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THE LIMNOLOGY OF LAKE ROOSEVELT, 1980

by

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1.0 SUMMARY

An intensive limnological investigation of Lake Roosevelt was conducted from December 1979 to September 1980. Physical, chemical and biological characteristics of the reservoir were substantially influenced by turbulence and retention time.

Upstream areas of the reservoir were characterized by unstratified, vertically homogeneous physical and chemical conditions related to the turbulent inflow of river water. In contrast, downstream areas and the Spokane River arm exhibited thermal stratification from May to August resulting from decreasing turbulence and increasing solar insolation. Concurrent with stratification periods, nitrate and orthophosphate depletion occurred in the euphotic zone, with levels typically below 10 µg/l. During similar times dissolved oxygen depletion occurred in the hypolimnion, with a minimum of 46 percent saturation.

Average phytoplankton standing crops over the study period were highest near the confluence with the Spokane River arm and standing crops decreased upstream and downstream from this area. Peak chlorophyll _a_ levels in the upstream areas of the reservoir averaged 7 mg/m^3 in June, with phytoplankton limited, in part, by turbulence. Peak chlorophyll _a_ in the downstream areas averaged 14 mg/m^3 in spring. Phytoplankton were primarily nitrogen-limited in the downstream areas, but phosphorus-limited in the Spokane River arm. Diatoms dominated the phytoplankton community over most of the study period. Maximum rates of primary production (669.6 and 794.5 $mgC/m^2/4$ hr) in the central reservoir occurred in April; however, the Spokane arm did not peak until September at 895.6 $mgC/m^2/4$ hr.

Total zooplankton densities were comprised of an average 71 percent rotifers at the main reservoir stations during the spring. Rotifers became abundant at about 120 km from the dam and persisted throughout the lower reach of the reservoir. Copepods comprised 95 percent of the total zooplankton during summer and became abundant about 80 km upstream of the dam. Cladocerans increased spatially downstream from 120 km above the dam and temporally from spring to summer representing up to 12 percent of the total. Rotifers and copepods comprised an average of 54 and 43 percent, respectively, of the total zooplankton in the Spokane arm from February to June, while copepods were predominant in August (88 percent) and cladocerans reached a maximum of 13 percent in summer. These results indicate the importance of the interaction of water retention times with seasonal changes in water temperature and zooplankton generation times for the development of large populations.

Mysis relicta, a non-native predaceous invertebrate, was found in the upper portion of Lake Roosevelt.

The trophic status of Lake Roosevelt using orthophosphate, total-P and primary production values indicates the main reservoir and the Spokane arm are slightly eutrophic. Chlorophyll *a* values indicate a mesotrophic classification over the entire reservoir, while nitrates suggest a slightly eutrophic condition in the Spokane arm and oligotrophic to mesotrophic conditions in the main reservoir. Overall Roosevelt Lake should be considered under a broad trophic range of mesotrophic to slightly eutrophic.

2.0 ACKNOWLEDGEMENTS

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3.0 INTRODUCTION

Grand Coulee Dam has recently been significantly modified to expand the hydroelectric generation and irrigation diversion facilities. These modifications may result in operational changes potentially creating alterations to the Roosevelt reservoir ecosystem. Interest in the potential of this reservoir has increased due to the growth in water-based recreational use of Roosevelt Lake from 468,137 visitor days in 1975 (USBR 1976) to 835,598 visitor days in 1980 (Dan Farrell, U.S. National Park Service, personal communication 1981). A walleye population has developed in the reservoir during the last ten years which presently supports a substantial sport fishery, enhancing the recreational potential of this reservoir.

Previous biological information reviewed by Bennett and White (1977) on Lake Roosevelt has been fragmentary and insufficient for the formulation of sound fishery management strategies. A comprehensive limnological and fisheries study was initiated to provide the ecological information needed for management of this multiple-use annual storage reservoir during a time of expanding requirements for hydroelectric power and irrigation water supply. The limnological investigation of Roosevelt Lake was conducted to establish ecological baseline information on several important habitat parameters of potential significance to present and future gamefish production. This study was performed concurrently with a fishery investigation by the U.S. Fish and Wildlife Service. The brevity of this study, due to withdrawal of funding, precludes complete analysis of the water management factors affecting the ecology of Lake Roosevelt. The data generated during the ten-month field study are presented along with a review of the limited prior information. Further research will be required to identify the most fruitful management strategies for the future.

Specific objectives in the investigation of the limnology of Lake Roosevelt were to 1) determine the spatial and temporal variation in major physical and chemical parameters (temperature, transparency, conductivity, pH, macronutrients — nitrogen and phosphorus; 3) determine the phytoplankton distribution and abundance, species composition, and ^{14}C primary production; and 3) determine the distribution, abundance, and composition of the zooplankton community. Data collected from December 1979 to September 1980 are presented.

4.0 DESCRIPTION OF STUDY AREA

Franklin D. Roosevelt Lake was established in 1942 following the construction of Grand Coulee Dam across a section of the mid-Columbia River (Fig. 1). Roosevelt Lake is the largest lake in Washington, extending easterly and northerly 243.5 km (151 mi) up a sparsely populated section of the Columbia River valley (Wolcott 1964). The lower portion of the lake is located in the high scrub desert of central Washington, while the mid and upper sections are located in a mountainous region of eastern Washington dominated by ponderosa pine forests. Daily air temperatures at Grand Coulee Dam average 22.9°C (74°F) in the mid-summer, with the daily maximum commonly exceeding 32.2°C (90°F), while mid-winter temperatures average -3.5°C (26°F). Mid-summer daily temperatures at Colville near the upper end of the reservoir average 3°C (5.4°F) lower than at Grand Coulee Dam, while winter temperatures average 1.2°C (2.2°F) lower. Mean annual precipitation is 2.71 cm (10.66 in) at Grand Coulee Dam and 4.42 cm (17.4 in) at Colville. A significant ice cover has developed on portions of the lake during severe winters.

Grand Coulee Dam (pop. 1424), Kettle Falls (pop. 1095) and Northport (pop. 363) are the largest communities adjacent to Roosevelt Lake. The Colville and Spokane Indian Reservations border portions of the reservoir. Several lumber mills near the reservoir and the Sherwood Uranium Mine in the Spokane Arm constitute the major industries, although a molybdenum mine at Mt. Tolman and coal-fired powerplant at Creston are projected as large future developments in the area.

The original hydraulic capacity of Grand Coulee Dam (Right and Left Powerplants) was 2601 m^3/sec (92 kcfs), which has increased to 8227 m^3/sec

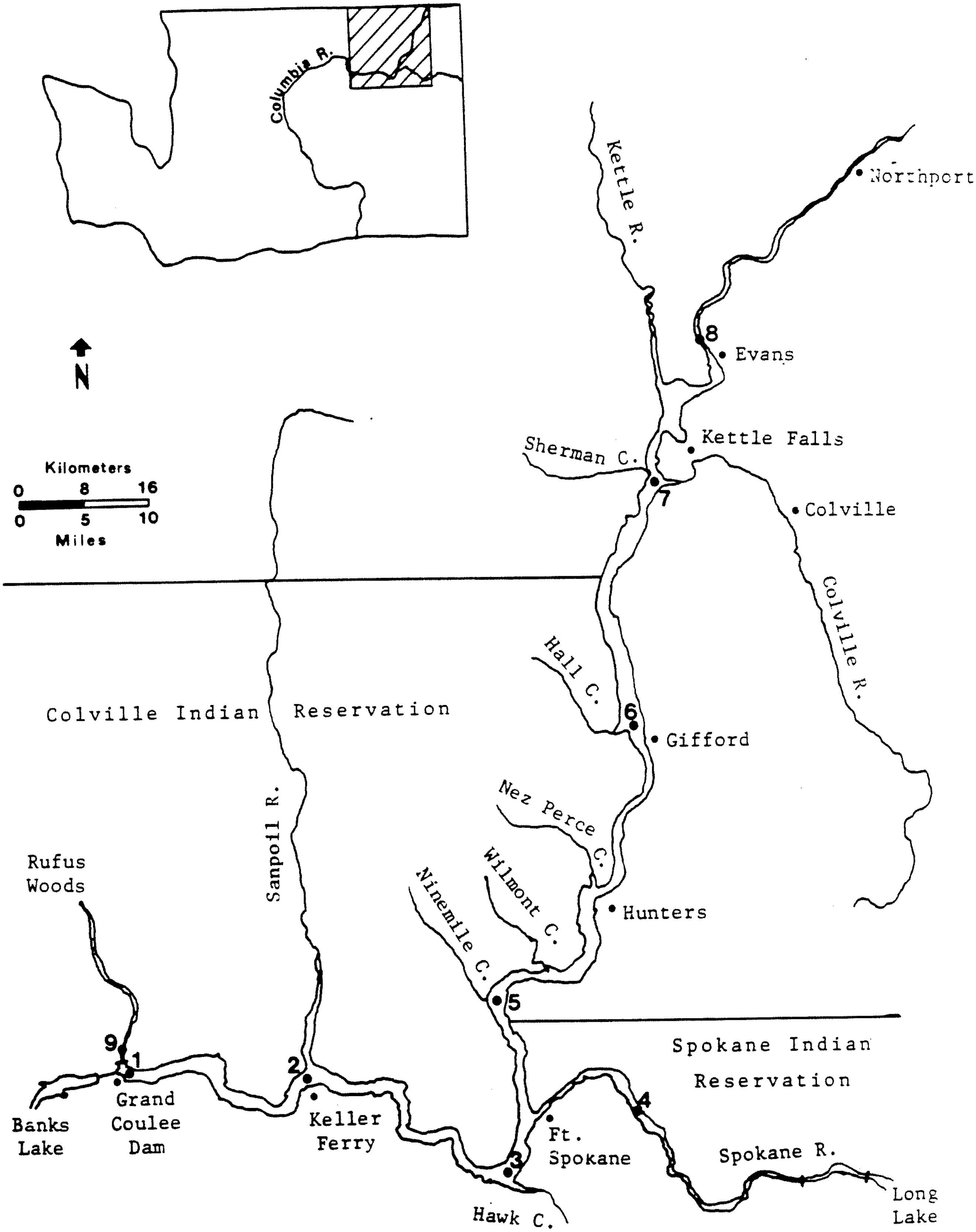

Figure 1. Map of Franklin D. Roosevelt Lake, major tributaries and reference points.

(291 kcfs) with the addition of the six generator units at the Third Powerplant (USBR 1975). Proposed extension of the Third Powerplant with an additional six generators would bring the total potential hydroelectric discharges from Grand Coulee Dam to 13,994 m^3/sec (495 kcfs). Diversion of water to Banks Lake for irrigation in the Columbia Basin is currently accomplished by six pump units and two pump-generator units rated at a total of 369 m^3/sec (13.1 kcfs). Present additions of four pump-generator units will produce a total diversion capacity of 567 m^3/sec (20.1 kcfs) (USBR 1976). The main irrigation diversion period is from May to August. The pump-generator units are designed to produce power during peaking periods, while discharging water to Roosevelt Lake from Banks Lake at a maximum rate of 73.5 m^3/sec (2.6 kcfs) each. Penstock elevations for the Right and Left Powerplants, Third Powerplant, and pump and pump-generator units occur at a mean elevation of 317.3 m (1041 ft), 347.0 m (1138 ft), and 363.7 m (1193 ft) above mean sea level, respectively. Additional releases occur by surface spilling and through spill tubes at 350.5 m (1150 ft) and 320.0 m (1050 ft) elevations.

Roosevelt Lake has a volume of 1,179,600 ha-m and a surface area of 33,490 ha at capacity (Table 1). Maximum depth is 122.3 m and mean depth is 36.0 m at full pool. The major period of drawdown is from January to June, with minimum surface elevations generally occurring in April. Lowering of the surface elevation during spring drawdown by 25 m to minimum operating levels reduces the volume and surface area by 54.7 percent and 45.2 percent, respectively, and the mean depth by 7.1 m. Shoreline development at capacity is high at 16.3. However, the steep shoreline and considerable drawdown

Table 1. Morphology of Franklin D. Roosevelt Lake, Washington.

	Capacity	Minimum operating level	Study period minimum	October 1974 to September 1979 average minimum
Surface elevation (m)	393.2	368.2	373.2	372.7
Area (ha)	33,490	18,361	22,286	20,994
Volume (ha-m)	1,179,600	543,190	635,700	623,950
Length (km)	243.5	—	—	—
Maximum width (km)	3.1	2.2	2.3	2.3
Mean depth (m)	36.0	29.1	28.5	29.7
Maximum depth (m)	122.3	97.3	102.3	101.8
Perimeter (km)	1,048	—	—	—
Shoreline development	16.3	—	—	—

precludes development of significant littoral areas. The drawdown level and corresponding morphology of Roosevelt Lake during the study period was similar to the average for the previous five years.

The average retention time (volume/discharge) of water in Roosevelt Lake was calculated for current withdrawal rates and lake surface elevations (Fig. 2). Computed values, based on uniform release from all depths, are expected to decrease for some water layers during periods of stratified flow (Jaske 1969). Withdrawal rates during the study period ranged from 1046 cms to 5094 cms, while the average yearly minimum and maximum for the previous five years was 1079 cms and 5123 cms. Retention times for the study period averaged 39.9 days (range 29.8 to 56.9 days) from December 1979 to June 1980 and 55.3 days (range 40.9 to 76.0 days) from July to September 1980 (Fig. 3).

Major hydrologic input to Roosevelt Lake arises from the Columbia, Spokane, and Kettle Rivers. They contribute approximately 89 percent, 7 percent and 3 percent, respectively, of the average annual input of water. The remaining 1 percent is contributed by the Colville and Sanpoil Rivers as well as numerous small streams.

Eight sampling stations were established at maximum depth along the main body of Roosevelt Lake from the forebay to Evans and in the Spokane River arm. Station 9 (RM 596) was located in the Grand Coulee Dam tailrace 1.5 km below the dam. Station 1 (RM 597) was 0.5 km from the dam face and corresponded to the forebay station sampled by Stober et al. (1977). Station 2 (RM 614) was located at Keller Ferry. Station 3 (RM 634) was 6.9 km downstream from the Spokane River. Station 4 (RM 13) was located in the Spokane River arm of Porcupine Bay. Station 5 (RM 648) was located near

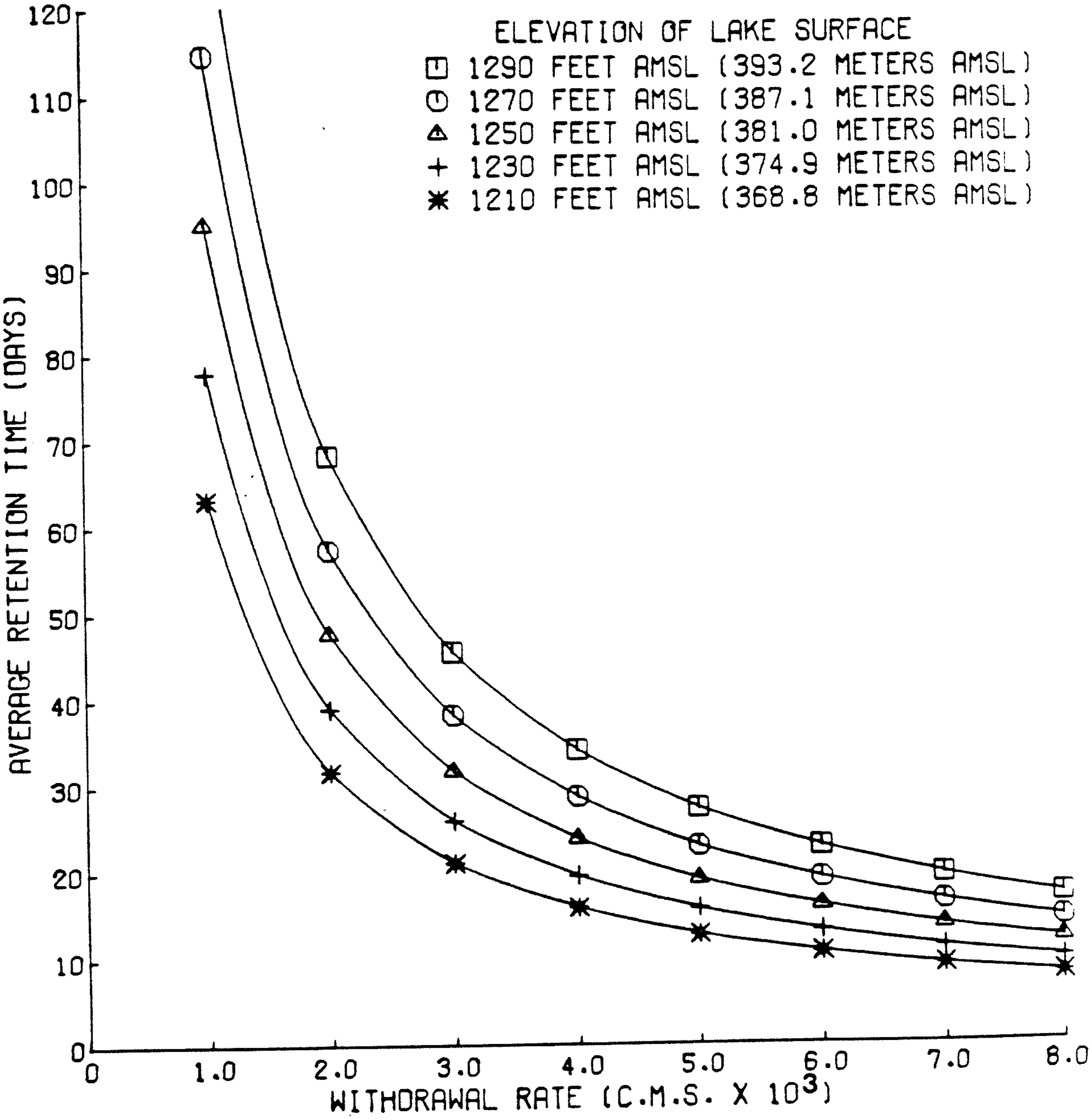

Figure 2. Average retention time of water in Roosevelt Lake at current withdrawal rates and lake surface elevations.

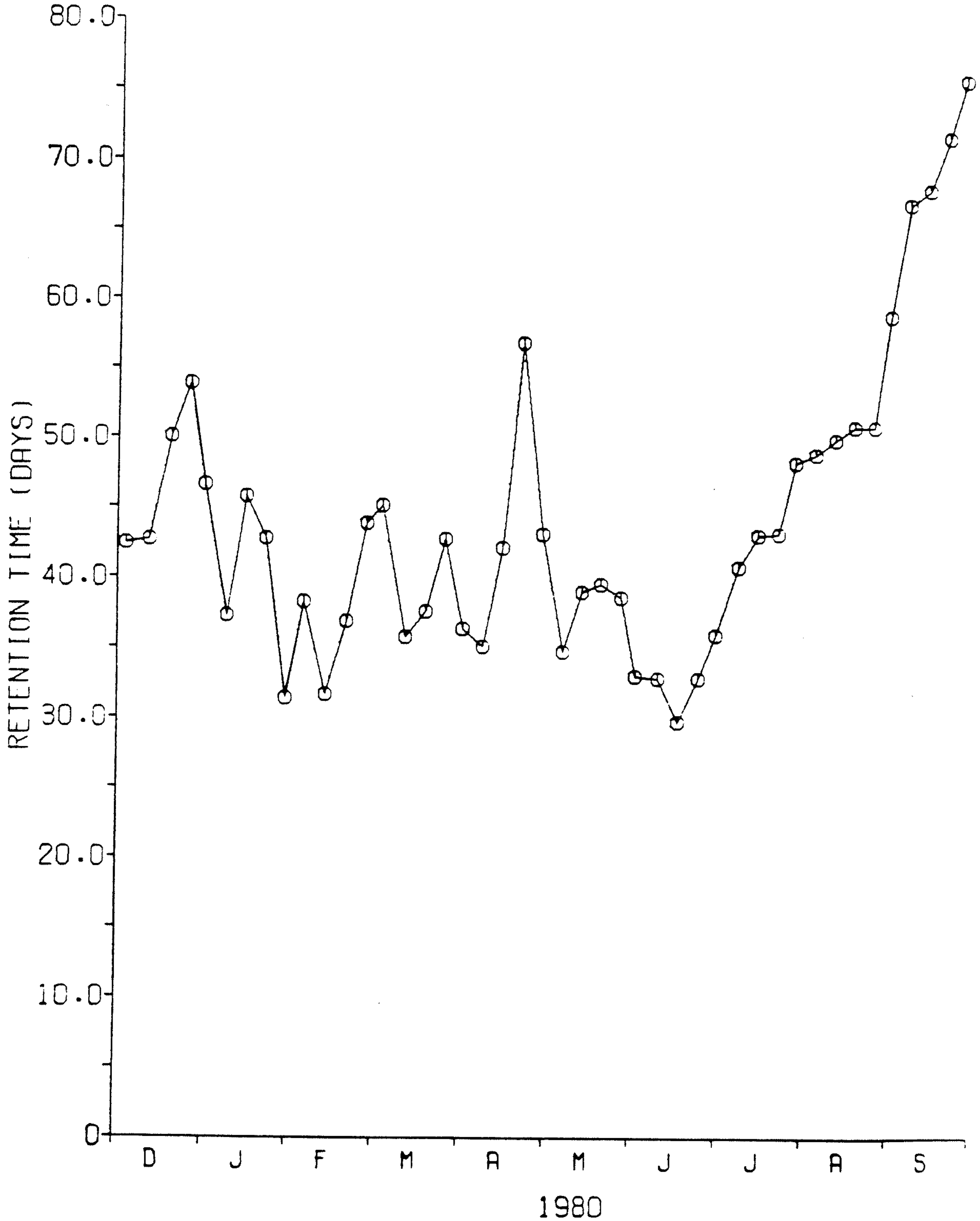

Figure 3. Average retention time of water in Roosevelt Lake from December 1979 to September 1980.

Nez Perce Creek. Station 6 (RM 676) was established at Hall Creek. Station 7 (RM 699) was located at the Colville River. Station 8 (RM 713) was situated near Evans.

Stations were sampled at monthly intervals from December 1979 to September 1980, with additional semi-monthly sampling at stations 1, 4 and 6 from May to September. Inclement weather and equipment deficiencies prevented complete sampling during December and January. Sampling during mid-May was temporarily interrupted by the ash cloud and subsequent fallout from the May 18th eruption of Mt. St. Helens. Additionally, ash that fell on the city of Spokane during this eruption was washed into the Spokane River and formed a plume of high turbidity in the Spokane River Arm of Roosevelt Lake in June.

5.0 MATERIALS AND METHODS

5.1 Physicochemical

Temperature, conductivity, pH, dissolved oxygen and oxidation-reduction potential profiles were taken from the surface to the bottom of the reservoir with a Hydrolab Surveyor Model 6D in-situ water quality analyzer. Readings were made at the surface, 1, 2 and 4 m and at a minimum of 4 m depth intervals thereafter to the bottom. Additional readings at 1 m intervals were taken in the metalimnion during periods of stratification. Data at station 9 in the river was taken from the shore 1 m below the surface.

Water transparency was measured at stations 1-8 with a 20 cm Secchi disc. Readings were taken from the shaded side of the boat with depth being recorded as the mean of the point of disappearance upon lowering and the point of reappearance upon raising.

Water chemistry samples were collected from depth with a 2-liter Van Dorn water bottle and placed in 1-liter Nalgene plastic bottles. Depths sampled were 1, 2, 4, 8 and 16 m below the surface and 10 m above the bottom at stations 1, 3, 4 and 5; 1, 4 and 8 m below the surface and 10 m above the bottom at stations 2, 6 and 7; and 1 m below the surface at stations 8 and 9. After collection, samples were placed on ice, field chemistry was conducted, and the samples were frozen within 24 hrs and subsequently transported to the University of Washington for complete chemical analysis. Samples collected at 1 and 8 m below the surface and 10 m above the bottom were analyzed for ortho-phosphate, total phosphate, nitrate, nitrite, ammonia, silica, total organic carbon, total filterable residue, hardness and alkalinity. Samples taken at 2, 4 and 16 m below the surface were analyzed for ortho-phosphate, nitrate, nitrite, ammonia and silica. Chemical analysis on semi-monthly (May to September) samples involved determinations of orthophosphate, nitrate, nitrite, ammonia and silica at 1, 4 and 8 m below the surface from stations 1, 4 and 6.

Field determinations were made for total hardness and total alkalinity. Total hardness was measured by standard techniques (APHA 1975) as modified in the Hach Chemical Company method manual, and represents calcium and magnesium hardness expressed as mg $CaCO_3$/l. Total alkalinity was determined by titration with sulfuric acid against bromocresol green-methyl red indicator (APHA 1975).

Laboratory analysis of total phosphate consisted of persulfate digestion to orthophosphate and subsequent spectrophotometric determination by the molybdate method (APHA 1975). Total organic carbon was measured with a Perkin-Elmer infrared elemental analyzer. Total filterable residue concentrations were determined using the techniques outlined in APHA (1975).

Orthophosphate, nitrate, nitrite, ammonia and silica concentrations were determined with a Technicon Autoanalyzer 1 using standard methods (APHA 1975) as modified by Pavlou (1972). Orthophosphate was analyzed with the molybdate-ascorbic acid method (APHA 1975). Nitrate was measured by cadmium reduction to nitrite and subsequent diazotization, while nitrite determination involved diazotization without cadmium reduction (APHA 1975). Free ammonia was measured by nesslerization and silica was analyzed by the colorimetric molybdosilicate method (APHA 1975).

5.2 Phytoplankton

5.2.1 Standing Crop

Phytoplankton standing crop was estimated by determining chlorophyll *a* concentrations according to Parsons and Strickland (1972). Samples were collected with a 2-liter Van Dorn water bottle at depths corresponding to those for water chemistry samples. One liter of sample was placed in a dark bottle and filtered within six hours through a 24 mm GF/C Gelman glass fiber filter. The filters were subsequently dried over silica gel, frozen and transported to the laboratory within one week for chlorophyll *a* analysis.

In the laboratory, chlorophyll was extracted by grinding the filters in 90 percent acetone using a Thomas tissue grinder in an ice bath. Samples were subsequently centrifuged and the extract was examined spectrophotometrically using a Bausch and Lomb Spectronic 70 spectrophotometer. Absorbances were measured at 665, 664, 663, 650, 647, 645, 630, 510 and 480 mm, using small volume 10 cm path length cells. The spectrophotometric equations of Parsons and Strickland (1972) were used to calculate the concentration of chlorophyll *a*.

5.2.2 Composition

Phytoplankton composition was determined by Utermohls method as outlined by Vollenweider (1974). Samples of 100 ml were taken from 4 m below the surface and preserved with Lugol's solution. Based on phytoplankton density, a volume of 25 to 100 ml was settled for two days. Sedimentation chamber bottoms were examined on a Leitz inverted microscope in phase contrast under low magnification (156X) to enumerate large phytoplankton, and under high magnification (468X) to count smaller forms. Composition estimates were obtained at a maximum bi-monthly interval for stations 9, 1, 2, 3, 4 and 5 from March to September and for stations 6, 7 and 8 from May to September. Taxonomic composition, cell density and total cell volume per liter was calculated for each sample. Identification was to the genus level using Prescott (1954), Stein (1975) and Bourrelly (1966, 1968, 1970). Cell volumes of the dominant genera were determined by fitting their cell shapes (cube, cylinder, sphere) to simple geometric forms (Ellie Duffield, personal communication). Critical cell dimensions were measured for a subsample of the population, and an appropriate geometric equation used to calculate volume. As an example, the radius of Chlorella, which exhibits a spherical shape, was measured and the volume was calculated by substitution into the equation for the volume of a sphere ($V = 4/3 \pi r^3$).

5.2.3 Primary Production

Primary productivity rates were determined by the in situ ^{14}C technique described by Vollenweider (1974). One dark and five light bottles were arrayed at each of seven depths spanning the euphotic zone. The deepest array was set at three to five times the observed Secchi depth. Fixed array depths of 1, 2, 4, 8 and 16 m below the surface were supplemented with arrays at 3, 6, 12, 20 or 24 meters as necessary.

Water samples from each depth were innoculated with 1 ml of $Na_2{}^{14}CO_3$ solution of known activity (3.24 µci/ml) in 130 ml pyrex bottles and returned to the depth of collection. Incubation periods varied in length from 4 to 6 hours (midday) over the study period. One exception, however, occurred at station 3 on May 18th, when incubation was terminated after two hours due to heavy ash fallout from the major eruption of Mt. St. Helens.

Upon retrieval, the bottles were immediately placed in a dark box, and within an hour subsamples of 100 ml from each bottle were filtered through 24 mm .045 m Millepore HA filters. The filters were then fumed for one minute over concentrated HCl to remove extracellular $Na_2{}^{14}CO_3$, and placed into 20 ml liquid scintillation vials for transportation to the University of Washington.

In the laboratory, ten milliliters of Bray's solution was added to each vial and stabilized for one month prior to counting on a Searle Model Delta 300 6890-system liquid scintillation counter. Counter efficiency was determined for each set of samples with a standard solution of known activity, and remained constant at 98.5 percent. Net counting efficiency (quenching) was determined by the addition of ^{14}C of known activity to selected samples (Wang and Willis 1965). The mean net counting efficiency for the study period of 76.7 percent was not judged significantly different at $p < .05$ over stations and dates.

Total available carbon was calculated with alkalinity, pH and temperature values, using the correction factor obtained from Vollenweider (1974). Alkalinity was determined within one hour of collection for each depth of incubation by the gran plot method (Edmond 1970). Temperature and pH were measured _in situ_ for each depth sampled. Solar radiation was recorded for each incubation day on a Belfort Pyranograph located at Fort Spokane and subsequently generated solar insolation values were used in estimating daily production rates.

5.3 Zooplankton

Replicate zooplankton samples were taken at stations 1 through 8 using two simultaneously towed Miller high-speed samplers equipped with No. 20 nets (73 µ openings) and calibrated, internally mounted TSK flowmeters. Oblique hauls were utilized for sample collection by towing the Miller samplers at a horizontal speed of approximately 40 m/min while lowering them from the surface to a predetermined depth and then raising them back to the surface at a vertical rate of 30 m/min. Depths of 10, 30 and 5 m off the bottom were utilized at stations 1, 2, 3, 5 and 6, while depths of 10 m, and 5 m off the bottom at stations 4 and 7 and 10 m at station 8 were utilized due to the shallowness of these stations. The zooplankton collected were washed into plastic screw-top bottles and preserved in 4 percent neutral formalin. Samples were collected monthly at stations 1 through 8 from January to September and semi-monthly at stations 1, 4 and 6 from May to September.

Zooplankton samples were subsampled in the laboratory by removal of two to five one-milliliter subsamples with a 1 ml Stempel pipet. Each subsample was counted in a Sedwich-Rafter cell under a binocular microscope at 40X magnification to the genus level, or species level where practical, using Edmondson (1959), Ruttner-Kolisko (1974), and Brandlova et al. (1972). This method represents a subsample volume from 1 percent to 20 percent of the total sample, with a minimum of 200 organisms counted for any one sample. After subsampling, the entire sample was examined and all *Leptodora kindtii* were enumerated because of their density.

