FRI-UW-7802
January 1978

FISHERIES RESEARCH INSTITUTE
College of Fisheries
University of Washington
Seattle, Washington 98195

COLLECTION AND ANALYSIS OF BIOLOGICAL DATA FROM THE WOOD RIVER LAKE SYSTEM, NUSHAGAK DISTRICT, BRISTOL BAY, ALASKA

FERTILIZATION OF LITTLE TOGIAK LAKE

by

Donald E. Rogers

FINAL REPORT
For the Period May 15, 1977 to December 1, 1977
Alaska Department of Fish and Game

Approved

Submitted January 30, 1978

Roy E. Nakatani
for Director

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FERTILIZATION OF LITTLE TOGIAK LAKE[1]

INTRODUCTION

The catches of sockeye salmon in the Nushagak District of Bristol Bay have declined greatly since the initial buildup of the fishery in the late 1800's. The most recent decline, from an annual average catch of near 3 million (1919-1948) to just under 1 million (1949-present), began when 5 successive brood years with above-average escapements (1944-1948) produced very small returns. The Wood River Lake system is the major producer of sockeye salmon in the Nushagak District and the smolts that migrate from these lakes are presently among the smallest in Bristol Bay. The growth of juvenile sockeye in the Wood River lakes is partly dependent on their density and is directly related to the abundance of their food (zooplankton and insects).

We hypothesized that the production of zooplankton and chironomids was limited by the biomass of phytoplankton and that primary productivity was limited by the scarcity of phosphorus. Therefore, if phosphorus was added to a lake, it should ultimately result in increased growth and survival of juvenile sockeye salmon and an increase in the abundance of adult runs. We chose Little Togiak Lake to test these hypotheses because it is relatively small and the sockeye populations had a history of high density and poor growth relative to the populations in the other Wood River lakes.

We added commercial fertilizers (primarily diammonium phosphate) to the upper end of Little Togiak Lake in August 1974 and 1975; then, in July 1976 we added a technical grade of diammonium phosphate to most of the lake. There was an immediate increase in the concentration of chlorophyll and a decrease in water transparency following each addition of phosphate; however, a significant increase in the abundance of zooplankton was only observed in 1976 when the entire lake was fertilized in July.[2] Through the summer of

---

[1]Supported by the Alaska Department of Fish and Game and the National Marine Fisheries Service.

[2]Rogers, Donald E. 1976. Fertilization of Little Togiak Lake. Univ. of Washington, Fish. Res. Inst. Part B, Final Report to ADF&G, FRI-UW 7617-B.

1976 we had not detected a significant increase in the abundance of chironomids nor a significant increase in the growth of the fish during June-August. However, the smolts that migrated from Little Togiak Lake in the spring of 1976 were significantly larger than the other smolts in the lake system.

Our primary objectives in 1977 were to 1) fertilize Little Togiak Lake, but in a different manner than done in previous years; 2) determine the effects of the fertilization on standing crops of phytoplankton, zooplankton, and chironomids, and the growth of fish during the summer; 3) determine the effects of the fertilizations in 1975 and 1976 on the size and age compositions of the smolts that migrated from the lake in the spring of 1977; and 4) estimate the escapement into Little Togiak Lake.

METHODS

The sampling stations on Little Togiak Lake are shown in Fig. 1 and the areas on which phosphates were applied are shown in Fig. 2. The annual additions of diammonium phosphate are given in Table 1. The fertilizer was dissolved in water in a 55-gal drum and then sprayed over the lake from a moving boat. In 1974 and 1975 the diammonium phosphate was in a commercial fertilizer (21-53-0), whereas in 1976 and 1977 we used a technical grade of diammonium phosphate. We have used fertilizers that were high in phosphates because in 1962 and 1963 there were sufficient concentrations of nitrogen during the summer (0.1 to 0.3 mg/l of nitrate nitrogen); likewise, silicates did not appear to be limiting to phytoplankton growth as the averages for the lakes ranged from 2.1 to 3.5 mg/l of silicon. However, the concentrations of phosphate phosphorus were never greater than 0.02 mg/l and were usually lower than the detectable limit of 0.006 mg/l (Gadau 1966). The concentration of phosphorus that was added to Little Togiak Lake on a given day was less than one-tenth of the concentration that is commonly applied to fish ponds in the southeastern United States (Liehtkoppler and Boyd 1977); and on an annual basis the concentration added to Little Togiak Lake was about one one-hundredth of the amounts added to fish ponds.

The concentrations of phosphorus and nitrogen were measured before, during, and after the applications of fertilizer in 1976 and 1977. Water samples were collected at 5, 15, and 20 m at each of two stations on Little

Togiak and at one station on Lake Nerka. The chemical determinations were done in Seattle. Specific conductance was measured with a solu bridge on water collected from 5 and 15 m at both stations on Little Togiak Lake at weekly intervals and at two stations on Lake Aleknagik at monthly intervals.

Incident solar radiation was measured daily with a Belfort phyheliometer and the relative lake level (0 = mean annual low water which occurs in April) was measured in Lake Nerka daily from June through September. Surface water temperature was measured with all field sampling so that observations were taken at six or more stations at two-three day intervals throughout the summer, and temperature profiles were taken at three stations on Little Togiak at weekly intervals and on Lake Aleknagik at monthly intervals. Secchi depth was measured weekly at six stations and almost daily while fertilizer was being applied.

The relative standing crop of phytoplankton was estimated by the concentration of chlorophyll *a*. Two liters of water were collected from 1, 3, 5, 7, 10, 15, 20, 30, and 45 m. The water was filtered through an HA Milapore Filter (0.8μ) and absorbances were measured with a spectrophotometer. The chlorophyll was calculated from the Parsons and Strickland equations. Phytoplankton counts and cell volumes were measured from samples of water collected from 5, 15, and 20 m.

The abundance of zooplankton was estimated from vertical hauls from 60 m or near the bottom with a 1/2-m net of No. 6 mesh. The volume of plankton was measured after the sample had settled for 1/2 hr and the number of organisms was determined from expanded average counts of two-three subsamples. The abundance of individual species or categories of zooplankton was then calculated in terms of the number per m^2 of lake surface area. The No. 6 mesh does not retain many of the small zooplankters, e.g., nauplii stages of copepods and most rotifers, but it does sample most of the plankton that is eaten by the small fish. Zooplankton and phytoplankton sampling were conducted weekly in Little Togiak and monthly in Lake Aleknagik.

Emergent insect traps that sampled 1/2-m^2 of lake bottom were placed in the lake as soon as the ice was gone. Traps were located at 5 stations on Little Togiak and 3 stations on Lake Aleknagik. The traps sampled continuously but the catches were usually enumerated at 2- or 3-day intervals. Bottom samples were collected with an Ekman sampler at insect traps Nos. 1 and 5, biweekly, to estimate the relative abundance of midge larvae and other benthic organisms in Little Togiak Lake.

The relative abundance and average length of fishes in the littoral zone during the early summer was measured from beach seine hauls at seven stations on Little Togiak and ten stations on Lake Aleknagik. Hauls were made at about weekly intervals between June 26 and August 3. The catches or subsamples of large catches were preserved in 10% Formalin and then enumerated and lengths of the fish were measured after 1 or 2 days. Mean lengths were calculated for the major age groups and these were then converted to the equivalent lengths of live fish by multiplying by a shrinkage factor (1.031 for sockeye and char fry, and 1.015 for threespine stickleback).

The relative abundance and size of fish in the limnetic zone were estimated from townet sampling conducted during the night. Tows were made on 3 nights in Little Togiak Lake and Lake Nerka and on 1 night in each of the other lakes (Aleknagik, Beverley, and Kulik). We used a 9x9 ft net that was towed at the surface for 5 min. Tows had been made at both the surface (0-3 m) and below (3-6 m) during the years 1958-1971, but only at the surface since 1972. The geometric means of the catches in recent years were adjusted to be comparable to past years because catches of sockeye in Little Togiak Lake tended to be greater in the deep tows than in the surface ones, whereas catches of threespine stickleback were usually greater in the surface tows.

The number of smolts that migrated from Little Togiak Lake in 1977 was estimated by expanded fykenet catches (as in 1976). The opening of the net was 8 ft wide at the wings and 2 locations in the river were used, one where the river was 160 ft wide (6/14-21) and another where it was 48 ft wide (6/22-8/14). During the first week of sampling the water level was about 6 inches above the net and the efficiency of sampling may have been reduced; nevertheless, the catch for a 24-hr period was multiplied by either 20 or 6 to estimate the total number of smolts. Daily samples of smolts were collected to determine the size and age composition in the migration. The abundance, size, and age composition of smolts from the lake system were estimated in the Wood River (outlet of Lake Aleknagik) by the Alaska Department of Fish and Game.

The number of adult sockeye salmon that migrated into Little Togiak Lake was estimated from expanded 1/2-hr counts made during daylight hours. The age composition of the escapement was estimated from otoliths that were collected from spawned-out fish in September, and the runs for each age group were estimated by multiplying the number of fish in the escapement in the Nushagak District.

RESULTS

Figs. 3 and 4 show several of the physical conditions that prevailed during the summers of 1973-1977. Spring weather was exceptionally warm in 1974, ice breakup was early, water level was low, and temperatures were unusually high that year. Conditions in 1977 were atypical in that the lake level was very high through August, water temperatures in September were warmer than normal, water transparency was low, and conductivity varied during the summer from very low in early July to very high in early September.

The concentration of phosphorus increased and the nitrogen to phosphorus ratio decreased following the additions of fertilizer in both 1976 and 1977 (Table 2). In 1977, the concentration of phosphorus increased in the upper end of the lake (station 1) even though phosphates were not directly added there (Table 3).

Primary Productivity

When fertilizer was applied to the middle of Little Togiak Lake in mid-July of 1977, the concentration of chlorophyll was low in the upper end of the lake and slightly above average in the lower part (station 5). Although fertilizer was not directly applied to the upper end of the lake, the effect of the added phosphates was greater there than in the area where it was applied (Fig. 5). In 1974 and 1975, when fertilizer was added only to the upper end of the lake, it did not immediately affect the phytoplankton in the remainder of the lake. Surface currents probably transported some of the phosphates up the lake (i.e., in the opposite direction from the outlet) in 1977 and kept most of the fertilizer in the upper basin in 1974 and 1975.

Blue-green algae were not observed in the phytoplankton samples from 1976; and although they did occur in some samples in 1977, the blue-green algae made up only 0.2% of the average total phytoplankton volume during that summer. Thus the low N/P ratios that occurred in August of 1977 apparently did not cause a significant bloom of blue-green algae. Diatoms were still most abundant in the phytoplankton.

The concentration of chlorophyll in Little Togiak from mid-July to mid-August exceeded the concentrations in past years almost two-fold. Although most of the high concentration of chlorophyll in Little Togiak was probably caused by the addition of diammonium phosphate, part of the increase was likely caused by other factors, e.g., high runoff in 1977, because the concentration of chlorophyll in Lake Aleknagik was higher in 1977 than in any previous year (1967-1976).

The abundance of herbivorous zooplankton was very low in 1977 until late August. The decrease in phytoplankton (chlorophyll) during August coincided with the increase in abundance of the large forms of herbivorous zooplankton (Fig. 6). Therefore, the high concentration of phytoplankton in 1977 may have been partially caused by a relatively low rate of predation by zooplankton.

Secondary Productivity

The purpose of our artificial fertilization is to increase the abundance of food for juvenile sockeye salmon, i.e., zooplankton and chironomids (midges) and hence their rates of growth. The abundance of zooplankton is controlled by their rates of growth, reproduction, and mortality. If growth and reproduction are limited by the abundance of phytoplankton, then the production of zooplankton should increase with an increase in phytoplankton and the abundance of zooplankton should also increase unless mortality rates equally increase, e.g., from predation by fish.

Our sampling of zooplankton in Little Togiak Lake ended in mid-September of 1977 and this was before the seasonal peaks in the abundances of calanoid copepods and *Daphnia* (Fig. 7). *Bosmina* was less abundant in 1977 than in any year except 1974 and *Holopedium* was very scarce in 1977. The average abundance of zooplankton during late-August to early-September in the lake system was lower in 1977 than in any previous year (1967-1976). There were large escapements of sockeye in 1974 and 1975 and subsequently high densities of fry in 1975-1976. The escapement in 1976 was about average for the lake system but there were higher than average escapements in lakes Aleknagik and Little Togiak. The high abundance of fry and holdover yearlings probably caused the low abundance of zooplankton. Calanoid copepods and *Daphnia* are particularly vulnerable to sockeye predation. *Daphnia* was especially low in abundance in 1977 in all of the lakes except Little Togiak. The fertilization probably increased the abundance of *Daphnia* in 1976 and perhaps also in 1977.

The average catches of emergent chironomids in Lake Aleknagik during the summers of 1969 through 1977 are shown in Figs. 8 and 9. In most years there is a peak emergence in late-July or early-August, but in some years and at some stations there was a very large emergence 1 to 2 weeks after ice breakup. An early emergence occurred in Bear Bay in 1977 when, during a 5-day period, the daily catches averaged 500 midges; however, catches at the other locations were lower in 1977 than in any previous year.

Midges are less abundant in Little Togiak Lake than in Lake Aleknagik. Emergent catches and the number of larvae in bottom samples have both been lower in Little Togiak Lake because it contains much less mud bottom and shallow littoral area than Lake Aleknagik. The fertilization of Little Togiak has probably caused some increase in the abundance of midges; however, the evidence is not conclusive (Fig. 10). Station 1 is located within the largest concentration of sockeye spawning in the lake and probably the densest concentration of fry in the spring. Therefore, if production of midges were increased there, it might not be evident from the catches. The abundance of midge larvae in bottom samples from the west end of the lake declined after

1974 (Table 4). However, the catches of emergent midges increased in 1977 at stations 3, 4, and 5 which could have been affected by the fertilization in 1976.

