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SOUTHEAST LAKE FERTILIZATION
PROJECT PROGRESS REPORT
LIMNOLOGY INVESTIGATIONS
AT BAKEWELL LAKE (1981-1982)
AND AT BADGER LAKE (1982)

by

J.P. Koenings

Number 5

Alaska Department of Fish & Game
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TABLE OF CONTENTS

Section	Page
ABSTRACT	1
INTRODUCTION	2
Study Site Description	2
METHODS	2
RESULTS	7
Physical features	7
Dissolved Gases	9
Water Quality Parameters	9
Nutrient Profiles	11
Nutrient Ratios	13
Algal Standing Crop	13
Zooplankton	15
DISCUSSION	17
RECOMMENDATIONS	24
ACKNOWLEDGEMENTS	25
REFERENCES	26

LIST OF TABLES

Table		Page
1	Depth of the euphotic zone (EZ) and the thermocline (TC); and euphotic zone to thermocline depth ratios for both Bakewell Lake in 1981 and 1982, and for Badger Lake in 1982.	8
2	Water quality parameters for both Bakewell and Badger lakes for 1981 and 1982. Values are mean concentrations followed by the number of observations in parenthesis. The epilimnetic zone was characterized by sampling at depths of 2-4 meters while the hypolimnetic zone was sampled at depths of 25-50 meters depending upon thermal structure.	10
3	Depth distributions of chlorophyll a ($\mu g\ L^{-1}$) found in Bakewell Lake during 1981 and 1982, and in Badger Lake in 1982.	14
4	Density (No./m^2) and species composition of the macro-zooplankton community observed in Bakewell Lake during 1981 and 1982, and in Badger Lake during 1982.	16

LIST OF FIGURES

Figure		Page
1	Bathymetric map of Bakewell Lake showing lake sampling Stations (A and B).	3
2	Bathymetric map of Badger Lake showing lake sampling Station (A).	5
3	Seasonal changes in iron concentration ($\mu g\ L^{-1}$) within the epilimnion and hypolimnion of Bakewell Lake during 1981 and 1982.	12
4	Community representation (percent of total macro-zooplankton) and body-size of three zooplankton species found concurrently in both Bakewell and Badger lakes during the summer of 1982.	18
5	Generalized relationship between lake rearing salmonids during the first year of lake residence and the body-size of forage (zooplankton) capable of being retained.	20

ABSTRACT

Limnological studies were initiated in 1981 on Bakewell and Badger lakes (a two lake chain) for the purpose of defining existing rearing conditions for salmon fry in order to apply applicable enhancement techniques. The clear headwater lake, Badger, has a surface area of 205 ha and is steep sided with a mean depth of 69 m while the organically stained Bakewell Lake is larger (269 ha) with a mean depth of only 24 m. Both are oligotrophic (although Bakewell does show a depression in hypolimnetic oxygen after partial overturn periods), extremely dilute, softwater lakes with little buffering capacity. Of the primary nutrients: phosphorus, nitrogen, and silicon only the inorganic nitrogen levels of both lakes underwent a summer period depression within the epilimnion.

Primary production was low as chlorophyll a concentrations were consistently below 0.5 $\mu g\ L^{-1}$ in Badger Lake, and usually at or below 1 $\mu g\ L^{-1}$ in Bakewell Lake. The zooplankton community of both lakes was dominated by *Cyclops bicuspidatus thomasi* followed by *Holopedium gibberum, Bosmina longirostris* and *Daphnia longerimus*. The species composition and body-size of the zooplankton indicate a low level of fish feeding pressure in Badger Lake, and an intermediate level in Bakewell Lake. Thus, both lakes have the ability to rear additional salmonid fry, but because of the characteristics of the zooplankton community successful lake rearing may be confined to sockeye, and to a lesser extent, to coho salmon.

INTRODUCTION

The evaluation of lake systems for to their existing potential as rearing areas for juvenile salmonids has matured in recent years to include detailed limnological studies. Such investigations are intended to quantify the basis for fish production in freshwater lakes particularly in regard to the forage (zooplankton) component. Zooplankters are extremely important food items for juvenile salmonids especially for the pelagic feeding sockeye salmon (*O. nerka*) fry. In turn, other studies center on the factors within the lake which affect zooplankton production including nutrient levels and algal standing crop. It is the ultimate coupling of the physical factors of a lake (e.g. light penetration, temperature regimes etc.) with the nutrient levels that ultimately result in the production of fish food organisms. Our purpose is to describe trophic level couplings as they relate to the capability of Bakewell and Badger Lakes to rear juvenile salmonids.

Study Site Description

The Bakewell system, (1,172 total lake acres), comprising Bakewell and Badger Lakes is located southeast of Ketchikan in the Misty Fjords National Momument, and drains into Smeaton Bay off of Behm Canal[1]. Bakewell (lower lake) and Badger (upper lake) make up a chain with Bakewell being the larger of the two (Figures 1 and 2). Bakewell is nearly 4.5 miles long, but only 0.25 miles wide with a surface area of 665 acres (2.8 x 10^{+6} m^2), and a maximum depth of 59 m. In contrast, Badger Lake is 2.1 miles long and 0.5 miles wide with a surface area of 507 acres (2.05 x 10^{+6} m^2), and a maximum depth of 146 m. Thus, Badger Lake is a clear, very deep system compared to the slightly larger, organically stained and shallower Bakewell Lake.

METHODS

Transportation to and from both lakes was provided by float-equipped aircraft. Limnological samples were collected from float plane pontoons during all surveys that were conducted between May and October 1981, and between May and August 1982. The frequency of sampling was designed to characterize the lake at 4 critical periods: spring overturn, early and late summer, and finally the fall overturn. The lake was sampled for algal nutrients (nitrogen, phosphorus, silicon and carbon) as well as other water quality parameters (see Alaska Department of Fish and Game, Lake Fertilization Guidelines) from both the epilimnetic and mid-hypolimnetic zones. Water samples from multiple (4) casts with a non-metalic Van Dorn sampler were pooled, stored in 8-10 liter transluscent carboys, cooled, and immediately transported in light-proof containers to Ketchikan for filtering and preservation. Subsequent filtered and unfiltered water samples were stored either refrigerated or frozen in acid cleaned pre-rinsed polybottles. The preprocessed water samples were then sent to the Soldotna Limnology laboratory for analysis.

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[1]Badger formally drained directly into Boca de Quadra Bay off Behm Canal.

