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Potential for Sockeye Salmon (*Oncorhynchus nerka*)
Enhancement of Portage Lake, Afognak Island

by
L. E. White and J. A. Edmundson

Number 129

Alaska Department of Fish & Game
Division of Fisheries Rehabilitation,
Enhancement and Development

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ABSTRACT

Portage Lake is one of two important salmon-producing systems of the Perenosa Bay fishing district on Afognak Island. In 1969, a fish pass was installed in the outlet of Portage Lake to improve passage of pink salmon over the partial barrier; however, adult sockeye and coho salmon escapements into Portage Lake also increased. By 1977, sockeye salmon escapements had peaked at nearly 25,000, and ~11,000 were harvested in 1981 and 1982. Over the next 10 years, escapements decreased by more than 50% despite continued operation of the fish pass. Consequently, to achieve the managed escapement goal, fewer sockeye salmon were available for harvest. Concern over the decline in sockeye production prompted the Alaska Department of Fish and Game, in cooperation with Kodiak Regional Aquaculture Association, to initiate fisheries and limnological investigations in 1990. Fish surveys revealed that the spawning area is being under-utilized by the current number of spawners. In addition, limnological studies revealed that Portage Lake is nutrient poor (oligotrophic); and as a result, primary productivity (chlorophyll a) and zooplankton biomass are very low. As zooplankton are the primary forage for rearing sockeye juveniles, increasing juvenile recruitment through higher escapements or fry stocking could further reduce the rearing capacity of Portage Lake and result in a severe reduction of zooplankton. Because current productivity is low, we recommend a nutrient enrichment project in conjunction with balanced fry recruitment to increase the amount of forage available and rearing capacity for sockeye juveniles.

INTRODUCTION

Portage Lake (also referred to as Perenosa Lake) is located 60 km north of the City of Kodiak (Figure 1) on Afognak Island. Both Portage Lake and nearby Paul's Lake comprise the two most important sockeye-producing lakes of the Perenosa fishing district. A denil-type fishway (steeppass) was installed over the Portage Creek falls in July 1969 primarily to allow passage of pink salmon (*Oncorhynchus gorbushka*) across the partial barrier; however, sockeye (*O. nerka*) and coho salmon (*O. kisutch*) also utilize the fishway. Since 1968 sockeye salmon escapements have averaged 6,200, but have been as high as 25,000 (1977) and as low as <100 (1986 and 1988). The sockeye salmon escapement goal established by the Alaska Department of Fish and Game (ADF&G) is ~8,000; however, in the last 10 years escapements have been ~50% lower than the historical average. In addition, recent commercial harvests have declined to fewer than 100 sockeye salmon. During the mid-1970's, total returns exceeded 20,000, but since 1990 have averaged only ~5,000. Because this system experienced a wide fluctuation in escapement and a major decline in run strength, Portage Lake was considered to be a high priority by the ADF&G and Kodiak Regional Aquaculture Association (KRAA) for evaluation of further sockeye salmon enhancement.

In 1990, the Division of Fisheries Rehabilitation, Enhancement, and Development Division (FRED) of the ADF&G, in cooperation with KRAA, initiated fisheries and limnological investigations of Portage Lake. In 1991, the spawning areas in the major stream systems were surveyed and spawner distribution was assessed. Since 1990, a salmon counting weir was operated in Portage Creek by the Commercial Fisheries Division of ADF&G. The purpose of this report is to evaluate sockeye salmon production in Portage Lake and characterize current productivity relative to potential lake enhancement.

Description of Study Area -- Portage Lake (58° 16'N, 152° 25'W) is located on the north end of Afognak Island 60 km north of the City of Kodiak. The lake is 2.6 km long and up to 0.9 km wide, and encompasses a total surface area of 1.6 million m^2 (Figure 2). The maximum depth is 23 m, mean depth is 7.6 m, and the total volume is 13×10^6 m^3. The annual precipitation on Afognak Island averages 155 cm (Dugdale and Dugdale 1961;

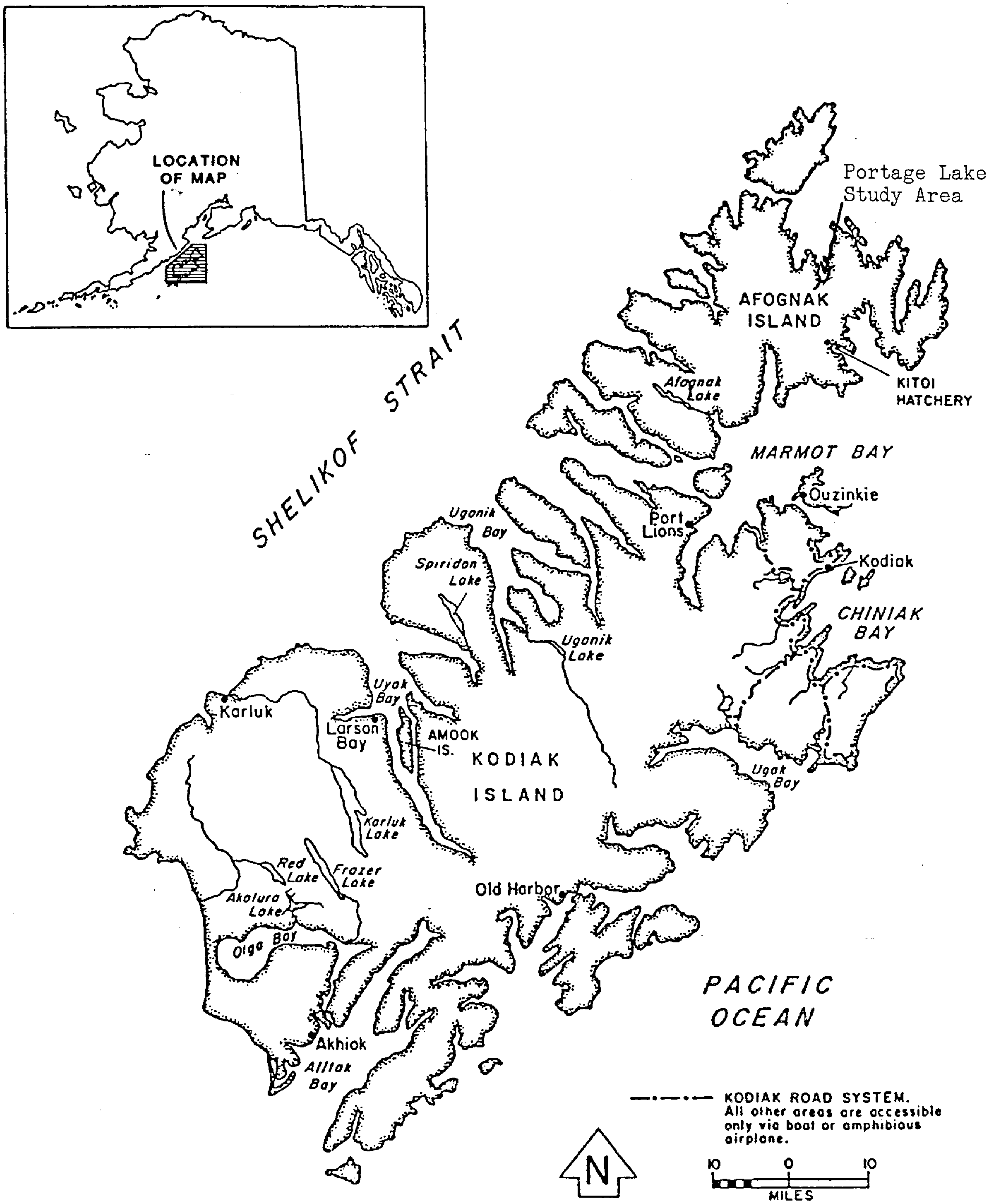

Figure 1. Geographic location of Kodiak and Afognak Islands showing the Portage Lake study area.

