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Dear Dr. Darby,

I'm sorry this is so late, pure procrastination on my part. Better late than never! I'm leaving for Africa today, Yahoo!! John and I are going to bum around in a land rover for two wks. Are you jealous?!! We'll be back just before the end of the year.

I have sent an abstract off to the ASLO meeting and plan to give a talk at their June conference in Mpls. When I get back from Africa, in Jan. I plan to pull a paper out of the thesis and send it to the Jour. of Grt. Lakes Res. Ha! ... famous last words!

Thanks again for all your help!

Sincerely,
Barbara Halfman

SUSPENDED SOLIDS IN THE
WESTERN ARM
OF
LAKE SUPERIOR

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
BY
BARBARA MARY HALFMAN

IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
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ACKNOWLEDGEMENTS

I gratefully acknowledge the many people who made this project possible. Sea Grant Institute provided partial funding with a Sea Grant traineeship. Dave Anderson, I thank for his cheerful piloting of the R/V Viking. Dr. Steve Eisenreich and Joel Baker helped both with fieldwork and with interpretation of the field results. Dr's R. W. Ojakangas and D. Schimpf gave helpful advice on the writing and organization of the manuscript. Dave Darby gave invaluable advice on the manuscript and also made long distance connections much easier. John Kingston deserves special thanks for his patient instruction and review of my diatom studies. A special thanks also goes to Tom Johnson, a good friend and advisor whose ready help and timely suggestions for work in the field, in the lab, and on the manuscript ensured smooth progress towards completion of the project.

Saving the best for last, I want to thank my husband, John. Without his help, encouragement, warm support and love, I'd have given up the first time things got tough. Thanks, buddy.

Dr. Darby,
Just a general heartfelt
thank you. An item by item
list would make a volume.

Barbara Halfman
12-6-84

ABSTRACT

Suspended solids in the western arm of Lake Superior were analyzed for their distribution and composition. A grid of up to 26 stations was selectively sampled from spring mixing in May 1983 to fall overturn in October 1983. Water temperatures and turbidity (as percent light transmission) were monitored for temporal and spatial change. Suspended solids were analyzed for concentration, grain size, organic carbon, chlorophyll-a, phaeophytin, and diatom species abundances.

This study provides the first substantial evidence for the existence of a persistent, well-developed nepheloid layer in the bottom 10 to 20 m of the western arm of Lake Superior. A layer of suspended particulates near the lake floor, derived from river suspended load from spring runoff, wave erosion of the Wisconsin shoreline, and resuspension of lake floor silt and clay, developed in spring during the onset of thermal stratification. The nepheloid layer was well-developed and persistent throughout the period of thermal stratification. The details of mechanisms contributing to the maintenance of the layer are uncertain. The layer may be supplemented by sediment introduced by density flows, abrasion of the thermocline against the bottom in shallow depths, and/or local resuspension. Extremely low shear velocity values (U* values typically 1.0 to 4.0 x 10^{-3} cm/sec), calculated from concentration

gradients and low resuspension rates taken from the sediment load, suggest that very little energy is needed to maintain the layer. Comparisons of sedimentation rates and the spring runoff sediment load indicate that the nepheloid layer does not contribute a significant amount to the sediment budget for the extreme western arm of the lake. Fall overturn disrupts the bottom turbidity and sediment is more uniformly distributed throughout the water column. The destratification probably allows much of the suspended solids to move out of the study area in the extreme western arm into other portions of the lake.

The median grain size of the suspended solids ranged from 3.6 to 6.8 um (8.1 to 7.2 phi) and was moderately sorted (standard deviations of .75 to 1.0 phi) and very to extremely leptokurtic (2 to 3). Particulate organic carbon was typically 29% of the total suspended solids in surface waters and 10% below the thermocline. Concentrations of particulate organic carbon ranged from 0 to 2.0 mg/l. The concentrations of chlorophyll-a and phaeophytin averaged 3.7 ug/l and 0.4 ug/l respectively. These concentrations are typical of an oligotrophic to ultra-oligotrphic lake.

Common diatom species and species succession trends in this study were comparable to those of earlier studies. The enumeration of diatoms indicates a potential usefulness for certain diatom species as tracers of polluted water from the Duluth/Superior harbor into the lake.

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INTRODUCTION

The role of suspended solids in water has received an increasing amount of attention in recent years. Studies of suspended particles in the oceans have ranged in scale from whole ocean basins (Atlantic Ocean: Biscaye and Eittreim 1977) through specific areas within basins (e.g. Northern Bering Sea: McManus and Smyth 1970; Northern Gulf of Mexico: Manheim et al. 1972) to estuaries and fjords (Castaing and Allen 1981; Syvitski and Murray 1981). The focus of suspended sediment studies has been on widely varying aspects of suspended matter. Temporal and spatial distributions have been studied by Bothner et al. (1981) and Young et al. (1981). Changes in concentration and response to storms have been studied by Rudolfo et al. (1971), Young (1978) and Cacchione and Drake (1982). Response to upwelling and waves has been treated by Karl et al. (1981), Clarke et al. (1982) and Kennedy et al. (1981). Various other reports deal with compositions, transport mechanisms, resuspension and sources of suspended solids.

Biscaye and Eittreim (1977) found that suspended particulate matter, by virtue of its action as an extractor, transporter and source within the water column, is responsible for maintaining most oceanic chemical concentration gradients. Bothner et al. (1981) stated that the surfaces of organic and inorganic particles have high affinities for pollutants such as trace metals, PCB's, and petroleum, with the result that the fate and transport of these may be controlled by distribution, composition and concentration of suspended matter.

The study of suspended particles in lacustrine systems has been, in contrast to marine systems, relatively neglected. Pharo and Carmack (1979) dealt generally with sedimentation processes in a small intermontane lake in British Columbia. Dominik et al. (1983) did a preliminary investigation on the Rhône River plume into Lake Geneva. Some work on suspended particulates has been done in the United States. Chambers and Eadie (1981) identified persistent suspended particulates in Lake Michigan. Harrsch and Rea (1983) subsequently determined the composition and distribution of these during summer stratification. Lee et al. (1981) reported on the entrainment and deposition of fine-grained sediments under steady flow conditions from Lake Erie.

The common occurrence of a substantial red clay turbidity plume entering the western arm of Lake Superior (Figure 1) from the Nemadji River via the Superior entry prompted several workers to take advantage of the remote sensing capabilities of Landsat I. Sydor (1975) attempted to provide a numerical model for the dispersal of this plume based on ERTS imagery and ground truth measurements. Diehl et al. (1977), using Landsat I data in part, calculated transport patterns in response to wind stresses on the lake.

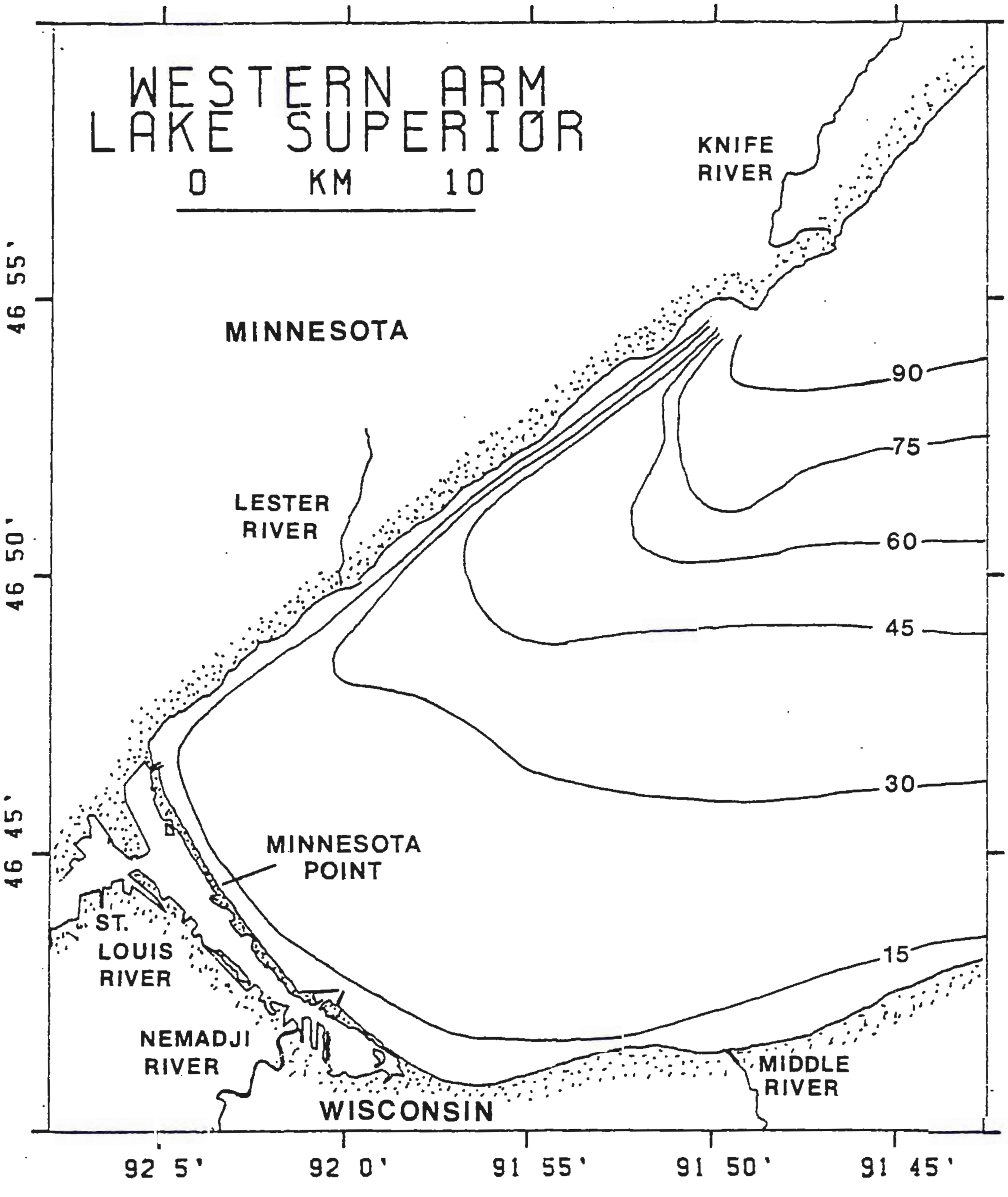


FIGURE 1: Map of study area in Lake Superior. Contour interval is 15 meters.

DATE OF CRUISE	DAY NO.	STATIONS
5/18/83	138	1, 2, 3, 4, 5, 6, 7, 8, 9
6/07/83	158	1, 2, 3, 4, 5, 6, 8
6/08/83	159	3
6/09/83	160	3, 10, 11, 12
6/23/83	174	1
6/27/83	178	2, 3
6/30/83	181	1, 9, 10, 11, 12
7/05/83	186	1, 2, 3, 4, 9, 10, 11, 12
7/13/83	194	4, 11, 12
7/19/83	200	1, 2, 3, 4, 8, 9, 10, 11, 12
7/20/83	201	10
7/27/83	208	10, 12
8/02/83	214	A - W
8/17/83	229	10, 12
8/23/83	235	B - I, K - X, Z
8/31/83	243	P, 3, 10, 11, 12
9/09/83	252	10, 12
9/22/83	265	F - H, L - O, U
10/6/83	279	10, 12

TABLE 1a: Stations visited for each cruise date.