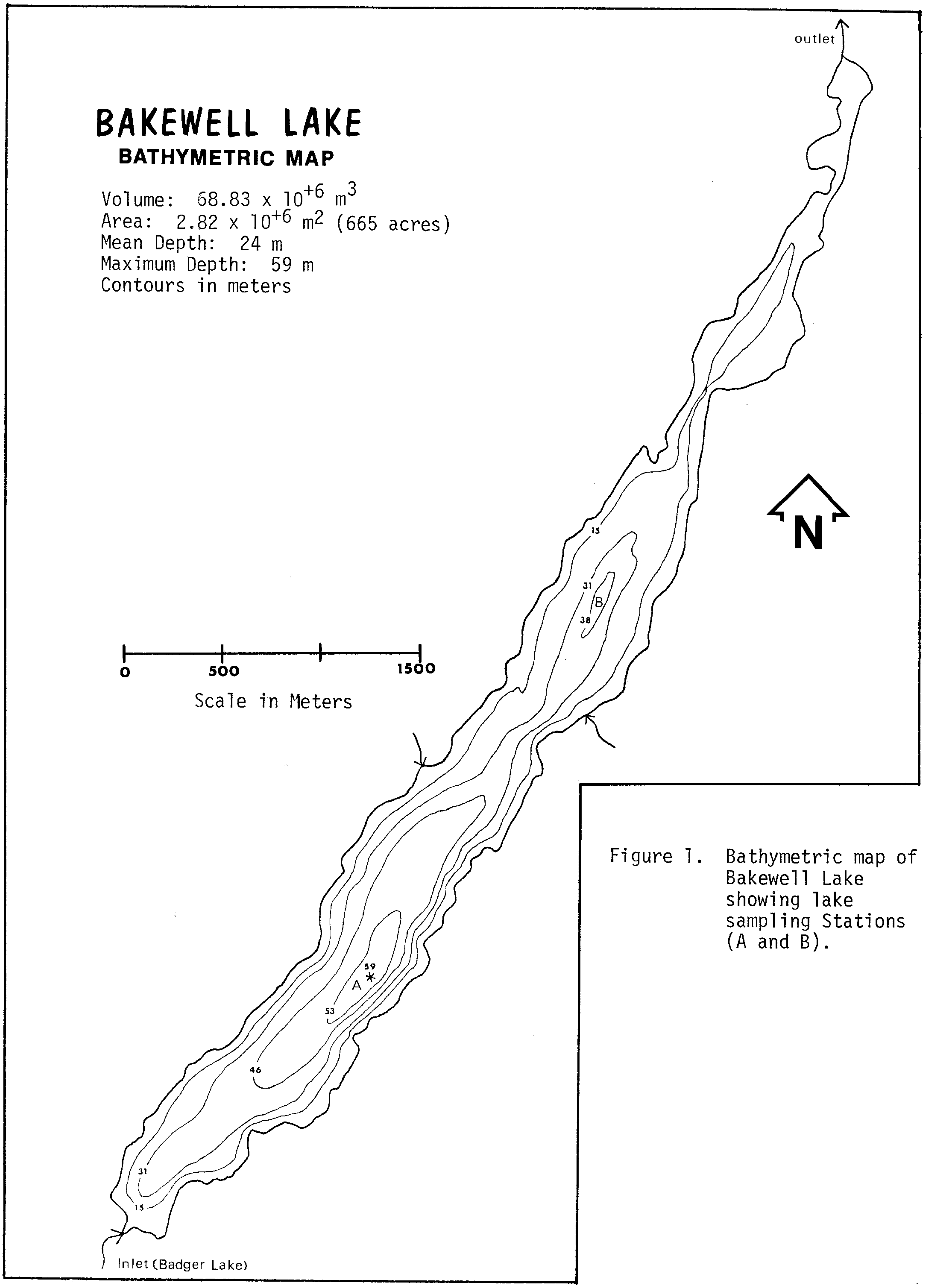

Figure 1. Bathymetric map of Bakewell Lake showing lake sampling Stations (A and B).

All chemical and biological samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology manual. In general, 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 the FRP procedure after persulfate digestion. Nitrate and nitrite were determined as nitrite following Stainton et al. (1977) after cadmium reduction of nitrate. Ammonium analysis followed Stainton et al. (1977) using the phenolhypochlorite methodology while silica analysis followed the procedure of Strickland and Parsons (1972). Inorganic carbon was calculated according to Saunders et al. (1962) after determining alkalinity by acid titration to pH 4.5 using a Corning model 399A specific ion meter.

Particulate carbon, nitrogen, and phosphorus were estimated directly from filtered seston prepared by drawing 1 to 2 liters of lake water through pre-cleaned 4.2 cm GF/F filters. The filters were stored frozen in individually marked plexislides until analyzed.

Primary production (algal standing crop) was estimated by chlorophyll a (chl a) analysis after the fluorometric procedure of Strickland and Parsons (1972). We used the low strength acid addition recommended by Reimann (1978) to estimate phaeophytin. Water samples (1-2 liters) were filtered through 4.2 cm Whatman GF/F filters to which a 1 to 2 mls of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in plexislides for later analysis.

Zooplankton were collected from either duplicate bottom to surface or surface to 50 m vertical tows using a 0.5 m diameter, 153 μ mesh conical zooplankton net. The net was pulled at constant 1m/second, and washed well before removing and then preserving the organisms in 10% neturalized sugar-formalin (Haney and Hall 1973).

Identification within the genus *Daphnia* followed Brooks (1957); of the genus *Bosmina* after Pennak (1978); and of the copepods after Wilson and Yeatman (1959), and Harding and Smith (1974). Enumeration consisted of counting triplicate 1 ml subsamples taken with a Hansen-Stempel pipette in a 1 ml Sedgewick-Rafter cell. Size (length) of individual zooplankton were obtained by counting at least ten individuals along a transect in each of the 1 ml subsamples used in identification and enumeration. Zooplankton were measured to the nearest 0.01 mm as described in Edmondson and Winberg (1971).

Bottom profiles were recorded with a Raytheon fathometer along several lake transects and from these depth recordings bathymetric maps were developed. Using each map, the area of component depth strata were determined with a polar planimeter and lake volume (V) was computed by summation of successive strata after Hutchinson (1957):

$$\text{Lake Volume} = \sum_{i=1}^{n} \frac{h}{3} (A_1 + A_2 + \sqrt{A_1 A_2})$$

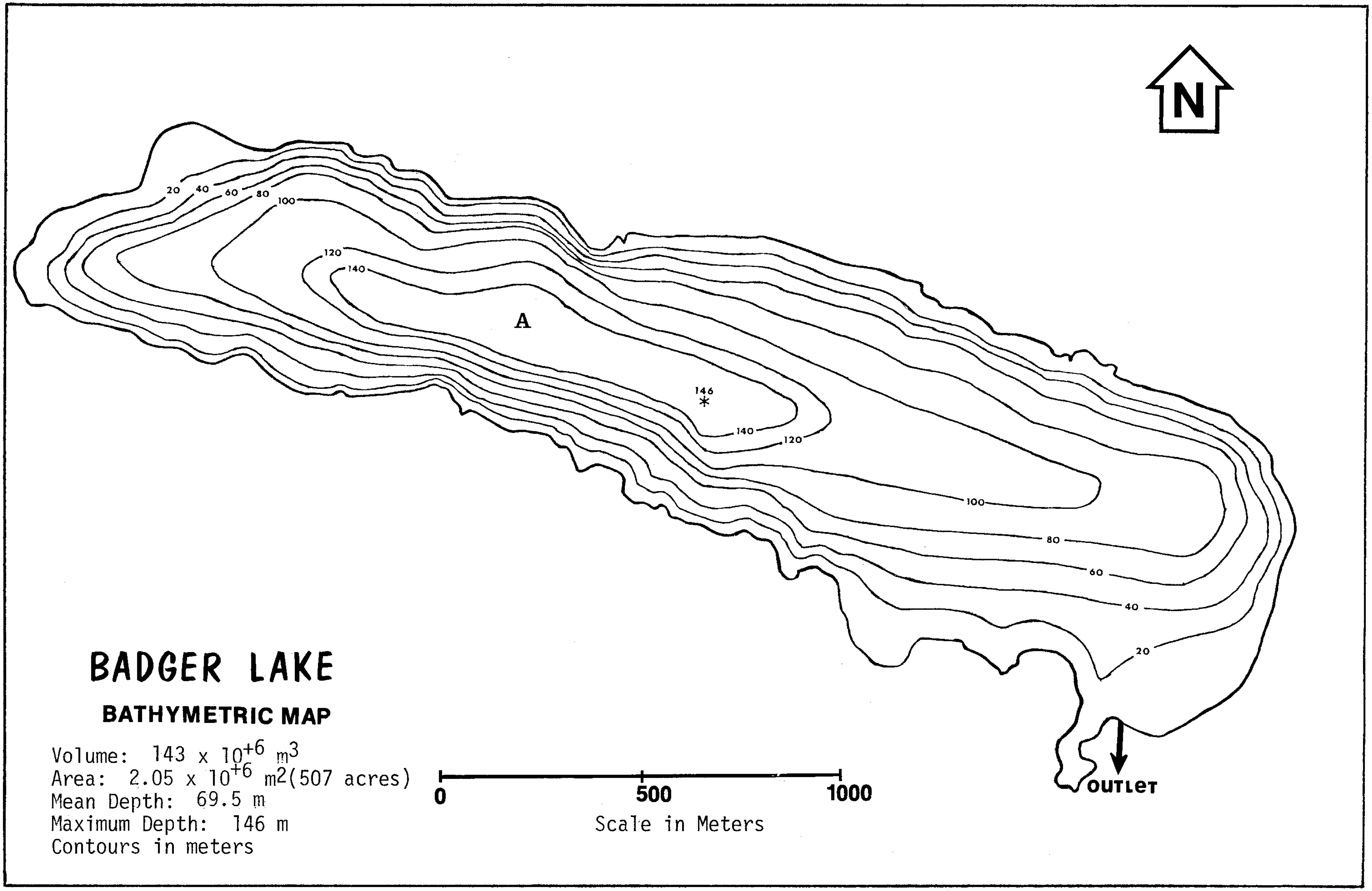

Figure 2. Bathymetric map of Badger Lake showing lake sampling Station (A).