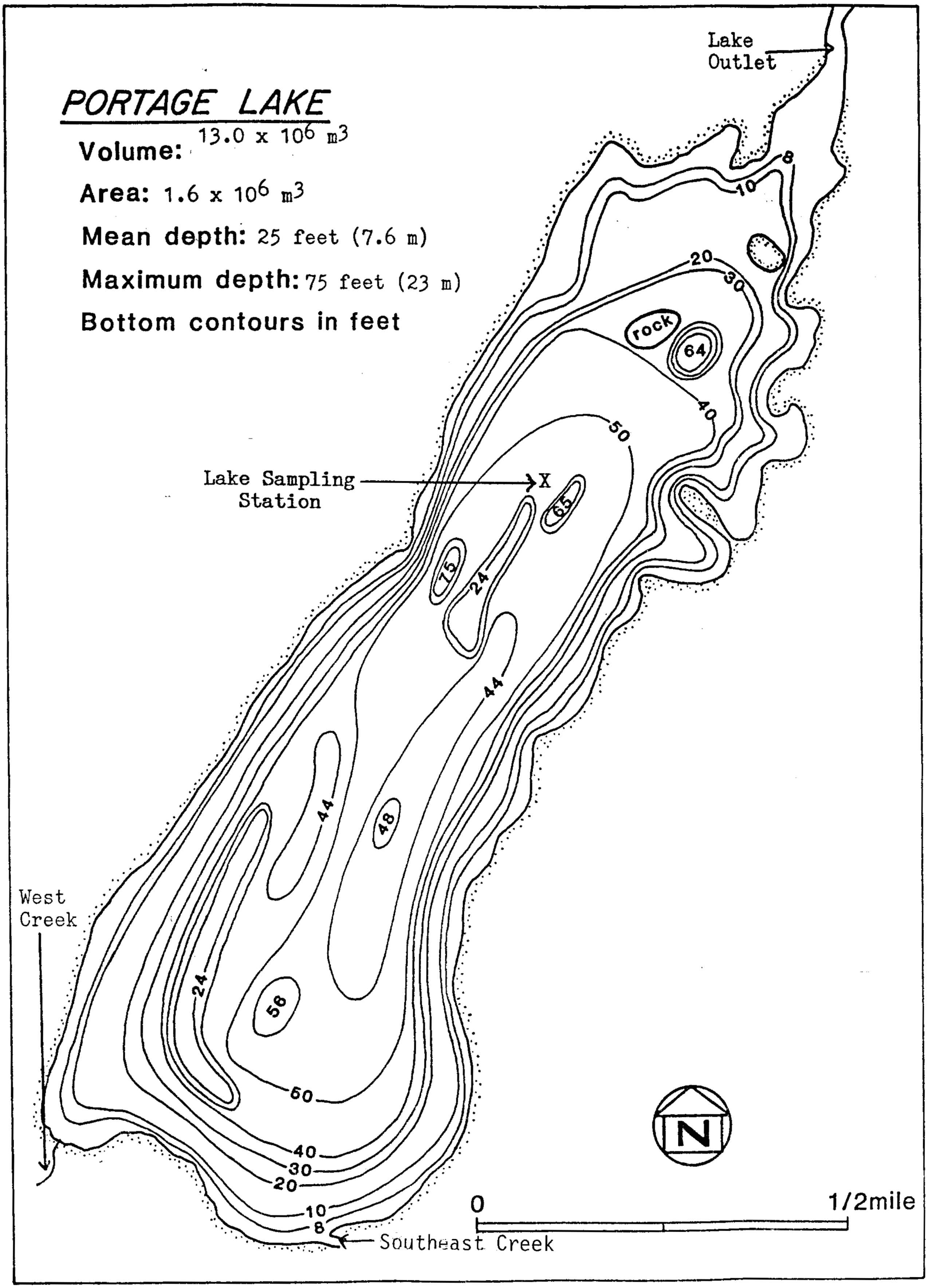

Figure 2. Morphometric map of Portage Lake, Afognak Island.

Anonymous 1979), and the water residence time is estimated to be 0.20 years (or conversely the lake flushes 5 times per year) which is considerably less compared to other sockeye nursery lakes (Koenings *et al.* 1986).

Sockeye salmon begin migrating into the Portage Lake system in mid-June and spawn from August through September, but peak spawning occurs in late August. There are two major spawning tributaries that flow into the south end of the lake. In addition, spawning occurs along the lake shore and a small number of fish also spawn in the lake outlet (Portage Creek). Other fish within the Portage Lake drainage include: chum salmon (*O. keta*) rainbow or steelhead trout (*O. mykiss*), Dolly Varden char (*Salvelinus malma*), three spine stickleback (*Gasterosteus aculeatus*), and freshwater sculpin (*Cottus aleuticus*).

METHODS AND MATERIALS

Fishery Assessment

Spawning Area -- Areas where spawning has been observed in the Portage Lake drainage were measured and evaluated to estimate the number of sockeye salmon that could be supported. The West Creek and East Creek sections of Portage Lake were surveyed. Two transects were randomly selected in each section of the stream surveyed and the cross-section 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 averaged dimensions of width and length were multiplied to estimate the total area (m^2) of the spawning section. The total usable spawning area was determined by estimating the percentage of usable spawning area in each survey section and multiplying by the estimated total area. Usable spawning area 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 lake shore spawning area was estimated based on the following assumptions/techniques: 1) spawning area was limited to a depth of 1.5 m; 2) the 1.5 m shoreline area was determined by planimetry of a morphometric map; and 3) approximately 25% of the shoreline spawning area has usable spawning area as defined above.

Adult Escapement and Harvest -- Aerial spawning surveys have been conducted since 1968 by the Commercial Fisheries Division of ADF&G, and peak aerial counts were doubled to estimate escapements (Barrett *et al.* 1984). In addition, FRED personnel conducted foot surveys of spawning tributaries in 1991 to determine spawner distribution. During 1990-1992, weir counts were conducted in Portage Creek (outlet) to enumerate all salmon species. Estimating the historical commercial harvest of Portage Lake sockeye salmon is somewhat problematic due to a mixed-stock fishery in Perenosa Bay (section 251-83 and 251-82) and similar run timing of these fish. The estimate of the historical contribution of Portage Lake's sockeye salmon commercially caught in the Perenosa Bay section (251-83 and 251-82) of the Afognak fishing district (nearest to Portage) was pro-rated based upon escapement ratio of Portage and nearby Paul's Lake systems. For example, if there were 1,000 fish in Portage Lake and 10,000 in Paul's lake, only 10% of the commercial catch was attributed to Portage.