STATION	DEPTH (m)
1*	8
2*	29
3*	31
4*	27
5*	22
6*	20
7*	20
8*	22
9*	19
1	22
2	22
3	21
4	46
5	73
6	69
8	10
9	81
10	36
11	19
12	29

STATION	DEPTH (M)
A (8)	130
B	75
C	62
D (4)	46
E	19
F	21
G	44
H	55
I	72
J	111
K (9)	81
L	55
M	43
N (10)	36
O (11)	19
P	19
Q	31
R	40
S	46
T	34
U (12)	29
V	27
W (3)	20
X	25
Y	24
Z	22

TABLE 1b: Depth of water column at each station. Stars denote stations occupied on 5/18/83 only.

Schuter et al. (1978) and Sydor et al. (1978), using Landsat data applied to the red clay plume, discussed respectively, a horizontal eddy diffusivity term applicable to Lake Superior and the identification of specific contaminants within the plume. Little work has been done on suspended sediments in Lake Superior in addition to Landsat work except by Bahnick et al. (1978). They investigated chemical loadings to the lake by red clay erosion and resuspension and found that the particles in suspension have a large capacity for 'scrubbing' copper and manganese ions from Lake Superior water.

Bottom sediments in Lake Superior have been studied in some detail by various workers. Thomas and Dell (1978) described the surface sediments of the lake and their source, Pleistocene glacial deposits. Thomas and Jaquet (1975) used statistical parameters of grain size to describe the surficial sediments for the entire lake. Kemp et al. (1978) discussed sedimentation rates and a sediment budget for the lake and found that the majority of fine-grained modern sediment comes from the Wisconsin red clay bluffs. The bluffs are interpreted to be proglacial lacustrine deposits (Farrand 1969). The bluffs line the lake from the Apostle Islands to Duluth and constitute the only readily erodable shoreline on the lake, much of the rest of the shoreline is erosion-resistant bedrock (Matheson and Munawar 1978). Sedimentation rates based on ^{210}Pb geochronology were calculated by Evans et al. (1981). Johnson (1980) discussed post-glacial sedimentation in the lake based on seismic reflection profiles.

This project was designed to determine the distribution and composition of suspended sediments throughout the water column in the western arm of Lake Superior and to monitor any changes through an ice-free season. The concentration of suspended solids was measured both with filtering techniques and a transmissometer. Composition was separated into organic and inorganic fractions. The inorganic fraction was analyzed for grain size and the organic fraction was analyzed for percent organic carbon, chlorophyll-a, and phaeophytin. Special attention was paid to the movement of the inorganic fraction throughout the entire water column in order to supplement previous studies of the movement of surface suspended sediment in the lake (i.e., Sydor 1975, Schuter et al. 1978 and Sydor et al. 1978). Organic parameters were monitored in order to determine their contribution to the total supended sediment load and to see if they could be used to identify or 'tag' polluted water from the Duluth/Superior harbor. A limited survey of diatom abundance was undertaken to compare with the results from earlier phytoplankton studies (e.g. Munawar and Munawar 1978, Stoermer and Kreis 1978, and Thayer 1981), to determine their usefulness both to trace various sources of suspended sediment (e.g. harbor vs. open lake) and to identify resuspension events. Both the organic and inorganic fractions were monitored over time for changes in distribution with both depth and distance from the shoreline.

The results of this study provide new information about the composition, distribution, and movement of suspended solids in the western arm of Lake Superior. They aid in determining the fate and transport of chemical pollutants associated with them, and may also aid in future feasibility studies for the offshore disposal of harbor dredge spoils.

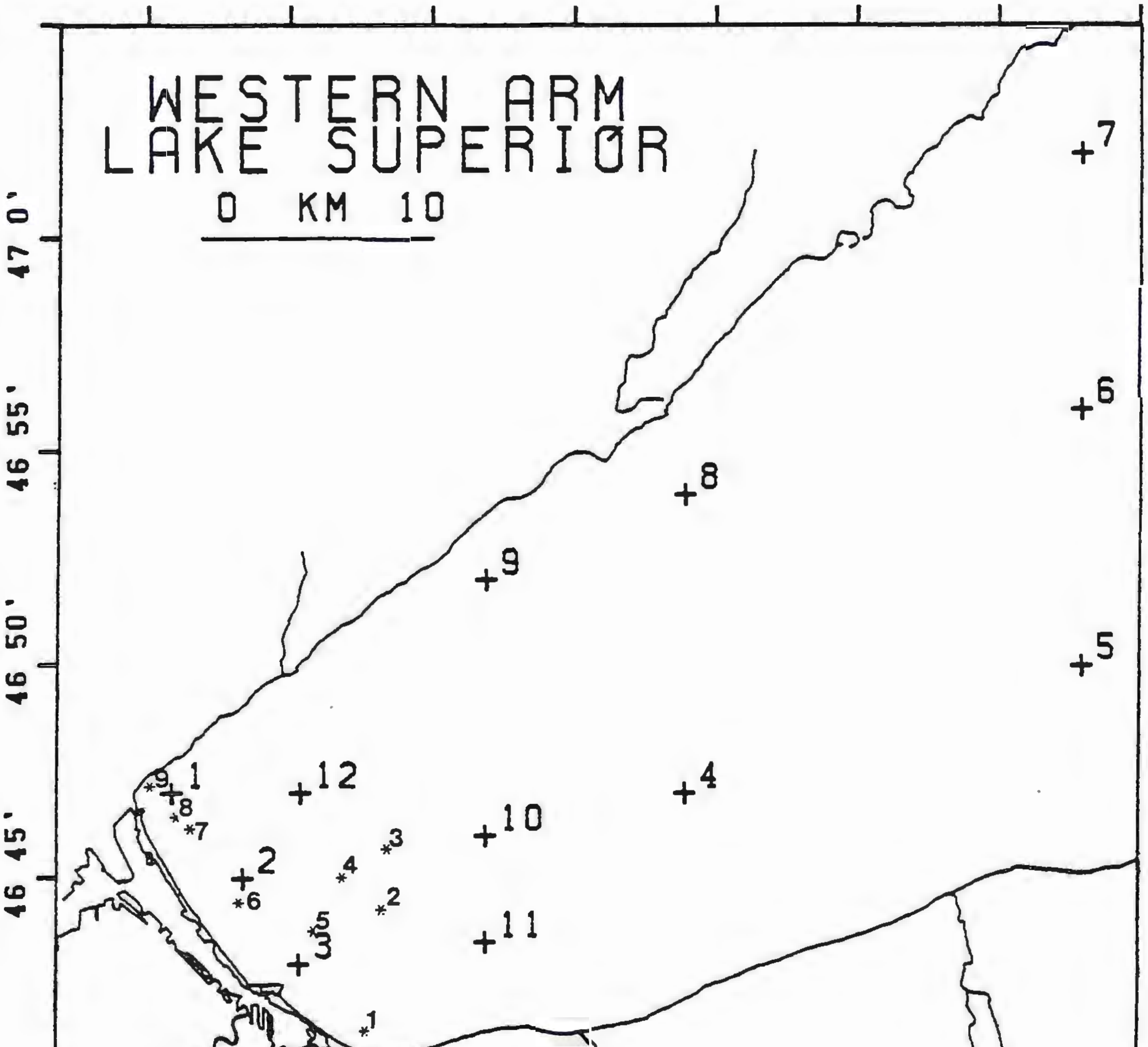


FIGURE 2: Location of numbered stations in the study area. Stars represent stations occupied on 5/18/83 only.

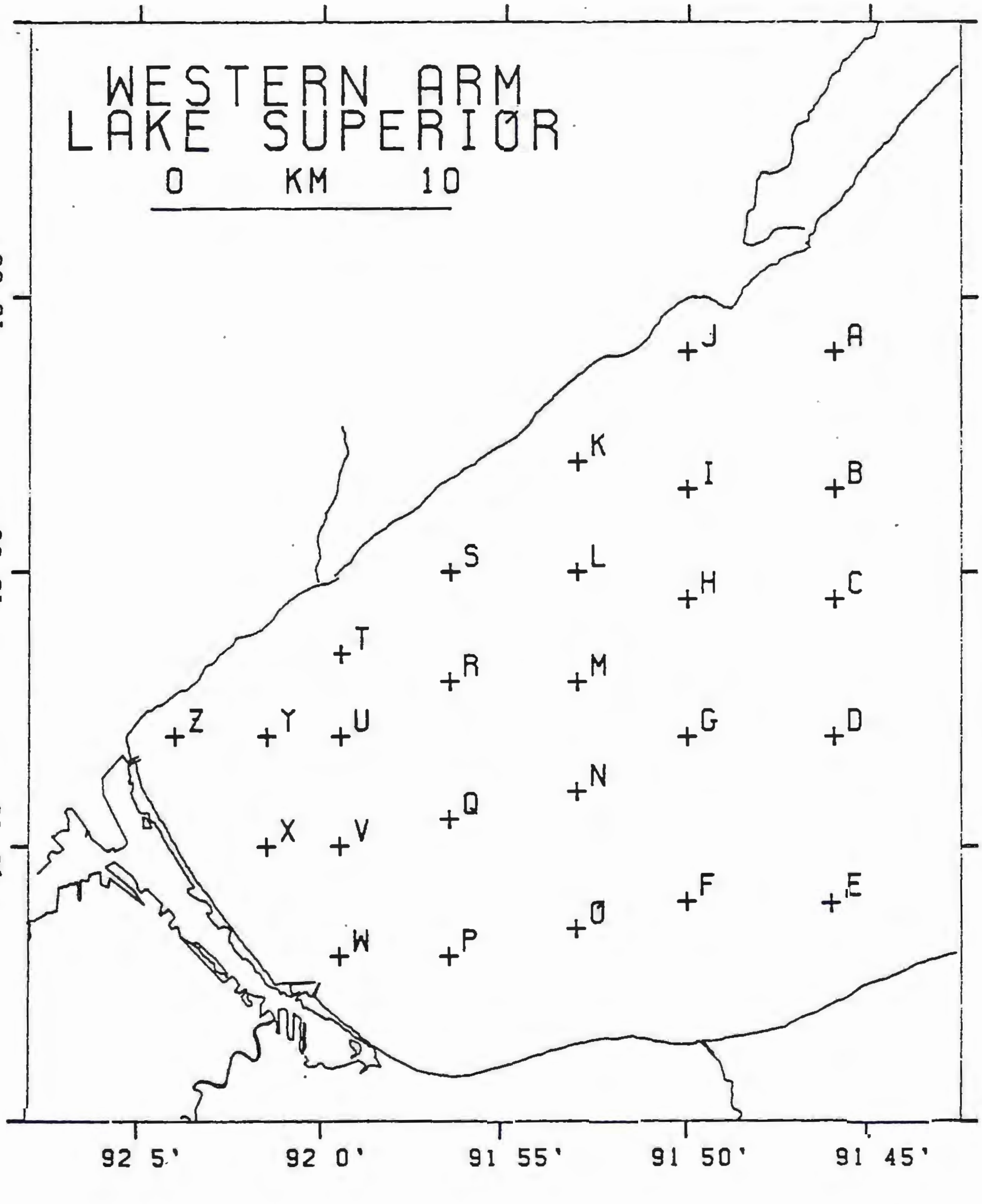


FIGURE 3: Location of lettered stations in the study area.

