7 |
| Alkalinity (mg/L) | 1m | 14-16 | 15 | 16-17 | 17 | 14-18 | 17 | 17-19 | 18 |
| | hypo | 14-16 | 15 | 15-18 | 17 | 13-18 | 16 | 17-18 | 18 |
| Turbidity (NTU) | 1m | 0.3-0.5 | 0.4 | 0.6-0.6 | 0.4 | 0.3-1.6 | 0.7 | 0.5-0.8 | 0.6 |
| | hypo | 0.3-1.2 | 0.6 | 0.4-0.5 | 0.4 | 0.4-0.6 | 0.5 | 0.5-0.5 | 0.6 |
| Color (Pt Units) | 1m | 3-14 | 9 | 9-15 | 12 | 5-6 | 6 | 4-8 | 6 |
| | hypo | 3-10 | 7 | 9-14 | 11 | 5-14 | 10 | 3-8 | 6 |
| Calcium (mg/L) | 1m | 6.3-7.4 | 6.9 | 7.4-8.7 | 8.1 | 5.8-7.4 | 7 | 6.8-7.8 | 7.5 |
| | hypo | 6.3-6.3 | 6.3 | 7.4-8.3 | 7.8 | 6.3-7.4 | 6.8 | 6.8-7.9 | 7.5 |
| Magnesium (mg/L) | 1m | 0.7-0.8 | 0.8 | <0.2-1.5 | 0.6 | 0.6-0.8 | 0.7 | 0.5-1.5 | 1.3 |
| | hypo | 0.8-0.8 | 0.8 | 0.2-0.6 | 0.4 | 0.6-1.2 | 0.8 | 0.7-1.5 | 1.1 |
| Iron (ug/L) | 1m | 16-18 | 17 | <3-27 | 11 | 6-27 | 19 | <3-56 | 21 |
| | hypo | 25-30 | 28 | 3-39 | 21 | 18-33 | 24 | 9-15 | 28 |
| Total-P (ug/L) | 1m | 2.5-3.0 | 2.7 | 2.7-4.8 | 3.8 | 3.1-4.7 | 3.6 | 2.7-4.8 | 4 |
| | hypo | 3.2-3.9 | 3.5 | 3.4-7.7 | 5.5 | 2.5-4.3 | 3.5 | 4.4-6.7 | 5.6 |
| Total filterable-P (ug/L) | 1m | 1.4-2.8 | 2 | 1.8-2.7 | 2.2 | 2.2-2.7 | 2.3 | 1.8-4.1 | 2.5 |
| | hypo | 1.6-3.1 | 2.2 | 1.6-2.1 | 1.8 | 2.1-4.4 | 2.9 | 1.8-5.4 | 2.9 |
| Filterable reactive-P (ug/L) | 1m | 2.0-3.6 | 2.7 | 1.0-2.1 | 1.4 | 1.8-2.7 | 1.9 | 1.9-4.0 | 2.5 |
| | hypo | 2.0-2.5 | 2.2 | 0.9-1.4 | 1.2 | 1.8-4.6 | 2.5 | 2.2-5.3 | 3 |
| Total Kjeldahl-N (ug/L) | 1m | 59-71 | 64 | 102-109 | 106 | 49-77 | 66 | na | na |
| | hypo | 70-92 | 78 | 71-181 | 119 | 53-73 | 61 | na | na |
| Ammonia (ug/L) | 1m | 1.1-2.9 | 1.7 | 1.1-7.8 | 4.5 | 5.0-7.5 | 5.9 | 1.3-3.9 | 2.7 |
| | hypo | 1.7-2.3 | 2.1 | 2.7-4.3 | 3.6 | 4.4-8.1 | 5.5 | 1.9-7.4 | 3.9 |
| Nitrate+nitrite (ug/L) | 1m | 315-505 | 387 | 400-461 | 425 | 305-613 | 386 | 313-523 | 358 |
| | hypo | 316-505 | 406 | 406-498 | 438 | 305-622 | 471 | 317-537 | 413 |
| Reactive silicon (ug/L) | 1m | 2255-2596 | 2596 | 2122-2315 | 2221 | 2019-3747 | 2729 | 2091-2537 | 2290 |
| | hypo | 2360-2926 | 2638 | 2266-2284 | 2276 | 2062-3389 | 2496 | 2136-2537 | 2317 |
| Chlorophyll a (ug/L) | 1m | 0.30-0.65 | 0.46 | 0.38-0.68 | 0.55 | 0.18-0.39 | 0.31 | 0.17-1.03 | 0.58 |
| | hypo | 0.58-0.75 | 0.69 | 0.53-1.44 | 0.86 | 0.24-0.75 | 0.49 | 0.42-0.55 | 0.48 |
| Phaeophytin a (ug/L) | 1m | 0.29-0.50 | 0.34 | 0.27-0.36 | 0.3 | 0.04-0.35 | 0.18 | 0.10-0.66 | 0.42 |
| | hypo | 0.43-1.45 | 0.77 | 0.48-0.69 | 0.56 | 0.10-0.83 | 0.37 | 0.26-0.48 | 0.35 |

Table 3. Range and seasonal mean values for general water quality parameters, metals, nutrients and algal pigments within the 1-m stratum and hypolimnion (hypo) of English Bay Lake 3, 1988-1991.