Abundance and Size of Fish During Summer

The mean catches from beach seining in Little Togiak Lake are shown by date in Fig. 11 and the annual mean catches from townetting are given in Tables 5 and 6. Beach-seine catches of sockeye fry and threespine stickleback are probably better measures of their relative abundance than are townet catches. Townet catches of fry in Little Togiak Lake are not correlated with the abundance of parent spawners whereas the beach seine catches are somewhat correlated; also there is a closer correlation between beach-seine catches and number of spawners than townet catches and spawners in Lake Aleknagik. However, townet sampling provides an estimate of the abundance of sockeye yearlings whereas they are not commonly caught by beach seining unless sets are made near migration routes.

Through 1977, the fertilization of Little Togiak Lake has not caused a significant increase in the abundance of small fish as judged by beach seine catches. Sockeye catches were higher in 1975-1977 than 1973-1974, but the parent escapements were also higher. Catches of threespine stickleback have likewise increased since 1973 but this has also occurred in Lake Aleknagik (Fig. 12). The abundance of sticklebacks throughout the lake system was reduced following the cold springs in 1971 and 1972, then an abundant year class was produced in 1974 and sticklebacks were abundant in the next 3 years.

Based on aerial surveys over 90% of the sockeye spawning in Little Togiak Lake usually occurs in the upper end of the lake (Area A). Although the fry appear to be well distributed around the lake by mid-summer as judged by beach seine and townet catches, the fry were usually smaller in Area A except in 1975 and 1976 after fertilizer was applied (Tables 7 and 8). The effect of the fertilization on the early summer growth of sockeye fry was nevertheless quite small because the fish were still well below average in length during 1975-1977. The growth of Arctic char fry and age I threespine stickleback also reflects the increased abundance of sockeye during those years (Fig. 13).

The growth of sockeye fry during 1976 and 1977 was greater than in 1975, whereas the growth of Arctic char and threespine sticklebacks was about equally poor during 1975-1977 (Table 9). The sockeye fry in Little Togiak Lake were exceptionally small (25.5 mm) in the spring of 1977 perhaps because there was a late hatching or emergence. The smallest fry observed in Lake Aleknagik on June 20 averaged 28 mm (1973, Table 10); however, the fry in Little Togiak Lake grew at an above average rate during the early summer of 1977.

The growth of sockeye fry in Lake Aleknagik and in Little Togiak Lake is correlated with their abundance and the abundance of large forms of zooplankton (Fig. 14). The difference in the early summer growth that is attained in the two lakes appears to be related to the abundance of midges. The catches of midges is greater in Aleknagik and the growth of fry in that lake is better at a given abundance of zooplankton. The relatively high abundance of zooplankton in Little Togiak Lake during September 1977 suggests that pelagic fish should have grown at a rapid rate during September-October. The threespine sticklebacks were smaller than average in the spring of 1977 so they at least did not benefit from the high abundance of zooplankton. The growth of sockeye fry during September-October can only be estimated from the size of smolts in the following spring.

Abundance and Size of Smolts

We estimated that about 510,000 smolts (72% age I and 28% age II) migrated from Little Togiak Lake in 1977. This was nearly three times as many smolts than we estimated to have migrated in 1976 (Rogers 1976). The abundance of age II smolts was unexpectedly high (144,000) because our estimate of the number of age I smolts in 1976 was 167,000 and the average townet catch of yearlings in 1976 (1974 brood) was very low (Table 7). There was either an exceptionally high survival for these yearlings or our townet estimate was erroneously low.

The main objective of our sampling in Little Togiak River was to estimate the size of the smolts and to compare their size in 1977 with the sizes of smolts in previous migrations from Little Togiak and in migrations from the other lakes in 1977. These comparisons, along with the size of the fish when they were age 0, were used to determine the effect of fertilization in Little Togiak on the growth of the juvenile sockeye to the smolt stage.

Smolts begin migrating out of Little Togiak and the other lakes about the time of ice breakup. The smolts from Little Togiak reach the outlet of the lake system (Wood River), a distance of about 65 km, in about 11 days (Burgner 1962). The total abundance of sockeye in Little Togiak Lake is small relative to the populations in the other, much larger, lakes of the system and the smolts from Little Togiak became mixed with smolts from the upper lakes during their migration through lakes Nerka and Aleknagik. The earliest smolts to leave the lake system are those from Lake Aleknagik where ice breakup is usually at least a week earlier than in the other lakes.

The mean lengths of age I smolts from Wood River and Little Togiak River are shown by days after ice breakup in Fig. 15 for those years in which data was available from both locations. The smolts from Wood River in 1977 were the smallest ever observed since observations began in 1951, whereas those from Little Togiak Lake were slightly above average in length. Over the entire 1977 migration the age I smolts from Little Togiak Lake averaged 84.4 mm in length and 5.8 g in weight and in 1976 they averaged 85.2 mm and 5.5 g. The age II smolts in 1977 were both longer and heavier than the age II smolts in 1976 (101.3 mm, 9.5 g to 100.5 mm, 8.0 g).

Prior to spring growth, i.e., during the first 20 days of the migration, the age I smolts from Little Togiak Lake weighed an average of 4.7 g in 1976 and 5.4 g in 1977. When these fish were fry on September 1 of the previous years they weighed 0.8 and 1.06 g respectively. Their relative growth rates (not all fry migrate at age I) were 588% and 509%, and during past years the relative growth rates of fry in the lake system to smolts at Wood River averaged 191% and the annual range was 131 to 291%. The age II smolts from Little Togiak Lake weighed an average of 7.6 and 9.4 g during the first 20 days following breakup in 1976 and 1977, whereas when they were yearlings on the previous September 1 their average weights were 4.02 and 5.64 g; therefore, they increased 189 and 167% in weight. The average growth from age I juveniles to age II smolts in the lake system was 46% and the annual range was 0 to 120%.

The mean lengths of age I smolts from Little Togiak and Lake Aleknagik are plotted against their mean lengths at age 0 in Fig. 16. Although there are only four years of observations from Little Togiak (1961, 1975-1977), the mean lengths of the Little Togiak smolts in 1976 and 1977 appear to be exceptionally large relative to the apparent correlation in the Lake Aleknagik data.

Adult Escapement to Little Togiak Lake

The escapement into Little Togiak Lake in 1977 (estimated from sample counting) was 26,000 and constituted 4.6% of the total escapement to the lake system (562,000).[3] The escapements to Little Togiak Lake have been correlated with those to the lake system (Table 11); however, in only 3 prior years (1965, 1970, 1973) did the escapement to Togiak Lake exceed 4% of the escapement to the lake system. Little Togiak contains only 1.4% of the total surface area of the system. The adult returns in 1977 were only slightly affected by fertilization because only the age 1.2 and 2.2 fish were in the lake when it was first fertilized in 1974 and the returns of these age groups in 1977 (14,000) constituted only 38% of the run.

The daily passage of fish into Little Togiak Lake in 1975 and 1976 coresponded quite closely to the passage into the lake system with a lag of 3 and 4 days respectively; therefore fish bound for Little Togiak Lake were probably uniformly distributed among those bound for the lake system (Fig. 17). The patterns of entry in 1977 were not as close as in the two previous years. The fish bound for Little Togiak Lake were either more abundant in the latter part of the run or their movement through the lakes was slower since there was a difference of 5 days between the dates on which 50% of the fish passed into the lake system and into Little Togiak Lake.

---

[3]Preliminary data provided by ADF&G.

SUMMARY

Diammonium phosphate was added to the upper end of Little Togiak Lake in August of 1974 and 1975, to the entire lake in July of 1976, and to most of the lake in July of 1977 to determine whether artificial fertilization would increase productivity and hence the growth of juvenile sockeye salmon. There were immediate increases in the standing crops of phytoplankton in each year and the largest increase, over the entire lake, occurred in 1977. Although we could not demonstrate subsequent significant increases in the abundance of zooplankton nor the growth of the fish from June through mid-August, there was a significant increase in the abundance of zooplankton in September 1976 and significant increases in the size of the smolts that migrated from the lake in each of the years that followed fertilization. There was only a small effect on the abundance of midges because there is a limited amount of suitable habitat in Little Togiak Lake. Fertilization of other Wood River lakes with more extensive littoral zones would probably produce increases in the abundance of aquatic insects which are an important source of food for sockeye juveniles during the early summer.

A final evaluation will be made when the adult salmon from the fertilized brood years return (1978-1981) and their relative abundance is compared to prior unfertilized brood years. So far the observed effects of fertilization in Little Togiak Lake have been close to those predicted if indeed phosphorus is a major factor limiting the growth and production of sockeye in the Wood River lakes. Therefore, experimental fertilization should be continued in the lake system by fertilizing one of the large lakes. Lake Aleknagik is preferred because the biological data base for that lake is more detailed and extensive. No additional fertilizer should be added to Little Togiak Lake but conditions in the lake should be monitored to determine any residual effects from the additions through 1977, and the smolts that migrate from the lake should be sampled at least in the next two years.

LITERATURE CITED

Burgner, R. L. 1962. Studies of red salmon smolts from the Wood River lakes, Alaska. *In* Studies of Alaska Red Salmon. Univ. Washington, Publ. in Fish., New Ser: 1(6):247-314.

Gadau, E. L. 1966. Mineral study of the four lake systems in the Nushagak District of Alaska. M.S. thesis. Univ. Washington. 299 pp.

Lichtkoppler, F., and C. E. Boyd. 1977. Phosphorus fertilization of sunfish ponds. Trans. Amer. Fish. Soc. 106(6):634-636.

Table 1. Additions of diammonium phosphate to Little Togiak Lake (surface area of 6 km^2)

	1974	1975	1976	1977
Period of applications	Aug. 13-29	Aug. 13-20	July 12-21	July 13-22
Number of dates	8	3	6	5
Area of lake (km^2)	1	1	5	3.3
Total amount added (kg)	661	220	1,334	1,334
Average density of applications (kg/km^2)	165	73	97	155

Table 2. Means and standard deviations of the concentrations (mg/ℓ) of phosphorus and nitrogen in unfiltered water from 5, 15, and 20 m in Little Togiak Lake and central Lake Nerka

			Total phosphorus		Total nitrogen		Nitrate nitrogen		
Location	Date	n	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	N/P*
Little Togiak Lake	7/8/76	6	.011	.004	.108	.026	.128	.016	11.6
	7/14/76	6	.029	.013	.158	.076	.109	.020	5.4
	7/22/76	6	.027	.014	.121	.054	.102	.013	4.5
	8/3/76	6	.022	.003	.083	.016	.105	.015	4.8
Little Togiak Creeks	7/1/76	5	.021	.003	.117	.055	.112	.031	5.6
Lake Nerka	7/25/76	5	.024	.006	.086	.019	.128	.004	5.3
Little Togiak Lake	7/9/77	8	.010	.005	.105	.067	.035	.011	10.5
	7/16/77	6	.017	.010	.091	.024	.054	.024	5.4
	7/23/77	6	.017	.015	.090	.047	.057	.026	5.3
	7/30/77	6	.021	.006	.081	.009	.044	.017	3.9
	8/6/77	6	.027	.011	.077	.015	.034	.019	2.9
	8/13/77	6	.034	.007	.103	.014	.060	.047	3.0
Lake Nerka	7/10/77	3	.004	.004	.119	.035	.067	.011	29.7
	7/30/77	3	.008	.007	.084	.009	.073	.010	10.5
	8/6/77	3	.007	.003	.101	.013	.060	.012	14.4

* The higher of total nitrogen or nitrate nitrogen divided by phosphorus.

Table 3. Concentrations (ppm or mg/ℓ) of phosphorus and nitrogen in unfiltered water from samples collected in Little Togiak Lake and central Lake Nerka in 1977

Location	Date	Depth	Total phosphorus Sta. 1	Total phosphorus Sta. 5	Nitrate nitrogen Sta. 1	Nitrate nitrogen Sta. 5	Total nitrogen Sta. 1	Total nitrogen Sta. 5
Little Togiak	7/9	5	.013	.008	.021	.041	.090	.105
		10	.008	.003	.038	.024	.055	.135*
		15	.020	.005	.030	.037	.062	.064
		20	.013	.010	.056	.032	.069	.256*
	7/16	5	.008	.013	.093	.040	.084	.105
		15	.008	.033	.052	.071	.048	.117
		20	.025	.013	.027	.042	.093	.099
	7/23	5	.040	.003	.090	.048	.070	.065
		15	.028	.000	.089	.038	.055	.075
		20	.013	.018	.048	.031	.182	.093
	7/30	5	.025	.018	.064	.031	.090	.091
		15	.013	.023	.063	.027	.086	.077
		20	.015	.030	.048	.032	.071	.072
	8/6	5	.028	.023	.021	.027	.080	.105
		15	.023	.025	.029	.027	.067	.075
		20	.048	.015	.026	.072	.066	.070
	8/13	5	.040	.038	.132	.017	.083	.108
		15	.028	.033	.047	.006	.104	.093
		20	.023	.040	.070	.087	.105	.123
Central Nerka	7/10	5	.008		.054		.152*	
		15	.005		.074		.122*	
		20	.000		.073		.083	
	7/30	5	.000		.084		.083	
		15	.010		.066		.094	
		20	.013		.068		.076	
	8/6	5	.010		.046		.116	
		15	.005		.064		.093	
		20	.005		.070		.093	

* Values may be too high

Table 4. Geometric means of the number of organisms (four most abundant) in bottom sample grabs (225 cm^2) from depths of 3-10 m

