

Exxon Valdez Oil Spill
State/Federal Natural Resource Damage Assessment Final Report

Sockeye Salmon Overescapement

Fish/Shellfish Study Number 27
Final Report

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Key Words: Escapement, Kenai River, Kodiak Island, lake ecosystems, limnology, *Oncorhynchus nerka*, overescapement, overwinter survival, rearing, smolt production, sockeye salmon, zooplankton.

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EXECUTIVE SUMMARY

This status report is the third in a series describing progress on studies conducted on the effect of overescapement on the production of sockeye salmon from selected major rearing lakes impacted by the *Exxon Valdez* oil spill. Large escapements can result in the over abundance of juvenile salmon rearing in lakes. By exceeding the rearing capacity, prey resources are altered through changes in species, size composition, and biomass (Koenings and Burkett 1987; Kyle et al. 1988; Koenings and Kyle 1991). In some sockeye salmon systems, escapements of two to three times normal levels create major changes in the nursery lakes which affect the number, size, and age structure of sockeye salmon smolts. These alterations to nursery lakes may be sustained and adversely affect productivity in succeeding years.

We report an update on the results of studies of the 1989 overescapement event caused by the presence of oil on the fishing grounds. Three sockeye salmon systems (Kenai/Skilak in Cook Inlet; Red and Akalura on Kodiak Island) were selected as examples for study because they received significantly higher than normal escapement. Upper Station Lake (Kodiak) and Tustumena Lake (Cook Inlet) did not receive large escapements in 1989 and are used as controls (Figures 1 and 2). In the summer of 1992, two additional glacial lakes on the Kenai Peninsula (Ptarmigan and Grant lakes) were used to assess zooplankton communities in systems with a low number of planktivores.

Preliminary data are available on the 1992 smolt production; including size, age structure, and abundance. Major decreases in smolt abundance from the Kenai River system continued with poor overwintering survival as the primary cause. Projected returns from the 1992 smolt production would fail to meet current escapement goals established for this system. The Red Lake system demonstrated a significant migration of age-2 smolt from the 1989 broodyear, and simultaneously a decrease in growth rates of juvenile sockeye. A low number of smolt in 1991 were in part attributed to a major shift to age-2 smolt, coupled with very poor production from the 1988 rearing of fry. The production of smolt remains very low for this system. The enumeration method of smolt used on the Red Lake system on Kodiak Island was verified by weir counts. These data suggest the mark-recapture method provides similar results in the estimation of smolt production.

Because of the collapse of smolt production in the Kenai River system, the cause of the decline is receiving more intensive investigation. Vertical distribution of zooplankton in numerous glacial lakes was assessed, and found to be very different in Skilak and Kenai lakes compared to Tustumena, Ptarmigan, and Grant lakes. Tustumena Lake during recent years has had escapements similar to the ten year average while Ptarmigan and Grant lakes are barriered and do not have significant salmon runs. Zooplankton in Skilak Lake demonstrated a major daytime avoidance of the surface, particularly the egg-bearing individuals compared to the other glacial lakes. From these data we have hypothesized that predation of zooplankton by juvenile sockeye salmon affects food availability and subsequent years fish production by selectively cropping egg-bearing individuals. Future studies should support or refute this hypothesis by observing responses of the zooplankton community to reduced sockeye escapements.

INTRODUCTION

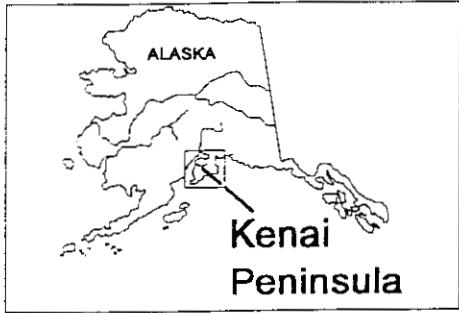
Following the *Exxon Valdez* oil spill (EVOS) in 1989, the presence of oil in the waters of traditional fishing areas in the Gulf of Alaska resulted in the closure of many commercial fisheries. This closure resulted in the escapement of large numbers of sockeye salmon (*Oncorhynchus nerka*) into some sockeye salmon systems. Investigations of the impact of large escapements on future years production were initiated in 1990. Specifically, these investigations assessed the impacts to the production and ecology of major sockeye salmon rearing lakes on Kodiak Island and the Kenai Peninsula (Figures 1 and 2).

In the Kodiak Island area, the 1989 Red Lake sockeye salmon escapement was 768,000; more than twice the management goal of 200,000 to 300,000. At Akalura Lake, the escapement was 116,000, surpassing the 40,000 to 60,000 goal by 100%. However, not all systems were received higher-than-average escapements. For example, nearby Upper Station Lake had a 286,000 escapement, which is reasonably close to the 200,000 to 275,000 goal.

The Kenai Peninsula in Southcentral Alaska contains several major glacial lakes that have produced large runs of sockeye salmon over the past decade. From 1987 to 1989, escapements of adults into the Kenai River system were approximately double those of previous years, and double the Alaska Department of Fish and Game's management goal of 550,000 adults.

The first three years of study (1990-1992) were designed to characterize the population parameters of sockeye salmon smolts resulting from escapements before and during 1989, when oil on the fishing grounds curtailed fishing. Smolt sizes, ages, and numbers reflect the density-dependent effects of escapements consistent with established goals, and thus help to establish pre-impact conditions. The limnological assessment determined the rearing conditions during the initial impact of large numbers of rearing fish and the effects of large nutrient additions to the systems from salmon carcasses. Because high densities of planktivorous fish can exert top-down control over lower trophic levels, measurable ecosystem changes within the affected lakes are expected to occur. For example, major forage items within the zooplankton community may be reduced or eliminated, prey item body-sizes may be reduced and preferred food items may be replaced by forms resistant to predation. Kyle et al. (1988) found that large sockeye escapements into Frazer Lake on Kodiak Island resulted in subsequent reductions in smolt size that was correlated to a depressed zooplankton community. The resulting reduction in the number of outmigrant smolt may foretell a major collapse of the commercial, sport and subsistence fisheries on effected stocks of salmon in Cook Inlet and on Kodiak Island.

In 1991 we reported the first indication of major decreases in smolt production from Red Lake on Kodiak Island and from the Kenai River. We continue investigations to examine the cause of these declines. Density-dependent mechanisms may decrease production whereby predation exhausts or alters the availability of the food resources. This reduction in food resources may subsequently lead to limited survival. Alternatively, climatic variation, such as extended winters could be a primary (or an associated) cause of poor survival.



Study Lakes Kenai Peninsula Overescapement Studies

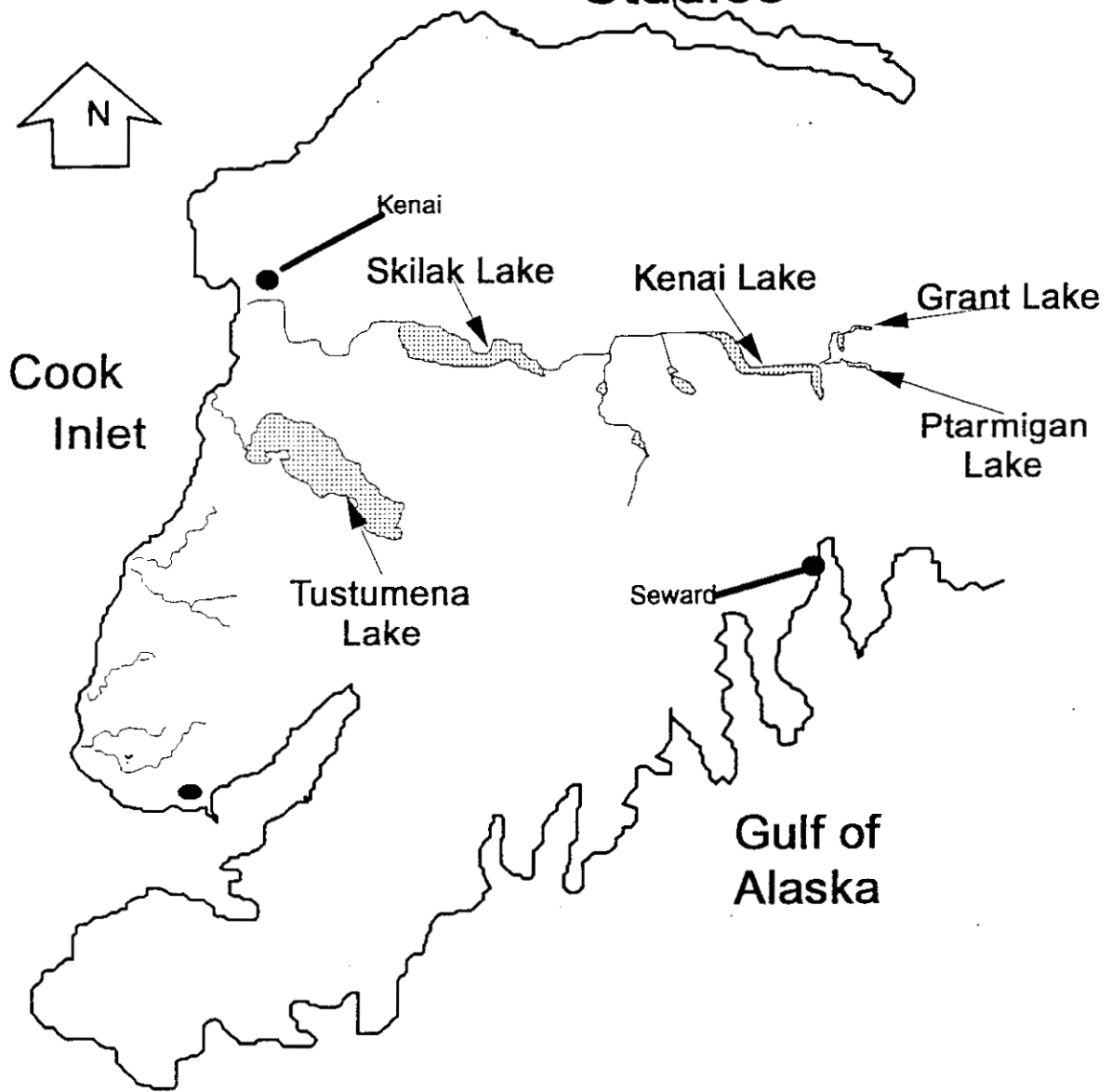


Figure 1. Location of study lakes within the Kenai River drainage, Kenai Peninsula, Alaska.

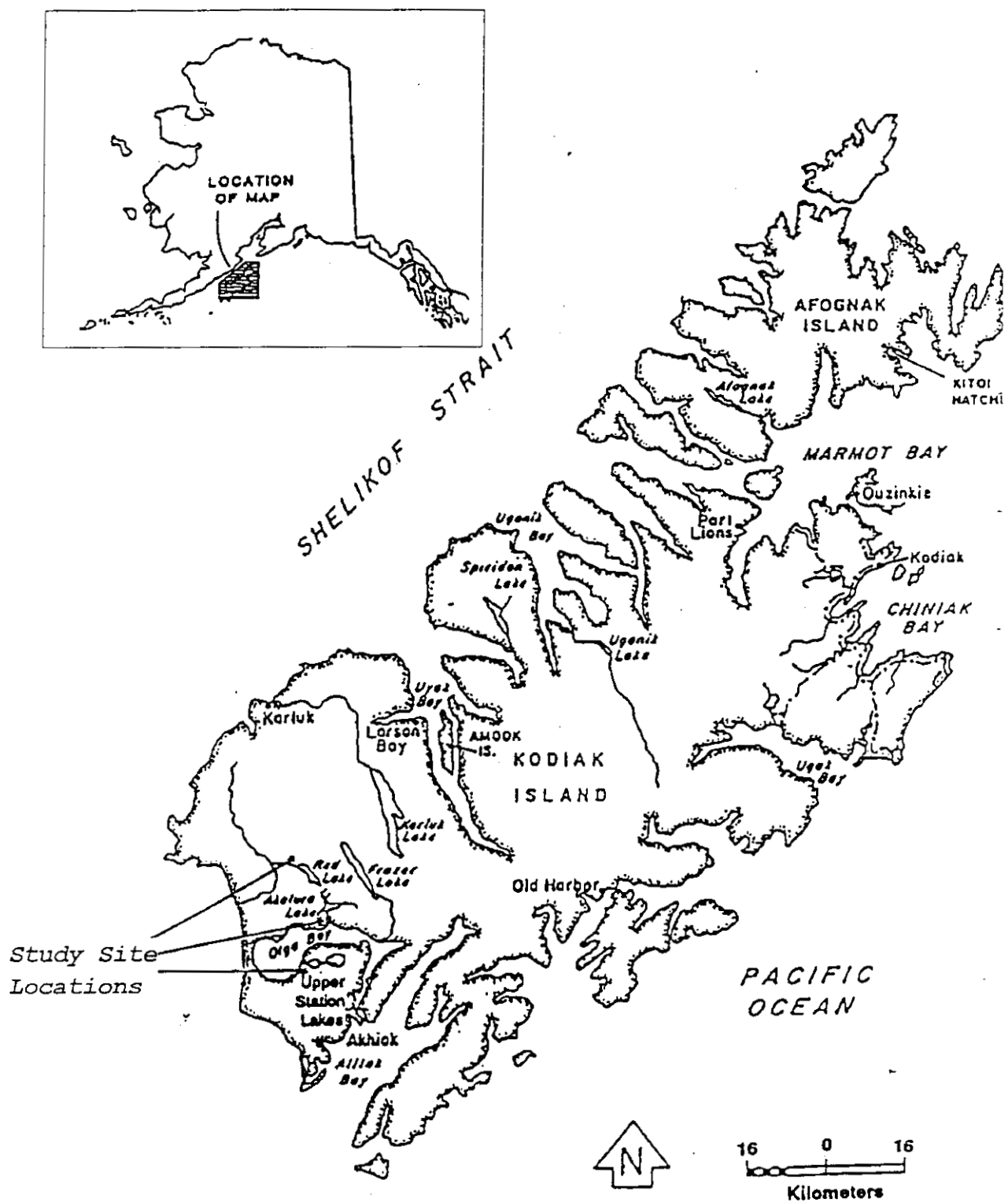


Figure 2. Location of Red, Akalura, and Upper Station lakes on the southern end of Kodiak Island.

Although measuring the magnitude of losses to fish production is a high priority, the measurement of nutrients and the zooplankton community provides information to support potential rehabilitation programs required to restore lost productivity. Our investigations examine the availability of food resources to sockeye salmon fry in five glacial lake systems on the Kenai Peninsula and three clearwater lakes on Kodiak Island that have had varying densities of sockeye salmon fry recruited to the pelagic environment. Our studies attempt to link measurements of the food supply in these lakes with the fall condition and survival of juvenile sockeye salmon. These data also are essential to determine if the production changes in fish are related to density rather than climatic or other non-density dependent sources.

OBJECTIVES

The following objectives of this study are required to assess impacts of overescapement on the production of sockeye salmon.

1. Measure critical biological attributes (number, age, size) of juvenile sockeye in sockeye salmon nursery lakes of the Kenai Peninsula and Kodiak Island.
2. Determine effects on smolt production and subsequent adult returns caused by large escapements resulting from fishery closures after the EVOS. These effects will be inferred by studying the changes in the rearing capacity of selected nursery lakes which were either affected or unaffected by the oil spill. Data used for these inferences include:
 - a. abundance, age, and growth of juveniles and smolts
 - b. nutrient budgets, plankton populations, and other physical and chemical parameters.
3. Identify potential alternative methods and strategies for restoration of lost use, populations, or habitat where injury is identified.

Although not included in the original study plan, the collected data inherently provides an opportunity for examination of the feasibility of alternative restoration opportunities.

This report provides interim observations as to changes which occurred in the biological, physical, and chemical properties during the course of these studies and relies on other investigations for comparative data. We provide preliminary analyses of some of these data with the intent of determining if existing monitoring programs are adequate to measure the biological responses and provide evidence as to the cause of observed changes.

METHODS

Adult sockeye salmon assessment

Escapements of sockeye salmon was estimated by weirs at Red, Upper Station, and Akalura lakes. Escapement into the Kenai and Kasilof rivers was estimated by sonar counters using fish wheels for capturing samples of the escapement for species apportionment, sex ratios, and size data (King and Tarbox 1991). Adjusted sonar counts are used for in-season management on the Kenai and Kasilof rivers. Spawners in the Kenai River were estimated from the sonar counts minus the estimated sport fishing harvests above the counting sites. Kasilof River sport fishing harvests were considered negligible; therefore spawner counts are considered equal to spawners. Kenai River spawner estimates were further adjusted by removing escapement estimates from the Russian River and Hidden Lake (weir counts). Spawner estimates of adult sockeye escapement and harvest will continue at each of the study sites. Adult scales were collected for age analysis from the fishery and fish collection devices near the sites where escapements were enumerated.

Juvenile sockeye salmon assessment

For each of the three lake studies on the Kenai Peninsula, and from three lakes on Kodiak Island, the abundance, size, and freshwater age of juveniles from the 1989 escapement were estimated through hydroacoustic surveys with townet sampling. The townet sampling was conducted to determine species composition and to collect specimens for size and age data. Fish lengths and weights were measured after preservation in 5% formalin. Occasionally, frozen or unpreserved fish were measured. Lengths were corrected for shrinkage caused by the preservative (Honnold 1992). In 1992, hydroacoustic surveys were conducted only on the Kenai Peninsula lakes. Tow net samples from the Kodiak lakes collected during 1990 and 1991 were primarily composed of three-spined stickleback, with very few sockeye salmon collected. Projected sockeye salmon juvenile abundances from the sonar survey using the tow net data for apportionments resulted in sockeye salmon fall juvenile abundances that were significantly below the total smolt counts enumerated in 1991 and 1992 in these lakes. Without an improved method of species apportionment, the sonar data provided little useful information in determining fall sockeye salmon abundance and was consequently discontinued (Honnold 1992). Detailed survey methods are documented for the Kenai River lakes in Tarbox and King (1992), for Tustumena Lake in Kyle (1992), and for the Kodiak Island lakes in Honnold (1992). Freshwater growth and age of juvenile sockeye salmon from all study systems were determined from scale and otolith measurements made either by direct visual analysis of scales or for otoliths with an optical pattern recognition system. Additional collections of hydroacoustic data and its analysis to determine the vertical distribution of sockeye salmon juveniles within Skilak, Kenai, and Tustumena lakes were initiated in 1992 to further understand potential limitations to sockeye production. One of the hydroacoustic transects used in the fall of 1991 was surveyed again in May of 1992 on Skilak Lake. Multiple recordings of hydroacoustic data from this same transect were obtained from twilight through darkness to determine diel changes in distribution of fry. Extended fry sampling in the fall of 1992, and improved sampling nets for collecting fry

from these lakes are planned for the 1993 season. Because overwintering has been identified as the time period for juvenile salmon mortality within the Kenai River system lakes, we have improved the measurement of fry condition in the fall and spring by measuring lipid content.

Sockeye salmon smolt enumeration

The total number of sockeye salmon smolt (with 95% confidence intervals) migrating from each of the lake systems in 1990-1992 was estimated by a mark-recapture technique (Rawson 1984). Estimated size and age of sockeye salmon smolts was compared by broodyear. Smolt were collected from traps of various designs. At weekly intervals, a sample of fish was marked with Bismark Brown dye and released upstream. Recovery rates of the dyed fish were used to estimate trap efficiency. This efficiency rate was then applied to estimate the total smolt outmigration. Methods deviated slightly each year but specific details of sampling are available in Barrett et al. (1993) for the Kodiak lakes, in King et al. (1991) for the Kenai River, and in Kyle (1992) for the Kasilof River. Subsamples of smolts from Red Lake were stored frozen and sent to the University of Alaska in Fairbanks to determine the relative levels of marine versus terrestrial nitrogen from selected Kodiak Island systems. These samples were taken to determine the effects of carcass nutrient additions in maintaining the productivity of Red Lake. We obtained otoliths from a subsample of smolt for growth rate analysis and freshwater pattern determinations. These two sample sets will be reported in the final report or in a later progress report.

Limnological studies

Limnological sampling has been conducted in the Kenai River control lake (Tustumena Lake) at three stations since 1981. Two stations were sampled from Skilak and Kenai lakes from 1986-1989, and beginning in 1990 three stations were used to collect limnological parameters. Zooplankton data were collected from Skilak Lake at five stations in 1990, 10 in 1991, and three in 1992. Zooplankton samples from Kenai Lake were collected at three stations during 1990-1992. Limnological data were collected from three stations in Red Lake, two stations in Akalura Lake, and two stations in Upper Station Lake. Samples were collected at about three week intervals on each lake during May through October. Study site locations, sampling dates, physical, chemical and biological parameters, and data summaries are provided in Appendix A. Water nutrients and basic physical parameters, chlorophyll *a*, and zooplankton samples were analyzed at the State of Alaska's Limnology Laboratory located in Soldotna. Analytical procedures followed standardized laboratory and quality assurance methods (Koenings et al. 1987). In cases where prior years data are available, limnological parameters during residence of juveniles from the 1989 escapement were compared to parameters during prior years.

The vertical distribution of zooplankton in 1992 was obtained from two locations in Skilak Lake during daylight hours on May 19, June 8, July 1, July 30, August 26, September 25 and October 27. Night samples were collected on May 19, June 11, July 17, August 6, September 2, October 8, October 12, and October 27. Vertical distribution of zooplankton

in Tustumena Lake during 1992 was sampled at a single location during daylight hours on October 7 and October 26, 1992 and during the night hours on October 7 only. Vertical zooplankton samples were collected from one location in Kenai Lake during daylight hours on August 21, September 28, and November 11, and during the night on October 12 and November 11. Daylight vertical distribution samples were obtained from one location on September 14 from Ptarmigan Lake and on September 3 from Grant Lake.

To collect quantitative data representative of the vertical distribution of the zooplankton community, a closing zooplankton net was utilized. The net is constructed of 153- μ Nitex mesh with a 0.5-m stainless steel ring at the mouth and a 200-ml collection bucket. Essentially, this netting procedure is identical to the methods used for collecting water column zooplankton samples used for biomass estimates. The net is vertically lowered to the desired depth as measured with a tow line marked in 1-m increments. After vertically retrieving a 5- or 10-m tow, the line is sharply jerked triggering the release of a closure mechanism at the opening of the net. Triggering this mechanism causes the net to fold over on itself stopping any further collection of zooplankton. After the collection bucket is thoroughly rinsed with distilled water, the release mechanism is reset and the net lowered to the depth at which collection had previously been halted.

RESULTS AND DISCUSSION

Kenai River System Investigations

Adults Returns and Escapement

Major departures from the established escapement goals in the Kenai River occurred during 1987-1989 (Figure 3). The 1989 event corresponded with closures associated with the *Exxon Valdez* oil spill. Escapements did not greatly exceed targeted values in the nearby Kasilof River/Tustumena Lake sockeye system during this same time period (Figure 4), and was the primary reason this system has been studied as a control. We evaluated the relationship between fall fry abundance and potential egg deposition (PED) in the Skilak/Kenai lake system from 1985 to 1991 using regression analysis. The fall fry abundance estimate errors were assumed to be random, uncorrelated, and unbiased and thus absorbed in the model error term (Neter et al. 1989). Potential egg deposition is a linear expansion from female escapements and mean fecundity data. A scatter plot of the data indicated that a linear model would provide an adequate fit (Figure 5). Fall fry counts (dependent variable) were based on combined estimates from the two lakes (1986-1992) and egg counts (independent variable) were estimated by multiplying the number of mainstem female spawners by 3,500 eggs/female for the corresponding broodyears (1985-1991).

The relationship between potential egg deposition and fall fry numbers in Skilak and Kenai lakes over the available time series was assessed by applying two models -- one with and one without the y-intercept (constant) term. The first model (constant included) gave the maximum possible correlation coefficient within the domain of egg counts and provided a way to test the constant. The 0-intercept model adhered to the biological requirement of including the origin. Tests of significance for both models were conducted at the $P = .05$

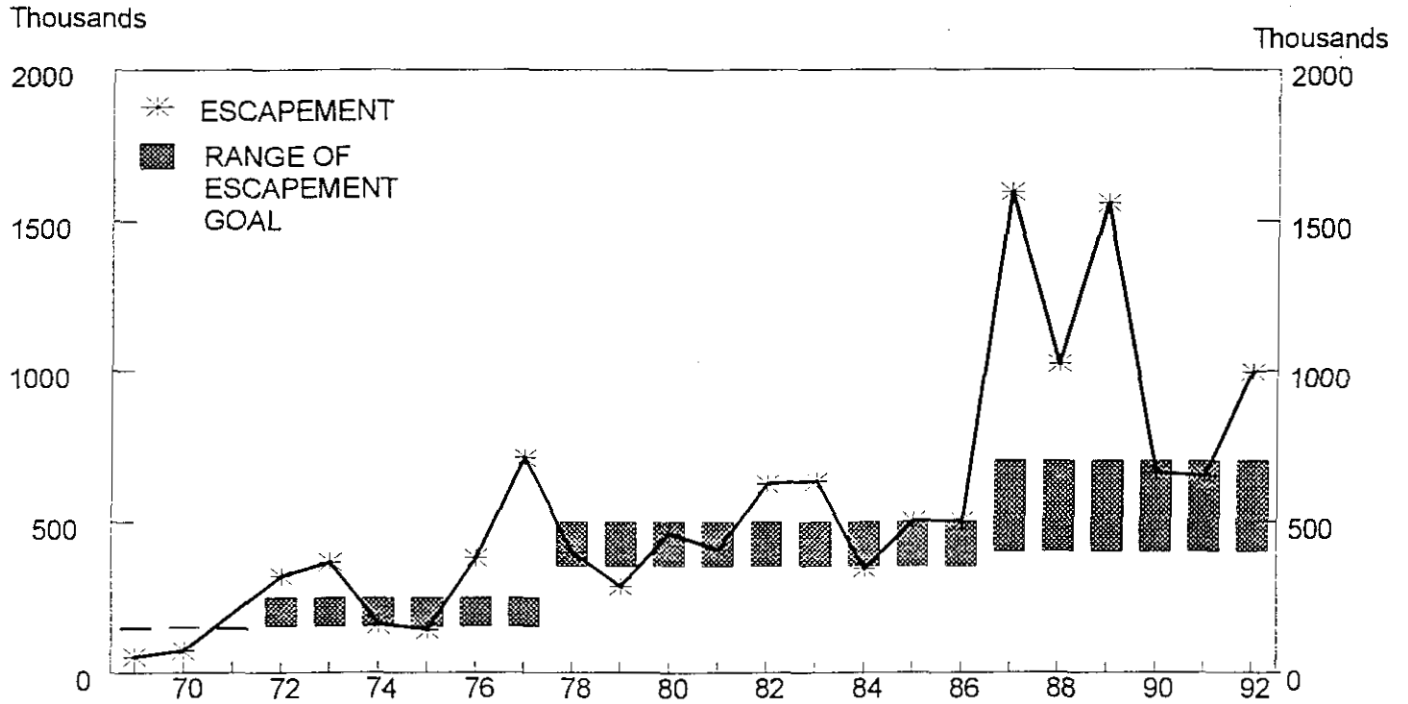


Figure 3. Summary of sonar count sockeye salmon escapements and historical escapement goal ranges for the Kenai River. Data represent total cumulative daily apportioned sonar counts at mile 19 of the Kenai River. Height of bars represents maximum escapement goal with the bottom of the gray bar representing the minimum escapement goal.