5.4 Mysids

In response to the appearance of mysids in the stomachs of whitefish collected in the upper reservoir (Kemper McMaster, USFWS, personal communication 1980), sampling procedures were initiated to document the occurrence of resident mysid populations in the reservoir. Sampling was conducted by epibenthic tows with a beam trawl (Fürst 1965) fitted with a No. 6 net. Tows of 5 or 10 minutes were made in September at Marcus Flats and at stations 3, 4, 6 and 7. The collected sample was washed into a 946 ml screw-top jar, preserved with 5 percent formalin and returned to the laboratory for enumeration of mysids.

6.0 RESULTS AND DISCUSSION

6.1 Physicochemical Limnology

6.1.1 Temperature

Water temperatures recorded in Roosevelt Lake showed distinct variation in the thermal conditions of upstream and downstream areas (Figs. 4 and 5). Differences within the thermal regime were noted in average water temperatures between stations and in the intensity and timing of stratification between stations.

Initial data collected in December and January indicated steadily decreasing water temperatures over winter with some inverse stratification due to surface cooling. Minimum average water column temperatures, ranging from 1.3 to 1.9°C, were recorded in February (Table 2), with homiothermous conditions prevailing throughout the reservoir (Fig. 6). Ice formation, occurring in January and February, was noted only in the Spokane River Arm (station 4).

Mean water column temperatures increased at all stations in early spring, with initial weak stratification forming at stations 1 to 5 in mid-April, but unstratified conditions persisting at stations 6, 7 and 8 (Figs. 4 and 5). As water temperatures increased in mid-June, stratification intensified at stations 1 to 5 (Fig. 6), and the onset of weak stratification was noted at station 6 (Fig. 5). The epilimnion in mid-June at stations 1 to 5 was very shallow, with the discontinuity layer situated primarily in the upper 12 meters of the water column. The maximum temperature gradient at stations 1 to 5 occurred in mid-June and ranged from 0.7°C per meter to

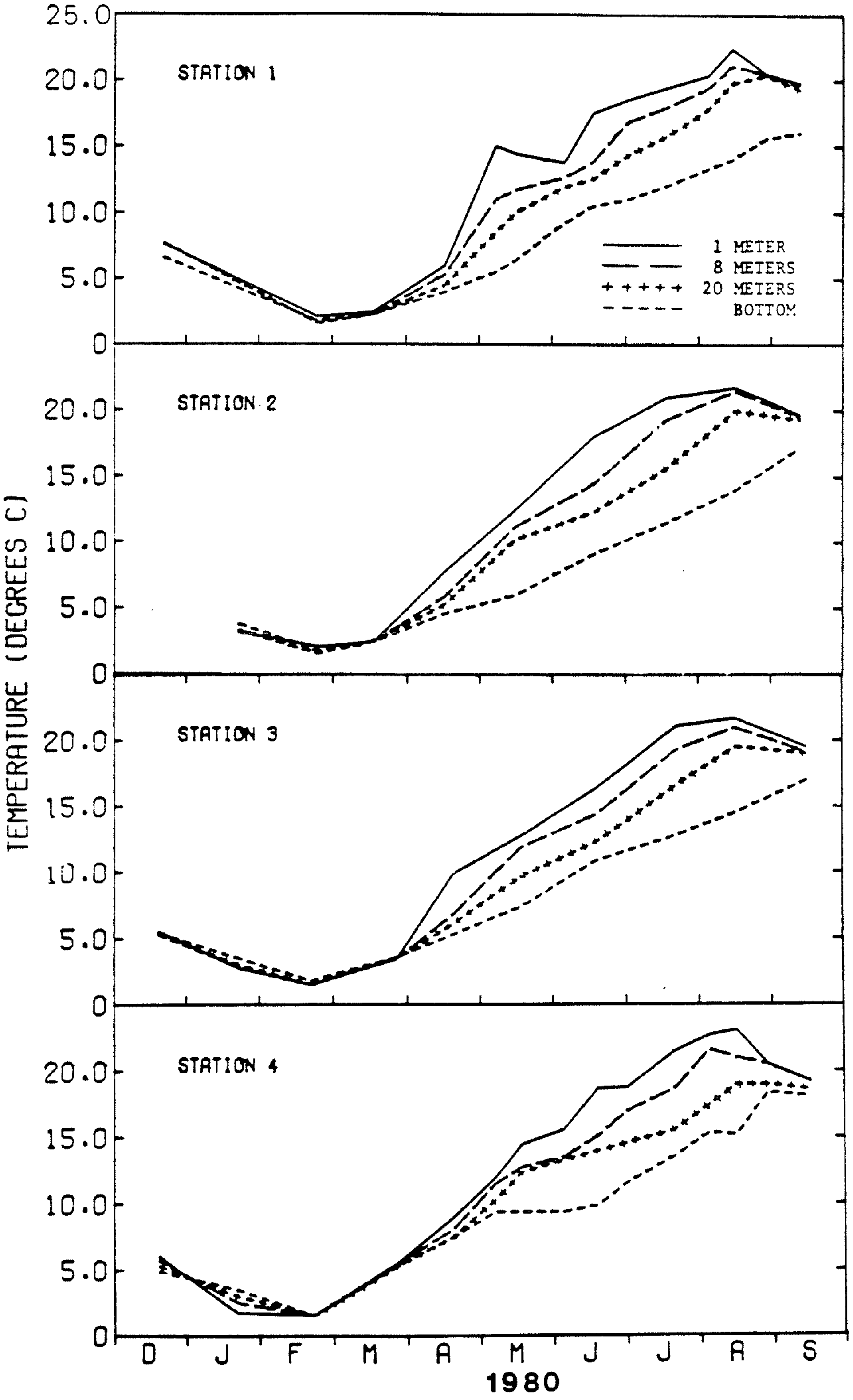

Figure 4. Water temperatures of selected strata at stations 1 to 4 in Roosevelt Lake from December 1979 to September 1980.

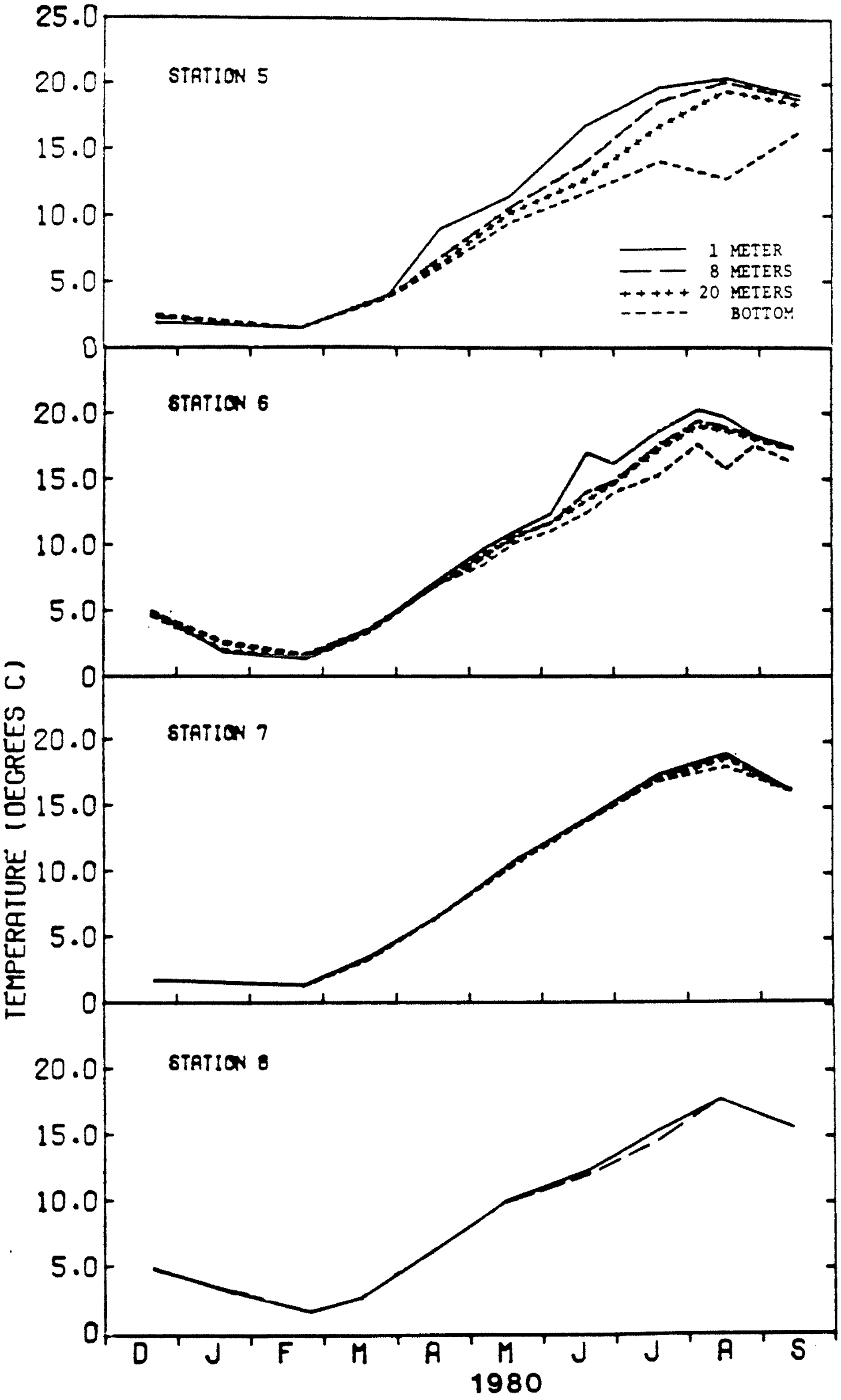

Figure 5. Water temperatures of selected strata at stations 5 to 8 in Roosevelt Lake from December 1979 to September 1980.

Table 2. **Mean surface and water column temperatures** (°C) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

Station	Depth	December	January	February	March	April	May	June	July	August	September
9	1 m	+	3.1	2.0	4.1	5.0	9.9	12.2	15.1	17.7	18.6
1	*0-4 m	7.6	+	1.9	2.4	5.9	14.3	16.8	19.2	22.0	19.7
	**0-bottom	7.2	+	1.7	2.3	3.4	9.0	11.9	14.7	17.5	18.3
2	0-4 m	+	3.2	1.3	2.5	6.9	12.3	17.5	20.5	21.8	19.7
	0-bottom	+	3.5	1.3	2.5	5.3	8.7	12.8	14.6	17.5	18.4
3	0-4 m	5.5	2.7	1.5	3.5	8.6	12.8	17.0	20.9	21.7	19.3
	0-bottom	5.3	2.9	1.6	3.6	6.3	9.7	12.3	15.7	18.1	18.0
4	0-4 m	5.9	1.7	1.5	5.6	9.2	15.0	17.8	21.4	22.7	19.1
	0-bottom	5.5	2.8	1.5	5.5	8.4	12.5	13.7	17.1	19.3	18.7
5	0-4 m	+	2.0	1.5	3.8	8.3	11.4	16.2	19.6	20.5	19.1
	0-bottom	+	2.4	1.5	3.8	6.4	10.2	13.1	16.4	17.6	17.5
6	0-4 m	4.8	1.8	1.3	3.5	7.4	11.0	16.2	18.1	19.4	17.3
	0-bottom	4.7	2.2	1.3	3.4	6.3	10.3	13.4	16.6	18.1	16.7
7	0-4 m	+	1.7	1.3	3.3	6.5	11.0	14.1	17.4	18.9	16.1
	0-bottom	+	1.7	1.3	3.3	6.5	10.8	13.8	17.0	18.4	16.0
8	0-4 m	5.0	1.4	1.9	3.0	6.5	10.2	14.3	16.6	18.1	15.9
	0-bottom	5.0	1.4	1.9	3.0	6.5	10.2	14.0	16.4	18.0	15.9

*0-4m: Surface to 4-meter mean.

**0-bottom: Water column mean.

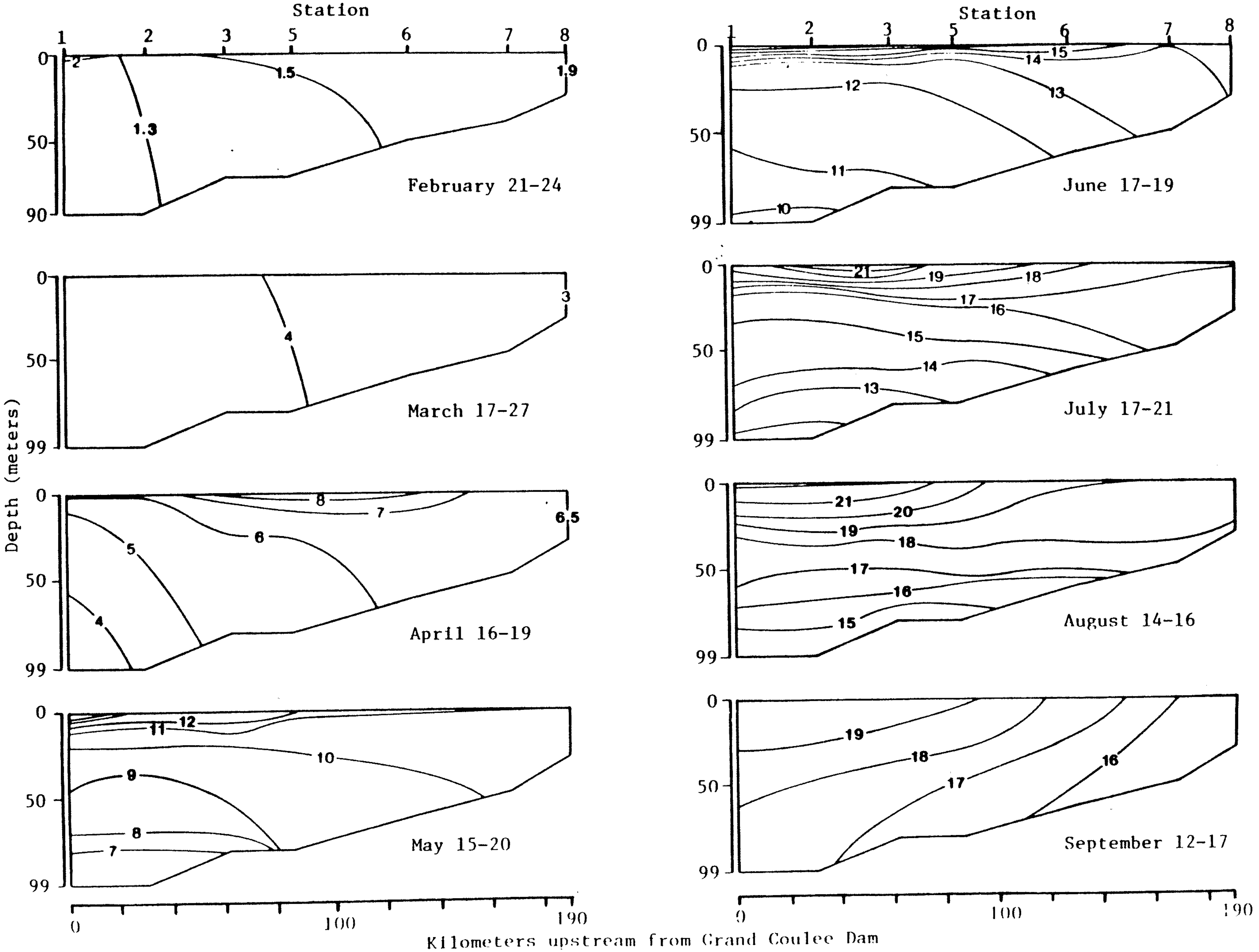

Figure 6. Isotherms (°C) in the main body of Roosevelt Lake from February 1980 to September 1980.

2.0°C per meter.

Average water column and surface temperatures continued to increase throughout the reservoir during summer, with peak surface temperatures occurring in mid-August (Table 2). Summer surface temperatures were noted to average 2.1°C higher at the downstream stations 1, 2, 3 and 5 than at the upstream stations 6, 7 and 8, while the maximum recorded temperature of 23.1°C was noted at station 4 in mid-August. Peak water column temperatures were observed at stations 3 to 8 in mid-August and subsequently decreased in September, while temperatures at stations 1 and 2 continued to increase into September.

Thermal stratification over the summer was marked by a gradual depression, decrease in thermal gradient, and decay of the discontinuity layer (Fig. 6). The degree of stratification in the main reservoir during the summer generally decreased from station 1 to 8, indicating that turbulence due to the inflowing Columbia River increased toward the upper end of the reservoir.

Temperatures encountered during this study were within the range of previously reported data (Earnst et al. 1963; Jaske and Snyder 1967; Jaske 1969; Bishop and Lee 1972; Stober et al. 1977a, 1977b). Average surface and water column temperatures during spring and summer were generally highest at station 4, concurring with previous studies showing warmer temperatures in the Spokane River Arm than in the receiving waters of Roosevelt Lake (Earnst et al. 1963, Bishop and Lee 1972). Temperatures at station 9 were higher than the average water column temperature at station 1. This phenomenon is related to the density flow patterns in Roosevelt Lake and is discussed in detail by Jaske and Snyder (1967) and Jaske (1969).

Previous studies on the thermal regime in the forebay (Stober et al. 1977a) and in the main body of the reservoir (Jaske and Snyder 1967, Jaske 1969) indicated a pattern similar to the present study. Jaske (1969) characterized the typical annual thermal cycle as follows: 1) January to June — generally mixed and turbulent in late spring due to high flow, with little or no stratification; 2) July to September — poorly mixed, with the stratification at the discharge end, at times extending up to Kettle Falls; 3) October to December — cooling and unmixed with oblique orientation of the isotherms. The thermal pattern during this study was similar to Jaske's, but characteristic changes occurred earlier in 1980.

The thermal regime of Roosevelt Lake appears to be controlled by several important variables. Primary heating and cooling of the water column is accomplished from inflow and displacement by upstream river water. This is indicated by the recurring pattern of average water column temperature changes occurring initially at the upper end of the reservoir and later, at a period roughly equal to the residence time, at the downstream stations. Primary heating of the surface waters and the degree of stratification is dependent upon solar insolation and turbulence induced by the downstream flow of the water mass. The heated surface waters are constantly mixed into the water column by turbulence at the upper areas of the reservoir, and little stratification develops. As turbulence declines downstream, mixing also decreases and surface heated water remains at the surface resulting in greater reservoir stratification downstream.

6.1.2 Transparency

Secchi depth transparency in Roosevelt Lake exhibited distinct seasonal and spatial variation during the study period (Fig. 7). Stations 1 to 5 showed similar temporal patterns, with initially high winter transparency of 2.8 to 5.2 m steadily decreasing in spring to minimum values ranging from 0.4 to 1.2 m. The low of 0.4 m at station 4 on June 4 was turbidity resulting from the runoff of volcanic ash in the Spokane River following the eruption of Mt. St. Helens. Secchi depths increased in summer, and attained maximum values higher than winter levels, with a maximum of 7.5 m at station 1 on August 28.

Transparency at stations 6, 7 and 8 showed a similar winter-to-spring trend, with high February Secchi depths of 4.5 to 5.2 m steadily decreasing into spring to minimum values of 0.8 to 2.0 m. Secchi readings subsequently increased to summer, but transparency was lower than during winter.

The transparency of Roosevelt Lake was previously reported as characterisically poor during all months except early fall (Earnst et al. 1963, Bishop and Lee 1972, Stober et al. 1977a). Maximum Secchi depths of 10 m in the forebay (Stober et al. 1977a) and 10.6 m at Keller (Earnst et al. 1963) have been noted in October. Transparency in the reservoir has been correlated to silt turbidity (Robeck et al. 1953, Earnst et al. 1963) and to phytoplankton densities (Robeck et al. 1953). Suspended sediment in the water results, in part, from the inflow of turbid water in the Columbia River (Robeck et al. 1953) and from reservoir bank slumping and erosion (USBR 1976).

Water transparency in Roosevelt Lake during the present study was

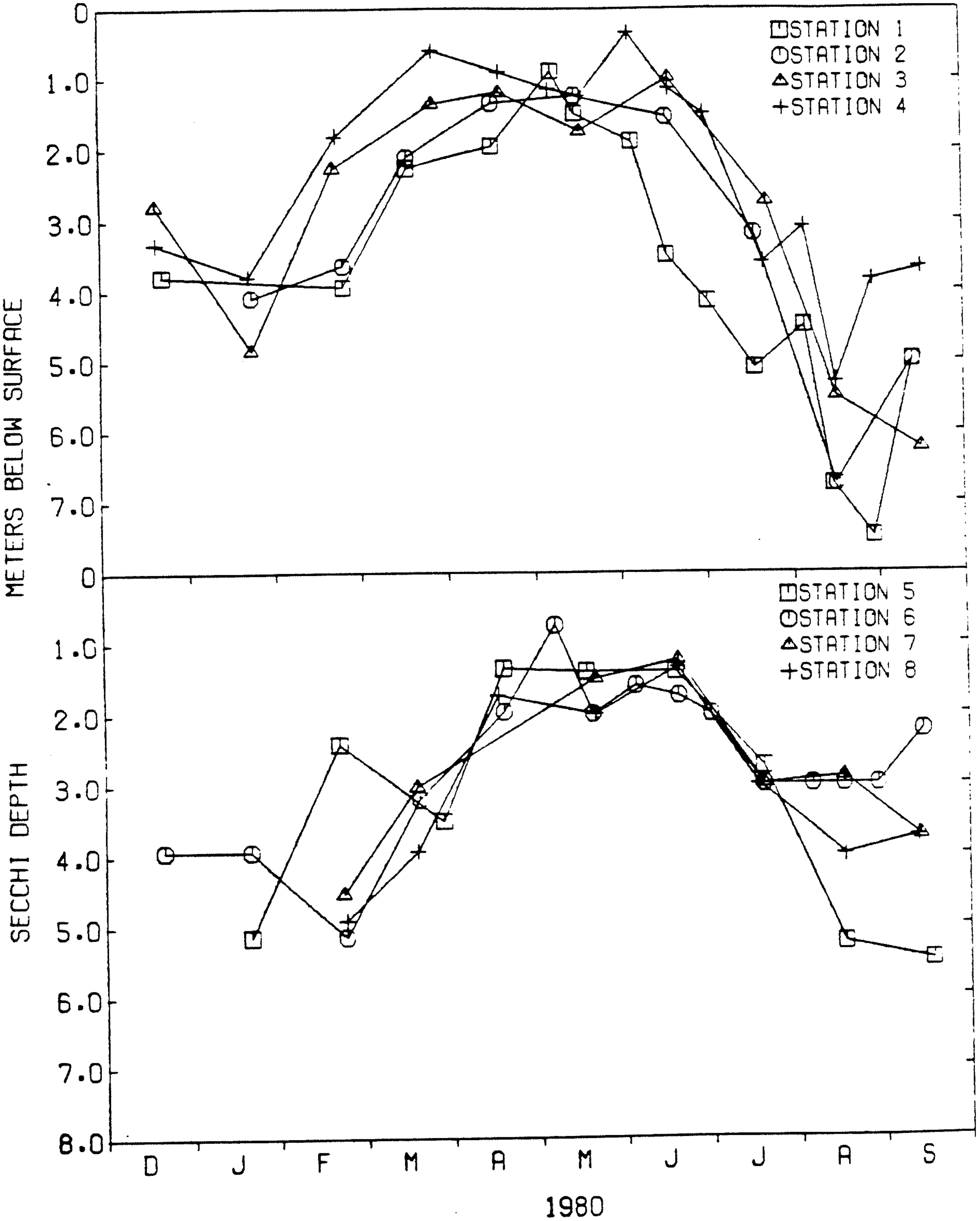

Figure 7. Secchi depth transparency by date and station in Roosevelt Lake.

related to phytoplankton abundance and turbidity from suspended sediments. Low Secchi depths from late winter to early spring were primarily the result of increased turbidity from runoff. Low water transparency was coincident with periods of high phytoplankton standing crops in late spring. Summer increases in Secchi depths generally coincided with decreasing runoff and declining phytoplankton standing crops. Deposition of suspended material due to decreasing turbulence was indicated from upstream to downstream stations during summer by an increase in Secchi depth transparency.

6.1.3 pH

Average pH values ranged from 6.7 to 8.5 during the study period (Table 3). Highest values occurred in the surface waters from May to August, while lowest values generally occurred in the bottom 4 m during August. A general decrease in pH from surface to bottom was noted over most dates, with the contrast most pronounced at stations 1 to 6 during summer. Surface to bottom pH values at stations 7 and 8 were always within 0.3 pH units of each other due to vertical mixing. pH values recorded during this study were within the range of values previously reported by Bishop and Lee (1972) and USGS (1978, 1979), but were below values reported in the forebay by Stober et al. (1977a).

6.1.4 Dissolved Oxygen

Dissolved oxygen saturation values were high throughout the study period, ranging from 46 percent to 160 percent (Table 4). Reservoir mean surface saturation levels varied from 88 percent to 131 percent, with peak values recorded from April to July, coinciding with the peak phytoplankton growing

Table 3. Average pH in Roosevelt Lake and the tailrace from December 1979 through September 1980.

Station	Depth	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
9	1 m	+	7.6	7.5	7.6	7.9	7.4	7.8	7.5	7.1	7.3
1	*0-6	7.5	+	7.5	8.0	7.6	8.5	8.0	8.0	7.9	7.7
	** B4	7.4	+	7.2	8.0	7.5	7.6	7.5	7.6	7.1	6.9
	*** WC	7.4	+	7.3	8.0	7.6	7.9	7.6	7.8	7.4	7.2
2	0-6	+	8.0	7.6	7.7	7.6	8.5	8.2	8.2	8.1	7.9
	B	+	7.6	7.2	8.0	7.5	7.8	7.4	7.4	7.1	7.0
	WC	+	7.8	7.3	7.9	7.6	7.9	7.5	7.7	7.5	7.3
3	0-6	7.7	7.8	7.7	7.5	8.1	8.5	8.3	8.4	7.8	8.0
	B	7.4	7.5	7.3	7.4	7.7	7.7	7.5	7.4	7.0	7.2
	WC	7.6	7.6	7.5	7.4	7.9	7.9	7.8	7.7	7.2	7.5
4	0-6	7.5	7.5	7.7	7.9	7.9	8.2	8.1	8.4	8.5	8.2
	B	7.4	7.3	7.4	7.7	7.7	7.2	7.0	7.1	6.7	7.5
	WC	7.5	7.4	7.6	7.8	7.8	7.4	7.5	7.4	7.3	7.8
5	0-6	+	7.7	7.7	7.9	7.8	8.1	8.1	8.2	8.0	8.3
	B	+	7.7	7.4	7.7	7.5	7.6	7.5	7.5	7.0	7.4
	WC	+	7.5	7.5	7.8	7.7	7.8	7.8	7.8	7.4	7.6
6	0-6	7.5	7.5	7.7	7.9	8.0	8.0	8.0	8.1	8.0	7.9
	B	7.4	7.4	7.5	7.7	7.8	7.8	7.6	7.5	7.0	7.4
	WC	7.5	7.4	7.6	7.8	8.0	7.8	7.8	7.8	7.3	7.6
7	0-6	+	7.4	7.5	7.7	7.7	8.1	8.1	7.8	7.6	8.0
	B	+	+	7.3	7.5	7.6	7.9	7.9	7.6	7.3	7.8
	WC	+	+	7.4	7.6	7.7	8.0	7.9	7.6	7.6	7.9
8	WC	7.6	7.4	7.7	7.9	7.8	8.0	7.8	7.6	7.6	8.0

* 0-6: Mean of surface to 6 meters.

** B4: Mean of bottom 4 meters.

*** WC: Mean of water column.

Table 4. Percent dissolved oxygen saturation at selected depth strata in Roosevelt Lake and the tailrace from December 1979 to September 1980.

Station	Depth	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
9	1 m	+	108	109	95	109	104	104	98	160	96
1	* 0-6	94	+	98	106	107	131	105	107	91	99
	** B4	90	+	94	101	102	106	94	93	78	75
	*** WC	92	+	96	103	103	98	97	100	93	87
2	0-6	+	103	103	103	114	127	109	107	109	98
	B4	+	99	93	102	104	93	82	85	77	83
	WC	+	101	96	103	106	101	98	98	96	90
3	0-6	97	103	104	104	124	118	119	125	100	104
	B4	98	99	94	101	99	90	95	108	76	97
	WC	98	100	99	102	106	99	95	119	94	99
4	0-6	88	96	89	107	109	116	117	121	106	102
	B4	87	94	85	102	97	84	61	73	65	73
	WC	87	94	80	105	104	101	94	87	93	87
5	0-6	+	101	101	109	126	117	117	125	112	107
	B4	+	99	98	105	100	109	102	130	49	91
	WC	+	100	99	107	105	105	107	119	95	91
6	0-6	101	101	107	110	114	107	121	126	119	107
	B4	98	101	106	104	101	105	103	108	61	99
	WC	99	100	108	106	104	107	108	115	97	101
7	0-6	+	111	100	104	106	109	121	114	115	107
	B4	+	+	100	103	106	112	112	114	110	101
	WC	+	+	100	103	106	112	112	118	113	103
8	WC	107	107	107	110	107	112	117	123	113	104
	Low	86	93	78	95	95	81	59	70	46	70
	High	107	108	109	113	132	134	125	135	160	114

*0-6: Mean of surface to 6 meters

**B4: Mean of bottom 4 meters

***WC: Mean of the water column

season. Bottom saturation levels ranged from 49 percent to 130 percent, with minimum saturation generally in August. Station 4 showed reduced hypolimnetic dissolved oxygen levels throughout summer, with bottom values averaging 68 percent from June to September. In contrast, saturation levels at stations 7 and 8 were never below 100 percent during the study due to high turbulence. The effects of surface spilling on dissolved oxygen saturation were noted at station 9 when values reached 160 percent in August.

Saturation curves during April and August sampling periods illustrate the extremes that occurred during the study period (Figs. 8 and 9). Temperature and dissolved oxygen curves in April were essentially orthograde, with minimum saturation values above 95 percent at all stations. Surface saturation maxima were observed at stations 2 to 6 and apparently resulted from phytoplankton production. Thermal stratification had developed at stations 1 to 6 in August, with resulting clinograde oxygen curves, while turbulence and the associated lack of thermal stratification resulted in orthograde oxygen curves at stations 7 and 8. Minimum saturation was noted at the bottom of stations 4 and 5 with values of 50 percent and 46 percent, respectively.