METHODS

Field Methods

Water samples and turbidity/temperature profiles were collected from the R/V VIKING on a total of 19 one-day cruises from 5/18/83 through 10/6/83 (Table 1). Cruises were not made during the winter months of 82-83 because of ice cover on the lake. Sampling stations were established on two different grid patterns. The first grid pattern (Figure 2) was designed to obtain both water samples and turbidity/temperature profiles at a maximum number of stations in the western arm within one day. This provided a data base for both distribution and composition of the suspended solids in the lake for any given sampling date. The average spacing between stations in this grid isabout 7 km. The second grid pattern (Figure 3) was designed to obtain turbidity/temperature profiles alone from as many stations as possible within one day and the ship's cruising capabilities. This grid facilitated development of a 3-dimensional picture of the suspended solid distribution within a one day time frame. The average spacing between stations on this grid is about 2 km. The majority of stations in the first grid pattern were also included in the second grid pattern.

All navigation was done using LORAN-C. Precipitation, wind direction, and wind speed were obtained from the National Weather Service at the Duluth International

Airport.

A turbidity/temperature profile was taken immediately upon arriving on station. The profiling system used was a transmissometer (25 cm pathlength, manufactured by Sea Tech Inc., Corvallis, OR) for turbidity in conjunction with an RSVP probe (designed by Dr. T. Dillon at Oregon State University) for temperature and pressure/depth. To cross-check pressure/depth readings, a meter wheel was used to mark the record every 5 or 10 meters. The system was connected to an XY graphic recorder (Hewlett-Packard #7035B) which provided instantaneous profiles. These profiles were then used to determine what water samples, if any, would be taken and at what depths. Water samples were often taken above the thermocline, within it or just below it, and in the bottom turbid layer.

Water samples were obtained for grain size analysis and for on board filtering of the suspended solids. The filters were analyzed for total suspended solids (TSS), particulate organic carbon (POC), chlorophyll-a and phaeophytin concentrations and diatom species abundances. A submersible pump with 3/4 inch tubing was used to pump the samples on board where they were temporarily stored in 4-liter plastic carboys. The length of tubing was flushed before sampling at each depth. The water samples in the carboys were shaken to ensure homogeneity. The sample was immediately split into duplicate 250 ml glass bottles for grain size distributions and approximately two liters were filtered under vacuum through Millepore filters (type HA, 0.45 um pore diameter) and/or precombusted (550°C - 1 hr), preweighed Gelman glass fiber filters (type A/E 0.4 um nominal pore diameter). The exact amount of water filtered was measured with a graduated cylinder. The 250 ml water samples were refrigerated and the filters were placed in individual petri dishes and frozen until analysis in the lab.

Laboratory Methods

Grain size distributions were obtained with an Elzone Model 80 XY electronic particle analyzer (manufactured by Particle Data, Inc.). The Elzone analyzer passes a suspension of particles in electrolyte through an orifice which also passes an electric current. Each particle passing through the orifice causes a momentary resistance change in proportion to its volume. The particle analyzer then electronically processes the resistance change caused by each particle to yield particle count and size distribution data. The size range of particles analyzed is determined by the size of the orifice selected. For this work, an orifice of 38 um (serial #895) was chosen. This orifice was calibrated to analyze particle sizes from 1.18 to 15.73 um (9.73 to 6.02 phi). 126 sizes between these two endpoints were counted. The machine settings used to obtain this size range were: current 4.5, gain 2.5, diameter of channel one 1.18 um, true log 11.19, volumetric 50.3 ul and preset total

20,000 counts. For a more detailed explanation of the theory, calibration and use of the Elzone particle analyzer refer to Halfman (1982).

The water samples used for analysis on the Elzone were removed from refrigeration and placed under a sonic horn for 45 sec to disperse any aggregate that may have formed. The entire sample was shaken by hand for 1 min and immediately, two 10 ml aliquots were withdrawn with automatic pipette and transferred to two separate 25 ml glass vials. These 10 ml samples were brought to a 1% electrolyte solution by adding 400 ul of a 30% NaCl stock which had been filtered three times through Millepore 0.45 um filters. Each vial was shaken by hand for 1 min and then analyzed on the Elzone particle analyzer. A thrice filtered 1% saline solution was used for flushing the apparatus between samples. Each of the two duplicate samples was run twice for a total of four runs. A third vial was prepared and run twice if the average medians of the two vials were not within 5 channels (0.15 phi units). The total number of runs was then added by the Elzone to give the final size distribution data. This information was transmitted to a computer for storage and calculations. Statistical parameters were calculated using formulas outlined by Folk (1974).

Total suspended solid concentrations (TSS) were determined from the pre-weighed glass-fiber filters which were freeze-dried, brought to room temperature and weighed.

TSS concentrations were calculated using the following formula:

$$\mathrm{TSS}\ (\mathrm{mg/l}) = \frac{Ws - Wf}{V} \qquad (1)$$

where: Ws = weight of filter and sediment
Wf = filter weight
V = volume of water filtered

The filters were then combusted at 550°C for 1 hr and reweighed to determine particulate organic carbon (POC) for samples from cruise dates 5/18/83 through 7/20/83. The formula used was:

$$\mathrm{POC}\ (\mathrm{mg/l}) = \frac{Ws - Wc}{V} \qquad (2)$$

where: Ws = weight of filter and sediment
Wc = weight of combusted filter and sediment
V = volume of water filtered

Samples from cruise dates 7/27/83 through 10/6/83 were analyzed for POC by Joel Baker, Department of Civil Engineering, University of Minnesota, using the method outlined by Menzel and Vaccaro (1964) on a carbon analyzer. This was in order to get more accurate and reliable values. Correlation between the two methods that determined POC was done by sets of four duplicate filters from various stations sampled after 7/27/83. Duplicate filters were analyzed by each method.

Chlorophyll-a, phaeophytin and diatom point counts were determined from the Millepore filters. In most cases several duplicate filters were made so that all analyses could be accomplished. Chlorophyll-a and phaeophytin were determined using a Turner fluorometer following methods established by Dr. R. Cook, Lake Superior Basin Studies Center, Duluth, MN. The filters were dissolved in 90% acid-free acetone, releasing the pigment into solution. The amount of pigment present was then measured by comparing the level of fluorescence to that of a known chlorophyll-a standard solution.

Point counts of diatom populations were performed by microscopic analysis of Millepore filters. The filters were freeze-dried then cut and mounted on glass slides. Several drops of clove oil or immersion oil were placed on the filter and it was covered with a glass cover slip. The clove oil rendered the filter transparent after about a week, the immersion oil after about 24 hrs. The slides were then sealed with clear fingernail polish. The diatoms were examined using an oil immersion lens at 1000x magnification. At least 300 valves per slide were identified to the species level when possible and counted in order to obtain a representative number. Individual diatoms were identified to the genus level when they could not be identified to species because of air bubbles or excessive detritus on the filter.

RESULTS

The temperature profiles taken throughout the summer show the change in the thermal characteristics of the lake through the late spring, summer, and early fall (Figure 4). The earliest profiles taken in 1983 were on 5/18/83. These show nearly isothermal conditions in the western arm. Some stations near shore (see Figure 2 for non-grid stations established for 5/18/83 only) show a very weak stratification developed with a difference of only 2-3° C between surface and bottom waters. The stratification strengthened and the thermocline became more defined as the lake gradually warmed through the rest of May, June, and the first part of July. By 7/13/83, profiles show the type of thermal stratification that remained typical of the lake throughout the summer. There was generally a shallow mixed layer, usually less than 10m in depth. The thermocline was fairly thick, commonly 15-20m. The hypolimnion was very stable and most stations, excluding those less than 20 meters deep, had water at least 6°C or colder at the bottom of the water column. The stratification remained until fall overturn in late September and early October. Figure 5 shows typical profiles of late spring, summer, and early fall.

Weather information from the National Weather Service at the Duluth International Airport has been plotted from May through October 1983 (Figure 6). In general, the weather during July and August was calm. The summer, June, July,

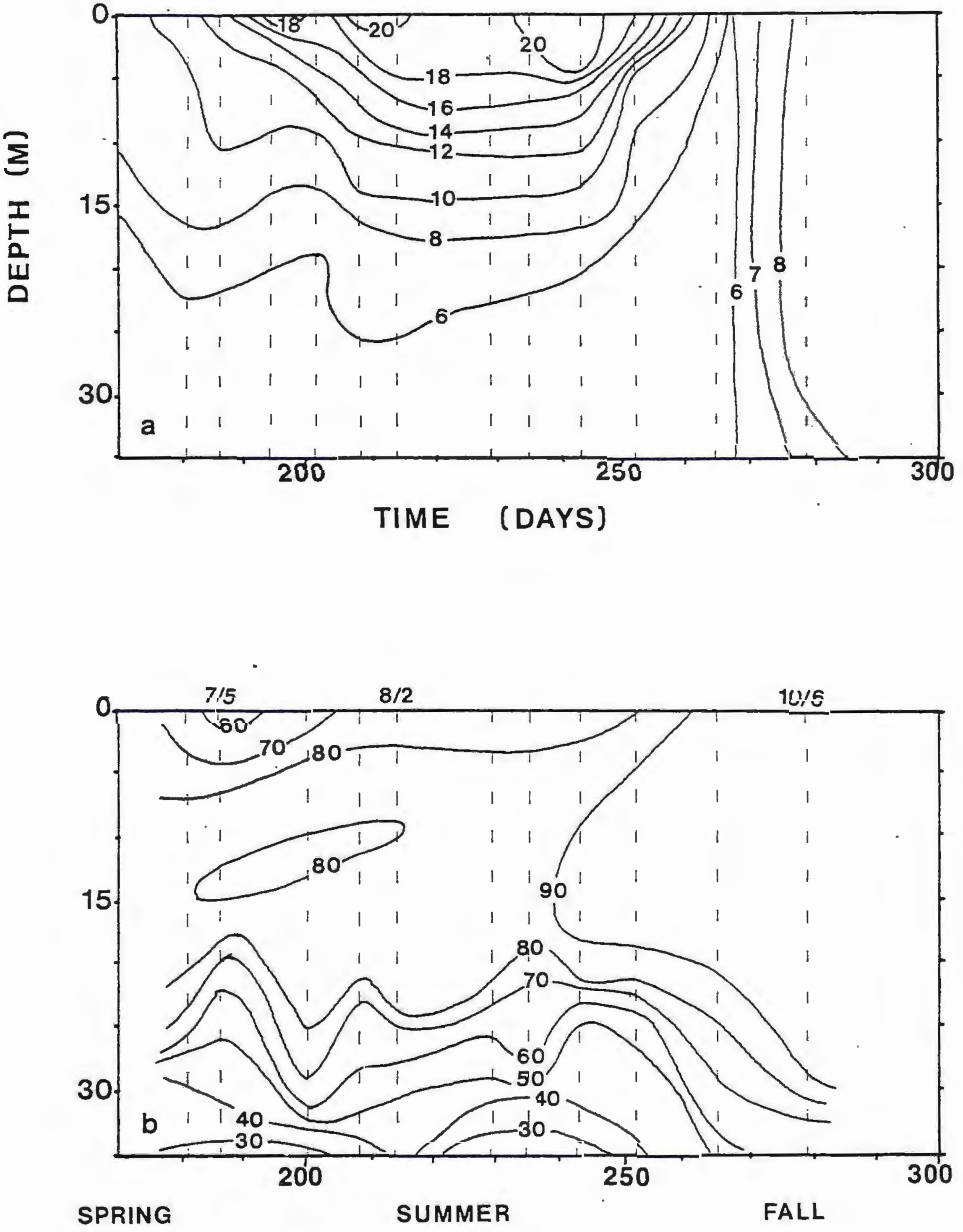


FIGURE 4: Temperature (top) and percent light transmission (bottom) at station 10 over time. Temperature contours are in intervals of 2 C. See Figure 2 for station location.