Limnological Sampling

During 1990-1992, limnological surveys at Portage Lake were conducted four times from May to September. Transportation to and from the lake was provided by a float-equipped aircraft and the sampling was conducted after mooring to a permanent mid-lake site (Figure 2). In addition to obtaining light penetration, temperature, and dissolved oxygen profiles, water quality and biological samples were collected and analyzed by the ADF&G Limnology Laboratory in Soldotna.

Physical Parameters -- Measurements of light penetration (footcandles) were recorded at 0.5-m increments from the surface to a depth of 5 m, and then at 1-m increments to a depth equivalent to 1% of the sub-surface light using an International Light® or Protomatic

®Mention of commercial products and trade names does not constitute endorsement by ADF&G.

submarine photometer. The euphotic zone depth (EZD) or the depth at which 1% of the subsurface light (photosynthetically available radiation [400-700 mm]) penetrates (Schindler 1971) was calculated as the y-intercept derived by regressing depth against the natural logarithm of the percent light. The vertical-attenuation coefficient (Kd) or amount of light retained (attenuated) per meter is the reciprocal of the regression slope (Koenings *et al.* 1987). Water clarity was measured with a 20-cm Secchi disk by lowering the disk and recording the depth at which it disappeared from view. In-lake temperatures and dissolved oxygen levels were recorded at 1-m increments from the surface to 5 m and at 2-m increments from 6 m to the bottom using a YSI model-57 analyzer.

Morphometry and Water Residence Time -- A bathymetric map (Figure 2) was developed from bottom profiles recorded with a fathometer along numerous lake transects. The area of each depth strata was determined with a polar planimeter, the lake volume (V) was computed by summation of successive strata, and the mean lake depth was determined (Hutchinson 1957):

$$z = V/A_L$$

Where: z = lake mean depth (m)

V = volume ($\bullet 10^6 m^3$)

A_L = lake surface area ($\bullet 10^6 m^2$)

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

$$T_w(yr) = V/TLO$$

Where: T_w = theoretical water residence time (years)

V = total lake volume ($\bullet 10^6 m^3$)

TLO = total lake outflow ($\bullet 10^6 m^3\ yr^{-1}$).

Water Quality -- Lake water samples were collected form the 1 m (epilimnion) and ~15-20 m (hypolimnion) depths using a non-metallic Van Dorn sampler. Eight liters of water were collected from each depth, stored in pre-cleaned 8-10 L translucent carboys, immediately transported to Kodiak, and then filtered or preserved for laboratory analysis. Subsequent filtered and unfiltered water 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 and frozen for analysis of dissolved nutrients (Koenings *et al.* 1987) in pre-cleaned polybottles and sent to the Limnology Laboratory for analysis.

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 1 N magnesium carbonate ($MgCO_3$) were added prior to completion. Filters were stored frozen in separate plexiglass holders.

Zooplankton -- Replicate bottom-to-surface vertical zooplankton hauls were taken using a 0.2-m diameter, 153 μ mesh, conical net. The net was pulled at a constant 1 m/s, rinsed prior to removing the organisms, and all specimens were preserved in neutralized 10% formalin (Koenings *et al.* 1987).

Laboratory Analysis

General Water Quality -- Conductivity, temperature compensated to 25°C, was measured with a YSI model-32 conductance meter and pH was measured with an Orion 399A ion analyzer using a two-buffer calibration. Turbidity, expressed in nephelometric turbidity units (NTU), was measured with a HF model-DRT100 turbidimeter and color was determined on a filtered sample by measuring absorbance at 400 nm and converting to equivalent platinum cobalt (Pt) units (Koenings *et al.* 1987). Alkalinity levels were determined by acid titration (0.02 N H_2SO_4) to pH 4.5 (APHA 1985). Calcium and magnesium were determined from separate EDTA (0.01 N) titrations after Golterman (1969); and total iron was determined by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion after Strickland and Parsons (1972).

Nutrients-- All chemical and biological samples were analyzed by methods detailed by Koenings *et al.* (1987). Filterable reactive phosphorus (FRP) was analyzed by the molybdenum-blue/ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich *et al.* (1975). Total phosphorus was determined using the FRP procedure after persulfate digestion. Estimates of annual phosphorus loading in Portage 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:

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

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

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

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

T_w = water resident time (yr)

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

Nitrate and nitrite (NO_3 + NO_2) was determined as nitrite following cadmium reduction and diazotization with sulfanilamide; and total ammonia was determined using the phenylhypochlorite procedure (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. 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 from the algal pigment chlorophyll a (chl a). Chl a was extracted after homogenizing the glass-fiber filters in 90% acetone using a Thomas tissue grinder and pestle. Chl a concentrations (corrected for phaeophytin) were determined using the fluorometric procedure of Strickland and Parsons (1972) with a dilute acid (0.03 N HCl) addition after Reimann (1978).

Zooplankton -- Identification of *Daphnia* followed Brooks (1957), *Bosmina* after Pennak (1978), and the copepods after both Wilson (1959) and Yeatman (1959). Zooplankton were enumerated from triplicate 1-ml subsamples taken with a Hansen-Stempel pipette and placed into a 1-ml Sedgewick-Rafter counting chamber. Zooplankton body sizes from 30 organisms of each species were measured to the nearest 0.01 mm along a transect in each of the 1-ml subsamples using a calibrated ocular micrometer. Finally, zooplankter 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

Fishery Assessment

Spawning Area -- The total stream spawning area in the Portage Lake system was estimated to be 10,758 m^2 in West Creek and 3,735 m^2 in East Creek for a total area of 14,493 m^2. Based on an optimal spawning density of 2.0 m^2 per female (Burgner *et al.* 1969), West Creek could support 5,379 females and East Creek 1,867 females. The desired escapement at a 50:50 sex ratio is 10,758 for West Creek and 3,735 for East Creek for a total of 14,493 stream spawners. In addition, the usable lake-shore spawning area was estimated to be 4,713 m^2 which would equate to 2,356 females or a total of 4,713 lake-shore spawners. Thus, based on the combined useable tributary and lake shore spawning areas, the total spawning area is capable of supporting 19,206 sockeye.

Sockeye Escapement and Total Returns -- Since 1968, adult sockeye salmon escapements in Portage Lake ranged from 282 in 1968 to a high of nearly 25,000 in 1977 (Table 1). During 1975-1982, annual escapements averaged 12,200, but from 1983 to 1989 escapements decreased and averaged 2,100. Since 1990, escapements have increased slightly and averaged 5,060. Over the past 25 years escapements averaged 6,200, which is very close to the mid-point escapement goal of 8,000 (range 5,000-10,000) set by the ADG&G Commercial Fisheries Division (Barrett *et al.* 1990). Prior to 1975, no commercial harvest records were available for the Portage Lake system. During the next eight years, commercial harvests gradually increased and reached a high of ~11,000 in 1981 and 1982; however, since then harvests have declined and averaged ~200 sockeye. Total returns averaged 5,120 prior to 1975 compared to 16,115 during 1975-1982, but recent (1983-1992)

Table 1. Adult sockeye salmon escapement, commercial harvest, and total return for Portage and Paul's 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	10,522	19,463	22,374	41,269
1982	17,926	18,547	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	18,574	0	1,388	0	19,962
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**	**15,222**	**1,433**	**2,551**	**8,112**	**17,912**

nd indicates no data

0 indicates none observed

returns averaged only 3,210. Thus, escapement and harvest estimates indicate that total returns to the Portage Lake systems have been cyclic, and in recent years declining.