Bishop and Lee (1972) previously reported reduced dissolved oxygen levels in Porcupine Bay coinciding with summer stratification, but noted orthograde oxygen curves in the main body of Roosevelt Lake in the summer. Stober et al. (1977a) observed generally saturated oxygen levels in the forebay of Roosevelt Lake, with values rarely declining below 100 percent. Although oxygen values observed during this study were below previously noted levels, the fact that saturation was principally above 50 percent and the general occurrence of oxidation-reduction potentials above 300 mV

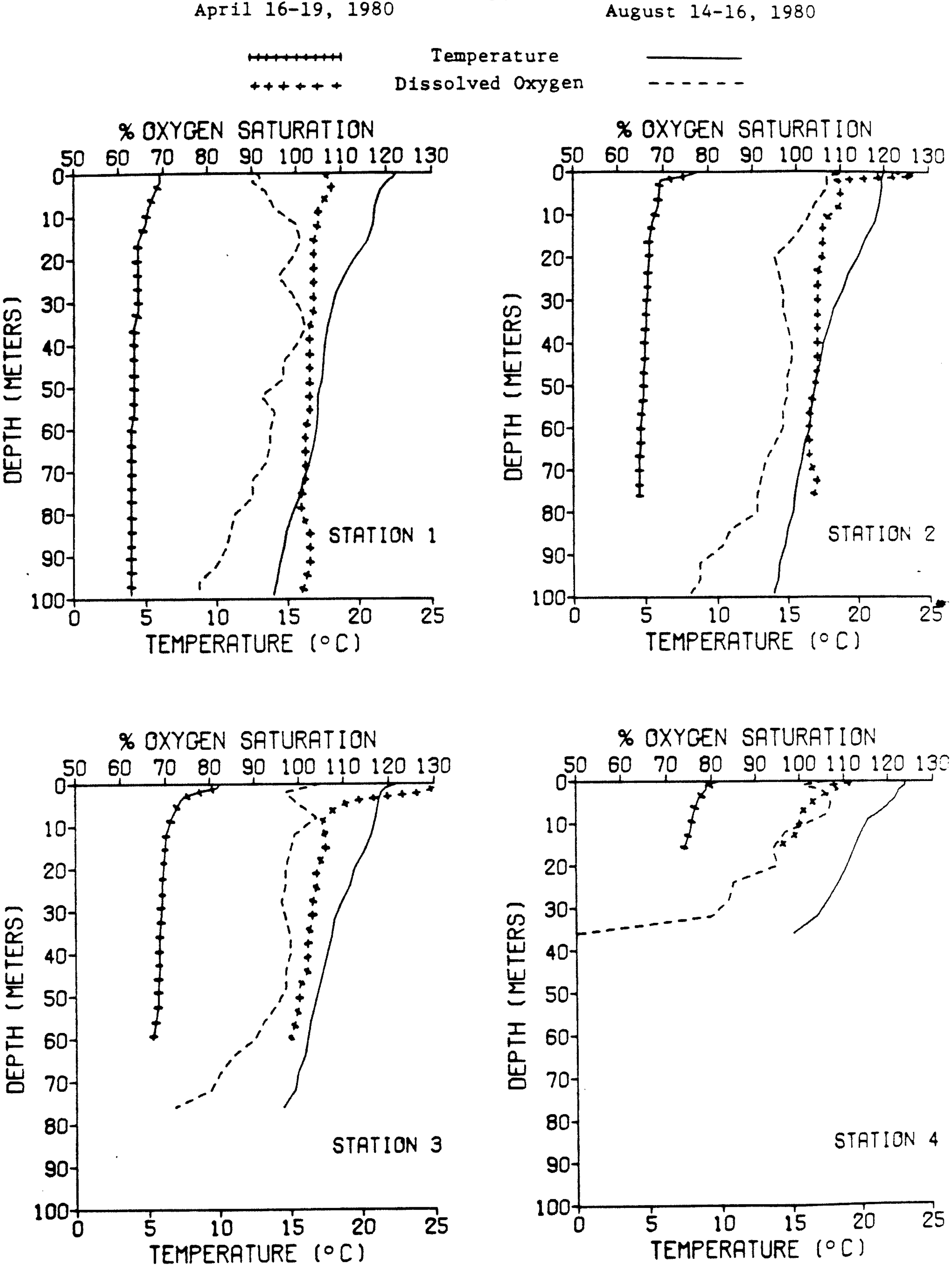

Figure 8. Temperature and dissolved oxygen saturation curves for stations 1 to 4 in Roosevelt Lake during sampling periods April 16-19, 1980 and August 14-16, 1980.

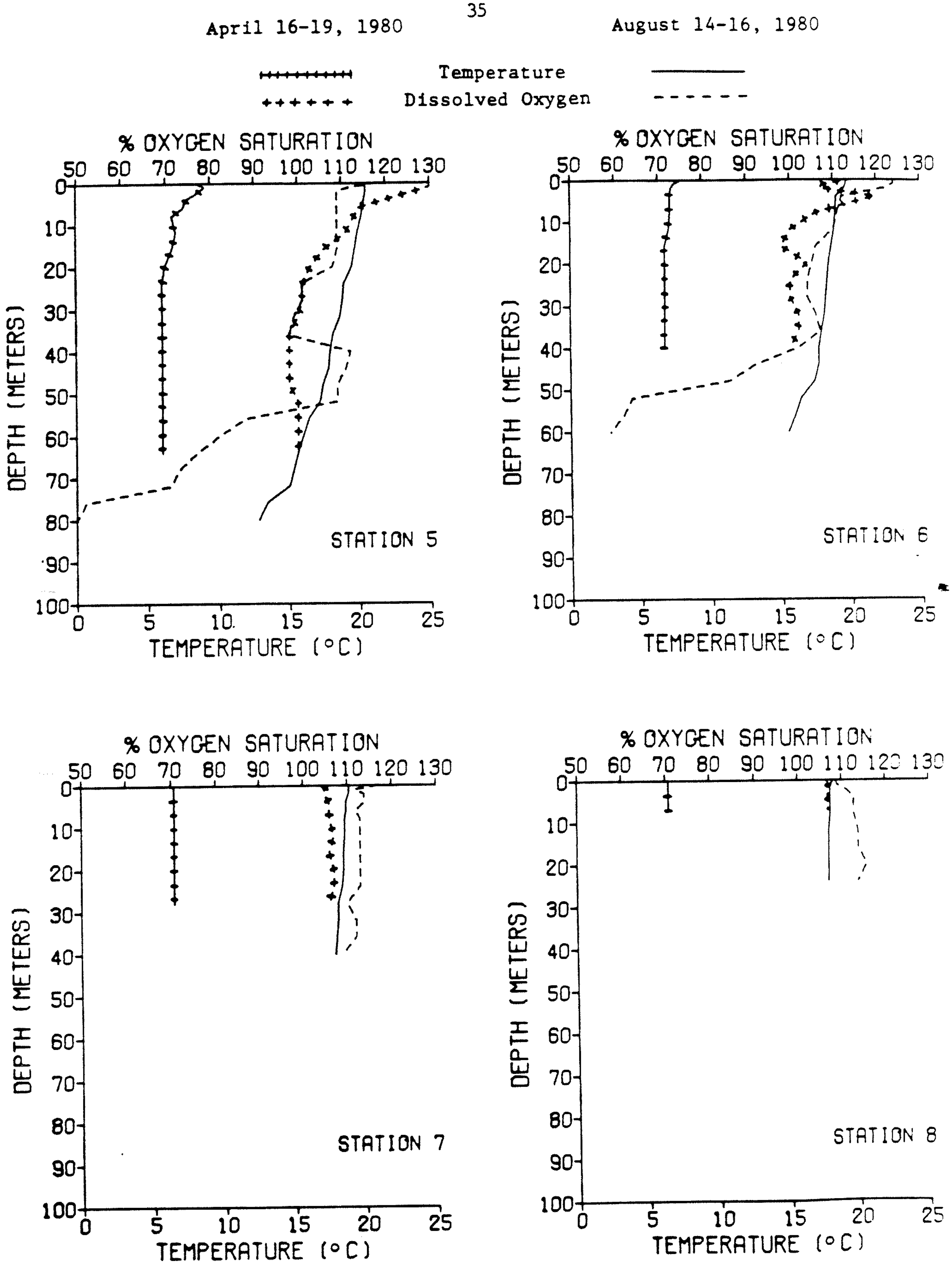

Figure 9. Temperature and dissolved oxygen saturation curves for stations 5 to 8 in Roosevelt Lake during sampling periods April 16-19, 1980 and August 14-16, 1980.

(Appendix I) indicates the prevalence of oxidative conditions throughout Roosevelt Lake. This lack of reduction near the bottom during summer stratification is characteristic of oligotrophic conditions (Welch 1952).

6.1.5 Conductivity, Alkalinity, Hardness

Conductivity, alkalinity, and calcium-magnesium hardness levels in Roosevelt Lake showed distinct temporal contrasts between the main reservoir stations 1, 2, 3, 5, 6, 7 and 8, and station 4 in the Spokane River Arm (Fig. 10). Conductivity at the main reservoir stations was highest from December to April, with a mean reservoir value of 116 µmhos/cm during this period and a peak value of 129 µmhos/cm occurred in January. A decline in average conductivity to 100 µmhos/cm occurred in May and June, subsequently increased to 113 µmhos/cm in July, and then decreased to a mean conductivity level of 98 µmhos/cm in September.

Alkalinity and hardness showed a seasonal pattern similar to conductivity, but the contrast between winter to early spring concentrations and late spring to summer concentrations was more distinct. Average alkalinity and hardness concentrations from December to April were 64 mg/l and 75 mg/l, with a range of 61 to 69 mg/l and 71 to 80 mg/l, respectively. In contrast, May to September alkalinity and hardness levels were 52 mg/l and 58 mg/l, with a range of 42 to 61 mg/l and 51 to 71 mg/l, respectively.

The concurrent decrease in conductivity, alkalinity, and hardness from April to May coincided with maximum inflow of water from the Columbia River. This pattern of high levels of conductivity, alkalinity, and hardness during winter preceding runoff, and reduced levels during late spring and summer were reported in the forebay of Roosevelt Lake (Stober et al. 1977a) and at

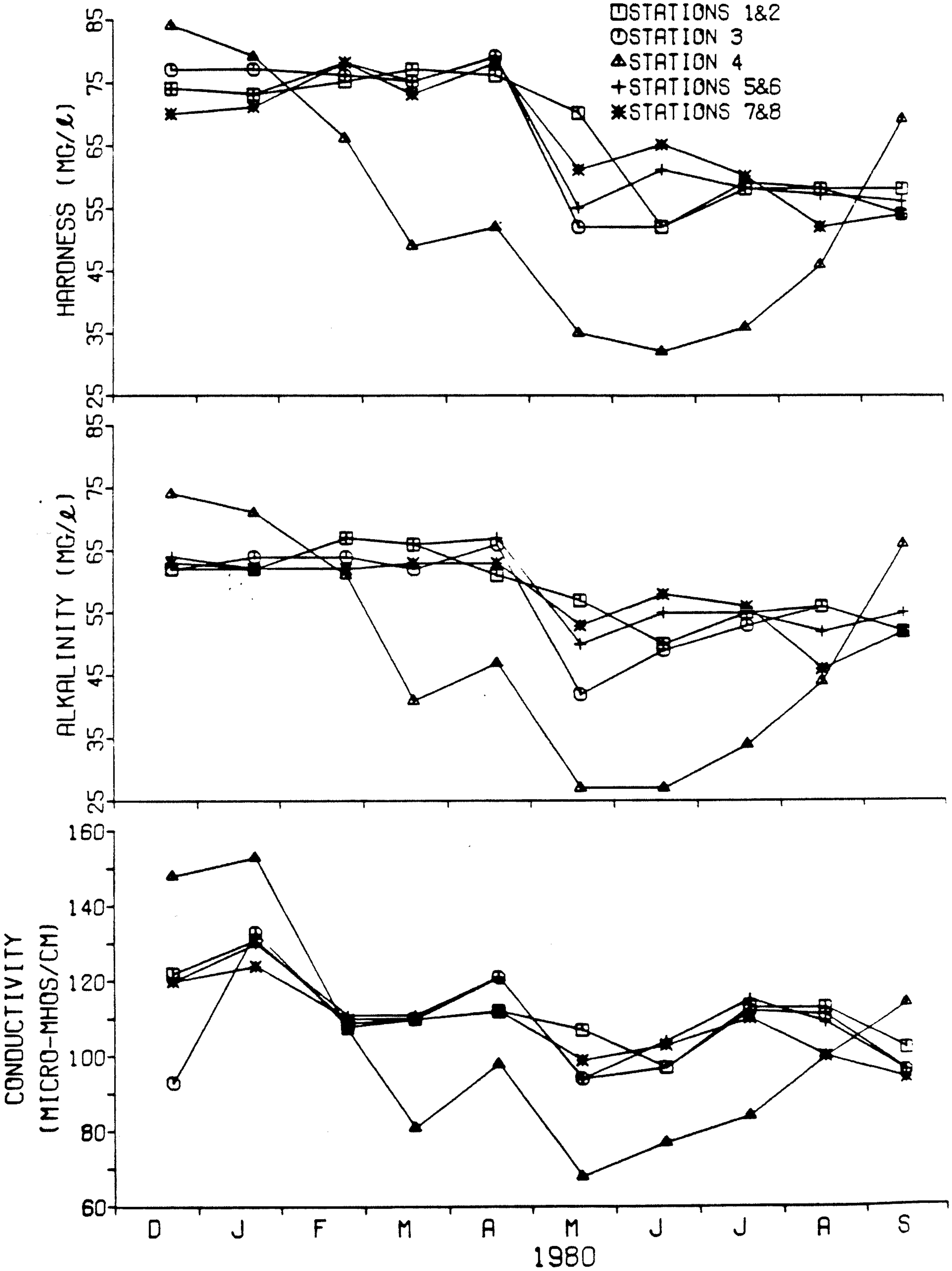

Figure 10. Mean surface to bottom conductivity, alkalinity and calcium-magnesium hardness in Roosevelt Lake from December 1979 to September 1980.

Northport (USGS 1978, 1979). Similarly, a reduction in conductivity during peak runoff months was observed in Roosevelt Lake near the mouth of the Spokane River (Bishop and Lee 1972).

Conductivity, alkalinity, and hardness levels at station 4 in December and January, averaging 151 µmhos/cm, 73 mg/l, and 82 mg/l, respectively, were initially higher than main reservoir levels. Concentrations at station 4 subsequently declined rapidly in early winter and spring to levels below those in the main reservoir, and remained low until September. Minimum conductivity, alkalinity, and hardness levels at station 4 of 68 µmhos/cm, 27 mg/l, and 32 mg/l, respectively, were recorded in late spring. Reduced conductivity, alkalinity, and hardness levels in spring and summer during periods of high runoff have been reported in the Spokane River below Long Lake (USGS 1978, 1979). Conductivity measurements in Porcupine Bay have also shown a similar pattern (Bishop and Lee 1972).

Mean surface and bottom values for conductivity (Table 5), alkalinity (Table 6), and hardness (Table 7) indicated no significantly consistent trend between surface and bottom levels over the study period. Some differences were noted at station 4 between surface and bottom levels during the summer, but neither the surface nor the bottom was uniformly higher. Additionally, major differences between surface and bottom levels were found at stations 2 and 3 in May, with surface levels approximating upstream conditions and bottom values similar to downstream values. This condition indicates the overflow of a dissimilar water mass arising upstream.

Conductivity, alkalinity, and hardness levels observed during this study were within the range of previously reported values for Roosevelt Lake

Table 5. **Mean surface and bottom conductivity (μmhos/cm at 25°C) in Roosevelt Lake and the tailrace from December 1979 to September 1980.**

	Station – Depth														
	9	1		2		3		4		5		6		7		8
Month	S	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S
December	+	120	127	+	+	91	95	147	150	+	+	119	120	+	+	120
January	139	+	+	129	132	131	135	150	158	131	135	125	132	125	+	124
February	110	109	110	110	110	110	108	109	107	116	110	110	110	115	110	109
March	124	110	110	110	110	110	110	81	80	110	115	110	110	110	110	110
April	110	110	113	113	113	118	122	99	96	121	122	118	120	110	110	115
May	115	115	119	92	120	84	110	67	76	91	90	101	97	97	96	102
June	96	92	96	97	110	90	110	71	89	101	108	101	105	102	107	102
July	115	110	111	110	112	110	111	82	78	112	117	113	119	110	110	111
August	110	110	112	112	111	110	114	99	87	108	121	101	117	110	101	101
September	100	110	106	104	98	97	97	99	138	90	95	98	105	94	97	94
Mean*	110	108	110	106	109	104	109	88	94	106	110	107	110	105	105	106

* Mean – February to September.

Table 6. Surface and bottom alkalinity (mg $CaCO_3/\ell$) in Roosevelt Lake and the tailrace from December 10, 1979 to September 10, 1980.

	Station — Depth															
	9	1		2		3		4		5		6		7		8
Month	S	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S
December	+	65	60	+	+	65	60	73	75	+	+	63	65	+	+	63
January	65	+	+	64	60	66	62	73	70	64	62	60	62	62	+	63
February	65	65	68	67	68	63	65	58	64	71	68	66	64	63	60	62
March	62	65	63	64	74	63	62	41	42	63	73	66	64	66	61	63
April	63	62	63	60	61	65	67	47	47	69	69	65	65	62	61	65
May	79	61	62	42	62	35	50	26	28	47	45	53	54	50	51	58
June	48	48	51	46	55	46	52	29	25	53	58	56	55	57	60	58
July	60	52	52	54	60	56	50	37	32	55	56	57	54	56	56	55
August	55	53	59	57	57	58	54	50	38	49	54	49	56	46	46	45
September	54	53	51	54	51	52	53	60	72	54	60	53	52	51	51	54
Mean	61	58	59	56	61	57	58	50	50	58	61	59	59	57	56	59

Table 7. Surface and bottom calcium-magnesium hardness (mg $CaCO_3/\ell$) in Roosevelt Lake and the tailrace from December 19, 1979 to September 17, 1980.

	Station — Depth															
	9	1		2		3		4		5		6		7		8
Month	S	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S
December	+	73	75	+	+	80	75	83	85	+	+	75	75	+	+	70
January	73	+	+	72	73	75	80	78	80	77	72	73	70	73	+	70
February	80	76	70	78	76	75	77	67	65	78	80	78	77	78	76	80
March	75	76	77	79	78	78	72	48	50	76	71	77	77	78	70	72
April	76	75	76	72	79	78	80	55	50	79	82	77	79	79	77	79
May	66	69	72	59	80	45	60	35	35	58	54	54	55	58	59	65
June	50	50	52	53	54	55	50	33	31	61	60	61	61	64	66	67
July	65	55	61	54	60	60	59	40	32	59	58	57	59	60	58	62
August	60	57	60	60	55	55	62	53	40	53	61	51	63	50	56	50
September	59	60	61	59	53	55	53	58	81	58	58	55	55	52	55	55
Mean	67	66	67	65	68	66	67	55	55	67	66	66	67	66	65	67

(Bishop and Lee 1972; Stober et al. 1977a; USGS 1978, 1979). The hardness levels reported classify Roosevelt Lake water as soft to moderately hard (Hem 1970).

6.1.6 Ammonia

Ammonia concentrations in Roosevelt Lake were low throughout the study period (Fig. 11), with average water column concentrations ranging from 5.4 to 90.0 μg/l, but remaining generally below 40 μg/l. A maximum level of 92.5 μg/l occurred at station 7 in March. A similar but lesser peak was noted at station 8 in April and later at station 3 in May, indicating a moving body of water high in ammonia. Bottom concentrations were variable, while a general decrease in surface ammonia levels was noted from April to September with levels consistently below 20 μg/l during this period. Ammonia levels were within the range of values reported for Northport (USGS 1978, 1979).

Ammonia in water is primarily in the NH_4^+ and undissociated NH_3 forms, with the latter form highly toxic to aquatic organisms. Calculations of the concentration of undissociated ammonia in Roosevelt Lake according to Trussell (1972) indicated a maximum level of 0.0006 mg/l, significantly below the suggested water quality criteria of 0.02 mg/l (as un-ionized ammonia) (USEPA 1976).

6.1.7 Total Phosphorus

Total phosphorus concentrations in Roosevelt Lake ranged from 2 to 85 μg/l during the study period (Fig. 12). Levels at the main reservoir stations 1, 2, 3, 5, 6, 7 and 8 were observed to decrease from spring to summer, with a February to May average water column concentration of 51 μg/l

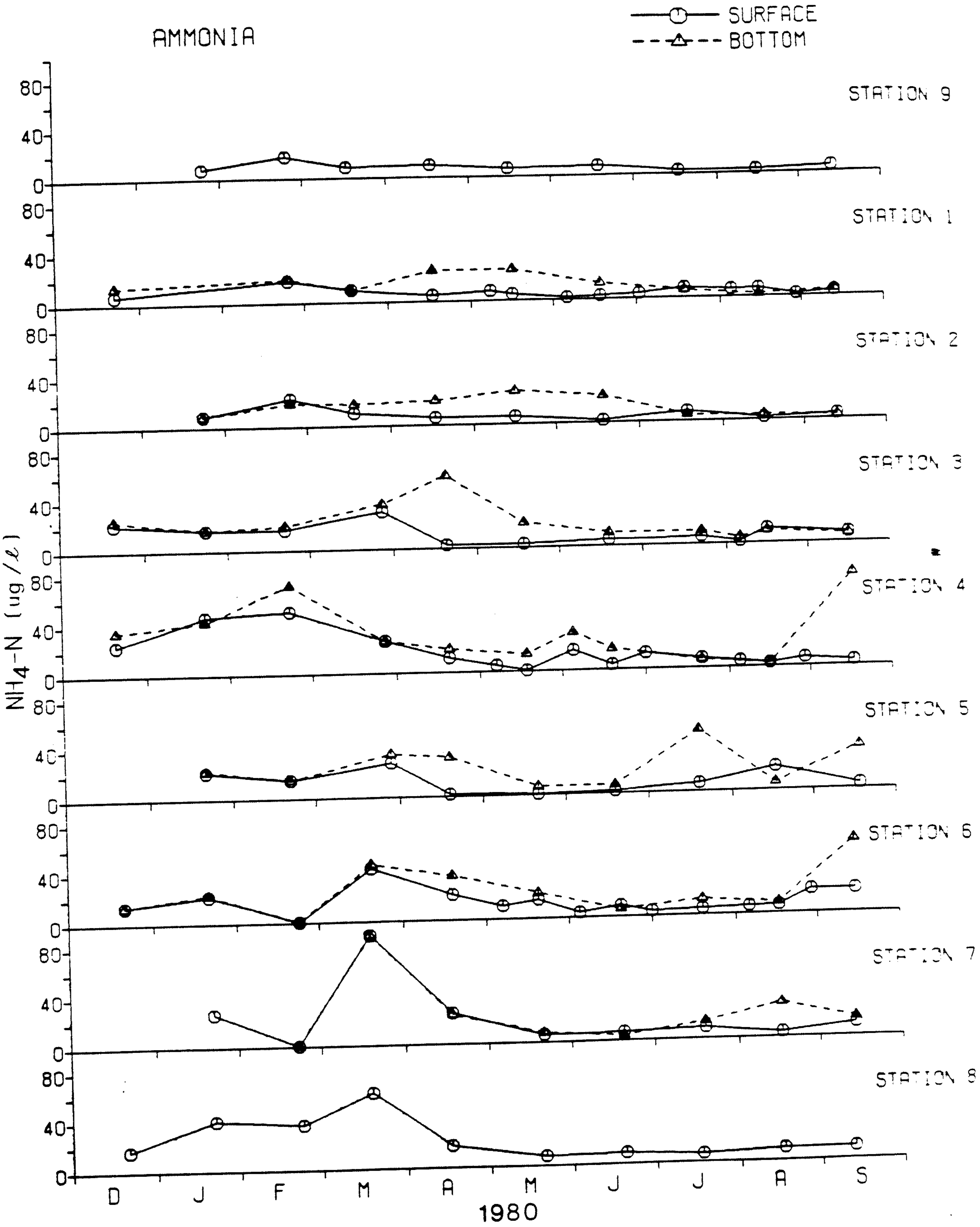

Figure 11. Surface and bottom ammonia concentrations (µg/ℓ) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

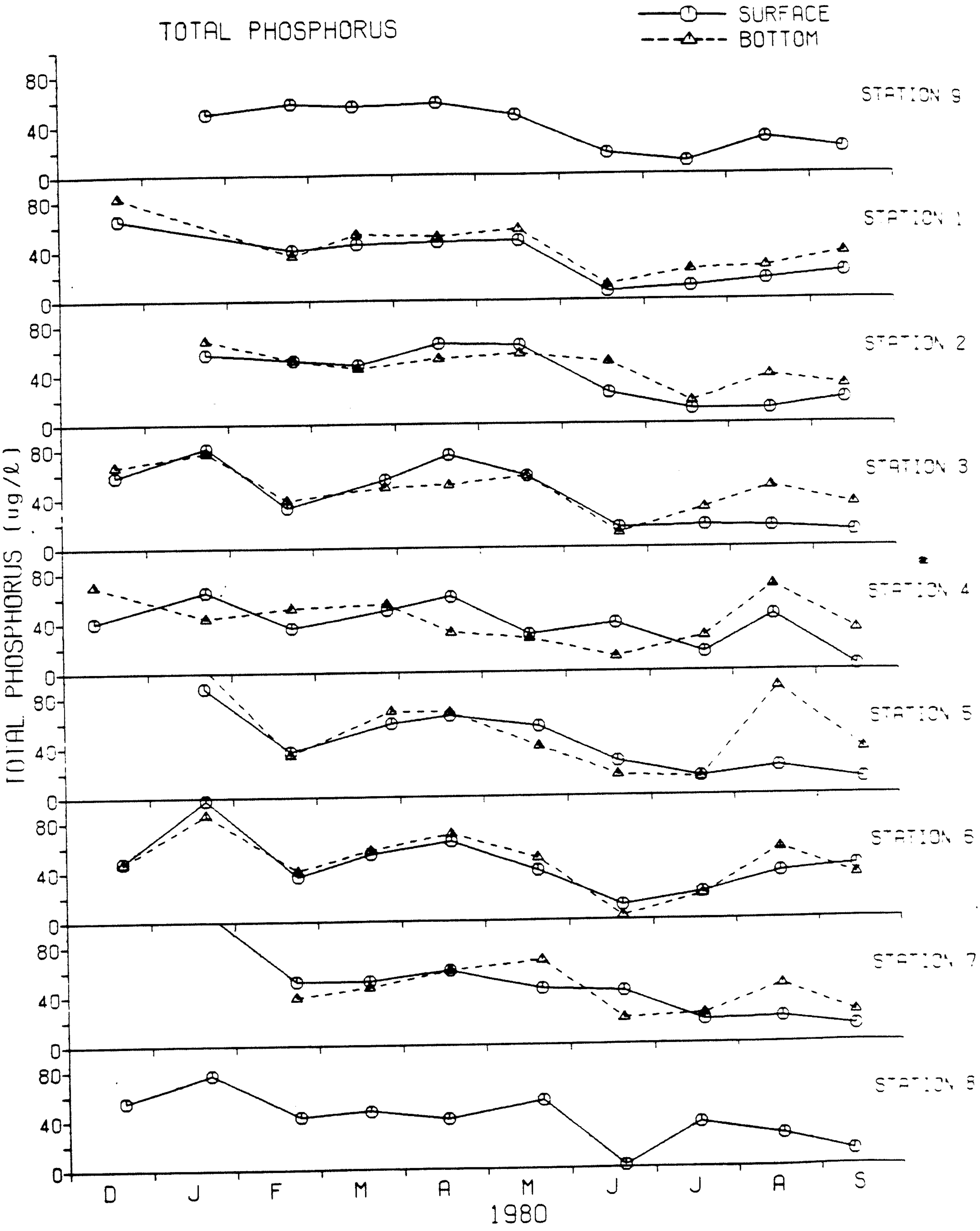

Figure 12. Surface and bottom total phosphorus concentrations (µg/ℓ) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

and a June to September average of 24 µg/l. Station 4 total phosphorus concentrations were temporally variable, but the study period average water column concentration of 33 µg/l was similar to the average main reservoir concentration of 35 µg/l. Total phosphorus levels determined were similar to previously reported values (Bishop and Lee 1972; Stober et al. 1977a; USGS 1978, 1979).

6.1.8 Silica

Mean reactive silica concentrations in the surface and bottom waters were generally above 1.5 mg/l throughout the study period (Fig. 13), with determinations ranging from 0.57 to 4.91 mg/l. The average water column concentration at the main reservoir stations from January to September was 2.24 mg/l, but at station 4 the average silica concentration was higher at 3.75 mg/l. Silica levels were similar to previously reported values for the forebay (Stober et al. 1977a) but below levels reported for Northport (USGS 1978, 1979).

Reduced silica concentrations in the surface waters were noted at several stations. Stations 1 and 2 showed surface depletion throughout most of spring and summer. Stations 3, 5 and 6 exhibited slightly decreased surface levels in spring and distinct surface depletion in summer. Silica depletion was variable at station 4, and imperceptible at station 7.