| | | Sample year | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1988 (n = 2) | | 1989 (n = 3) | | 1990 (n = 3) | | 1991 (n = 3) | |
| Parameter | | Range | Mean | Range | Mean | Range | Mean | Range | Mean |
| Conductivity (umhos/cm) | 1m | 56-58 | 57 | 58-67 | 64 | 58-65 | 60 | 49-67 | 61 |
| | hypo | 58-58 | 58 | 57-66 | 63 | 35-58 | 54 | 52-65 | 61 |
| pH (Units) | 1m | 6.8-7.1 | 7 | 7.0-7.9 | 7.4 | 6.9-7.2 | 7.1 | 7.0-7.1 | 7.1 |
| | hypo | 6.9-7.9 | 7.4 | 7.0-7.5 | 7.2 | 7.0-7.2 | 7 | 6.8-7.1 | 7 |
| Alkalinity (mg/L) | 1m | 14-15 | 15 | 14-17 | 16 | 13-17 | 15 | 15-17 | 15 |
| | hypo | 13-15 | 14 | 13-16 | 14 | 11-15 | 14 | 13-16 | 15 |
| Turbidity (NTU) | 1m | 0.3-0.3 | 0.3 | 0.3-1.4 | 0.8 | 0.3-0.6 | 0.5 | 0.5-0.9 | 0.8 |
| | hypo | 0.4-0.4 | 0.4 | 0.4-2.4 | 1.2 | 0.4-1.0 | 0.6 | 0.4-0.8 | 0.6 |
| Color (Pt Units) | 1m | na | na | 9-15 | 12 | 5-5 | 5 | 4-8 | 6 |
| | hypo | 4-4 | 4 | 10-15 | 12 | 8-9 | 9 | 3-10 | 6.8 |
| Calcium (mg/L) | 1m | 6.3-6.3 | 6.3 | 6.9-7.2 | 7 | 5.8-6.4 | 6.3 | 6.6-6.9 | 6.7 |
| | hypo | na | na | 7.0-8.6 | 7.5 | 6.1-7.3 | 6.5 | 6.6-7.8 | 7 |
| Magnesium (mg/L) | 1m | 0.7-0.7 | 0.7 | 0.2-0.7 | 0.5 | 0.6-0.7 | 0.7 | 0.5-1.5 | 1 |
| | hypo | na | na | 0.2-0.7 | 0.4 | 0.2-1.2 | 0.8 | 0.5-1.5 | 1 |
| Iron (ug/L) | 1m | 30-54 | 42 | 15-42 | 24 | 23-56 | 37 | 3-60 | 29 |
| | hypo | 26-26 | 26 | 9-95 | 46 | 8-43 | 29 | 3-64 | 34 |
| Total-P (ug/L) | 1m | 2.1-2.2 | 2.2 | 3.5-5.2 | 4.5 | 2.8-3.1 | 3 | 3.1-6.2 | 4.7 |
| | hypo | 2.6-2.6 | 2.6 | 3.0-4.2 | 3.6 | 3.3-4.7 | 4 | 4.2-6.2 | 5.1 |
| Total filterable-P (ug/L) | 1m | 0.9-1.1 | 1 | 1.4-2.6 | 1.9 | 2.2-3.0 | 2.4 | 1.8-3.8 | 2.8 |
| | hypo | 1.1-1.1 | 1.1 | 1.5-3.4 | 2.3 | 2.0-2.7 | 2.3 | 1.8-2.5 | 2.1 |
| Filterable reactive-P (ug/L) | 1m | 1.5-1.7 | 1.6 | 1.1-1.6 | 1.3 | 1.9-2.5 | 2.1 | 1.9-3.8 | 2.8 |
| | hypo | 2.7-2.7 | 2.7 | 1.0-1.2 | 1.1 | 1.8-2.0 | 1.9 | 1.9-2.6 | 2.2 |
| Total Kjeldahl-N (ug/L) | 1m | 42-48 | 45 | 101-109 | 105 | 37-73 | 55 | na | na |
| | hypo | 59-59 | 59 | 97-127 | 108 | 60-77 | 68 | na | na |
| Ammonia (ug/L) | 1m | 1.2-1.9 | 1.6 | 1.1-3.5 | 2.6 | 3.8-5.6 | 4.7 | 1.3-2.4 | 1.6 |
| | hypo | 1.1-1.1 | 1.1 | 1.3-4.0 | 2.9 | 4.4-6.3 | 5.2 | 1.3-3.4 | 2.3 |
| Nitrate+nitrite (ug/L) | 1m | 264-361 | 313 | 357-402 | 385 | 148-634 | 285 | 281-480 | 354 |
| | hypo | 446-446 | 446 | 400-417 | 409 | 148-634 | 305 | 294-472 | 363 |
| Reactive silicon (ug/L) | 1m | 2202-2431 | 2431 | 2075-2256 | 2155 | 2079-3334 | 2449 | 2001-2217 | 2217 |
| | hypo | 2640-2640 | 2640 | 1992-2244 | 2082 | 2079-3362 | 2489 | 1956-2391 | 2205 |
| Chlorophyll a (ug/L) | 1m | 0.27-0.43 | 0.35 | 0.13-0.58 | 0.37 | 0.19-0.44 | 0.27 | 0.09-0.63 | 0.29 |
| | hypo | 1.09-1.09 | 1.09 | 0.39-2.35 | 1.52 | 0.18-0.89 | 0.55 | 0.23-0.66 | 0.43 |
| Phaeophytin a (ug/L) | 1m | 0.19-0.20 | 0.2 | 0.24-0.44 | 0.36 | 0.04-0.29 | 0.15 | 0.14-0.30 | 0.22 |
| | hypo | 0.29-0.73 | 0.51 | 0.94-1.34 | 0.88 | 0.07-0.40 | 0.26 | 0.17-0.31 | 0.29 |