Where: $\sum_{i-1}^{n}$ = sum of strata volumes i through n.

A_1 = surface area of upper depth strata (m^2)

A_2 = surface area of lower depth strata (m^2)

h = distance between A_1 and A_2 (m)

Lake surface area (A_L) and drainage area (A_D) were computed from topographic maps using a polar planimeter. Lake mean depth ($\bar{z}$) was calculated as:

$$\bar{z} = V/A_L$$

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

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

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

The mean watershed elevation was determined from a topographic map by marking increments at 250 m (scaled) intervals along the shoreline. For each each increment, elevations were recorded at distances of 1 km (scaled) away from and perpendicular to the shore (or the limit of the watershed when this was <1 km).

Annual precipitation was determined from hydrologic maps of long-term precipitation (U.S. Environmental Data Service 1973). Thornwaite climatic water balance tabulations (Phillips 1976), as described by Stockner and Shortreed (1979), were used to calculate lake evaporation and drainage area evapotranspiration. Annual total lake outflow (TLO) was then calculated using the following equations:

$$TLO = (P_L - E_L)\ (A_L) + (P_{DA} - E_{DA})\ (A_{DA})$$

Where: TLO = total lake outflow ($\cdot 10^6 m^3$)

P_L = annual precipitation for the lake (m)

E_L = annual lake evaporation (m)

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

P_{DA} = annual drainage area precipitation (m)

E_{DA} = annual drainage area evapotranspiration (m)

A_{DA} = drainage area ($\cdot 10^6 m^2$)

The theoretical water residence time (T_w) was then calculated as:

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

Where: T_w = theoretical water residence time (years)

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

TLO = total lake outflow ($\cdot 10^6 m^3 yr$)

The collection of physical data included the measurement of lake temperatures and light penetration at both Stations A and B. Lake temperature profiles were measured using a Montedoro-Whitney Mark IV meter. These recordings were taken at 1 m increments from the surface to 5 m, at 2 m increments from 6-12 m, and at 10 m increments from 20-50 m. The algal light compensation point was defined as the depth at which 1% of the subsurface light [photosynthetically available radiation (400 to 700 mm)] penetrated, and was measured using a Protomatic submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. Using these data, the natural logarithm of light intensity was plotted against depth, and the slope of this line was used to calculate the mean extinction coefficient. In addition, water transparency was estimated using a 20-cm Secchi disk.

RESULTS

Physical Features

The euphotic zone of Bakewell Lake extends to a little more than 4 meters (Table 1), and shows little variation within season and between years as light penetrated from 5.5 to 3.5 m. The yellow organic stain decreases the penetration of light (in the photosynthetic wavelengths) by direct absorption thereby reducing the light available for algal photosynthesis. As light absorption is rapid within upper layers of the lake (mean extinction coefficient equalled 1.13/m), the epilimnion quickly warms after ice-out in the spring and thereafter Bakewell Lake exhibits a classic thermal structure. The upper epilimnetic layer rapidly heats forming a shallow distinct stratum with the thermocline becoming strongly developed between 4 and 5 meters. Below this depth, hypolimnetic water remains at 4°C as a result of the rapid warming and wind generated mixing of only the upper few meters of the water column.

As a consequence of both rapid heating and shallow wind mixing, the euphotic zone (EZ) and the thermocline (TC) depths (Table 1) are closely aligned during the summer period. The EZ:TC ratio ranges from 1.1:1 to 1.3:1 during the summer, and of course, decreased or increased primarily as a function of temperature changes that occurred during the spring and fall periods.

The euphotic zone depth in Badger Lake was found to be considerably greater than that of Bakewell Lake. The depth of the photic zone extended from 10

Table 1. Depth of the euphotic zone (EZ) and the thermocline (TC); and the euphotic zone to thermocline depth ratios for both Bakewell Lake in 1981 and 1982, and for Badger Lake in 1982.

Date	Bakewell Lake A Depth (m) EZ	A Depth (m) TC	A Ratio EZ:TC	Bakewell Lake B Depth (m) EZ	B Depth (m) TC	B Ratio EZ:TC
1981						
15 May	4.1	1.0*	4.1:1	4.8	1.0*	4.8:1
23 Jul	4.2	3.5	1.2:1	4.4	3.5	1.3:1
20 Aug	4.3	4.0	1.1:1	4.2	4.0	1.1:1
8 Oct	3.5	10.0	0.3:1	-	-	-
1982						
28 May	3.8	1.0*	3.8:1	3.9	1.0*	3.9:1
24 Jun	5.3	4.5	1.2:1	5.4	4.5	1.2:1
29 Jul	4.9	4.0	1.2:1	5.5	5.0	1.1:1
24 Aug	- Unavailable -			- Unavailable -		
Badger Lake	**A**					
1982						
24 Jul	9.9	7.0	1.4			
04 Aug	13.4	7.0	2.0			
24 Aug	- Unavailable -					

*Thermal structure poorly defined

to nearly 14 m compared to only 4 to 5 m in Bakewell Lake. The increased clarity of the water (i.e., a lack of yellow organic acids) is visibly apparent in Badger Lake. As a consequence of deeper light penetration and the slower heating of the surface strata, the thermocline formed at 7 m or nearly double the thermocline depth found for Bakewell Lake. Thus, the euphotic zone depth was up to double the depth of the epilimnion (EZ:TC equalled 1.4:1 and 2.0:1) i.e., algae could grow and reproduce at depths well within the hypolimnion.

Temperatures within the epilimnion reached above 23°C in Bakewell Lake, and were somewhat lower in Badger reaching a maximum of 19°C. However, hypolimnetic temperatures remained fairly constant in both ranging from 3.6°C to 4.6°C in Bakewell, and from 3.1 to 4.4°C in Badger Lake. Finally, deep water heating during both the spring or fall turnover periods was limited to depths <20m. That is, approximately 4°C water was present year round at depths greater than 20 m.

Dissolved Gases

Dissolved oxygen levels in Bakewell Lake varied seasonally, but usually the increases and/or decreases found in oxygen concentrations were not biologically mediated and merely reflected a decrease and/or increase respectively in temperature. For example, in the spring of 1981, dissolved oxygen levels to as deep as 50 m equalled 12.5 mg L^{-1} (i.e., >95% saturated). However, in the spring of 1982, dissolved oxygen levels were observed to have dropped to 5.8 mg L^{-1} (at 30 m) or to levels <44% saturation. Evidently, during the prolonged ice-covered period of winter (1981-1982), dissolved oxygen levels fell in the deeper layers. After ice-out, the lake quickly warmed at the surface leaving the deeper layers uncirculated and thus, still partially devoid of oxygen.

Unlike Bakewell Lake, Badger Lake appeared to have dissolved oxygen levels consistently greater than 90% saturation on all dates and at all depths sampled.

Water Quality Parameters

Bakewell Lake is an extremely soft-water system exhibiting conductivity values ranging from 6-9 μmho/cm^2 (Table 2) within both the epilimnion and the hypolimnion. Such dilute waters are typical of Southeast Alaska and are caused by a combination of small, geologically new, steep-sided watersheds; and heavy precipitation which causes rapid flushing of the lake. Like Bakewell Lake, Badger is also an extremely soft-water system with conductivity values ranging from 11 to 13 μmho/cm^2 (Table 2). Both lake systems have very low reserves of inorganic carbon (present as the bicarbonate ion) as alkalinity values ranged from 1-4 mg L^{-1} (as $CaCO_3$). In addition, pH values ranged from 5.97 to 5.82 in Badger, and were even slightly lower in Bakewell, i.e., 4.85 to 5.37. As an aside, both these systems would be very susceptable to acid-rain poisoning, therefore, any new industrial development in the area should be closely checked as to its emissions profile.

Table 2. Water quality parameters for both Bakewell and Badger lakes for 1981 and 1982. Values are mean concentrations followed by the number of observations in parenthesis. The epilimnetic zone was characterized by sampling at depths of 2-4 meters, where the hypolimnetic zone was sampled at depths of 25-50 meters depending upon thermal structure.