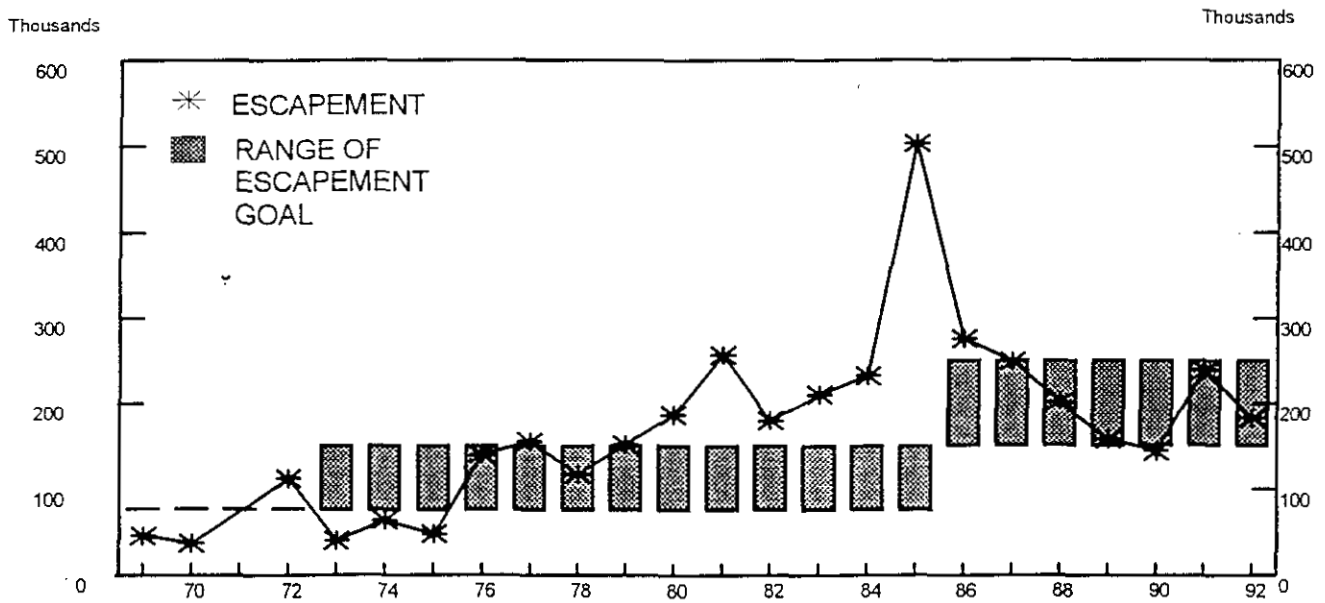


Figure 4. Summary of sonar count sockeye salmon escapements and historical escapement goal ranges for the Kasilof River. Escapement data represent total cumulative daily apportioned sonar counts at mile 11 of the Kasilof River. Height of bars represents maximum escapement goal with the bottom of the gray bar representing the minimum escapement goal.

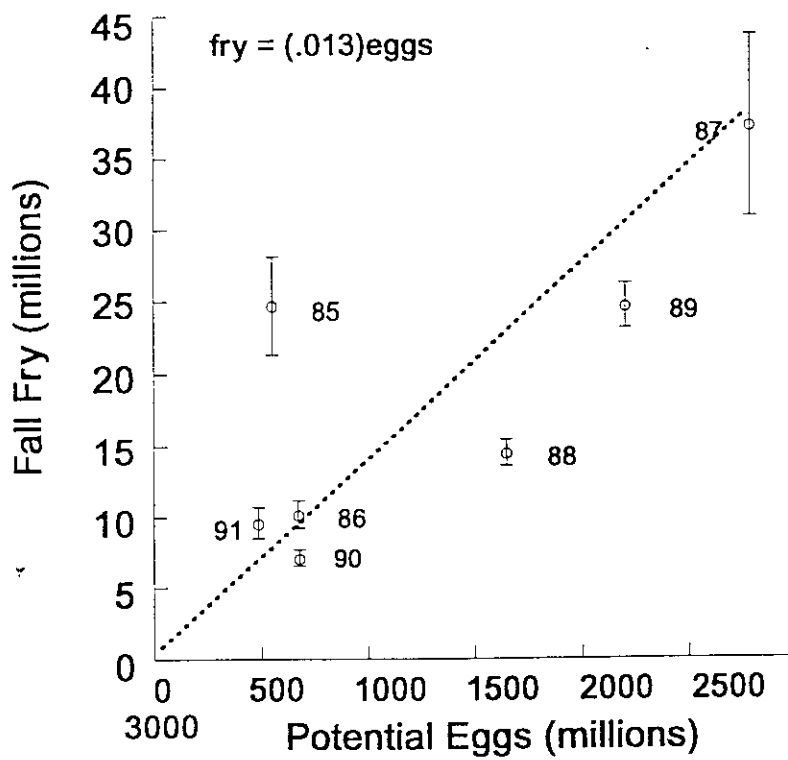


Figure 5. Relationship between number of age-0 fall fry in Kenai and Skilak lakes and mainstem potential egg deposition. Values listed indicate brood year of the eggs and fry. Vertical bars are standard errors of estimated fry abundances.

level. Both models had significant slopes ($P < .05$), although the model with the constant accounted for more variation in fall fry abundance ($R^2 = .591$) than the 0-intercept model ($R^2 = .461$). However, the constant term in the former was not significantly larger than zero ($P = .26$). The Durbin-Watson statistic indicated no autocorrelation ($P > .05$). Age-0 fall fry abundance in 1986 (1985 broodyear) had a studentized residual of 4.06 and is therefore a possible outlier. These data indicate the age-0 fall fry abundance in the lakes were a function of escapements. To test the hypothesis of compensatory fry production, we applied Ricker's non-linear stock recruitment model. An attempt to fit the data to the model resulted in a non-significant slope ($P = .274$). Consequently we conclude that no compensation was observed in fall fry production related to variations in escapement; thus the egg-to-fall fry survival rate (the slope of this line) during this limited time period is likely the result of density-independent factors.

Smolt Production

Detailed study results are listed in King et al. (1991) for the Kenai River smolt investigations and in Kyle (1992) and Todd and Kyle (1992) for the Kasilof River smolt investigations. Juvenile (fall fry) and smolt production from the Kenai River system and smolt production from the Kasilof River system are presented in Figures 6 and 7. The abundance and population characteristics of smolts which migrated from the Kenai and Kasilof rivers are presented in Tables 1 and 2, respectively. The 1989 escapement in the Kenai River had minimal impact on the 1990 smolts, while the 1991 and 1992 smolts were primarily effected by the 1988, 1989 and 1990 escapements. These data indicate major decreases in smolt production from 1990 to 1991 in the Kenai River system, but not in the Tustumena (Kasilof River) system. A shift of Kenai River smolt age composition in 1992 to predominantly age-2 and the increase in mean weight of age-2 smolt, is most likely the result of increased presence of smolt from the Russian River and other minor systems in the samples obtained from the lower Kenai River. The low numbers of smolt produced from Kenai and Skilak lakes apparently resulted in these minor systems now being the major producer of sockeye salmon smolt.

Juvenile Production

The juvenile sockeye salmon production within Kenai and Skilak lakes as reflected by fall fry abundances are illustrated in Figure 6. The percentages of age-0 fall fry that outmigrated as age-1 smolt the following spring are illustrated in Figure 8, along with the estimated potential egg deposition-to-fall fry survival. As the Kenai River smolt age composition is dominated by age-1 smolts, and there is no evidence of significant numbers of holdovers, overwintering mortality appears to be the cause of the collapse in smolt production in the Kenai River. No such decrease in smolt production for the same time period is evident from the Kasilof River system (Figure 7), which did not receive excess escapement in 1989. This decrease during the winter of 1991-1992 was verified by a hydroacoustic survey conducted in May of 1992. A single transect sampled at this time indicated densities of juvenile sockeye in Skilak Lake were less than 10% of those observed during the fall of 1991 in the same area. This is approximately the decline observed from the 1990 fall fry to 1991 smolt during the previous year's investigations.

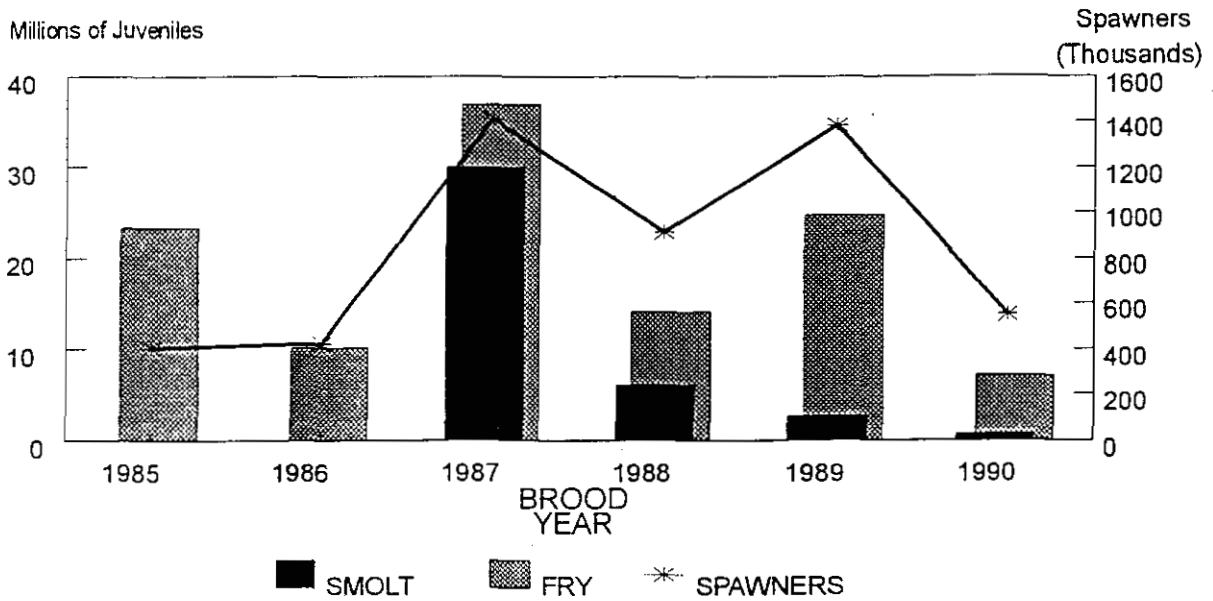


Figure 6. Interannual variation of the mainstem Kenai River sockeye spawners, smolt production, and combined fall fry estimates from Kenai and Skilak lakes. Mainstem spawner abundance is estimated annually from apportioned sonar counts less sport fish harvests and estimated escapements into the Russian River and Hidden Lake. Smolt production are total smolt numbers estimated at Kenai River mile 19.

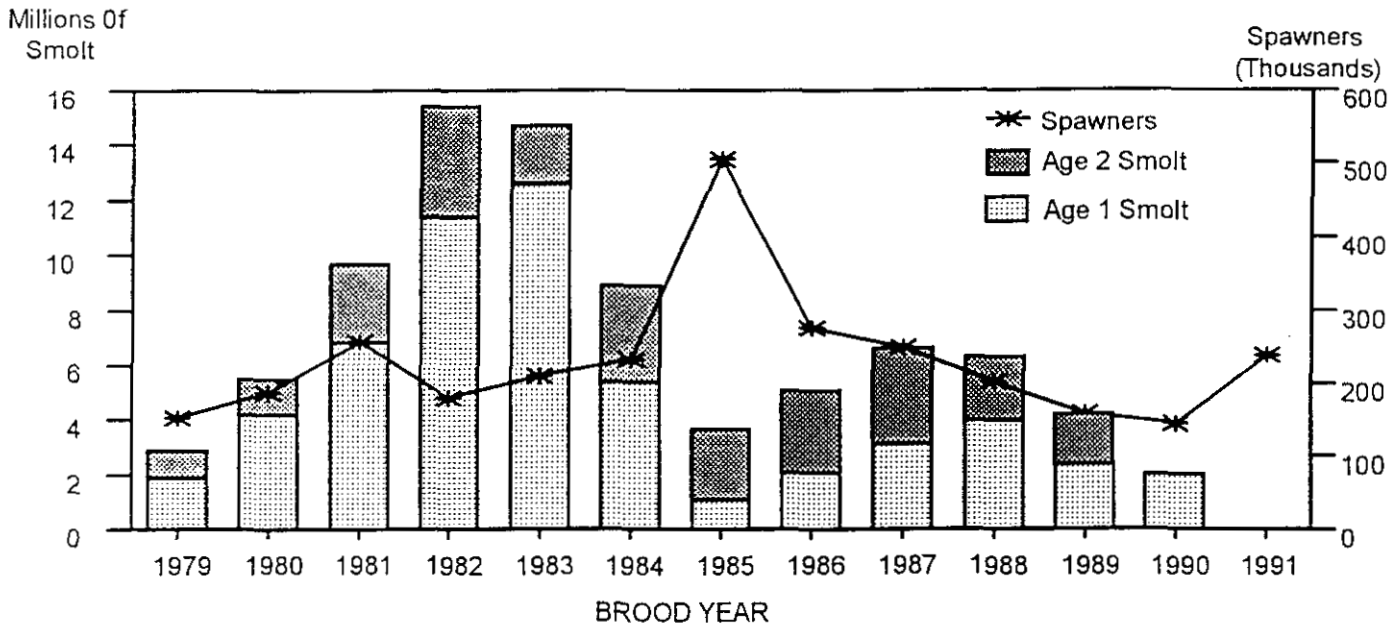


Figure 7. Interannual variation of the Kasilof River sockeye salmon escapements and broodyear production of smolt from Tustumena Lake. Spawner abundance is estimated annually from apportioned sonar counts as sport fishing removals are considered negligible. Smolt production are total smolt numbers estimated at Kasilof River mile 10.

Table 1. Sockeye salmon adult escapement and smolt production in the Kenai River for broodyears 1986-1992.

Brood Year	Spawning Escapement*	Total Number of Smolt Produced			Broodyear Total
		Age-1.0	Age-2.0	Age-3.0	
1986	422,000		71,000	16,000	88,000**
1987	1,408,000	23,804,000	5,758,000	1,000	29,563,000
1988	910,000	5,069,000	418,000	0	5,487,000
1989	1,379,000	2,582,000	312,000		2,894,000
1990	519,000	65,000			**
1991	431,000				
1992	798,000				

Smolt Year	Age Composition (%)			n
	Age-1.0	Age-2.0	Age-3.0	
1989	99.7	0.3	0	3567
1990	46.8	53	0.2	3422
1991	86.1	13.9	0	3741
1992	23	77	0	981

Smolt Year	Smolt Fork Length (mm)					
	Age-1.0			Age-2.0		
	Mean	SD	n	Mean	SD	n
1989	59.6	4.4	3567			
1990	67.6	7.4	3422	74.4	5.4	1738
1991	65.6	4.9	3040	79.7	5.7	700
1992	77	9	226	92	7	755

* Spawning escapement equals total counted escapement minus sport fish harvest.

** Indicates incomplete data.

n = sample size; S.D. = 1 standard deviation.

Table 2. Sockeye salmon adult escapement and estimated smolt production in the Kasilof River for broodyears 1981-1992.

Brood Year	Spawner Escapement	Numbers of smolt with percent hatchery contribution					
		Age-1*1000	% Hatchery	Age-2 *1000	% Hatchery	Total *1000	% Hatchery
1981	256,625	6,817	40.7	2,869	20.6	9,686	34.7
1982	180,239	11,390	36.3	4,001	7.7	15,391	28.9
1983	210,270	12,580	27.8	2,223	11.1	14,803	25.2
1984	231,685	5,268	30.2	3,540	31.1	8,808	30.9
1985	505,049	1,074	59.2	2,549	17.0	3,623	29.5
1986	275,963	2,056	52.0	3,009	10.2	5,065	27.3
1987	249,246 ^{1a}	3,109	30.3	3,521	3.0	6,630	15.8
1988	204,000	3,916	2.0	2,335	1.0	6,251	1.8
1989	158,206	2,400	7.0	2,012	1.3	4,412	4.7
1990	144,136	2,107	7.5			2,107	
1991	238,269						
1992	183,178						

Smolt Year	% Age Comp Composition		
	n	Age-1	Age-2
1983	1163	84	16
1984	1192	80	20
1985	1263	76	24
1986	1348	70	30
1987	1635	23	77
1988	1275	45	55
1989	1125	51	49
1990	1150	53	47
1991	1018	51	49
1992	1150	56	44

Smolt fork length by outmigration year						
Year	Age-1			Age-2		
	Mean	n	SD	Mean	n	SD
1983	70	712	3.8	83	451	5.4
1984	73	1005	3.5	85	187	4.4
1985	70	981	2.8	84	282	5.4
1986	69	983	3.9	84	365	5.1
1987	64	412	6.1	77	1223	4.8
1988	68	623	4.0	78	652	4.5
1989	66	609	4.4	81	516	4.5
1990	69	683	4.4	82	467	4.2
1991	68	529	3.5	80	489	3.2
1992	74	594	3.8	87	556	4.7

^{1a} Because of sonar failure, escapement estimates were from stream surveys and spawning stream weir counts above Tustumena Lake.

(Values are in mm; n = sample size; SD=1 standard deviation).

See Kyle (1992) for statistics of smolt abundance precision estimates.

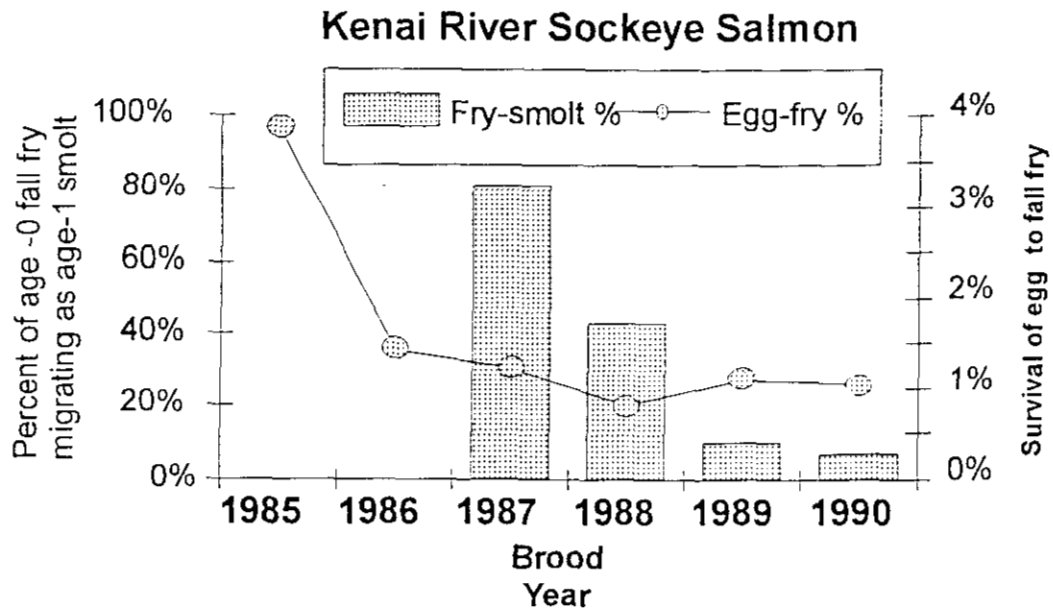


Figure 8. Interannual variation of Kenai River mainstem potential egg deposition, Kenai/Skilak lakes fall fry survival, and overwintering survival of fall fry (approximated by the ratio of Kenai/Skilak lakes age-0 fall fry abundance to Kenai River age-1 smolt outmigration). The years represent the broodyear of eggs, fall fry, and smolt. Smolt abundance was not measured for brood years 1985-86.

Fall fry length and weight data from Skilak, Kenai, and Tustumena lakes are presented in Table 3). The Skilak and Kenai lake fall fry are generally smaller than in Tustumena Lake. No trend in average weights over the time series is evident for Skilak and Kenai lakes. Further investigations of growth of juvenile sockeye in these lakes are planned, and we will evaluate if historic sampling procedures have provided representative samples.

The diel vertical distribution of 1992 spring fry in the lake was compared with the vertical distribution in the fall of 1988 (Figure 9). Note the large differences in abundance (approximately 100-fold) between these two time periods. The decrease in cumulative total numbers of fish from all depth strata during the daylight in September of 1992 compared to the night totals, and the reverse trend in May of 1992 is thought to be caused by near-surface distribution of fish that are not detectable by the hydroacoustic gear. These limited data suggest fish migrate toward the surface during the night in the spring but exhibit reverse migration in the fall with surface feeding occurring during the day. Further investigations are planned during 1993.

Limnological Studies

The limnological data for the Kenai Peninsula lakes are listed by lake, station, and depth in Appendix A. These data, coupled with fish production and condition data, and biological data from the zooplankton community of these lakes was used to examine various hypotheses. Because overwintering mortality is the cause of poor smolt production, we limited the hypotheses to those relationships which were most likely to explain high winter mortality. Low dissolved oxygen, a cause commonly attributed to poor overwintering survival in lakes, was quickly eliminated because of the physical nature of the lake, low loading of organic materials, and no historical data suggesting winter water quality limits survival. We screened fish samples for general disease and the IHN virus from fry collected within Skilak Lake in the spring of 1992 and found that all 20 specimens were IHN negative. We next examined correlative data with the most obvious physical parameters effecting survival. These exploratory analyses are incomplete but cursory examination reveal no obvious trends which could explain the poor overwinter survival in recent years. Synchrony of the emergence of spring fry with zooplankton blooms is one mechanism which could account for high summer fry mortality. However, as we found fall fry estimates to fluctuate less than smolt estimates, we have limited our examination to those factors which may effect condition of fry in the fall, or those factors which occur in the spring which may limit survival of the pre-smolt.

In the Kenai Lake system, Skilak Lake has been the dominant sockeye salmon producer, and has been the focus of much of the sampling effort. Nearby Tustumena Lake has been studied for 12 years to evaluate spring fry stocking (Kyle 1992). Similar data from these two lakes were compared since 1990 to provide a control to the Kenai River glacial lakes which received overescapement. Figure 10 provides a graph of comparative temperature data for Skilak and Tustumena lakes. The data indicate indistinguishable variations between these two lake systems so we have assumed identical timing and duration of seasonal temperature cycles. We would therefore expect any biological responses to temperature to occur in both systems. To evaluate the effects of the timing of spring and winter, we estimated the dates

Table 3. Kenai Peninsula lakes fall fry sockeye mean fork length and weight data.

Location	Year	Age-0				Age-1							
		Length		Weight		Length		Weight					
		(n)	(mm)	S.D.	(n)	(g)	S.D.	(n)	(mm)	S.D.	(n)	(g)	S.D.
Skilak	1986	15	57	n/a				8	74				
	1988	109	50	5.3	109	0.9	.4						
	1989	136	50	3.3	136	1.2	.3	126	64	6	126	2.8	.7
	1990	928	49	4.3	290	1.3	.3	34	72.8	3.3	20	4.0	.4
	1991	863	51	4.9	286	1.5	.5	55	73.8	3.8	14	4.7	.5
	1992	883	54	6	883	1.8	.6	10		3.6	10	7.0	.8
Kenai	1986	227	52	n/a	227			2	77				
	1989	38	48	4.5	38	1.0	.2	56	64	4.6	56	2.5	.6
	1990	1484	52	4.6	1484	1.5	.4	62	69.4	4.2	22	3.6	.6
	1991	1364	53.5	6.5	1364	2.0	.6	40	75.9	4.8	15	5.5	1
	1992	1492	56	7.3	1492	2.0	.8	12	78	10	12	5.6	1.7
Tustumena	1980	222	59	6.1	222	2.3	.7	20	80	3.5	20	5.7	.7
	1981	197	55	5.1	197	1.6	.4	21	73	4.6	21	3.8	.7
	1982	194	54	5.1	194	1.8	.5	17	74	3.9	17	4.	.9
	1983	562	60	6.1	562	2.5	.7	55	80	5.0	55	5.8	1.1
	1984	388	61	4.6	388	2.5	.6	186	79	3.7	186	5.3	.8
	1985	173	56	5.6	173	2.1	.6	52	78	5.0	52	5.6	1.2
	1986	156	50	6.4	156	1.3	.5	92	73	4.5	92	4.1	.7
	1987	143	53	5.9	143	1.8	.6	50	71	3.8	50	4.2	.6
	1988	303	55	5.3	303	1.8	.5	89	75	3.6	89	4.5	.6
	1989	47	52	5.7	47	1.9	.6	18	74	4.6	18	5.1	.9
	1990	200	57	5.5	200	1.5	.4	50	75	2.9	50	3.4	.5
	1991	202	57	5.4	202	2.0	.5	47	78	6.5	47	5.1	1.2

Missing values indicate no data available. n = sample size; S. D. = 1 standard deviation.