averaging 3.7 and 2.8 $\mu g\ L^{-1}$ in lakes 2 and 3, respectively. Such low concentrations of ammonia are typical in well-oxygenated waters as these compounds are quickly oxidized to nitrite + nitrate (Wetzel 1975). Total Kjeldahl nitrogen (TKN [ammonia plus organic nitrogen]) in both lakes were relatively low compared to other Alaskan lakes, and averaged 82 and 73 $\mu g\ L^{-1}$ in lake 2 and 3, respectively. Thus, given the absence of significant quantities of ammonia nitrogen, the low TKN concentration is indicative of low algal biomass.

Phosphorus is often a limiting factor for primary production (Vollenweider 1976; Schindler 1978; Smith 1979), and to fish yield (Foerster 1968; Hanson and Legget 1982). In the English Bay Lakes, total phosphorus (TP) concentration in the epilimnion was low, averaging ~4.0 $\mu g\ L^{-1}$ in both lakes (Tables 2 and 3), indicating a highly oligotrophic (nutrient poor) condition. Although, the phosphorus loading rate is high (670 and 720 mg $m^{-2}\ yr^{-1}$ in lake 2 and 3, respectively); the rapid flushing rate does not increase lake fertility because it counteracts the accumulation of nutrient loading (Dillon 1975; Uttormark and Hutchins 1985). Filterable reactive phosphorus (FRP) or orthophosphate (the fraction of TP immediately available for uptake by autotrophic plants) was also quite low in both lakes averaging ~2 $\mu g\ L^{-1}$. Finally, reactive silicon levels exhibited little seasonal or inter-lake variation, but are considered somewhat higher compared to other Alaskan lakes as concentrations averaged 2,445 and 2,334 $\mu g\ L^{-1}$ in lake 2 and 3, respectively (Tables 2 and 3).

**Phytoplankton** -- During 1988-1991, chl a levels (an index of algal biomass) in both lakes were higher in the hypolimnion compared to the 1-m stratum (epilimnion). Seasonal concentrations in the epilimnion averaged 0.48 and 0.32 $\mu g\ L^{-1}$, and hypolimnetic concentrations averaged 0.63 and 0.90 $\mu g\ L^{-1}$ in lake 2 and 3, respectively (Tables 2 and 3). The chl a levels in the English Bay Lakes are ~50% lower compared to the average concentration found in other sockeye nursery lakes in Alaska.

**Zooplankton Abundance and Body Size --** The macrozooplankton community in the English Bay Lakes 2 and 3 comprised of three species of cladocerans, the preferred prey of juvenile sockeye salmon (Brocksen et al. 1970; Hall and Hyatt 1974; Kyle et al. 1988), and two species of copepods (Table 4). The cladocerans were represented by *Bosmina* sp., *Daphnia longiremus* and *Holopedium* sp., and the copepods consisted of *Cyclops columbianus* and *Epischura* sp. The seasonal mean total macrozooplankton (TMZ) density (number $m^{-2}$) in lake 2 was 47,637, 56,617, 46,156, and 38,282 during 1988-1991, respectively, and in lake 3 TMZ densities were 44,718, 62,456, 22,025, and 87,352 during 1988-1991, respectively.

As a group, cladocerans comprised ~95% of the TMZ density, with *Bosmina* being the most dominant species in both lakes (Table 4). During 1988-1991, seasonal mean *Bosmina* densities ranged from 29,843-48,744 $m^{-2}$ in lake 2 and ranged from 19,042-79,950 $m^{-2}$ in lake 3. Prior to stocking, *Bosmina* densities were relatively low and the seasonal mean body sizes were smaller than 0.40 mm, which is considered the minimum threshold size for elective feeding by sockeye salmon fry (Koenings and McDaniel 1983; Kyle et al. 1988). The lowest density of *Bosmina* was in lake 3 during 1990 (19,042) concomitant with the stocking of 375,000 sockeye fry, which suggests excessive predation. However, *Bosmina* populations did rebound in 1991 (79,950) when the stocking density was reduced to 155,000 fry. In addition, *Daphnia* populations were much lower than expected for a clearwater system and ranged from 619-2,566 $m^{-2}$ in lake 2 and from 398-3,220 $m^{-2}$ in lake 3. *Daphnia* comprised only 1-8% of the TMZ density and were also very small sized (mean = 0.58 mm), and *Holopedium* populations appeared sporadically and comprised only ~2% of the TMZ.