Lake	Bakewell Lake								Badger Lake	
Time	May-October 1981				May-August 1982				June-August 1982	
Station	A		B		A		B		A	
Parameter / Depth	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion	Epilimnion	Hypolimnion
Conductivity (μmho/cm^2) at 25°C	7 (n=4)	6 (n=4)	7 (n=4)	7 (n=2)	8 (n=3)	9 (n=3)	8 (n=3)	8 (n=3)	13 (n=2)	11 (n=2)
pH[1]	--	--	--	--	5.29(n=4)	4.85(n=4)	5.37(n=4)	5.02(n=3)	5.97(n=3)	5.82(n=3)
Alkalinity (mg L^{-1} as $CaCO_3$)	4 (n=4)	4 (n=4)	4 (n=3)	3 (n=3)	2 (n=3)	1 (n=3)	2 (n=3)	2 (n=3)	2 (n=2)	2 (n=2)
Calcium (mg L^{-1})	2 (n-4)	1 (n=3)	2 (n=2)	3 (n=1)	0.3 (n=2)	0.3 (n=2)	0.3 (n=2)	0.3 (n=2)	0.5 (n=1)	0.5 (n=1)
Magnesium (mg L^{-1})	<0.5(n=4	<0.5 (n=3)	<0.5(n=2)	<0.5 (n=1)	<0.3 (n=2)	<0.3 (n=2)	<0.3 (n=2)	<0.3 (n=2)	<0.4 (n=1)	<0.4 (n=1)
Iron (μg L^{-1})	90 (n=4)	198 (n=4)	139 (n=3)	169 (n=3)	103 (n=4)	406 (n=4)	95 (n=4)	301 (n=4)	17 (n=3)	19 (n=3)
Reactive Silicon (μg L^{-1} as Si)	685 (n=4)	633 (n=4)	571 (n=3)	645 (n=3)	592 (n=4)	682 (n=4)	625 (n=4)	640 (n=4)	853 (n=3)	845 (n=3)
Total Phosphorus (μg L^{-1} as P)	6.8(n=4)	5.3 (n=4)	6.2(n=3)	6.2 (n=3)	4.8(n=4)	5.8 (n=4)	4.5(n=3)	5.6 (n=4)	2.6(n=3)	3.1 (n=3)
Total Filterable Phosphorus (μg L^{-1} as P)	5.0(n=4)	3.8 (n=4)	3.7(n=3)	4.3 (n=3)	3.0(n=4)	4.1(n=4)	2.8(n=4)	3.7 (n=4)	1.9(n=3)	2.6 (n=3)
Filterable Reactive Phosphorus (μg L^{-1} as P)	3.2(n=4)	2.4 (n=4)	2.2(n=3)	2.4 (n=3)	1.8(n=4)	2.7(n=4)	1.9(n=4)	2.5 (n=4)	1.4(n=3)	1.5 (n=3)
Ammonium (μg L^{-1} as N)	10 (n=4)	14 (n=4)	6 (n=3)	13 (n=3)	7 (n=4)	6 (n=4)	6 (n=4)	8 (n=4)	5 (n=3)	3 (n=3)
Nitrate + Nitrite (μg L^{-1} as N)	4 (n=4)	23 (n=4)	1 (n=3)	19 (n=3)	3 (n=4)	30 (n=4)	2 (n=4)	21 (n=4)	5 (n=3)	34 (n=3)

[1]Acid radical concentrations averaged to give mean negative log values.

Calcium and magnesium levels are also very low in both systems often reaching undetectable concentrations (≤0.3 mg L^{-1}). Apparent concentrations of calcium in Bakewell Lake (1981) ranged from 1 to 3 mg L^{-1} however, in both Badger and Bakewell in 1982, calcium and magnesium concentrations were reduced to at or below 0.5 mg L^{-1}. Differences between hypolimnetic and epilimnetic strata were not apparant for both Bakewell and Badger Lakes i.e., concentrations of calcium and magnesium were virtually equivalent.

However, unlike calcium and magnesium levels, iron concentrations varied considerably between these two systems. The clear-water system (Badger) contained between 17 and 19 $\mu g\ L^{-1}$ of iron in the epilimnion and hypolimnion respectively. Bakewell, on the other hand, contained from 90-506 $\mu g\ L^{-1}$ of iron with the epilimnion and hypolimnion showing distinct differences (Figure 3). That is, iron levels in the hypolimnion were as much as 4 to 5 fold those found in the epilimnion. Not only were iron concentrations different between strata, but iron levels also exhibited quite different seasonal patterns between years. For example, in 1981 epilimnetic and hypolimnetic iron concentrations were equivalent (approximately 100 $\mu g\ L^{-1}$) during the spring overturn (i.e., May) through July period. However, by August hypolimnetic iron concentrations began to rise whereas those in the epilimnion remained at approximately 100 $\mu g\ L^{-1}$. In 1982, the trend was somewhat different. That is, the epilimnetic iron concentrations remained at approximately 100 $\mu g\ L^{-1}$ as was observed in 1981, but hypolimnetic iron concentrations rose immediately after the partial lake overturn in late May to levels approaching 500 $\mu g\ L^{-1}$.

Nutrient Profiles

The primary nutrients studied include the algal nutrients; phosphorus, nitrogen, and silicon (Table 2). In the Bakewell system, total phosphorus (as P) levels ranged from 5.8 to 6.8 $\mu g\ L^{-1}$ in 1981, and from 4.5 to 5.8 $\mu g\ L^{-1}$ in 1982. Particulate phosphorus within the epilimnion ranged from 1.8 to 2.5 $\mu g\ L^{-1}$ in 1981, and from 1.8 to 1.7 $\mu g\ L^{-1}$ in 1982. Filterable reactive phosphorus was always detectable in Bakewell within both the epilimnion and hypolimnion ranging from 2.2 to 3.2 $\mu g\ L^{-1}$ in 1981, and from 1.8 to 2.7 $\mu g\ L^{-1}$ in 1982. In general, epilimnetic values were less than those found for the hypolimnion although the absolute differences were slight.

Inorganic nitrogen values were consistently low in both years for the Bakewell system. In addition, the epilimnion contained less nitrogen than did the hypolimnion. Nitrate + nitrite levels ranged from 1 to 4 $\mu g\ L^{-1}$ (as N) in the epilimnion in 1981, and from 2 to 3 $\mu g\ L^{-1}$ in 1982. During the summer sampling period, nitrate + nitrite levels within the epilimnion were often undetectable and ammonium levels were extremely low. In contrast, the hypolimnion contained detectable concentrations of both species throughout the sampling period. For example, in 1981 hypolimnetic nitrate + nitrite ranged from 19 to 23 $\mu g\ L^{-1}$, and in 1982 ranged from 21 to 30 $\mu g\ L^{-1}$.

Reactive silicon (as Si) levels showed much the same trend as did reactive phosphorus i.e., generally showing a slight depression in the epilimnion over that found for the hypolimnion. Again, the differences were small.