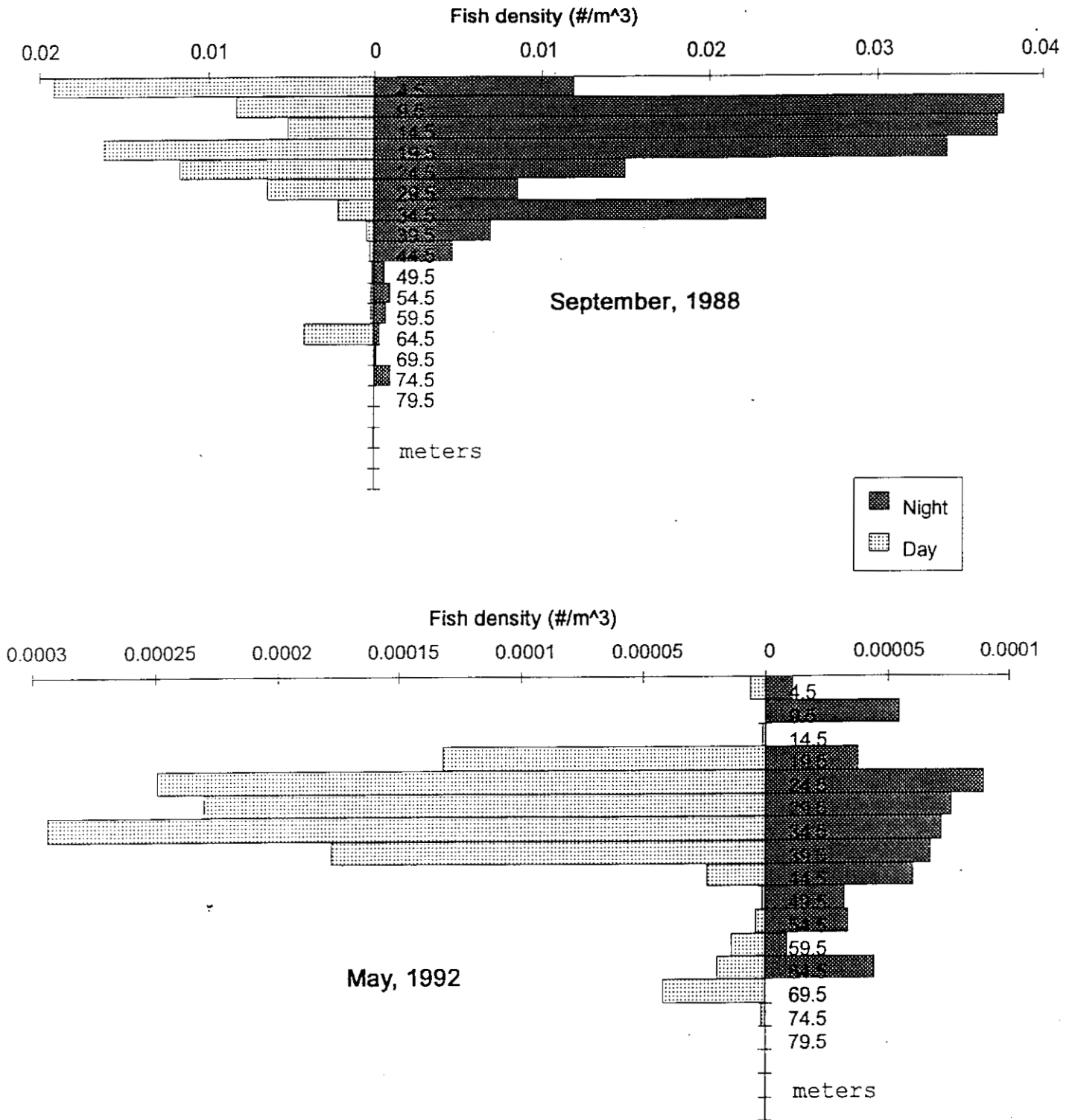


Figure 9. Vertical distribution of juvenile sockeye salmon in Skilak Lake, September 1988 and May 1992. Note that the low cumulative values for daylight September 1988 and night May 1992 are likely caused by near-surface distribution which is not detected. Values are density estimates by depth stratum for a replicated transect and the vertical axis reflects mid-point of depth strata in meters.

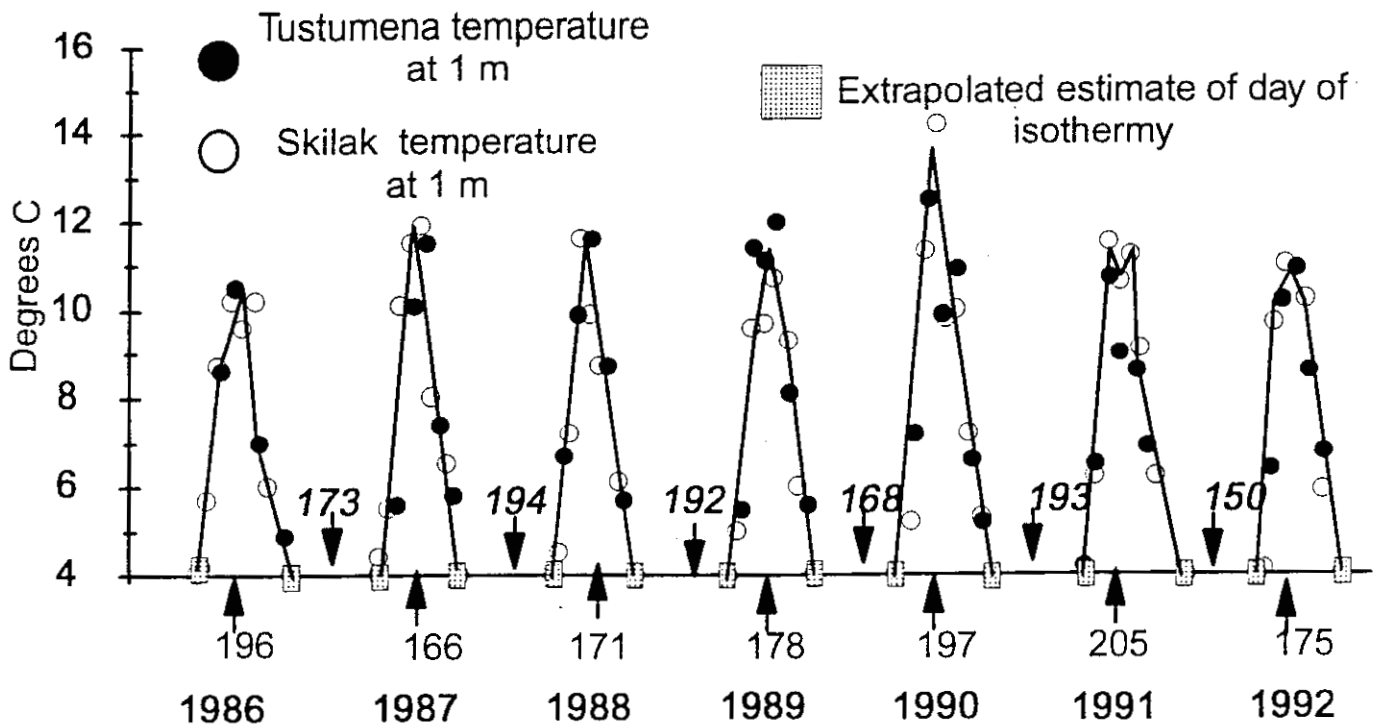


Figure 10. Comparison of 1-m depth water temperatures in Tustumena and Skilak lakes, 1986-1992. Lower line of numbers indicate days above 4 C (summer) and upper (italics) indicate days below 4 C (winter). Onset of summer and winter were estimated by linear regression of the upward and downward seasonal trends in the data.

of spring and fall isothermy (4° C) by regressing 1 meter water temperatures from Tustumena and Skilak lakes versus time during the period of increasing temperature in the spring and during the period of decreasing temperature in the fall. The date at which the temperature is projected to reach 4° C was used in further analysis. Figure 11 presents total phosphorous and chlorophyll *a* values over the growing season from Skilak Lake. Very minor variation has occurred suggesting changes in primary production because of differential nutrient loading to be an unlikely cause of changing fish productivity. Finally, Figure 12 illustrates variations in seasonal mean turbidity and euphotic zone depth (EZD) in Skilak Lake. Note that the trend illustrates increased turbidity in recent years which would correlate with the decreasing survival of 1988-1991 fall fry. However, adult returns from earlier rearing years (1986-1987) suggest corresponding adult sockeye salmon returns have been high when age-0 juveniles were exposed to similar levels of turbidity. Although turbidity may have been a contributing factor, it is unlikely to have been the primary contributor reduced overwintering survival.

With no obvious explanation of the poor survival apparent from physical parameters, we examined variations in the zooplankton community. Koenings et al. (1990) established that glacial lakes provide a very limiting environment for filter-feeding zooplankton. This limits the zooplankton community to two primary taxa of copepods, *Diaptomus* and *Cyclops*. These taxa apparently have an annual life cycle with one egg clutch being produced annually. Figure 13 reveals that the seasonal mean biomass of these taxa in Skilak Lake since the onset of these studies varied modestly. Similar collapses in sockeye salmon production related to density dependency in Frazer Lake on Kodiak Island demonstrated a major change in the zooplankton community (Kyle et al. 1988). Olsson et al. (1992) monitored an increase in fecundity of cladocerans in a lake fertilization experiment but not in standing crop biomass, presumably because of cropping effects. Copepods are the only taxa and prey for sockeye salmon in the Kenai Peninsula glacial lakes, and these taxa are apparently more resistant than cladocerans to sockeye salmon predation. Earlier studies by Yanusz (1989) indicate that sockeye salmon actively feed on copepods in nearby Tustumena Lake, but have a high selectivity against copepods in a clearwater system which had both cladocerans and copepods present.

These findings provided the impetus to look at other mechanisms which may regulate growth and condition of sockeye salmon fry. Other investigators have established that ovigerous zooplankton may be selectively cropped by planktivores and obtain nutritional advantage (Winfield and Townsend 1983; Maly 1970; Hairston et al. 1983). In Tustumena Lake, Kyle (1992) found no significant relationship between fall fry biomass and zooplankton biomass over a 12 year period. We further examined these zooplankton data to assess relationships of egg-bearing individuals to fry weight and overwintering survival, and to examine similar relationships for the more limited time series from the Kenai River lakes. Figure 14 illustrates the time series of ovigerous copepod densities from Skilak and Tustumena lakes. Note that the peak abundance of copepod eggs in Skilak Lake in 1988 apparently forecasted the peak abundance in copepod biomass (especially *Cyclops*) which occurred in 1989 (Figure 13). However, there is no relationship between the interannual zooplankton biomass variations and average weight or survival of age-0 fall fry in Skilak Lake. The limited baseline data on age-0 fall fry size from Skilak Lake prior to the large escapements of the

Skilak Lake Tustumena Lake

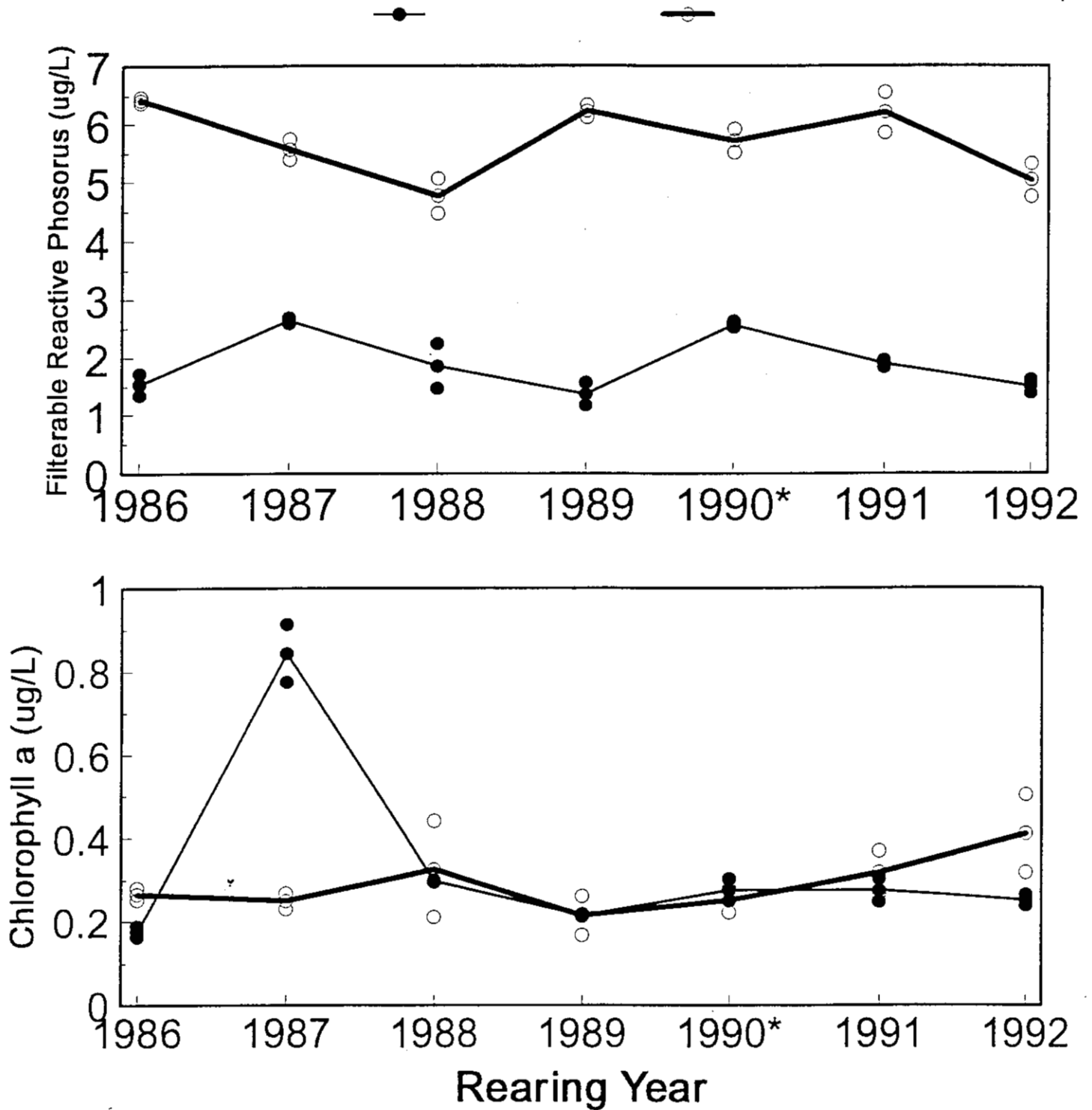


Figure 11. Interannual variation of filterable reactive phosphorous and chlorophyll *a* from Tustumena and Skilak lakes 1986-1992. Values are seasonal mean concentrations within the 1-m stratum. Dots represent one standard error from the mean from samples taken from three sampling stations on the Tustumena Lake and two sampling stations from Skilak Lake, 1986-89; (*) indicates initiation of three sampling stations on Skilak Lake (1990-92).

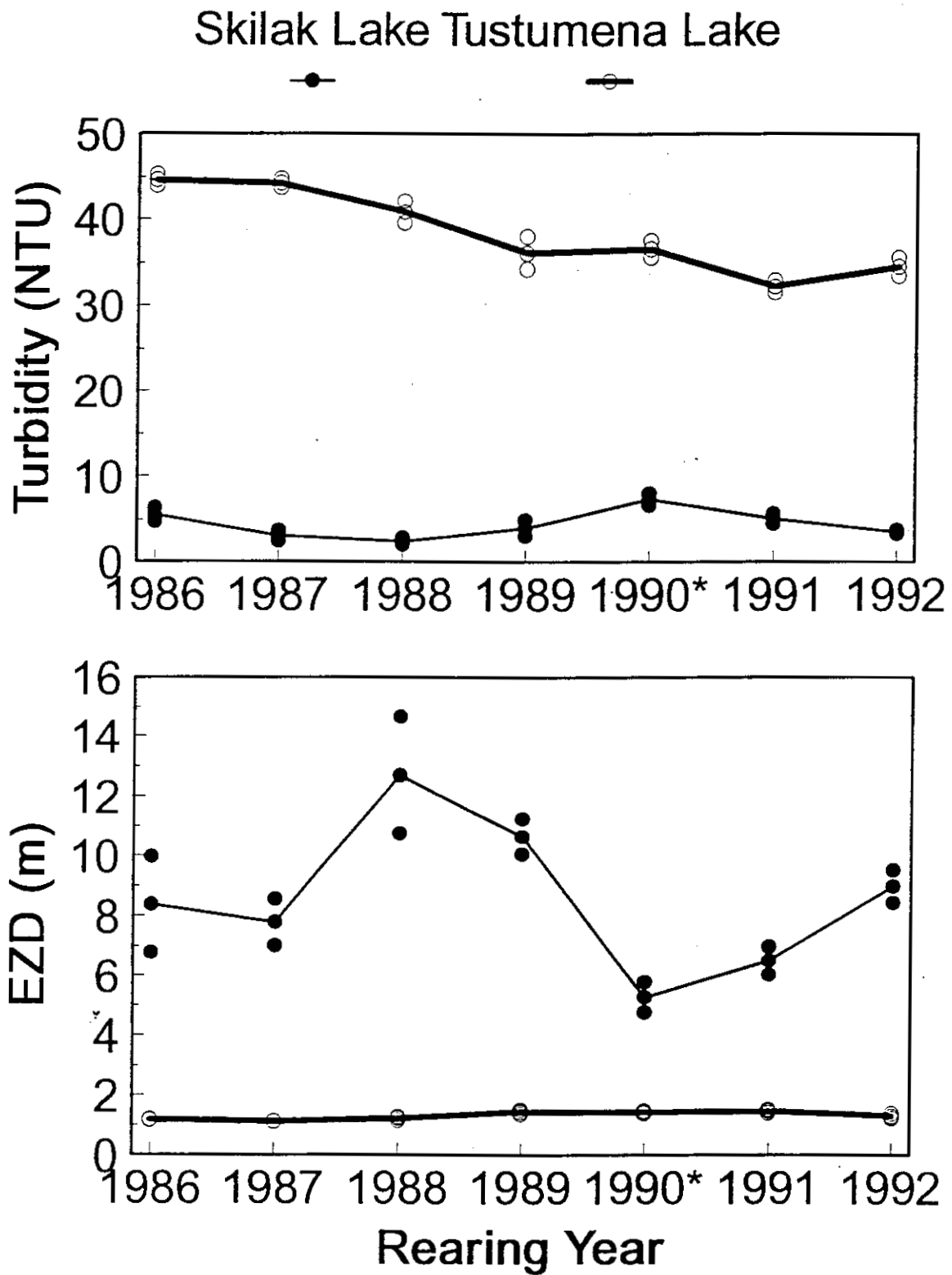


Figure 12. Interannual variation in seasonal mean turbidity and euphotic zone depth in Skilak and Tustumena lakes. Dots represent one standard error from the mean from samples taken from three sampling stations on Tustumena Lake and two sampling stations from Skilak Lake, 1986-89; (*) indicates initiation of three sampling stations on Skilak Lake (1990-92).

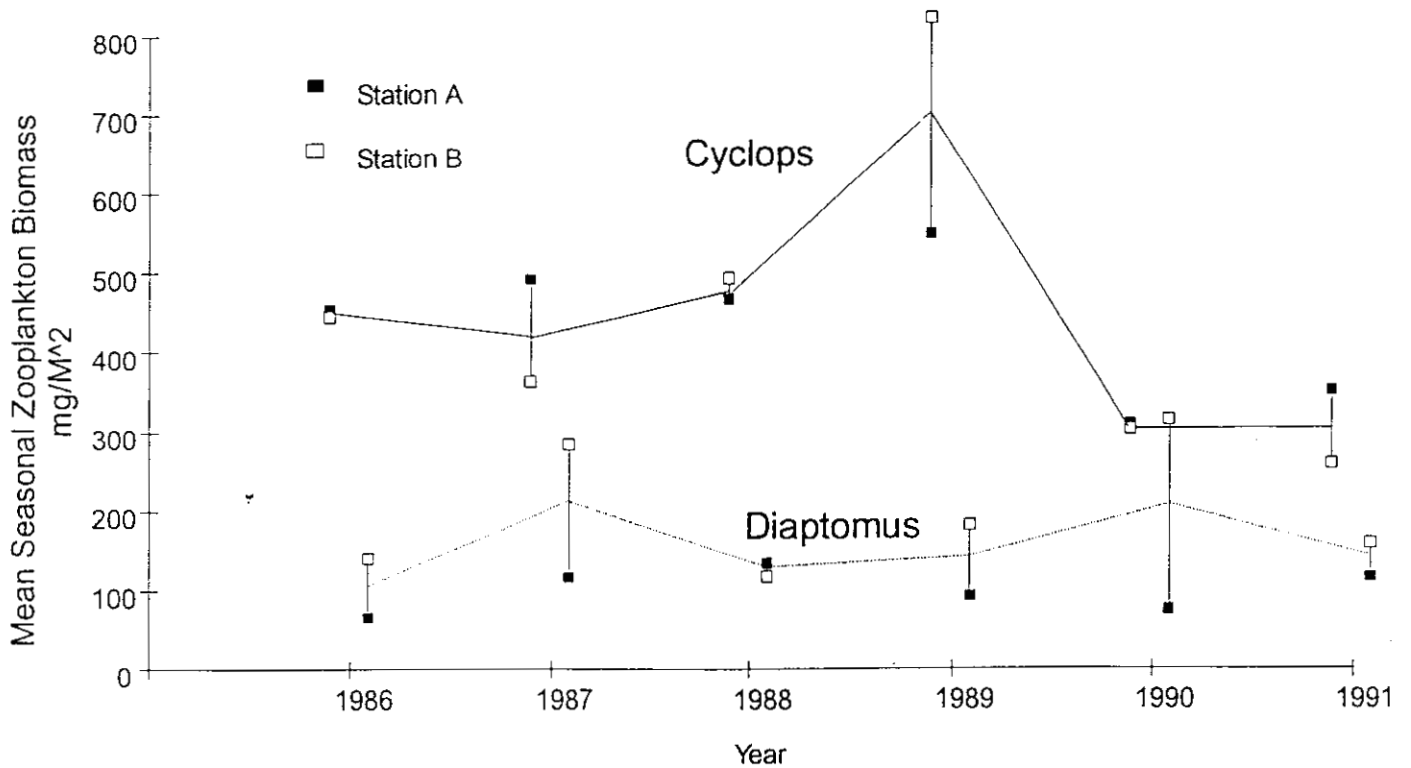


Figure 13. Interannual variation of the seasonal mean biomass of Skilak Lake copepods. Error bars reflect range of two fixed location stations that were sampled annually.