Limnological Assessment

Light Penetration -- On a seasonal basis, the mean euphotic zone depth (EZD) in Portage Lake ranged from 6.8-8.2 m (Table 2). The EZD was shallowest (3.9 m) in October 1990 and deepest (10.9 m) in August 19991. Over all years, the EZD averaged 7.6 m and the euphotic volume (EV) was estimated to be 12.2 x 10^6 m^3 or about 12 EV units. Thus, the EV comprises nearly all (93%) of the total lake volume. The vertical extinction coefficient (Kd) averaged 0.65 and is consistent with the median Kd (0.62) for Alaskan stained lakes (Koenings and Edmundson 1991). Secchi disk (SD) transparency averaged 3.4 m and the product of KdxSD and the ratio EZD:SD (both indices of the principal light attenuating component) averaged 2.2 and 2.3, respectively which characterizes Portage Lake as organically stained (Koenings and Edmundson 1991).

Temperature and Dissolved Oxygen -- Temperature profiles obtained during 1990-1992 sampling periods showed progressively colder spring (May) temperatures (Figure 3). That is, surface temperatures reached 8°C in May 1990, but were 5°C at the same time in 1991 and only 3°C in 1992. Nonetheless, temperatures during July and August for all years showed the formation of a distinct thermocline. Surface temperatures reached 15-16°C, cooled rapidly between 7 and 10 m to ~10°C, and then decreased to ~8°C near the bottom. The epilimnion occurs at depths <7 m, the metalimnion (thermocline) occurs from ~7 to 10 m, and the hypolimnion occurs at depths >10 m. In late September Portage Lake undergoes turnover and is isothermal at ~8°C. The epilimnion was well-oxygenated as dissolved oxygen (DO) levels and corresponding percent saturation ranged from 8.9-13.8 mg L^{-1} and 88-110%, respectively (Table 3). The lowest DO concentrations were near the bottom during August and ranged from ~7-9 mg L^{-1} (60-70% saturation), but these levels are still well within standards acceptable for salmonids (Davies *et al.* 1979).

Table 2. Seasonal changes in euphotic zone depth (EZD), Secchi disk (SD) transparency, vertical attenuation coefficient (Kd) in Portage Lake, 1990-1992.

Date	EZD (m)	SD (m)	EZD/SD	Kd (m^-1)	KdxSD
05/14/90	6.9	4.8	1.5	0.59	2.82
07/10/90	9.3	4.0	2.3	0.40	1.61
08/20/90	7.0	3.5	2.0	0.69	2.43
10/09/90	3.9	3.3	1.2	1.07	3.46
Mean	**6.8**	**3.9**	**1.7**	**0.69**	**2.58**
05/17/91	5.3	2.8	1.9	0.82	2.25
06/12/91	6.6	3.4	2.0	0.72	2.45
08/01/91	10.9	3.3	3.4	0.38	1.25
09/19/91	8.5	2.8	3.1	0.62	1.70
Mean	**7.8**	**3.0**	**2.6**	**0.64**	**1.91**
05/14/92	6.4	3.3	2.0	0.65	2.12
06/24/92	10.7	3.3	3.3	0.56	1.81
08/17/92	6.6	2.8	2.4	0.69	1.90
09/30/92	8.9	3.8	2.4	0.53	1.98
Mean	**8.2**	**3.3**	**2.5**	**0.61**	**1.95**

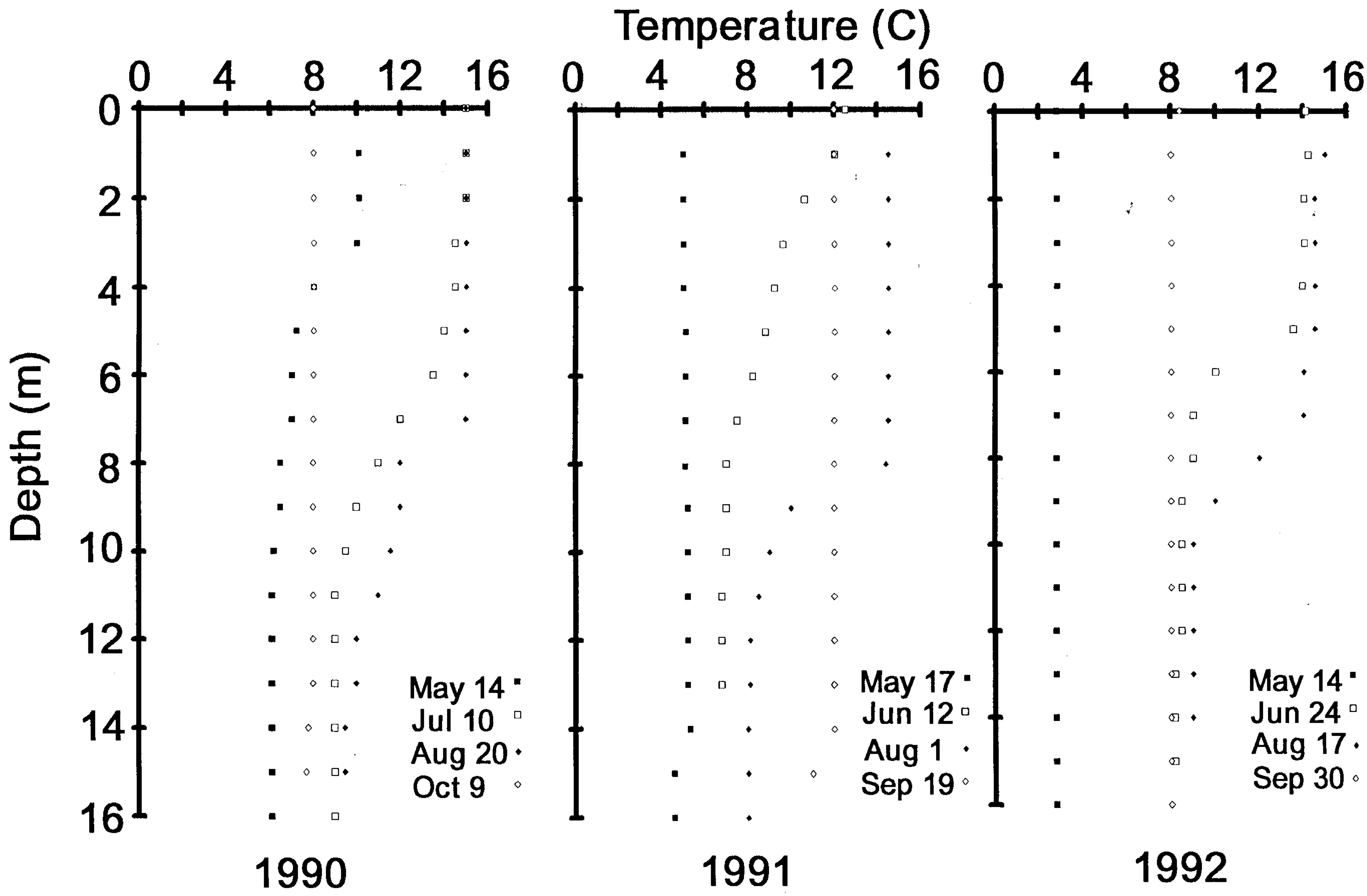

Figure 3. Seasonal temperature profiles in Portage Lake, 1990-1992.