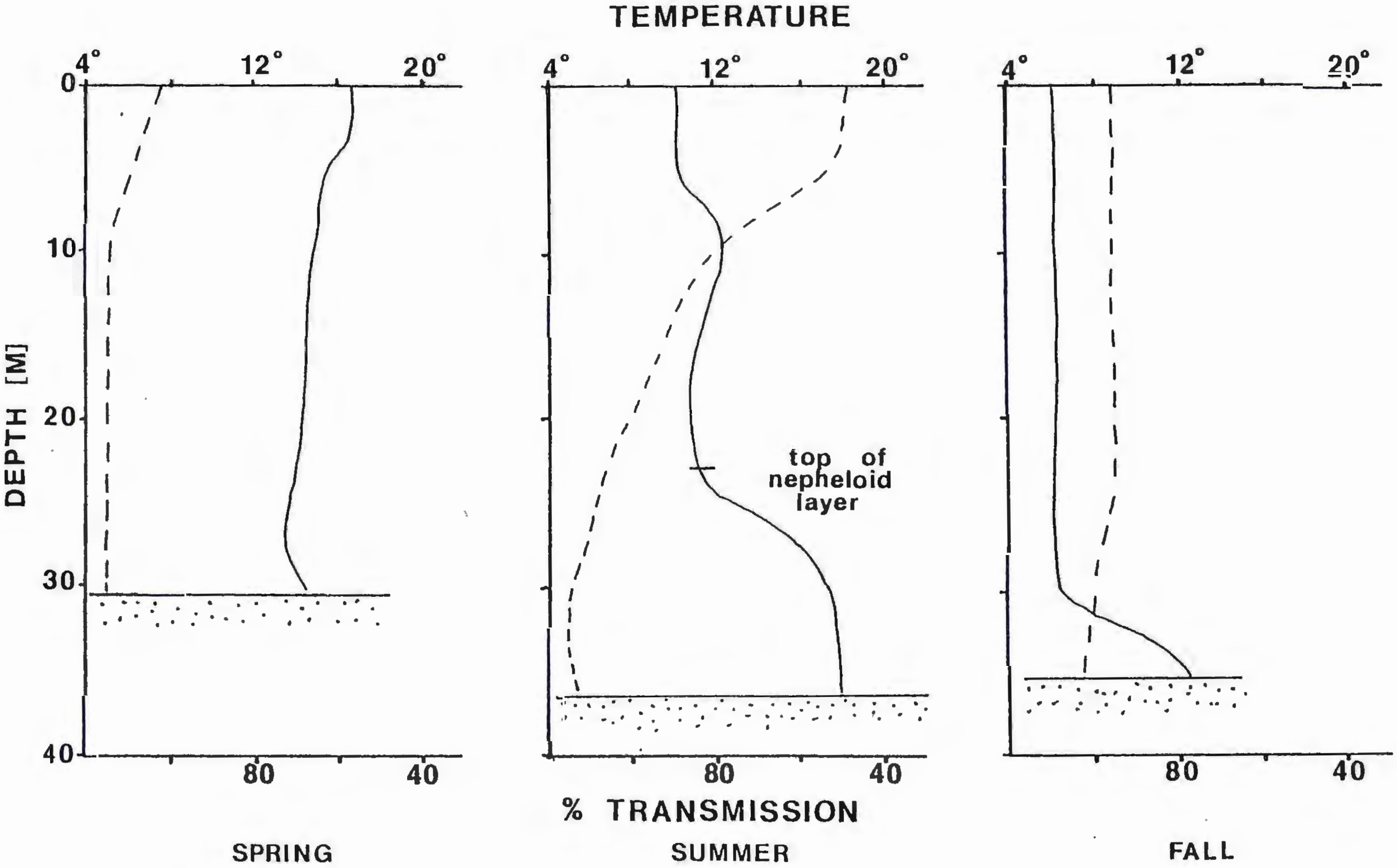
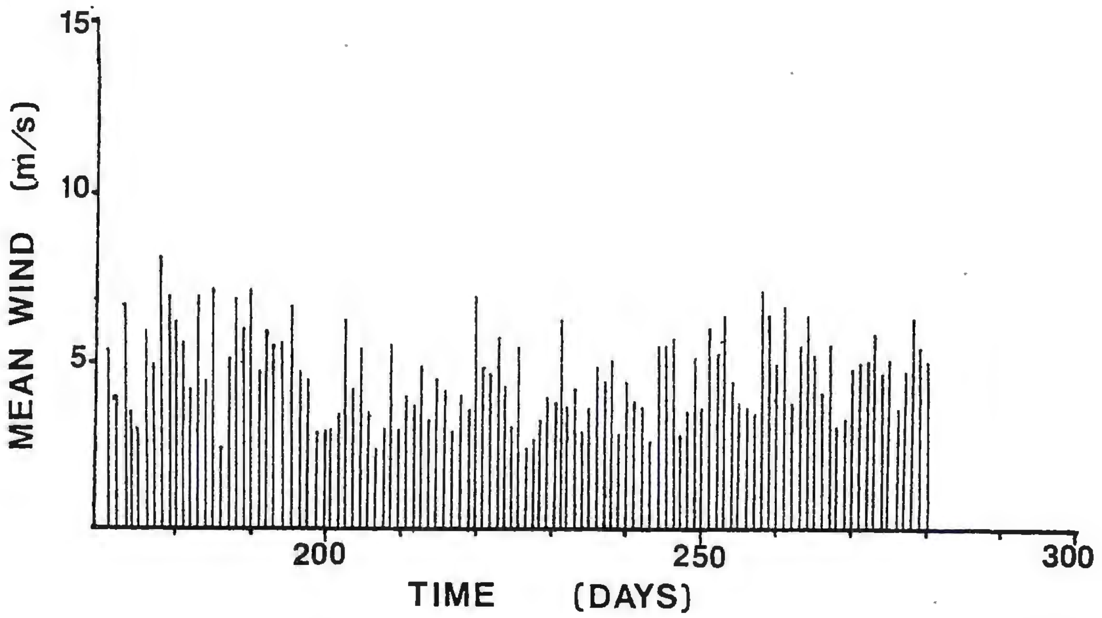


FIGURE 5: Typical profiles of temperature in °C (---) and turbidity as % light transmission (——) during spring (station 3, 5/18/83), summer (station 10, 8/2/83) and fall (station 10, 10/6/83). See Figure 2 for station locations.



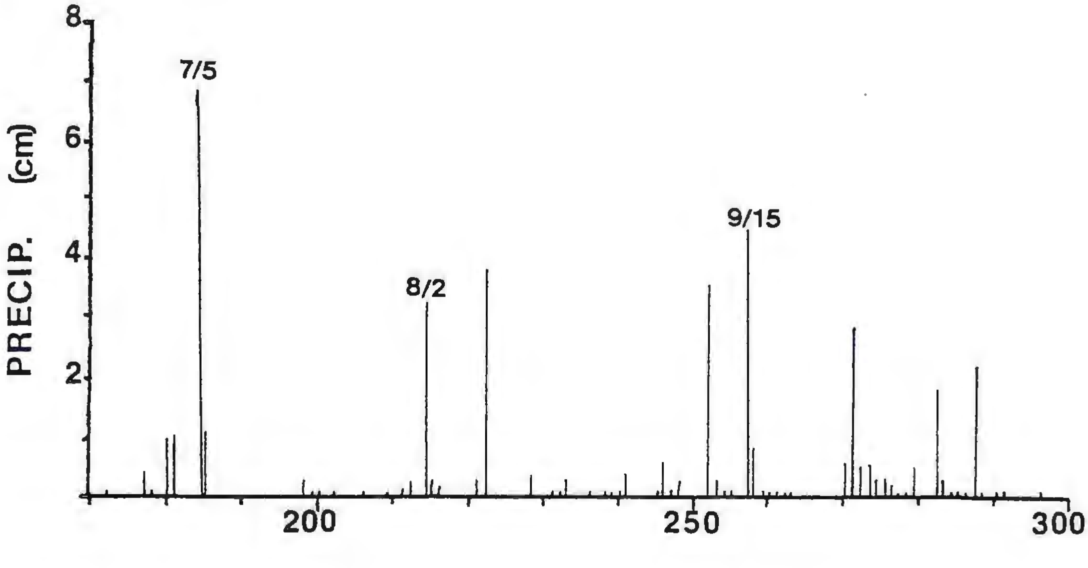


FIGURE 6: Wind speed (mph) and precipitation (inches) at Duluth International Airport over time.

and August, was the second warmest on record at the Duluth International Airport (National Weather Service). Average temperatures for the three months were 16°, 21° and 21° C, respectively. September and October had nearly normal precipitation, temperatures and wind speeds. The rainfall data from the Duluth International Airport show several major storms which occurred during the sampling period (Figure 6). The largest storm of the season, 7/2/83 - 7/4/83, dropped nearly 8 cm of rain and maintained average wind speeds of 10 - 15 m/s for over a 24 hr period.