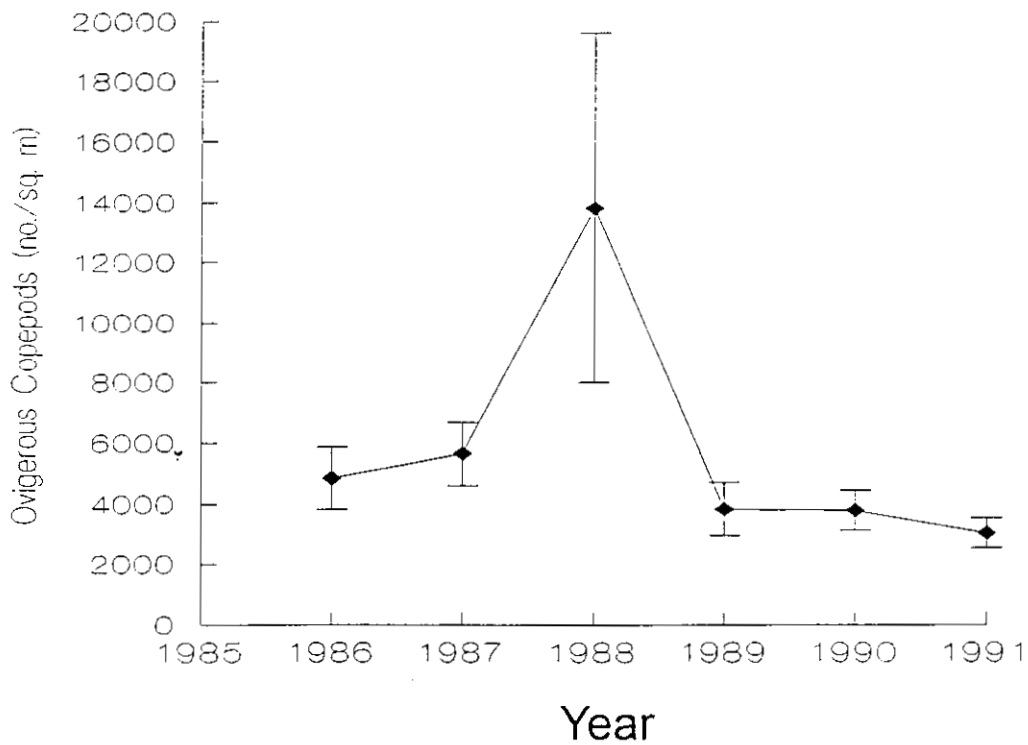
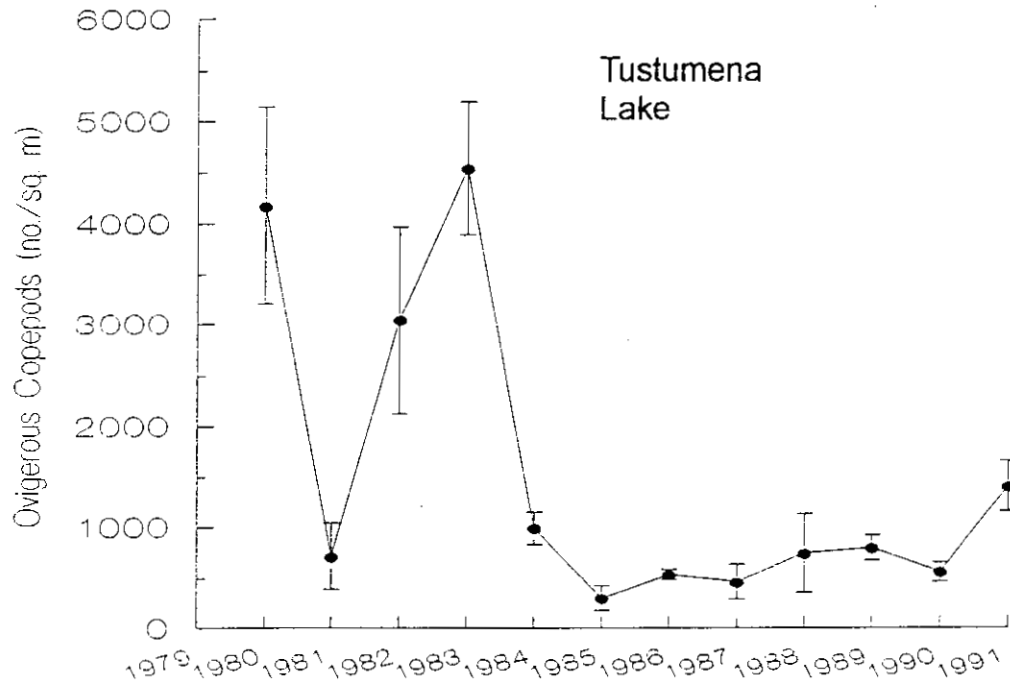


Figure 14. Interannual variation of the seasonal mean abundance of ovigerous copepods from Tustumena and Skilak lakes. Note differences in the scale of the ovigerous copepod abundance between the two lakes. Error bars represent one standard error from the mean from samples taken from three sampling stations on Tustumena Lake and from two sampling stations from Skilak Lake during 1986-89 and three sampling stations during 1990-92.

late 1980's limits the value of data in inferring cause and effect.

Because Tustumena Lake has had a significantly longer time series of data, analysis of the relationships of various biological parameters over time may provide insight into the processes at work in glacial lakes of the Kenai River. Figures 15 and 16 provide casement plots of selected variables. Based on this exploratory analysis and with the added caveat that the relationship has some biological reasoning, we selected certain parameters for more intensive review. We investigated the relationship between age-0 fall fry weight, and the relationship between survival of age-0 fall fry to smolt, with density of ovigerous copepods (LOGEGG and LEGGLAG, Figure 15) in Tustumena Lake from 1980 to 1991 using linear regression analysis. Fry weights (dependent variable) are means of townet samples collected in September of each year. Fry- to-smolt survival (dependent variable) was calculated as the percent of outmigrating age-1 and age-2 smolt from the age-0 fry cohort. The independent variable, ovigerous copepod density (no./m²), is the seasonal mean from three sampling stations collected yearly in June, July, August, September, and October. Three separate analyses were conducted. First, fry weights and ovigerous copepods from the same year were analyzed. Second, the two variables were offset one year, so that ovigerous copepod density from the current year was paired with fry weight from the following year. Third, fall-fry to smolt survival was used with the current year ovigerous copepod density. The ovigerous copepod densities were log_e transformed to help linearize the relation with fry weight.

The fall fry weight model using same year data (Figure 17, top) had a marginally insignificant slope ($P = .072$), while the fall fry weight model using offset annual data had a significant slope ($P = .038$) (Figure 17, bottom). The Durbin-Watson statistic indicated no autocorrelation in any model ($P > .05$). In the model using offset data, fry weight in 1981 (1980 ovigerous copepods) had a studentized residual of 4.18 and is therefore a possible outlier. With the survival data (Figure 18), the relationship also produced a significant slope ($P = .019$). Percent survival in 1981 had a studentized residual of 2.4 and is therefore a possible outlier.

These comparisons suggests that the fall weight of age-0+ sockeye salmon juveniles may be better estimated by egg abundance of the previous year, than by egg abundance of copepods from the current rearing year. Variation in rearing fry abundance may affect average egg abundance or zooplankton biomass by differential rates of annual cropping. The lack of a significant relationship between fall fry weight (FRYWHT) and survival (SURVIVE) (Figure 15) and the lack of any relationship between fall fry weight (FRYWHT), biomass (FRYMASS), or abundance (FRYABN), and the seasonal average number of eggs/copepod (PEGGAVE) (an index of cropping) (Figure 16), may result from measurement error or may be masked because of the short time series evaluated. If the relationships (Figures 17 and 18) do represent a cause and effect, they offer an explanation for the one year lag in the survival of juvenile sockeye salmon produced from Skilak and Kenai lakes. However, the abundance of ovigerous copepods remained significantly higher per unit surface area in Skilak Lake when compared with Tustumena Lake (Figure 14). This prompted further investigations of food availability during the summer of 1992.

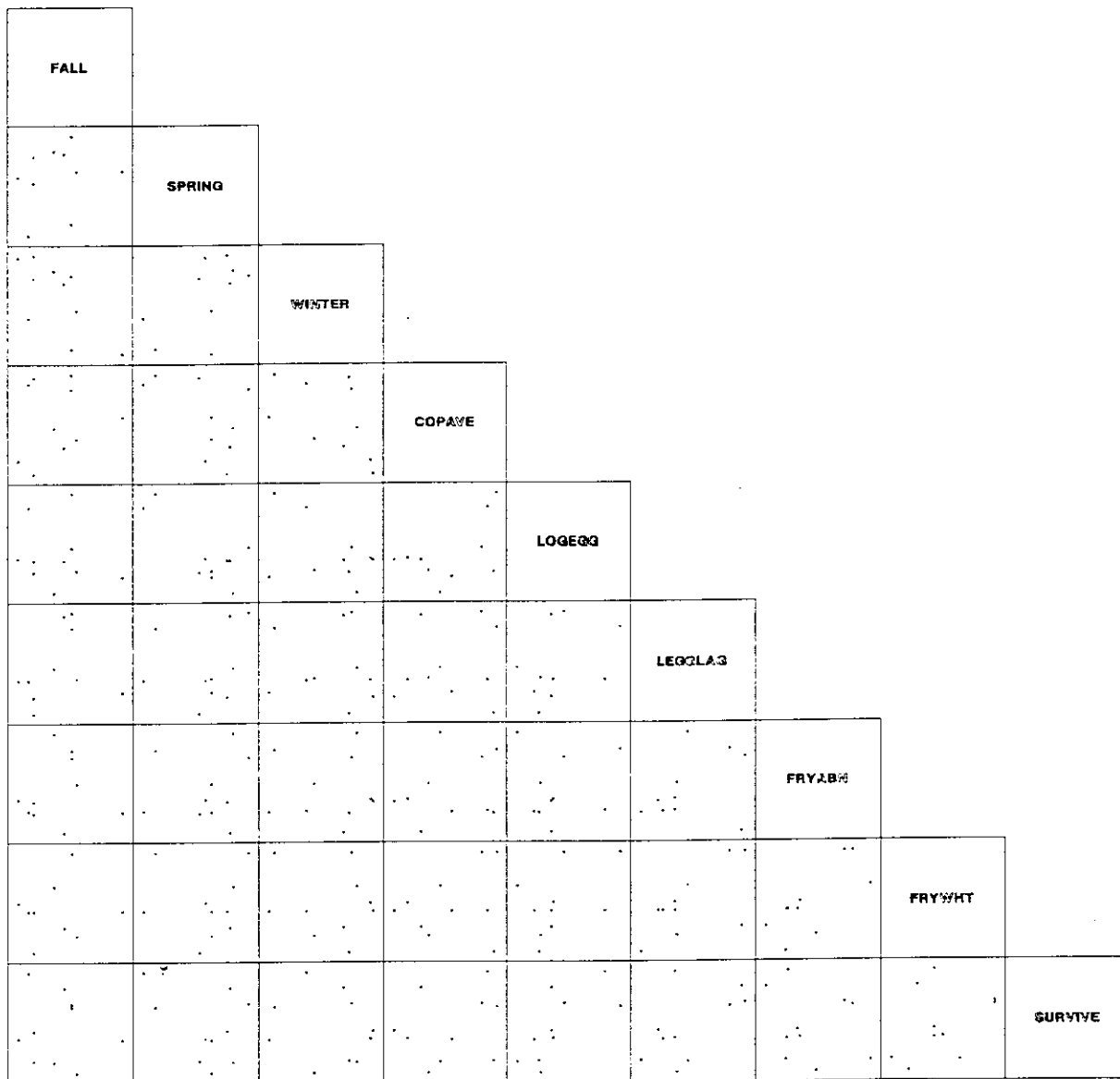


Figure 15. Casement plot of variables measured at Tustumena Lake, 1981-1990. The last row shows the relationship between percent survival of fall fry to outmigrating smolt (survive), mean fry weight (frywht), fall fry abundance (fryabn), ln of ovigerous copepod density mean copepod density of the previous year (legglag), ln of ovigerous copepod density of the current year (logegg), copepod seasonal mean biomass of all copepods (copave), number of winter days (winter), first day (Julian date) above 4 C°(spring), and first day below 4 C°(fall).

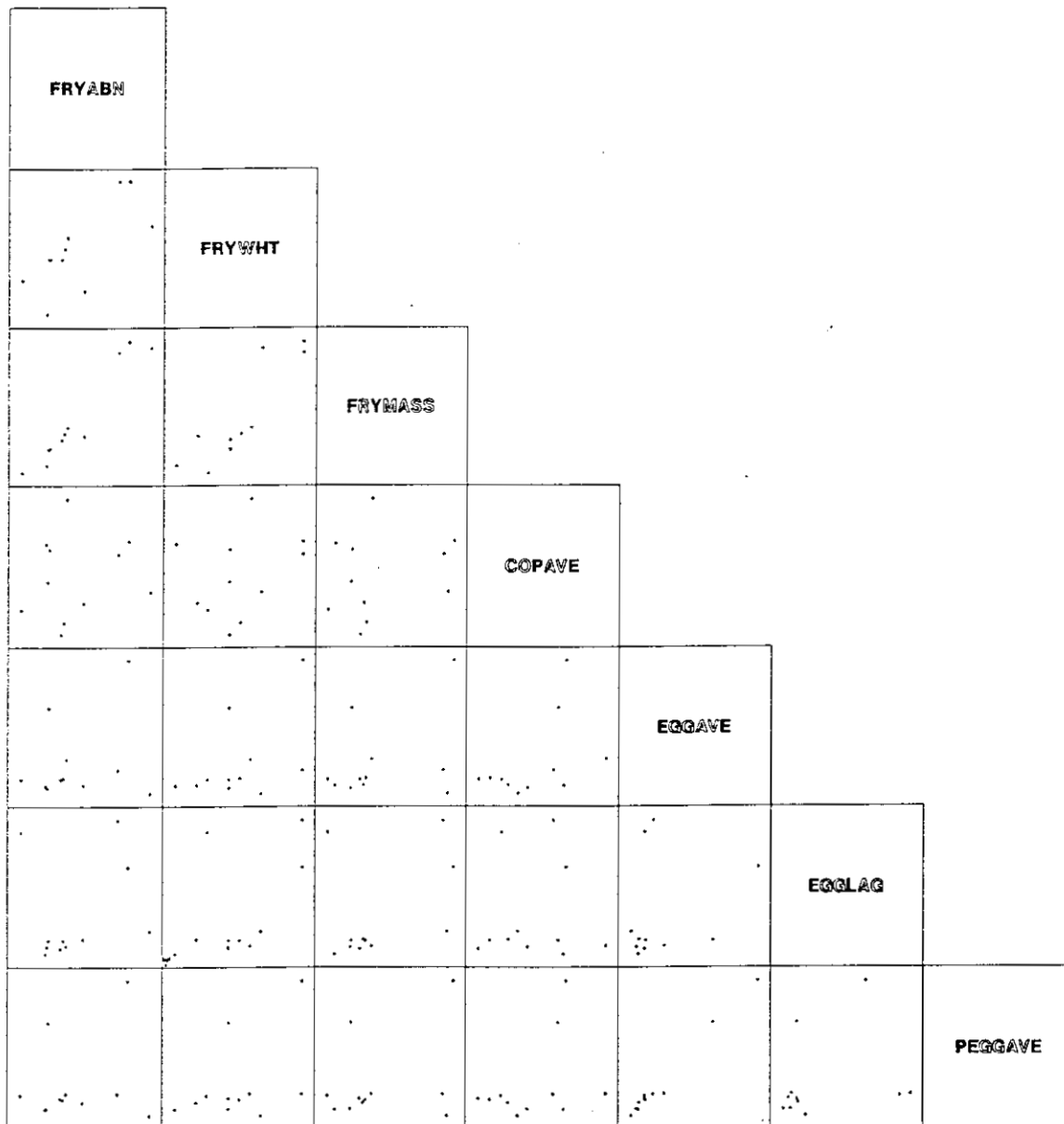


Figure 16. Casement plot of variables measured at Tustumena Lake, 1981-1991. The last row shows the relationship between the proportion of ovigerous copepods to total copepods (peggave), mean density of ovigerous copepods of the previous year (egglag), mean density of ovigerous copepods of the current year (eggave), mean density of all copepods (copave), total biomass of fall fry (frymass), average weight of fall fry (frywht), and fall fry abundance (fryabn).

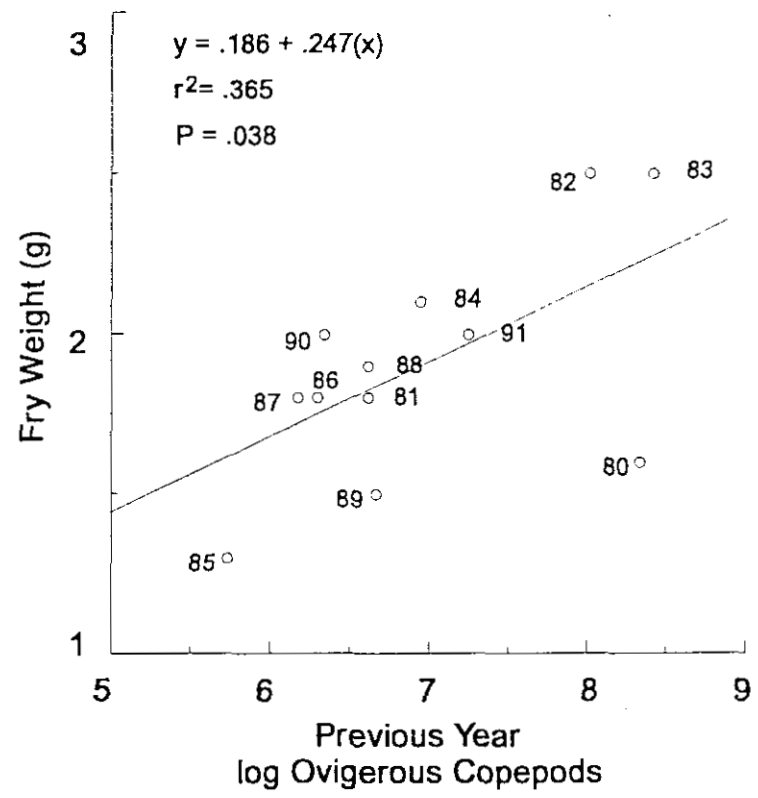
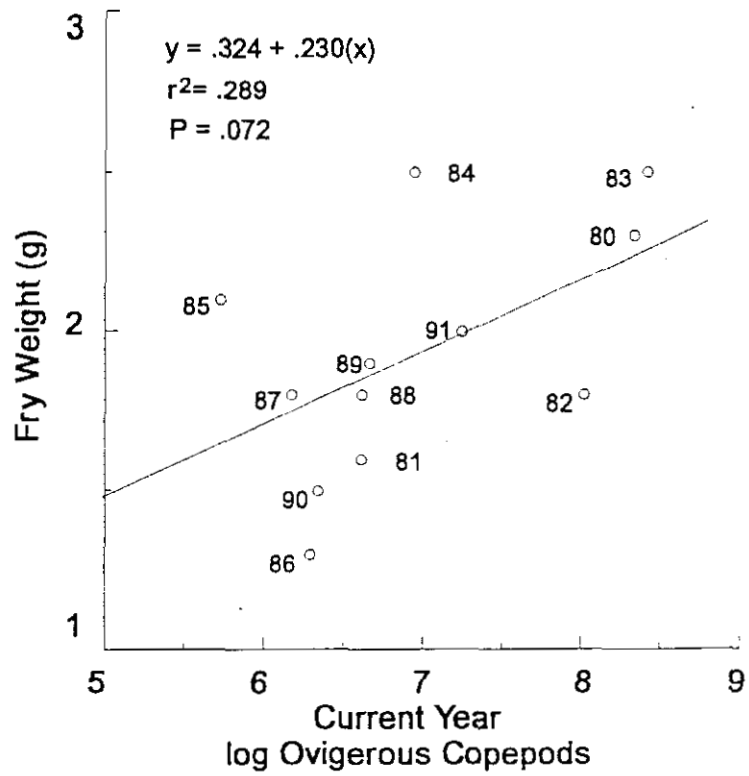


Figure 17. The upper graph depicts the relationship between mean weight of age-0 fall fry and ovigerous copepod density (no./m², ln transformed) in Tustumena Lake, 1980-1991. Points are labelled by the year that the data were collected. The lower graph illustrates the relationship between mean weight of age-0 fall fry and previous years' ovigerous copepod density (no./m², ln transformed) in Tustumena Lake, 1980-1991. Points are labelled by the year that the ovigerous copepods were collected.

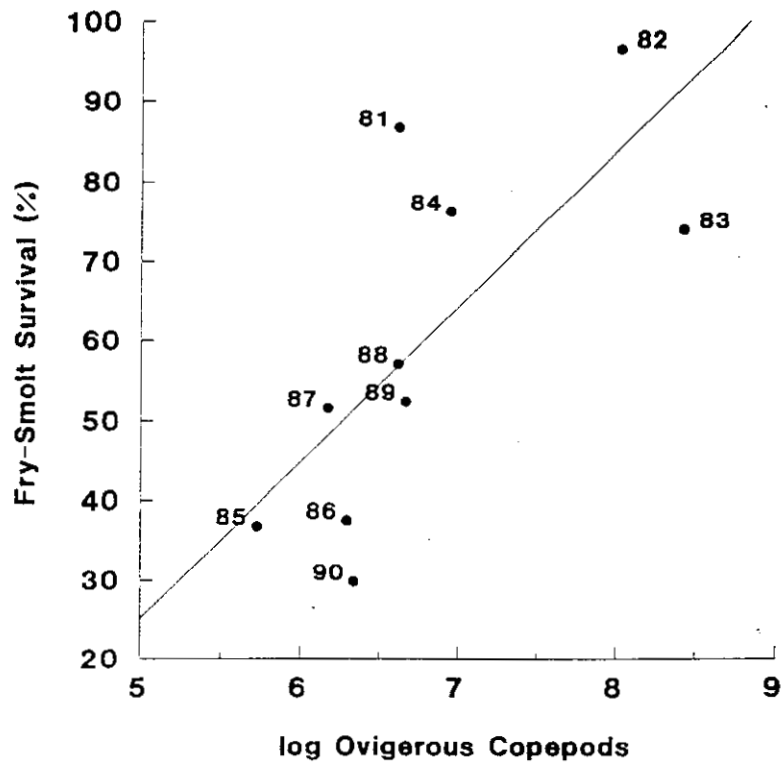


Figure 18. Relationship between percent survival of age-0 fall fry to age-1 and age-2 smolt and ovigerous copepod density (no./m², *ln* transformed) in Tustumena Lake, 1981-1990. Points are labelled by the year that fall fry and ovigerous copepod data were collected.

Because of low smolt production in 1991, a hydroacoustic estimate of the relative abundance of rearing fry in Skilak Lake was conducted during May of 1992. Although the lake was isothermal at the time of the survey (approximately 3° C), the daytime distribution of fish was between 30-40 m (*see* Figure 9). Subsequent measurements on the same transect suggested vertical movement toward the surface with the onset of darkness. This was contrary to findings on Tustumena Lake (Thorne 1982) and from the 1988 fall distribution of juvenile sockeye salmon in Skilak Lake. These latter data indicated a reverse migration from that usually observed in clearwater sockeye salmon systems (Levy 1990a; 1990b; Eggers 1978). The spring data indicate behavior more consistent with clearwater systems. This prompted investigations as to the vertical distribution of zooplankton.

Numerous studies have indicated that predators have a role in inducing diel vertical migration (DVM) in zooplankton (Bollens and Frost 1989; 1992; Frost 1988; Frost and Bollens 1992; Gabriel and Thomas 1988; Lampert 1989; Neill 1990; Ohman 1990; Ohman et al. 1983; Stirling et al. 1990; Vuorinen et al. 1983; Zaret and Suffern 1976). Because this phenomena has been well established in clearwater systems, we initiated studies to evaluate the vertical distribution of zooplankton in the Kenai Peninsula glacial lakes. The lack of previous data during years of low escapement in Skilak or Kenai lakes limited our ability to infer any change in DVM pattern of zooplankton was induced by predation. To assess if predator-induced DVM was a viable hypothesis for limiting food availability to lake rearing sockeye salmon, we sampled the daytime distribution of zooplankton in Ptarmigan and Grant lakes located within the Kenai River drainage. These lakes have no (Grant) or limited (Ptarmigan) salmon in them because their outlets have a major falls. Limited surveys of Ptarmigan Lake reveal no significant resident fish populations and the system has not been stocked. Grant Lake has had limited coho juvenile stocking. Hydroacoustic studies conducted on Grant Lake in 1983 (ADF&G, FRED Div., Soldotna, AK, unpublished data) indicated the limnetic density of rearing fish prior to coho stocking (presumably stickleback) at 0.08 fish/m².

Figures 19 and 20 illustrate the day and night distribution of ovigerous *Diaptomus* in lakes from data collected during the summer of 1992. The data suggests that the feeding zone at night is somewhat deeper in Skilak Lake than in Tustumena Lake. This would be consistent with the differences in euphotic zone depth between these lakes (approximately 2 m in Tustumena Lake and 10 m in Skilak Lake). Figure 21 compares the daytime distribution of ovigerous *Cyclops* from all of the glacial lakes. These data are consistent with the hypothesis that DVM of zooplankton reflects the degree of predation. The lack of migration in Tustumena Lake suggests that this system is limited by low food production caused by the higher turbidity levels. This effectively prevents zooplankton from migrating because of the need to spend more time feeding. This phenomenon provides a reasonable explanation of the production of larger fall fry and smolt from Tustumena Lake than from Skilak Lake, despite the larger biomass of zooplankton per unit surface area in Skilak Lake. However, these data do not establish that predators induced a change in the migratory behavior of zooplankton in Skilak Lake. Improved measurements of the diel and seasonal distribution of zooplankton in these lakes are planned to provide better estimates of food availability. Future monitoring of the response of the plankton community to reduced predation as poor runs return in 1994 and 1995 should indicate whether this, or some other mechanism is responsible for the reduced production of sockeye salmon smolt.

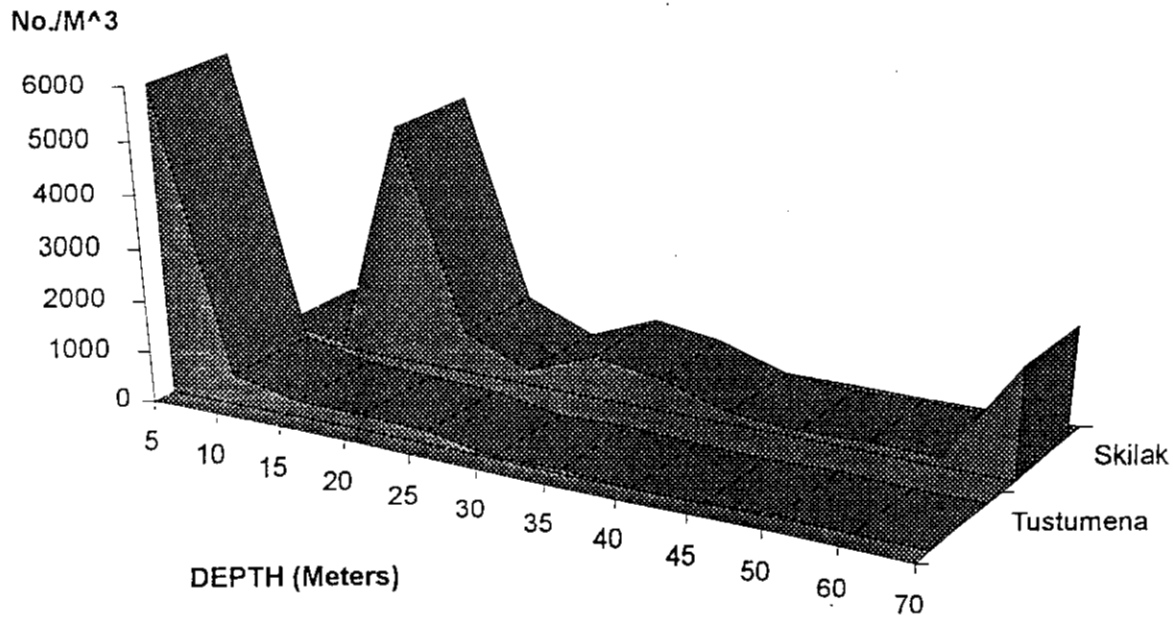


Figure 19. Comparison of night densities of ovigerous *Diaptomus* by depth in Skilak and Tustumena lakes during the fall of 1992.