Table 3. Dissolved oxygen concentrations (mg/L) and percent saturation within the epilimnion (1-m), metalimnion (10 m), and hypolimnion (15-20 m) in Portage Lake, 1990-1992.

	1990				1991				1992			
Strata	**14-May**	**10-Jul**	**20-Aug**	**9-Oct**	**17-May**	**12-Jun**	**1-Aug**	**19-Sep**	**14-May**	**24-Jun**	**17-Aug**	**30-Sep**
Epilimnion	11.2	9.2	10.6	11.8	13.8	10.5	10.1	10.8	13.7	10.2	8.9	11.7
	92%	92%	104%	99%	110%	96%	100%	100%	100%	99%	88%	99%
Metalimnion	11.2	8.4	8.0	10.5	14.0	10.7	9.1	10.4	13.1	10.0	7.5	11.8
	92%	74%	73%	88%	108%	87%	78%	95%	96%	85%	65%	99%
Hypolimnion	8.4	8.4	6.8	10.2	13.8	10.6	8.7	9.6	12.9	10.0	7.4	11.6
	68%	73%	60%	85%	105%	87%	74%	88%	95%	83%	63%	96%

General Water Quality -- General water-quality parameters exhibited little variation within a season or by depth (Table 4). Portage Lake is a soft-water system as conductivity, which is proportional to the concentrations of major ions e.g., calcium and magnesium (Wetzel 1975), is low ranging from 46-54 μmhos cm^{-1}. Alkalinity averaged 12 mg L^{-1} and indicates a low inorganic carbon supply (Hutchinson 1957; Wetzel 1975). The pH is below neutrality ranging from 6.2-7.0 units and averaged 6.8 units, which is typical for lake waters containing large amounts of humic organic matter (Stumm and Lee 1960; Wetzel 1975). Color and turbidity levels were characteristic of an organically-stained system and averaged 21 Pt units and 0.8 NTU, respectively (Koenings and Edmundson 1991).

The essential micronutrients calcium and magnesium are usually present in soft-water lakes in excess of that required for normal biotic growth and typically exhibit little seasonal variation by depth (Wetzel 1975). Calcium concentrations in Portage Lake ranged from 3.0-5.7 mg L^{-1} and averaged 4.2 mg L^{-1} whereas, magnesium levels ranged from <0.2-3.9 mg L^{-1} and averaged 1.1 mg L^{-1}, which is ~50% lower than the mean for other Alaskan stained lakes (Koenings and Edmundson 1991). Under chemical equilibria, iron concentrations in clearwater lakes are generally <20 μg L^{-1} (Stumm and Lee 1960). In contrast, higher iron content is associated with organically-stained waters as humic acids and organic complexes increase the solubility of ferrous iron (Koenings and Hooper 1976). Indeed, iron levels in Portage Lake were elevated and ranged from 112-297 μg L^{-1} and averaged 182 μg L^{-1} (Table 4).

Nutrient Levels -- In many oligotrophic lakes, epilimnetic concentrations of inorganic nitrogen decrease sharply during the summer as nitrate is assimilated by phytoplankton (Hutchinson 1957; Wetzel 1975). In turn, inorganic nitrogen reserves are replenished in the upper strata following fall turnover and nitrification. This cycle is also apparent in Portage Lake as nitrate+nitrite concentrations within the epilimnion ranged from 60-90 μg L^{-1} in May, decreased to <20 μg L^{-1} by August, and then increased to ~30 μg L^{-1} by late September (Table 4). In contrast, nitrate+nitrite levels within the hypolimnion remained relatively consistent over the growing season averaging 55 μg L^{-1}, but decreased slightly in September

Table 4. General water-quality parameters, metals, nutrient concentrations, and algal pigments within the 1-m stratum and hypolimnion of Portage 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 filterable-P (ug/L P)	Filterable reactive-P (ug/L P)	Total Kjeldahl nitrogen (ug/L N)	Ammonia (ug/L N)	Nitrate+ nitrite (ug/L N)	Reactive silicon (ug/L Si)	N:P atom ratio	Chlorophyll a (ug/L)	Phaeophytin a (ug/L)
05/14/90	1	55	6.9	10.0	1.2	18	3.5	0.7	172	7.5	2.4	2.2	86.9	0.9	55.4	2079	42	0.50	0.22
05/14/90	17	55	7.0	10.0	1.4	18	4.4	0.7	206	9.2	2.5	2.1	88.4	<1	67.7	2197	38	0.19	0.13
07/10/90	1	54	7.2	12.0	0.8	17	4.5	1.0	135	8.6	2.7	1.5	111.0	<1	7.7	2162	31	0.49	0.41
07/10/90	15	54	6.8	12.0	0.4	17	4.5	1.0	189	6.9	2.2	2.1	77.5	3.5	50.5	2380	41	0.11	0.21
08/20/90	1	49	7.0	12.0	0.5	19	3.9	1.2	283	2.5	4.5	1.5	76.0	<1	0.8	1786	68	0.62	1.12
08/20/90	15	55	6.7	12.0	0.4	17	4.8	1.2	112	3.8	1.9	1.7	110.2	12.4	45.6	1816	91	0.10	0.26
10/09/90	1	50	6.8	12.5	0.6	29	3.6	0.7	286	5.6	2.3	2.1	175.7	11.9	17.1	2615	76	0.37	0.24
10/09/90	15	50	6.9	13.0	0.6	29	3.6	0.7	250	4.6	2.5	2.5	178.2	11.2	17.1	2658	94	0.22	0.39
05/17/91	1	46	6.7	11.0	0.8	24	3.0	1.5	208	9.2	4.2	3.2	110.0	4.6	62.4	2100	41	0.37	0.13
05/17/91	14	46	6.7	11.0	1.2	24	3.0	1.5	236	7.1	3.8	2.2	113.1	4.1	59.3	2055	54	0.21	0.21
06/12/91	1	46	6.9	10.0	0.7	20	3.8	0.9	158	5.6	2.7	2.2	113.2	4.1	34.9	1790	59	0.46	0.31
06/12/91	12	46	6.8	10.0	0.8	24	3.8	0.9	154	6.1	3.6	3.5	107.7	5.6	52.2	1875	58	0.16	0.20
08/01/91	1	49	7.0	9.0	0.7	19	5.6	0.2	112	5.1	3.0	3.1	117.8	4.1	18.6	1828	59	0.61	0.55
08/01/91	16	48	6.4	7.0	0.5	18	3.7	0.8	135	5.8	3.1	2.8	102.7	10.2	39.0	1935	54	0.12	0.28
09/19/91	1	50	6.9	14.0	1.3	15	4.9	0.8	114	8.4	3.3	2.7	130.2	9.2	24.7	1834	41	0.75	0.34
09/19/91	13	49	7.0	13.0	1.4	24	4.9	0.8	118	9.0	4.0	2.6	132.6	9.2	24.7	1834	39	0.68	0.33
05/14/92	1	48	6.6	10.5	0.9	18	3.7	1.7	266	5.3	4.7	3.1	128.0	<1	90.3	2330	91	0.19	0.25
05/14/92	16	49	6.6	10.0	0.9	17	3.7	1.7	230	5.7	3.7	2.8	136.6	<1	92.4	2342	89	0.46	0.33
06/24/92	1	51	6.9	11.0	0.5	14	5.7	0.2	130	3.8	2.9	2.2	135.9	<1	38.9	1939	102	0.23	0.13
06/24/92	15	46	6.7	10.5	0.5	17	4.7	0.2	160	5.2	4.3	3.1	135.9	0.9	70.4	2199	88	0.07	0.21
08/17/92	1	49	6.5	15.0	1.1	21	4.7	1.3	297	6.5	4.3	3.1	162.4	<1	9.5	1854	59	1.13	0.54
08/17/92	13	49	6.2	12.0	1.0	38	4.7	0.2	142	7.2	12.5	14.2	127.4	10.6	75.6	2154	62	0.09	0.25
09/30/92	1	50	6.9	14.5	1.6	19	5.0	3.9	133	5.0	10.2	8.0	148.1	3.8	3.0	1939	67	0.77	0.46
09/30/92	14	50	6.9	13.5	0.5	33	4.2	2.5	152	5.8	6.2	4.7	na	2.4	61.6	1958	na	0.64	0.44