Within the copepod community, *Cyclops* was the most numerically dominant species with seasonal densities ranging from 909-4,724 $m^{-2}$ in lake 2 and from 1,380-3,337 $m^{-2}$ in lake 3 (Table 4). *Cyclops* body sizes were small and averaged 0.58 mm. Finally, *Epischura* densities were extremely low and populations were virtually absent during 1990 when sockeye fry were abundant.

Table 4. Macrozooplankton density and body size (mm) for each taxa in English Bay Lake 2 and 3, 1988-1991.

| Year/ | 1988 | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date/ | Jun 23 | | Aug 03 | | Oct 14 | Jul 12 | | Aug 16 | | Oct 13 | |
| Lake/ | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 |
| Taxa | | | | | | | | | | | |
| *Bosmina sp.* | 26,008 | 26,539 | 68,737 | 54,140 | 28,662 | 48,301 | 53,609 | 78,822 | 87,580 | 19,108 | 32,113 |
| | 0.34 | 0.33 | 0.28 | 0.32 | 0.36 | 0.33 | 0.32 | 0.31 | 0.31 | 0.33 | 0.34 |
| *Daphnia longiremus* | 796 | 796 | 265 | 0 | 796 | 2,654 | 0 | 4,512 | 2,654 | 531 | 2,123 |
| | 0.63 | | 0.72 | | | 0.62 | 0.74 | 0.56 | 0.60 | 0.46 | 0.53 |
| *Holopedium sp.* | 3,185 | 1,327 | 929 | 1,858 | 0 | 1,062 | 0 | 531 | 1,592 | 0 | 0 |
| | 0.52 | 0.51 | 0.48 | 0.43 | | 0.59 | 0.67 | 0.62 | 0.64 | | 0.66 |
| *Cyclops columbianus* | 11,412 | 4,246 | 796 | 265 | 0 | 9,554 | 4,246 | 2,389 | 2,123 | 265 | 796 |
| | 0.51 | 0.60 | 0.52 | 0.56 | | 0.56 | 0.61 | 0.66 | 0.53 | 0.75 | 0.63 |
| *Epischura sp.* | 1,327 | 0 | 0 | 265 | 0 | 1,592 | 0 | 531 | 531 | 0 | 0 |
| | 0.62 | | | 0.76 | | 0.94 | | 1.03 | 1.17 | | |
| *Total* | 42,728 | 32,908 | 70,727 | 56,528 | 29,458 | 63,163 | 57,855 | 86,785 | 94,480 | 19,904 | 35,032 |

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Table 4 continued. Macrozooplankton density and body size (mm) for each taxa in English Bay Lake 2 and 3, 1988-1991.

| Year/ | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date/ | May 10 | | Jun 08 | | Aug 02 | | Sep 13 | |
| Lake/ | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 |
| Taxa | | | | | | | | |
| *Bosmina sp.* | 175 | 955 | 6,210 | 10,244 | 36,624 | 32,484 | 127,999 | 32,484 |
| | 0.33 | 0.33 | 0.35 | 0.36 | 0.29 | 0.29 | 0.31 | 0.29 |
| *Daphnia longiremus* | 32 | 557 | 557 | 265 | 3,025 | 3,185 | 4,087 | 3,285 |
| | 0.46 | 0.45 | 0.63 | 0.60 | 0.51 | 0.55 | 0.55 | 0.55 |
| *Holopedium sp.* | 0 | 0 | 1,433 | 1,911 | 318 | 106 | 372 | 106 |
| | | | 0.45 | 0.41 | 0.41 | 0.43 | 0.58 | 0.43 |
| *Cyclops columbianus* | 159 | 478 | 955 | 2,707 | 1,592 | 1,168 | 929 | 1,168 |
| | 0.55 | 0.85 | 0.56 | 0.53 | 0.57 | 0.55 | 0.60 | 0.55 |
| *Epischura sp.* | 0 | 0 | 0 | 0 | 159 | 0 | 0 | 0 |
| | | | | | 1.07 | | | |
| *Total* | 366 | 1,990 | 9,155 | 15,127 | 41,718 | 36,943 | 133,387 | 37,043 |

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Table 4 continued. Macrozooplankton density and body size (mm) for each taxa in English Bay Lake 2 and 3, 1988-1991.

| Year/ | 1991 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date/ | Jun 06 | | Jul 03 | | Sep 04 | | Oct 10 | |
| Lake/ | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 |
| Taxa | | | | | | | | |
| *Bosmina sp.* | 18,312 | 24,363 | 28,450 | 58,280 | 48,328 | 198,301 | 24,283 | 38,854 |
| | 0.38 | 0.35 | 0.34 | 0.34 | 0.33 | 0.35 | 0.36 | 0.37 |
| *Daphnia longiremus* | 796 | 717 | 2,017 | 1,592 | 4,777 | 6,589 | 2,468 | 3,981 |
| | 0.64 | 0.56 | 0.76 | 0.64 | 0.59 | 0.61 | 0.53 | |
| *Holopedium sp.* | 1,592 | 995 | 1,274 | 1,486 | 239 | 212 | 0 | 0 |
| | 0.41 | 0.38 | 0.55 | 0.60 | 0.60 | 0.62 | | |
| *Cyclops columbianus* | 5,042 | 1,354 | 11,783 | 11,146 | 1,672 | 849 | 398 | 159 |
| | 0.66 | 0.59 | 0.61 | 0.59 | 0.54 | 0.59 | 0.71 | 0.60 |
| *Epischura sp.* | 0 | 0 | 1,380 | 531 | 239 | 0 | 80 | 0 |
| | | | 0.75 | 0.73 | 1.14 | 0.96 | 1.30 | |
| *Total* | 25,742 | 27,429 | 44,904 | 73,035 | 55,255 | 205,951 | 27,229 | 42,994 |