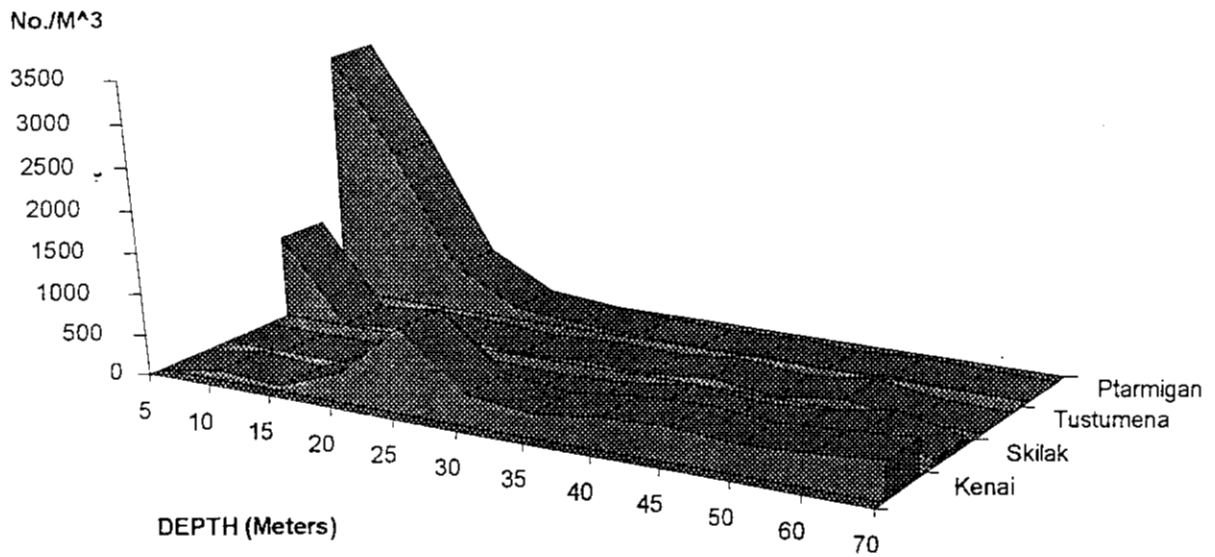


Figure 20. Comparison of daylight densities of ovigerous *Diaptomus* by depth in Kenai, Skilak, and Ptarmigan lakes during the fall of 1992.

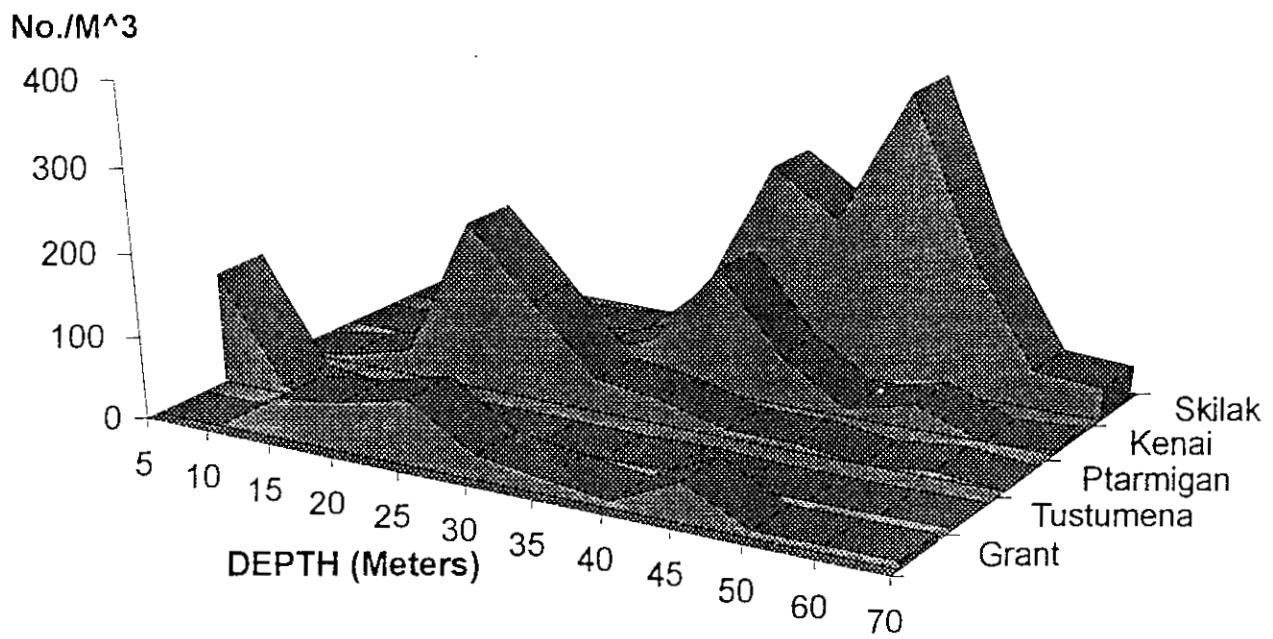


Figure 21. Comparison of daylight densities of ovigerous *Cyclops* by depth in Skilak, Kenai, Ptarmigan, Tustumena, and Grant lakes during the fall of 1992.

If the hypothesized change in the plankton community proves to be a density-dependent mechanism responsible for the poor smolt production, restoration of the plankton community to a more productive state would be desirable. Other authors suggest that predatory responses of zooplankton may be induced behavioral and subsequently may recover instantly once the stimulus is removed (Stirling et al. 1990). The most likely stimulus removal could occur naturally by predator reduction through lowering of sockeye spawners in the future. The availability of zooplankton would probably increase as food limitations would provide an adequate stimuli to promote increased time of surface feeding. This would be expected to occur when the system converts from top-down control over the systems trophic state to bottom-up control as sockeye salmon predation is reduced (Carpenter et al. 1985). Other investigators have experimentally established food reduction as a method of increasing the amount of time spent near the surface or even elimination of the DVM response (Johnsen and Jakobsen 1987). Alternatively, this response may be caused by natural selection of those individuals which have the propensity to migrate, probably at the expense of reproduction. Genetic differences have been demonstrated in *Daphnia* between individuals exhibiting DVM and those which do not (Weider 1984). We know some genetic variation occurs in the *Diatomus* taxa in the Kenai River system because of a pigmented racial variate which occurs in Ptarmigan lake. In this and other lakes which are absent of planktivores, a red carotinoid pigment is present in virtually all individuals within these subpopulations of this taxa. This pigment apparently is an adaptation to harmful near-surface sun radiation (Hairston 1976). We would expect significantly longer recovery times if the sockeye salmon production has been reduced because of genetic changes in the zooplankton community.

Kodiak Lake Investigations

Smolt Production

Smolt population estimates for the three lakes on Kodiak Island over the duration of these studies are listed in Table 4. The enumeration method of smolt used at Red Lake was verified by weir counts. Estimates obtained by the mark-recapture method in 1992 was 1.210 million compared with 1.314 million by direct weir count. These data suggest the mark-recapture method provides similar results in the estimation of smolt production.

The Red Lake system demonstrated much higher production of age-2 smolt from the 1989 broodyear. In addition, the 1991 data suggests a low number of smolt which was caused in part by a holdover of the 1989 broodyear juveniles to age-2 smolt, coupled with apparently very poor production of the 1988 broodyear fry. Although the total smolt numbers are actually higher from the 1989 broodyear than from the 1988, the single smolt trap and its late installation in the spring of 1990 may have resulted in significant underestimation of the smolt production during this first year of the study. Adult returns will be required to verify if the numbers generated for this year class are accurate. The production of smolt from the 1989 broodyear was very low for this system given the historical return of adults and expected smolt survival. In addition, the average weight of age-1 smolts from Red Lake was significantly lower in 1991 compared to 1990, but weight increased in 1992 (Figure 22; Table 5). In addition, the Red Lake smolts showed a major increase in the proportion of

Table 4. Sockeye smolt population estimates and age composition for Red, Akalura, and Upper Station lakes for broodyears 1986-1991.

Year	Escapement	Number of Smolt by Age Class					Total	95% C.I.	
		0	1	2	3	Lower		Upper	
Red Lake									
1986	318,135	a	a	a	6,427				
1987	261,913	a	a	493,026	38,184	531,210	294,277	768,143	
1988	291,774	a	240,500	119,849	25,794	386,143	232,243	540,043	
1989	768,101	0	105,467	1,365,082	b	1,470,549	1,145,584	1,795,514	
1990	371,282	0	29,484	b	b				
1991	374,859	0	b	b	b				
Akalura									
1986	9,800	a	a	a	0				
1987	6,116	a	a	408,331	1,251	409,582	273,835	544,078	
1988	38,618	a	66,460	299,591	8,315	374,366	281,153	467,579	
1989	116,029	0	9,086	182,963	a	192,049	152,427	231,671	
1990	47,181	0	1,921	b	b				
1991	44,189	0	b	b	b				
Upper Station									
1986	466,385	a	a	a	43,710				
1987	232,195	a	a	1,141,133	15,389	1,156,522	647,116	1,665,928	
1988	306,560	a	193,416	245,673	1,444	440,533	231,391	649,675	
1989	286,288	5,511,474	224,621	362,990	b	6,099,085	3,435,884	8,762,286	
1990	254,446	1,959,423	80,238	b	b	2,039,661	1,059,251	3,020,071	
1991	292,886	1,950,244	b	b	b				

a Smolt outmigration not monitored.

b Smolt of this age class have not outmigrated.

Table 5. Summary of preliminary information on the 1990-1992 population characteristics of sockeye salmon for Red, Akalura, and Upper Station lakes. Systems with overescapements in 1989 are indicated by (T) and those with normal escapements by (C).

System	Smolts				No. 10 ⁶	Fall Juveniles			
	Age 1. L. (mm)	Wt. (g)	Age 2. L. (mm)	Wt. (g)		Age 0+ L. (mm)	Wt. (g)	Age 1+ L. (mm)	
Kodiak Island: 1990 Smolt						1990 Fall Fry*			
Red L. (T)	106.5	10	111.8	11	0.73		1.8		
Akalura L. (T)	73.9	3.6	85.9	5.3	1.16		1.8		
U. Station L. (C)	81.4	4.9	99.7	8.3	6.87		2.2		
Kodiak Island: 1991 Smolt						1991 Fall Fry**			
Red L. (T)	88.2	5	106.7	9.5	0.26	51	1.2	81	4.4
Akalura L. (T)	77.2	4.3	77.5	4	0.31	52		74	3.8
U. Station L.	94	7.1	102.3	9.3	2.4	56	1.7	91	7
Kodiak Island: 1992 Smolt						1992 Fall Fry***			
Red L. (T)	99.5	8.8	110.2	11.8	1.37	68	2.6	94	7.7
Akalura L. (T)	75.7	3.7	78.8	3.9	0.19				
U. Station L. (C)	93.7	7.9	103.3	10.1	2.4	67	2.9	90	8.4

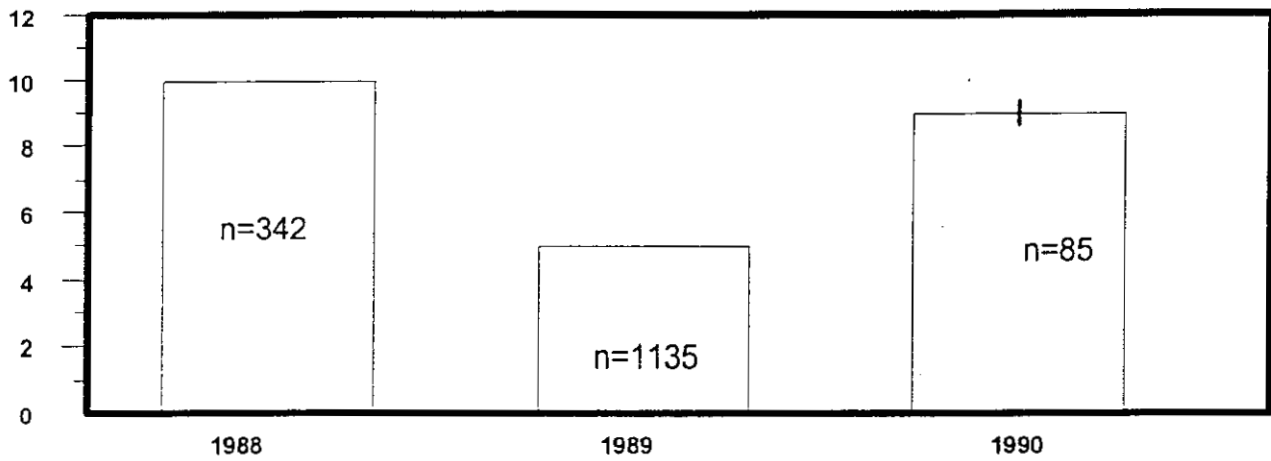
* Unpreserved gross average weights for 1990. Individual lengths and weights not available. Mean for both age classes.

** Preserved weights and lengths.

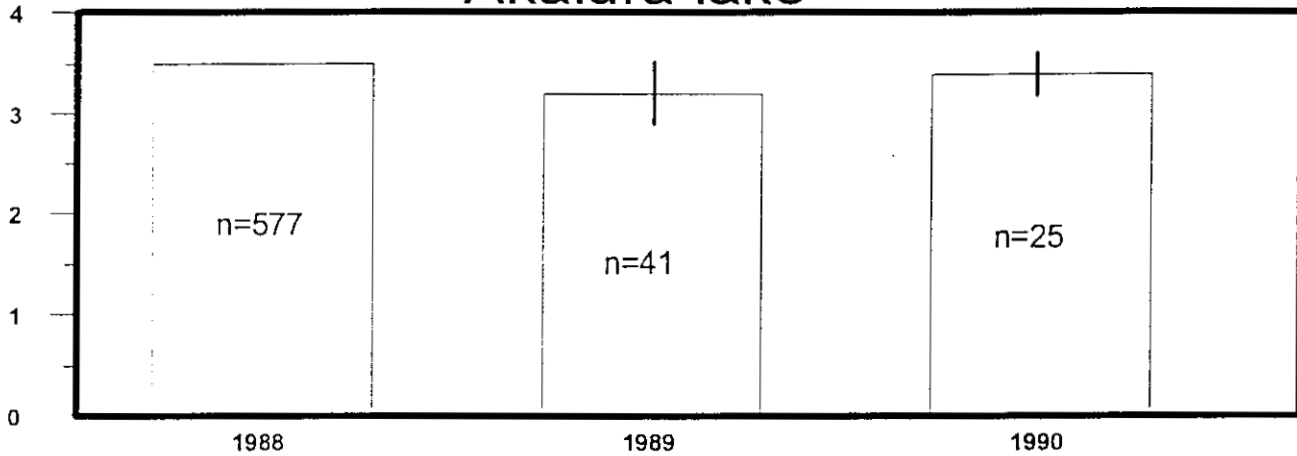
*** Unpreserved weights and lengths.

See Barrett et al. (1993) and Honnold (1993) for sample size and standard errors of mean values reported..

Red Lake



Akalura lake



Upper Station

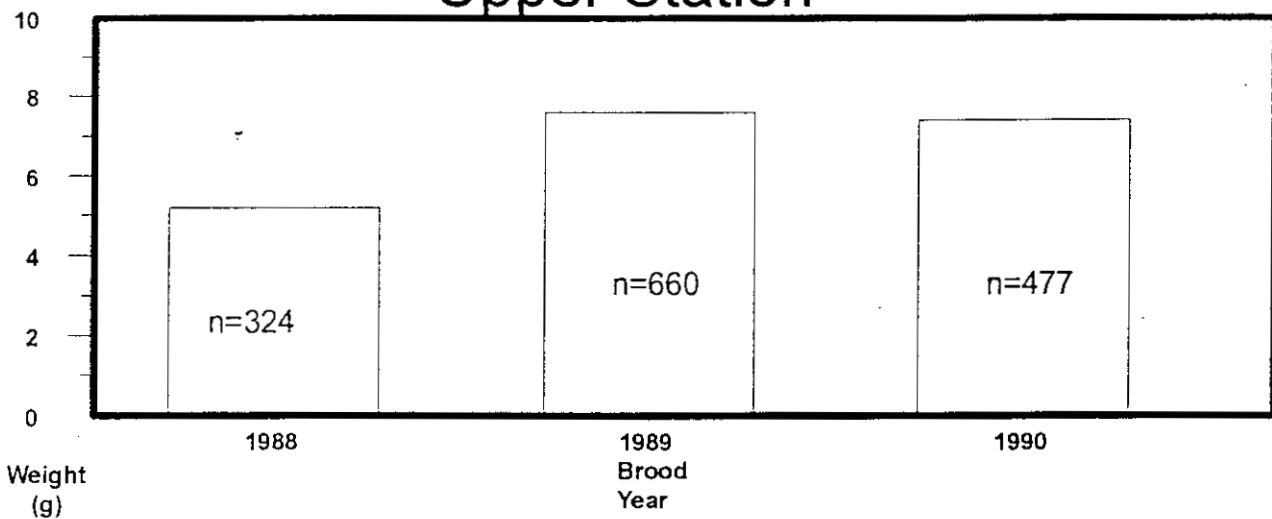


Figure 22. Changes age-1 smolt mean weight for 1988-1990 brood years in Red, Akalura, and Upper Station lakes. Standard errors are less than 2% of the mean except where indicated with error bars.

age-3 smolt (1987 broodyear). This is consistent with very poor production of smolt from the 1988 and 1989 broodyears. Also, during 1988-1990, the age class composition of smolt shifted significantly to an older age class of smolt in Akalura, with few outmigrants of the 1989 year class (age-1).

Juvenile Production

The population estimates of juvenile sockeye salmon in the fall of 1990 and 1991 in Red Lake based on hydroacoustic survey and townetting were 101,000 and 632,000, respectively (Honnold 1992). The total fish population estimates in the fall of 1990 and 1991 were substantially greater at 7.2 million and 9.4 million, respectively. Thus, the townet catches revealed a very low proportion (< 2%) of juvenile sockeye salmon. These fall population estimates of juvenile sockeye salmon do not correspond with resulting smolt population estimates (Table 4); suggesting the hydroacoustic population estimates along with townetting apportionment do not provide accurate estimates of the juvenile sockeye salmon population. The major bias appears to be in the townet catch data.

In 1989, the year of high escapement, the resulting age-1 sockeye salmon fry rearing in the lake in May of 1991 averaged 83 mm and 2.9 g in May, and 97 mm and 5.3 g in October (after corrections were made for the method of preservation). The age-1 fall fry sampled (unpreserved) in September of 1992 (broodyear 1990) averaged 102 mm and 9.0 g, or a 70% increase in weight (Table 5). This suggests that the age-1 fry of broodyear 1989 reared under conditions that limited growth, whereas the age-1 fry from the subsequent broodyear reared under more favorable conditions. Thus, there appeared to be interspecific competition among fry rearing from broodyear 1989, but a lack of interspecific competition between juveniles from the two broodyears; the age-0 fry rearing in 1991 (broodyear 1990) were not substantially impacted by the high number of rearing age-1 fry from broodyear 1989.

In Akalura Lake, as in Red Lake, the population estimates of juvenile sockeye salmon in the fall of 1990 and 1991 were low compared to the subsequent spring smolt estimates. In the fall of 1990, based on the hydroacoustic and townet survey, an estimated 200,340 juvenile sockeye salmon were rearing in Akalura Lake. However, in the spring of 1991, Barrett et al. (1993) estimated the migration of 310,000 smolts. Similarly, from the hydroacoustic and townet survey conducted in the fall of 1991, an estimated 44,380 juvenile sockeye salmon were in the lake. The 1992 smolt estimate was 193,200 (Barrett et al. 1993). The underestimation of fall fry in Akalura Lake is believed to also be biased because of poor representation of age groups through townetting, and in addition, the near-surface (undetectable) distribution of fish.

The age-1 fall fry sampled in October of 1991 from Akalura Lake were produced from a large escapement in 1989. The average size of these fry was 89 mm and 4.6 g after correction for preservation. Although fall fry size information is not available for other broodyears with lower escapements, the weight of age-1 smolts for broodyears 1988-1990 did not fluctuate much (Barrett et al. 1993). Thus, it appears the high escapement had little effect on juvenile sockeye salmon size.

In Upper Station Lake, the population estimates of juvenile sockeye salmon in the fall of 1990 and 1991 were considerably different. In 1990 an estimated 1,171,200 juvenile sockeye salmon were rearing in the lake, while in 1991 a total of 391,000 were estimated. These estimates were also lower than the smolt estimates of 2,445,000 in 1991 and 2,395,000 in 1992 (Table 4). The vertical distribution does not indicate the possibility of missing targets due to near-surface distribution of the fry (Honnold 1992). Also, the horizontal distribution was quite uniform for the three sections of the lake (Honnold 1992). Thus, the most likely explanation for the underestimation of fall fry is the bias of species composition determination from townetting. In addition, as Upper Station Lake, as the control lake, did not receive a high escapement in 1989; the size of neither age-1 or age-2 smolts fluctuated much.

Limnological Studies

Limnology and water quality studies from the three Kodiak Island lakes have been conducted since 1990 with samples taken in 1986 prior to the oil spill. The zooplankton biomass is summarized in Figure 23. The cladoceran community in Red Lake apparently demonstrated a density-dependent response in 1990 as indicated by a 5- to 10-fold decrease in *Bosmina* and *Daphnia* numbers. The 50% increase in 1991 biomass of these taxa generally followed the weight trend observed for age-1 smolt. The reduction in total zooplankton biomass in 1991 relates to a reduction in copepods, with relative abundances of the zooplankton taxa reflecting the 1986 data (Figure 24). In clearwater lakes that have both cladocerans and copepods, the copepods provide minimal food resources as reflected in food electivity studies (e.g., Yanusz 1989; Kyle et al. 1988). In Upper Station Lake, zooplankton biomass was very different between stations and the species composition is different from Red Lake. These differences are sufficiently large to defeat any attempt at demonstrating the significance of the multiple year trends illustrated in Figures 23 and 24. Also, Akalura Lake did not show any trends in biomass or species composition related to sockeye salmon escapement levels. The species composition of this system is also quite different from that observed in Red Lake, probably reflecting its very different morphology. In essence, Red Lake's zooplankton community responses may be much more comparable with Frazer or Karluk lakes, and they may be more suitable controls for evaluating zooplankton changes in Red Lake in the future. These lakes have not been used as controls in the past because of nutrient enrichment programs.

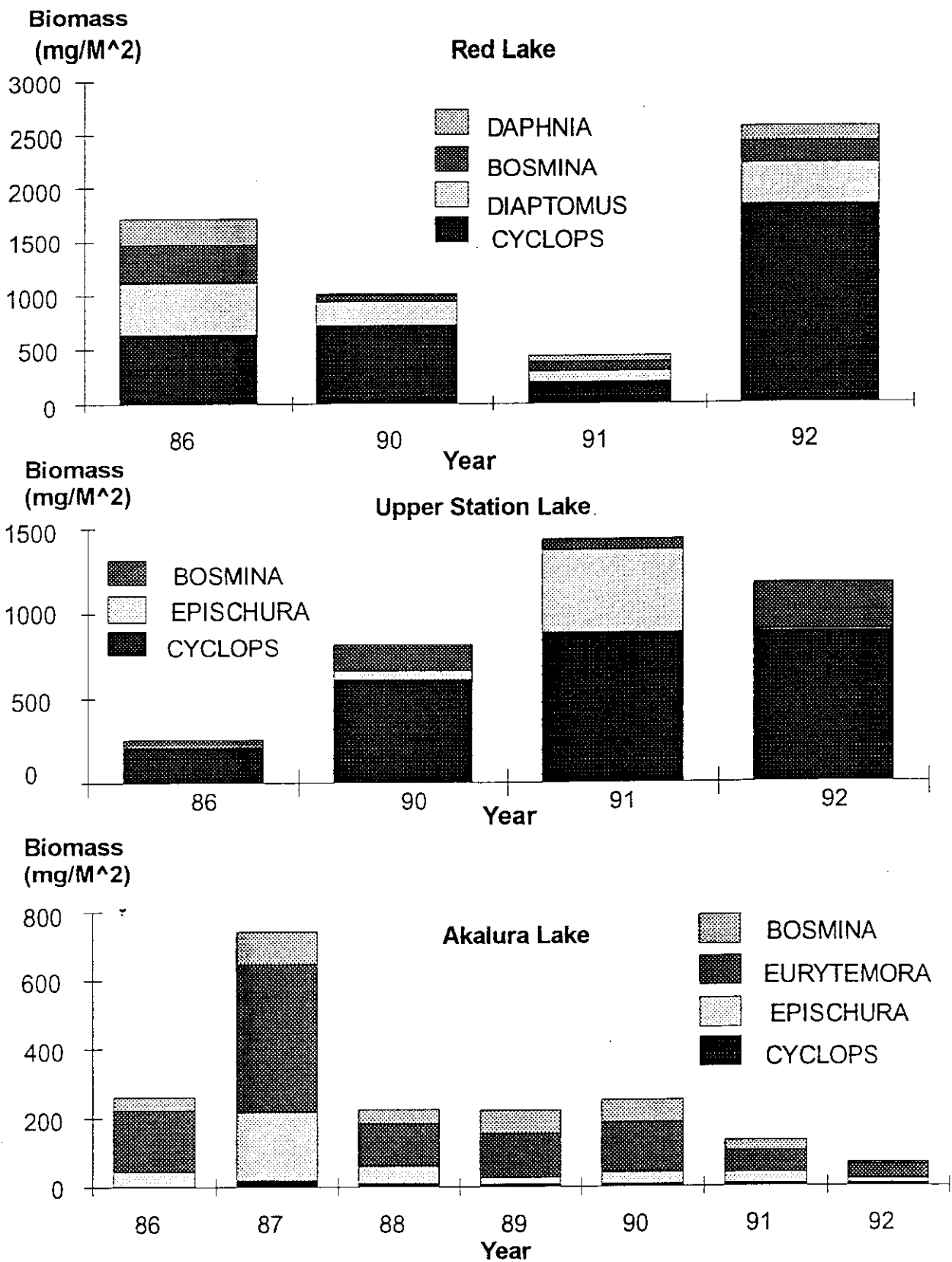


Figure 23. Interannual variation of mean zooplankton biomass for the Kodiak Island study lakes.