Year	Date	Oligochaetes WE[1]	Oligochaetes EE[2]	Chironomids WE	Chironomids EE	Gastropods WE	Gastropods EE	Pelecypods WE	Pelecypods EE
1974	8/3	222	26	112	79	93	17	35	18
	8/15	217	32	73	121	75	6	11	24
	9/10	105	17	141	39	78	1	9	3
	9/20	33	39	146	93	206	2	7	18
1975	6/21	237	19	216	15	55	1	22	10
	7/7	147	34	91	50	39	7	11	11
	7/20	252	16	135	30	53	1	26	7
	8/3	57	24	33	18	38	6	12	7
	8/20	128	12	52	9	77	4	28	7
	8/30	94	43	19	51	47	3	19	8
	9/26	333	99	83	64	66	5	19	22
1976	6/25	69	13	36	9	8	0	2	4
	7/9	13	14	48	25	8	1	3	5
	7/23	74	16	61	21	39	2	25	6
	8/6	103	14	63	33	58	2	47	9
	8/20	83	10	40	17	42	1	18	7
	9/7	29	9	19	31	17	4	10	14
1977	6/27	89	9	32	29	57	1	24	8
	7/15	76	8	24	9	57	1	30	5
	7/31	67	15	12	61	33	5	46	24
	8/13	116	21	41	56	70	4	43	20
	8/26	113	20	26	19	81	6	29	6
	9/12	225	46	50	23	111	8	41	22

[1] WE: west end of lake near insect trap no. 1

[2] EE: east end of lake (outlet) near insect trap no. 5

Table 5. Geometric means of tow net catches in Little Togiak Lake by sampling area, 1958-1977

	Sockeye (Age 0)			Sockeye (Age I)			Threespine stickleback		
Year	A	B	C	A	B	C	A	B	C
1958	64.9	40.3	18.3	1.7	0.3	1.2	125.8	47.6	77.1
59	549.7	109.8	93.4	3.0	0.8	0.8	38.6	61.2	67.5
60	278.0	60.1	99.3	8.3	0.7	0.4	18.6	7.1	25.4
61	266.2	159.7	145.3	12.7	17.0	26.0	26.5	39.7	47.1
62	19.1	33.0	14.7	13.5	10.5	2.9	41.5	63.3	23.5
63	37.7	303.5	43.5	0.0	4.6	0.7	26.8	97.8	43.3
64	14.1	89.9	11.2	8.3	3.5	0.2	13.3	90.8	112.0
65	130.3	56.7	141.8	9.9	4.2	8.1	7.1	52.9	83.5
66	32.0	10.6	7.0	11.3	7.4	3.5	18.9	151.5	9.6
67	101.6	98.5	8.3	4.4	9.0	1.2	116.9	66.3	12.2
68	127.5	48.5	35.8	15.1	0.9	0.7	39.9	171.5	234.8
69	2.8	2.7	3.3	2.3	0.3	1.0	3.7	25.2	35.9
70	353.2	57.1	6.0	3.3	0.0	0.0	48.9	113.0	36.1
71	18.3	9.2	5.2	4.0	1.9	1.7	2.4	10.2	5.4
72	0.4	7.3	44.2	7.0	52.6	102.1	3.5	172.2	246.8
73	4.3	9.8	4.7	2.4	14.7	5.3	3.4	3.7	1.6
74	46.6	49.4	29.5	0.7	0.2	0.5	89.3	49.0	71.6
75	26.2	21.2	24.1	5.8	1.6	1.0	251.9	1657.4	77.2
76	29.3	39.4	27.8	2.5	2.9	3.7	24.3	43.5	52.5
77	7.6	76.6	6.8	8.6	6.7	3.4	56.3	42.4	23.3

Table 6. Geometric means of tow net catches in Little Togiak Lake from sampling during August 16 to September 10, 1958-1977

	Sockeye salmon		Threespine stickleback			
Year	Age 0	Age I	Total	Age 0	Age I	Age II+
1958	38	1	82	0	10	72
59	228	1	57	0	4	53
60	138	3	18	1	6	11
61	184	20	39	1	22	16
62	21	8	40	2	13	25
63	120	2	55	0	24	31
64	36	4	78	0	24	54
65	113	7	53	0	5	47
66	15	7	55	0	3	52
67	62	4	58	1	13	44
68	66	5	161	9	131	21
69	3	1	24	0	5	19
70	120	1	63	0	4	59
71	10	2	6	0	3	3
72	21	60	156	0	4	152
73	6	7	3	0	1	2
74	40	1	70	4	41	24
75	24	2	738	0	682	56
76	32	3	52	0	11	41
77	28	6	47	0	3	44

Table 7. Mean tow net catches and lengths on September 1 of juvenile sockeye salmon in Little Togiak Lake according to abundance of parent spawners and sampling area

Escapement	Brood	Age 0 (year + 1)								Age I (year + 2)							
		Geometric mean catch				Mean length (mm)				Geometric mean catch				Mean length (mm)			
(thousands)	year	A	B	C	mean[1]	A	B	C	mean[2]	A	B	C	mean[1]	A	B	C	mean[2]
6	1957	65	40	18	38	59	61	61	60	3	1	1	1	107	105	104	106
10	1962	38	304	44	120	61	60	63	61	8	4	0	3	97	96	94	97
10	1967	127	48	36	66	60	54	58	56	2	0	1	1	99	105	95	98
11	1961	19	33	15	21	59	57	57	57	0	5	1	2	105	100	102	100
14	1972	4	10	5	6	56	56	57	56	1	0	1	1	85	87	82	84
14	1973	47	49	29	40	51	55	54	54	6	2	1	3	79	77	90	80
15	1964	130	57	142	113	48	53	53	51	11	7	4	7	80	92	88	86
16	1958	550	110	93	228	63	62	66	63	8	1	0	3	95	100	99	96
17	1960	266	160	145	184	53	55	57	55	14	10	3	8	90	92	87	90
18	1976	8	77	7	28	45	45	47	45								
20	1956	--	--	--	--	--	--	--	--	2	0	1	1	102	96	93	97
20	1968	3	3	3	3	44	53	56	51	3	0	0	1	91	--	--	91
20	1969	353	57	6	120	54	61	59	54	4	2	2	2	87	91	88	88
21	1963	14	90	11	36	49	54	57	54	10	4	8	7	86	85	88	87
22	1966	102	99	8	62	51	54	55	53	15	1	1	5	87	90	90	87
24	1971	0	7	44	21	--	47	49	49	2	15	5	7	82	85	86	85
26	1965	32	11	7	15	44	45	49	45	4	9	1	4	86	86	91	87
30	1975	29	39	28	32	51	47	50	49	9	7	3	6	79	84	87	83
40	1959	278	60	99	138	57	53	53	55	13	17	26	26	86	90	87	88
48	1974	26	21	24	24	45	45	43	45	3	3	4	3	88	88	90	89
55	1970	18	9	5	10	47	48	50	47	7	53	102	60	76	79	77	77

[1] weighted by surface area, i.e., $(\bar{C}_A \times 1.7) + (\bar{C}_B \times 1.8) + (\bar{C}_C \times 2.5) \times Y_6$

[2] weighted by surface area times mean catch

Table 8. Mean lengths (live equivalent in mm) of juvenile sockeye salmon and threespine stickleback (age I) on September 1, 1952-1977 by sampling area in Little Togiak Lake. Numbers in parenthesis are based on small samples

Year	Sockeye salmon Age 0 A	B	C	Sockeye salmon Age I A	B	C	Threespine stickleback (age I) A	B	C
1958	59.0	61.2	60.9	102	96	93	40.2	39.9	39.2
59	62.8	61.7	65.6	107	105	104	44.6	45.1	46.6
60	57.1	52.7	53.0	95	100	99	40.6	45.0	44.5
61	52.7	55.2	57.5	86	90	87	40.7	42.6	44.2
62	57.8	56.7	57.5	90	92	87	44.8	44.2	42.9
63	60.7	60.2	63.0	105	100	102	45.0	48.1	49.1
64	48.7	54.4	56.5	97	96	94	40.1	42.6	43.2
65	48.3	52.8	53.0	86	85	88	41.7	43.0	42.9
66	43.7	45.4	48.9	80	92	88	41.1	40.1	44.2
67	51.1	54.2	55.0	86	86	91	40.3	40.6	42.9
68	59.9	54.0	58.5	87	90	90	44.5	42.8	43.8
69	43.6	52.6	56.3	99	105	95	43.1	44.6	45.8
70	53.6	60.7	59.2	91	--	--	44.1	47.6	43.6
71	47.1	48.4	(49.9)	87	91	(88)	36.7	39.8	(39.2)
72	(51.2)	46.7	49.1	76	79	77	39.0	42.5	41.6
73	56.4	55.7	57.0	82	85	86	39.2	36.4	(36.7)
74	51.2	54.7	54.0	85	87	82	48.4	48.0	48.7
75	44.9	44.8	43.2	79	77	90	40.1	41.1	41.6
76	50.9	47.0	49.6	88	88	90	41.7	43.1	43.5
77	45.0	45.2	46.7	79	84	87	38.2	38.8	39.0

Table 9. Mean lengths (mm) on selected dates (A) and growth rates in mm/day (B) for sockeye salmon fry, threespine stickleback (age I) and Arctic char fry from Little Togiak Lake, 1973-1977

	Year	Sockeye salmon (age 0)			Threespine stickleback (age I)			Arctic char (age 0)		
		6/20	7/20	9/1	6/20	7/20	9/1	6/20	7/20	8/10
A.	1973	28.5	35.0	56.3	27.0*	31.0*	42.0*	28.0	31.5	37.0
	1974	30.5	33.0	53.9	30.5	35.0	48.5	29.5	35.0	46.0*
	1975	28.5	31.0	44.6	29.5	34.0	41.0	29.0	31.5	35.0*
	1976	29.0	31.5	49.0	26.5	33.5	41.0	29.0	30.5	34.5*
	1977	25.5	33.0	45.4	25.0	28.5	38.5	28.5	31.0	34.5*
		6/20-7/20	7/20-9/1	6/20-9/1	6/20-7/20	7/20-9/1	6/20-9/1	6/20-7/20	7/20-8/10	
B.	1973	.22	.50	.38	.13	.26	.21	.12	.26	
	1974	.08	.49	.32	.15	.31	.25	.18	.52	
	1975	.08	.32	.22	.15	.16	.16	.08	.17	
	1976	.08	.41	.27	.23	.17	.20	.05	.19	
	1977	.25	.29	.27	.12	.23	.18	.08	.17	

* Estimates from small sample sizes

Table 10. Mean lengths (mm) on selected dates (A) and growth rates in mm/day (B) for sockeye salmon fry, threespine stickleback (age I) and Arctic char fry from Lake Aleknagik, 1962-1977

		Sockeye salmon (age 0)			Threespine stickleback (age I)			Arctic char (age 0)	
	Year	6/20	7/20	9/1	6/20	7/20	9/1	6/20	7/20
A.	1962	30.6	38.1	54.1	29.1	33.9	43.6	--	--
	63	--	44.9	62.1	--	36.9	46.7	--	35.3
	64	30.3	36.4	60.4	31.4	34.0	43.0	28.3	32.7
	65	29.0	35.5	53.6	28.1	31.8	39.5	28.6	32.9
	66	29.8	33.0	47.5	27.0	30.6	39.4	28.9	31.8
	67	29.5	35.1	43.4	28.2	31.5	41.3	27.6	32.3
	68	30.8	43.9	57.9	30.2	35.4	43.4	30.0	34.7
	69	30.6	39.2	61.4	32.0	35.3	44.0	27.9	33.6
	70	29.8	40.4	59.0	31.4	36.6	42.6	28.4	34.6
	71	29.5	33.5	54.6	28.8	33.1	42.9	28.5	31.5
	72	28.5	34.3	54.8	27.8	32.8	44.4	26.6	33.2
	73	28.0	36.6	66.7	29.0	35.4	49.5	28.3	33.2
	74	35.9	42.2	62.8	32.8	39.7	50.1	28.9	37.0
	75	28.5	34.1	55.3	31.1	34.7	42.3	29.0	32.8
	76	28.6	35.1	49.8	26.3	31.8	39.6	27.8	32.3
	77	29.5	34.1	48.0	28.2	32.5	40.8	28.5	31.0
		6/20-7/20	7/20-9/1	6/20-9/1	6/20-7/20	7/20-9/1	6/20-9/1	6/20-7/20	
B.	62	.25	.37	.32	.16	.23	.20	--	
	63	--	.40	(.43)	--	.23	(.22)	(.18)	
	64	.20	.56	.41	.09	.21	.16	.15	
	65	.22	.42	.34	.12	.18	.16	.14	
	66	.11	.34	.24	.12	.20	.17	.10	
	67	.19	.19	.19	.11	.23	.18	.16	
	68	.44	.33	.37	.17	.19	.18	.16	
	69	.29	.52	.42	.11	.20	.16	.19	
	70	.35	.43	.40	.17	.14	.15	.21	
	71	.13	.49	.34	.14	.23	.19	.10	
	72	.19	.48	.36	.17	.27	.23	.22	
	73	.29	.70	.53	.21	.33	.28	.16	
	74	.21	.48	.37	.23	.24	.24	.27	
	75	.19	.49	.37	.12	.18	.15	.13	
	76	.22	.34	.29	.18	.18	.18	.15	
	77	.15	.32	.25	.14	.19	.17	.08	

Table 11. Escapements and returns of sockeye salmon to Little Togiak Lake and escapements and return per escapement to the Wood River lake system