**Zooplankton Biomass** -- During 1988-1991, zooplankton biomass was quite low averaging 44, 56, 41, and 45 mg $m^{-2}$, respectively in lake 2 and 44, 61, 20, and 100 mg $m^{-2}$ in lake 3 (Table 5). Similar to TMZ density, zooplankton biomass was lowest in 1990 when stocking occurred, but the biomass increased five-fold in 1991 when the stocking level was reduced. Over the four years, *Bosmina* populations comprised an average of ~80% of the TMZ biomass in both lakes, whereas *Daphnia* and *Holopedium* combined comprised ~10% of the TMZ biomass. In addition, *Cyclops* and *Epischura* comprised ~10% and <2% of the biomass, respectively. Finally, a comparison of TMZ density and biomass for 23 sockeye nursery lakes in Alaska shows that the English Bay Lake system has the lowest average zooplankton biomass (Table 6).

## Fish Assessment

**Sockeye Escapement and Total Returns** -- During 1961-1991, adult sockeye salmon escapements into the English Bay Lake system ranged from a low of 2,000 in 1962 to a high of 20,000 in 1982, and averaged 7,500 (Figure 4). Since 1985, commercial fishing has been closed in the Port Graham subdistrict (which includes English Bay), but surprisingly, escapements have not increased. Specifically, during 1985-1991 escapements averaged only 4,600 compared to ~13,000 prior to the fishery closure. Commercial harvests ranged from a low of 2,100 sockeye in 1966 to a record high catch of 30,500 in 1978. Thus, excluding a subsistence fishery which harvested an average of 870 sockeye annually during 1981-1991, the total return over the past 30 years ranged from 3,300-44,000, and averaged 16,700 sockeye.

**Juvenile Abundance, Size and Distribution** -- A total of 16,600 sockeye smolts were captured in the fyke-net trap between 25 May and 14 July 1991. Sampling revealed that a significant number of smolts were migrating prior to installation of the trap on 24 May, and the migration peaked during 13-17 June when over 5,000 smolts were captured (Figure 5). However, the trap was not fished from 19-22

Table 5. Seasonal mean macrozooplankton biomass (mg/m^2) for each taxa in English Bay Lakes 2 and 3, 1988-1991.

| | Sample year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1988 | | 1989 | | 1990 | | 1991 | |
| Taxa | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 | Lake 2 | Lake 3 |
| *Bosmina sp.* | 35.7 | 38.0 | 43.7 | 52.7 | 36.1 | 15.3 | 32.5 | 89.3 |
| | 81% | 86% | 78% | 86% | 88% | 77% | 72% | 89% |
| *Daphnia longiremus* | 0.9 | 0.0 | 3.5 | 2.1 | 2.3 | 2.2 | 4.0 | 5.1 |
| | 2% | 0% | 6% | 3% | 6% | 11% | 9% | 5% |
| *Holopedium sp.* | 3.0 | 2.8 | 1.7 | 2.0 | 0.9 | 0.7 | 1.5 | 1.6 |
| | 7% | 6% | 3% | 3% | 2% | 4% | 3% | 2% |
| *Cyclops columbianus* | 3.5 | 2.7 | 4.6 | 2.7 | 1.0 | 1.5 | 6.1 | 3.7 |
| | 8% | 6% | 8% | 4% | 2% | 8% | 14% | 4% |
| *Epichura sp.* | 0.5 | 0.3 | 2.9 | 1.2 | 0.2 | 0.0 | 1.1 | 0.2 |
| | 1% | 1% | 5% | 2% | 0% | 0% | 2% | 0% |
| *Total* | 44 | 44 | 56 | 61 | 41 | 20 | 45 | 100 |

Table 6. Comparison of seasonal mean macrozooplankton density and biomass for a variety of sockeye nursery lakes showing the relatively low standing stock of zooplankton in the English Bay lakes.

| Lake and geographical location \a | Sampled years | Seasonal mean weighted macrozooplankton | |
|---|---|---|---|
| | | Density (no./m^2) | Biomass (mg/m^2) |
| Chenik (CI) | 87-90 | 871,677 | 2,223 |
| Hidden (CI) | 81-90 | 619,203 | 2,331 |
| Chelatna (CI) | 84-85,88-90 | 409,413 | 1,313 |
| Chilkat (NSE) | 87-90 | 645,849 | 1,287 |
| Karluk (Kodiak) | 81-91 | 520,383 | 1,041 |
| Eshamy (PWS) | 81-86,89-90 | 439,595 | 972 |
| Packers (CI)\b | 81-90 | 177,815 | 617 |
| Leisure (CI) | 85-90 | 249,758 | 398 |
| Skilak (CI)\c | 86-91 | 230,361 | 556 |
| Hugh-Smith (SSE)\b | 81-87 | 290,404 | 523 |
| McDonald (SSE)\b | 81-90 | 91,245 | 297 |
| Bakewell (SSE)\b | 83-85,88-90 | 115,398 | 221 |
| Frazer (Kodiak) | 88-91 | 147,852 | 220 |
| Afognak (Kodiak) | 87-91 | 143,241 | 185 |
| Redoubt (NSE) | 84-87,90 | 137,040 | 159 |
| Frazer (Kodiak) | 85-87 | 114,086 | 155 |
| Chilkoot (NSE) | 87-90 | 88,443 | 145 |
| Crescent (CI)\d | 81-82 | 87,958 | 145 |
| Tustumena (CI)\c | 81-91 | 41,249 | 105 |
| Virginia (NSE) | 86,88-91 | 45,318 | 103 |
| Redoubt (NSE) | 82-83 | 76,818 | 90 |
| Coghill (PWS) | 86,88-91 | 47,465 | 79 |
| English Bay 3 (CI) | 88-91 | 54,138 | 56 |
| English Bay 2 (CI) | 88-91 | 47,173 | 47 |