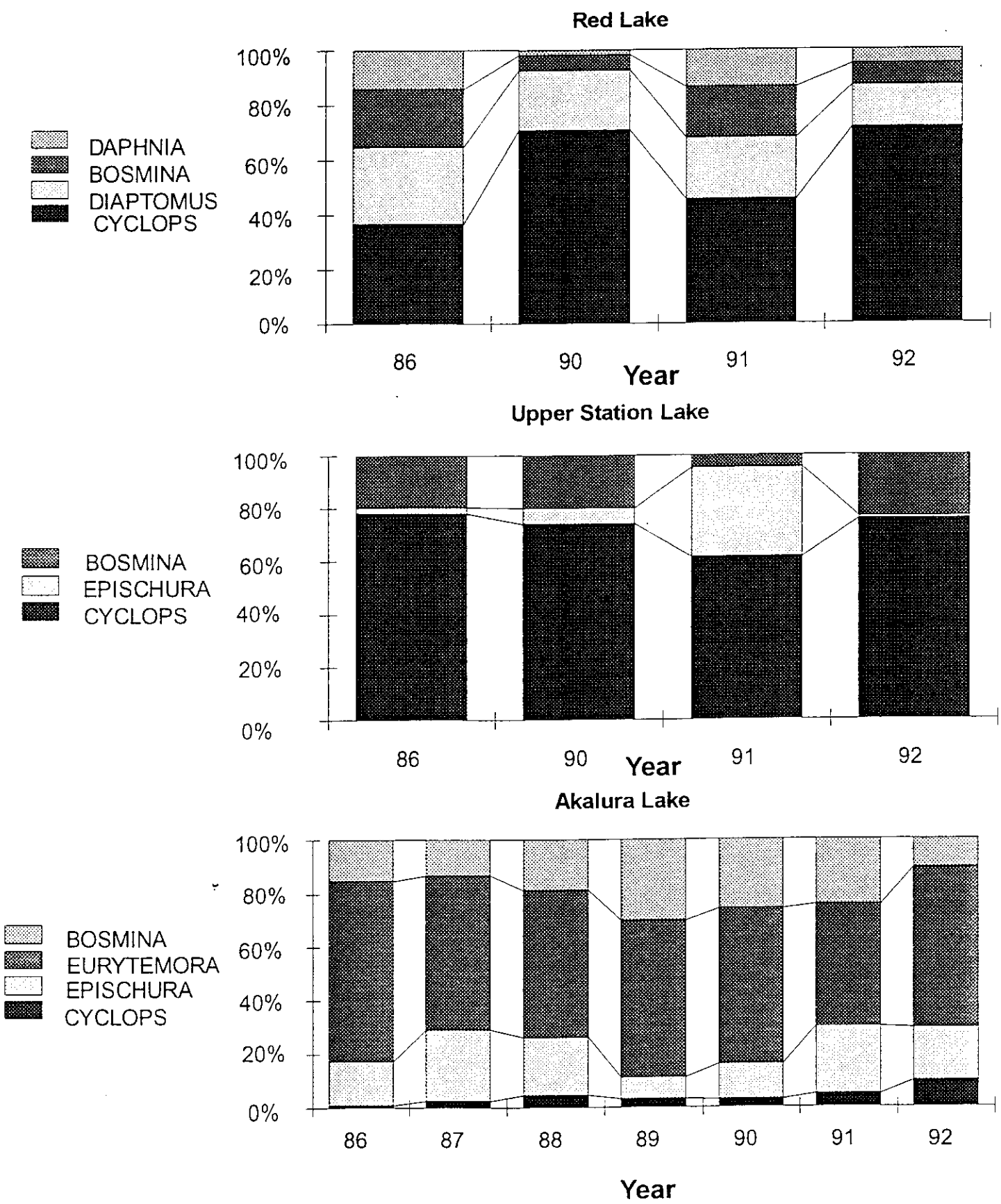


Figure 24. Interannual variation of relative abundance of zooplankton taxa for the Kodiak Island lakes.

STATUS OF INJURY ASSESSMENT

The 1992 studies have provided additional insight into the plausible reason for the collapse of smolt production in the Kenai River and from Red Lake on Kodiak Island. The Kenai River smolt production has decreased over time and major reductions in run returns from these smolt years are likely. The fall fry data coupled with limited sampling in the spring of 1992 provide support for the contention that overwintering mortality of fry in the lake is primarily responsible for the collapse. This collapse was not paralleled in Tustumena Lake, a nearby glacial lake that had average escapements. The cause of the increased winter mortality has not been clearly defined but we suggest that it relates directly to the size and condition of fall fry prior to the overwintering period. We further hypothesize that this decrease in condition is caused by density-dependent interactions of planktivorous juvenile sockeye salmon during their first rearing year with the zooplankton community of these lakes. The poor survival during the winter of 1991-1992 suggests these changes are persistent, or at least effect the subsequent year. Data collected during the upcoming years as density of sockeye salmon spawners and juveniles decrease in these lakes is essential to determine if subtle effects on the zooplankton community were responsible for decrease production or if other factors, unrelated to density, provide alternative explanations of the decreased production.

Limited studies of the vertical distribution of zooplankton, particularly of ovigerous zooplankton, in five Kenai glacial systems suggests differences in lakes with and without major number of planktivores. Reduced egg production of zooplankton because of predation and reduced food availability by induction of diel vertical migration are hypothetical mechanisms which can account for the poor overwintering survival of juvenile sockeye in Kenai and Skilak lakes. Detailed investigations of these phenomena are underway; however, measurement of changes in the zooplankton community when reduced escapement decreases fry loading into Kenai and Skilak lakes in subsequent years will be required to provide more conclusive evidence of density-dependent effects.

The weir project on Red River has verified the mark-recapture method of estimating smolt abundance and provides increased validity to the numbers generated the previous year. As this system was most likely to have trap avoidance problems, we conclude that biases induced by differential trap avoidance of marked and unmarked fish are minimal and unlikely to substantially affect estimates of the smolt migration. However, the 1990 smolt abundances estimated with a single trap which was installed late makes these data suspect and requires confirmation by adult returns. The apparent density-dependent effect on Red Lake sockeye salmon production is most likely a reduction in growth and a major shift to the production of age-2 smolt. In addition, the production of smolt is significantly below the number estimated to produce the return experienced throughout the 1980's. Preliminary data on the composition and abundance of the Red Lake zooplankton community in the summer of 1992 suggests the system has recovered to pre-oil spill status. We recommend continuation of the Red Lake smolt monitoring program to determine if smolt production has recovered as predicted by the zooplankton community. Also, we recommend an additional year of monitoring of the zooplankton community to provide improved estimates of desired spring fry stocking, if the 1994 adult return falls below the escapement goal. This activity is

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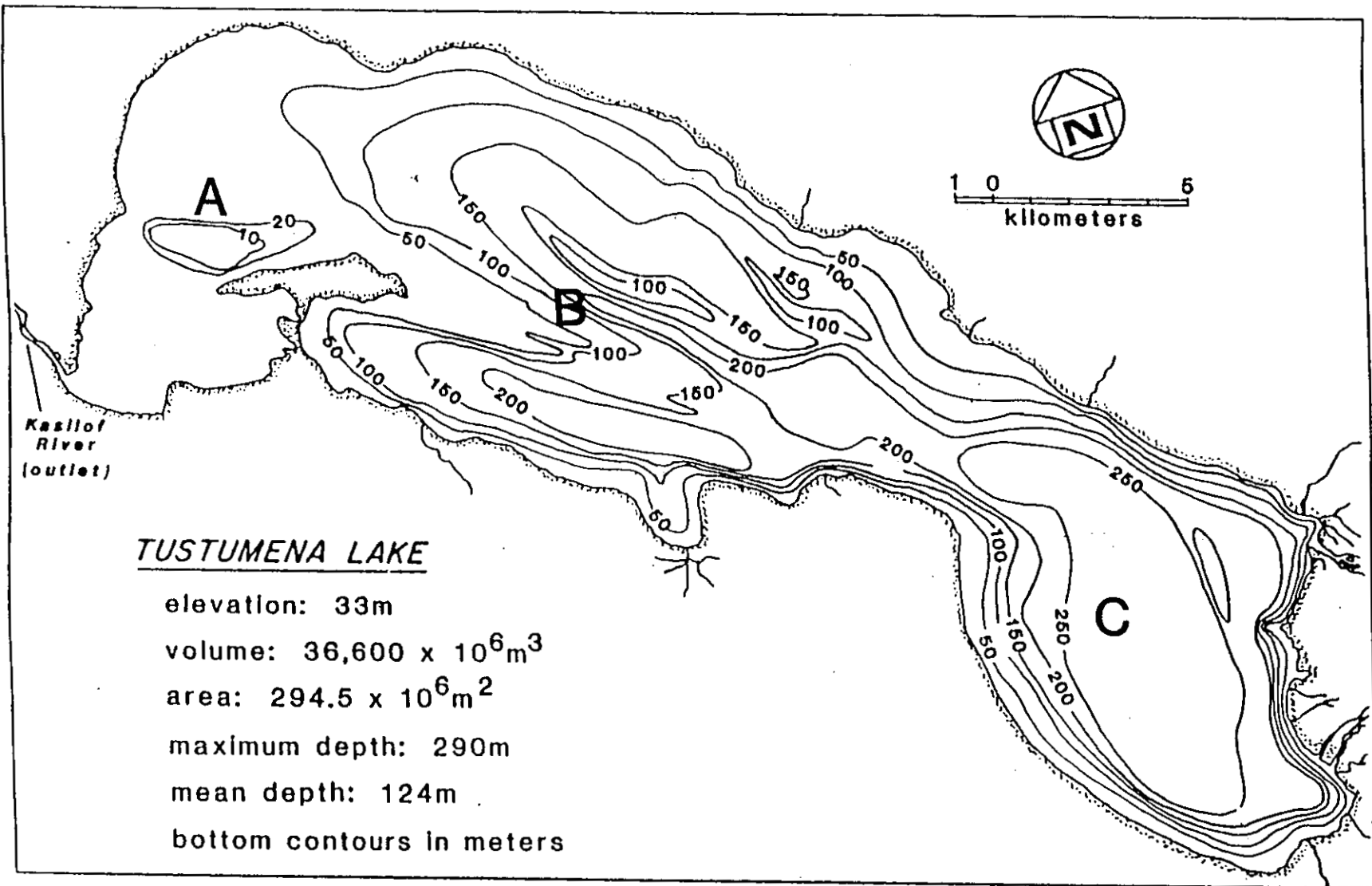
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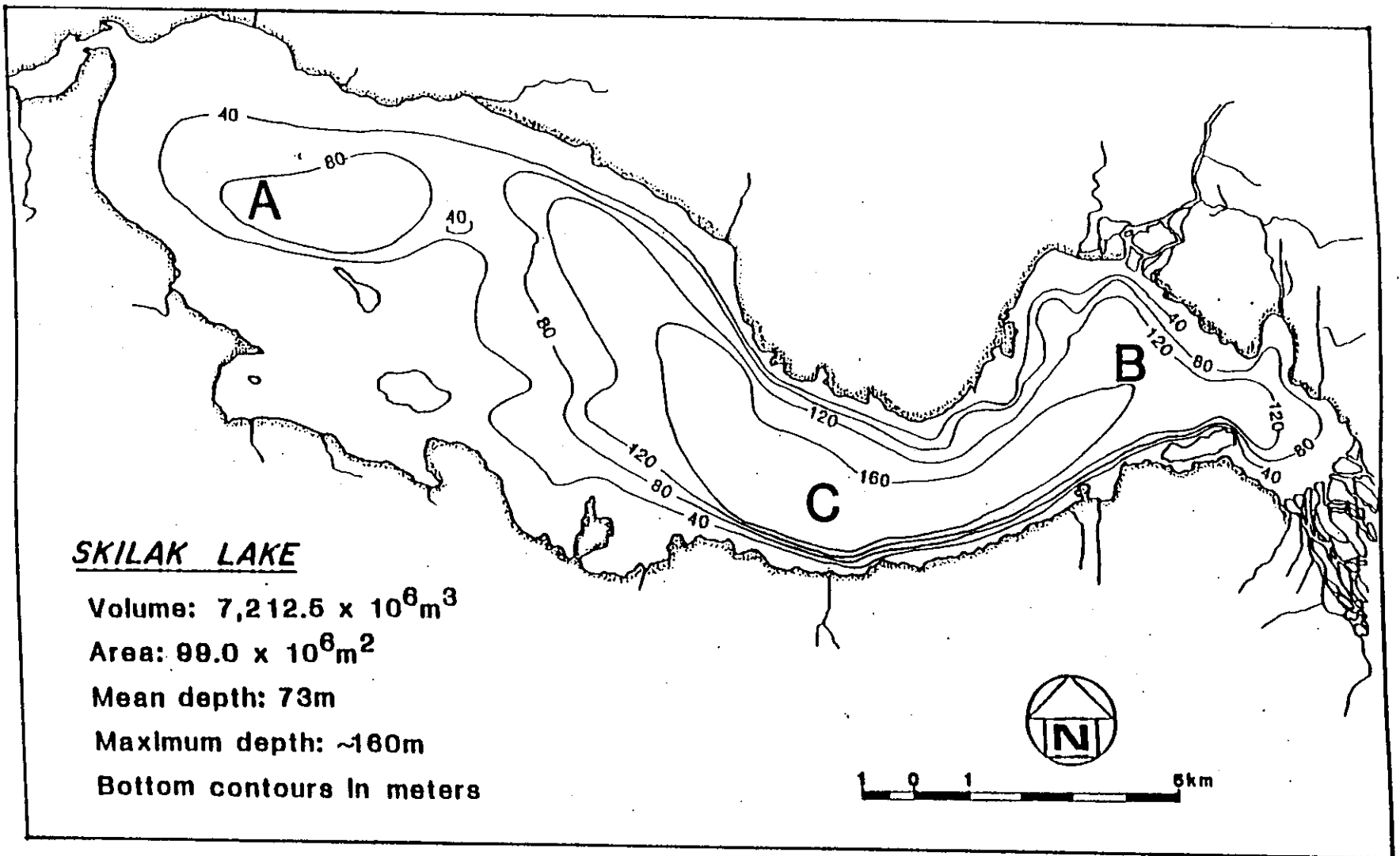
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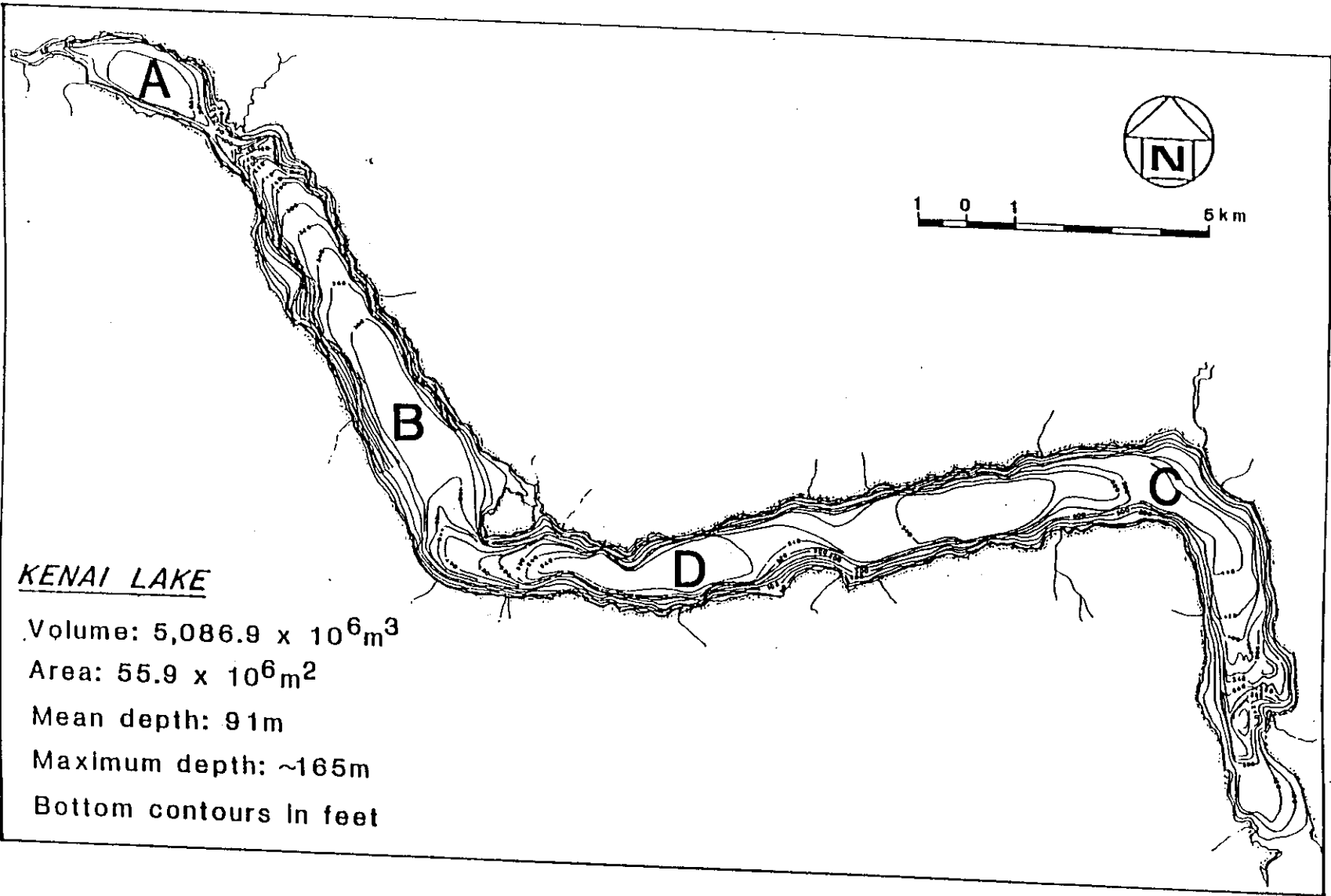
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APPENDIX A

Kenai Peninsula lakes morphometric maps showing sample stations and water quality summaries by year, station, and depth.







KENAI LAKE

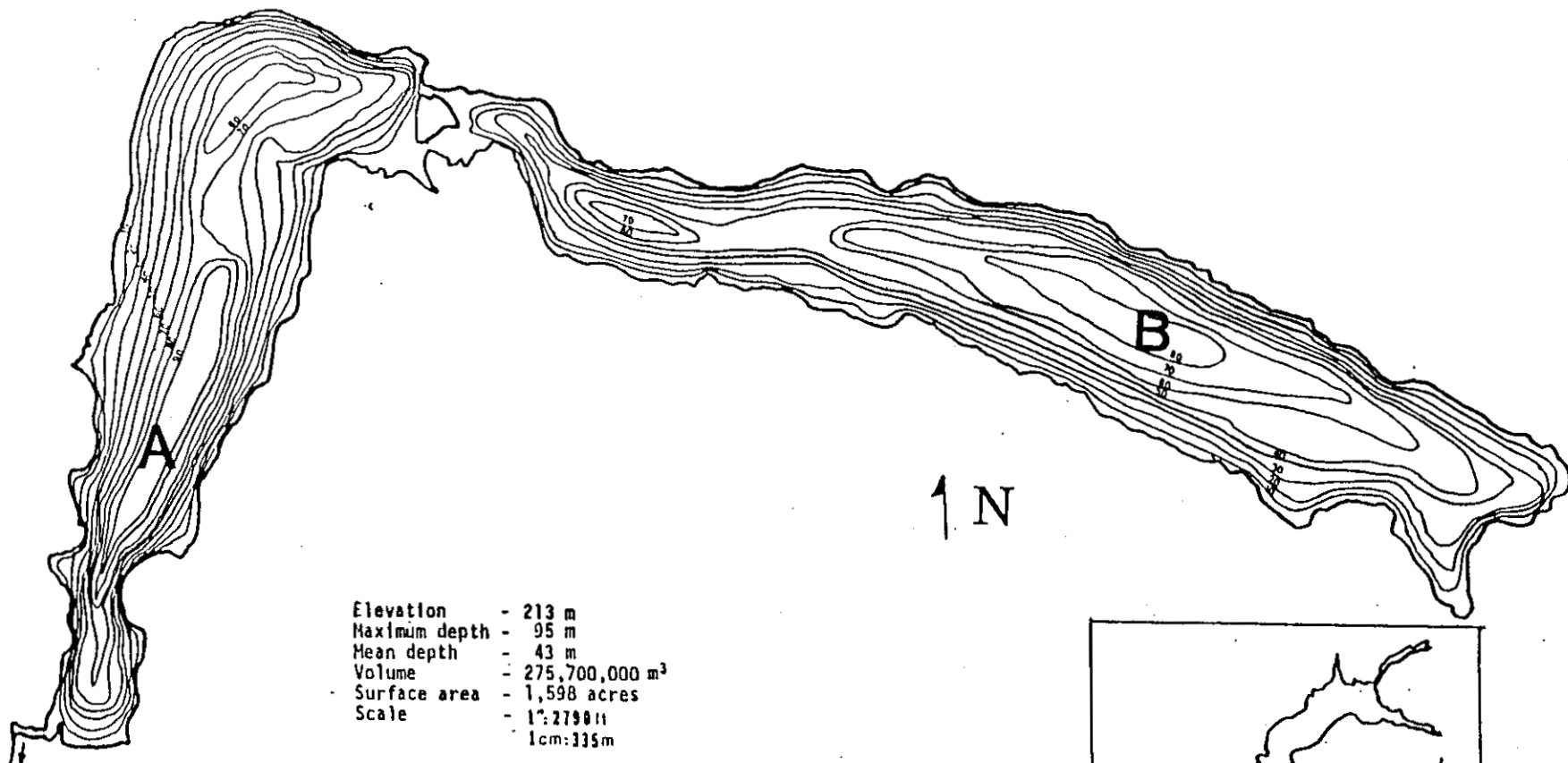
Volume: $5,086.9 \times 10^6 \text{m}^3$

Area: $55.9 \times 10^6 \text{m}^2$

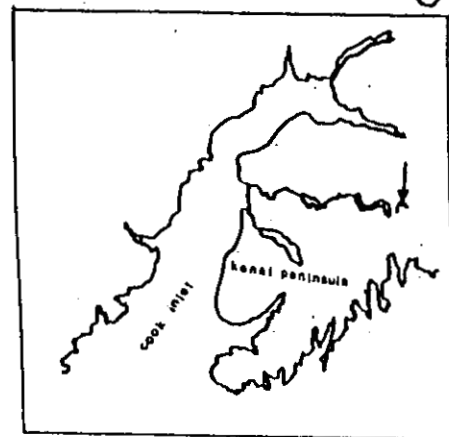
Mean depth: 91m

Maximum depth: ~165m

Bottom contours in feet



BATHYMETIC MAP OF GRANT LAKE

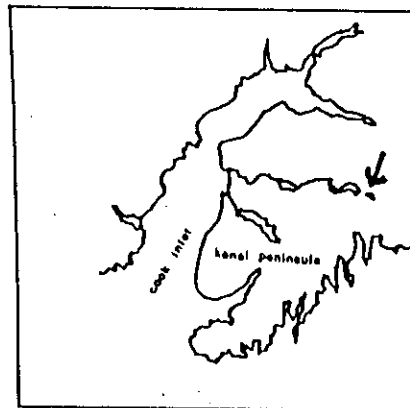


BATHYMETIC MAP OF PTARMIGAN LAKE

LAKE CONTOURS IN FEET

51

N ↑



Elevation - 230 m
Maximum depth - ~75 m
Mean depth - 35 m
Volume - 107,000,000 m³
Surface area - 751 acres
Scale - 1" = 1540 ft
1 cm = 185 m

A

B

200

150

100

200

100

150

100

50

10

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrient, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Kenal Lake, 1981-1982.