Brood year	Escapement (thousands)	Return (thousands) Age 1.2	1.3	2.2	2.3	Total	R/E	Wood River Escapement	R/E
1951	6	20	12	8	*	40	6.7	458	4.9
52	5	19	8	*	0	27	5.4	227	5.2
53	10	3	16	3	1	23	2.3	515	1.2
54	16	14	2	9	2	27	1.7	575	3.9
55	20	49	10	10	2	71	3.6	1383	2.7
56	20	9	11	1	0	21	1.0	773	1.4
57	6	3	5	*	0	8	1.3	289	1.3
58	16	20	13	2	*	35	2.2	960	2.4
59	40	24	5	7	*	36	0.9	2209	0.7
60	17	18	8	16	3	45	2.6	1016	2.2
61	11	18	15	1	*	34	3.1	461	2.5
62	10	18	9	*	0	27	2.7	874	1.7
63	21	11	21	2	0	34	1.6	721	1.7
64	15	10	5	3	2	20	1.3	1076	0.9
65	27	23	15	15	1	54	2.0	675	2.1
66	22	45	28	2	1	76	3.5	1209	1.4
67	10	11	8	2	1	22	2.2	516	1.5
68	20	9	15	0	0	24	1.2	649	1.0
69	20	2	18	15	1	36	1.8	604	1.2
70	55	25	13	24	5	67	1.2	1162	2.2
71	24	1	6	5	12	24	1.0	851	1.4
72	14	16	11	6	(2)	(35)	(2.5)	431	(3.0)
73	14	8						330	
74	48							1709	
75	30							1270	
76	18							817	
77	26							562	

* Less than 1,000

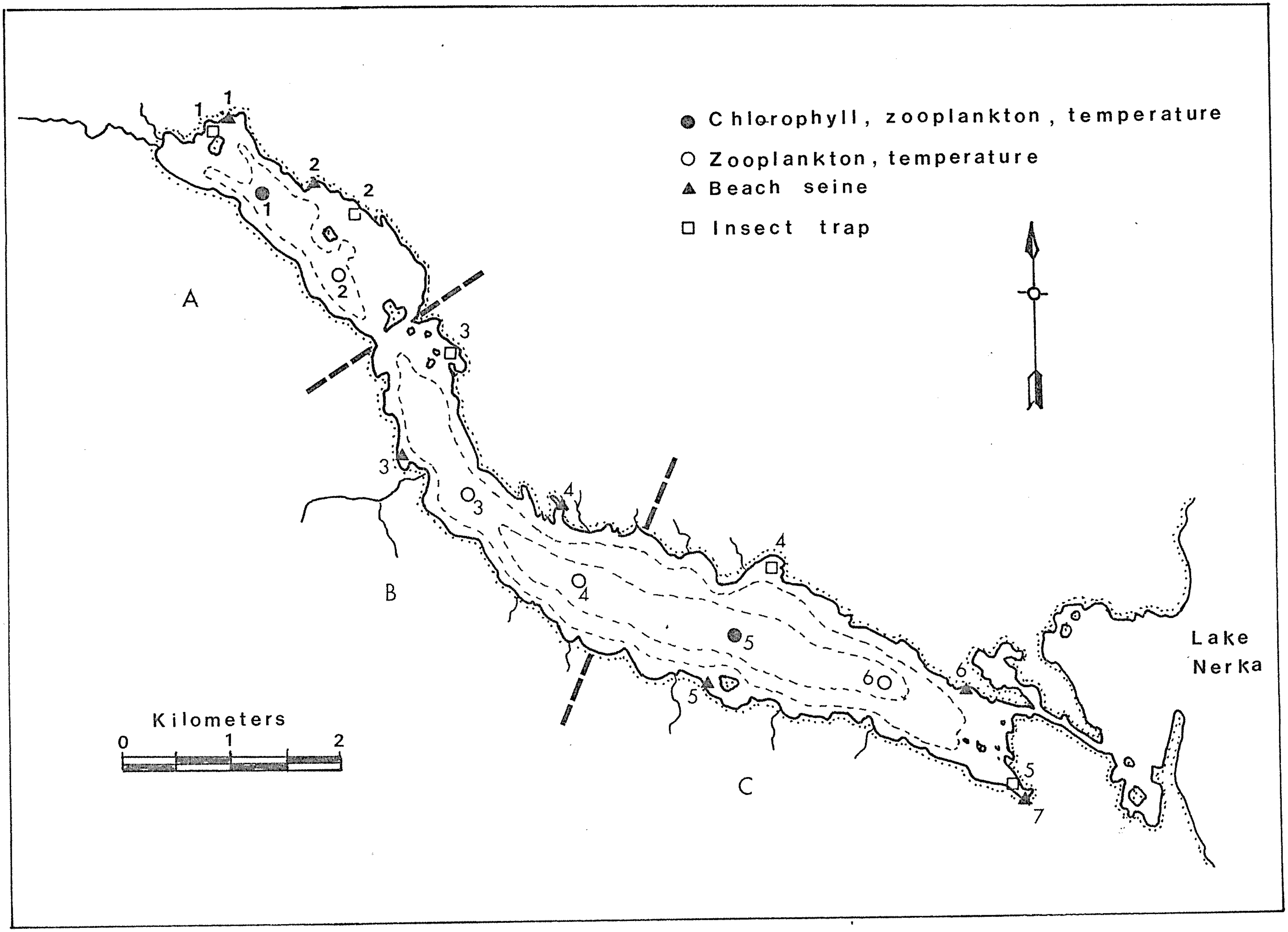

Fig. 1. Sampling stations on Little Togiak Lake. Depth contours at 20 m and 60 m indicated by dashed lines.

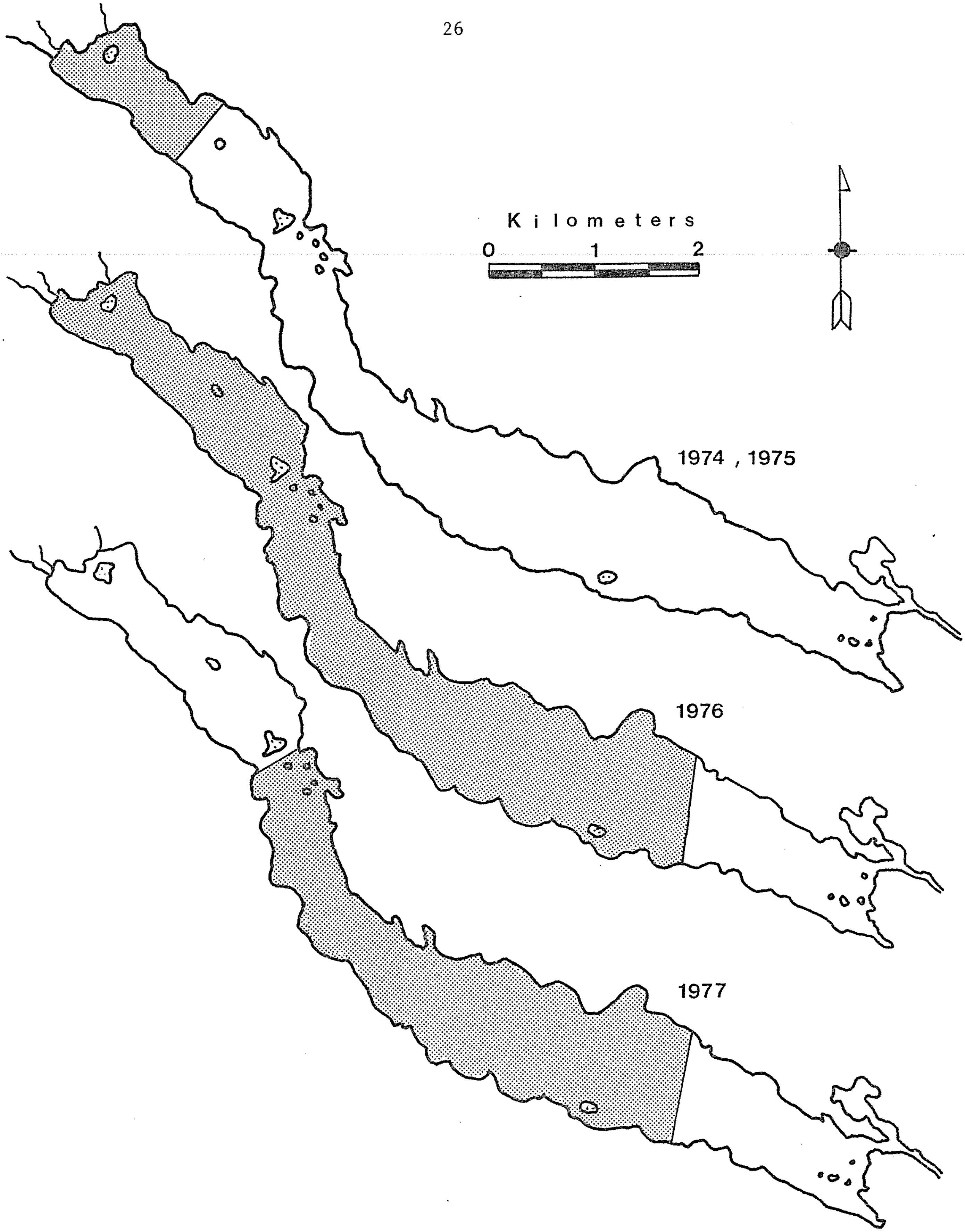

Fig. 2. Areas fertilized (shaded) in Little Togiak Lake.

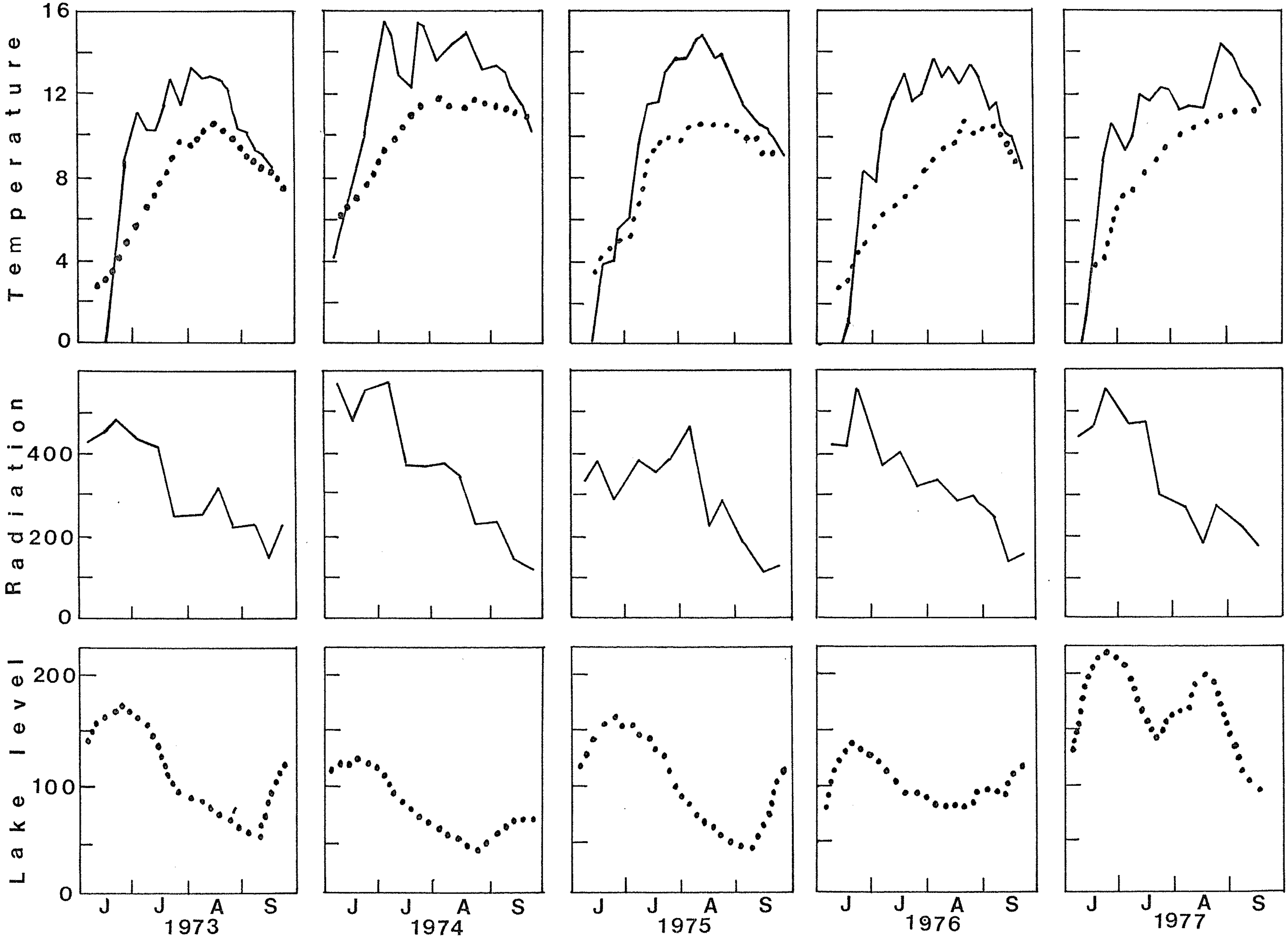

Fig. 3. Water temperature (surface ——, 0-20 m ---), solar radiation (g/cal/cm^2/day) 10-day means, and lake level (cm).