na indicates not available

as nutrients were circulated throughout the water column during turnover. Ammonia levels were very low ranging from <1-12.4 $\mu g\ L^{-1}$ (Table 4). The slight increase in ammonia during August and September is attributed to excretion by spawners and decaying salmon carcasses. Total Kjeldahl nitrogen (TKN [ammonia + organic nitrogen]) levels ranged from 76-178 $\mu g\ L^{-1}$ and are considered average for Alaska stained lakes (Table 4).

Oligotrophic lakes are often limited by phosphorus (P), but contain excess amounts of nitrogen (N). As such, increases in primary productivity are usually tied to increases in P loading (Vollenweider 1976; Schindler 1978; Smith 1979). In addition, phosphorus has been correlated with fish yield through food-chain or trophic level linkages (Foerster 1968; Brocksen *et al.* 1970; Hanson and Leggett 1982; Koenings *et al.* 1989). This is especially important in sockeye nursery lakes as the decomposition of adult salmon carcasses provides an important source of nutrients (phosphorus) that are essential for algal growth (Foerster 1968). In Portage Lake, total phosphorus (TP) levels ranged from 2.5-9.2 $\mu g\ L^{-1}$ and averaged 6.2 $\mu g\ L^{-1}$, whereas, spring (May) TP concentrations were slightly higher averaging 7.3 $\mu g\ L^{-1}$ (Table 4). However, large amounts of non-biologically available P is associated with organic stain (Frankco and Heath 1979; Kuenzler *et. al* 1979). For example, fractionation experiments revealed that colloidal P comprised ~40% of TP in organically-stained (color 29 Pt units) Packers Lake (Koenings *et. al* 1987). Thus, Portage Lake TP values need to be corrected for non-biologically available (colloidal) P. As a result, based on the three-year average of spring TP (60% x 7.3 $\mu g\ L^{-1}$ = 4.4 $\mu g\ L^{-1}$) the surface-specific loading rate is 240 mg P $m^{-2}\ yr^{-1}$, the critical P loading rate is 550 mg P $m^{-2}\ yr^{-1}$, and permissible supplemental P loading (90% of the critical loading rate) is 254 mg P $m^{-2}\ yr^{-1}$. Based on a surface area of 1.6 x $10^6\ m^2$ the amount of permissible loading would equate to 400 kg P yr^{-1}.

Total filterable (TFP) and filterable reactive phosphorus (FRP) levels exhibited little variation by season or depth, except for two samples in 1992 which were ~3 times higher (TFP = 11.4 $\mu g\ L^{-1}$, FRP = 11.1 $\mu g\ L^{-1}$) compared with other values and were attributed to contamination of the filtrate. Thus, excluding these aberrant values TFP and FRP averaged 3.4 and 2.6 $\mu g\ L^{-1}$, respectively (Table 4). Finally, reactive silicon concentrations ranged from 1,786-2,658 $\mu g\ L^{-1}$ and averaged 2,069 $\mu g\ L^{-1}$ (Table 4). Concentrations decreased slightly from ~2,200 to 1,800 $\mu g\ L^{-1}$ during the summer and may reflect increased assimilation of silica by diatoms (Hutchinson 1957).

Productivity depends not only on the amount of nutrients available, but equally as important are their relative ratios. In particular, optimal production of diatoms and green (favorable) algae occurs at a total nitrogen (N) to phosphorus (P) atom ratio of ~18:1 (Schindler 1978; Smith 1982). That is, primary production is nitrogen limited at ratios <17:1 and phosphorus limited when N:P ratios are > 17:1. In Portage Lake, the N:P ratios ranged from 31:1 to 102:1 (mean 63:1) indicating that phosphorus is the primary nutrient limiting phytoplankton production (Table 4).

Phytoplankton -- Chl a levels within the epilimnion were twice that of the hypolimnion averaging 0.54 and 0.26 $\mu g\ L^{-1}$, respectively (Table 4), but were ~50% lower compared to the mean concentration for other Alaska stained lakes (Koenings *et al.* 1990; Koenings and Edmundson 1991). Maximum chl a concentrations occurred in August and equalled 0.62 $\mu g\ L^{-1}$ in 1990, 0.61 $\mu g\ L^{-1}$ in 1991, and 1.13 $\mu g\ L^{-1}$ in 1992. Current production of phytoplankton (as indexed by chl a) in Portage Lake is due to low fertility (nutrients) rather than excessive algal grazing as the zooplankton biomass estimates are very low.

Zooplankton Abundance and Body Size -- The total macrozooplankton (TMZ) community in Portage Lake is comprised of three species of cladocerans and four species of copepods (Table 5). The cladocerans were represented by *Bosmina* sp., *Daphnia* sp. and *Holopedium* sp. and the copepods consisted of *Epichura* sp., *Cyclops* sp., *Egrasilus* sp., and *Diaptomus* sp. Maximum densities occurred during mid-August to September and were dominated by populations of *Bosmina*. On a seasonal basis, the TMZ densities (number m^{-2}) were relatively consistent averaging 24,550 in 1990, 26,950 in 1991, and 30,800 in 1992.

Cladocerans comprised ~85% of the TMZ densities (Figure 4) and *Bosmina* was by far the most abundant species. Cladoceran densities (number m^{-2}) gradually increased from 15,347 m^{-2} (range 80-29,618) in 1990 to 19,307 m^{-2} (range 64-52,548) in 1991, and reached a high

Table 5. Macrozooplankton densities (number/m^2) and body sizes (mm) by taxa and total density in Portage Lake, 1990-1992.