Parameter		1981 (n=6)						1982 (n=6)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	60	6	59	5	58	6	65	5	63	5	63	4
	hypo	60	5	59	5	57	6	62	7	62	6	62	4
pH (Units)	1 m	6.5	0.4	6.4	0.3	6.3	0.4	7.6	0.1	7.6	0.2	7.5	0.1
	hypo	6.4	0.3	6.4	0.3	6.4	0.4	7.5	0.1	7.6	0.1	7.4	0.1
Alkalinity (mg/L)	1 m	28.0	7.2	25.7	7.2	25.3	7.5	23.5	2.6	24.7	1.0	24.8	0.8
	hypo	27.2	7.2	26.0	6.9	26.0	6.6	24.8	1.0	24.8	0.8	24.2	1.0
Turbidity (NTU)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Color (Pt Units)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Calcium (mg/L)	1 m	10.8	1.0	10.9	0.7	11.0	0.5	9.8	1.5	10.1	1.3	10.2	1.3
	hypo	10.8	0.9	11.5	0.6	10.7	0.7	10.3	1.3	10.1	1.3	10.2	1.4
Magnesium (mg/L)	1 m	0.7	0.8	0.6	0.6	0.4	0.3	0.6	0.5	0.3	0.2	0.4	0.5
	hypo	0.7	0.7	0.3	0.3	0.4	0.3	0.5	0.7	0.4	0.5	0.6	0.9
Iron (ug/L)	1 m	247	65	313	123	572	498	203	90	259	163	530	463
	hypo	272	80	284	76	494	311	228	82	303	207	632	412
Total-P (ug/L)	1 m	11.2	2.1	12.3	4.6	14.7	6.8	8.4	2.3	7.9	2.1	11.7	5.4
	hypo	10.0	1.2	11.8	2.7	18.7	8.2	8.0	1.6	8.1	2.8	12.3	6.0
Total filterable-P (ug/L)	1 m	2.1	0.5	2.6	0.9	3.2	2.0	4.2	3.5	2.8	1.5	2.8	0.5
	hypo	2.6	0.5	2.4	0.6	2.3	0.3	3.9	2.6	2.3	0.5	3.0	1.4
Filterable reactive-P (ug/L)	1 m	2.0	0.2	2.1	0.5	2.7	1.2	1.7	0.5	2.0	0.5	2.0	0.4
	hypo	2.4	0.5	2.2	0.4	2.1	0.5	1.8	0.5	1.9	0.3	2.2	0.4
Total Kjeldahl-N (ug/L)	1 m	28	13	22	11	17	7	22	10	21	10	35	27
	hypo	21	12	9	6	18	13	17	4	16	10	19	11
Ammonia-N (ug/L)	1 m	3.3	0.8	3.1	1.6	4.8	2.6	15.2	14.5	6.8	4.1	5.6	3.5
	hypo	5.2	1.7	3.6	1.2	6.7	3.0	8.3	5.6	4.9	2.9	5.0	2.7
Nitrate+nitrite (ug/L)	1 m	225	46	208	29	206	41	204	10	204	11	204	9
	hypo	231	31	218	28	188	55	213	5	209	6	202	10
Reactive silicon	1 m	1570	241	1595	180	1584	160	1584	137	1584	114	1565	120
	hypo	1692	76	1577	142	1554	199	1598	135	1565	131	1565	1565
Chlorophyll a (ug/L)	1 m	0.42	0.29	0.32	0.32	0.30	0.21	0.18	0.08	0.13	0.10	0.15	0.05
	hypo	0.15	0.09	0.16	0.11	0.09	0.04	0.13	0.12	0.15	0.09	0.12	0.05
Phaeophytin a (ug/L)	1 m	0.20	0.07	0.22	0.17	0.15	0.07	0.15	0.04	0.14	0.10	0.12	0.04
	hypo	0.11	0.04	0.10	0.03	0.08	0.02	0.20	0.09	0.17	0.04	0.11	0.02

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrient, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Kenai Lake, 1986 and 1990.

Parameter		1986 (n=4)				1990 (n=7)					
		B		C		B		C		D	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	68	2	60	9	64	4	63	4	64	3
	hypo	68	2	61	4	65	4	63	3	64	4
pH (Units)	1 m	7.3	0.2	7.3	0.1	7.4	0.1	7.4	0.1	7.4	0.1
	hypo	7.5	0.1	7.3	0.2	7.4	0.1	7.4	0.1	7.4	0.1
Alkalinity (mg/L)	1 m	23.6	1.7	23.3	1.5	23.8	1.6	23.7	2.2	23.9	2.2
	hypo	24.6	1.5	23.0	1.0	24.0	1.8	24.0	2.0	24.2	1.8
Turbidity (NTU)	1 m	4.2	2.7	10.5	1.7	8.2	2.9	11.8	3.4	10.9	3.7
	hypo	4.4	2.0	15.3	7.6	8.1	3.1	12.4	3.8	10.1	3.6
Color (Pt Units)	1 m	6.5	2.4	11.3	7.7	5.4	3.0	4.7	1.5	4.9	0.7
	hypo	6.3	1.3	7.7	1.5	4.7	1.5	4.3	1.0	4.9	0.7
Calcium (mg/L)	1 m	9.5	0.0	na	na	10.4	1.0	10.4	0.9	10.5	1.0
	hypo	9.9	0.6	na	na	10.4	0.9	10.7	1.1	10.7	1.0
Magnesium (mg/L)	1 m	0.2	0.0	na	na	0.5	0.3	0.6	0.2	0.5	0.3
	hypo	0.2	0.0	na	na	0.3	0.3	0.4	0.3	0.3	0.3
Iron (ug/L)	1 m	178	97	624	277	467	194	654	229	577	262
	hypo	133	76	851	587	460	207	717	310	632	222
Total-P (ug/L)	1 m	8.8	3.9	16.0	4.3	14.9	3.9	20.3	5.6	18.2	4.9
	hypo	8.0	1.9	25.9	14.7	13.7	3.8	22.6	8.3	17.6	4.9
Total filterable-P (ug/L)	1 m	2.0	1.0	5.9	5.3	2.4	1.8	1.9	0.7	1.9	0.7
	hypo	2.4	1.2	3.1	0.3	1.9	0.5	2	0.4	2.1	0.5
Filterable reactive-P (ug/L)	1 m	2.0	0.4	5.9	5.0	2.9	2.3	2.5	0.7	2.2	0.7
	hypo	2.3	0.6	3.4	0.4	2.4	0.4	2.4	0.3	2.6	0.4
Total Kjeldahl-N (ug/L)	1 m	10	3	13	4	36	7	34	6	32	4
	hypo	9	6	17	7	29	7	31	4	34	6
Ammonia-N (ug/L)	1 m	2.6	0.4	2.6	0.8	2.5	3.0	2.6	3.4	2.9	3.1
	hypo	2.3	0.4	2.2	0.5	2.9	3.2	3.4	3.6	2.4	3.1
Nitrate+nitrite (ug/L)	1 m	201	30	177	16.1	209	16	207	21	205	23
	hypo	192	79	152	43	224	16	215	15	217	17
Reactive silicon	1 m	1861	201	1666	25	1531	126	1527	146	1552	140
	hypo	1846	175	1678	74	1570	133	1566	137	1586	150
Chlorophyll a (ug/L)	1 m	0.10	0.08	0.32	0.18	0.19	0.16	0.13	0.11	0.09	0.07
	hypo	0.07	0.03	0.09	0.07	0.08	0.04	0.04	0.04	0.11	0.18
Phaeophytin a (ug/L)	1 m	0.13	0.05	0.17	0.05	0.08	0.16	0.10	0.06	0.11	0.07
	hypo	0.11	0.02	0.10	0.01	0.11	0.03	0.09	0.04	0.11	0.08

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Kenai Lake, 1991-1992.

Parameter		1991 (n=6)						1992 (n=7)					
		B		C		D		B		C		D	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	67	2	68	2	67	2	68	2	68	3	68	2
	hypo	67	2	66	3	67	1	69	1	68	1	68	1
pH (Units)	1 m	7.4	0.1	7.4	0.1	7.4	0.1	7.3	0.2	7.2	0.2	7.3	0.2
	hypo	7.4	0.1	7.4	0.1	7.3	0.1	7.2	0.2	7.3	0.2	7.3	0.1
Alkalinity (mg/L)	1 m	22.6	3.3	22.7	3.3	22.8	3.3	22	2.7	21.8	1.7	22.4	1.5
	hypo	22.7	3.3	22.5	3.4	22.7	3.3	22.2	1.8	22.9	2.1	22.7	3.4
Turbidity (NTU)	1 m	7.1	3.4	9.1	5.8	7.8	3.7	5.5	1.7	10.1	6.0	8.7	3.2
	hypo	8.2	3.2	11.6	4.7	8.6	2.9	5.1	1.8	9.6	4.7	8.0	4.3
Color (Pt Units)	1 m	5.7	2.1	6.0	1.7	6.5	2.1	4.0	2.0	4.0	1.0	4.0	1.0
	hypo	6.0	2.1	5.3	1.5	5.2	1.9	4.0	1.0	4.0	1.0	5.0	3.0
Calcium (mg/L)	1 m	10.9	0.5	10.2	0.7	10.3	0.7	11.2	1.5	11.7	1.6	11.2	1.1
	hypo	10.8	0.5	10.1	0.7	10.5	0.6	12.0	1.8	11.0	0.7	10.9	0.7
Magnesium (mg/L)	1 m	0.5	0.3	0.6	0.4	0.7	0.3	0.7	0.5	0.6	0.3	0.5	0.3
	hypo	0.5	0.3	0.7	0.3	0.4	0.3	0.7	0.5	0.6	0.4	0.4	0.3
Iron (ug/L)	1 m	310	142	430	254	409	161	269	133	352	187	257	125
	hypo	357	121	641	267	450	131	254	139	360	303	240	126
Total-P (ug/L)	1 m	13.0	2.7	16.7	5.3	14.8	3.1	7.6	3.0	11.8	7.4	9.7	5.0
	hypo	13.9	3.3	24.4	13.8	15.9	2.8	7.6	3.0	12.0	6.6	9.0	5.8
Total filterable-P (ug/L)	1 m	2.6	0.6	2.3	0.4	2.9	1.3	1.2	0.3	1.6	1.2	1.4	0.4
	hypo	2.4	0.5	2.7	0.4	2.3	0.2	1.4	0.3	1.8	0.9	2.2	0.8
Filterable reactive-P (ug/L)	1 m	1.6	0.6	1.6	0.4	2.4	0.9	1.3	0.7	1.8	1.1	1.7	0.6
	hypo	2.0	0.6	1.9	0.5	1.9	0.3	1.6	0.6	2.0	0.6	2.6	1.0
Total Kjeldahl-N (ug/L)	1 m	28	8	29	6	28	6	23.6	9.5	24.9	15.8	26.0	16.0
	hypo	28	9	26	6	27	11	23.8	13.5	22.9	14.3	19.6	14.9
Ammonia-N (ug/L)	1 m	5.1	1.2	6.6	2.3	6.4	1.8	1.2	0.3	1.0	0.3	1.1	0.0
	hypo	5.8	2.3	6.6	2.5	4.5	1.4	1.1	0.0	1.1	0.0	1.1	0.0
Nitrate+nitrite (ug/L)	1 m	189	11	195	12	188	8	219	21	218	34	219	24
	hypo	199	9	187	16	193	6	228	20	223	27	223	20
Reactive silicon	1 m	1491	61	1476	67	1486	59	1513	59	1481	84	1499	61
	hypo	1514	70	1479	68	1503	68	1528	51	1506	61	1508	47
Chlorophyll a (ug/L)	1 m	0.24	0.16	0.15	0.12	0.21	0.27	0.21	0.20	0.17	0.13	0.14	0.04
	hypo	0.11	0.05	0.04	0.01	0.06	0.01	na	na	na	na	na	na
Phaeophytin a (ug/L)	1 m	0.13	0.05	0.19	0.15	0.12	0.12	0.18	0.07	0.24	0.20	0.20	0.11
	hypo	0.11	0.06	0.08	0.02	0.08	0.02	na	na	na	na	na	na

na Indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 2 sampling stations in Skilak Lake, 1986-1988.

Parameter		1986 (n=5)				1987 (n=6)				1988 (n=7)			
		A		B		A		B		A		B	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	61	3	64	5	61	3	63	2	63	4	64	2
	hypo	62	3	61	3	62	3	61	3	64	1	65	2
pH (Units)	1 m	7.2	0.3	7.1	0.4	7.1	0.5	7.1	0.4	7.5	0.2	7.5	0.3
	hypo	7.2	0.3	7.2	0.3	7.0	0.3	7.1	0.4	7.3	0.1	7.3	0.2
Alkalinity (mg/L)	1 m	23.7	1.0	22.4	3.1	23.1	1.3	23.7	1.5	22.5	1.0	22.5	1.0
	hypo	24.3	1.5	23.6	1.1	23.3	1.4	22.7	1.0	23.0	1.3	22.7	1.8
Turbidity (NTU)	1 m	4.7	2.8	6.3	2.9	2.4	1.0	3.7	0.7	2.0	1.0	2.9	1.6
	hypo	5.6	2.8	6.0	4.1	3.0	1.7	6.5	6.6	2.4	1.9	3.4	1.7
Color (Pt Units)	1 m	4.8	2.0	6.0	2.5	5.8	2.1	5.8	2.3	6.8	2.0	7.3	2.2
	hypo	6.2	2.8	6.3	2.6	6.3	3.8	7.3	1.5	8.0	6.2	8.3	6.4
Calcium (mg/L)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Magnesium (mg/L)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Iron (ug/L)	1 m	233	173	347	217	149	63	268	77	94	60	128	103
	hypo	274	173	343	396	213	120	556	454	117	162	151	74
Total-P (ug/L)	1 m	9.6	3.2	10.8	4.1	14.6	8.9	13.8	4.8	5.3	1.1	7.5	1.6
	hypo	10.0	3.5	11.9	5.4	14.9	8.9	20.1	10.9	6.1	3.3	8.6	2.8
Total filterable-P (ug/L)	1 m	4.6	4.3	4.3	5.6	3.5	1.1	2.9	0.9	2.2	0.5	2.7	0.8
	hypo	5.0	5.3	3.5	1.5	4.0	1.1	3.4	0.6	3.8	2.8	3.8	3.0
Filterable reactive-P (ug/L)	1 m	2.6	3.0	4.3	5.7	2.7	0.8	2.6	0.4	1.5	0.4	2.2	0.7
	hypo	3.6	4.4	2.9	1.4	3.2	1.2	2.9	0.6	2.8	2.5	3.4	3.5
Total Kjeldahl-N (ug/L)	1 m	22	12	17	8	46	11	44	16	46	9	42	12
	hypo	10	8	16	11	40	14	36	14	36	7.4	38	6.0
Ammonia-N (ug/L)	1 m	4.2	0.8	4.8	1.1	5.6	3.2	6.6	3	1.9	0.8	2.2	1.2
	hypo	4.7	1.4	4.3	1.4	6.0	3.0	5.8	3.5	3.2	2.5	2.1	1.0
Nitrate+nitrite (ug/L)	1 m	165	7	156	16	172	11	181	9	180	17	199	18
	hypo	127	77	180	9	183	5	184	6	205	11	210	21
Reactive silicon	1 m	1719	213	1757	231	1620	261	1637	284	1548	140	1660	109
	hypo	1676	192	1804	360	1640	275	1675	346	1618	113	1627	106
Chlorophyll a (ug/L)	1 m	0.16	0.09	0.19	0.14	0.78	0.63	0.91	0.95	0.30	0.09	0.30	0.16
	hypo	0.09	0.06	0.08	0.03	0.16	0.09	0.10	0.07	0.14	0.10	0.12	0.09
Phaeophytin a (ug/L)	1 m	0.14	0.09	0.13	0.07	0.23	0.08	0.28	0.14	0.18	0.05	0.22	0.10
	hypo	0.11	0.02	0.10	0.01	0.24	0.08	0.19	0.06	0.15	0.04	0.13	0.05

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Skilak Lake, 1989-1990.

Parameter		1989 (n=7)				1990 (n=7)					
		A		B		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	63	2	64	2	60	3	62	2	61	2
	hypo	63	2	63	2	61	2	60	3	60	2
pH (Units)	1 m	7.4	0.3	7.4	0.3	7.4	0.2	7.4	0.2	7.5	0.2
	hypo	7.4	0.2	7.4	0.3	7.4	0.1	7.4	0.1	7.4	0.1
Alkalinity (mg/L)	1 m	22.6	1.9	23.3	1.2	22.4	1.9	23.4	2.2	23.2	1.5
	hypo	22.7	1.8	22.7	1.9	22.4	1.0	23.1	2.0	23.1	1.7
Turbidity (NTU)	1 m	3.0	0.9	5.0	3.1	4.5	3.8	8.6	3.9	7.2	4.8
	hypo	3.9	2.1	9.5	8.9	7.8	4.2	9.3	6.3	7.4	5.2
Color (Pt Units)	1 m	3.9	2.4	3.5	3.4	6.4	1.5	5.4	0.5	6.8	3.5
	hypo	4.9	1.8	5.0	2.2	6.3	1.9	5.7	0.5	6.0	1.1
Calcium (mg/L)	1 m	10.0	0.8	10.1	0.9	9.6	0.8	10.3	1.6	10.1	0.9
	hypo	10.0	0.9	9.8	0.9	9.3	0.4	10.5	2.7	9.9	1.1
Magnesium (mg/L)	1 m	0.4	0.0	0.2	0.0	0.7	0.1	0.7	0.4	0.4	0.3
	hypo	0.2	0.0	0.4	0.2	0.7	0.1	0.6	0.3	0.4	0.2
Iron (ug/L)	1 m	159	162	294	206	336	278	518	172	426	268
	hypo	211	148	593	601	441	278	636	364	481	299
Total-P (ug/L)	1 m	9.7	5.9	12.2	6.5	10.0	5.3	15.3	3.8	12.7	4.4
	hypo	11.4	6.0	18.9	12.6	12.4	4.7	21.2	19.4	14	5.6
Total filterable-P (ug/L)	1 m	2.0	0.7	2.9	2.5	2.4	1.3	2.4	0.9	3.5	3.2
	hypo	2.1	0.5	2.3	0.8	2.3	1.0	2.6	1.0	2.4	0.7
Filterable reactive-P (ug/L)	1 m	1.2	0.6	1.6	1.2	2.6	1.2	2.6	0.8	3.6	2.8
	hypo	1.4	0.5	1.6	0.5	2.7	1.1	3.2	0.9	2.9	0.5
Total Kjeldahl-N (ug/L)	1 m	27	14	20	12	38	11	35	2.4	32	4
	hypo	22	13	39	40	29	6	31	6.4	27	4
Ammonia-N (ug/L)	1 m	7.0	2.9	10.5	10.7	1.8	1.4	2.2	2.2	2.3	1.6
	hypo	7.2	3.0	7.1	1.8	2.0	1.4	2.0	2.1	1.8	1.4
Nitrate+nitrite (ug/L)	1 m	192	12	202	15	189	12	203	22	191	8
	hypo	208	9	207	207	205	11	206	22	207	11
Reactive silicon	1 m	1403	101	1468	156	1436	121	1458	118	1399	97
	hypo	1396	89	1477	1477	1433	138	1434	114	1396	99
Chlorophyll a (ug/L)	1 m	0.21	0.13	0.21	0.08	0.32	0.21	0.23	0.15	0.29	0.20
	hypo	0.14	0.06	0.12	0.10	0.12	0.05	0.07	0.03	0.08	0.05
Phaeophytin a (ug/L)	1 m	0.14	0.05	0.16	0.04	0.36	0.44	0.22	0.11	0.20	0.05
	hypo	0.16	0.04	0.15	0.08	0.16	0.04	0.15	0.05	0.13	0.03

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Skilak Lake, 1991-1992.

Parameter		1991 (n=6)						1992 (n=8)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	60	3	62	3	61	2	61	2	62	2	61	1
	hypo	60	2	59	3	60	2	61	1	61	2	61	1
pH (Units)	1 m	7.4	0.2	7.5	0.1	7.4	0.1	7.0	0.3	7.0	0.2	7.1	0.1
	hypo	7.4	0	7.4	0	7.4	0	7.0	0.1	7.1	0.2	7.1	0.2
Alkalinity (mg/L)	1 m	21.8	2.7	22.0	2.6	21.8	2.6	19.3	3.3	20.9	1.2	21.3	1.4
	hypo	21.8	3.0	21.6	3.7	21.7	2.7	21.4	1.3	20.6	0.8	21.1	1.1
Turbidity (NTU)	1 m	4.0	1.6	6.0	1.0	9.9	9.9	3.1	2.1	3.7	2.5	3.9	2.2
	hypo	5.0	1.9	10.8	7.0	6.2	3.0	2.6	1.6	8.1	7.9	4.2	2.4
Color (Pt Units)	1 m	5.2	3.1	5.0	1.8	4.5	1.0	4.0	2.0	3.0	1.0	4.0	1.0
	hypo	4.5	1.4	5.2	1.7	4.8	0.8	4.0	2.0	3.0	1.0	4.0	1.0
Calcium (mg/L)	1 m	9.8	0.9	9.8	1.0	9.9	0.6	10.1	0.8	10.6	1.8	10.0	0.6
	hypo	9.9	0.8	9.4	0.5	9.5	0.6	10.5	1.4	9.7	0.9	10.1	1.0
Magnesium (mg/L)	1 m	0.9	1.1	0.5	0.3	0.5	0.3	0.4	0.3	0.5	0.3	0.4	0.3
	hypo	0.4	0.3	0.4	0.3	0.4	0.3	0.3	0.2	0.6	0.3	0.5	0.3
Iron (ug/L)	1 m	187	77	324	99	270	45	202	170	323	191	284	180
	hypo	259	97	489	366	302	129	217	175	610	591	328	205
Total-P (ug/L)	1 m	6.8	1.7	11.0	2.6	9.2	2.2	5.6	3.5	7.8	4.1	7.1	3.6
	hypo	8.7	2.1	20.5	14.9	10.7	3.7	5.7	4.0	13.9	13.3	7.4	4.4
Total filterable-P (ug/L)	1 m	2.6	1.3	4.4	4.4	2.6	1.3	2.5	2.8	1.6	0.4	1.8	0.8
	hypo	2.5	0.6	2.7	0.5	2.9	1.1	1.5	0.6	1.7	0.6	1.6	0.5
Filterable reactive-P (ug/L)	1 m	1.8	1.0	3.0	2.6	1.9	0.9	1.7	1.6	1.3	0.3	1.5	0.7
	hypo	1.9	0.5	1.9	0.3	2.3	1.0	1.3	0.4	1.4	0.5	1.4	0.3
Total Kjeldahl-N (ug/L)	1 m	30	8	31	7	29	5	37.0	15.0	27.5	15.7	35.3	14.0
	hypo	23	3	24	6	22	2.2	27.9	12.2	29.4	17.6	27.7	16.7
Ammonia-N (ug/L)	1 m	7.8	2.2	9.7	2.0	7.6	1.7	3.7	2.8	2.5	2.7	2.6	1.6
	hypo	7.8	1.6	7.6	1.9	7.1	1.8	1.7	1.3	1.8	1.4	2.7	1.9
Nitrate+nitrite (ug/L)	1 m	169	16	185	12	180	14	199	21	217	38	196	20
	hypo	191	5	185	16	193	8	216	22	213	34	213	23
Reactive silicon	1 m	1315	49	1353	52	1335	30	1345	57	1371	70	1349	65
	hypo	1325	31	1307	59	1343	39	1344	40	1343	43	1356	48
Chlorophyll a (ug/L)	1 m	0.33	0.14	0.25	0.16	0.25	0.16	0.27	0.08	0.19	0.08	0.26	0.13
	hypo	0.10	0.05	0.14	0.14	0.07	0.06	na	na	na	na	na	na
Phaeophytin a (ug/L)	1 m	0.23	0.07	0.17	0.07	0.17	0.09	0.24	0.04	0.28	0.07	0.24	0.06
	hypo	0.17	0.07	0.21	0.11	0.14	0.08	na	na	na	na	na	na

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1980-1981.