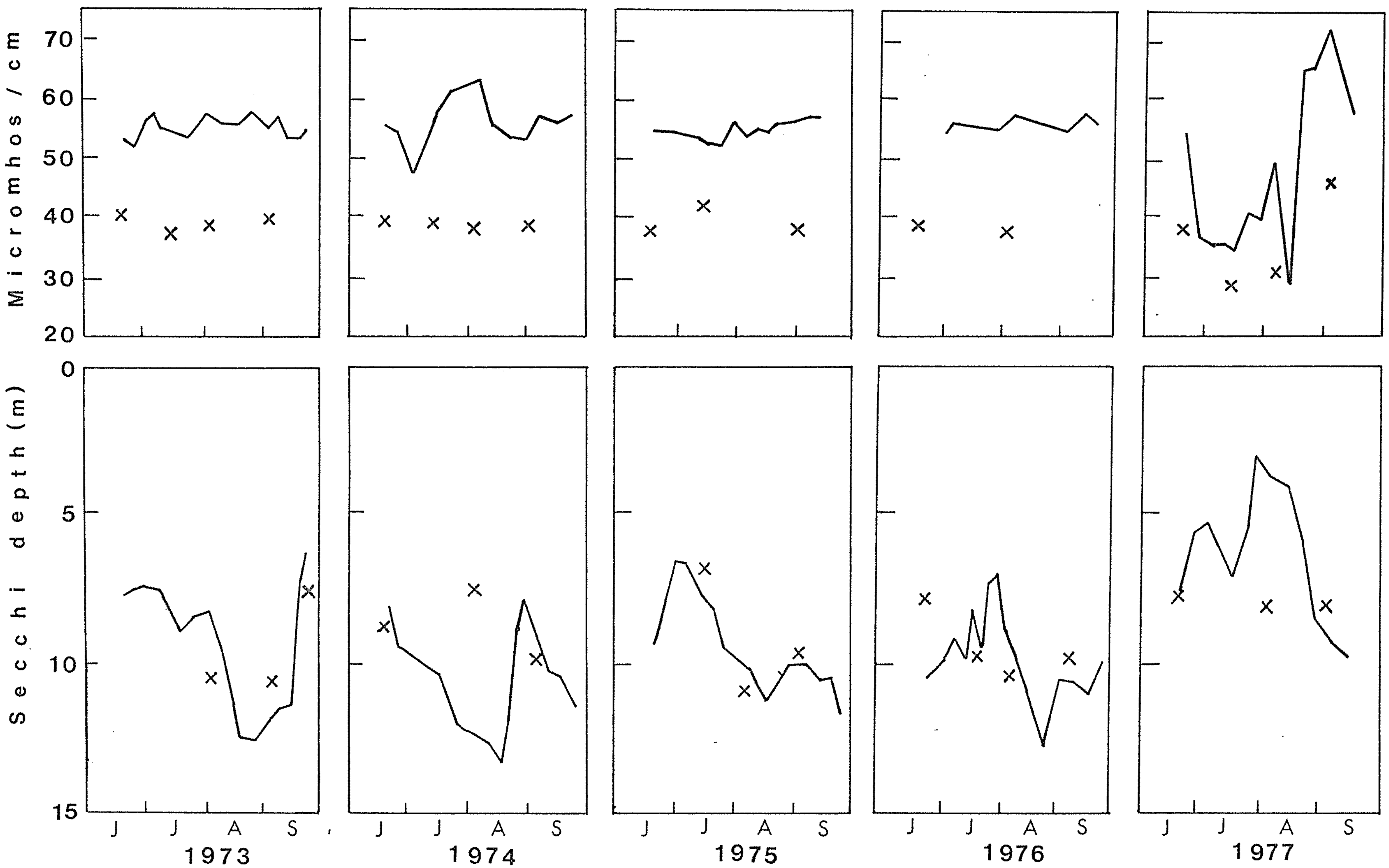

Fig. 4. Conductivity (top) and secchi depth (bottom) in Little Togiak Lake and Lake Aleknagik (x) during summers of 1973-1977.

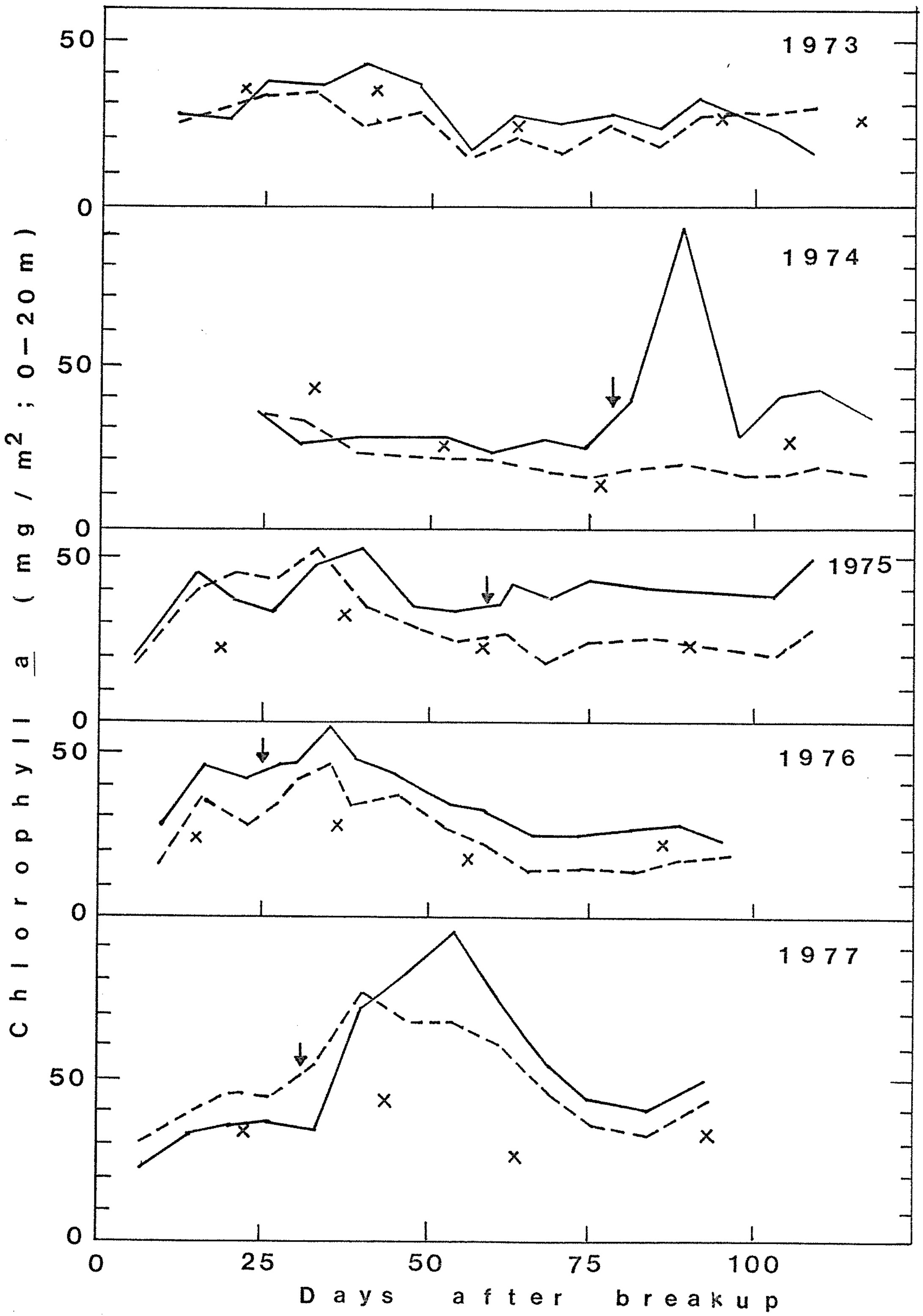

Fig. 5. Amount of chlorophyll "a" in the upper 20 m at two stations on Little Togiak Lake (Sta. 1-Sta. 5--) and in Lake Aleknagik (x). Arrows indicate when phosphates were added at station 1 in 1974 and 1975, to both stations in 1976, and at station 5 in 1977

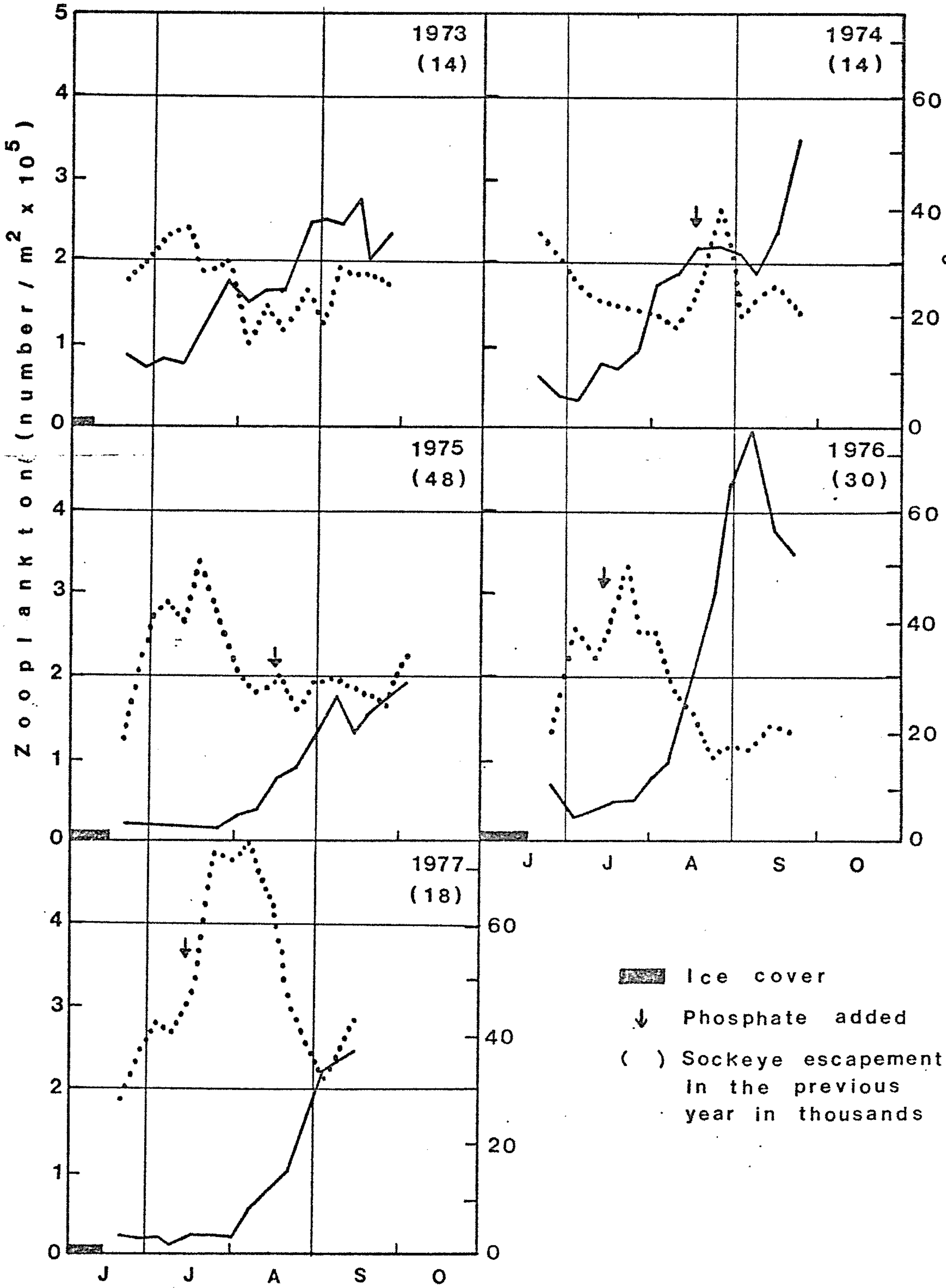

Fig. 6. Abundance of large zooplankters (Calanoid copepods, *Daphnia* and *Holopedium*) and the concentration of chlorophyll 20 m of Little Togiak Lake, 1973-1977.

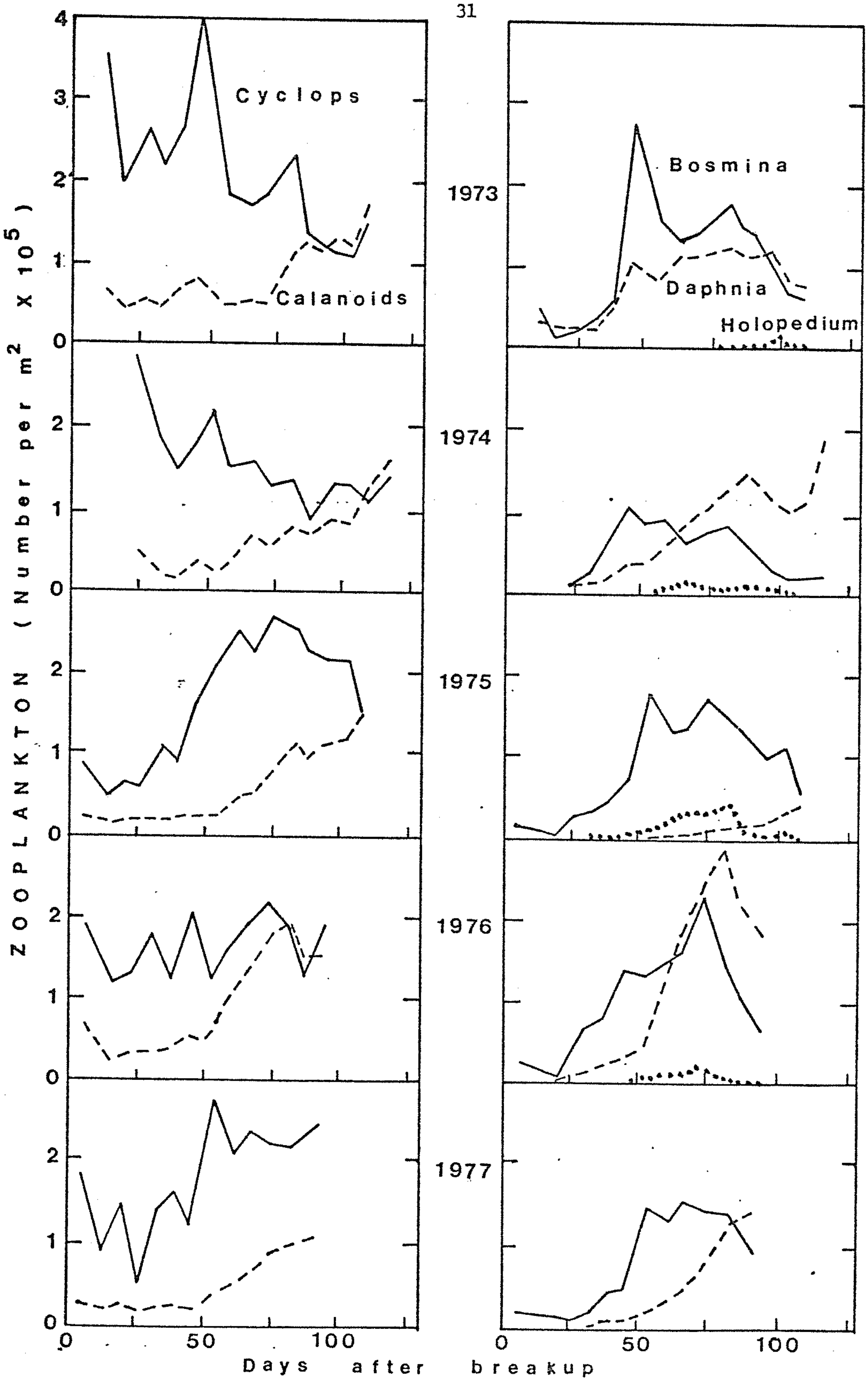

Fig. 7. Abundance of zooplankton in Little Togiak Lake, 1973-1977.