Date	Egrasilus		Epischura		Diaptomus		Cyclops		Bosmina		Daphnia		Holopedium		TOTAL
05/14/90	0	na	0	na	0	na	239	0.61	80	0.29	748	0.51	0	na	1,067
07/10/90	318	na	3,503	0.66	0	na	3,981	0.67	18,312	0.32	1,911	0.65	3,822	0.45	31,847
08/20/90	0	na	10,191	0.79	637	1.05	1,592	0.79	29,618	0.30	3,025	0.58	1,752	0.51	46,815
10/09/90	0	na	159	0.81	0	na	478	0.76	13,376	0.32	4,140	0.51	318	0.74	18,471
Mean	**80**	**na**	**3,463**	**0.75**	**159**	**1.05**	**1,573**	**0.71**	**15,347**	**0.31**	**2,456**	**0.56**	**1,473**	**0.57**	**24,550**
05/17/91	0	na	0	na	0	na	589	0.70	64	0.28	748	0.57	0	na	1,401
06/12/91	0	na	2,930	0.66	0	na	414	0.63	892	0.36	255	0.65	207	0.46	4,698
08/01/91	1,274	0.58	3,503	0.70	0	na	1,433	0.69	23,726	0.30	1,592	0.51	1,433	0.47	32,961
09/19/91	1,327	0.60	2,787	0.84	0	na	1,592	0.60	52,548	0.31	6,635	0.53	3,848	0.56	68,737
Mean	**650**	**0.59**	**2,305**	**0.73**	**0**	**na**	**1,007**	**0.66**	**19,308**	**0.31**	**2,308**	**0.57**	**1,372**	**0.50**	**26,949**
05/14/92	0	na	0	na	0	na	446	0.76	0	na	955	0.52	0	na	1,401
06/24/92	0	na	4,777	0.78	0	na	3,928	0.61	15,499	0.31	3,822	0.56	2,229	0.45	30,255
08/17/92	478	na	1,115	0.91	0	na	2,229	0.53	39,968	0.27	3,822	0.51	7,962	0.45	55,574
09/30/92	0	na	159	0.94	318	0.88	478	0.68	28,503	0.33	6,210	0.52	318	0.62	35,986
Mean	**120**	**na**	**1,513**	**0.88**	**80**	**0.88**	**1,770**	**0.65**	**20,993**	**0.30**	**3,702**	**0.53**	**2,627**	**0.51**	**30,804**

na indicates not available

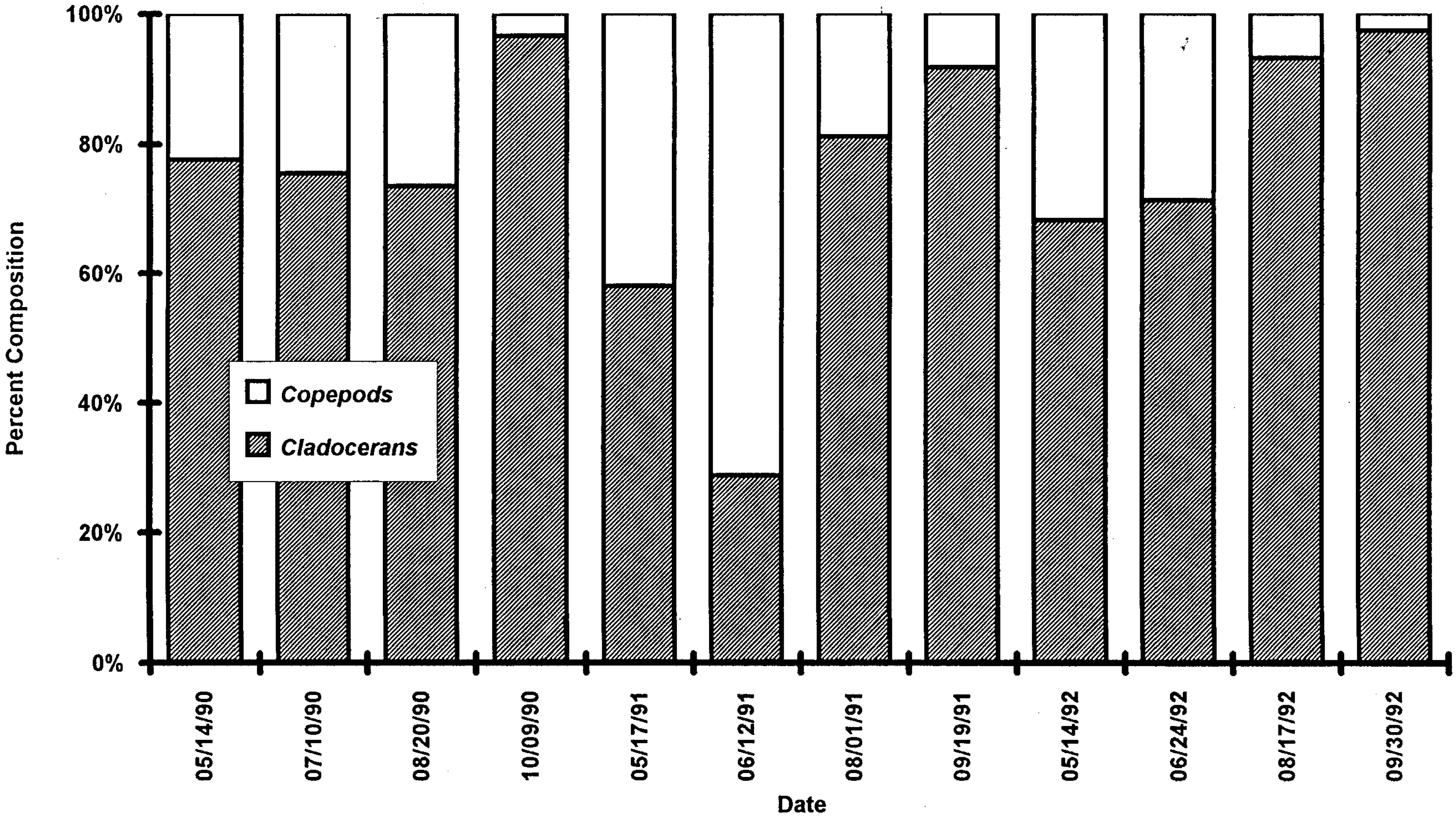

Figure 4. Percent composition of cladocerans and copepods in Portage Lake, 1990-1992.

of 20,993 m^{-2} (range 0-39,968) in 1992 (Table 4). *Daphnia* was the next most numerically dominant species followed by *Holopedium* with seasonal mean densities ranging from 2,308-3,702 m^{-2} and 1,372-2,628 m^{-2}, respectively. The weighted mean body sizes of *Bosmina* (0.31 mm) , *Daphnia* (0.54 mm), and *Holopedium* (0.49 mm) are very near the threshold size (0.40 mm) for elective feeding by sockeye salmon fry (Koenings and McDaniel 1983; Kyle *et al.* 1988), and may indicate excessive foraging pressure by rearing juveniles (Carpenter *et al.* 1985; Kyle *et al.* 1988). As a group, the copepods comprised ~16% of the TMZ density (Figure 4) and decreased slightly in abundance over the 3-year sampling period; i.e., from 5,275 m^{-2} in 1990 to 3,962 m^{-2} in 1991, and reached a low of 3,482 m^{-2} in 1992 (Table 5). Overall, *Epichura* densities ranged from 0-10,191 m^{-2} and averaged 2,427 m^{-2}, whereas *Cyclops* densities ranged from 239-3,981 m^{-2} and averaged 1,450 m^{-2}. In addition, both *Egrasilus* and *Diaptomus* appeared sporadically, but populations were much less abundant. The weighted mean body sizes of *Epichura* and *Cyclops* averaged 0.77 and 0.65 mm, respectively.