Parameter		1980 (n=6)						1981 (n=6)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	41	1	40	1	40	2	41	5	38	4	37	4
	hypo	40	0	41	1	41	1	39	3	38	3	37	5
pH (Units)	1 m	7.0	0.3	7.0	0.3	7.0	0.4	6.4	0.3	6.5	0.2	6.5	0.2
	hypo	7.0	0.2	7.0	0.3	6.9	0.3	6.4	0.3	6.6	0.3	6.5	0.3
Alkalinity (mg/L)	1 m	14.0	0.9	14.5	1.6	14.8	1.9	14.3	2.6	14.0	2.1	13.4	0.9
	hypo	15.0	1.7	13.8	0.4	13.4	2.8	14.7	1.8	14.3	2.4	13.2	0.8
Turbidity (NTU)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Color (Pt Units)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Calcium (mg/L)	1 m	4.8	0.7	4.5	0.3	4.5	0.2	5.2	0.9	5.1	0.5	4.8	0.3
	hypo	4.6	0.5	4.6	0.6	4.6	0.5	5.2	0.6	4.7	0.5	5.0	0.7
Magnesium (mg/L)	1 m	0.8	0.2	1.0	0.5	1.0	0.5	0.6	0.7	1.1	1.1	1.7	1.0
	hypo	0.9	0.3	1.0	0.3	1.0	0.5	0.9	0.8	1.1	1.0	1.0	1.2
Iron (ug/L)	1 m	2937	448	2892	735	3175	413	3008	724	3125	747	3393	546
	hypo	3403	488	3172	231	3835	716	3271	744	2971	937	3255	780
Total-P (ug/L)	1 m	38.8	3.2	44.9	3.2	43.3	3.5	50.1	3.5	52.7	5.8	51.3	6.2
	hypo	45.4	2.2	43.3	5.8	51.4	18.9	52.3	5.0	51.1	6.8	53.2	8.1
Total filterable-P (ug/L)	1 m	7.5	3.0	5.8	1.5	6.5	1.7	7.7	2.5	6.1	0.4	7.1	0.9
	hypo	8.0	3.8	6.9	1.9	6.6	1.8	7.6	0.4	7.6	1.0	6.4	1.1
Filterable reactive-P (ug/L)	1 m	5.9	3.1	5.0	1.6	5.1	1.8	6.1	2.2	5.0	0.4	6.0	1.3
	hypo	5.5	0.8	5.4	1.2	5.4	1.4	5.9	0.4	6.3	0.7	5.4	0.8
Total Kjeldahl-N (ug/L)	1 m	46	36	40	28	28	16	49	16	59	50	32	21
	hypo	33	15	37	22	40	32	34	21	25	15	51	43
Ammonia-N (ug/L)	1 m	5.7	3.9	6.9	3.3	8.3	4.3	4.0	2.0	1.6	1.4	2.0	1.5
	hypo	7.5	4.7	9.2	6.7	9.5	5.1	3.2	1.7	2.8	2.0	3.9	4.9
Nitrate+nitrite (ug/L)	1 m	88	27	91	22	96	19	95	8	98	6	100	6
	hypo	93	21	104	7	105	11	104	4	101	8	105	5
Reactive silicon	1 m	2250	131	2173	104	2472	548	2278	168	2245	124	1774	995
	hypo	2226	110	2181	95	2196	76	2199	121	2239	111	2222	77
Chlorophyll a (ug/L)	1 m	1.47	1.30	0.89	0.90	1.13	1.74	0.29	0.19	0.20	0.16	0.09	0.10
	hypo	0.13	0.10	0.16	0.16	0.18	0.20	na	na	na	na	na	na
Phaeophytin a (ug/L)	1 m	0.02	0.02	0.16	0.21	0.20	0.28	0.42	0.32	0.20	0.09	0.12	0.06
	hypo	0.22	0.30	0.04	0.01	0.04	0.00	na	na	na	na	na	na

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1982-1983.

Parameter		1982 (n=5)						1983 (n=5)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	39	4	38	3	38	3	41	2	40	0	40	1
	hypo	39	4	38	5	37	37	41	1	33	16	40	1
pH (Units)	1 m	7.0	0.3	7.2	0.2	7.2	0.1	7.2	0.2	7.2	0.3	7.2	0.2
	hypo	7.2	0.1	7.2	0.2	7.2	7.2	7.2	0.2	5.9	2.9	7.2	0.3
Alkalinity (mg/L)	1 m	14.6	0.9	14.8	0.8	14.6	0.5	16.2	1.8	15.0	0.0	16.0	2.8
	hypo	14.4	0.5	14.6	0.5	14.6	14.6	14.7	1.6	12.5	6.2	15.8	2.4
Turbidity (NTU)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Color (Pt Units)	1 m	na	na	na	na	na	na	na	na	na	na	na	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na
Calcium (mg/L)	1 m	4.4	0.7	4.4	0.6	4.4	0.6	4.6	0.4	4.9	0.3	5.6	1.0
	hypo	4.5	0.6	4.5	0.7	4.6	1.1	4.7	0.4	4.8	0.4	5.2	0.9
Magnesium (mg/L)	1 m	0.9	0.5	1.2	1.2	0.7	0.4	1.1	1.1	1.1	0.8	0.9	0.6
	hypo	1.1	0.9	0.6	0.4	0.4	0.4	1.5	1.2	1.1	0.7	0.8	0.6
Iron (ug/L)	1 m	2861	325	2978	315	3162	441	2838	270	3075	469	3151	374
	hypo	3015	365	3307	290	3274	379	3231	294	3166	460	3145	666
Total-P (ug/L)	1 m	47.5	4.7	50.3	3.8	51.7	5.5	58.4	4.9	57.4	7.2	59.1	2.6
	hypo	50.1	2.3	48.5	5.7	53.5	3.2	55.6	2.9	57.5	4.4	63.9	3.5
Total filterable-P (ug/L)	1 m	8.5	3.1	8.5	4.3	7.4	1.6	7.3	1.7	18.2	15.1	6.8	0.7
	hypo	7.8	0.6	8.7	1.7	9.5	3.3	7.7	1.6	7.8	0.7	14.9	5.6
Filterable reactive-P (ug/L)	1 m	6.3	2.6	6.7	2.6	6.7	1.9	6.1	2.3	10.8	14.0	5.5	1.8
	hypo	7.2	0.9	7.9	1.0	7.4	1.1	7.1	2.1	6.8	1.0	6.1	2.1
Total Kjeldahl-N (ug/L)	1 m	42	8	44	11	47	17	73	40	61	16	57.3	21
	hypo	34	11	33	12	42	15	60	21	51	24	52	15
Ammonia-N (ug/L)	1 m	6.4	3.9	5.0	1.6	4.2	1.4	16.4	8.9	7.5	3.0	8.9	5.8
	hypo	5.1	1.8	6.6	1.5	5.4	1.9	10.0	3.6	6.5	2.6	10.2	6.3
Nitrate+nitrite (ug/L)	1 m	87	20	86	24	89	28	85	18	77	40	85	32
	hypo	105	5	106	5	107	8	105	9	104	9	91	40
Reactive silicon	1 m	2186	125	2132	169	2106	139	2148	58	2108	75	2092	41
	hypo	2174	88	2146	161	1634	1018	2134	50	2131	82	2078	41
Chlorophyll a (ug/L)	1 m	0.47	0.50	0.87	1.13	1.21	1.62	0.96	1.08	0.40	0.38	0.44	0.28
	hypo	0.08	0.00	0.05	0.00	na	na	na	na	na	na	na	na
Phaeophytin a (ug/L)	1 m	na	na	na	na	na	na	0.65	0.05	0.39	0.08	0.51	na
	hypo	na	na	na	na	na	na	na	na	na	na	na	na

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1984-1985.

Parameter		1984 (n=5)						1985 (n=6)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	42	3	41	1	42	2	39	2	47	2	39	3
	hypo	42	1	41	1	42	1	38	2	38	3	39	3
pH (Units)	1 m	7.1	0.3	7.0	0.4	7.1	0.4	7.1	0.4	6.4	1.1	6.8	0.1
	hypo	7.0	0.3	6.9	0.3	7.0	0.2	6.9	0.2	6.9	0.2	6.8	0.1
Alkalinity (mg/L)	1 m	16.3	5.7	17.3	4.1	16.3	1.5	19.0	7.5	14.0	8.3	15.7	5.2
	hypo	15.3	2.5	15.0	2.8	15.3	0.6	14.3	1.5	15.6	4.3	15.2	4.0
Turbidity (NTU)	1 m	44	2	49	1	42	5	45	5	45	7	46	7
	hypo	49	2	52	1	47	5	45	3	48	3	39	22
Color (Pt Units)	1 m	4.6	1.3	4.0	1.0	5.8	2.5	5.7	2.8	8.0	7.8	4.5	1.2
	hypo	4.4	1.1	5.8	1.9	4.8	1.0	5.3	1.5	5.8	1.7	8.2	7.8
Calcium (mg/L)	1 m	4.3	0.3	4.5	0.7	5.0	0.8	5.1	0.6	4.7	0.5	4.5	0.7
	hypo	4.2	0.7	4.7	0.5	4.4	0.4	4.5	1.0	4.7	0.6	4.9	0.6
Magnesium (mg/L)	1 m	1.5	0.7	0.8	0.6	0.9	0.7	0.8	0.4	1.1	0.3	0.9	0.5
	hypo	1.3	0.3	0.6	0.4	1.0	0.5	1.0	0.5	1.2	0.3	1.4	0.6
Iron (ug/L)	1 m	2571	127	2885	112	2799	442	2671	244	2557	364	2930	446
	hypo	2927	209	3029	192	2894	602	2766	356	2662	514	2901	438
Total-P (ug/L)	1 m	45.0	10.1	45.9	5.9	43.9	8.2	43.7	10.5	46.0	9.7	51.2	5.6
	hypo	48.3	4.6	47.2	8.8	49.3	9.9	45.2	12.2	46.1	11.9	50.4	6.1
Total filterable-P (ug/L)	1 m	9.9	6.3	6.6	1.4	6.3	0.8	8.4	3.0	12.0	9.6	9.5	4.5
	hypo	8.4	1.6	7.4	1.2	7.4	2.1	9.0	3.4	8.3	2.4	8.9	2.6
Filterable reactive-P (ug/L)	1 m	4.7	0.7	5.3	1.2	5.8	0.5	5.1	1.5	8.4	7.7	5.8	1.4
	hypo	6.1	1.3	6.3	0.6	5.9	1.0	6.4	1.5	6.2	1.0	6.2	1.8
Total Kjeldahl-N (ug/L)	1 m	68	9	91	22	58	4	83	26	78	19	76	21
	hypo	71	15	59	40	56	5	68	17	66	21	59	6
Ammonia-N (ug/L)	1 m	4.7	2.9	7.4	9.4	3.2	0.9	4.0	3.4	1.9	1.6	1.4	1.0
	hypo	3.5	0.6	3.9	2.3	2.8	1.4	3.1	2.3	1.7	1.2	2.0	1.9
Nitrate+nitrite (ug/L)	1 m	88	7	90	16	97	7	133	47	123	28	124	40
	hypo	100	4	91	19	101	5	136	43	134	39	122	31
Reactive silicon	1 m	2151	153	2106	138	2145	2145	2495	52	2477	104	2441	58
	hypo	2176	148	2100	131	2153	40	2505	60	2490	70	2475	43
Chlorophyll a (ug/L)	1 m	0.96	0.24	0.56	0.25	0.47	0.46	0.31	0.25	0.43	0.79	0.33	0.45
	hypo	0.30	0.13	0.16	0.11	0.15	0.09	0.11	0.04	0.06	0.04	0.09	0.05
Phaeophytin a (ug/L)	1 m	0.76	0.27	0.67	0.34	0.45	0.23	0.61	0.30	0.67	0.58	0.63	0.09
	hypo	0.55	0.21	0.34	0.17	0.33	0.14	0.30	0.15	0.38	0.31	0.27	0.12

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1986-1987.

Parameter		1986 (n=7)						1987 (n=7)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	38	3	40	2	40	1	40	1	40	1	40	1
	hypo	40	2	39	1	40	1	41	1	40	1	40	1
pH (Units)	1 m	6.9	0.2	6.9	0.2	7.0	0.1	7.1	0.3	6.9	0.2	6.9	0.2
	hypo	6.9	0.4	6.9	0.2	7.0	0.2	7.0	0.1	7.0	0.2	7.0	0.1
Alkalinity (mg/L)	1 m	14.1	1.8	13.4	2.1	14.5	1.6	14.4	2.9	13.9	0.7	13.4	0.5
	hypo	14.9	6.0	13.4	2.1	14.2	1.3	13.9	1.0	14.1	2.4	13.3	0.7
Turbidity (NTU)	1 m	37	17	46	3	44	5	45	7	43	8	44	9
	hypo	46	3	45	5	38	19	46	7	47	7	47	6
Color (Pt Units)	1 m	6.7	2.1	6.0	1.0	6.2	1.5	14.3	6.5	8.3	4.4	11.5	5.5
	hypo	6.6	2.4	6.0	1.0	6.5	1.2	12.5	4.6	10.0	2.7	8.8	3.1
Calcium (mg/L)	1 m	5.2	na	4.8	na	4.4	na	na	na	na	na	na	na
	hypo	4.8	na	4.4	na	5.2	na	na	na	na	na	na	na
Magnesium (mg/L)	1 m	0.6	na	0.9	na	0.9	na	na	na	na	na	na	na
	hypo	0.6	na	0.9	na	0.6	na	na	na	na	na	na	na
Iron (ug/L)	1 m	2729	192	2845	506	2646	699	2758	715	2974	687	2991	753
	hypo	2849	404	2875	547	2896	582	2926	654	3147	706	3083	656
Total-P (ug/L)	1 m	43.7	10.5	53.7	4.5	49.2	6.3	52.8	7.8	56.3	3.8	54.6	5.7
	hypo	56.2	8.2	54.9	3.9	56.2	3.2	53.0	5.4	59.4	4.8	56.4	8.6
Total filterable-P (ug/L)	1 m	8.4	3.0	6.7	1.0	6.7	0.9	7.5	0.7	7.3	0.8	7.0	0.8
	hypo	7.6	1.5	6.8	1.1	7.2	1.0	7.7	1.0	7.9	1.6	7.4	1.0
Filterable reactive-P (ug/L)	1 m	5.1	1.5	6.5	0.9	6.5	0.9	5.8	0.6	5.6	0.6	5.2	0.9
	hypo	7.3	1.2	6.7	0.8	6.5	0.5	6.3	0.7	6.0	0.8	6.0	0.3
Total Kjeldahl-N (ug/L)	1 m	83	26	58	12	58	9	61	3	58	6	56	8
	hypo	53	13	56	18	44	10	55	8	52	9	55	9
Ammonia-N (ug/L)	1 m	3.8	2.3	3.0	1.9	3.0	1.8	1.3	0.2	1.2	0.2	1.3	0.4
	hypo	3.2	1.7	3.3	1.6	2.8	1.8	1.2	0.2	1.3	0.3	1.1	0.0
Nitrate+nitrite (ug/L)	1 m	77	23	82	8	90	10	84	23	96	6	98	3
	hypo	89	4	82	23	89	21	102	11	107	3	106	2
Reactive silicon	1 m	2466	229	2438	2438	2411	221	2534	377	2468	372	2484	123
	hypo	2473	226	2428	222	2418	243	2518	360	2466	373	2498	353
Chlorophyll a (ug/L)	1 m	0.13	0.13	0.27	0.22	0.24	0.41	0.28	0.35	0.26	0.32	0.21	0.37
	hypo	0.06	0.02	0.05	0.06	0.03	0.02	0.05	0.04	0.04	0.03	0.01	0.01
Phaeophytin a (ug/L)	1 m	0.11	0.11	0.30	0.11	0.31	0.19	0.38	0.17	0.37	0.17	0.28	0.16
	hypo	0.23	0.04	0.22	0.05	0.21	0.05	0.20	0.07	0.19	0.03	0.17	0.03

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1988-1989.

Parameter		1988 (n=6)						1989 (n=7)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	41	2	41	1	40	1	44	1	41	1	40	1
	hypo	41	0	41	1	40	1	41	1	41	1	41	1
pH (Units)	1 m	6.9	0.2	7.0	0.2	6.9	0.1	7.2	0.1	7.2	0.1	7.3	0.1
	hypo	6.9	0.1	7.0	0.2	7.0	0.2	7.2	0.1	7.2	0.1	7.2	0.2
Alkalinity (mg/L)	1 m	13.1	1.7	14.0	2.9	14.6	4.7	13.3	0.5	14.9	3.2	13.0	0.2
	hypo	13.0	1.6	12.9	2.0	13.1	1.2	13.6	0.5	13.3	0.5	13.2	0.4
Turbidity (NTU)	1 m	39	4	40	6	43	9	32	7	38	5	38	1
	hypo	44	2	43	3	44	5	35	4	37	5	41	3
Color (Pt Units)	1 m	6.4	1.1	5.9	1.1	6.3	1.6	4.1	0.9	5.6	2.9	4.7	1.0
	hypo	7.7	1.3	7.9	0.9	6.4	2.1	4.6	1.7	5.1	1.3	5.8	4.0
Calcium (mg/L)	1 m	na	na	na	na	na	na	4.9	0.4	4.7	0.5	5.2	0.9
	hypo	na	na	na	na	na	na	5.1	0.6	4.7	0.3	5.7	0.6
Magnesium (mg/L)	1 m	na	na	na	na	na	na	0.8	0.7	0.5	0.2	0.8	0.7
	hypo	na	na	na	na	na	na	0.4	0.4	0.6	0.3	0.4	0.5
Iron (ug/L)	1 m	2416	421	2581	406	2727	402	2385	228	2647	273	2597	384
	hypo	2725	453	2621	308	2964	405	2369	261	2478	266	2759	179
Total-P (ug/L)	1 m	52.8	3.3	51.9	3.3	56.0	3.4	47.5	1.7	49.9	2.0	49.8	1.7
	hypo	51.9	3.4	55.5	5.6	54.8	5.5	48.7	2.4	49.9	2.4	49.7	2.3
Total filterable-P (ug/L)	1 m	5.9	1.0	5.7	1.1	6.5	1.3	5.5	1.3	5.8	1.2	5.4	0.7
	hypo	7.1	1.3	6.5	0.6	6.0	1.1	5.9	0.7	5.6	0.9	6.8	3.2
Filterable reactive-P (ug/L)	1 m	4.5	0.4	4.4	0.6	5.4	1.6	6.1	1.3	6.4	1.6	6.1	1.0
	hypo	5.2	1.0	5.2	1.0	4.5	1.1	6.3	1.5	6.7	0.9	7.1	3.8
Total Kjeldahl-N (ug/L)	1 m	70	11	63	9	64	21	71	22	59	12	62	18
	hypo	53	5	59	5	56	13	57	15	57	8	56	9
Ammonia-N (ug/L)	1 m	1.4	0.6	1.5	0.9	1.1	0.0	1.9	1.0	1.6	0.7	2.4	1.4
	hypo	1.2	0.1	1.2	0.2	1.3	0.5	1.6	0.8	1.6	0.7	2.2	1.0
Nitrate+nitrite (ug/L)	1 m	93	13	100	10	105	8	97	12	100	8	102	8
	hypo	108	3	105	6	109	2	106	11	108	8	106	7
Reactive silicon	1 m	2470	397	2451	347	2377	297	2325	164	2251	97	2295	141
	hypo	2442	325	2451	317	2401	276	2283	112	2262	99	2224	102
Chlorophyll a (ug/L)	1 m	0.54	0.42	0.28	0.26	0.15	0.23	0.13	0.18	0.16	na	na	na
	hypo	0.05	0.03	0.11	0.10	0.02	0.02	0.04	0.02	0.31	na	na	na
Phaeophytin a (ug/L)	1 m	0.47	0.26	0.36	0.23	0.22	0.18	0.22	0.31	0.03	na	na	na
	hypo	0.22	0.10	0.21	0.08	0.13	0.04	0.21	0.06	0.31	na	na	na

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1990-1991.

Parameter		1990 (n=8)						1991 (n=7)					
		A		B		C		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	40	1	40	1	39	1	40	2	40	3	40	1
	hypo	40	1	40	1	40	1	40	2	40	1	40	2
pH (Units)	1 m	7.1	0.2	7.1	0.1	7.2	0.1	7.1	0.2	7.1	0.1	7.1	0.1
	hypo	7.1	0.1	7.1	0.2	7.2	0.1	7.1	0.2	7.1	0.1	7.0	0.1
Alkalinity (mg/L)	1 m	13.9	1.1	13.5	0.9	13.5	0.9	13.8	2.1	13.4	2.1	13.2	2.0
	hypo	13.9	1.2	13.8	1.1	13.6	0.8	13.9	2.2	13.8	2.0	13.0	2.0
Turbidity (NTU)	1 m	36	2	35	3	38	2	31	3	33	4	33	3
	hypo	38	2	39	1	37	4	33	3	35	2	37	2
Color (Pt Units)	1 m	5.5	1.2	5.8	1.0	5.8	1.5	6.1	2.0	6.7	2.4	8.0	3.1
	hypo	7.1	3.0	7.9	3.7	6.8	1.7	7.7	2.1	7.7	2.8	7.9	2.0
Calcium (mg/L)	1 m	5.9	1.7	6.8	3.8	5.1	0.6	4.8	0.5	4.7	0.4	4.6	0.4
	hypo	5.5	2.0	6.0	2.7	5.1	1.0	5.2	0.9	4.8	0.6	5.3	1.1
Magnesium (mg/L)	1 m	0.8	0.6	0.7	0.5	0.6	0.4	1.0	0.4	1.0	0.5	1.1	0.4
	hypo	0.8	0.6	0.6	0.4	0.7	0.5	0.8	0.5	1.0	0.4	0.8	0.5
Iron (ug/L)	1 m	2414	232	2390	448	2683	367	1707	284	1738	494	1977	435
	hypo	2384	535	2345	676	2530	483	1659	380	1929	359	1963	510
Total-P (ug/L)	1 m	44.7	3.6	46.7	3.9	51.4	4.8	36.7	2.3	39.4	3.1	40.3	3.9
	hypo	47.5	2.2	49.1	4.1	49.5	4.1	39.4	3.5	42.7	3.1	44.5	2.8
Total filterable-P (ug/L)	1 m	5.5	1.6	4.8	1.1	5.2	0.5	5.8	1.4	5.8	1.6	6.6	1.2
	hypo	6.4	1.5	6.1	1.7	5.9	0.5	6.7	0.9	6.8	1.0	6.6	1.2
Filterable reactive-P (ug/L)	1 m	6.1	1.4	5.4	1.1	5.7	1.1	5.8	1.4	5.9	1.4	6.9	1.0
	hypo	7.2	1.5	7.0	1.7	6.5	0.8	7.1	1.0	7.1	0.7	6.8	1.3
Total Kjeldahl-N (ug/L)	1 m	48	13	49	19	41	10	55	14	54	16	52	11
	hypo	44	15	42	10	38	11	49	9	48	13	46	10
Ammonia-N (ug/L)	1 m	1.8	1.0	1.6	0.9	1.6	0.9	6.6	2.7	5.7	2.9	5.7	2.9
	hypo	2.3	1.4	1.7	0.9	2.2	0.9	5.4	2.2	5.3	2.7	5.7	2.5
Nitrate+nitrite (ug/L)	1 m	91	11	97	12	101	14	91	16	94	13	99	9
	hypo	105	8	108	6	106	8	103	2	105	3	100	14
Reactive silicon	1 m	2348	231	2305	218	2278	227	2106	106	2095	79	2079	75
	hypo	2341	246	2325	209	2086	655	2145	93	2098	89	2076	68
Chlorophyll a (ug/L)	1 m	0.27	0.21	0.29	0.26	0.20	0.19	0.42	0.31	0.25	0.24	0.28	0.26
	hypo	0.06	0.06	0.03	0.03	0.07	0.10	0.04	0.04	0.12	0.20	0.02	0.02
Phaeophytin a (ug/L)	1 m	0.39	0.19	0.37	0.07	0.25	0.10	0.33	0.15	0.27	0.13	0.27	0.13
	hypo	0.27	0.09	0.19	0.04	0.17	0.05	0.18	0.05	0.21	0.12	0.15	0.02

na indicates not available

Seasonal mean values, number of observations (n), and standard deviations (Sd) for general water-quality parameters, metals, nutrients, and algal pigments within the 1-m stratum and hypolimnion (hypo) at 3 sampling stations in Tustumena Lake, 1992.

Parameter		1992 (n=8)					
		A		B		C	
		Mean	Sd	Mean	Sd	Mean	Sd
Conductivity (umhos/cm)	1 m	40	2	40	2	39	1
	hypo	39	1	39	1	39	1
pH (Units)	1 m	6.7	0.2	6.8	0.1	6.8	0.1
	hypo	6.8	0.1	6.8	0.1	6.8	0.1
Alkalinity (mg/L)	1 m	12.9	2.1	11.8	1.6	11.6	1.6
	hypo	12.2	1.0	13.2	2.6	12.4	0.7
Turbidity (NTU)	1 m	33	4	36	4	36	5
	hypo	35	6	37	4	38	6
Color (Pt Units)	1 m	5.0	1.0	6.0	1.0	6.0	1.0
	hypo	6.0	2.0	5.0	1.0	5.0	1.0
Calcium (mg/L)	1 m	4.9	0.3	5.1	0.5	4.9	0.3
	hypo	5.0	0.5	4.8	0.2	5.0	0.3
Magnesium (mg/L)	1 m	1.2	0.4	1.0	0.5	1.2	0.6
	hypo	1.2	0.6	0.9	0.5	0.9	0.6
Iron (ug/L)	1 m	2278	261	2285	482	2442	231
	hypo	2371	583	2427	447	2544	543
Total-P (ug/L)	1 m	35.1	3.2	36.3	1.5	39.4	5.6
	hypo	36.6	4.4	38.8	3.8	40.1	6.2
Total filterable-P (ug/L)	1 m	4.8	1.2	4.9	1.4	5.6	1.0
	hypo	5.6	1.2	5.4	1.4	5.6	1.2
Filterable reactive-P (ug/L)	1 m	4.7	0.9	4.8	0.8	5.6	0.7
	hypo	5.5	1.1	5.3	1.2	5.3	0.8
Total Kjeldahl-N (ug/L)	1 m	52	12	45	14	53	12
	hypo	44	10	45	9	55	24
Ammonia-N (ug/L)	1 m	2.3	2.1	2.3	2.8	1.0	0.5
	hypo	2.6	2.5	1.4	0.5	1.7	0.9
Nitrate+nitrite (ug/L)	1 m	97	14	100	14	102	8
	hypo	106	10	107	11	103	7
Reactive silicon	1 m	2140	90	2094	51	2071	47
	hypo	2151	79	2096	69	2072	61
Chlorophyll a (ug/L)	1 m	0.67	0.58	0.43	0.37	0.23	0.19
	hypo	na	na	na	na	na	na
Phaeophytin a (ug/L)	1 m	0.53	0.29	0.47	0.20	0.32	0.12
	hypo	na	na	na	na	na	na

na indicates not available