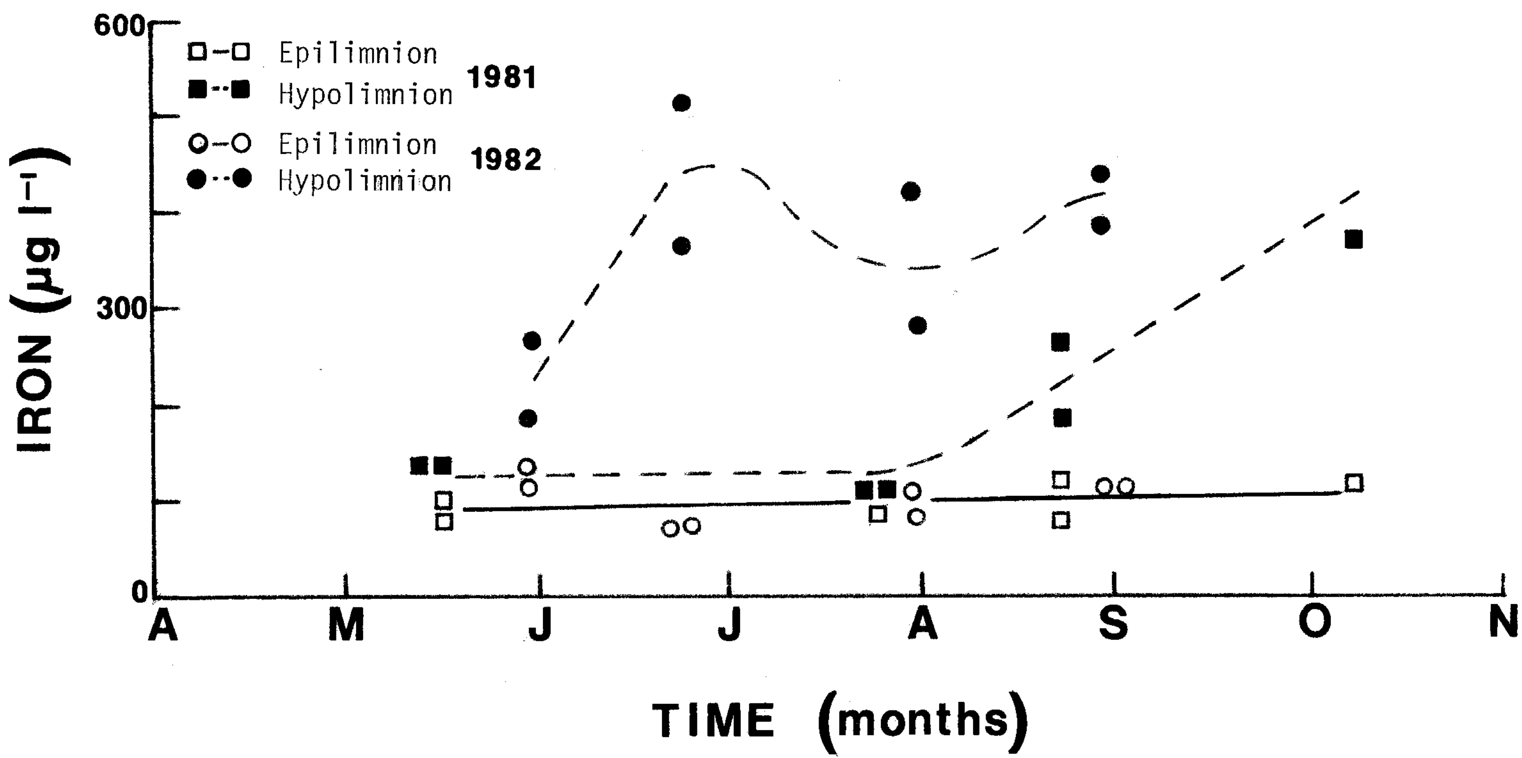

Figure 3. Seasonal changes in iron concentration ($\mu g\ L^{-1}$) within the epilimnion and hypolimnion of Bakewell Lake during 1981 and 1982.

Reactive silicon was moderately low in the Bakewell system ranging from 571 to 685 $\mu g\ L^{-1}$ in 1981, and from 592 to 682 $\mu g\ L^{-1}$ in 1982.

Badger Lake exhibited total phosphorus levels of 2.6 $\mu g\ L^{-1}$ in the epilimnion, and 3.1 $\mu g\ L^{-1}$ in the hypolimnion (Table 2). In general, total phosphorus values were less than those found for Bakewell Lake (4.5 to 5.8 $\mu g\ L^{-1}$). Filterable reactive phosphorus levels were also low ranging from 1.4 $\mu g\ L^{-1}$ (epilimnion) to 1.5 $\mu g\ L^{-1}$ (hypolimnion).

Inorganic nitrogen levels within Badger Lake were always detectable in both the epilimnion and the hypolimnion, although the levels were extremely low in the epilimnion especially in regard to nitrate + nitrite levels. Nitrate + nitrite averaged just 5 $\mu g\ L^{-1}$ (as N) in the epilimnion, but increased to 34 $\mu g\ L^{-1}$ in the hypolimnion. Ammonium levels were (like Bakewell Lake) very low with only 5 and 3 $\mu g\ L^{-1}$ recovered respectively in the epilimnion and hypolimnion.

Reactive silicon (as Si) levels within Badger Lake were virtually the same for both strata averaging 858 $\mu g\ L^{-1}$ in the epilimnion, and 845 $\mu g\ L^{-1}$ in the hypolimnion. Silicon concentrations in both strata were from 100 to 200 $\mu g\ L^{-1}$ higher than reactive silicon levels found in Bakewell Lake.

Nutrient Ratios

The ratio of Si:N:P [i.e., reactive silicon:inorganic nitrogen:total phosphorus (by atoms)] varied little in Bakewell or Badger Lakes by season within a defined stratum. The prevalent feature was for the Si:TP ratio to be near or above 100:1 in the Bakewell system, and ⩾300:1 in Badger Lake. In addition, there was very little consistent difference found in the Si:TP ratio between the epilimnion and the hypolimnion. In contrast, N:TP ratios (by atoms) ranged from 2:1 to 7:1 in the epilimnion of Bakewell Lake (in both years) compared to 12:1 to 17:1 in the hypolimnion. For Badger Lake, the N:TP ratio ranged from 7:1 to 14:1 in the epilimnion, and from 24:1 to 29:1 in the hypolimnion. In general, it appears that for every atom of total phosphorus (or reactive phosphorus) present in Bakewell Lake there exists less silicon and nitrogen when compared to Badger Lake. This could have important consequences to the algal flora found in each system, and may cause significant differences to arise between the upper (A) and lower (B) stations in Bakewell Lake.

Algal Standing Crop

The biomass of the phytoplankton was estimated by chlorophyll *a* (chl *a*) analysis at three depths: 1 m, mid-euphotic zone (ME), and the depth to which 1% of subsurface light penetrated (LE) (Table 3). The amounts of chl *a* recovered at Station A in 1981 showed a uniform depth distribution in early (May) and in the late fall (October) samples. Biomass levels at both dates were extremely low with mean values of 0.12 and 0.11 $\mu g\ L^{-1}$ during May and October respectively. However, during the summer period of July and August chl *a* levels reached 1.05 $\mu g\ L^{-1}$ and averaged 0.85 and 0.78 $\mu g\ L^{-1}$ respectively. In addition, the depth distributions were far from uniform with maximum chl *a* levels found in the upper strata.

Table 3. Depth distributions of chlorophyll a ($\mu g\ L^{-1}$) found in Bakewell Lake for 1981 and 1982, and in Badger Lake in 1982.

	Bakewell Lake					
	A			B		
Date	Depth			Depth		
1981	1 m	ME*	LE**	1 m	ME*	LE**
15 May	0.17	0.08	0.12	0.10	0.08	0.04
23 Jul	1.05	0.59	0.92	0.26	1.12	0.79
20 Aug	1.03	1.03	0.29	0.39	0.48	0.53
08 Oct	0.08	0.14	0.10	--	--	--
1982						
28 May	0.63	0.43	0.43	0.48	0.39	0.29
24 Jun	0.34	0.10	0.39	0.24	0.34	0.68
29 Jul	0.19	0.05	0.48	0.24	0.14	0.43
24 Aug	0.45	0.29	0.29	0.58	0.24	0.34
	Badger Lake					
	A					
1982						
24 Jul	0.10	0.24	0.34			
04 Aug	0.10	0.34	0.48			
24 Aug	0.14	0.29	0.29			

*Mid-euphotic zone (ME)
**Lower limit of the euphotic zone (LE) as defined by 1% of subsurface light penetration.

Chl a levels at Station B were on the average less than those found at Station A, however, the highest single chl a content (1.12 $\mu g\ L^{-1}$) was found in July at Station B.

In 1982, chl a levels and depth distributions were very much different than those found in 1981. Specifically, chl a levels in the spring were higher (0.50 $\mu g\ L^{-1}$ at Station A and 0.39 $\mu g\ L^{-1}$ at Station B) than those found in 1981 (0.12 $\mu g\ L^{-1}$ and 0.07 $\mu g\ L^{-1}$ at Stations A and B respectively). However, for the remainder of the summer growing season, June through August, chl a levels were reduced to almost one-third the 1981 levels at both stations. In addition, the chl a vertical distributions were more uniform.

In Badger Lake, chl a levels were very similar to those found in Bakewell Lake (1982) as June through August levels equalled 0.26 $\mu g\ L^{-1}$ compared to 0.29 $\mu g\ L^{-1}$ and 0.36 $\mu g\ L^{-1}$ at Stations A and B respectively in Bakewell Lake. However, the vertical distribution was much different. In Badger, higher levels of chl a were found in the lower depths compared to the surface strata. This was just opposite to the pattern found for Bakewell in 1981, and was different compared to Bakewell in 1982 when chl a levels at the three depths were very uniform.