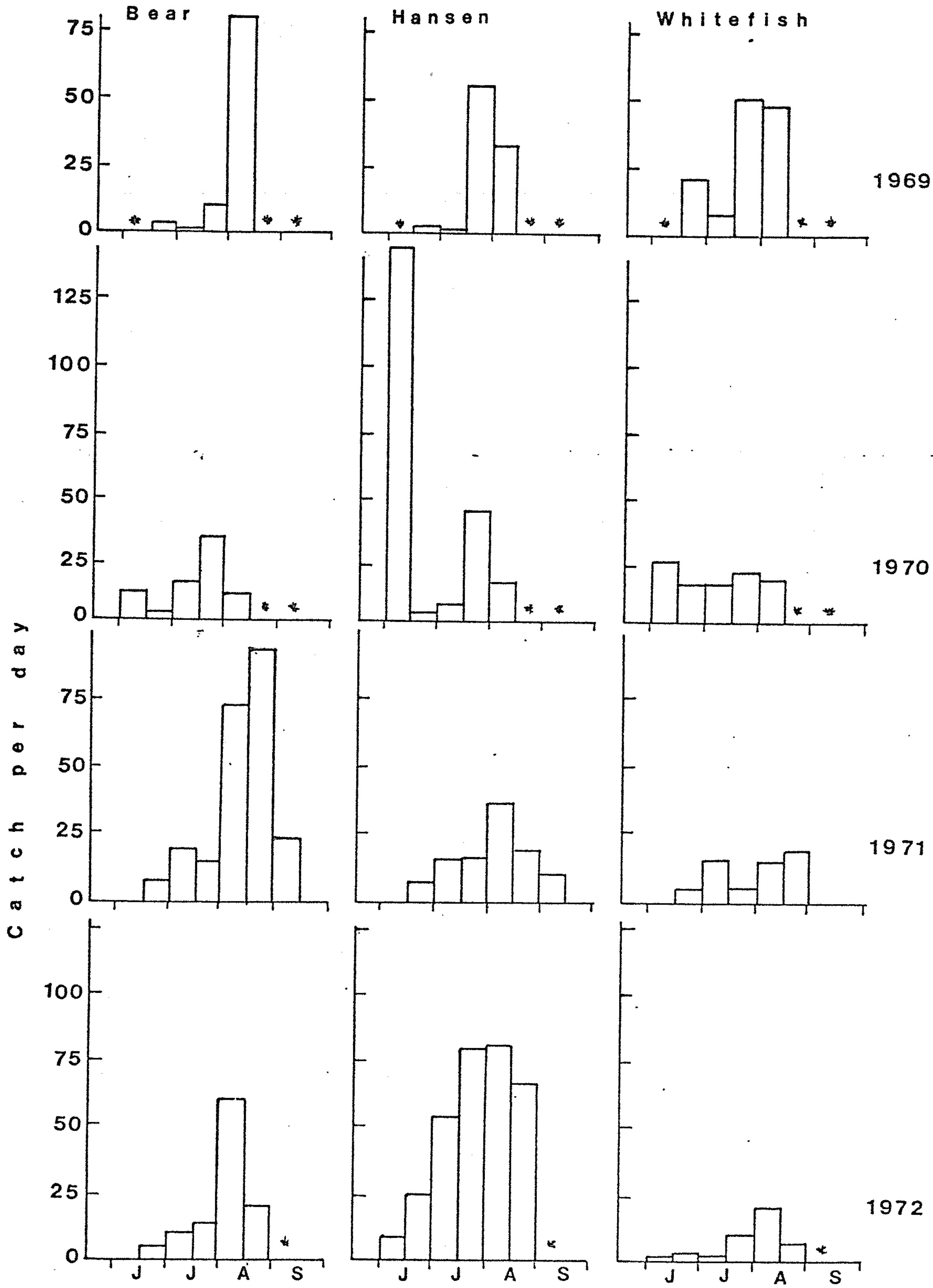

Fig. 8. Catches of chironomids in Lake Aleknagik by 15-day periods (* no sampling), 1969-1972.

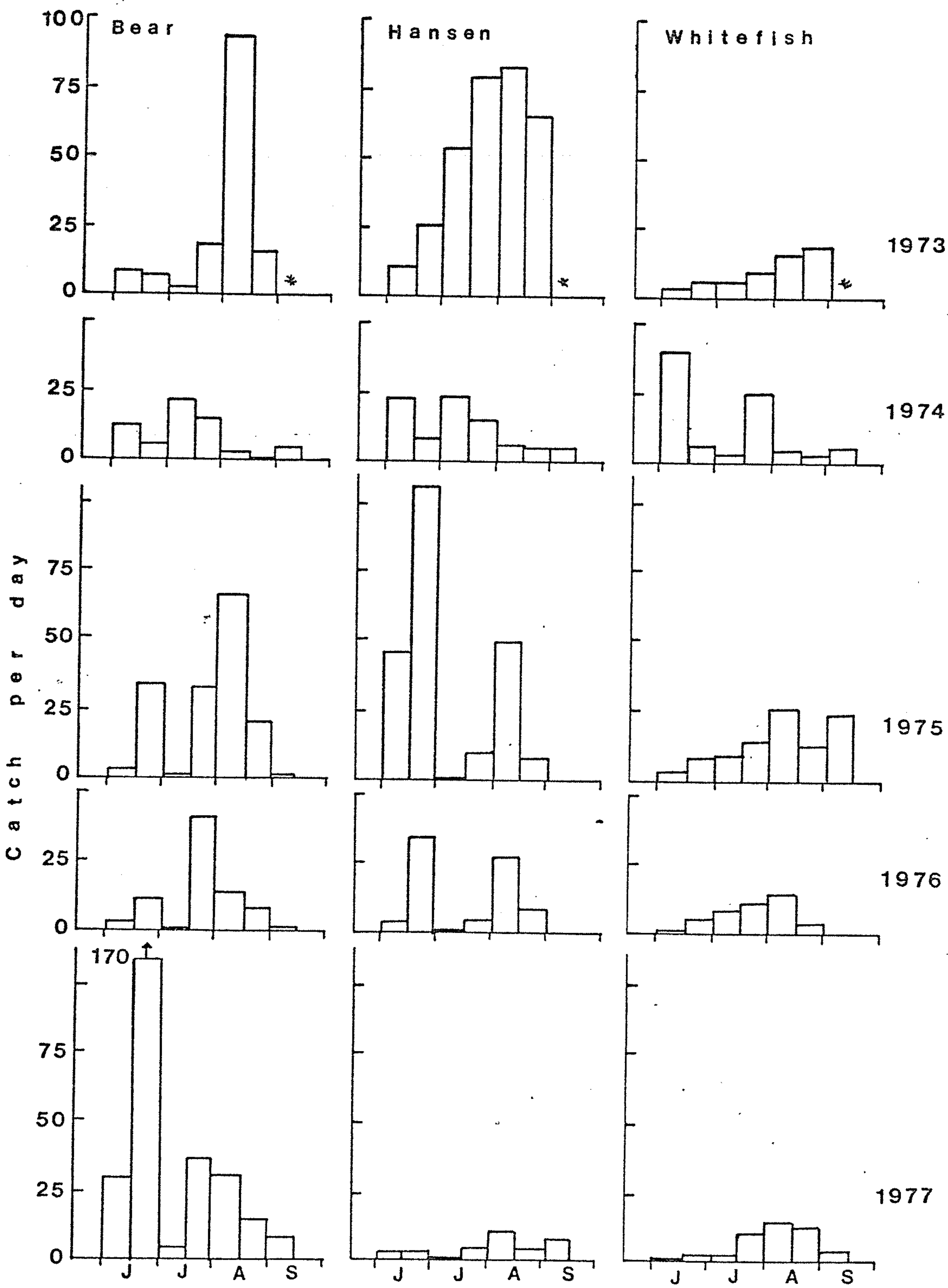

Fig. 9. Catch of chironomids in Lake Aleknagik by 15-day periods, 1973-1977.

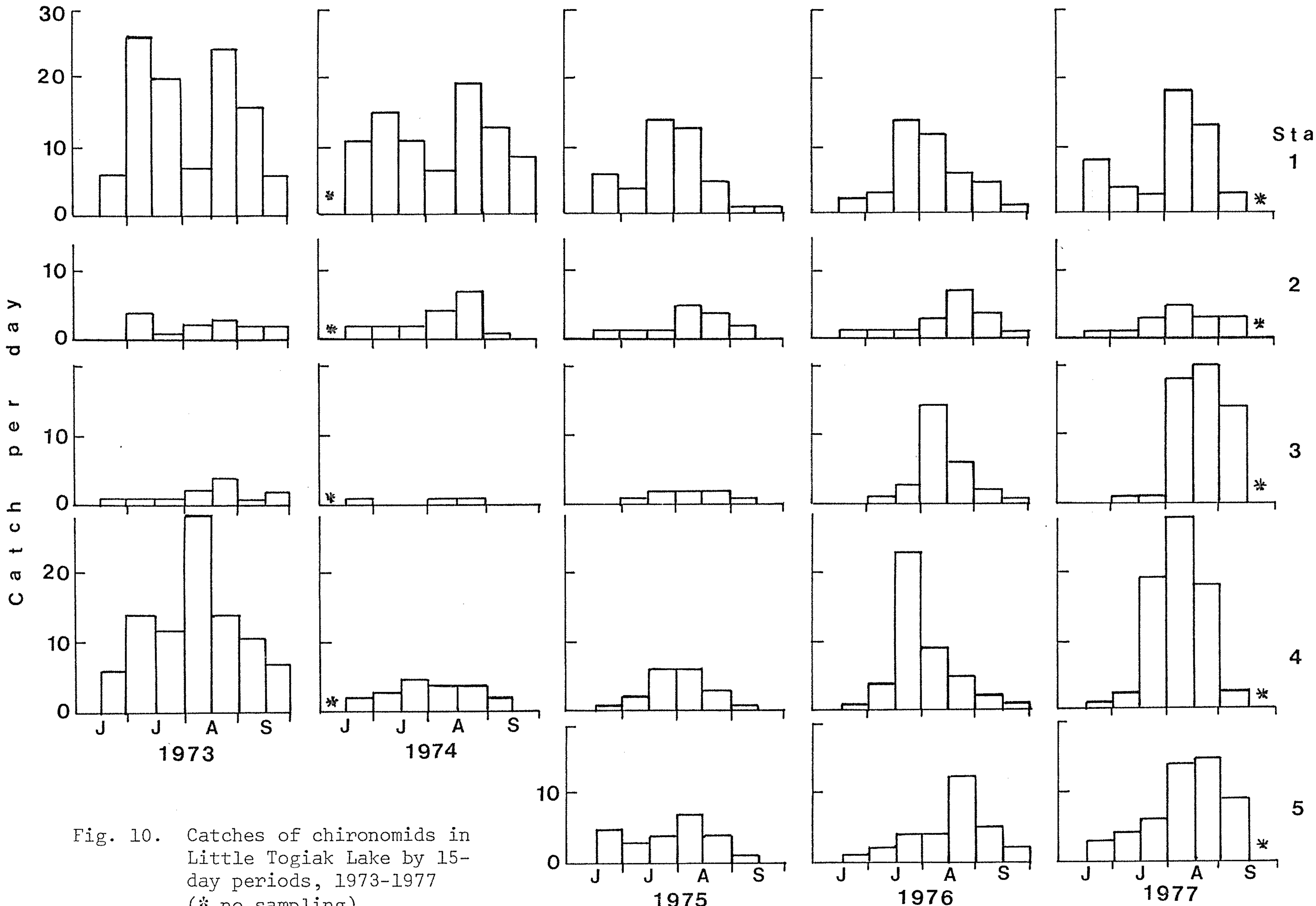

Fig. 10. Catches of chironomids in Little Togiak Lake by 15-day periods, 1973-1977 (* no sampling).