Silica depletion in the euphotic zone is well documented (Wetzel 1975). Diatoms are an important component of the Roosevelt Lake phytoplankton community and presumably were responsible for silica reductions in the surface waters. Thermal stratification was also important to silica depletion by preventing interchange between water layers and hence replenishment of silica

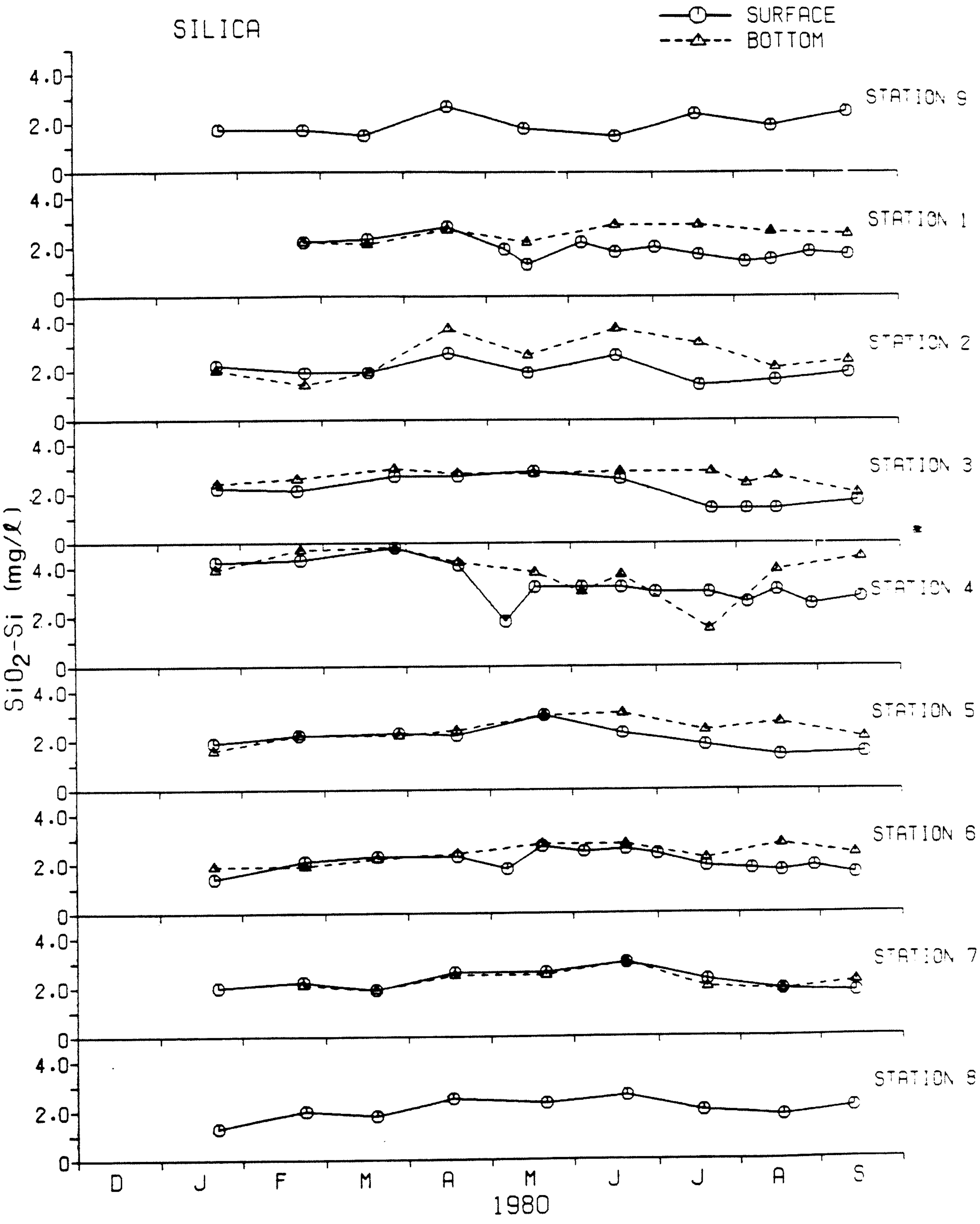

Figure 13. Surface and bottom silica concentrations (mg/ℓ) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

from the richer waters below the euphotic zone. Euphotic zone silica levels in Roosevelt Lake, being generally over 1 mg/l, were above the minimum silica level of 0.5 mg/l to 0.8 mg/l required by some diatoms (Wetzel 1975).

6.1.9 Nitrate and Orthophosphate

Plant nutrient analysis during the study period focused on the spatial and temporal variation in nitrate and orthophosphate concentrations. Nitrate levels in Roosevelt Lake were consistently highest at station 4, where concentrations averaged four times higher than at the main reservoir stations over the study period (Fig. 14). High nitrate levels in the Spokane River have been previously reported (Bishop and Lee 1972) and recent investigations indicate the persistence of elevated nitrate levels upstream (Soltero et al. 1979; USGS 1978, 1979).

Inflow of high-nitrate water from the Spokane River into the main reservoir produced increased nitrate levels downstream. Nitrate loading was very distinct in winter when levels averaged 97 μg/l at stations 5 to 8 but was significantly ($p = .05$) higher at stations 1 to 3 with average concentrations of 147 μg/l. Levels in the Spokane River during this period averaged 542 μg/l.

Nitrate concentrations in the main reservoir during spring and summer were substantially influenced by phytoplankton nutrient uptake and hydraulic conditions. From initially high levels in winter, nitrates decreased in spring at stations 6, 7 and 8 to levels below 10 μg/l in June, coinciding with increasing phytoplankton standing crops. Turbulence was sufficient at this time to prevent substantial surface and bottom differences. Declining

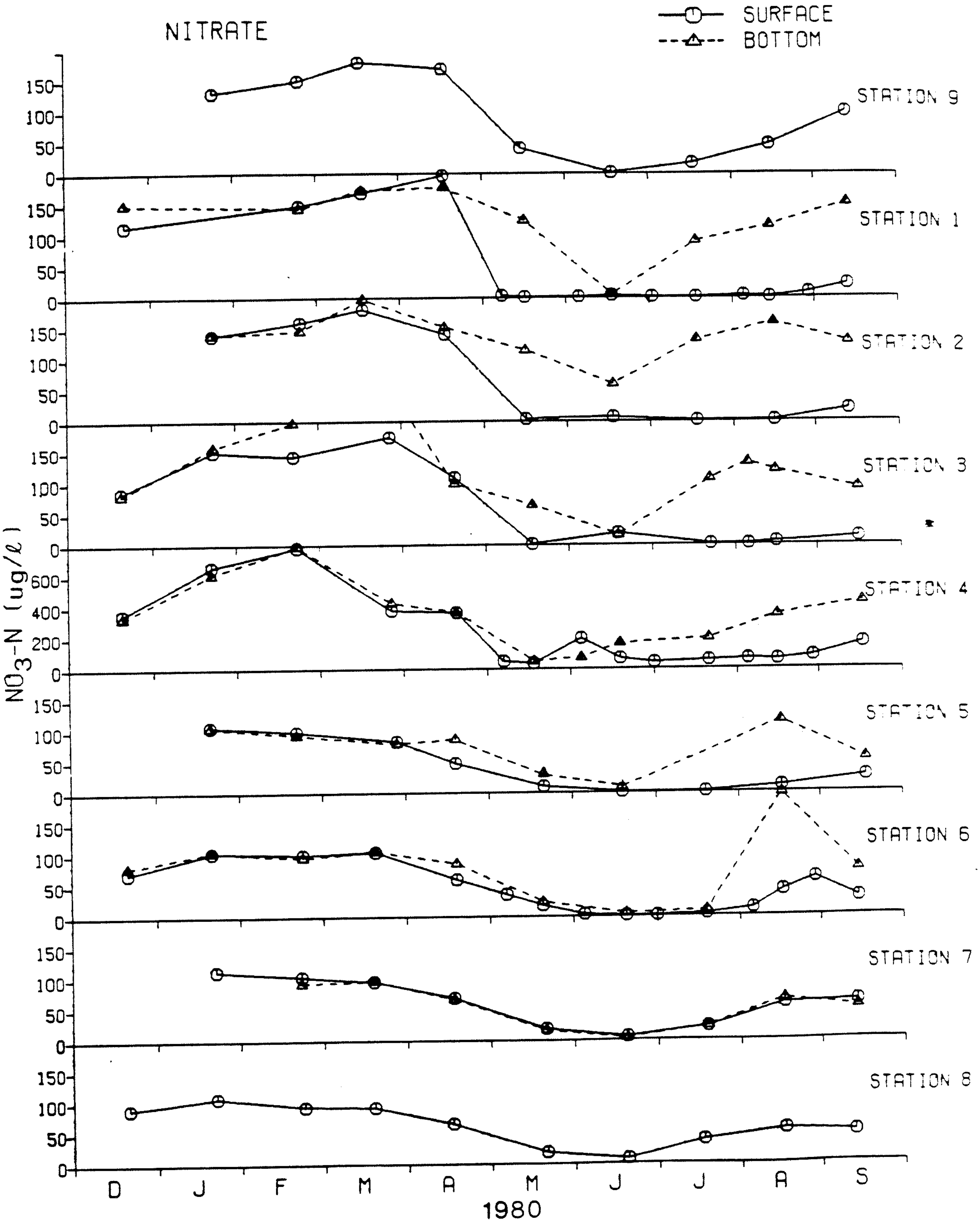

Figure 14. Bottom and mean surface (upper 1, 4 and 8 meters) nitrate concentrations (µg/ℓ) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

nitrate levels were also noted at stations 1, 2, 3 and 5 in spring, with distinct surface and bottom differences generally observed until June. The nitrate decline at stations 1, 2, 3 and 5 was, in part, related to increasing phytoplankton standing crops and to reduced mixing between surface and bottom waters. In addition, the decline of nitrate at the bottom indicates the inflow and displacement by nitrate-depleted water from upstream. This was distinctly evident in June when surface and bottom levels were generally below 10 µg/l at all main reservoir stations.

Nitrate levels increased in summer at stations 7 and 8, concurrent with declining phytoplankton standing crops. Bottom concentrations at stations 1, 2, 3, 5 and 6 also increased in summer, due in part to the inflow and displacement by higher nitrate water from upstream. Bottom nitrate levels at stations 1, 2, 3, 5 and 6 were substantially higher than levels at stations 7 and 8, suggesting increased nitrogen recycling in summer. Surface concentrations remained low throughout summer at stations 1, 2, 3 and 5, with concentrations rarely exceeding 10 µg/l until September (Table 8). Surface levels at station 6 ranged up to 41 µg/l in summer, but surface nitrate levels were still lower than bottom concentrations. Surface nitrate depletion in summer resulted, in part, from phytoplankton production in the euphotic zone and reduced mixing during stratification.

Spring surface and bottom nitrate concentrations at station 4 declined to 40 µg/l in May, resulting, in part, from increasing phytoplankton standing crops. Declining nitrate values in spring have been previously recorded in the discharge from Long Lake (USGS 1978, 1979) and a similar decline in 1980 (Greig Rupert, USGS, personal communication) may have contributed to the

Table 8. Mean NO_3- N (µg/ℓ) surface concentrations (average of upper 1, 4, and 8 meters) in Roosevelt Lake from December 1979 to September 1980.

	Station							
Month	1	2	3	4	5	6	7	8
December	115	+	85	350	+	70	+	90
January	+	139	151	658	107	104	113	108
February	148	160	143	783	99	100	103	94
March	169	181	175	377	83	105	96	93
April	197	142	109	366	48	60	69	66
May	< 1	4	2	37	10	18	19	19
June	3	7	19	65	1	< 1	6	8
July	2	1	< 1	54	< 1	4	21	38
August	< 1	< 1	5	60	10	41	59	56
September	22	19	12	167	26	29	62	49
Mean Dec. to April	157	120	133	507	84	88	95	90
Mean May to Sept.	6	6	8	77	9	16	33	34

nitrate decline at station 4. Surface concentrations subsequently increased in early June, coinciding with the runoff of volcanic ash and then decreased in mid-June as the ash plume moved downstream. Average surface concentrations at station 4 in summer remained below 65 µg/l until September, while bottom levels steadily increased from June to September and were consistently above 160 µg/l. Surface and bottom differences in summer were due, in part, to surface phytoplankton production and reduced mixing during stratification.

Orthophosphate concentrations in Roosevelt Lake were low throughout the study period, with values typically below 40 µg/l (Fig. 15). Orthophosphate levels were generally highest in winter, with average water column concentrations from December to March of 28 µg/l at the main reservoir stations and 19 µg/l at station 4.

Surface and bottom orthophosphate concentrations declined simultaneously at the main reservoir stations in spring. Declining orthophosphate concentrations at stations 7 and 8 coincided with increasing phytoplankton standing crops, suggesting that phytoplankton uptake at these stations was partially responsible for the low orthophosphate levels. Mechanisms were less distinct at stations 1, 2, 3, 5 and 6, although elevated phytoplankton standing crops during part of spring and low orthophosphate levels upstream suggest phytoplankton uptake and the inflow of orthophosphate-depleted water from upstream as possible causative factors.

Distinct surface and bottom differences in orthophosphate levels were observed at stations 1, 2, 3, 5 and 6 in summer. Surface levels at stations 1, 2, 3 and 5 were consistently below 10 µg/l (Table 9), while concentrations at station 6 were higher, attaining levels up to 15 µg/l. Surface depletion

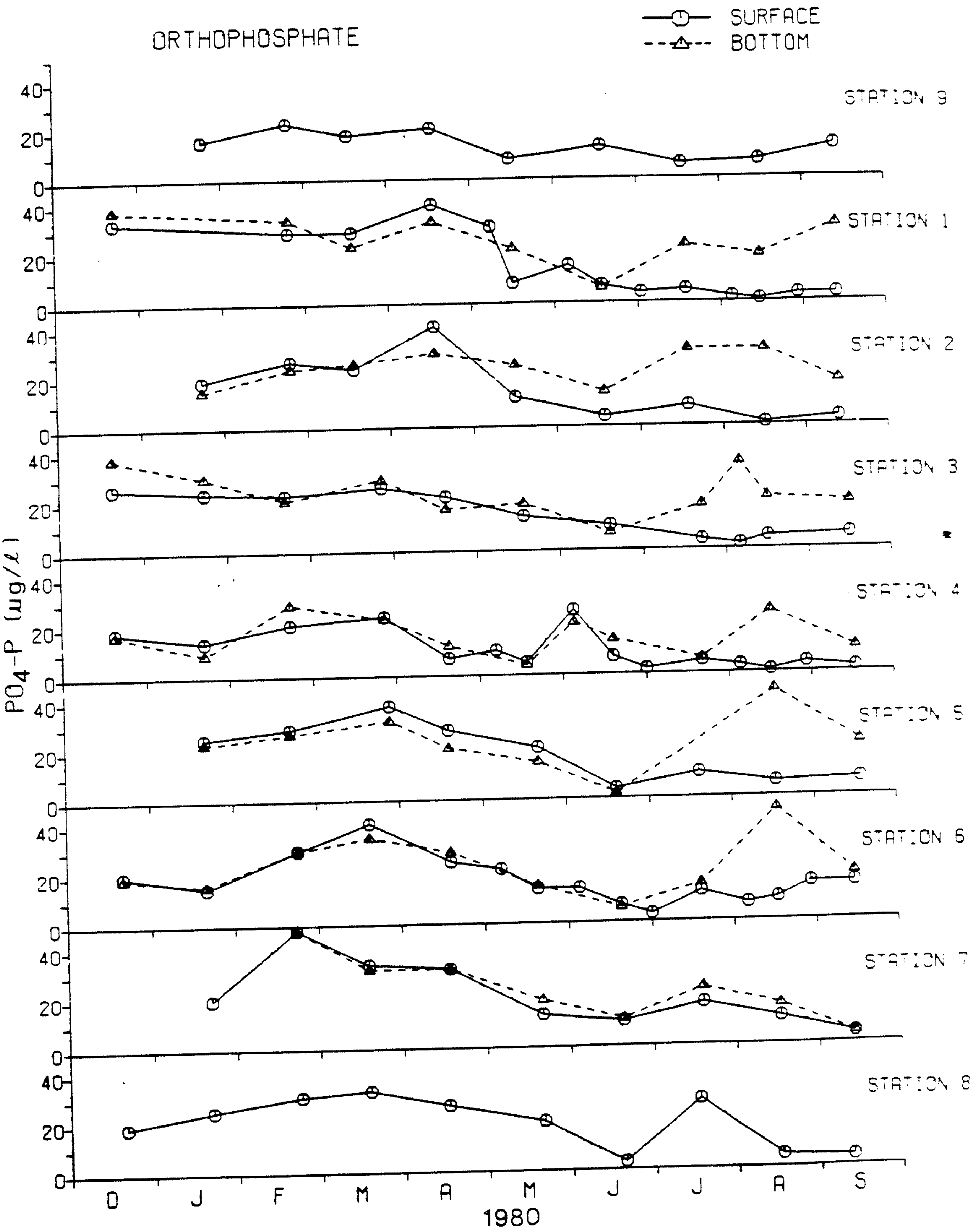

Figure 15. Bottom and mean surface (upper 1, 4 and 8 meters) orthophosphate concentrations (µg/ℓ) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

Table 9. Mean PO_4-P (μg/ℓ) surface concentrations (average of upper 1, 4, and 8 meters) in Roosevelt Lake from December 1979 to September 1980.

Month	Station							
	1	2	3	4	5	6	7	8
December	33	+	26	18	+	20	+	19
January	+	19	24	14	25	15	20	25
February	29	27	23	21	29	30	52	31
March	29	24	26	24	38	41	34	33
April	40	41	22	7	28	25	32	27
May	8	12	14	5	21	14	13	20
June	7	4	10	7	4	7	10	3
July	5	8	4	4	10	12	17	28
August	1	1	5	1	6	9	11	5
September	3	3	6	2	7	15	4	4
Mean Dec. to April	33	28	24	17	30	26	35	27
Mean May to Sept.	6	6	8	4	10	11	11	12

at these stations is thought, in part, related to phytoplankton production and reduced mixing during stratified conditions. Bottom concentrations at stations 1, 2, 3, 5 and 6 were generally above 20 μg/l in summer, distinctly higher than at stations 7 and 8, where average orthophosphate concentrations were 12 μg/l from July to September. Increased phosphate recycling in summer may be partially responsible for higher summer orthophosphate levels downstream.

Orthophosphate concentrations at station 4 declined in spring, resulting partially from increasing phytoplankton standing crops. Low orthophosphate levels upstream in the discharge water from Long Lake have been recorded in the spring of previous years (USGS 1978, 1979). A similar pattern in 1980 (Greig Rupert, USGS, personal communication 1981) suggests that inflowing waters may, in part, be responsible for low spring orthophosphate levels in the Spokane River Arm. Surface and bottom differences in orthophosphate levels were noted at station 4 in summer, with surface depletion attributed to phytoplankton production and reduced mixing during stratification. Surface orthophosphate concentrations in Roosevelt Lake during the phytoplankton growing season were lowest at station 4, with average levels of 4 μg/l from May to September.

Hydraulic characteristics of Roosevelt Lake were important to nitrate and orthophosphate dynamics. Nutrient increases and decreases, in part, originated upstream and influenced downstream nutrient levels through displacement. Additionally, declining turbulence and increasing stratification from upstream to downstream areas resulted in decreased mixing between nutrient-rich and nutrient-poor waters. This reduced mixing may have been, in part, responsible for the observed pattern of increasing nitrate and orthophosphate surface depletion downstream during the phytoplankton growing season (Tables 8 and 9).

Nitrogen and phosphorus are frequently limiting to plant production in natural waters and, as such, are important to establishing lake trophic status (Wetzel 1975). Algae generally require a relatively fixed atomic ratio of nitrogen to phosphorus of 16:1 (Ketchum 1969, Lee 1973). Nitrogen-to-phosphorus ratios below 16:1 indicate nitrogen limitation, while ratios above 16:1 suggest phosphorus may be limiting algal growth. The atomic ratio of 16:1 corresponds to a N:P mass ratio of 7.2:1. Low mass ratios of total inorganic nitrogen (ammonia, nitrite and nitrate) to orthophosphate at the surface of the main reservoir stations indicates that nitrogen may be primarily limiting to phytoplankton in spring and early summer, while higher ratios in September indicate that nitrate and orthophosphate may be limiting in late summer (Table 10). Stober et al. (1977a) found similar low N:P mass ratios in the forebay of Roosevelt Lake. In contrast, station 4 N:P ratios suggest phosphorus as limiting to phytoplankton production in the Spokane River Arm. Phosphorus limitation has been demonstrated upstream in the Spokane River at Long Lake (Soltero et al. 1979).

6.2 Phytoplankton

6.2.1 Standing Crop

Chlorophyll a concentrations in Roosevelt Lake showed distinct differences in standing crop between upstream and downstream stations during the study period (Fig. 16). Stations 1, 2, 3 and 5 exhibited generally similar

Table 10. Mass ratio of total inorganic nitrogen to orthophosphate in the surface waters (average of upper 1, 4, and 8 meters) of Roosevelt Lake from December 1979 to September 1980.

	Station							
Month	1	2	3	4	5	6	7	8
December	3.8	+	6.9	32.0	+	3.2	+	5.6
January	+	8.0	7.2	57.2	5.2	8.5	7.2	6.1
February	5.6	6.7	6.8	40.8	3.9	4.3	2.5	4.1
March	6.1	8.2	8.1	18.0	3.0	3.7	5.6	4.9
April	5.1	3.7	5.0	14.9	1.9	3.4	3.1	3.2
May	0.9	0.9	0.4	9.0	1.6	2.4	2.0	1.4
June	0.9	2.4	2.8	9.7	1.4	1.5	1.6	5.8
July	2.0	1.3	1.3	13.0	0.7	0.9	1.8	1.7
August	4.0	2.4	1.2	113.3	6.2	6.3	5.7	14.5
September	8.6	9.3	3.6	78.6	5.0	3.5	20.4	13.9
Mean Feb. to Sept.	4.1	4.4	3.6	42.0	3.0	3.2	5.3	6.2

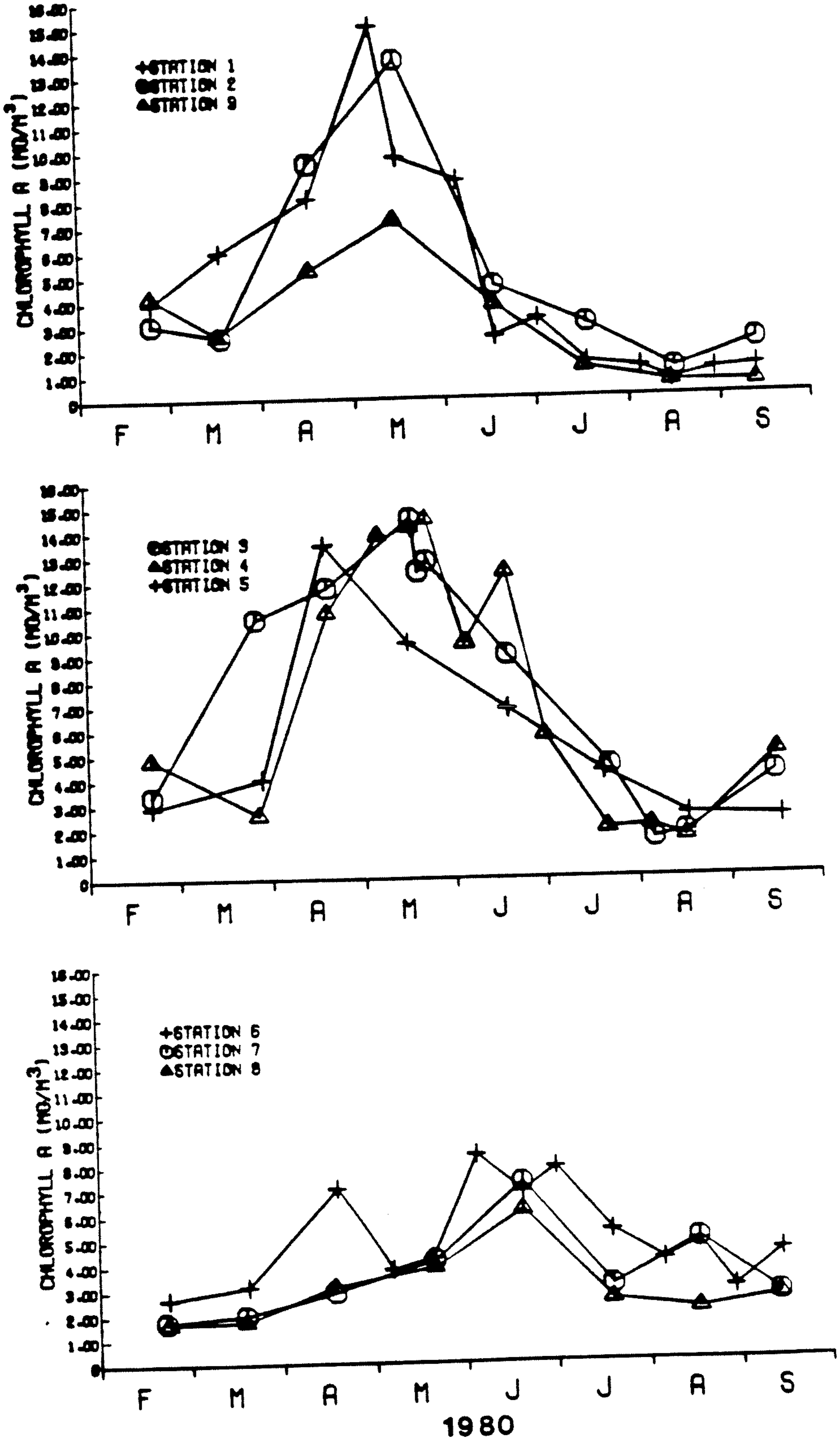

Figure 16. Mean chlorophyll a euphotic zone concentrations by dates for Roosevelt Lake and the tailrace.

temporal patterns, with peak chlorophyll a concentrations occurring in spring. Maximum levels were observed in May at stations 1, 2 and 3 with values of 15.00, 13.62 and 14.55 mg/m^3, respectively, and in April at station 5 with a value of 13.46 mg/m^3. Concentrations subsequently declined, with a rapid decrease at stations 1 and 2 to concentrations below 5 mg/m^3 by mid-June, and a slower decline at stations 3 and 5 to levels below 5 mg/m^3 by mid-July. This late spring decline coincided with low nitrate and orthophosphate concentrations throughout the water column. Summer chlorophyll a values were consistently below 4.00 mg/m^3, except for an increase to 4.60 mg/m^3 at station 3 in September. Minimum chlorophyll a concentrations at stations 1, 2, 3 and 5 occurred in August, with levels of 0.63 to 2.50 mg/m^3. Low summer chlorophyll a levels coincided with reduced surface nitrate and orthophosphate concentrations. Stober et al. (1977a) reported a similar trend in the forebay during 1976, with peak spring levels from 0 to 10 meters of 11.1 mg/m^3 followed by a summer decline to levels below 3.0 mg/m^3.

Chlorophyll a levels in the Spokane River Arm were generally similar to station 3 levels. Peak concentrations at station 4 were observed in May at 14.55 mg/m^3, coinciding with low orthophosphate concentrations. A decline to 9.47 mg/m^3 was noted in early June, coinciding with the runoff of volcanic ash, which reduced the Secchi disc transparency to 0.35 meters. Concentrations rose again in mid-June to 12.37 mg/m^3, concurrent with the movement of the volcanic ash plume downstream and an increase in the transparency to 1.15 meters. Chlorophyll a concentrations declined in summer and averaged 1.87 mg/m^3 in July and August, which were slightly below winter levels. Levels subsequently increased to 4.99 mg/m^3 in September, coinciding with reduced thermal stratification.

Chlorophyll a concentrations at station 6 showed a spring increase similar to the downstream stations, but the peak level was lower at 7.08 mg/m^3. Levels subsequently declined in May to 3.79 mg/m^3, coinciding with the minimum Secchi depth transparency at station 6 of 0.75 meters. Chlorophyll a levels rose in June to a maximum of 8.41 mg/m^3, and remained above 6.9 mg/m^3 until mid-July. Subsequent summer concentrations were variable, ranging from 2.91 to 5.28 mg/m^3 from mid-July to September.

At stations 7 and 8, chlorophyll a levels increased gradually over spring to a June maximum of 7.26 and 6.14 mg/m^3, respectively. Concentrations declined in summer, with generally constant levels at station 8 averaging 2.38 mg/m^3. Summer levels at station 7 were variable, ranging from 2.67 to 4.91 mg/m^3.

Chlorophyll a seasonal trends in the tailrace reflected patterns at station 1, but concentrations at station 9 were generally lower. Peak levels occurred in May at 7.18 mg/m^3. Erickson et al. (1977) noted a similar trend at a station 9.7 km below Grand Coulee Dam in Rufus Woods, with peak levels of 9.0 mg/m^3 in May.

Average chlorophyll a concentrations over the study period indicated a general spatial trend in the main reservoir, with concentrations increasing downstream from station 8 to a peak at station 3, and subsequently declining to station 1 (Fig. 17). The greatest increase occurred between stations 5 and 3, when average chlorophyll a concentrations increased by 1.71 mg/m^3 downstream from the inflow of the Spokane River. Concentrations at station 4 during the study period averaged 6.66 mg/m^3. Analyses of variance and least

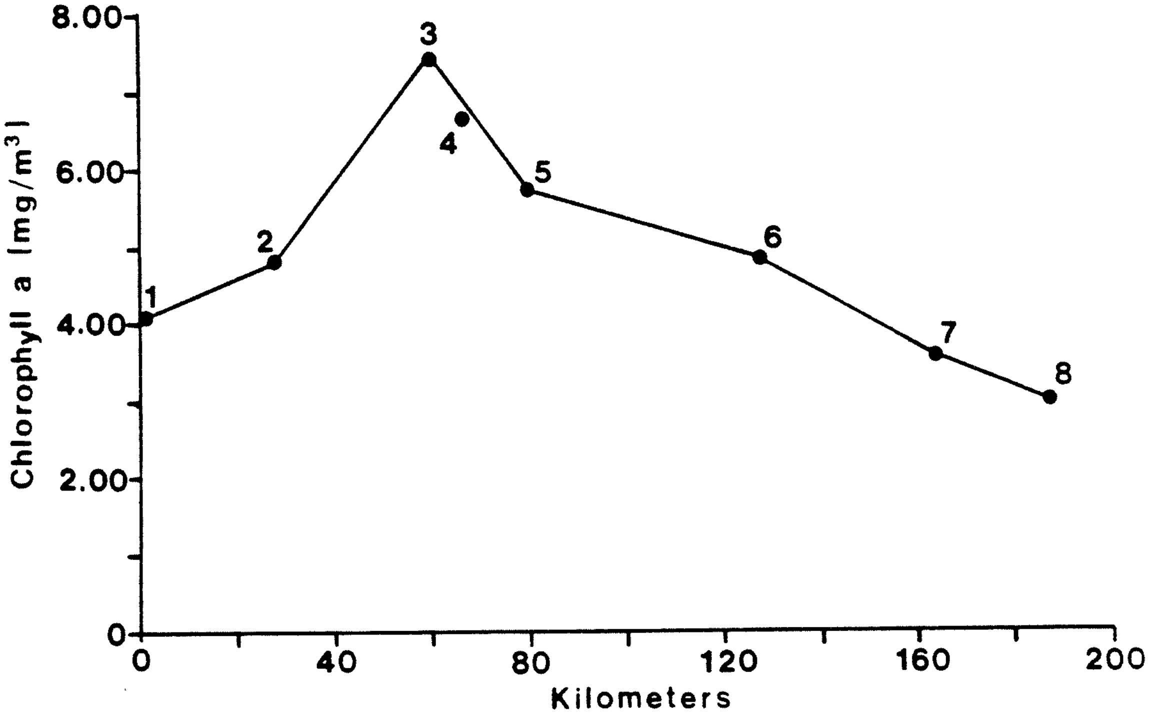

Figure 17. Mean May to September euphotic zone chlorophyll a concentrations (mg/m^3) by distance upstream from Grand Coulee Dam at stations 1 to 8 in Roosevelt Lake. The concentration for station 4 is located at the position of the confluence of the Spokane River arm with the main body of the reservoir.

significant difference (Sokal and Rolf 1969) statistical tests showed only significantly higher concentrations (p = .05) at stations 3 and 4 over stations 7, 8 and 9. Additional data are required to verify the observed spatial patterns.