Turbidity profiles were calibrated using total suspended solid concentrations obtained from filters. Transmission values in absolute volts were plotted against concentration values in mg/l. A linear regression analysis was run to determine the best fit straight line using various combinations of log and linear axes. The best 'r' value, -0.816, was obtained with a log transmission (volts) versus concentration (mg/l) plot. A transmission versus concentration plot using two linear axes, however, gave an 'r' value of -0.784. Since the difference between the two 'r' values was small, the linear-linear relationship (Figure 7) was used for calibration purposes. The least squares regression equation derived from the data is:

$$\text{CONCENTRATION (mg/l)} = \frac{\text{VOLTS} - 3.67}{-0.397} \qquad (3)$$

Transmission values in volts can be related to units of percent light transmission. These were determined by setting

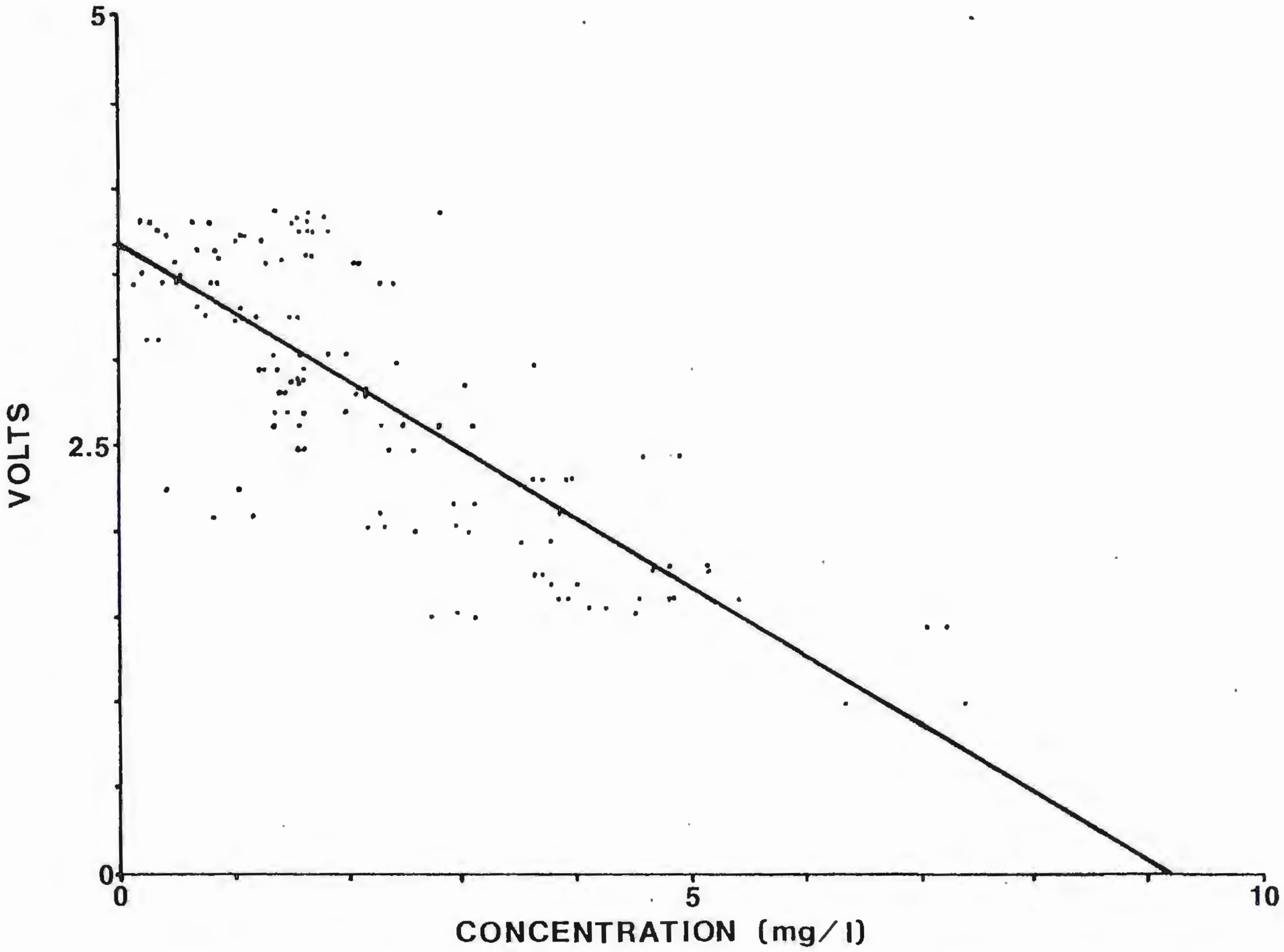


FIGURE 7: Linear calibration of transmission (volts) to concentration (mg/l).

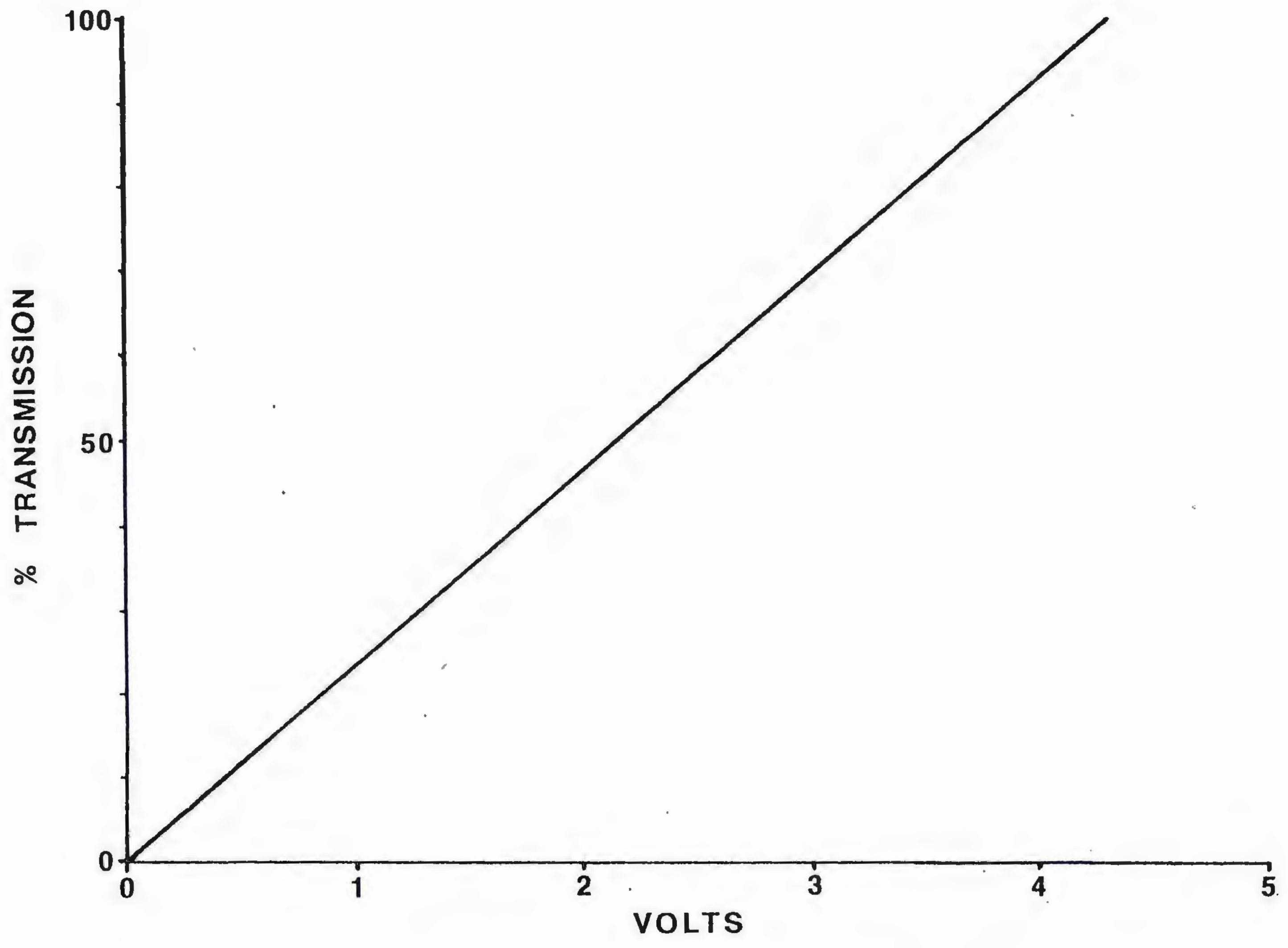


FIGURE 8: Linear calibration of volts to percent light transmission.

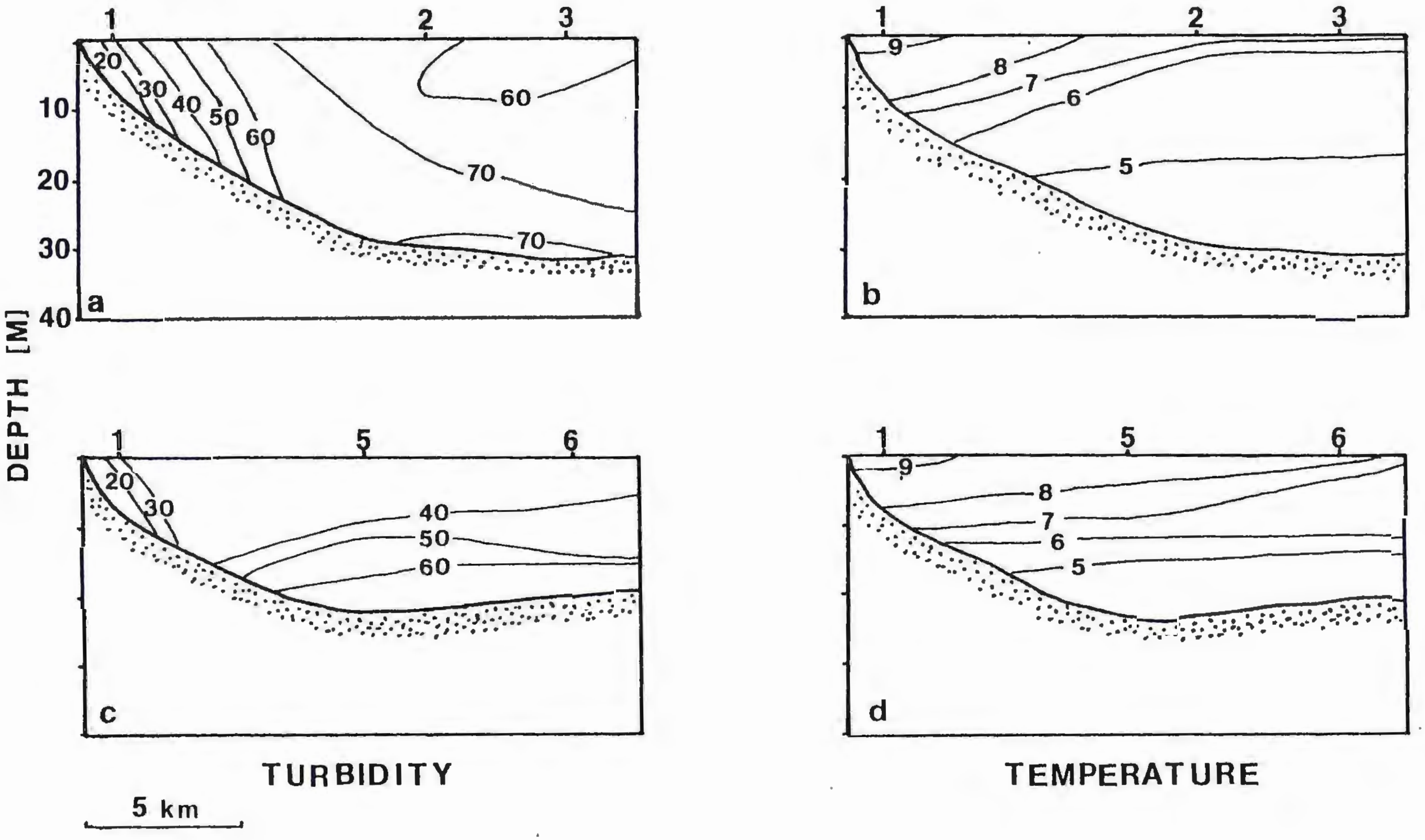


FIGURE 9: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) on 5/18/83. See Figure 2 for station locations.