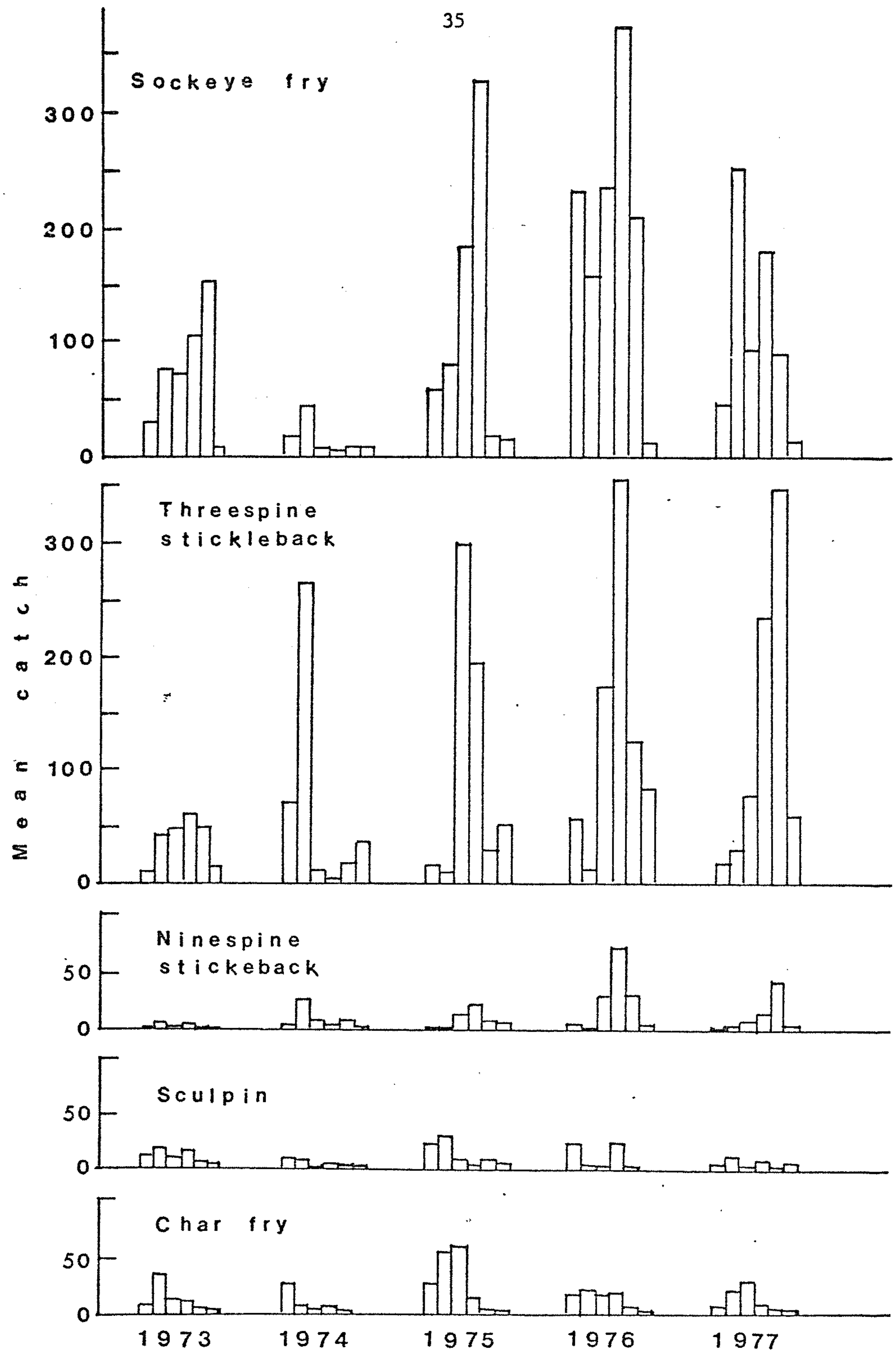

Fig. 11. Geometric means of beach seine catches in Little Togiak Lake by weekly periods during June 26 to August 3, 1973-1977.

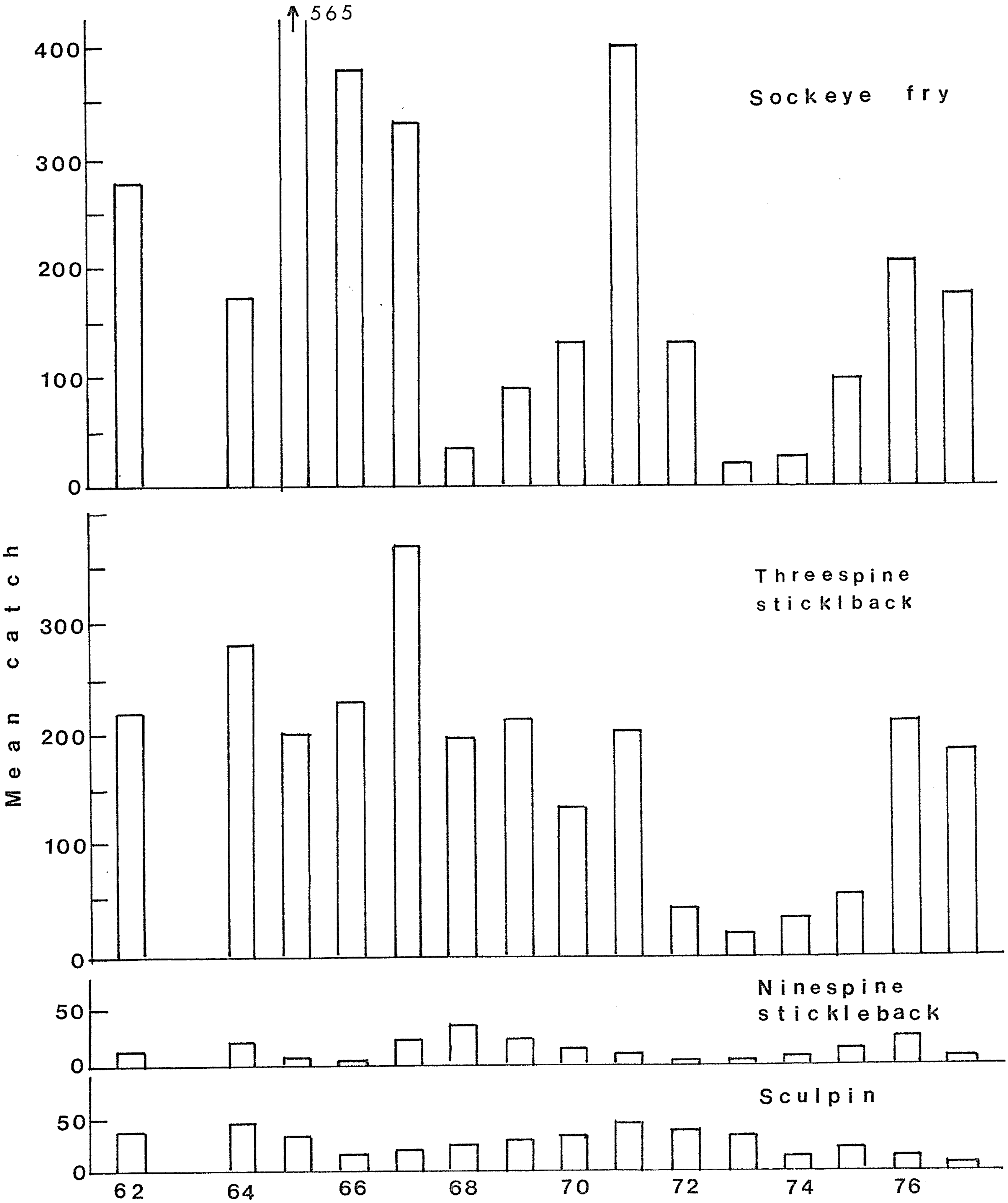

Fig. 12. Geometric means of beach seine catches made during June 20 to July 19 in Lake Aleknagik. No sampling in 1963.

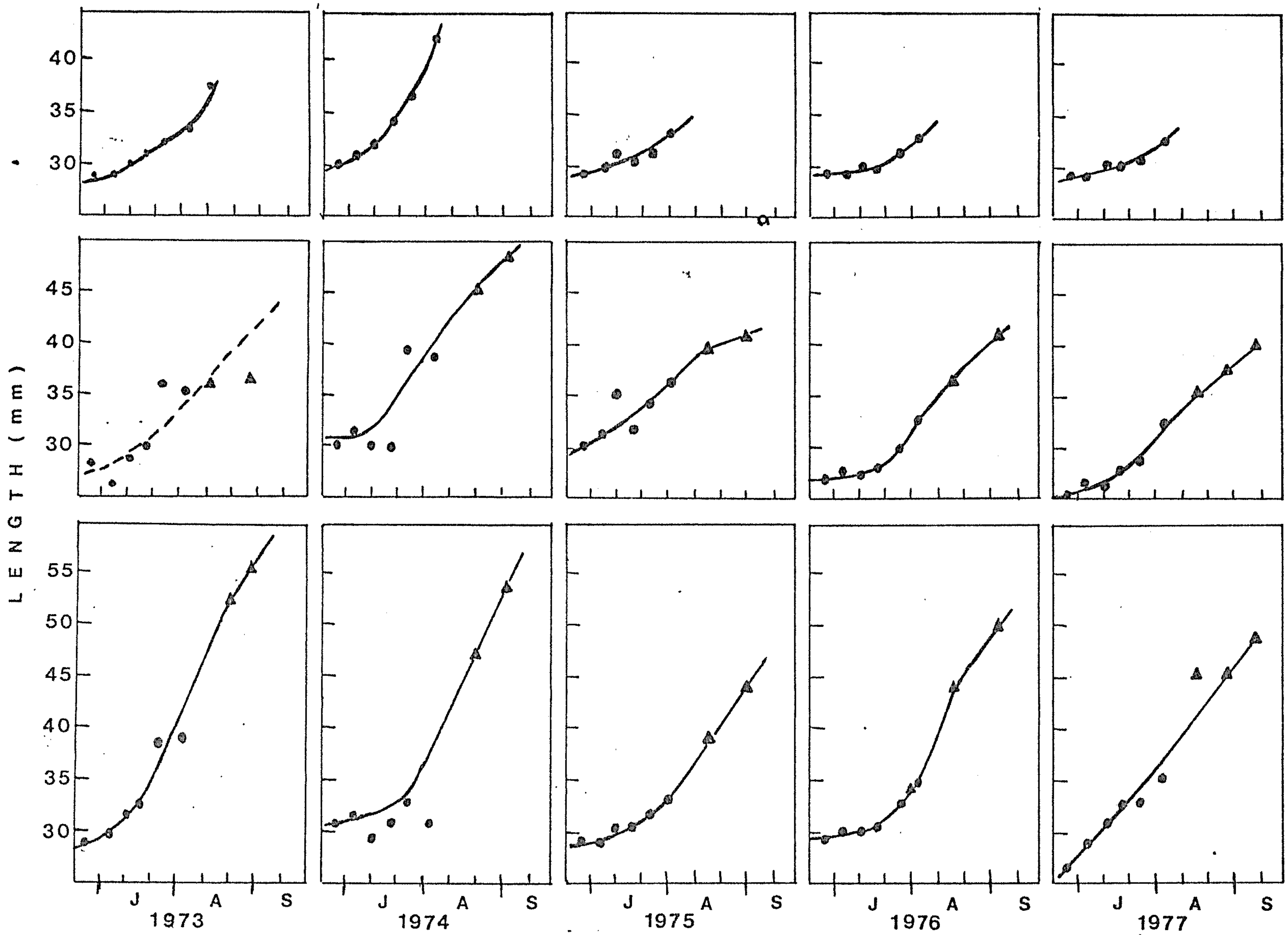

Fig. 13. Growth in length of Arctic char (age 0), threespine stickleback (age I), and sockeye salmon fry (from top to bottom) in Little Togiak Lake, 1973-1977.

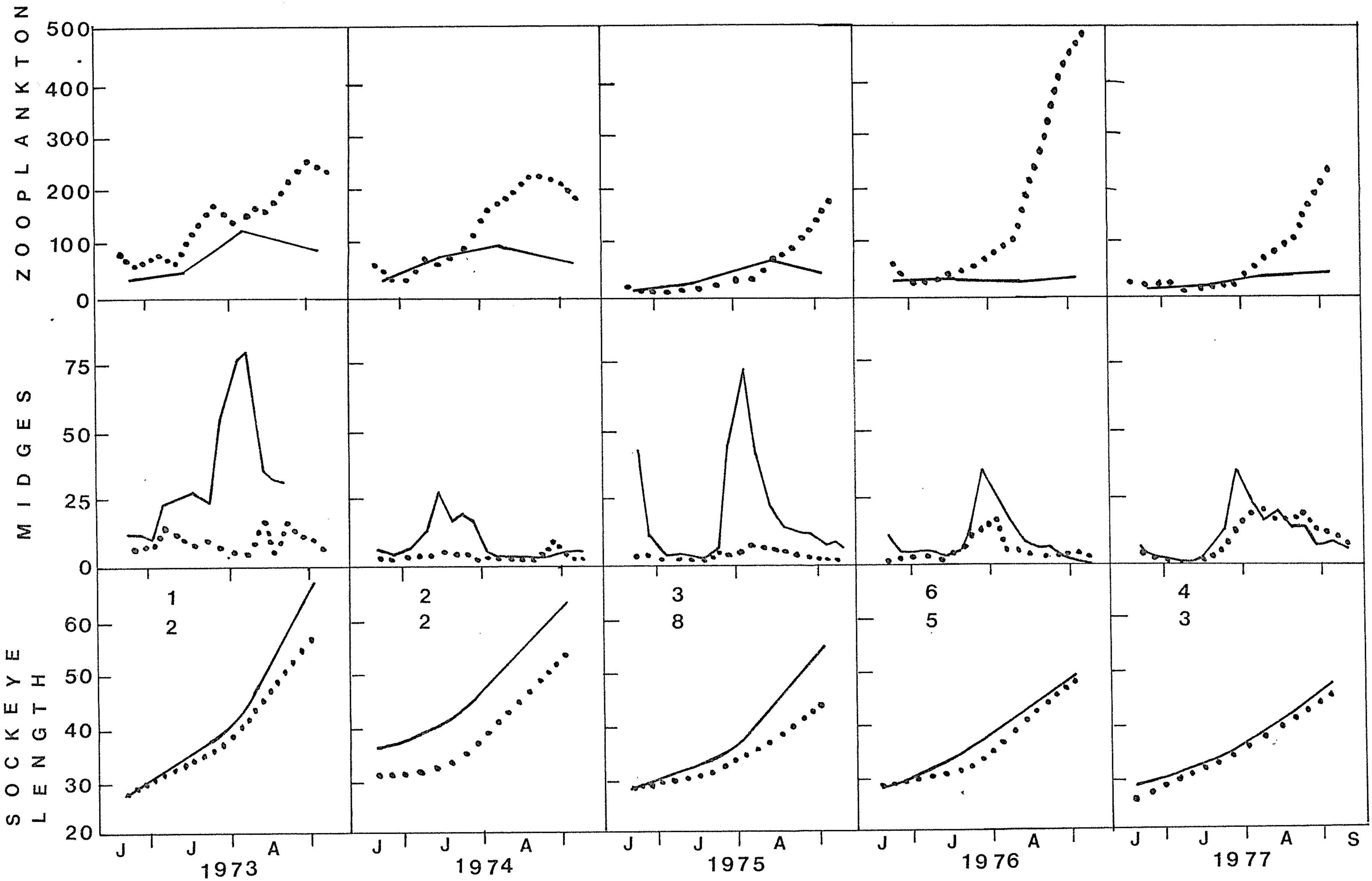

Fig. 14. Abundance of large zooplankton (1,000's/m^2), mean catch of emergent chironomids per day, and the growth in length (mm) of sockeye salmon fry in Lake Aleknagik (-) and Little Togiak (....). Densities of parent escapements (1,000's/km^2) given for Aleknagik (top) and Little Togiak (bottom).