Phytoplankton biovolume and cell density estimates exhibited comparable patterns during spring and summer (Fig. 18), except when small algae were abundant at stations 2 and 3 in late summer. Biovolume measurements ranged from 0.034 to 4.45 mm^3/l and cell densities ranged from 127,000 to 8,379,000 cell/l. Peak biovolume and cell density standing crops were noted in May at stations 9, 1, 2, 3 and 4, similar to chlorophyll a standing crop trends. Linear correlation between biovolume and chlorophyll a measurements was highest at stations 1 to 3 with a correlation coefficient of 0.80, while cell density and chlorophyll a at these stations correlated at r = 0.64. Biovolume and cell densities were variable at stations 5 to 8, and correlated only slightly (r = 0.32 and r = 0.34, respectively) with chlorophyll a measurements. Based on the small sample size collected for biovolumes and cell density measurements, we consider chlorophyll a values a better estimate of phytoplankton standing crops during this study. Cell densities encountered during this study were similar to previously reported densities in Porcupine Bay (Bishop and Lee 1972), and in the main body of the reservoir (Robeck et al. 1953).

Macronutrients were of prime importance in limiting reservoir productivity. Low surface nitrate levels and low N:P ratios indicate primarily nitrogen limitation in the main reservoir, while low phosphate levels and high N:P ratios indicate phosphorus limitation in the Spokane River Arm. Low nitrate and orthophosphate levels suggest nutrient limitation at stations 1

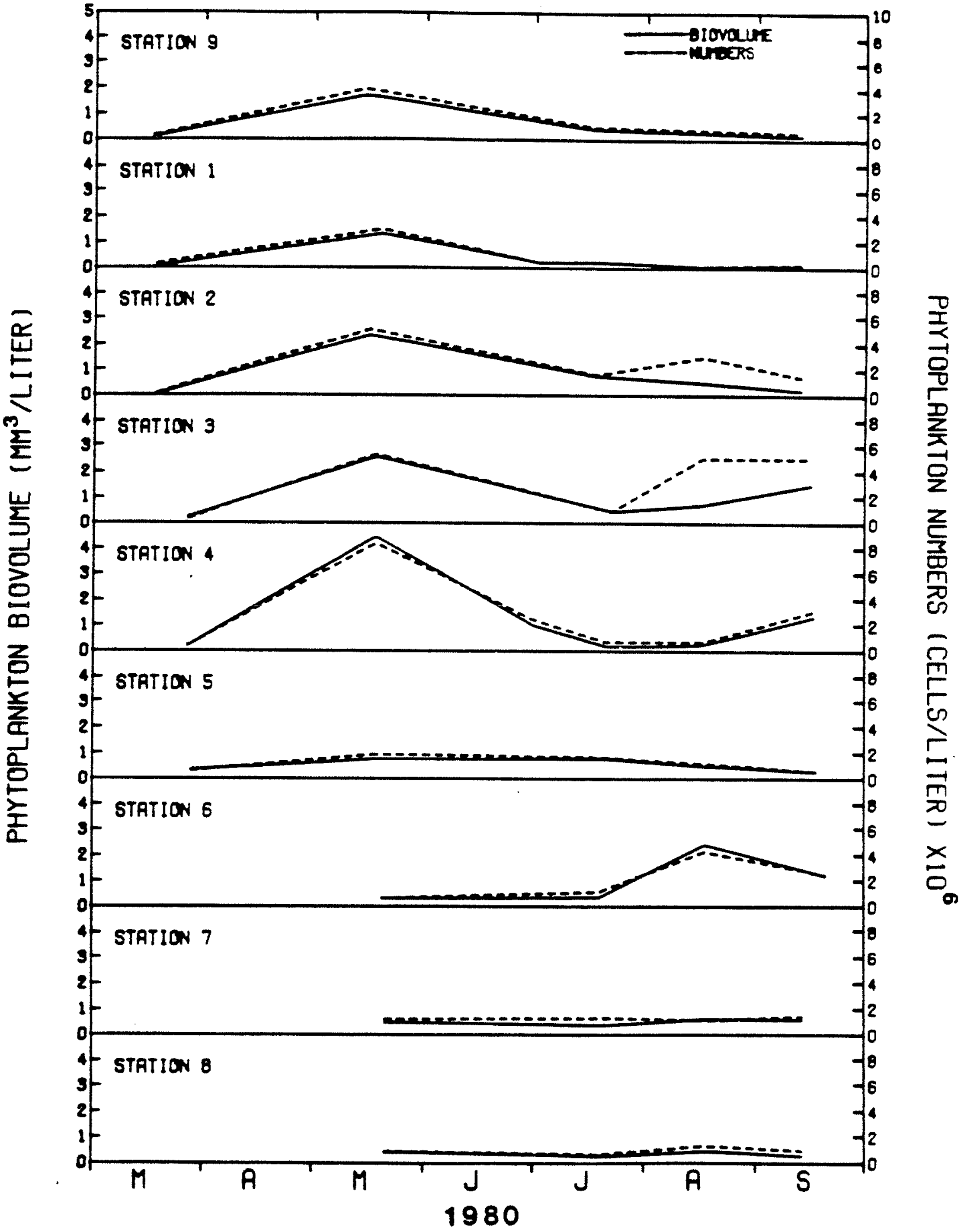

Figure 18. Phytoplankton biovolume and cell densities by dates for Roosevelt Lake and the tailrace.

to 5 during most of the phytoplankton growing season. The extent of nutrient limitation is less certain at stations 6, 7 and 8, but low nitrate and orthophosphate concentrations suggest nutrient limitation may have occurred in June and July at station 6 and, in June and possibly September, at stations 7 and 8.

Seasonal patterns of phytoplankton abundance in the upper reaches of the reservoir suggest that turbulence may also be important to limiting productivity. Erickson et al. (1977) reported substantial phytoplankton only in May and September under the turbulent conditions of Rufus Woods reservoir. Hynes (1970) noted that maximum phytoplankton levels almost always occurred during summer in sluggish, temperate river systems, concurrent with high incident light levels and high water temperatures. A similar pattern was observed at stations 7 and 8 in Roosevelt Lake, with peak chlorophyll _a_ concentrations occurring in June, coinciding with maximum solar insolation. Station 6 was somewhat transitional in 1980, with a summer chlorophyll _a_ peak similar to the turbulent upstream stations, and a spring increase similar to the downstream stations.

Input of water from the Spokane River to the main reservoir further complicates population dynamics. Jaske (1969) reported that water flowing into the main reservoir from the Spokane River either flowed over or dove to the same equilibrium depth depending upon the density difference of the two waters. Generally higher temperatures in the Spokane River from March to September suggest some overflow during spring and summer. The merging of these two systems with different nutrient levels and nutrient limitations may have, in part, stimulated phytoplankton growth and resulted in the increased chlorophyll a levels observed at station 3. Seasonally high chlorophyll a concentrations at station 4 suggest a substantial input of phytoplankton to the main reservoir may, at times, occur from the inflow of Spokane River water.

6.2.2 Composition

Twenty-eight genera of phytoplankton were identified from Lake Roosevelt during the spring and summer of 1980 (Table 11). The diatoms *Asterionella*, *Fragillaria* and *Melosira* were the dominant genera, collectively occurring in 95 percent of the samples and accounting for over 65 percent of the phytoplankton biovolume over all stations and dates. Green algae, dominated by *Chlorella* and *Ankistrodesmus*, were also frequently encountered, occurring in 97 percent of the samples and comprising 17.6 percent of the phytoplankton biovolume over the study period.

Phytoplankton compositional changes over spring and summer of 1980 are presented in Figures 19, 20 and 21. Composition in March was variable, with Chrysophytes, primarily *Fragillaria*, comprising 100 percent of the biovolume at station 4, and Chlorophyta, Chrysophyta, Cryptophyta and Pyrrophyta being variably important at stations 9, 1, 2, 3 and 5. In May, the phytoplankton community was dominated by diatoms at all stations, with *Fragillaria*, *Asterionella* and *Melosira* contributing over 95 percent of the total algal biovolume. Robeck et al. (1953) reported a similar spring diatom dominance in Roosevelt Lake, with *Asterionella* comprising 80 percent by numbers of the phytoplankton in April of 1952.

The diatoms *Fragillaria*, *Asterionella* and *Melosira* continued to dominate

Table 11. Phytoplankton genera identified from Roosevelt Lake samples collected from March to September, 1980. Source is Prescott (1954) unless noted.

CHLOROPHYTA (Green algae)

Class: Chlorophyceae

- *Ankistrodesmus*
- *Chlamydomonus*
- *Chlorella*
- *Gloeocystis*
- *Monoraphidium* (Stein 1975)
- *Pediastrum*
- *Scenedesmus*
- *Schroedaria*
- *Sphaerocystis*
- *Tetrastrum*
- *Triploceras* (Stein 1975)
- *Ulothrix*

CYANOPHYTA (Blue-green algae)

Class: Cyanophyceae

- *Anabaena*

CRYPTOPHYTA

Class: Cryptophyceae

- *Chroomonas*
- *Cryptomonas*

PYRRHOPHYTA

Class: Dinophyceae

- *Ceratium*
- *Gymnodinium*
- *Peridinium*

CHRYSOPHYTA (Diatoms)

Class: Bacillariophyceae

- *Achnanthes*
- *Asterionella*
- *Cyclotella*
- *Fragillaria*
- *Melosira*

CHRYSOPHYTA (Diatoms)

Class: Bacillariophyceae (cont.)

- *Rhizosolenia*
- *Stephanodiscus*
- *Synedra*
- *Tabellaria*

Class: Xanthophyceae

- *Botryochloris* (Bourelly 1966, 1968, 1970)

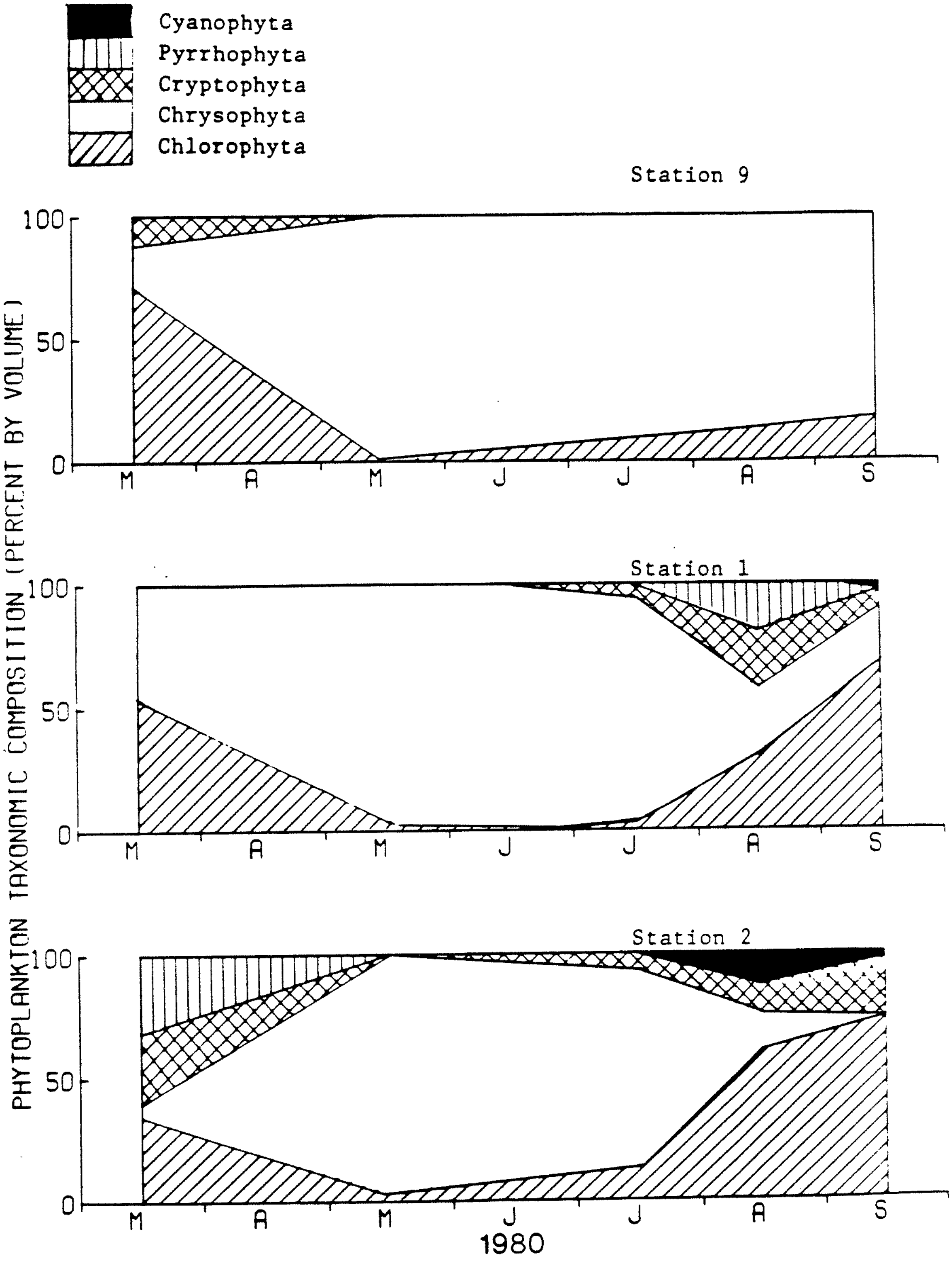

Figure 19. Phytoplankton taxonomic composition for stations 9, 1 and 2 in Roosevelt Lake and the tailrace from March to September 1980.

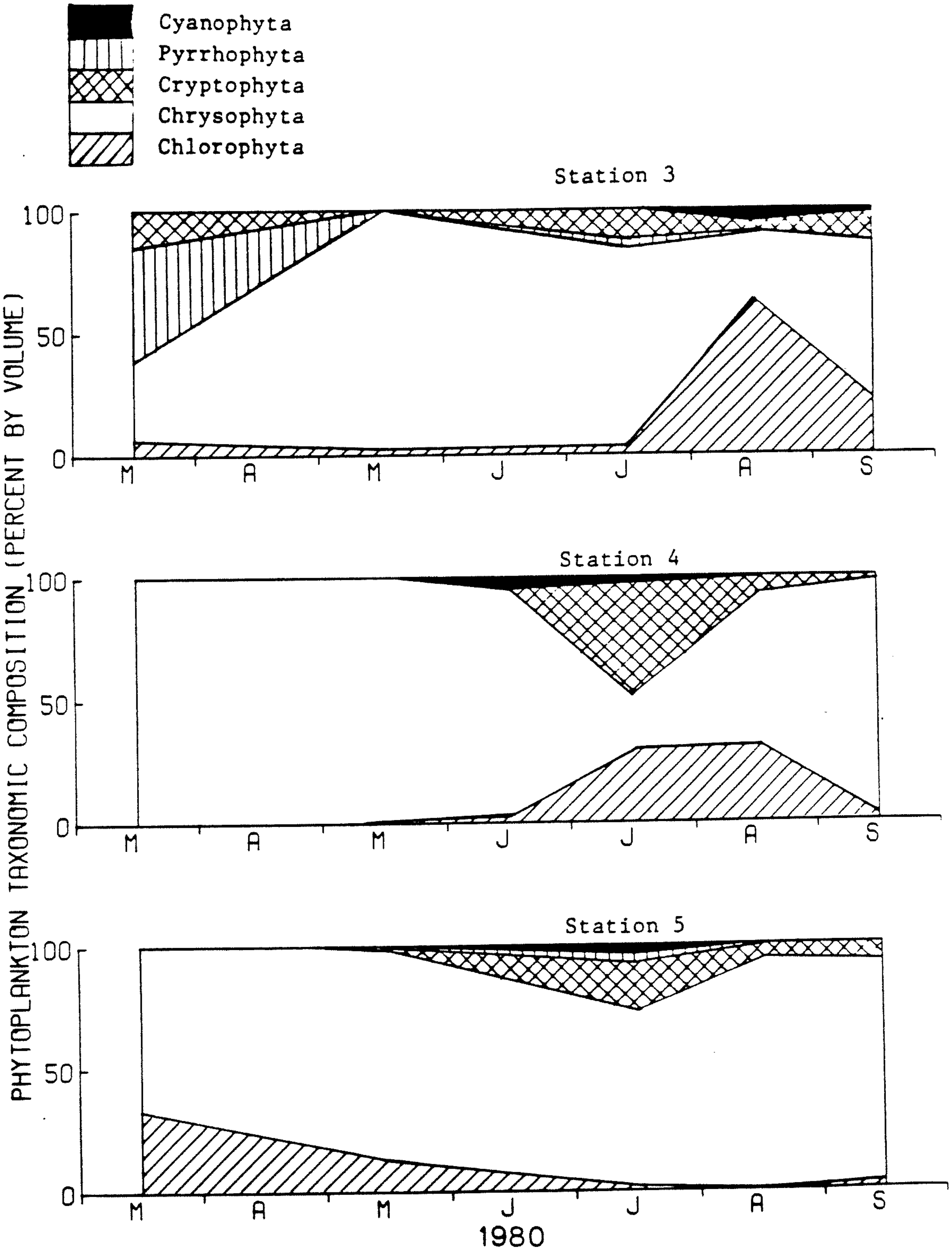

Figure 20. Phytoplankton taxonomic composition for stations 3, 4 and 5 in Roosevelt Lake from March to September 1980.

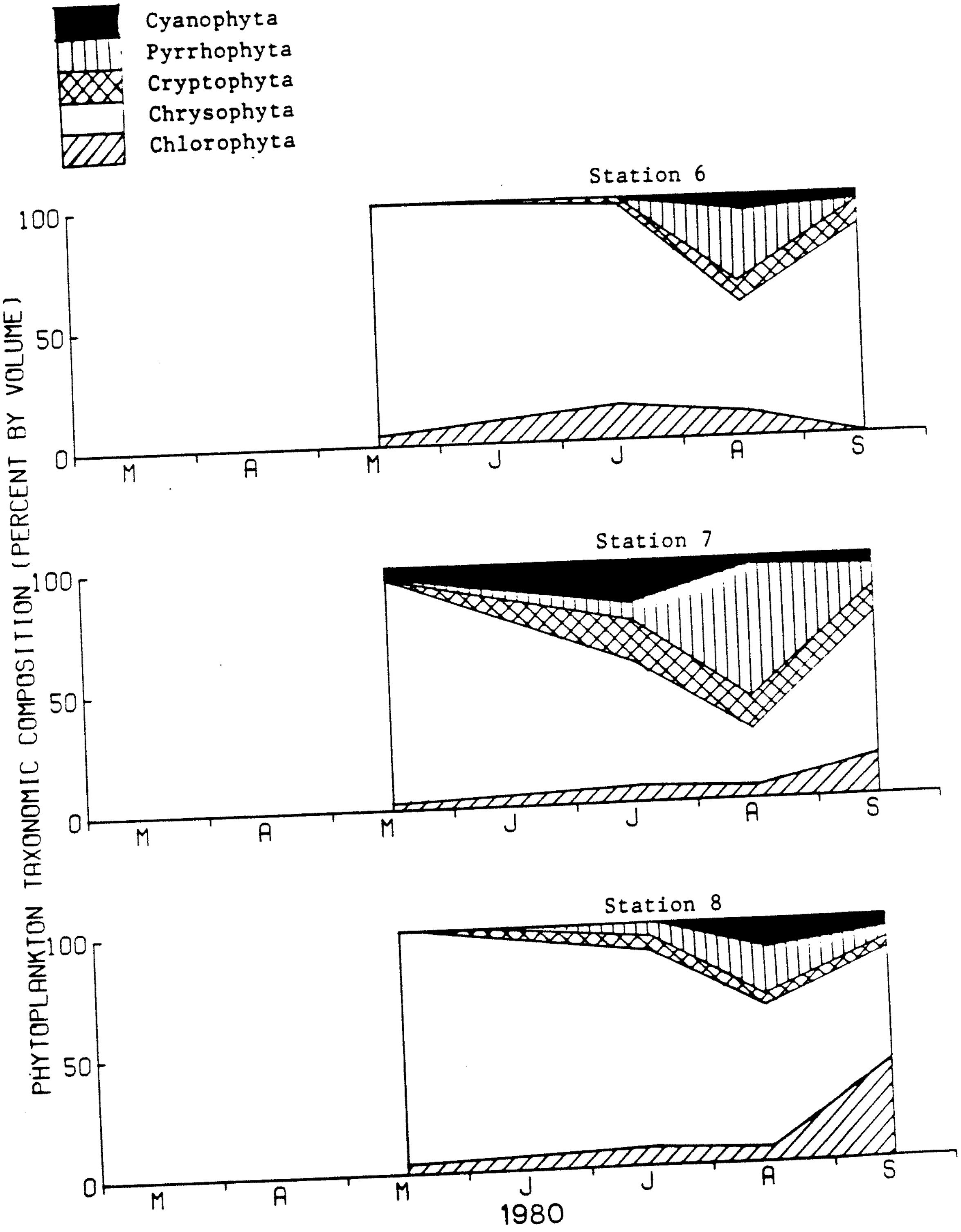

Figure 21. Phytoplankton taxonomic composition for stations 6, 7 and 8 in Roosevelt Lake from May to September 1980.

in early summer at the main reservoir stations, comprising 51 to 90 percent of the phytoplankton biovolume in July. Chlorella and Cryptomonas dominated at station 4 in July, representing 28.8 percent and 42 percent, respectively, of the algal biovolume.

Green algae, dominated by Chlorella, increased at stations 1, 2 and 3 in August and September, contributing from 23 to 74 percent of the phytoplankton biovolume, while diatoms generally declined. In contrast, diatoms, principally Fragillaria, increased at station 4 in August and by September accounted for 95 percent of the algal biovolume. At stations 5 to 8, Chrysophytes continued to persist into September, comprising from 23 to 94 percent of the biovolume, and generally dominating the phytoplankton assemblage. Pyrrophyta, predominately Peridinium, were observed to increase at stations 6, 7 and 8 in August, with a maximum contribution of 54 percent at station 7.

6.2.3 Primary Production

Primary production at stations 3, 4 and 5 in Roosevelt Lake occurred primarily in the upper 8 meters of the water column (Fig. 22). Maximum rates were observed at 1 meter below the surface at stations 3, 4 and 5 in April, with values of 669.6, 521.5 and 794.6 $mgC/m^2/4$ hours, respectively. Macronutrients were generally high during this period, while water transparency was low. As transparency increased temporarily, primary production was distributed deeper in the water column, with peak rates occurring deepest in September at 2 to 4 meters below the surface.

Areal primary production rates for stations 3, 4 and 5 are illustrated in Figure 23. A consistent decrease in primary production over the

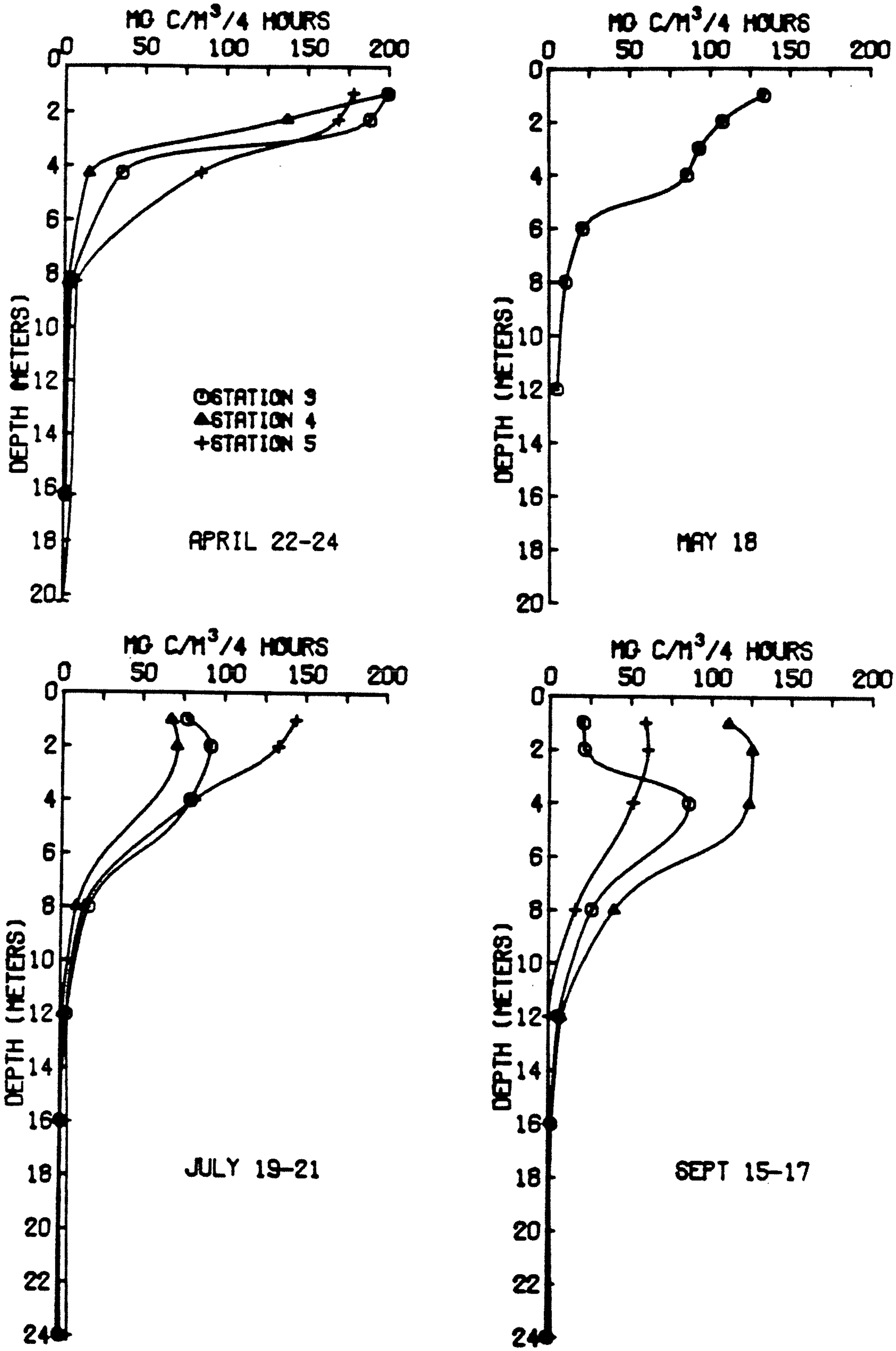

Figure 22. Depth profiles of ^{14}C primary production for Roosevelt Lake stations 3, 4 and 5 during 1980.

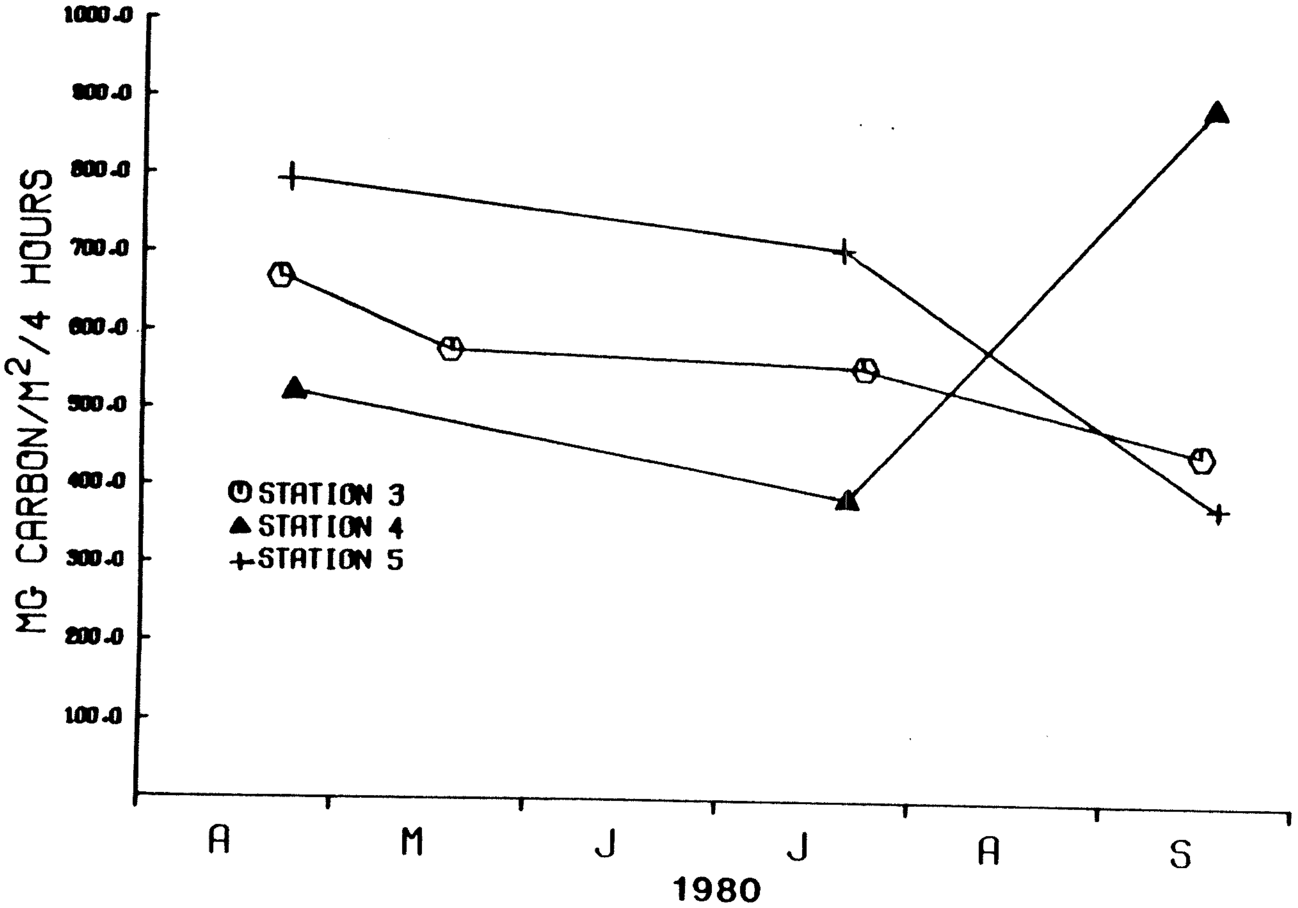

Figure 23. Areal ^{14}C primary production at Roosevelt Lake stations 3, 4 and 5 from April to September 1980.

phytoplankton growing season was noted at stations 3 and 5, with peak rates of 669.6 and 794.5 mgC/m^2/4 hours in April declining to low levels of 451.1 and 384.5 mgC/m^2/4 hours, respectively, in September. In contrast, rates at station 4 decreased from April to July, but increased in September to maximum levels of 895.6 mgC/m^2/4 hours, coinciding with the fall overturn.

Daily primary production rates from April to September averaged 1,233 mgC/m^2/day over stations 3, 4 and 5. Stober et al. (1977a) reported a lower rate in the forebay at 620 mgC/m^2/day from May to October. Substantial spatial and/or yearly variation in primary production rates in Roosevelt Lake are indicated.

6.3 Zooplankton

6.3.1 Total Zooplankton

A total of 42 organisms from 34 genera were identified from Roosevelt Lake zooplankton samples collected during the study (Table 12). Fourteen of these organisms were cladocerans, nine were copepods, and nineteen were rotifers. Daphnia and Diaptomus were the most diverse genera with 4 and 5 species, respectively, identified from each one.