Zooplankton

The numerically dominant organism found in the zooplankton community of Bakewell Lake during both years of study was the copepod *Cyclops biscuspidatus thomasi* which was numerically followed by *Bosmina longerostris, Holopedium gibberum,* and *Daphnia longiremis* (Table 4). *Cyclops biscuspidatus thomasi* represented from 33% to 87% of the zooplankton community in 1981, and from 66% to 98% of the zooplankton in 1982. In contrast, *Daphnia longiremis* represented from 8% to 22% of the macrozooplankton in 1981, and from <1% to 24% in 1982 with *Bosmina longirostris* representing from 4% to 50% of the zooplankton in 1981, and from <1% to 8% in 1982. Finally, *Holopedium gibberum* represented 1% to 4% of the zooplankton community during 1981, which increased in 1982 to range from 0% to 13%. The latter cladocerans were not only less numerous, but varied seasonally in abundance patterns. For example, *Daphnia longiremis* and *Holopedium gibberum* peaked earlier in the year (during the July-August period) whereas *Bosmina longerostris* apparantly peaked in numbers in the late fall-early winter.

Zooplankton densities in Bakewell Lake (excluding rotifers and copepod nauplii) ranged from 49,134/m^2 to 98,446/m^2 in 1981 at Station A, and from 30,111/m^2 to 244,126/m^2 at the same Station in 1982 (Table 4). Thus, overall density comparisons would indicate a rough doubling in zooplankton standing crop from 1981 to 1982 with most of the increase belonging to the *Cyclops bicuspidatus thomasi* population. In addition to the observed seasonal and yearly variations, station to station differences were just as evident. For example, Station A (upper end of the lake) contained consistently greater numbers of zooplankton on all dates sampled than did Station B. Differences at times reached two to three fold which were consistent over the entire range of species found. In addition, *Daphnia rosea* was never found at Station B, but was observed at Station A, albeit in very low densities. The latter pattern of occurrence suggests that this

Table 4. Density (No./m^2) and species composition of the macro-zooplankton community observed for Bakewell Lake during 1981 and 1982, and in Badger Lake during 1982.

Lake	Bakewell Lake												Badger Lake		
Year	1981				1982								1982		
Date	15 May	22 Jul		10 Oct	28 May		24 Jun		29 Jul		24 Aug		24 Jun	4 Aug	24 Aug
Organism / Station	A	A	B	A	A	B	A	B	A	B	A	B	A	A	A
Cladocerans															
Bosmina longirostris	6,648	4,203	1,414	49,287	2,296	764	535	255	3,642	1,656	9,628	4,101	5,986	11,462	22.542
Daphnia longiremis	4,050	21,651	764	9,806	4,356	3,171	3,566	728	3,744	3,439	14,264	1,350	2,165	586	0
Daphnia rosea	0	0	0	891	0	0	0	0	225	0	76	0	0	3,235	6,368
Holopedium gibberum	764	4,203	267	4,203	0	115	5,349	601	10,698	1,656	31,024	15,512	18,212	43,683	24,198
Chydorinae spp.	0	0	115	382	0	0	0	0	0	0	0	0	0	0	0
Polyphemus pediculus	0	0	0	0	0	0	0	5	178	382	255	178	225	76	0
Copepods															
Cyclops bicuspidatus thomasi	36,679	65,843	16,696	32,221	22,160	8,673	211,640	90,391	225,461	144,804	173,663	115,894	77,687	58,966	50,560
Diaptomus spp.	993	2,165	0	1,656	1,299	382	1,248	346	178	382	2,114	76	1,095	688	331
TOTAL	49,134	98,065	19,141	98,446	30,111	13,105	222,338	92,321	244,126	152,319	231,024	137,111	105,400	118,696	103,999

particular species could be a refugee from Badger Lake where its densities were found to be considerably higher.

In Badger Lake, the organisms comprising the zooplankton community were the same as that found in Bakewell, yet the relative composition was much different. First, *Daphnia longiremis* was poorly represented, its place being taken by the slightly more numerous and larger (body-size) *Daphnia rosea*. Second, *Bosmina longirostris* populations showed increased numbers ranging from 6% to 22% of the community. Third, *Holopedium gibberum* became a more dominant member of the zooplankton community with densities ranging from 17% to 37% of the total population. Yet, like Bakewell, the dominant zooplankton component still consisted of *Cyclops bicuspidatus thomasi*. However, the cyclopoid component represented only 49% to 74% of the community which was considerably below its representation in Bakewell for the same time period.

The total number of macro-zooplankton found in Badger Lake from June through August 1982, ranged from $104,000/m^2$ to $119,000/m^2$. This compared to a range of $92,000/m^2$ to $152,000/m^2$ at Station B, and from $244,000/m^2$ to $222,000/m^2$ at Station A in Bakewell Lake during the same time interval.

The shift in relative community composition of the zooplankton between these two lakes was accompanied by a difference in mean body-size (Figure 4). In all cases, within species body-size was smaller for the Bakewell representative compared to the same organism found in Badger Lake on comparable sampling dates. Specifically, mature copepods *Cyclops bicuspidatus thomasi* measured 0.40 to 0.44 mm on 24 June in Bakewell Lake whereas those in Badger Lake on the same date averaged from 0.65 to 0.69 mm. Further it was not until 24 August that the cyclopoid copepods in Bakewell reached the same size as those found in Badger Lake on 24 June. Likewise, representatives from the species *Holopedium gibberum* were consistently of greater size in Badger Lake compared to those in Bakwell Lake. In fact, on 24 August, *Holopedium* had a mean size of between 0.44 and 0.49 mm in Bakewell Lake but were nearly double in size (0.85 to 0.89 mm) at the same time in Badger Lake. The trend of larger body-sized individuals being found in Badger Lake not only applied to *Cyclops bicuspidatus thomasi*, *Bosmina longirostris*, and *Holopedium gibberum*, but to the rarer organisms as well e.g., *Diaptomus* sp., *Daphnia longiremis*, and *Daphnia rosea*. Finally, for both the *Holopedium* and *Bosmina* populations not only were the mean body-sizes greater in Badger Lake compared to Bakewell, but their relative population densities were also greater.

DISCUSSION

Both Bakewell and Badger lakes are unproductive (oligotrophic), extremely "soft-water" systems. However, this does not imply that both systems are incapable of rearing salmonid fry and producing salmon smolts. To the contrary, both lakes have excellent potentials to rear juvenile salmonids. This conclusion is based upon the combined physical, chemical, and biological features of each system.