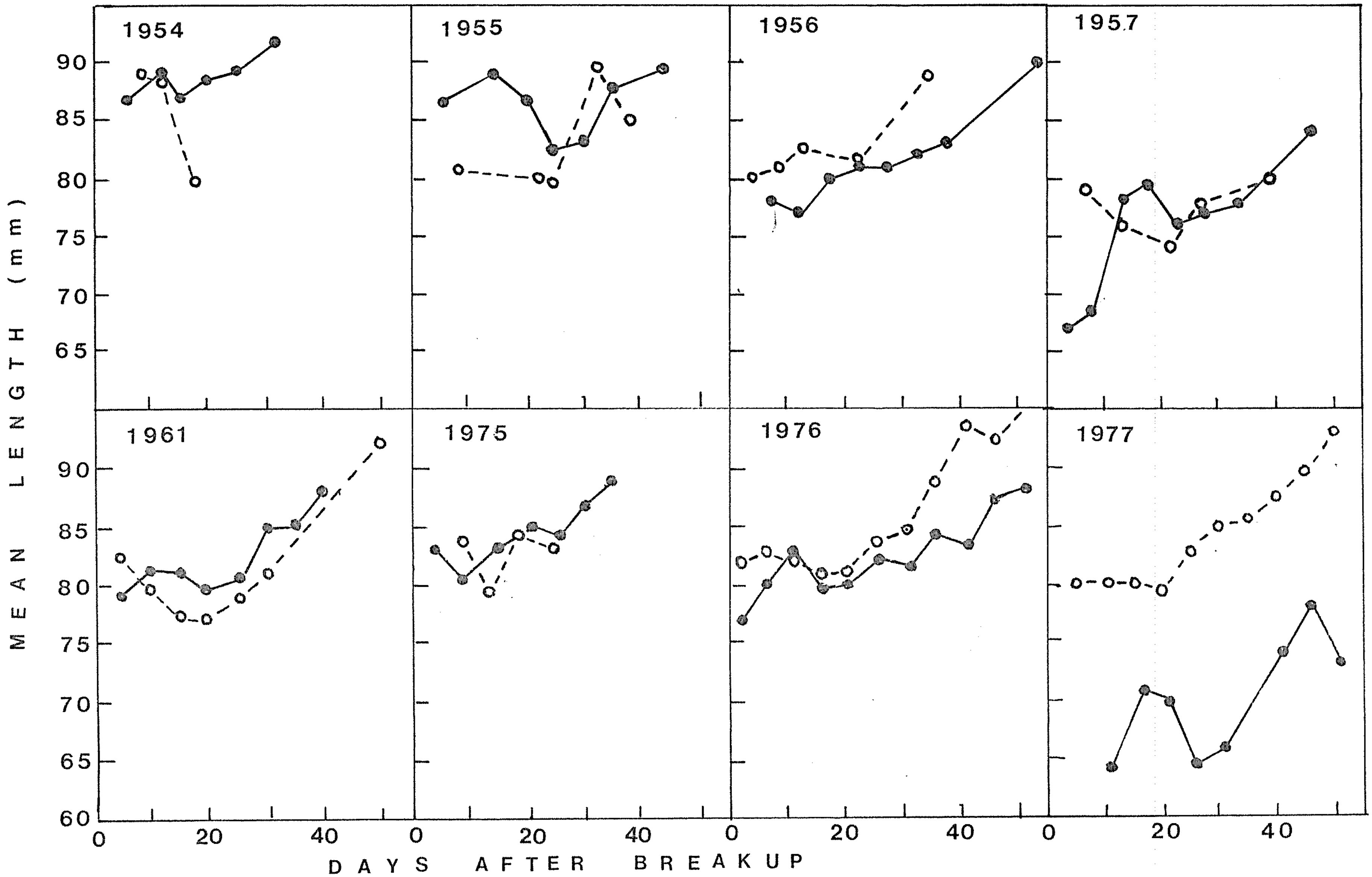

Fig. 15. Mean lengths of age I smolts from Little Togiak Lake (open points) and Wood River (closed points) according to days after ice breakup.

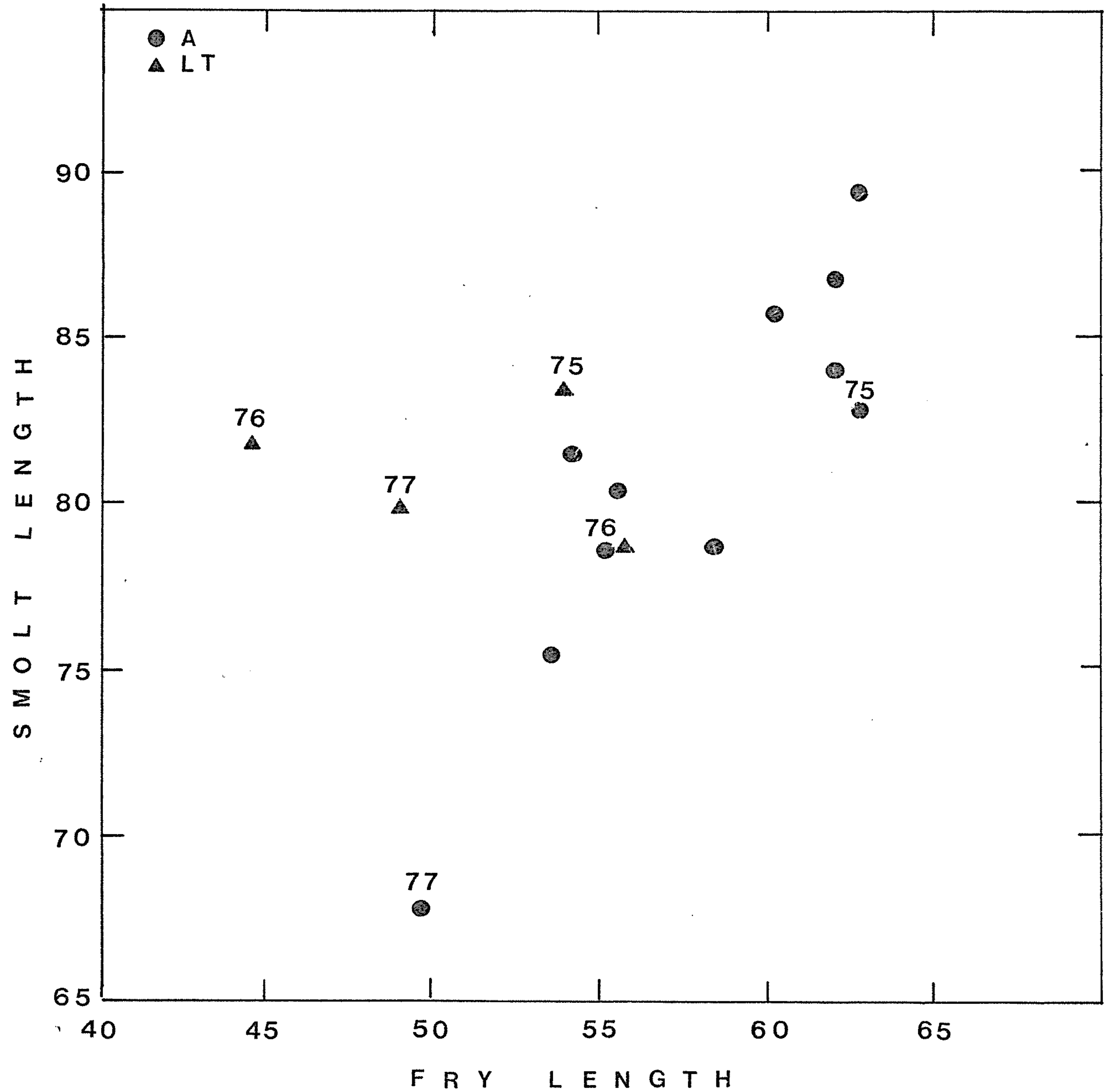

Fig. 16. Mean length of age I smolts from Little Togiak Lake during 20 days following ice breakup and from Lake Aleknagik during 10 days following ice breakup plotted against the mean length of fry on September 1 of the previous year.

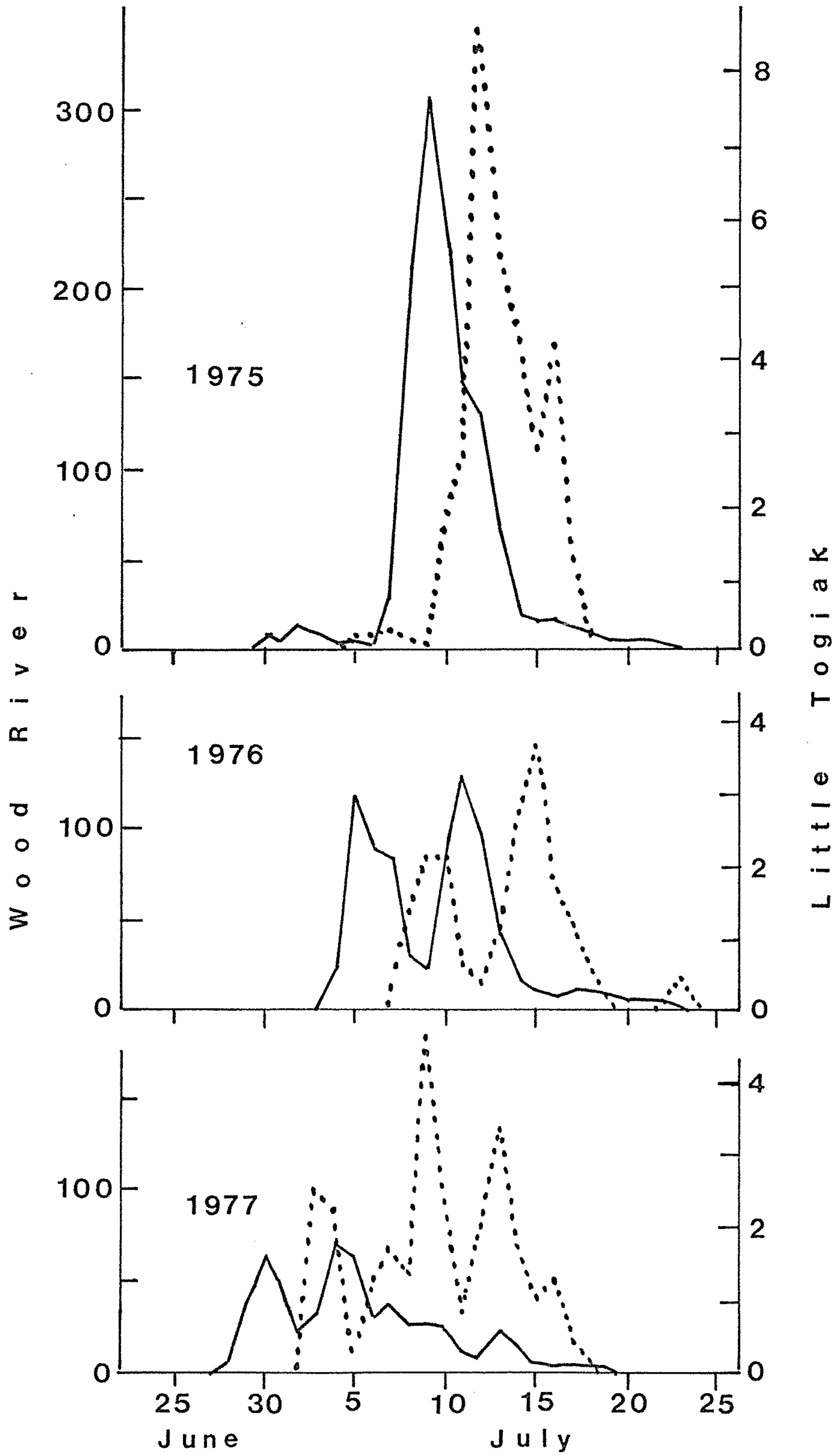

Fig. 17. Daily escapements (in thousands) to the Wood River lake system (solid) and Little Togiak Lake (dotted).