Volume estimates from the metered tows indicated reduced filtering efficiency from net clogging by phytoplankton on several dates, but was restricted primarily to tows at depths greater than 30 meters. Density estimates at stations 1, 2, 3, 5 and 6 from depths greater than 30 meters should be considered with caution. Depth comparisons in the text are restricted to the 10 and 30 meter samples, and at greater depths for only those periods without significant clogging effects.

Table 12. Zooplankton collected in Roosevelt Lake from December 1979 to September 1980.

Cladocera

Alona affinis
Bosmina sp.
Ceriodaphnia sp.
Chydorus sphaericus
Daphnia galeata mendotae
Daphnia parvula
Daphnia pulicaria
Daphnia retrocurva
Diaphanosoma leuchtenbergianum
Leptodora kinditii
Macrothrix sp.
Pleuroxus sp.
Scapholeberis aurita
Simocephalus serrulatus

Copepoda

Calanoida

Diaptomus ashlandii
Diaptomus leptopus
Diaptomus novamexicanus
Diaptomus oregonensis
Diaptomus reighardi
Epischura nevadensis

Cyclopoida

Cyclops bicuspidatus thomasi
Cyclops vernalis
Eucyclops agilis
Mesocyclops edax

Rotifera

Ascomorpha sp.
Asplanchna sp.
Brachionus sp.
Colurella sp.
Conochilus sp.
Euchlanis sp.
Filinia sp.
Kellicottia longispina
Keratella cochlearis
Keratella quadrata

Rotifera (cont.)

Lecane sp.
Monostyla sp.
Notholcu sp.
Platyas sp.
Ploesoma sp.
Polyarthra sp.
Synchaeta sp.
Trichotria sp.
Tricocera sp.

Total zooplankton densities at the main reservoir stations (Figs. 24 and 25) increased during spring from a February low to peak concentrations in June, comprised of an average 71 percent rotifers over this period. Maximum concentrations of 246,400/m^3 were found at station 5 in the upper 10 meters of the water column. Subsequently, levels declined to values generally below 20,000/m^3 by August. Composition during summer was also dominated by rotifers at stations 6, 7 and 8, which averaged 74 percent of the total zooplankton counted from these three stations during the study period. Summer composition at stations 1, 2, 3 and 5 was marked by an increasing dominance by copepods, with peak values of up to 95 percent of the total zooplankton counted. Cladoceran percent composition generally increased spatially downstream and temporally from spring to summer, representing up to 12 percent of the total zooplankton. Robeck et al. (1953) noted a similar compositional pattern, with rotifers dominant in April throughout the main reservoir, but rotifers dominating upstream and crustaceans dominating downstream in September.

In contrast, rotifers and copepods comprised an average of 54 and 43 percent, respectively, of the total zooplankton at station 4 from February to June. Peak zooplankton densities of 30,900/m^3 occurred during August in the upper 10 meters of the water column and were comprised of 88 percent copepods. Cladoceran percent composition was highest at station 4, averaging 4 percent over the study period with a maximum level of 13 percent in summer.

Zooplankton concentrations at stations 1 to 6 were typically highest in the surface waters. Concentrations in the upper 10 meters averaged 45 percent higher than in samples from 30 meters, suggesting a dilution of the

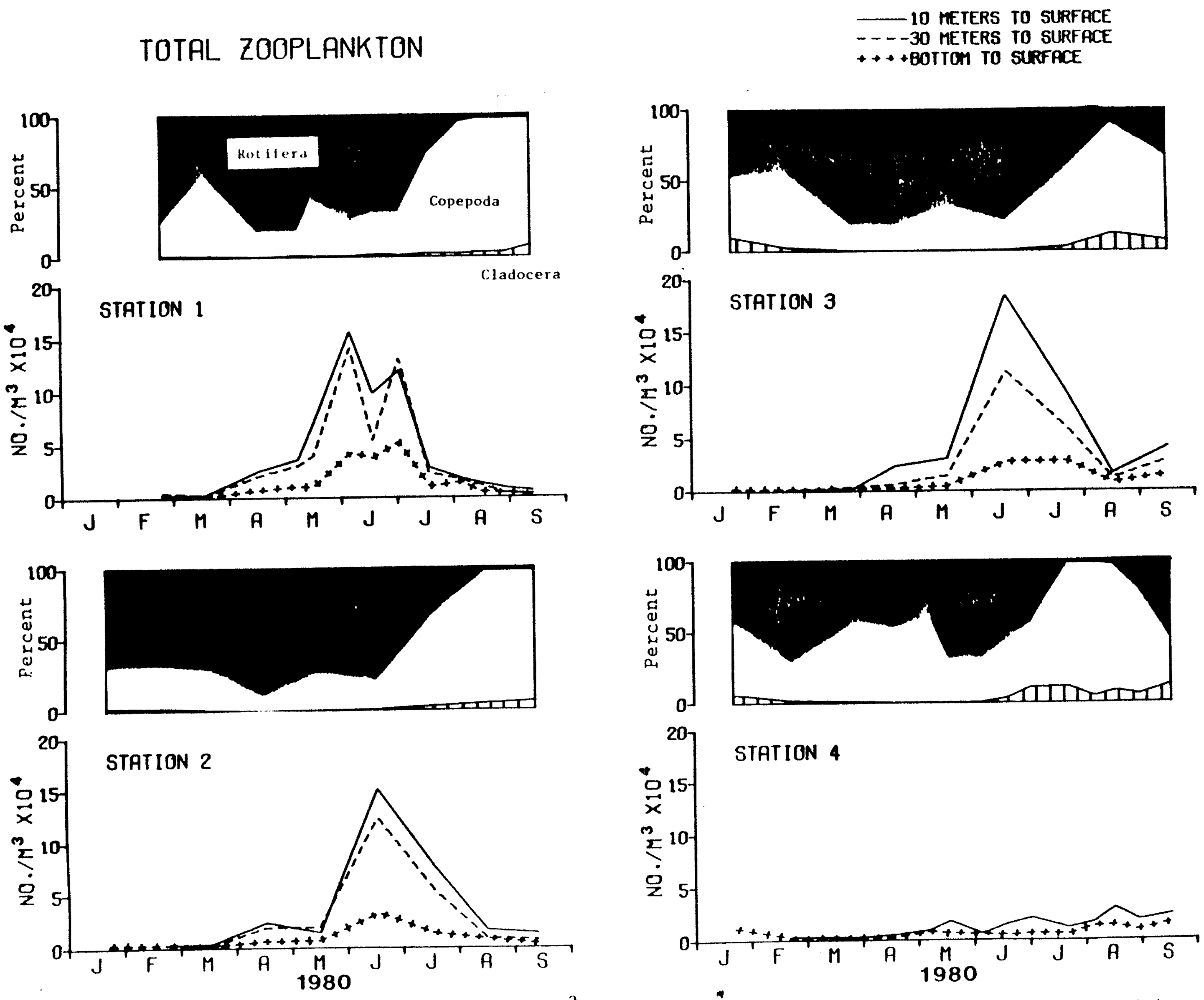

Figure 24. Total zooplankton densities (No.·m^{-3}) and percent composition at stations 1, 2, 3 and 4 in Roosevelt Lake from January to September 1980.

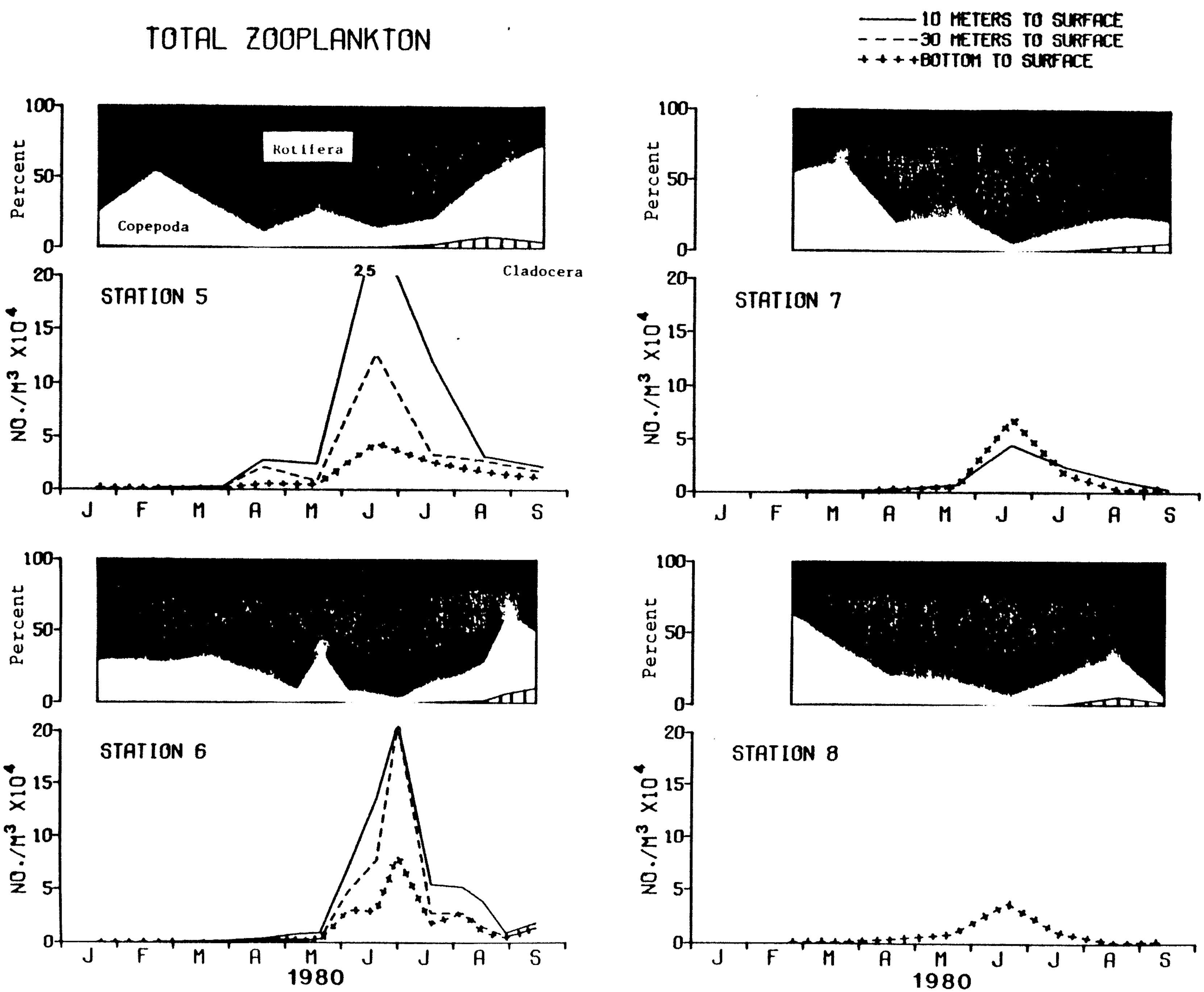

Figure 25. Total zooplankton densities (No.·m^{-3}) and percent composition at stations 5, 6, 7 and 8 in Roosevelt Lake from January to September 1980.

high zooplankton concentrations in the surface waters with lower concentrations from below. Similarly, concentrations in the bottom to surface samples were generally below densities determined from the 10 and 30 meters samples. Samples from station 7 did not indicate a substantial difference between surface and bottom concentrations, probably the result of high turbulence. Robeck et al. (1953) reported peak zooplankton concentrations in the surface waters of Roosevelt Lake and Stober et al. (1977a) noted a similar surface maximum for crustacean zooplankton in the forebay.

6.3.2 Rotifers

Temporal and spatial abundance during the study period of the four most numerous rotifers, Keratella, Polyarthra, Kellicottia and Synchaeta, are illustrated in Figures 26 to 29. Together these organisms comprised 97 percent of the rotifer densities in the reservoir.

Keratella concentrations were the highest for all rotifers at the main reservoir stations with a peak density of 152,300/m^3, while Synchaeta concentrations were highest at station 4 with a peak of 11,800/m^3. Keratella, Polyarthra and Kellicottia exhibited comparable temporal patterns at the main reservoir stations, with peak concentrations in June. Concentrations of these rotifers at station 4 were generally below levels at the main reservoir stations.

Synchaeta densities at stations 1 to 3 exhibited one peak during the study period, while concentrations at stations 5 to 8 showed a bimodal pattern. All stations exhibited a peak in spring, with maximum spring concentrations in April at the main reservoir stations and in May at station 4. A protracted

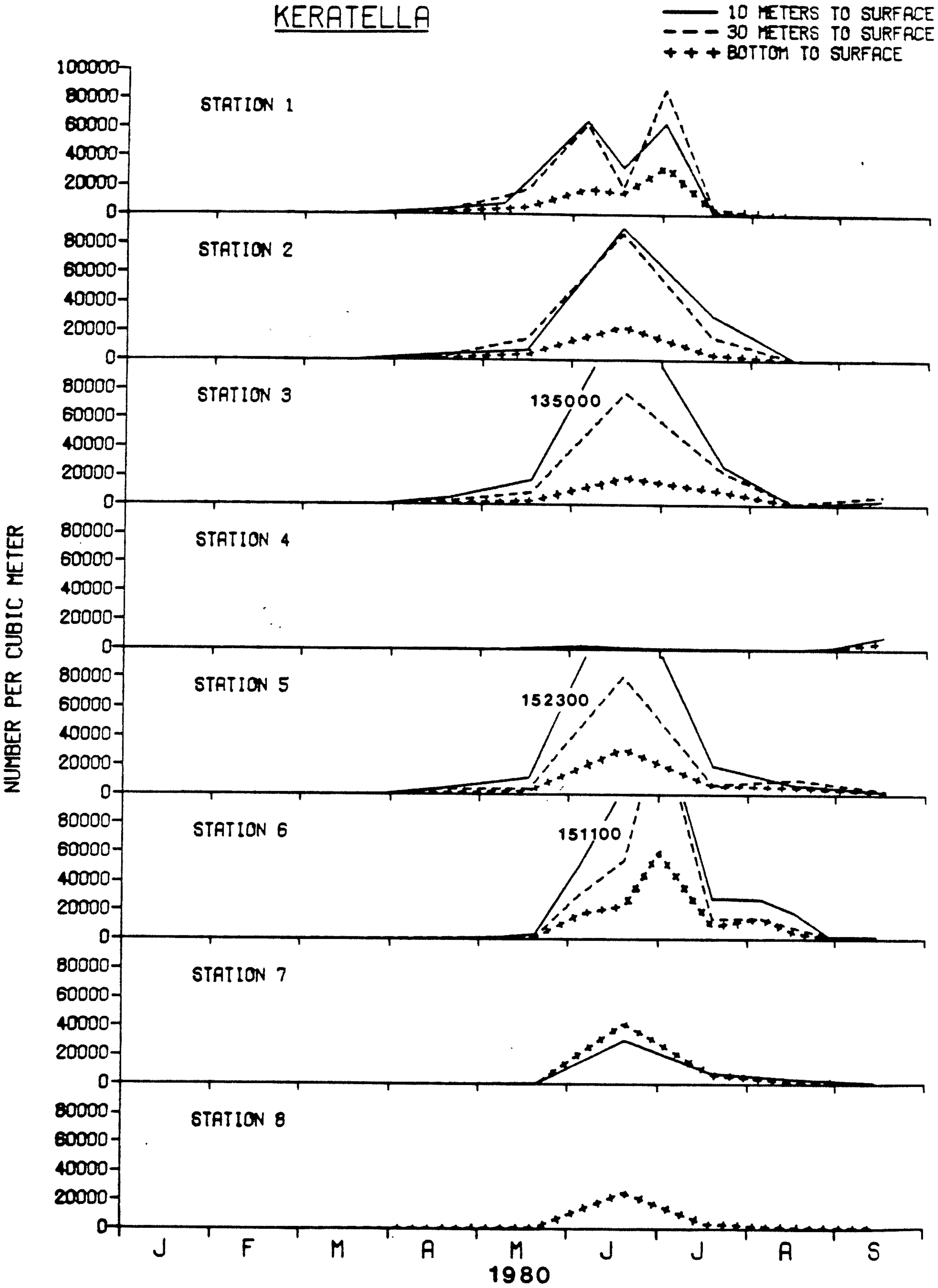

Figure 26. Keratella abundance in Roosevelt Lake from January to September 1980.

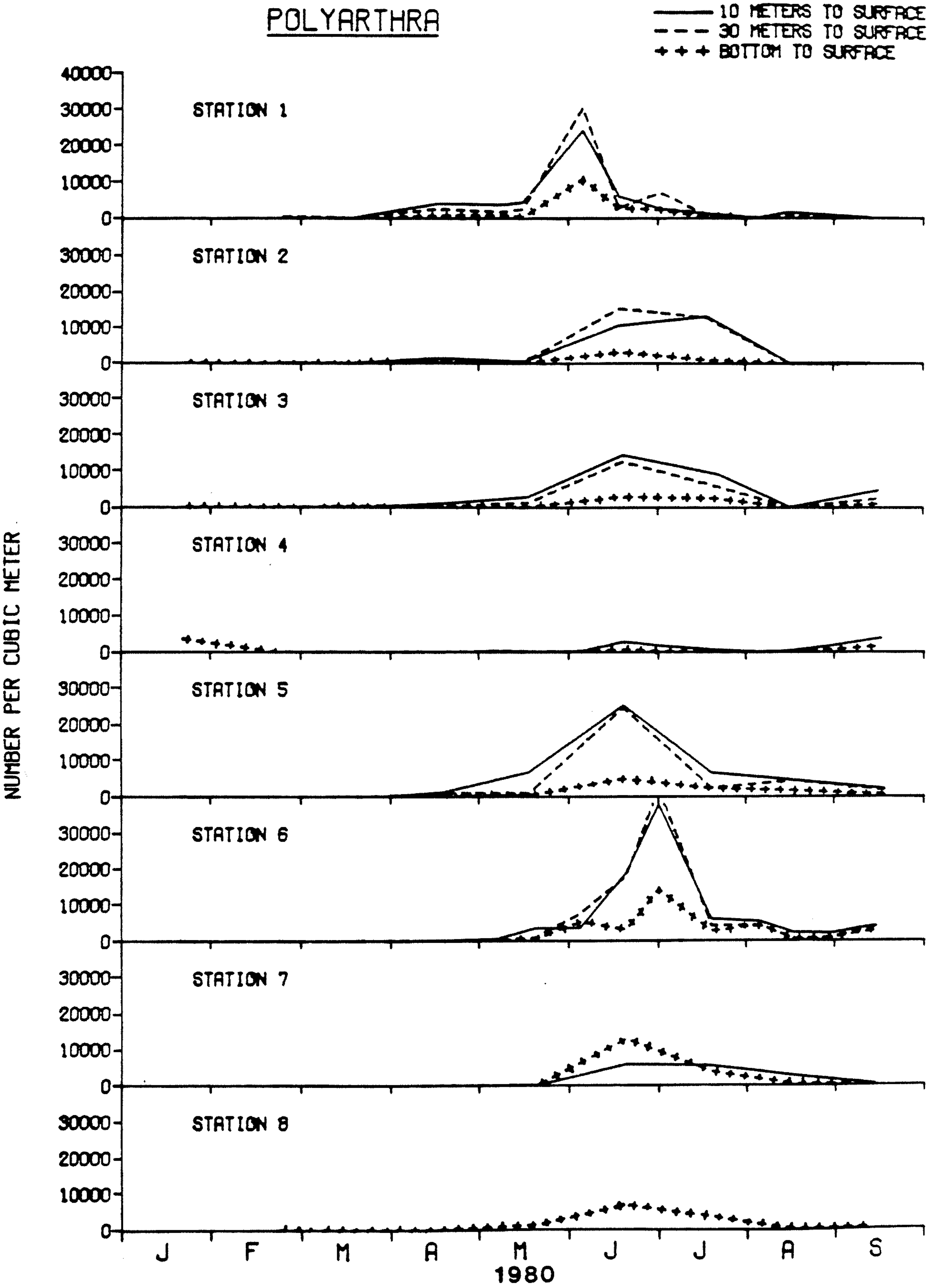

Figure 27. Polyarthra abundance in Roosevelt Lake from January to September 1980.

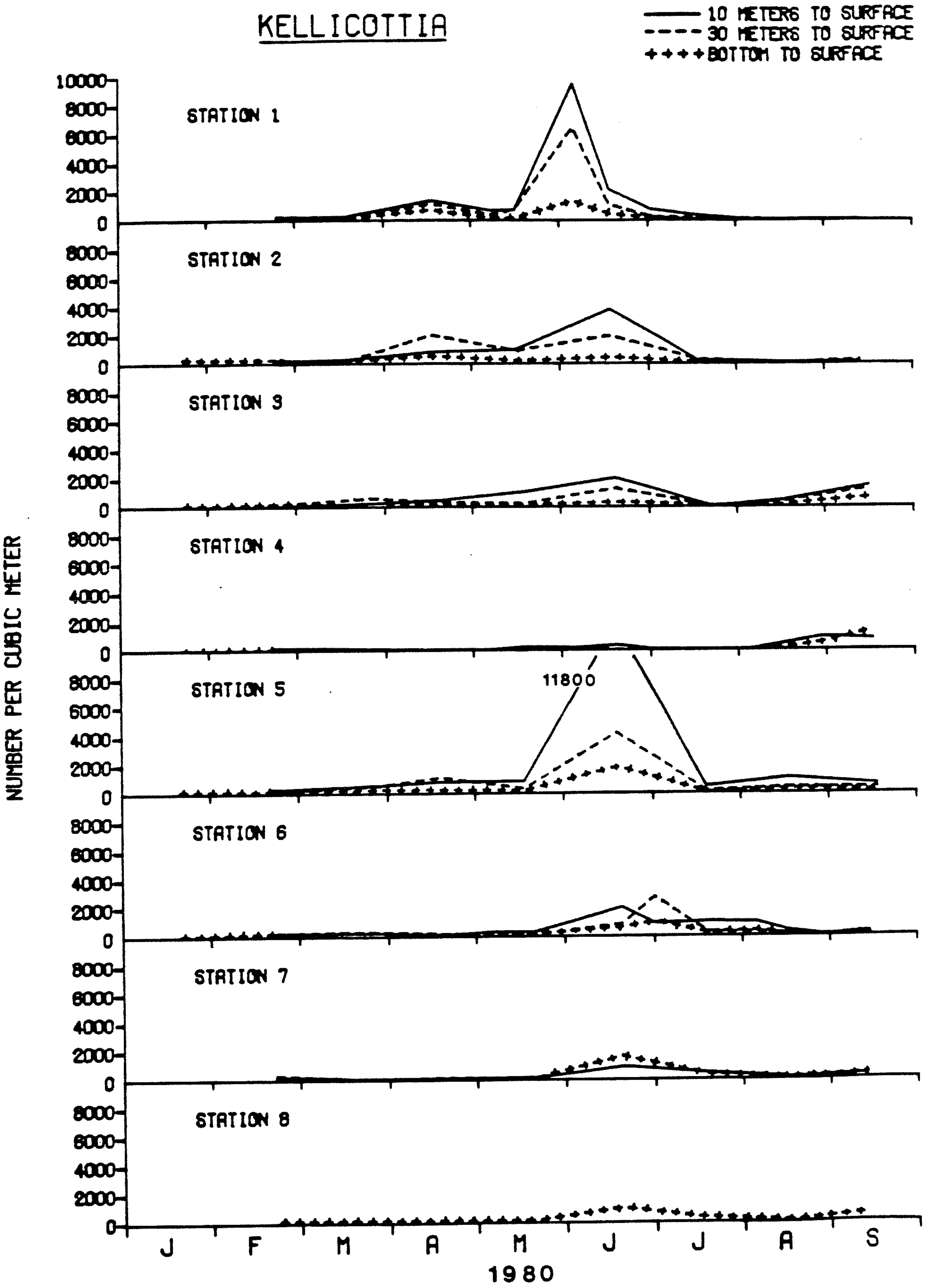

Figure 28. Kellicottia abundance in Roosevelt Lake from January to September 1980.

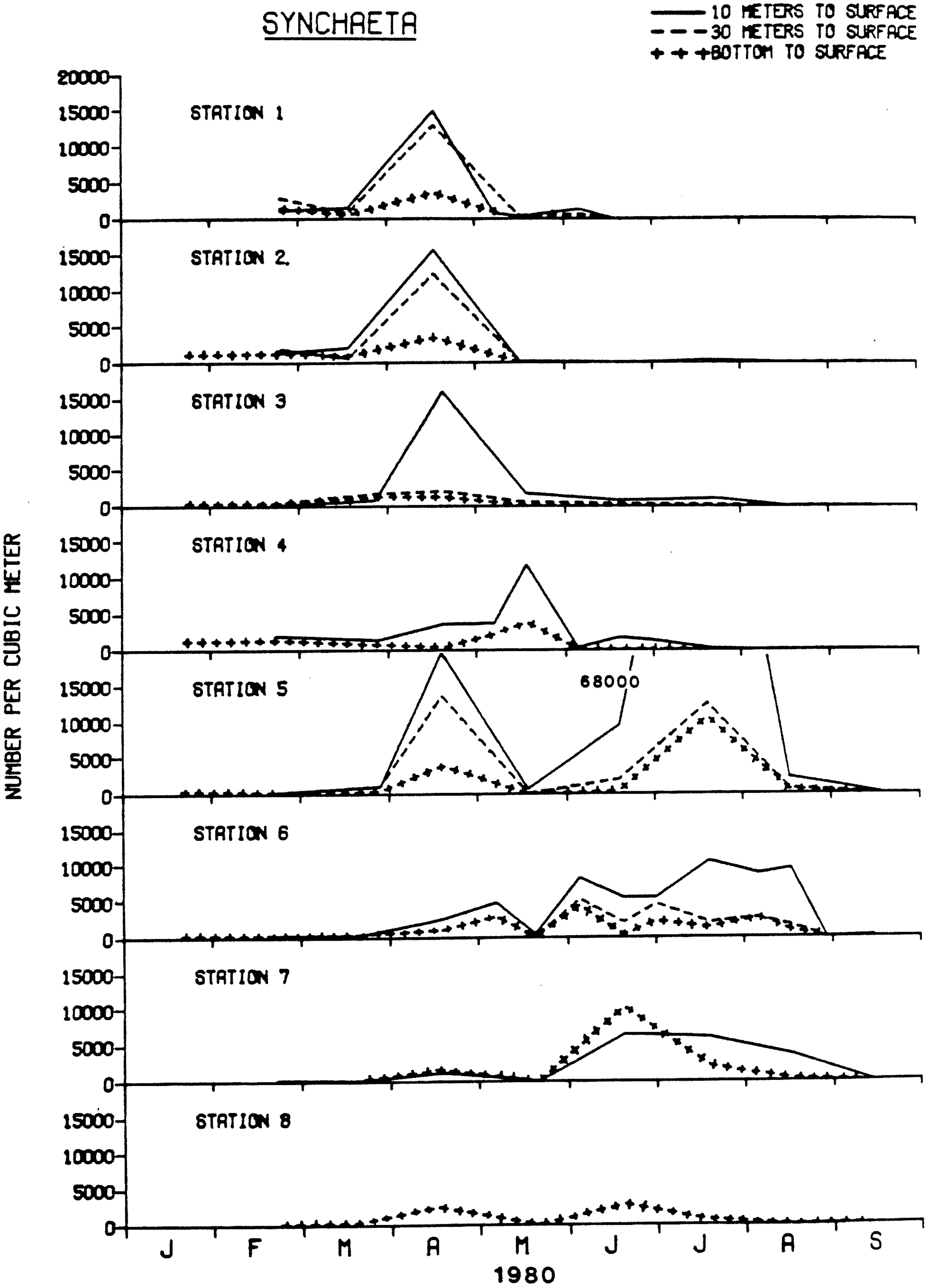

Figure 29. Synchaeta abundance in Roosevelt Lake from January to September 1980.

summer maximum was also noted at stations 5 to 8.

Keratella, Kellicottia and Synchaeta showed a similar spatial pattern in the main reservoir during summer. Concentrations of these rotifers increased from a low at station 8 to peak densities at station 5, and subsequently declined downstream to concentrations below those at station 5. Polyarthra exhibited a similar pattern, but peak densities occurred at station 6. The decline was most distinct for Synchaeta, where concentrations in July decreased from 68,900/m^3 at station 5 to 1100 at station 3.

Increasing concentrations from station 8 to station 5 resulted from the development of populations as the water mass moved downstream. The rate of increase between stations was, in part, dependent upon temperatures (hence, development rates), food availability, and residence times. Mechanisms responsible for the decline in rotifer abundance downstream from station 5 are less conclusive. The decline may be partially a dilution effect from Spokane River water with lower rotifer densities. Predation by Cyclops, as discussed later, and additional unknown factors are probably also important.

6.3.3 Copepoda

6.3.3.1 Calanoida. Calanoid copepod abundance, partitioned into nauplii, Diaptomus copepodids, and Epischura nevadensis copepodids, is presented in Figures 30 to 32. Concentrations were typically highest in the upper 10 meters of the water column for all groups. Calanoid density changes generally showed similar patterns for all sampling depths, with peaks most accentuated in the surface to 10 m depths.