\a CI = Cook Inlet; PWS = Prince William Sound; NSE = Northern Southeast;
SSE = Southern Southeast.
\b Denotes stained lakes.
\c Denotes glacial lakes.
\d Denotes semi-glacial lakes.

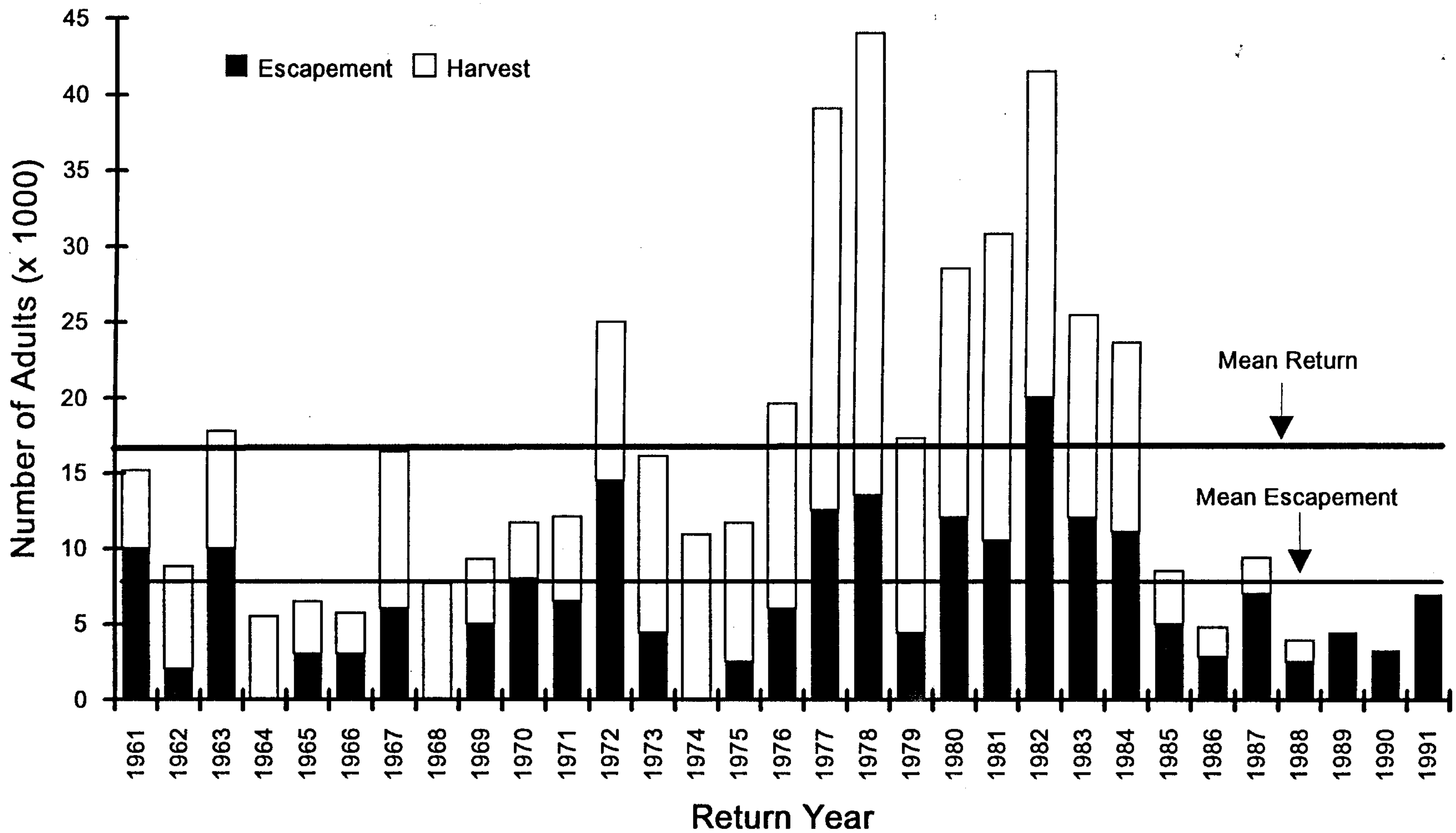


Figure 4. Adult sockeye salmon escapements and commercial harvests for the English Bay Lakes, 1961-1991.