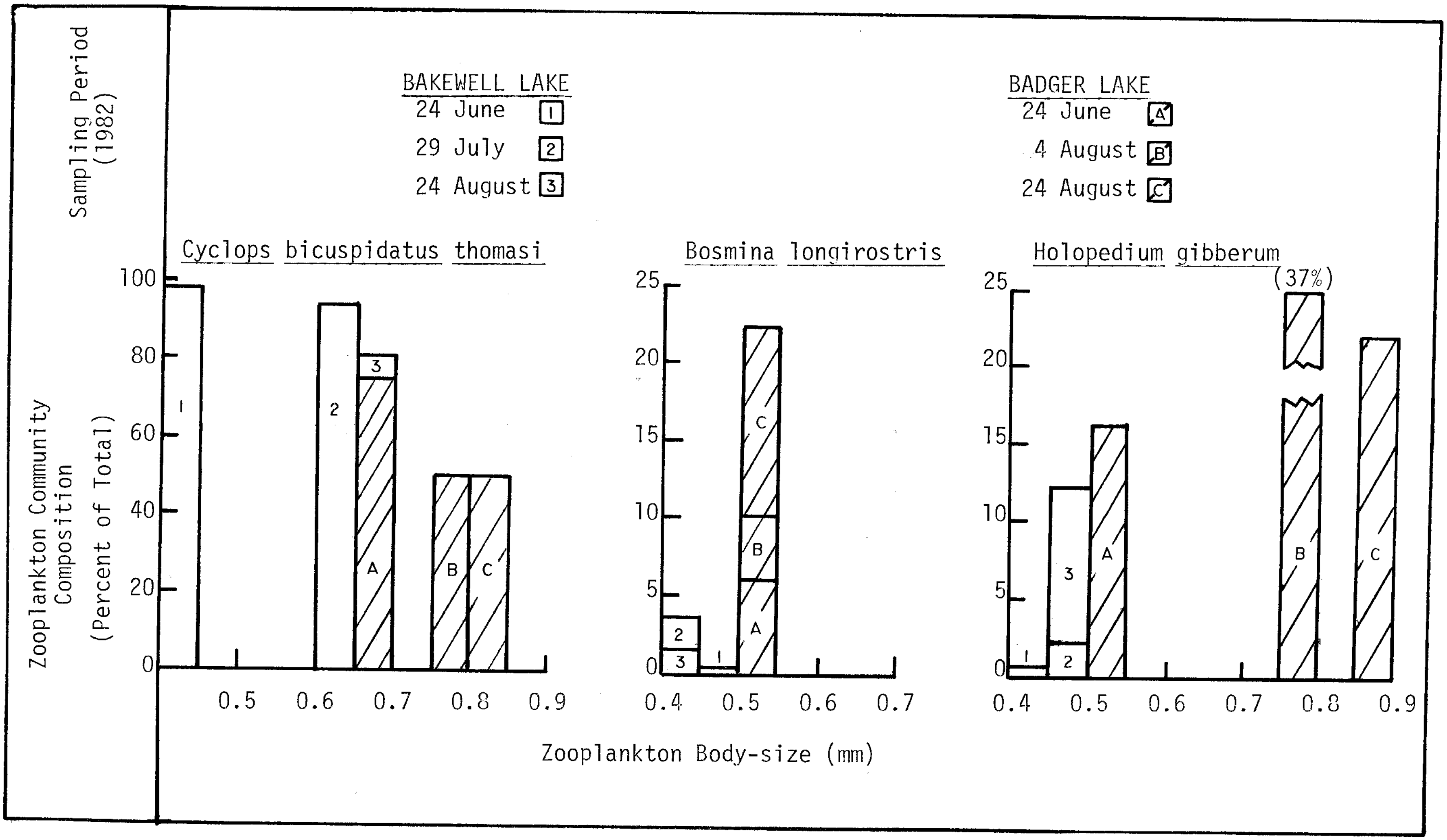

Figure 4. Community representation (percent of total macro-zooplankton) and body-size of three zooplankton species found concurrently in both Bakewell and Badger lakes during the summer of 1982.

Bakewell Lake is a brown-water system with an acid pH, and a shallow euphotic zone. Thermal stratification sets in early and is strongly developed throughout the summer growing season. As a consequence of the thermal heating of just the upper stratum, temperatures in Bakewell Lake can exceed 23°C, and in fact, may approach 25°C during a sunny calm period. This has the general effect of increasing biological production, yet may work to exclude the rearing sockeye fry from the upper strata as 24°C has been described as a lethal temperature for salmon fry (Scott and Crossman 1973). In addition, sockeye fry have been reported to have the greatest food conversion efficiencies at 9° to 13°C (Foerster 1968), and seem to prefer temperatures in the 12 to 14°C range. For example, Goodlad et al. (1974) found that within all lakes studied, sockeye fry and fingerlings were rarely found in temperatures exceeding 15°C. In addition, the effect of the warm temperatures may be to restrict the fry to only short excursions into the epilimnion and therefore the euphotic zone. Since sockeye fry are visual feeders (Eggers 1978) this mechanism could limit the amount of time the fry could spend feeding. Thus, in brown water systems like Bakewell a population of rearing sockeye fry may be forced to feed either at depths at or below the thermocline, or for only short periods within the epilimnion leaving the epilimnion open for longer periods of time to other pelagic rearing fishes [e.g. three-spined stickleback (*Gasterosteus aculeatus*)] that are more tolerant of warmer temperatures (Cannon 1981).

Another consequence of the rapid stratification of brown water systems is the tendency of such systems to skip an overturn period in the spring or to overturn partially. This was observed in the spring of 1982 for Bakewell Lake, which had the effect of changing the water quality of the hypolimnion (Figure 3). In particular, iron levels rose when dissolved oxygen levels became depressed. Had such a problem become aggravated by a prolonged winter the hypolimnion might well have become a less suitable environment for rearing salmonids.

In contrast, Badger Lake also stratified, but its epilimnetic volume is larger than that of Bakewell (per unit lake area). Consequently, the epilimnetic temperatures tended to be below 20°C yet, at the same time, temperatures were found at times to be greater than 15°C. In addition, the overall depth of Badger insures a large hypolimnetic-epilimnetic volume ratio (unlike Bakewell Lake) which reduces the possibility of any depletion in oxygen levels.

Like the more obvious temperature and oxygen limitations on rearing fry distributions, nutrient concentrations can also influence rearing conditions for salmonid fry. In Bakewell Lake, for example, the epilimnetic concentrations of nitrogen were extremely low during the growing season. At the same time, the concentrations of reactive phosphorus and reactive silicon were readily detectable, and more importantly were high relative to the amount of nitrogen present. The level (and ratio) of available nutrients within the euphotic zone (especially reactive silicon) suggested that diatoms were not an important or dominant member of the algal community. Thus, the algal flora may have consisted of mostly green and/or blue-green phytoplankton. It has been suggested that gelatinous green and colonial blue-green algae are, in general, less available as food to zooplankton (Porter 1975, 1977). Further, the nutrient ratios suggested that nitrogen could be acting as a primary nutrient determining algal species succession in Bakewell Lake. In essence then, both nutrient concentration (TP) and relative ratio data (N:TP) indicate that increasing the productive potential of Bakewell Lake for fish food organisms may involve the addition of inorganic nitrogen. This would act to decrease any competitive advantage for nutrient uptake by green and blue-green algal species by virtue of increasing a low N:P ratio (Schindler 1977, Barica et al. 1980).

Nonetheless, both Bakewell and Badger Lakes presently produce populations of zooplankton, a primary forage food for rearing salmonids. In 1982 (when comparative information is available), the density of zooplankton in Badger Lake was similar to that found at Station B in Bakewell Lake (Table 4). However, at Station A in Bakewell, the density of zooplankton was nearly double that of either Station B or Badger Lake. In addition, the relative density of cladocerans versus copepods was higher in Badger compared to Bakewell Lake, and the body-size of individual species was larger in Badger compared to either station in Bakewell Lake (Figure 4). So although the density of zooplankton may be somewhat less in Badger, the quality of zooplankton still available to rearing fry may be higher in Badger. Thus, community characteristics of the zooplankton (species composition and body-size) are just as important as overall density in regards to supporting a population of rearing fry.

The ability of various species of salmonids to utilize potentially different portions of the zooplankton community has become increasingly documented (Figure 5). The diet of rearing fry changes depending on seasonal variation in prey densities, the increasing size of the rearing fish, the seasonal (and diel) migration patterns for both the prey and predators; and the differential ability of the predator fish to consume prey, each type of which has different predator escape abilities (Drenner and McComas 1980). Empirically it has been found that sockeye fry, for example, can learn to consume members of the zooplankton community with a body-size $\geqslant$0.4 mm, but in general, even within a mixed zooplankton community elect to eat large cladocerans (Jacnicke et al. 1980, Rieman 1981). However, when preferred large body sized prey disappears (or is consumed), the fry will continue to feed size selectively concentrating on the smaller components of the cladoceran community. If the situation presents itself and cladocerans are entirely missing from the zooplankton community (glacial lakes) or if the lake is to shallow to allow effective diel migration of the zooplankton, sockeye will feed effectively on copepods including as a last resort the cyclopoid component. Thus, sockeye fry act as almost obligate planktivores. Coho salmon fry on the other hand can be described as more of a facultative planktivore that will only feed on larger zooplankton forms, and will then switch to the benthic feeding mode if prey size in the pelagic zone drops below approximately 1.0 mm (Crone 1981). Similarly, from what little information we do have, chinook fry shut down their pelagic feeding mode when zooplankton sizes fall below 1.5 mm (Craddock et al. 1976). In addition, Tobias (1982) found the stomachs of one year old chinook planted as fry in landlocked Scout Lake (Kenai Peninsula) to be packed with the littoral zone zooplankton *Eurycercus glacialis* which ranged in size from 4 to 6 mm. Heard (1982) reported that chinook fry planted in Tranquil Lake (Baronof Island) ceased growth when the lake