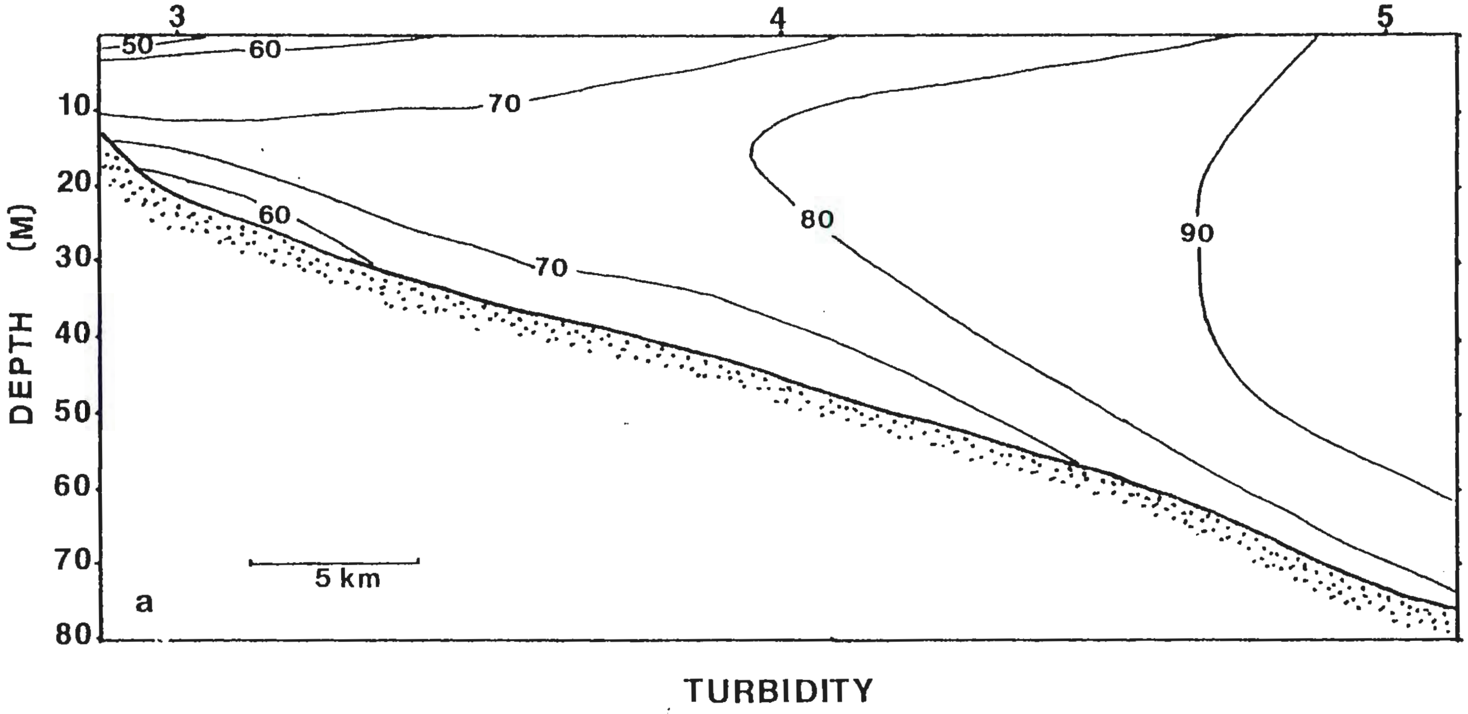


FIGURE 10a: Cross-sectional profile of turbidity (% transmission) on 6/7/83. See Figure 2 for station locations.

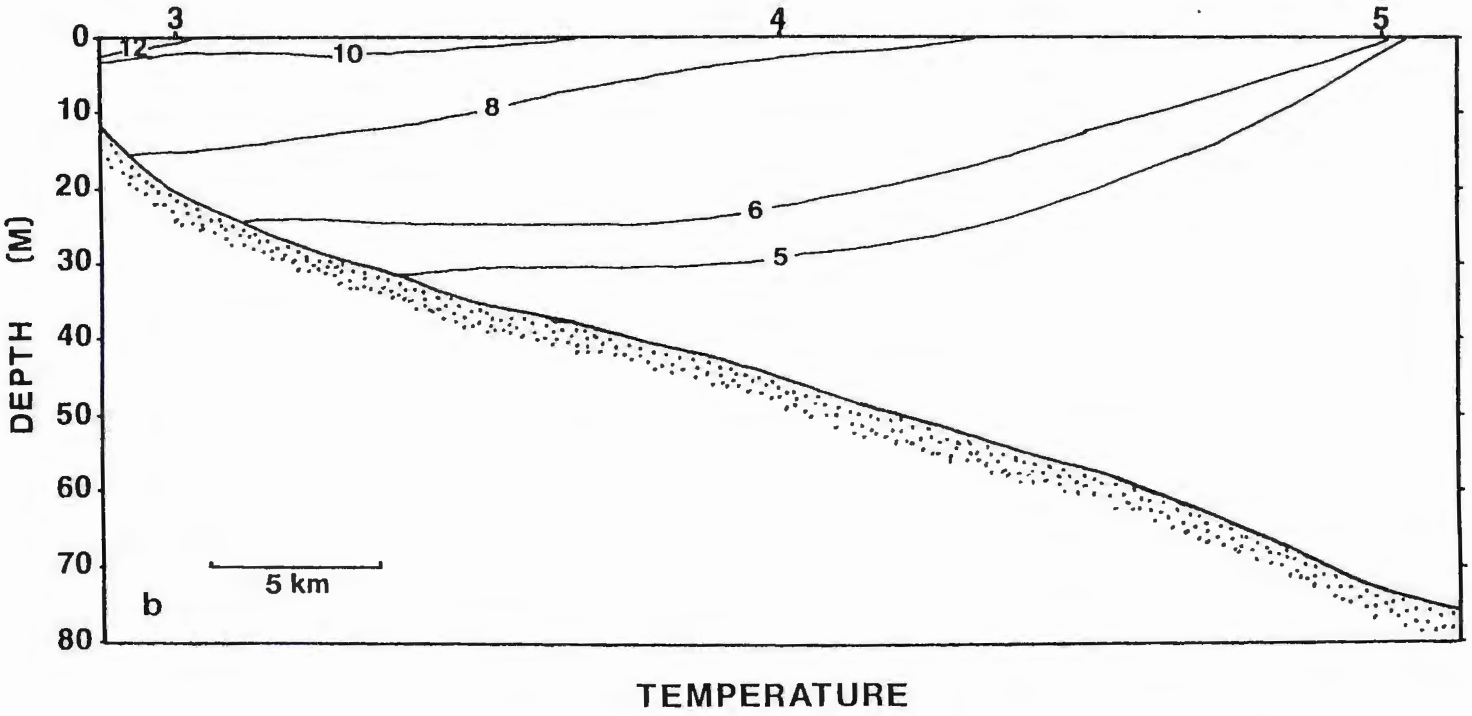


FIGURE 10b: Cross-sectional profile of temperature (°C) on 6/7/83. See Figure 2 for station locations.

0% transmission at 0 (zero) volts and 100% transmission at 4.30 volts, the maximum value in absolute volts encountered in the entire data set (Figure 8).

Turbidity profiles show distinct patterns that changed throughout the sampling period. The late spring profiles, taken on 5/18/83 (Table 1), show that the greatest turbidity, less than 25% transmission, was found close to the Wisconsin shoreline. In general, turbidity decreased with increased water depth and with distance away from the Wisconsin shoreline at the extreme western end of the lake (Figure 9ac). A slight turbidity increase, corresponding to less than a 5% transmission decrease, appeared in the bottom 1-2m of the deepest stations.

The suspended load at stations close to Minnesota Point and the Wisconsin shoreline had separated into two distinct layers of turbidity by 6/7/83. These layers were separated by a mid-depth clear water zone with greater than 70% transmission (stations 1-4, Figure 2). Surface and bottom layer turbidity maxima were present at stations 1, 3, and 4 and bottom turbidity maxima only developed at stations 2 and 5. Maximum values of turbidity for both surface and bottom layers were about 50% and 60% transmission, respectively, at station 3 (Figure 10). Transmission values increased with distance from the harbor entry. Stations farthest from the Wisconsin-Minnesota Point shoreline, numbers 6 and 8, showed low, uniform turbidity with depth and transmission values exceeded 90% throughout the entire water column.

Station 3 was profiled again two days later on 6/9/83. Surface turbidity had increased greatly to about 11% transmission and bottom turbidity remained relatively constant. Stations 10 and 11 also showed surface turbidity maxima though only station 10 had bottom turbidity as well. Station 12, the farthest from any shoreline, showed no surface turbidity and a small turbidity increase at the bottom, corresponding to a less than 15% transmission decrease from the clear water zone above.

Profiles taken through the end of June show that the bottom turbidity maxima were as great or greater than earlier at most stations. Surface turbidity, however, was either absent or very weak, less than 7% transmission decrease from the mid-depth clear water zone. Again, turbidity at all depths decreased with distance from the shore.