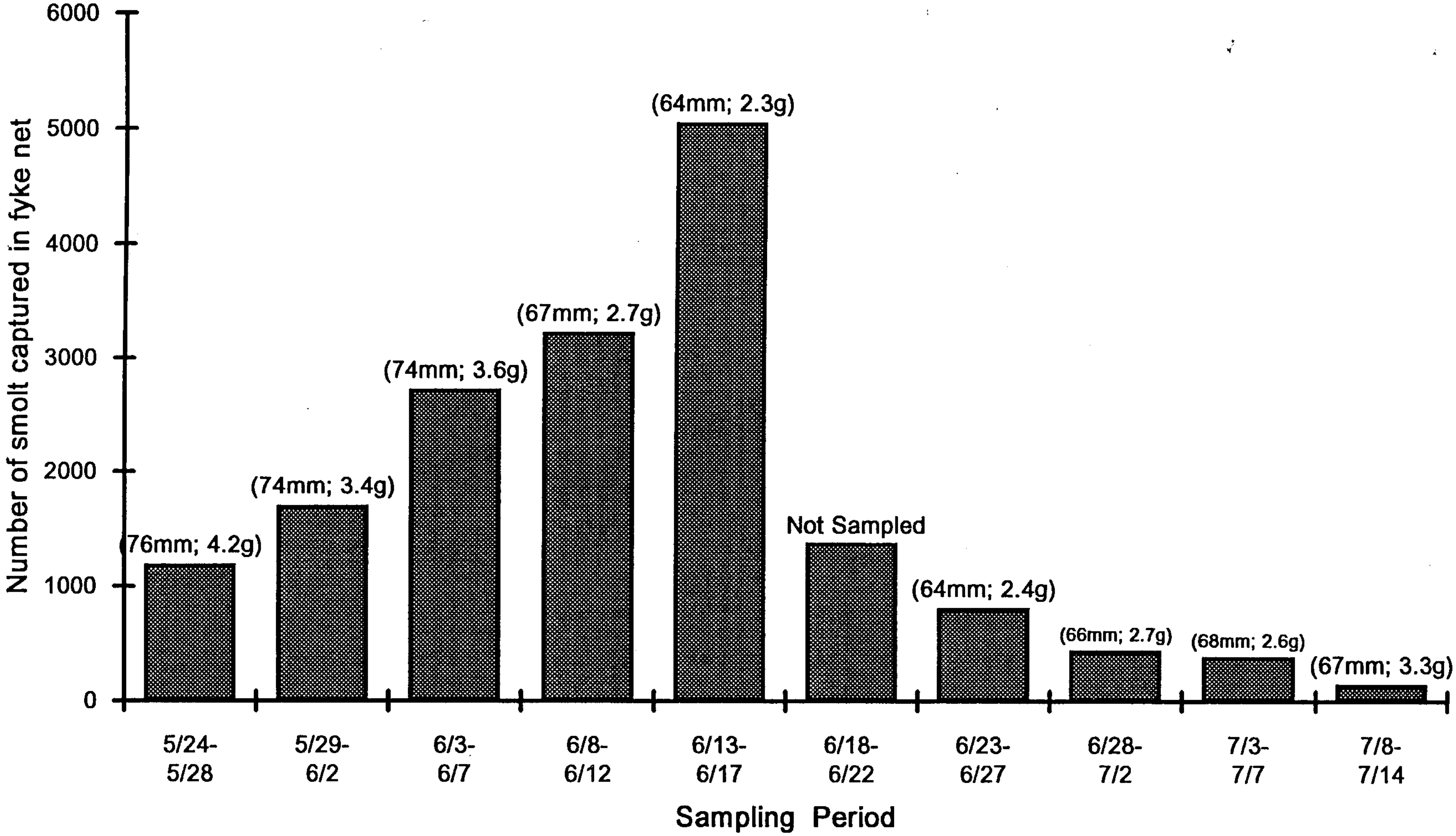


Figure 5. Number of sockeye smolts captured in the fyke net by five-day periods at the outlet of English Bay Lake 2, 1991. Also shown is the weighted mean size of smolts for each sample period.

June due to extreme high water, so it is possible that a large number of smolts also migrated during this period. By mid-July, very few smolts were migrating from the lake when sampling was discontinued. The majority (95%) of the smolts sampled reared for 1 year before emigrating from the lake, and averaged 69 mm and 2.9 g in size.

The hydroacoustic survey conducted in October 1988 at lake 2 revealed a total population estimate of 299,600 juvenile fish. Because of low fish density and poor weather no townetting was done to confirm species composition. Fish densities were highest near the deep basin of the lake and lowest near the outlet. In addition, the fish were most abundant within the 2-12 m stratum accounting for 48% of the total density, with 39% of the fish distributed within the 6-12 m stratum, and 13% in the 12-26 m stratum. Thus, from the 1988 survey, it appears juvenile fish were near surface, had undergone diel vertical migration typical of sockeye fry, and were not inhibited by cool rearing temperatures.