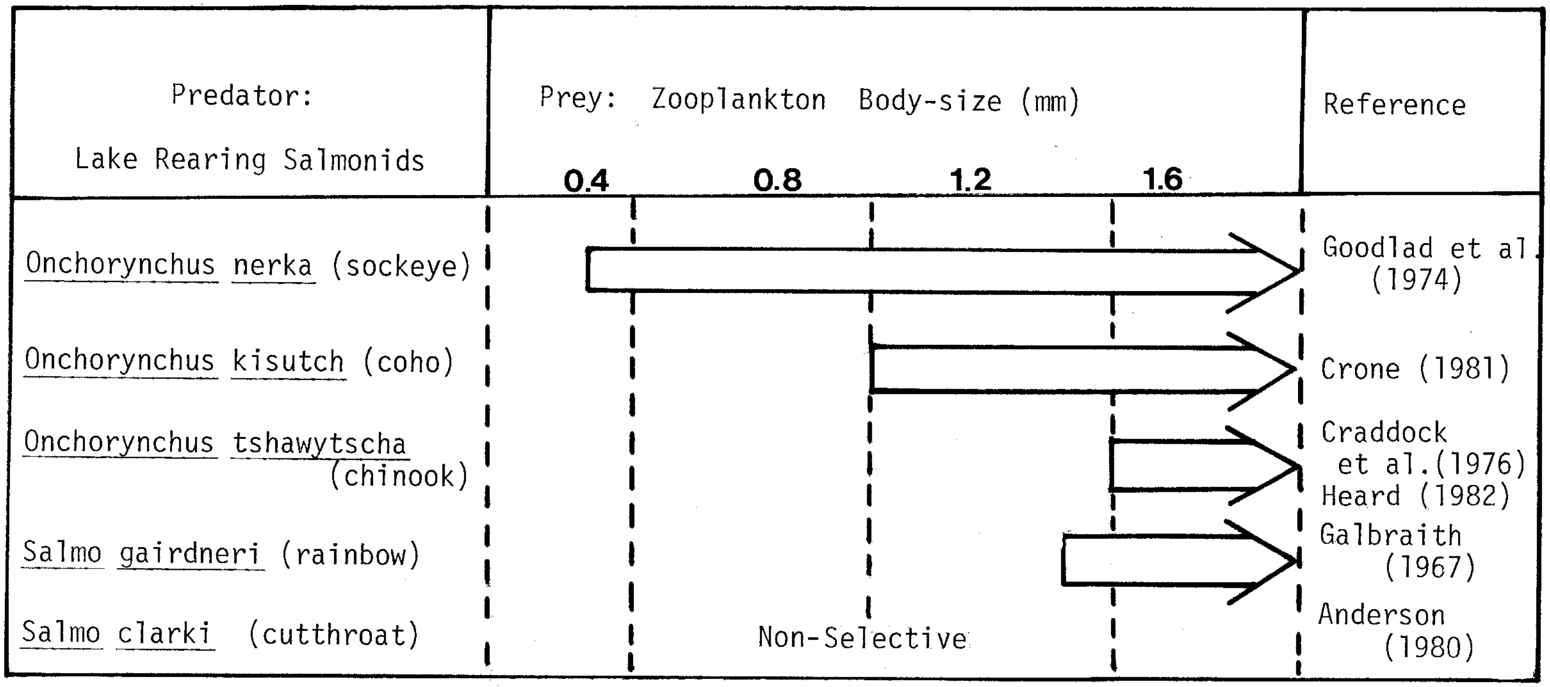

Figure 5. Generalized relationship between lake rearing salmonids during the first year of lake residence and the body-size of forage (zooplankton) capable of being retained.

became devoid of zooplankton ≥1.5 mm. At this time, the chinook fry (with empty stomachs) were found in the littoral zone undergoing intense competition with rearing coho fry.

It may well be that given the proper forage organisms all three species of salmon will rear in lakes. However, it appears that given a coho-sockeye mixture, the sockeye fry (by their efficient size selective feeding) tend to outcompete coho fry for zooplankton in the pelagic zone forcing the coho to the littoral area. However, without the sockeye pressure, coho fry will rear successfully on pelagic zooplankton (Crone 1981). In much the same manner, a chinook-coho mixture may find the coho fry feeding pelagically forcing the chinook fry into the littoral zone. However, without the pressure from the coho stocks, the chinook fry may well rear pelagically, but only if the lake contains the proper size of and/or type forage food which appears to be large, slow moving cladocerans (Craddock et al. 1976, Tobias 1982).

It must be stressed that it is difficult to find large (≥1.5 mm) body-sized zooplankton in the pelagic zone of many Alaskan lakes primarily because the sockeye, coho and/or rainbow fry usually present selectively remove and/or partition out the entire size range zooplankton [either < or ≥1.5 mm in size (Figure 5)]. Thus, the only habitat suitable for lake rearing chinook fry may be the pelagic/littoral zone of 'fishless' lakes or the weedy littoral zones of lakes containing fish such as Scout Lake. In both situations, chinook fry may rear successfully, and may smolt if the outlet attraction is sufficiently strong.

The apparent ability of these three species to rear successfully in lake i.e., sockeye greater than coho and coho greater than chinook, may be in part, do to their differential ability to retain zooplankton. That is, gill rakers in sockeye are more numerous and closer together than are those in coho. Likewise, the same relative relationship holds for coho versus chinook i.e., coho have a smaller gill raker distance than do chinook. Thus, the ability of rearing fry to use increasingly smaller forage organisms in the zooplankton community, as indicated by gill raker distribution, is sockeye greater than coho and coho greater than chinook. It is then suggested, that sockeye are the dominate feeders in the pelagic zone, and that coho can perform equally well either in the pelagic zone (with the right-sized forage) or in the littoral zone feeding on benthic invertebrates. However, chinook fry appear to be very weak pelagic zone feeders (again this may change given the proper sized forage), and thus, would perform better in a lake rearing mode either in lakes with good littoral development or in 'fishless' systems.

Applying this empirical feeding ecology to Bakewell and Badger lakes, it is apparent from the zooplankton community composition (Table 4) and the specific sizes of the organisms present (Figure 4) that rearing fry forage organisms ≤1.0 are heavily represented whereas those organisms >1.0 mm are under represented. Further, since the littoral areas in both systems are minimal (Figures 1 and 2), it may well be that the rearing fry in both systems are relatively dependent upon the pelagic zone for forage. In turn, within the pelagic zone, we have already detected a difference between the two systems in regard to both zooplankton community composition and the body-size of the individual species. It must be kept in mind that the zooplankton community found in both lakes was that remaining after fish predation had already taken place. Thus, the community composition and size of the zooplankton may well be dependent upon fish predation, and in turn tell us something about pre-existing predation pressure on each group.

The existing predation pressure on Badger Lake zooplankton standing stock comes from coho and rainbow trout fry both of which have forage preferences for larger body-sized zooplankton (Figure 5). However, the pressure on the Bakewell Lake zooplankton comes not only from coho and rainbow trout, but includes stickleback and sockeye fry as well. It is not surprising then that the zooplankton of Badger are larger in body-size (Figure 4) given the absence of predation pressure on zooplankton of body-size approximately <1.0 mm, i.e., the presence of rainbow trout and coho, but the absence of sockeye and stickleback. In essence, the types of zooplankton and their relative body-size all point to the conclusion that Badger Lake is under utilized as a rearing area when compared to Bakewell Lake. Further, in comparison to other Alaskan lakes it appears that the predation pressure on the zooplankton is not excessive in either lake, and thus both lakes can rear additional salmon fry.

RECOMMENDATIONS

1) Obtain adult sockeye and coho escapement estimates as well as smolt population characteristics (e.g., length, weight, age).

2) Increase access to Bakewell and, in particular, Badger Lakes by anadromous salmon (sockeye/coho) through modification/maintenance of the Bakewell Lake fishpass; and, if necessary, through improvement of the Bakewell-Badger connection.

3) Investigate the vertical, horizontal, and seasonal distribution of rearing sockeye and coho fry, particularly, in relation to that of the three-spine stickleback.

4) An increase in the production of fish forage (zooplankton) can be achieved through the addition of a high atom ratio (nitrogen:phosphorus) fertilizer principally in Badger Lake.

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