The 7/5/83 profiles (Figure 11) show bottom turbidity at stations nearest the Wisconsin shoreline, stations 2, 3, 4, 10, 11, and 12, while those near the northern shoreline, stations 1 and 9, show little if any turbidity at the bottom. The greatest bottom turbidity found, less than 35% transmission, was at station 10. Stations 10 and 3 show the only surface turbidity maxima. Values at station 3 dropped as low as 0% transmission for the first 4m of the water column which was much higher than the bottom turbidity

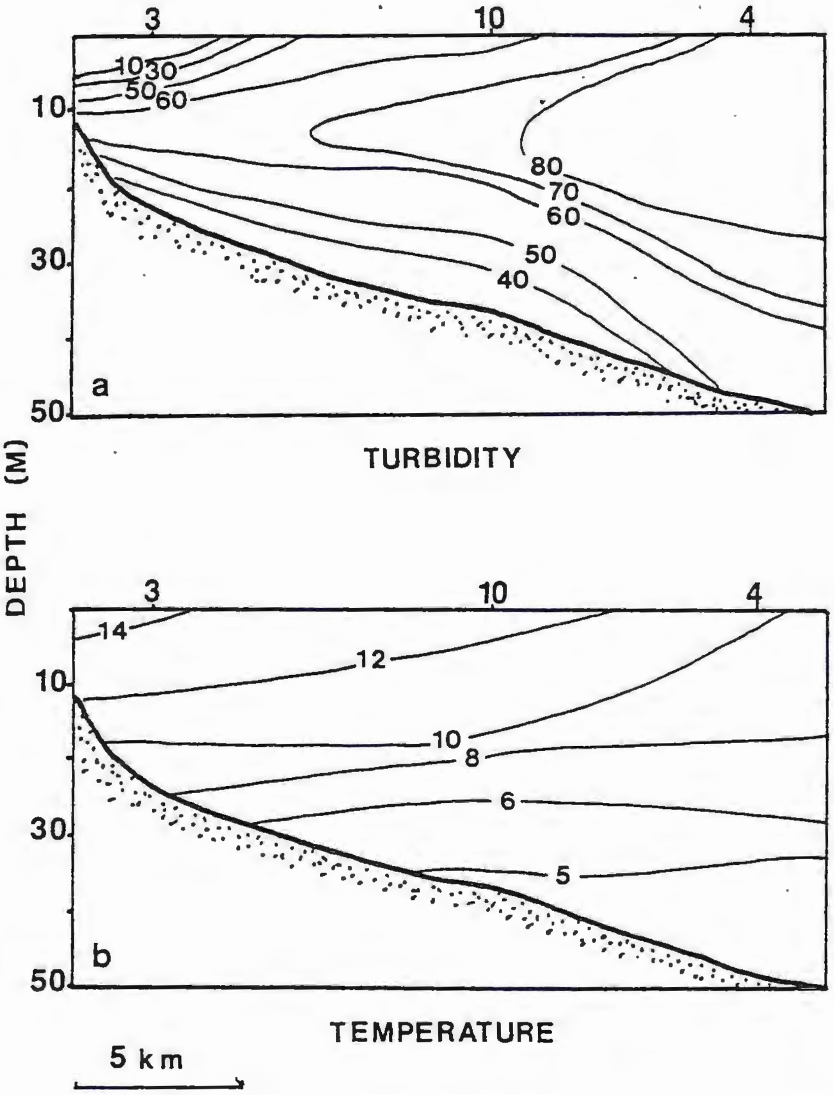


FIGURE 11: Cross-sectional profile of turbidity (% transmission) and temperature (C) on 7/5/83. See Figure 2 for station locations.

values at the same station, less than 46% transmission. Surface turbidity decreased from station 3 lakeward in all directions.

Profiles taken through the rest of July and August indicate that surface turbidity decreased in thickness and strength and after 7/13/83 was generally found only occasionally at less than 2m depth. After 7/13/83 a secondary surface maximum could be found at about 10-15m in the water column below clearer surface waters and above a persistent mid-depth clear water zone of up to 100% transmission. This mid-depth turbidity maximum usually was found at or near the top of the thermocline. The bottom turbidity layer was persistent and well-developed at all stations during this period. The thickness of the bottom layer seemed to be controlled in part by bathymetry because lines of equal thickness of the layer roughly follow bathymetric contours (Figure 12). The most turbid water in the bottom layer was generally offshore and along a line parallel to the axis of the western arm (Figures 13 - 16). The bottom layer was less turbid to either side of this axial line and decreased from the harbor entry lakeward. This turbidity distribution pattern is different from that seen during the late spring and early summer (5/18/83 up to 7/5/83) when turbidity decreased away from the shorelines. The bottom layer was clearly seen on profiles taken during late July and August because of the sharp, distinct boundary

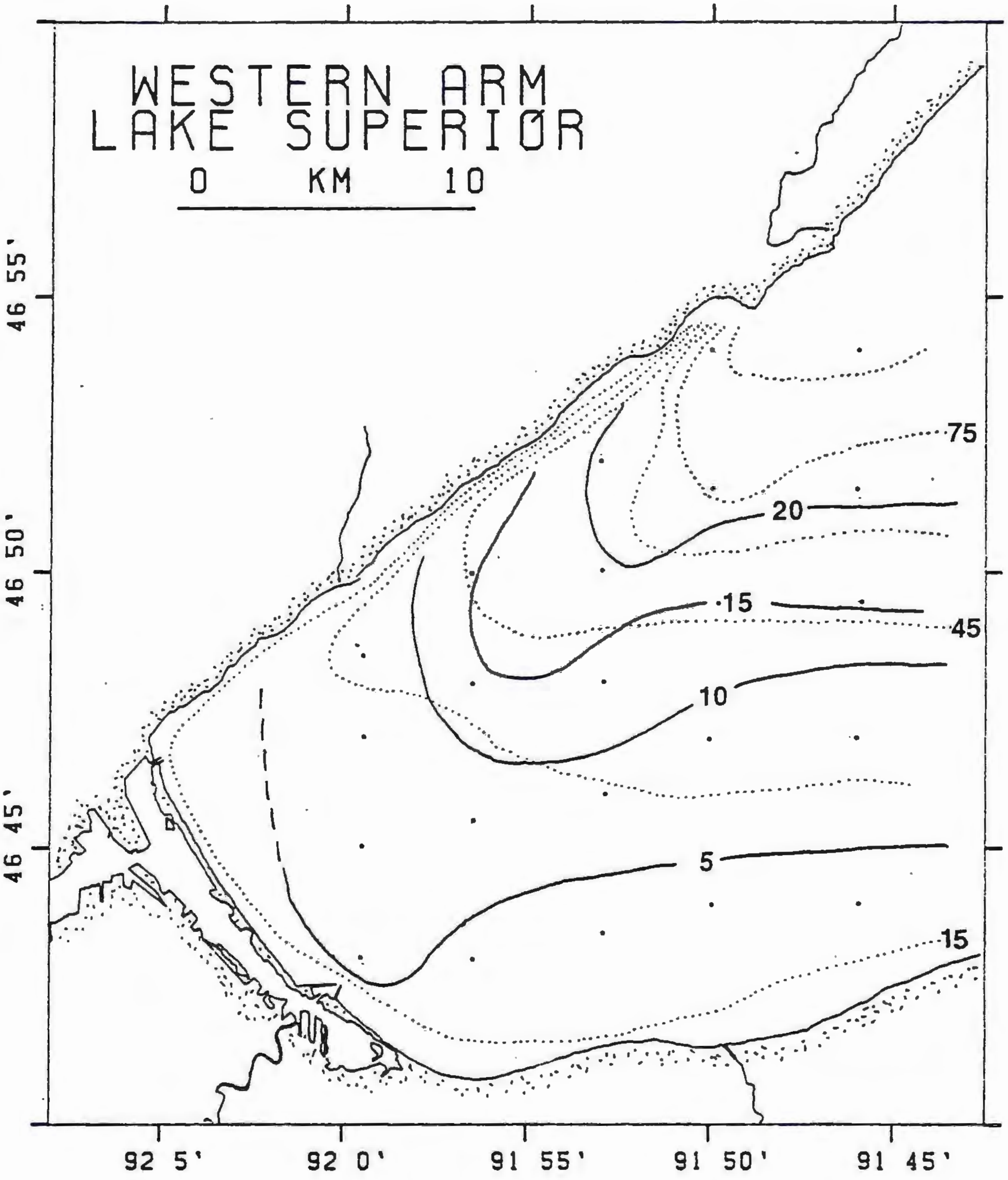


FIGURE 12: Map of bathymetric contours (intervals of 15m) with contours of nepheloid layer thickness (intervals of 5m) for 8/2/83.

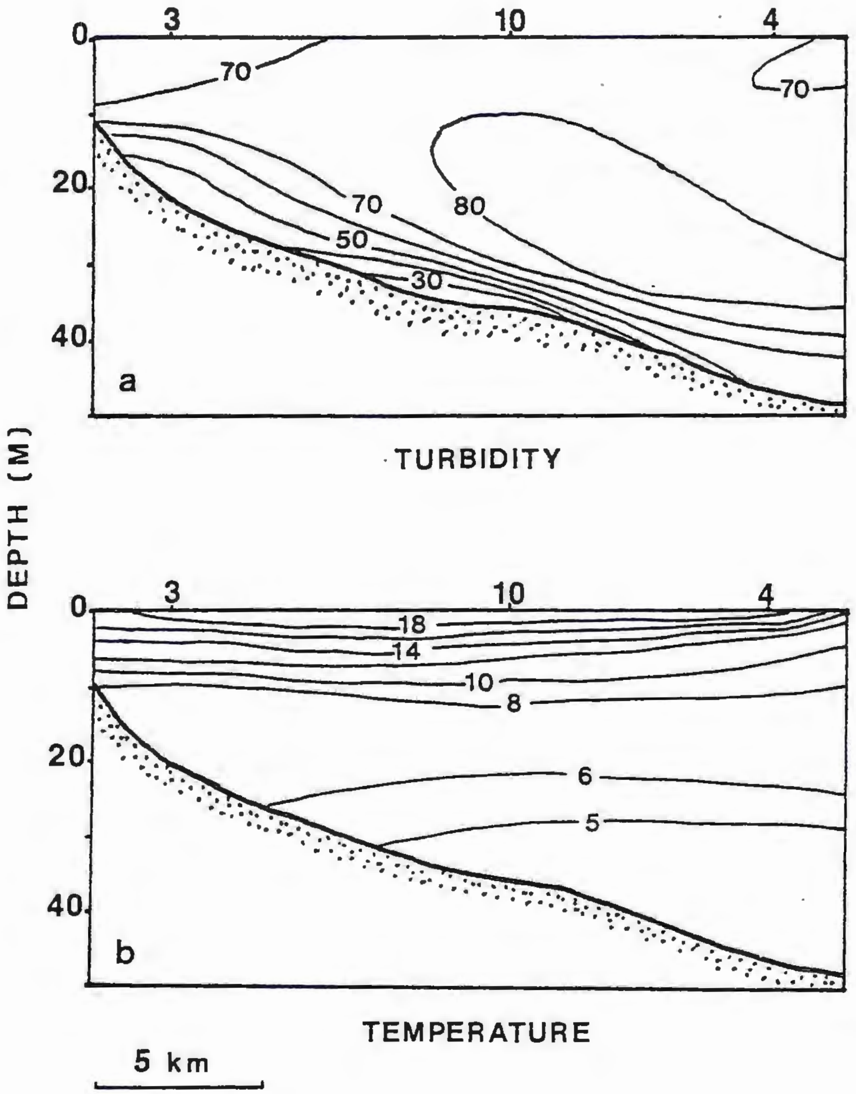


FIGURE 13ab: Cross-sectional profile of turbidity (% transmission) and temperature (°C) on 7/19/83. See Figure 2 for station locations.