**Potential Sockeye Salmon Production** -- Based on a 10% survival from potential egg deposition (number of females x fecundity) to spring fry (Foerster 1968), an estimated 550,000 spring fry were produced from the 1989 brood-year escapement. In addition, 375,000 sockeye fry were planted in lake 3 in the spring of 1990 for a total recruitment of 925,350 sockeye fry. In comparison, the 1990 brood-year escapement produced an estimated 404,000 spring fry, and an additional 155,000 hatchery fry planted in June provided a total recruitment of 504,000 spring fry. Under rearing limitation, Koenings and Burkett (1987) found an empirical relationship between euphotic volume (EV) and sockeye salmon production. Specifically, maximum fish densities per EV unit were estimated at 110,000 fry which would yield 23,000 age-1, threshold-sized (60 mm; 2.2g) smolts. The optimal density of 54,000 fry per EV unit is forecasted to produce fewer, but larger-sized (4.5 g) smolts capable of attaining a greater marine survival. Applying the optimal density of rearing fry in English Bay Lakes (EV=18 units), indicates an ability to produce ~980,000 sockeye salmon fry, which is very near the

1990 juvenile recruitment from wild spawners and hatchery stocking. Based on a 21% survival from spring fry-to-smolt (Koenings et al. 1989), an estimated 206,000 smolts would be produced. Using a smolt-to-adult survival of 20% for optimum size smolts (Koenings and Burkett 1987), a total of 41,000 adult sockeye would be predicted to return, which is consistent with the highest annual return (Figure 4). However, as observed in 1990 the zooplankton community (both density and size) were quite low, indicating the inability to support the EV-predicted number of spring fry.

## EVALUATION

Total adult returns to the English Bay Lakes during the late 1970's to early 1980's did approach the level of production estimated from the EV rearing-capacity model; however, recent (1985-1991) returns averaged only ~10% of the maximum historical level. Commercial fishing closures were initiated in 1985 to allow a greater number of returning adults to reach the spawning grounds, yet subsequent annual escapements were much lower than expected. Consequently, in order to increase production, fry stocking was initiated in 1990 to supplement wild production. However, age-1 smolts emigrating the English Bay Lakes in 1991 were not substantially greater than threshold size, indicating rearing conditions near capacity (Geiger and Koenings 1991). In addition, the low densities and small size of zooplankton in the English Bay Lakes, coupled with the smaller size smolts, suggests intense competition for food (Carpenter et al. 1985; Kyle et al. 1988).

Under density-dependent conditions, a significant relationship between smolt biomass and zooplankton biomass (Koenings and Kyle 1991) exists whereby smolt biomass (kg $km^{-2}$) = 2.1 x zooplankton biomass (mg $m^{-2}$). Using the combined averaged zooplankton biomass estimates for 1988-1991 (103 mg $m^{-2}$), this model would predict a total of 217 kg of smolt, which is equivalent to 140,000 threshold sized smolts (2.2 g) or 69,000 optimum-sized (4.5 g) smolts. Further, using a smolt-to-adult survivorship of 12% (Koenings and Burkett 1987) for threshold-size smolts or 21% for optimal-size smolts equates to a total return of ~15,000 adult sockeye. This adult production is considerably lower than predicted using the EV rearing-capacity model, but is consistent with the historical average return (16,700). Thus, the system may have produced a total return of over 40,000 sockeye; however, given the existing forage base, we caution against an aggressive fry stocking program with unrestricted escapements.

It is well documented that supplemental nutrient loading through lake fertilization results in the stimulation of lower trophic levels yielding greater zooplankton biomass, a larger production of smolts, and ultimately an increase in the number of returning adults (LaBrasseur et al. 1978; Shortreed and Stockner 1981; Koenings and Burkett 1987; Kyle et al. 1991). However, the fast flushing rate of the English Bay Lake system would quickly remove the nutrients, thereby counteracting the benefits of a lake fertilization. Thus, the system is a poor candidate for a nutrient enrichment program. Instead, balancing juvenile (wild + hatchery) recruitment with the capacity of the system to produce sufficient forage can eventually yield a sustainable level of smolt production and a consistent total return of 15,000-20,000 sockeye.

## RECOMMENDATIONS

The density of juvenile sockeye fry relative to the amount of available forage is an important consideration for successful fry stocking programs. Given the existing low zooplankton biomass in the English Bay Lakes, juvenile sockeye recruitment based on historical production levels would likely result in a complete collapse of the zooplankton community. Thus, we recommend if fry stocking is desired, a modest program be conducted in conjunction with a managed escapement goal, and as equally important, continuance of limnological and juvenile fisheries evaluations. Specifically, to balance juvenile fry densities with the existing forage base, we recommend a total juvenile spring fry recruitment of ~500,000 sockeye.

This can be accomplished by achieving an escapement goal of 4,000 adults: (2,000 females x 2,450 eggs/female) x 10% survival = 490,000 spring fry). If fry stocking is conducted, escapements of less than 4,000 should be targeted so that wild fry recruitment could be supplemented with hatchery fry. As an alternative, a pre-smolt stocking project should be considered for this system; although this could also impact the zooplankton community, it most likely would be minimal compared to stocking spring fry. This strategy would produce a larger adult return than the lake could produce naturally or from hatchery fry plants given the current low freshwater productivity. Finally, we recommend a sampling project to determine the population estimate, size, and age of migrating smolts, and limnological sampling should be conducted once per month from May-October to monitor nutrient levels, primary production, and most importantly zooplankton density, size, and biomass.

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