Nauplii exhibited peak densities from May to August at station 1 and

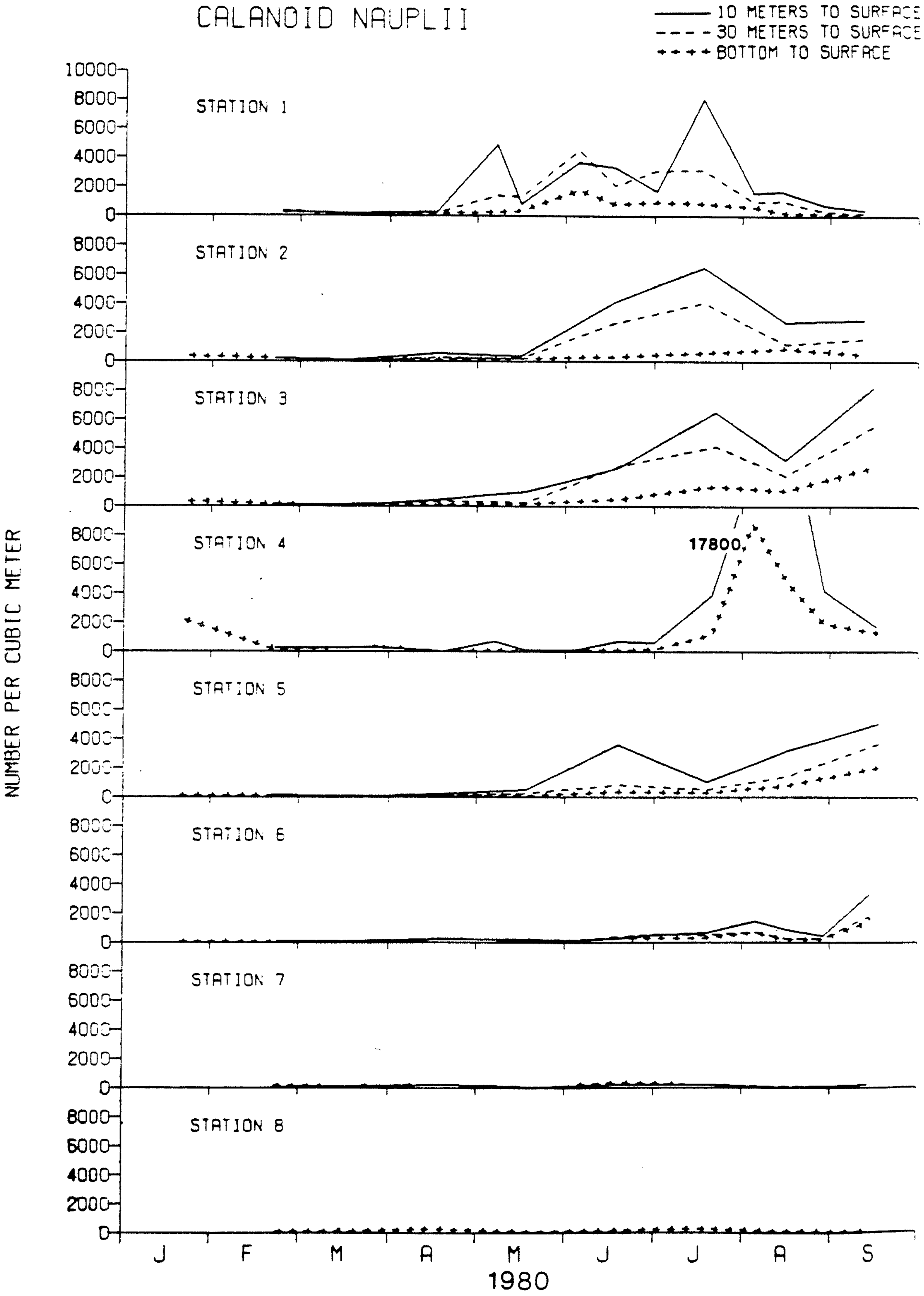

Figure 30. Calanoid nauplii abundance in Roosevelt Lake from January to September 1980.

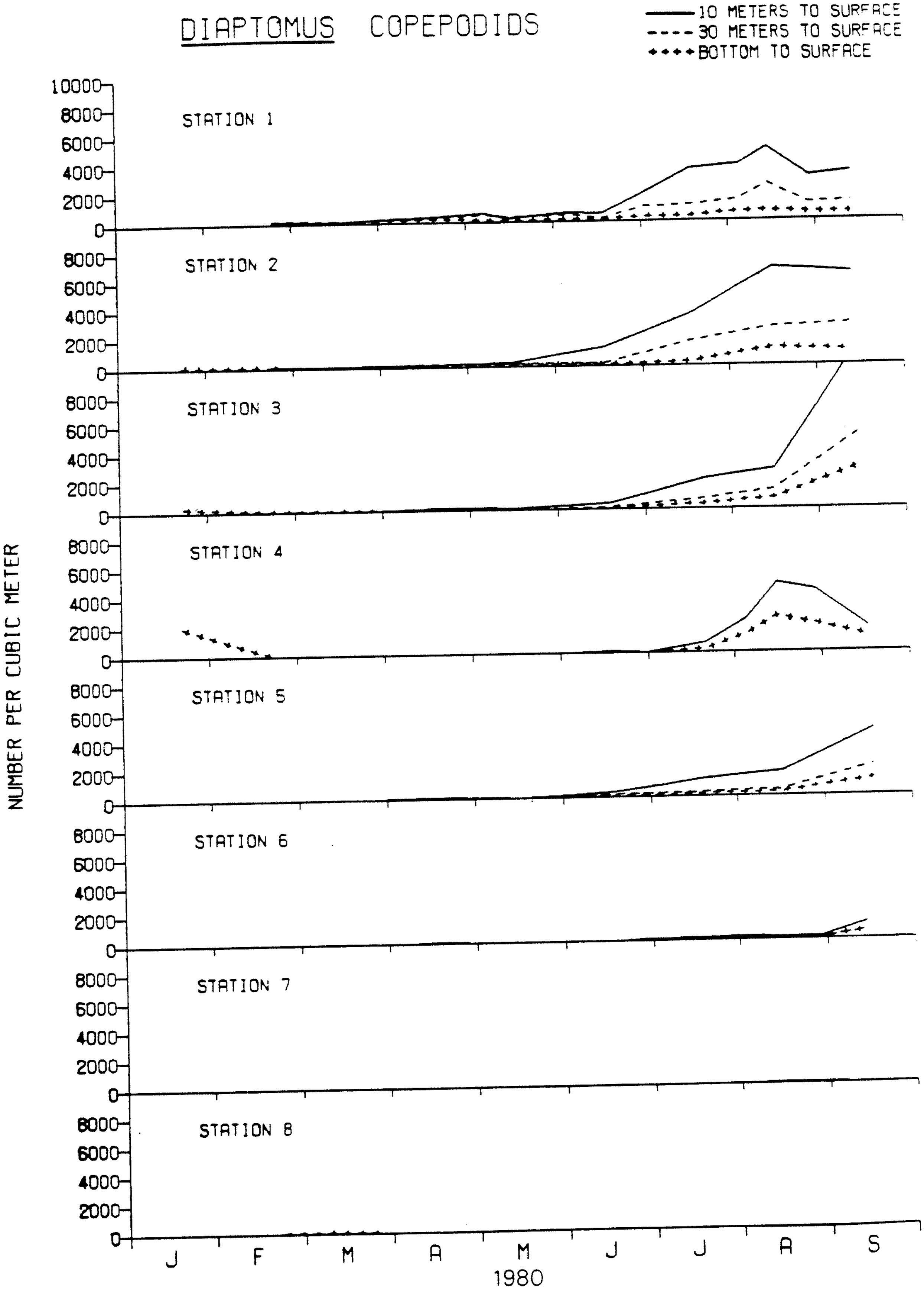

Figure 31. Diaptomus copepodid abundance in Roosevelt Lake from January to September 1980.

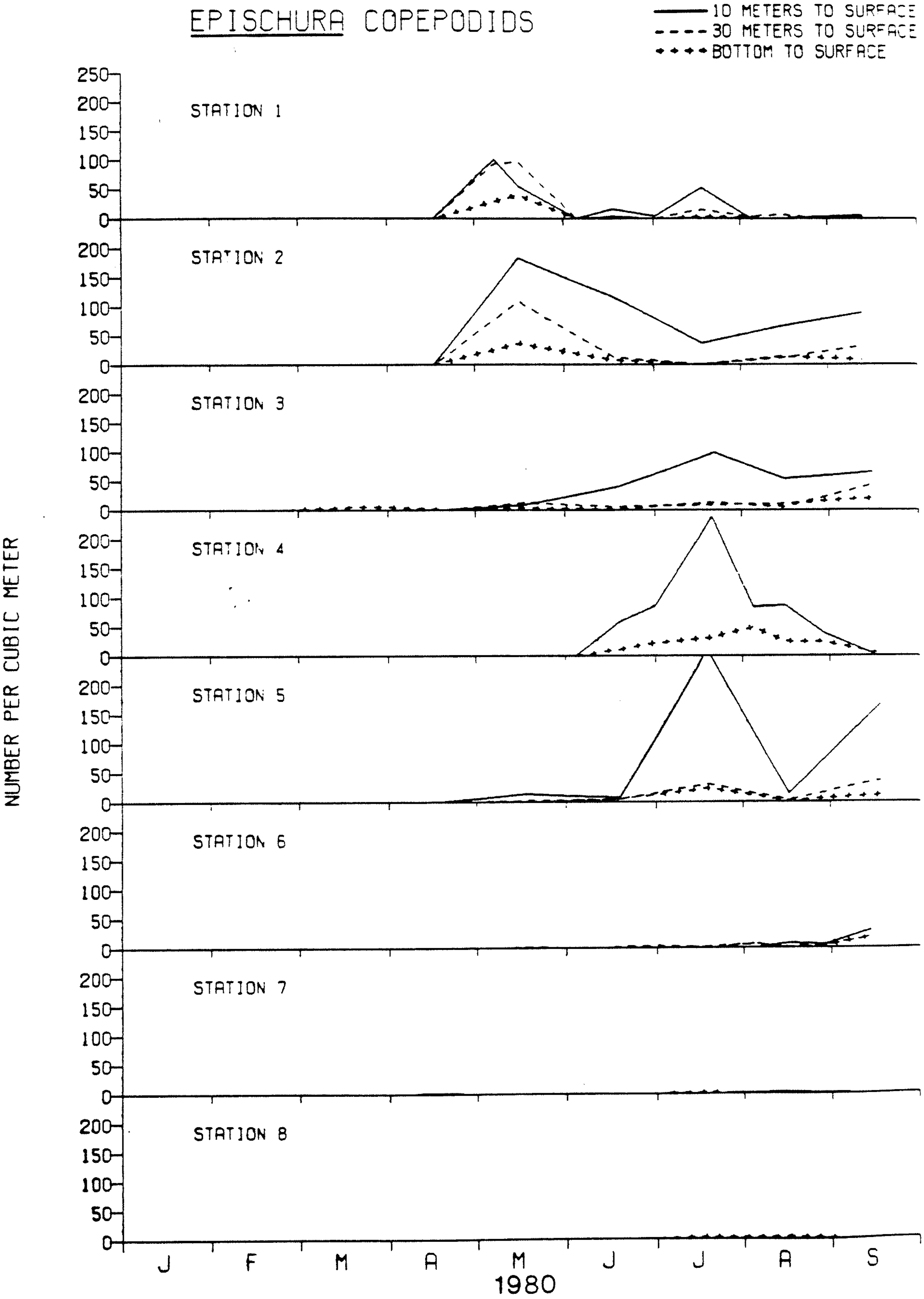

Figure 32. Epischura nevadensis copepodid abundance in Roosevelt Lake from January to September 1980.

from June or July to September at stations 2 to 8. Densities were noted to increase from station 8 to station 5 in summer, but were generally similar at stations 1 to 3 with a decline noted at station 1 in September.

Diaptomus abundance was dominated by D. ashlandi, D. oregonensis and D. reighardi. High densities were noted from July to September, with concentrations in the main reservoir during this period increasing from upstream to downstream stations. Peak densities of 11,600/m^3 were noted at station 3 in September. Kiser (1964) recorded a spatial pattern similar to the present study, with concentrations increasing from upstream to downstream areas. Stober et al. (1977a) reported Diaptomus densities to be highest from August to October in the forebay, with maximum concentrations of 23,400/m^3 in the upper 4 meters of the water column.

Epischura densities were significantly below Diaptomus concentrations, reaching peak levels of only 260/m^3. Epischura concentrations were low at stations 6 to 8 throughout the study period. Peak levels were noted at stations 1 and 2 in May and at stations 3 to 5 in July. The large size of Epischura, with adult size up to 2.5 mm, suggests its potential as a large prey item for fish.

The interaction of retention times and zooplankton development times has been previously shown to be a significant factor to the development of zooplankton populations in reservoirs (Brook and Woodward 1956, Benson 1968, Erickson et al. 1977). Generally, short retention times and long generation times preclude substantial development before the population is transported downstream. Diaptomus generation times, dependent primarily upon food and temperature, are among the longest of the zooplankton. Laboratory studies have indicated generation times of approximately 60 days at 10°C and 25 days at 15°C under conditions of unlimited food for temperate Diaptomus species of a size similar to Roosevelt Lake Diaptomus species (Eckstein 1964, Geiling and Campbell 1973). These values probably represent minimum generation times as field measurements have shown generations times of up to 387 days for Diaptomus ashlandi (Pederson 1974) and from 45 to 60 days in spring and summer for Diaptomus oregonensis (Rigler and Cooley 1974).

Comparison of minimum Diaptomus generation times at Roosevelt Lake temperatures with retention times over the study period indicated that Diaptomus generation times exceeded retention times only during summer. Thus, winter and spring populations were transported down the reservoir and discharged before developing significantly. In contrast, summer conditions permitted substantial development and reproduction before the population was discharged, which resulted in high summer densities.

6.3.3.2 Cyclopoida. Cyclopoid copepod populations in Roosevelt Lake were dominated by Cyclops species throughout most of the study period. Mesocyclops edax showed higher densities only at station 4 in August when concentrations of $1240/m^3$ in the upper 10 meters were recorded. At other times Mesocyclops densities were typically below $200/m^3$.

Cyclopoid nauplii (Fig. 33) and Cyclops copepodids (Fig. 34) generally showed highest concentrations in the upper 10 meters of the water column. Nauplii averaged four times more abundant than Cyclops copepodids over the study period, with both groups showing similar trends. High densities occurred at stations 1, 2, 3 and 5 from May or June to July. Stober et al.

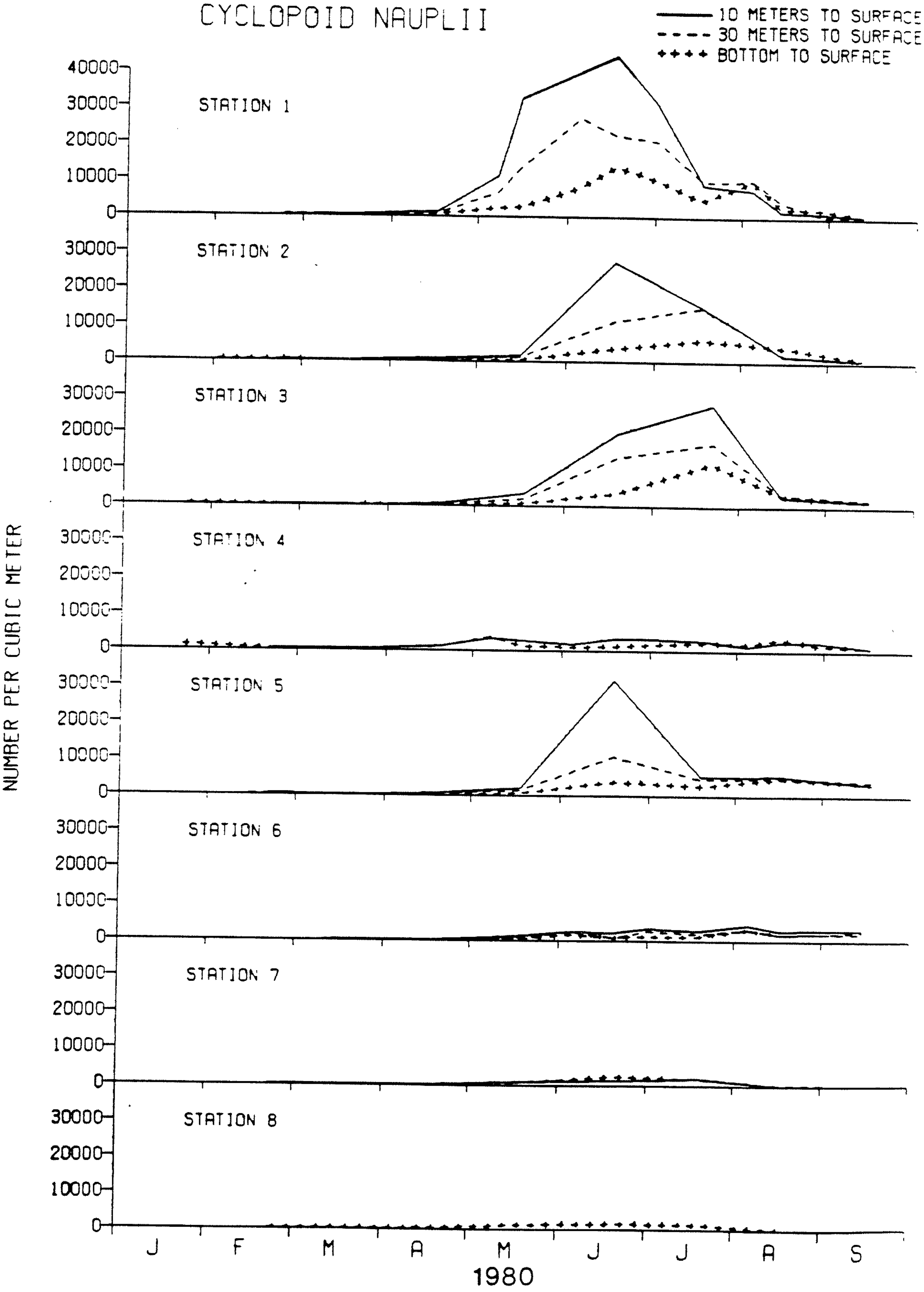

Figure 33. Cyclopoid nauplii abundance in Roosevelt Lake from January to September 1980.

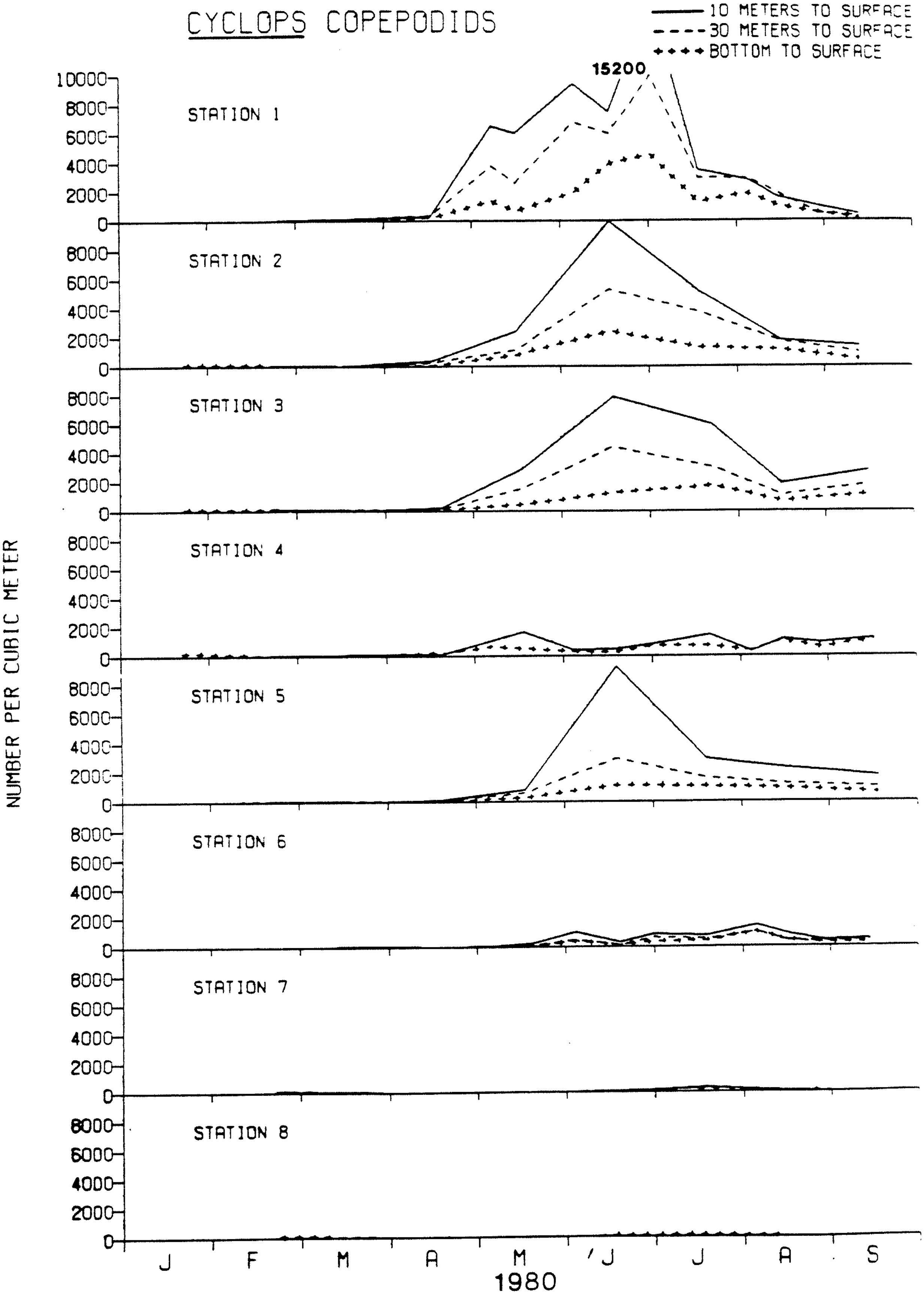

Figure 34. Cyclops copepodid abundance in Roosevelt Lake from January to September 1980.

(1977a) noted high concentrations in the forebay from June to September. Peak concentrations were generally noted to increase at the main reservoir stations from station 8 to station 1, with long developmental times and low retention times probably limiting populations upstream.

Increasing *Cyclops* copepodid abundance in the main reservoir of Roosevelt Lake was concurrent with high rotifer densities, while low rotifer and *Cyclops* densities were noted at station 4. Additionally, the decline in *Synchaeta*, *Keratella* and *Polyarthra* abundance at stations 1 to 3 coincides with high *Cyclops* copepodid densities.

Cyclops copepodid predation on rotifers is well documented (Fryer 1957, McQueen 1969, Williamson and Gilbert 1980). Although evidence is at present circumstantial, some interdependence between rotifer and *Cyclops* populations in determining temporal and spatial abundance patterns during the study period is implied.

6.3.4 Cladocera

6.3.4.1 *Daphnia*. The abundance of the dominant *Daphnia* species in Roosevelt Lake are presented in Figures 35 to 37. Maximum *Daphnia* densities occurred in the upper 10 meters of the water column throughout the majority of the sampling period.

D. galeata was the most abundant cladoceran in the reservoir, with a peak density of $4620/m^3$. *D. galeata* was, except for one date, the dominant *Daphnia* species at the main reservoir stations 2, 3, 5, 6, 7 and 8. High densities were noted from June to September at stations 2, 3 and 5, with concentrations generally decreasing upstream and downstream from these stations.

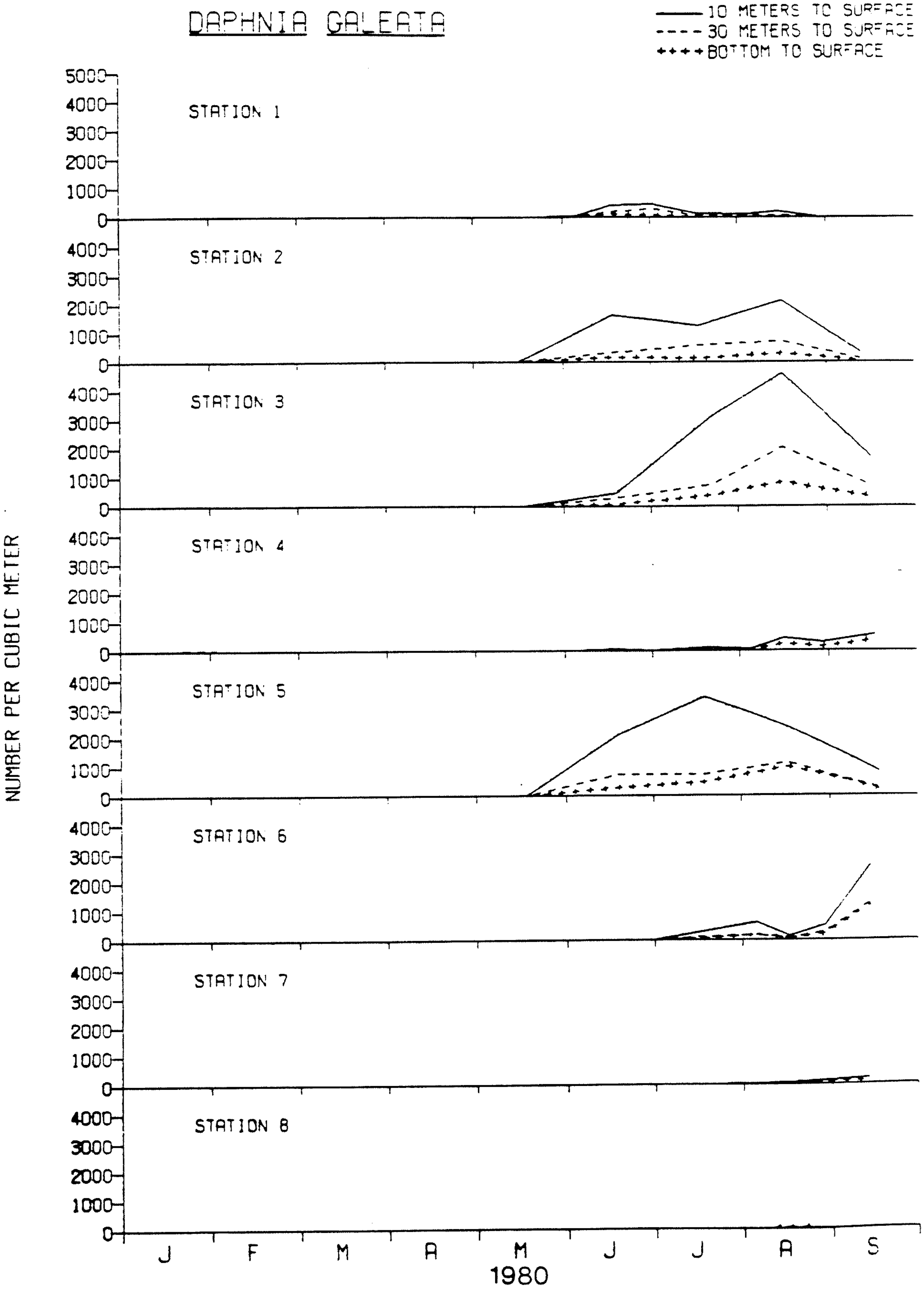

Figure 35. Daphnia galeata mendotae abundance in Roosevelt Lake from January to September 1980.

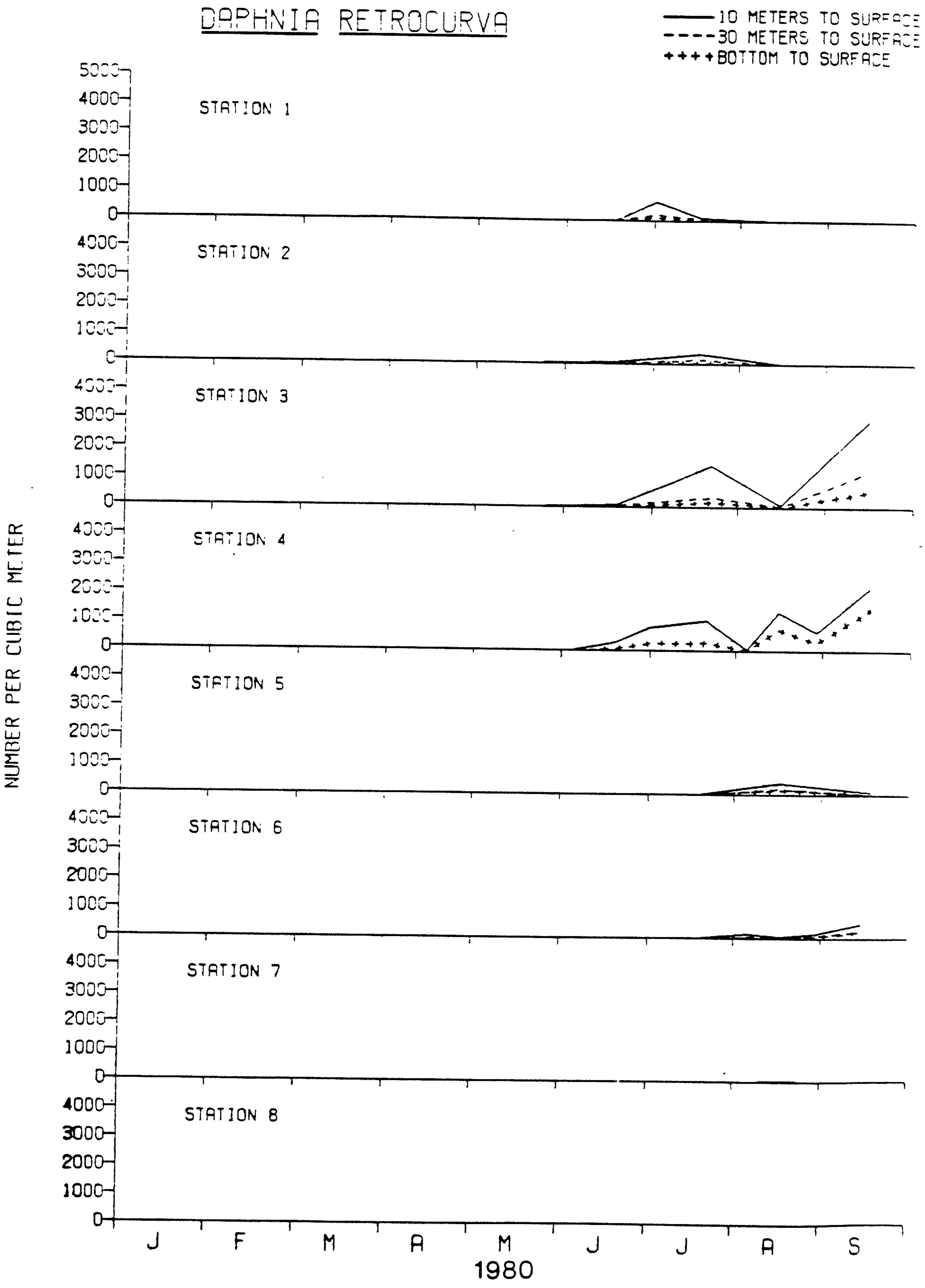

Figure 36. Daphnia retrocurva abundance in Roosevelt Lake from January to September 1980.