Zooplankton Biomass -- On a seasonal basis, the TMZ biomass remained relatively consistent averaging 29, 29, and 32 mg m^{-2} in 1990, 1991, and 1992, respectively (Table 6). As a group the cladocerans comprised ~75% of the TMZ biomass. In particular, *Bosmina* populations comprised ~52%; whereas, *Holopedium* and *Daphnia* each comprised ~12% of the TMZ biomass. In contrast, the copepods comprised ~25% of the TMZ biomass as *Epichura* and *Cyclops* comprised 16% and 7% , respectively. In addition, both *Diaptomus* and *Egrasilus* biomass estimates were very low each averaging only ~1% of the TMZ biomass. Portage Lake has one of the lowest TMZ biomass levels of all sockeye nursery lakes recently surveyed in the Kodiak area (Table 7).

EVALUATION

Potential Sockeye Salmon Production -- Based on spawning area, Portage Lake is estimated to support 17,300 sockeye salmon spawners. Assuming a 50:50 sex ratio, a fecundity of 2,500 egg/female, and a potential egg deposition to emergent fry survival of from 3.9% (Drucker 1970) to 10% (Foerster 1968; Koenings *et al.* 1988), predicted juvenile

Table 6. Seasonal mean macrozooplankton biomass (mg/m^2) and percent composition for each taxa in Portage Lake, 1990-1992.

Taxa/Year	1990	1991	1992
Bosmina	13.3	16.4	16.8
	47%	57%	52%
Holopedium	2.9	3.4	5.2
	10%	12%	16%
Daphnia	2.8	2.7	4.2
	10%	9%	13%
Epischura	5.8	4.2	3.7
	20%	15%	12%
Cyclops	2.8	1.4	2.1
	10%	5%	7%
Diaptomus	0.8	0.0	0.2
	3%	0%	<1%
Egrasilus	0.1	0.8	0.1
	<1%	3%	<1%
TOTAL	**28.5**	**28.9**	**32.3**

Table 7. 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

recruitment in Portage Lake is estimated to be between 843,000 and 2.2 million sockeye salmon fry. Under rearing limitation, Koenings and Burkett (1987) derived an empirical relationship between euphotic volume (EV) and sockeye salmon production. Specifically, maximum fish densities were estimated to be 110,000 per EV unit which would yield 23,000 age-1 threshold-sized (60 mm; 2.2 g) smolts. The optimal density of 54,000 per EV unit produces fewer, but larger sized smolts (4-5 g) which achieve greater marine survival. Given that Portage Lake has 12 EV units, we would predict that this system can support 577,800 sockeye fry (12 EV units x 54,000 fry/EV unit). The potential fry rearing capacity (578,000) is 30% less than the juvenile recruitment (843,000) based on spawning area, and thus it appears that Portage Lake is rearing area limited and not spawning area limited. In addition, assuming a 21% spring fry-to-smolt survival (Koenings *et al.* 1989), the EV model would predict that Portage Lake could produce 121,000 age-1 smolts. Finally, using a smolt-to-adult survival of 20% for optimum sized smolts (Koenings and Burkett 1987) a total of 23,000 adult sockeye salmon would be expected to return, which is nearly 4 times the current level of return (Table 1).

Over the past 25 years, total returns were near the predicted level (23,000) during 1977-1982 (Table 1). Returns since this period have diminished with the commercial catch declining to less than 1,000 fish per year. The fish ladder, which was installed in 1969, resulted in larger escapements and subsequently returns gradually increased. However, Kyle *et al.* (1988) showed that consecutive years of high escapements and subsequent juvenile recruitment in Frazer Lake reduced zooplankton densities, decreased body-sizes, and lowered zooplankton biomass through excessive grazing resulting in lower smolt production. Thus, fry recruitment from the high escapements in 4 of 6 years in Portage Lake may also have depressed the macrozooplankton community, resulting in decreased rearing capacity (Table 6). Further, under density-dependent conditions a significant relationship was derived between smolt biomass and zooplankton biomass (Koenings and Kyle 1991) in which smolt biomass (kg km^{-2}) = 2.1 x TMZ zooplankton biomass (mg m^{-2}). Using the combined averaged TMZ biomass of 30 mg m^{2}- for Portage Lake, this model would predict a total of 63 kg of smolt which translates to 29,000 threshold-sized (2.2 g) smolts or 14,000 optimum sized (4.5 g) smolts. Finally, 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 ~3,000 adult sockeye. This is very near the average total return of 3,207 during 1982-1992 and suggests that Portage Lake is currently forage limited.

One of the most efficient techniques to increase the capacity of a lake's rearing environment is through nutrient enrichment (e.g., Olsson *et al.* 1992). That is, supplemental nutrient loading can stimulate primary (algae) and secondary (zooplankton) production, thereby resulting in more (and larger) smolts and ultimately an increase in returning adults (LeBrasseur *et al.* 1978; Shortreed and Stockner 1981; Koenings and Burkett 1987; Kyle *et al.* 1991). Given the potential production of 23,000 adult sockeye (EV model) and a 60:40 harvest to escapement ratio (Koenings and Burkett 1987), the commercial catch for the Portage Lake component of the Peresona Bay district would be an estimated 13,800 adult sockeye. Thus, the benefit of a nutrient enrichment program based on purchasing the fertilizer and cost of application ($25,000) versus a potential harvest of 14,000 sockeye valued at $140,000 (ex-vessel dollars) is ~6:1.

RECOMMENDATIONS

The existing zooplankton biomass levels in Portage Lake are not sufficient to support increased juvenile recruitment from higher escapements or via fry stocking. However, increasing lake fertility through nutrient enrichment (fertilization) has been shown to be an effective means for increasing the rearing capacity (zooplankton biomass) of many sockeye nursery lakes (LeBrasseur 1978; Stockner and Hyatt 1984; Kyle *et al.* 1993). Therefore, nutrient enrichment of Portage Lake is recommended in order to increase the amount of forage (zooplankton) available for rearing sockeye juveniles. In order to achieve desired nutrient levels (TP = 10 $\mu g\ L^{-1}$) and maintain optimum nutrient ratios (N:P = 18) for favorable algal growth, we recommend applying 22 tons of 20-5-0 (20% nitrogen, 5% P_2O_5) liquid fertilizer to the surface of the lake. Fertilization should commence in late May to early June when surface temperatures have warmed sufficiently and continue through August (~12 weeks). Approximately 1.7 tons or 300 gal of 20-5-0 fertilizer should be applied evenly over the surface of the lake on a weekly basis. In addition, we recommend delaying any fry-stocking program for at least one year until the zooplankton community has rebounded to a level that can be sustained with increased juvenile recruitment. Moreover, until zooplankton biomass levels increase, adult sockeye escapements should not exceed the goal of 8,000; and preferably a lower escapement (5,000) would reduce pressure on the depressed zooplankton community. We also recommend hydroacoustic/townet surveys and/or qualitative smolt sampling to determine population estimates, sizes and ages of juvenile sockeye. Finally, limnological surveys at Portage Lake should continue on a three-week basis in order to monitor changes in nutrient levels and productivity and to evaluate the effects of lake fertilization.

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