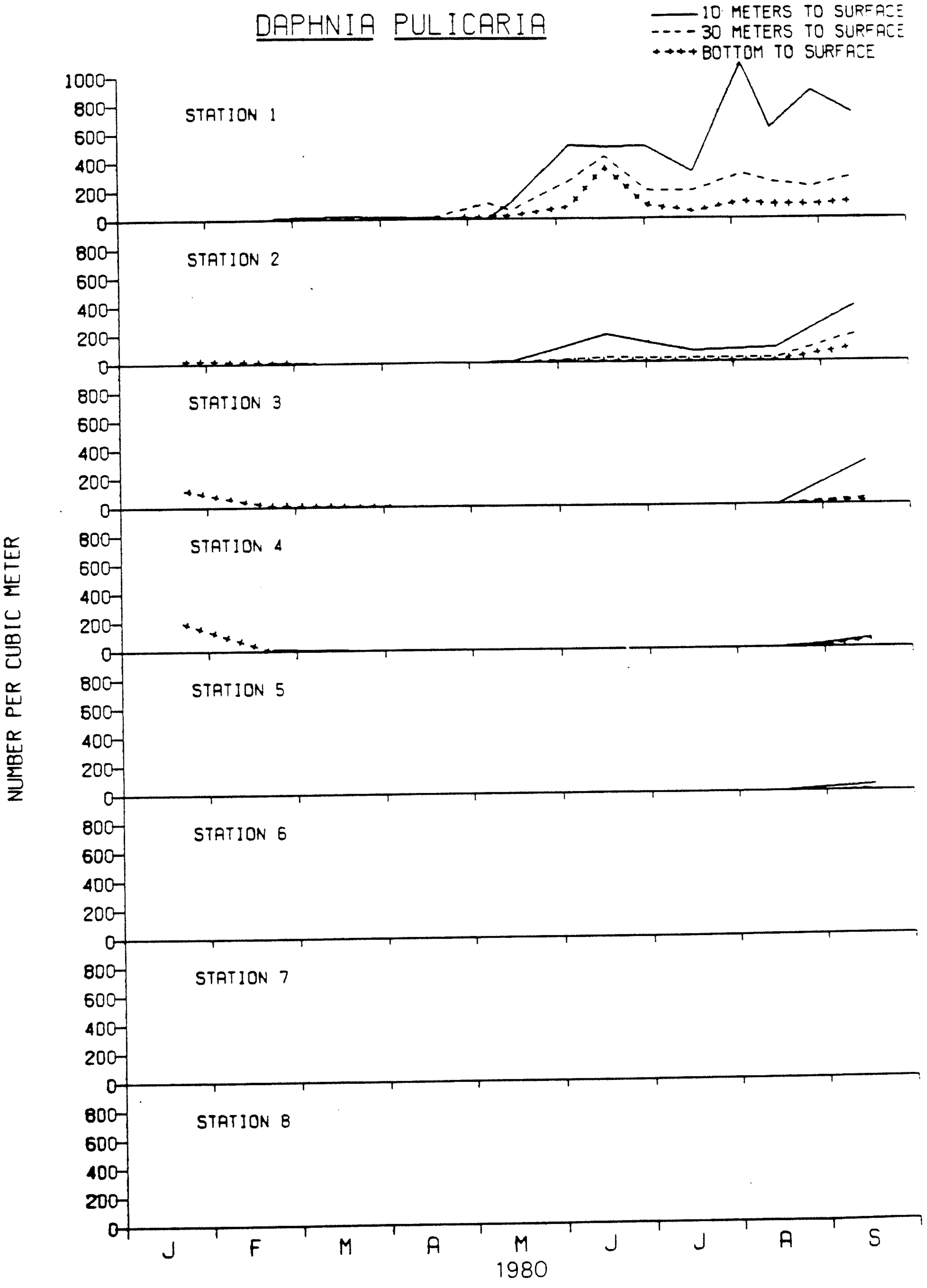

Figure 37. Daphnia pulicaria abundance in Roosevelt Lake from January to September 1980.

D. retrocurva was the dominant Daphnia species at station 4. Substantial populations of over $1000/m^3$ in the upper 10 meters at times occurred in the main reservoir at station 3. However, low abundances upstream and downstream from station 3, and high densities at station 4 during these periods suggest that peak concentrations at station 3 are derived primarily from the inflow of Spokane River populations.

D. pulicaria is the largest of the Daphnia species encountered in the reservoir. D. pulicaria was the dominant daphnid at station 1, with highest concentrations from June to September. Peak densities at station 2 also occurred from June to September, but concentrations were an average 3 times lower than at station 1. Densities at stations 3 to 8 were typically low and often below detection limits.

Daphnia is an important food item to planktivorous fish (Brooks 1968), including rainbow trout (Salmo gairdneri) (Galbraith 1967) and kokanee (Oncorhynchus nerka) (Lewis 1974). Peak Daphnia densities in Roosevelt Lake were recorded at $4710/m^3$, $2090/m^3$ and $1820/m^3$ for tows from 10 meters, 30 meters, and the bottom to the surface, respectively. Comparison of these values with Daphnia densities from two locally productive kokanee lakes showed similar peak densities to Pend Oreille Lake (Rieman and Bowler 1980) but levels below those in Banks Lake (Stober et al. 1977a). It should be emphasized that these comparisons are approximate at best, due to unknown yearly variation in Roosevelt Lake Daphnia estimates, and gear and sampling differences between studies. Seasonal abundance is also important, but evaluation and comparison are beyond the scope of this study. Low densities at stations 6, 7 and 8 suggest limited availability of Daphnia as a food source to fish species in the upper areas of the reservoir.

An important facet of *Daphnia* population dynamics in the main reservoir is exemplified by the spatial variation observed. *Daphnia* populations, similar to the other zooplankton, develop as the water mass moves downstream, with densities increasing over time and resulting in higher concentrations downstream. Generation times have been reported at 16.9 days at 20°C for *D. galeata* and at 18 days at 20°C for *D. pulex*, a species almost identical to *D. pulicaria* (Taylor 1980). These generation times are a minimum of 1/2 to 1/5 of the retention times in summer and probably do not allow substantial development before the population is transported downstream. In fact, significant populations did not develop at stations until September, concurrent with high water temperatures of 17°C and a maximum retention times during the study period of 80 days. Low *Daphnia* densities upstream may be also related, in part, to turbulence, as Hynes (1970) noted *Daphnia* to be virtually absent from river systems.

6.3.4.2 *Leptodora*. *Leptodora kindtii* showed greatest densities in the 10-meter samples (Fig. 38). Highest concentrations occurred during the summer, with levels above $20/m^3$ in the upper 10 meters of the water column at stations 3 and 5 from June to August. Densities in the main reservoir from station 8 to peak levels at stations 3 and 5, and subsequently declined downstream. *Leptodora* showed a distinct peak at station 4 in July, with a maximum concentration of $56/m^3$.

Leptodora densities were low when compared to other zooplankton species in Roosevelt Lake. However, the large size of *Leptodora*, with a total length

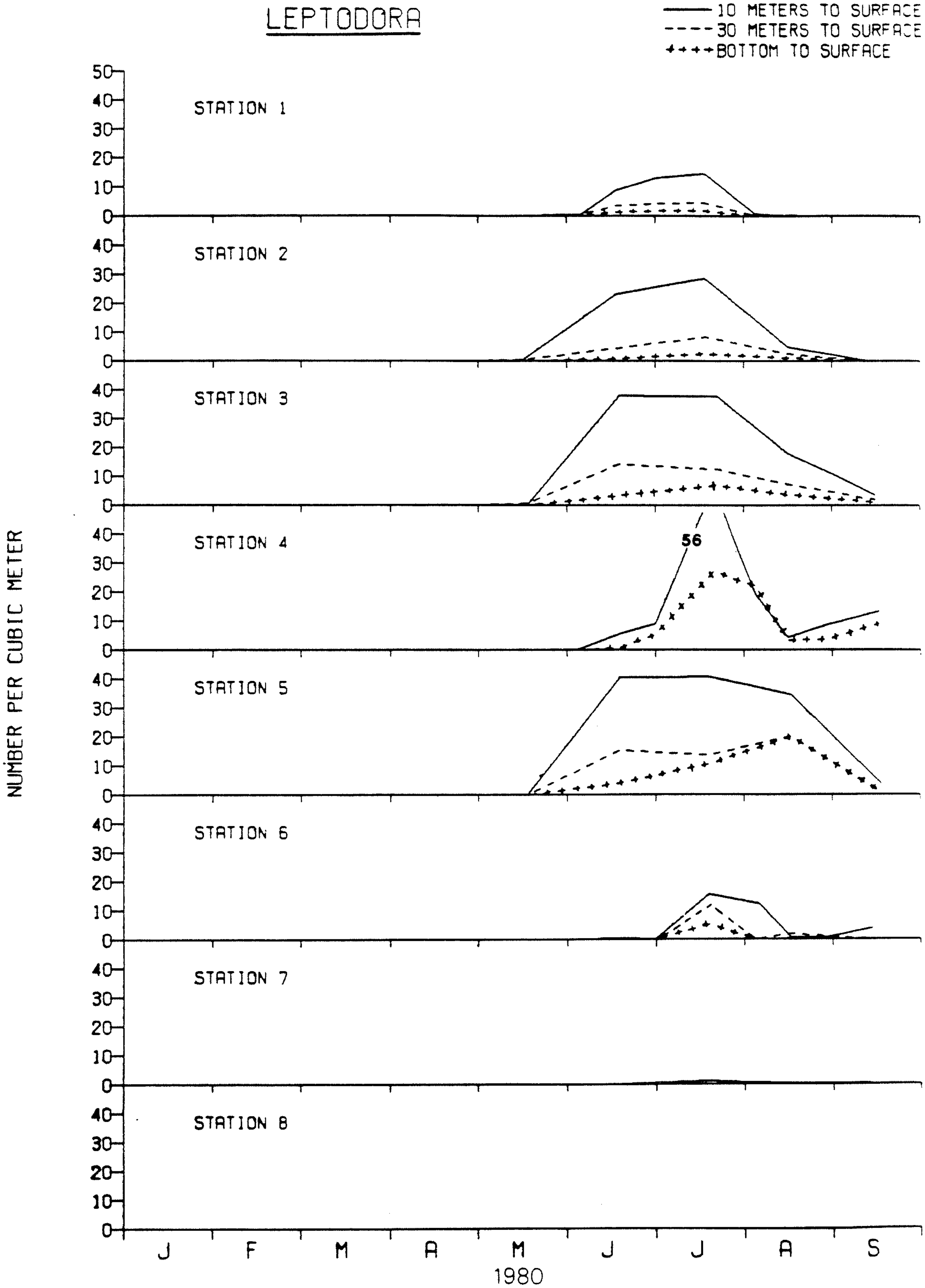

Figure 38. Leptodora kindtii abundance in Roosevelt Lake from January to September 1980.

of up to 13 mm observed in reservoir samples, suggests a much greater contribution to the zooplankton community in terms of biomass. Leptodora has been indicated as a prey species of planktivorous fish (Sebestyen 1960).

6.3.4.3 Bosmina. The abundance of Bosmina in Roosevelt Lake was typically low during the study period, with peak concentrations exceeding $200/m^3$ only at stations 1 and 4 (Fig. 39). Stober et al. (1977a) noted a similar low abundance in 1976, with densities in the forebay typically below $400/m^3$. Highest densities occurred during summer at stations 2 to 8, while levels at station 1 were maximal in early June.

In contrast to Daphnia populations, Bosmina densities at stations 6 and 7 were similar to downstream levels and Bosmina populations also developed earlier than Daphnia populations at the upstream stations. Generation times for Bosmina have been noted at 9 days at 20°C (Taylor 1980), or about 1/2 the generation times of D. galeata and D. pulex. The shorter generation times of Bosmina may allow for the more rapid development of populations at the upstream stations.

Bosmina populations showed maximum densities in both the upper 10-meter and the bottom tows, with densities in the 30-meter tows generally being intermediate. This variable depth distribution was related to Leptodora populations. Leptodora has been previously shown to be predatory on Bosmina (Cummins et al. 1969). Leptodora in Roosevelt Lake showed highest densities in the upper 10 meters of the water column. Periods of low Leptodora abundance at stations 1 to 6 coincided with peak Bosmina concentrations in the upper 10 meters of the water column. In contrast, high Leptodora densities

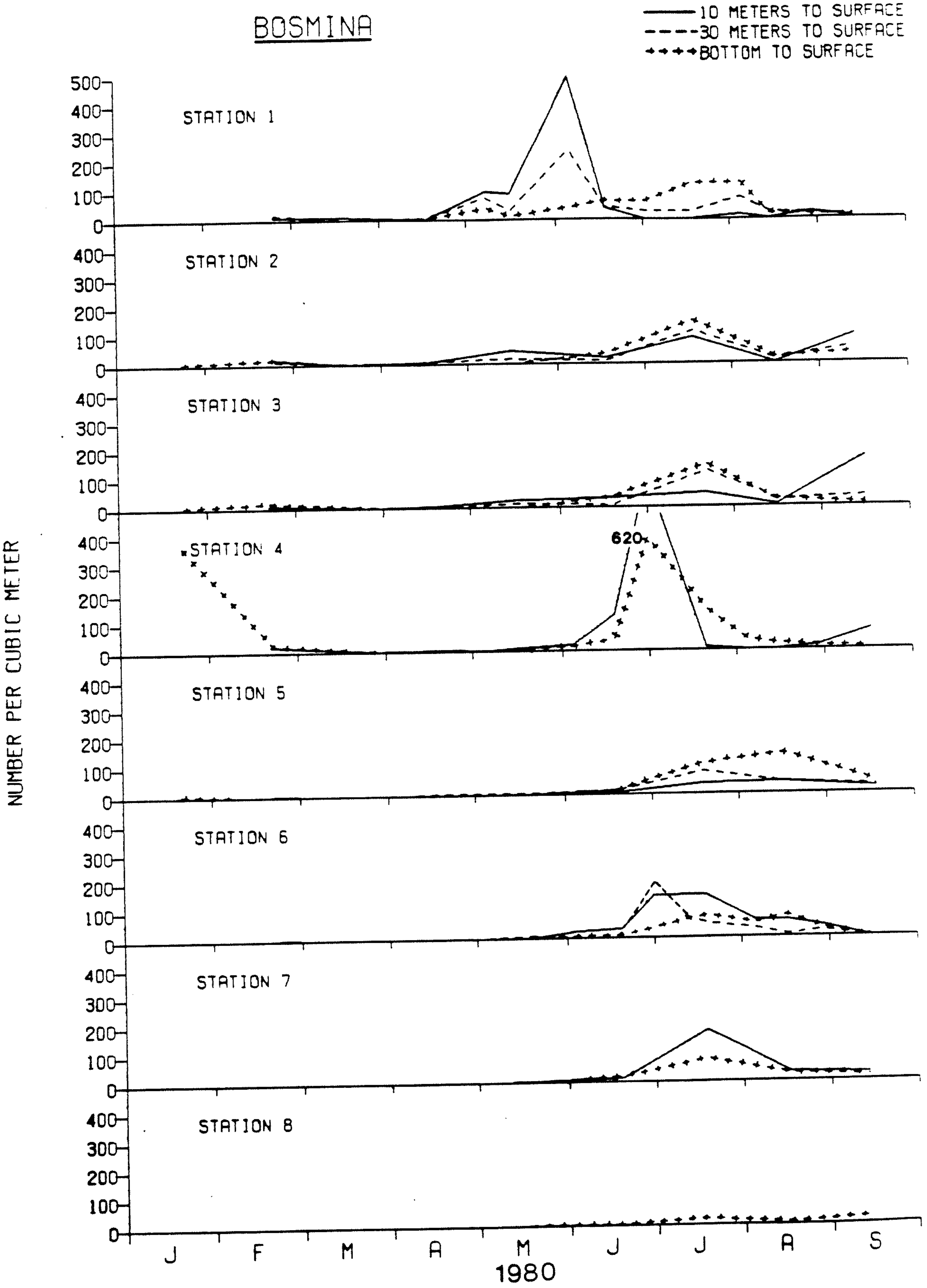

Figure 39. Bosmina abundance in Roosevelt Lake from January to September 1980.

typically were concurrent with peak Bosmina densities in the bottom to surface tows, indicating that Bosmina was most abundant below 30 meters. Additionally, station 7, with very low Leptodora densities, showed peak Bosmina abundance in the upper 10 meters throughout the study period. Although evidence is circumstantial, it appears that Leptodora does have some impact on Bosmina depth distribution. However, it is unclear whether the occurrence of Bosmina lower in the water column is a vertical change of position in response to increased predation by Leptodora or a result of the reduction of surface populations by increased mortality from predation.

6.3.4.4 Diaphanosoma. Substantial populations of Diaphanosoma were limited to stations 1 to 5 (Fig. 40). Highest concentrations occurred in the summer, with a maximum density of $1040/m^3$ recorded in the upper 10 meters of the water column at station 3. Diaphanosoma depth distribution was similar to that of Daphnia, with peak concentrations generally in the upper 10 meters of the water column.

6.3.5 Mysids

Twenty-seven Mysis relicta were collected in a 10-minute tow at station 7, but no mysids were found in other areas sampled. The mysids ranged in size from 7 mm to 13 mm in total length. Cursory examination of mysid stomachs revealed the remains of D. galeata, Bosmina, Alona, Keratella and copepods.

Introductions of Mysis relicta into temperate lakes are well documented (Gosho 1975). Recent investigations have focused on the impact of Mysis relicta to the zooplankton community following the establishment of self-

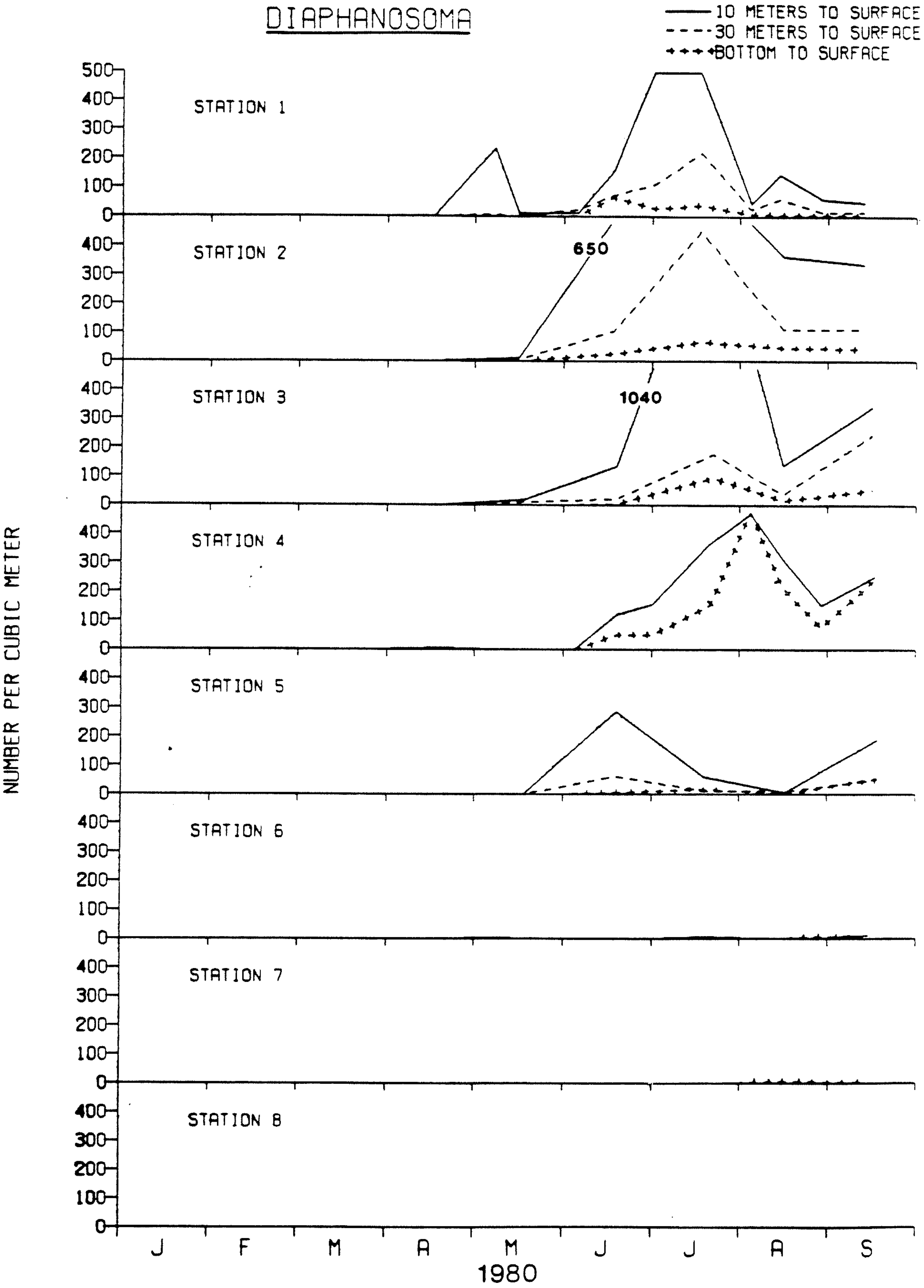

Figure 40. Diaphanosoma leuchtenbergianum abundance in Roosevelt Lake from January to December 1980.

sustaining populations. Rieman and Bowler (1980) implicated mysid predation in Pend Oreille Lake as being responsible for a shift in dominance from *Daphnia thorata* to *D. galeata* and for the restriction of peak cladoceran populations to short periods in summer. The disappearance of *Daphnia pulicaria*, *D. rosea* and *Bosmina longirostris* from the plankton of Lake Tahoe has been attributed to mysid predation (Goldman 1974). Additional studies have shown *Mysis relicta* to substantially deplete standing crops of *Epischura*, *Diaptomus* and *Kellicottia* (Threlkeld et al. 1980). This alteration of the zooplankton community by selective mysid predation has resulted in the decline of kokanee populations in Pend Oreille Lake (Rieman and Bowler 1980) and in Lake Tahoe (Morgan et al. 1978).

The application of previous investigations to predict future impacts of *Mysis relicta* in Roosevelt Lake is tenuous. Detailed investigations have been primarily confined to lake ecosystems with high retention times, while Roosevelt Lake represents a substantially different set of conditions imparted by the flowing water mass and the low retention times. However, the adaptability and success of *Mysis relicta* when introduced to various lake ecosystems, and the voracious nature of this predator and its ability to effect major change in the zooplankton community indicate the potential for significant impacts to Roosevelt Lake ecology.

6.4 Trophic Status

Nutrient, chlorophyll *a* and primary production estimates determined in Roosevelt Lake were compared to values employed in various lake classification schemes (Table 13). Using orthophosphate, total-P and primary production

Table 13. Summary of several trophic state indicators determined in Roosevelt Lake from December 1979 to September 1980.

Criteria	Roosevelt Lake Main Reservoir	 Spokane River Arm	Oligotrophic	Mesotrophic	Eutrophic	Source
Nitrate - N µg/ℓ (winter mean)	109	523			> 300	Welch and Spyridakis (1972)
Orthophosphate - P µg/ℓ (winter mean)	29	17			> 10	Welch and Spyridakis (1972)
Total P µg/ℓ	35	33	0-10	10-30	> 30	Vollenweider (1968)
Chlorophyll a (mg/m^3) (May-September mean)	4.6	7.0	0.3-3	2-15	10-500	Likens (1975)
mg C/m^2/day (May-September mean)	1247	1198	50-300	250-1000	> 1000	Likens (1975)

values, the main reservoir and the Spokane River arm classify as slightly eutrophic. Chlorophyll a values indicated a mesotrophic classification over the entire reservoir, while nitrates suggest slightly eutrophic conditions in the Spokane River arm and oligotrophic to mesotrophic conditions in the main reservoir.

Discrepancy between the various classification schemes is inherent in any artificial grouping and, hence, trophic classifications should be viewed in a general way (Wetzel 1975). Additionally, caution should be exercised when comparing reservoir values to classification schemes based on data derived from lakes (Stober et al. 1977a). Considering these shortcomings, Roosevelt Lake should be considered under a broad trophic range of mesotrophic to slightly eutrophic.

7.0 CONCLUSIONS

Roosevelt Lake is a complex reservoir ecosystem. Limnological conditions encountered during this study varied spatially and temporally on a continuum from an essentially lotic environment with high water velocities to circumstances characteristic of a lentic system. Associated variation in physical, chemical and biological parameters were noted.

Of particular interest from a management standpoint is the influence of operational procedures on the biotic components of the reservoir. Changes in reservoir operation would be expected to modify, among others, turbulence and retention times in the reservoir through altered discharge rates and drawdown levels for hydroelectric generation and irrigation diversion.

Turbulence was, in part, responsible for the lack of stratification at the upper end of the reservoir during the phytoplankton growing season. The result was a constant supply of nutrients (N and P) in the euphotic zone with levels approaching limiting conditions primarily during periods of low nutrient inflow. In contrast, downstream stations showed nutrient limitation from nutrient depletion by phytoplankton utilization and from reduced mixing during stratified periods. However, high turbulence also has a negative effect on production by moving cells into and out of the euphotic zone (Wetzel 1975). Low phytoplankton standing crops upstream suggest that turbulence had a more inhibitory than enhancing effect on phytoplankton production at upstream current velocities. The effects of turbulence on zooplankton populations was not investigated.

The importance of retention times to the development of zooplankton populations in Roosevelt Lake has been expressed previously (Robeck et al. 1954, Kiser 1963). Our data tends to confirm this idea, with retention times and zooplankton generation times interacting with other factors to determine the spatial and temporal abundance and composition of the zooplankton community.

The effects of dam operation on turbulence and retention times and the relation of turbulence and retention times to several aspects of Roosevelt Lake limnology logically implies a relation of dam operation to reservoir limnology. However, accurate prediction of the impact of operational changes on Roosevelt Lake limnology requires additional information.

8.0 RECOMMENDATIONS

1. Additional baseline sampling is required to provide information on reservoir limnology during fall and to determine the yearly variation in the presently observed temporal and spatial patterns. Information generated in subsequent years should also provide insight into the effects of operational changes on Roosevelt Lake ecology.
2. Determination of the effects of turbulence via the measurement and correlation of velocity with limnological parameters is regarded as essential to a complete understanding of the ecology of the reservoir. This information is especially important in the upper sections of the reservoir, where turbulence is highest. Accurate calculation of the residence times of water in various areas of the reservoir from velocity measurements should assist in explaining the development of zooplankton populations.
3. Additional sampling near the confluence of the Spokane River arm with the main reservoir is suggested to determine the contribution of nutrients, phytoplankton and zooplankton standing crops from the inflow of Spokane River water seasonally and at various drawdown levels.
4. An experimental approach in future zooplankton studies emphasizing generation times and reproductive rates of the major copepod and cladoceran species under various conditions is suggested. This information is essential to a thorough understanding of population development over the length of the reservoir.
5. Investigations on the effect of the depth and volume of water discharged on zoo- and ichthyoplankton entrainment through the dam are recommended.

6. Evaluation of the phytoplankton and zooplankton production in selected bay and other near-shore areas to assess near-shore ecology and contribution to the main reservoir is recommended.
7. Analysis of benthic populations over the reservoir is suggested to assess additional fish food resources.
8. The immigration and establishment of *Mysis relicta* may have substantial implications to reservoir ecology. Investigations into the ecology of this predator under reservoir conditions are essential to assessing the potential impact to Roosevelt Lake ecology and to the ecology of downstream reservoirs in the future.
9. These data should be correlated with the distribution and abundance of the important reservoir fishes and their food habits to define the forage base essential to the sustained production of adequate sport fish populations.

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Appendix Table 1. Oxidation-reduction potentials (mV) for selected depth strata in Roosevelt Lake from December 1979 to September 1980.

Station	Depth	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
9	1 m	+	321	348	336	345	352	352	362	370	391
1	*0-6	295	+	354	347	345	330	316	352	343	372
	** B4	301	+	366	366	370	419	422	419	432	450
	*** WC	299	+	360	360	361	390	391	397	398	422
2	0-6	+	271	358	347	340	343	295	332	350	365
	B4	+	295	371	360	369	419	413	421	432	434
	WC	+	286	365	357	360	392	378	389	402	414
3	0-6	334	266	348	358	338	348	286	335	343	354
	B4	315	292	366	371	372	419	395	425	424	418
	WC	334	281	359	366	359	395	375	391	394	387
4	0-6	332	254	346	360	340	340	262	333	316	361
	B4	333	259	360	371	357	404	394	426	421	395
	WC	333	256	354	366	349	362	342	375	365	373
5	0-6	+	270	348	360	324	361	285	340	357	368
	B4	+	288	360	371	360	406	384	407	444	423
	WC	+	281	354	366	343	385	356	384	402	400
6	0-6	333	333	354	353	347	363	327	349	354	373
	B4	345	339	360	360	360	397	378	397	427	421
	WC	339	335	356	356	355	382	360	376	398	391
7	0-6	+	326	347	362	343	369	355	357	354	381
	B4	+	+	355	370	350	387	379	380	388	397
	WC	+	+	351	366	347	379	371	370	370	389
8	WC	318	333	352	361	340	375	364	365	368	384

* 0-6: Mean of surface to 6 meters.

** B4: Mean of bottom 4 meters.

*** WC: Mean of water column.

Appendix Table 2. Mean water column total filterable residue (mg/l) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

	Station								
Month	9	1	2	3	4	5	6	7	8
December		99		90		90		92	101
January	104		96	99	98	95	92	96	104
February	136	117	150	212	177	132	175	158	151
March	99	95	100	91	105	104	107	110	82
April	157	99	101	97	105	101	105	94	61
May	101	108	92	58	82	89	94	104	64
June	69	64	67	61	68	68	68	63	57
July	88	86	84	88	92	93	84	93	63
August	95	113	111	97	101	85	93	94	85
September	65	63	65	55	75	73	68	62	81

Appendix Table 3. Mean surface and bottom NH_4+NO_2 (µg/l) in Roosevelt Lake and the tailrace from December 1979 to September 1980.

	Station															
	9	1		2		3		4		5		6		7		8
Month	S	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S
December	+	7	14	+	+	22	25	24	35	+	+	14	14	+	+	17
January	14	+	+	14	14	20	21	55	55	23	24	23	24	28	+	42
February	20	20	22	25	22	19	22	59	81	15	16	30	28	27	25	39
March	10	12	13	12	21	33	41	32	32	29	37	47	48	92	93	64
April	13	8	28	9	23	7	62	16	24	5	35	25	38	28	27	19
May	10	7	29	7	31	5	23	4	16	2	9	15	23	7	10	10
June	10	2	17	3	7	8	17	8	24	3	8	11	8	11	6	11
July	6	7	8	8	8	8	14	20	12	8	54	7	15	11	16	9
August	4	9	4	2	3	13	11	7	4	23	7	16	9	6	31	12
September	6	7	5	5	3	10	8	8	90	9	40	23	62	11	16	11

Appendix Table 4. Mean surface and bottom total organic carbon concentrations (mg/l) in Roosevelt Lake and the tailrace from December 1979 to July 1980.

	Station														
	9	1		2		3		4		5		6		7		8
Month	S	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S
December	+	5.2	11.7	+	+	10.6	10.4	1.2	2.7	+	+	5.2	3.1	+	+	6.2
January	2.7	+	+	1.4	14.5	1.0	1.6	2.8	3.6	1.8	8.6	4.4	1.8	8.3	+	1.9
February	2.6	1.9	2.2	3.8	2.9	1.6	7.4	5.0	3.6	1.6	6.8	2.7	1.7	2.9	1.3	2.2
March	1.4	4.5	2.8	2.6	2.9	3.7	8.5	3.2	3.5	1.9	5.7	2.7	5.3	3.4	1.1	3.6
April	2.1	1.4	1.7	2.1	1.8	3.1	0.5	2.3	1.9	1.9	1.8	2.2	1.7	2.0	2.1	1.7
May	4.0	3.4	2.4	4.4	2.0	3.8	3.8	2.3	1.9	3.6	2.8	3.3	4.3	3.7	3.9	3.3
June	3.4	4.4	3.3	4.9	2.5	2.9	4.4	4.9	3.7	3.7	3.6	5.6	5.4	3.1	3.4	4.9
July	4.6	5.3	7.6	6.3	3.9	+	+	+	+	+	_	4.3	+	4.0	+	+