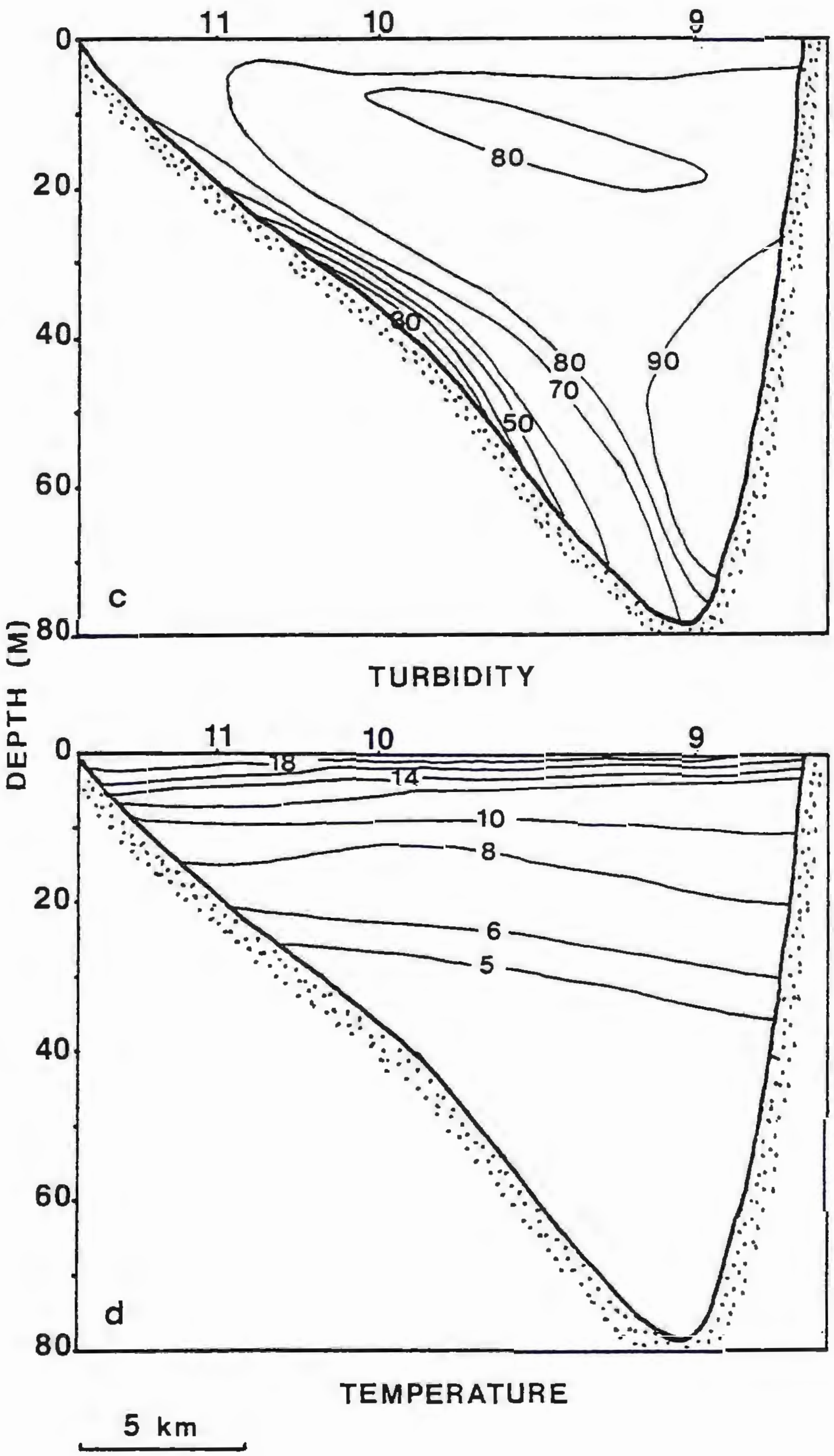


FIGURE 13cd: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) on 7/19/83. See Figure 2 for station locations.

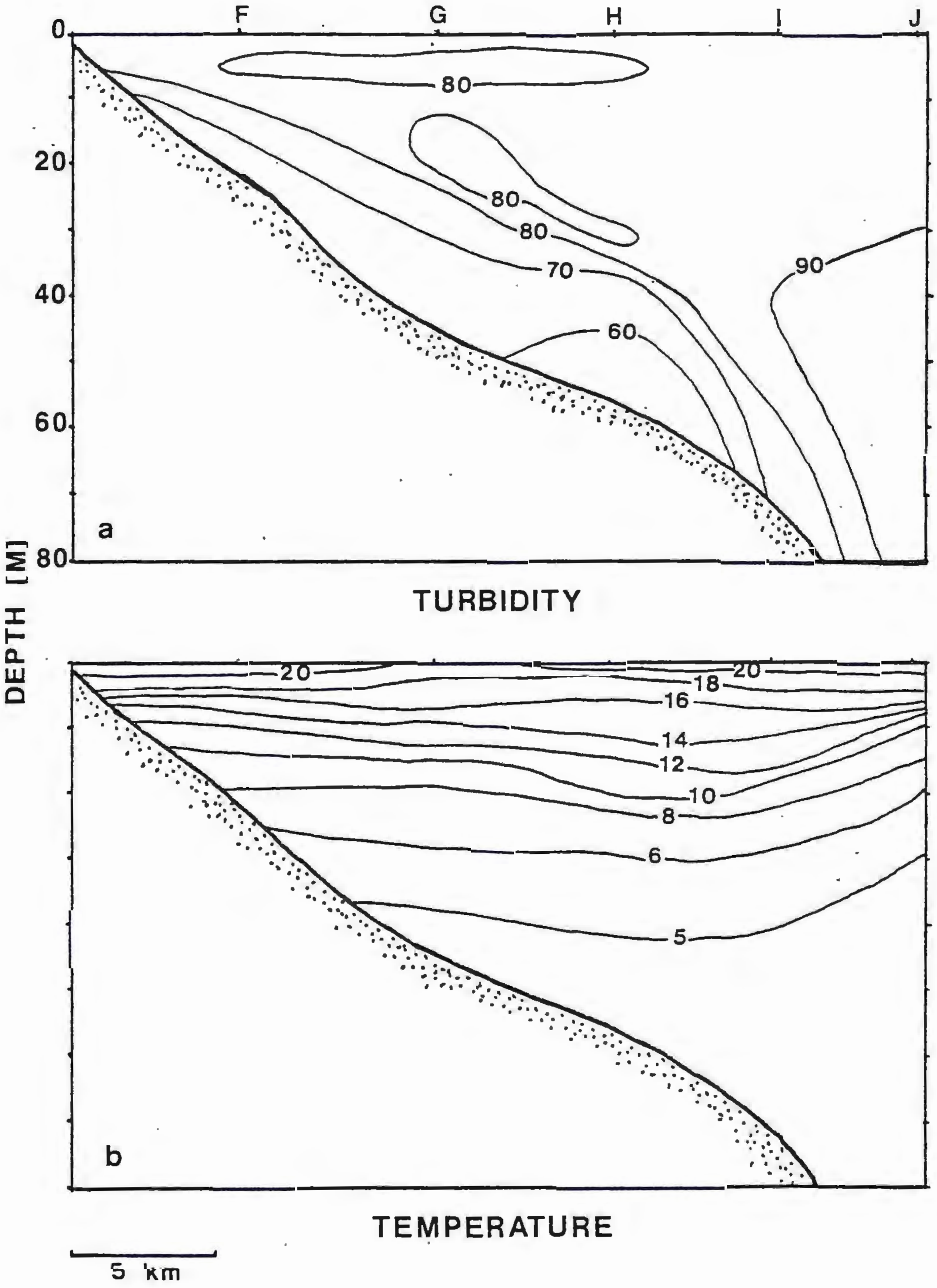


FIGURE 14ab: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) for 8/2/83. See Figure 3 for station locations.

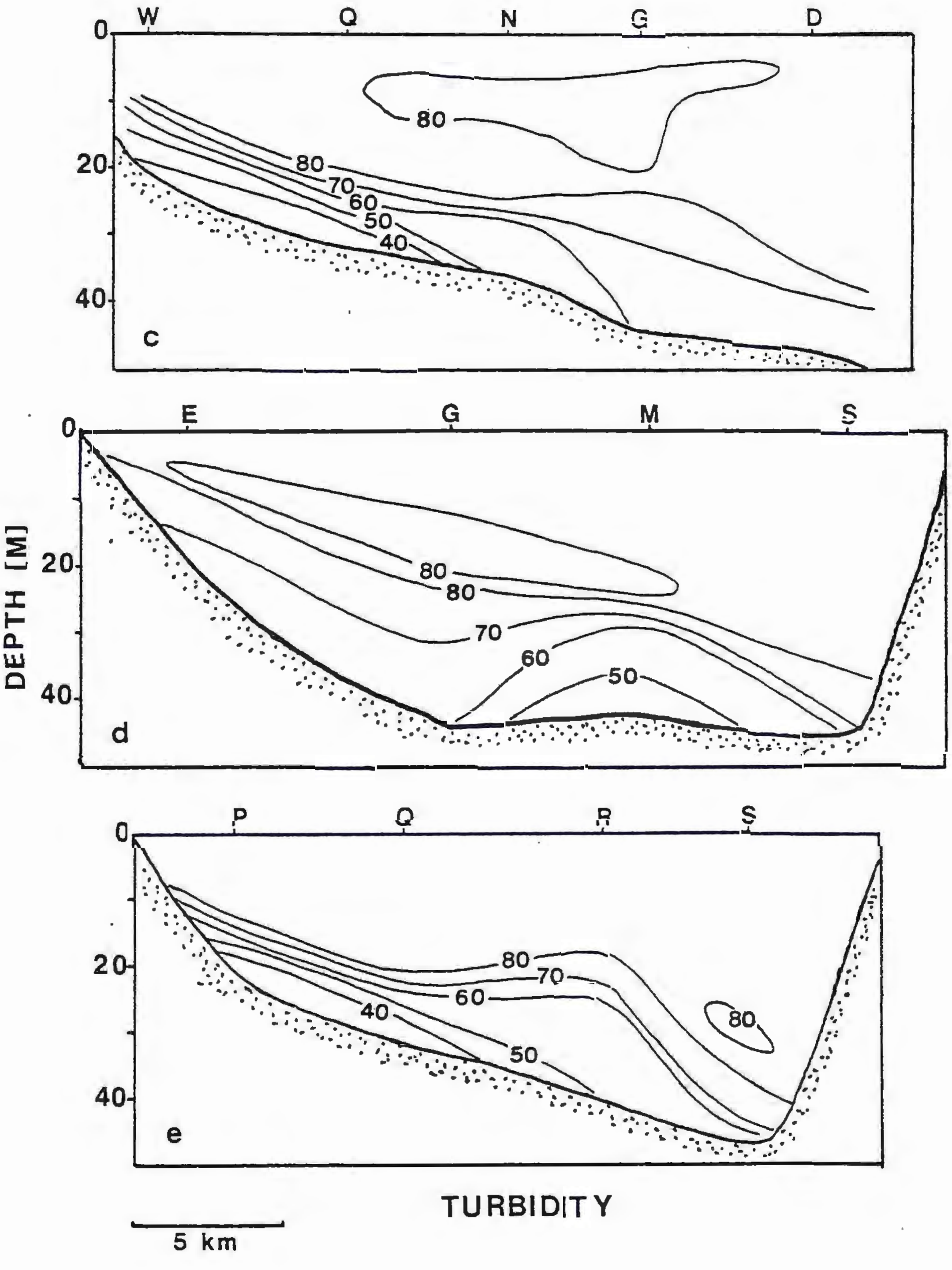


FIGURE 14cde: Cross-sectional profiles of turbidity only (% transmission) on 8/2/83. See Figure 3 for station locations.

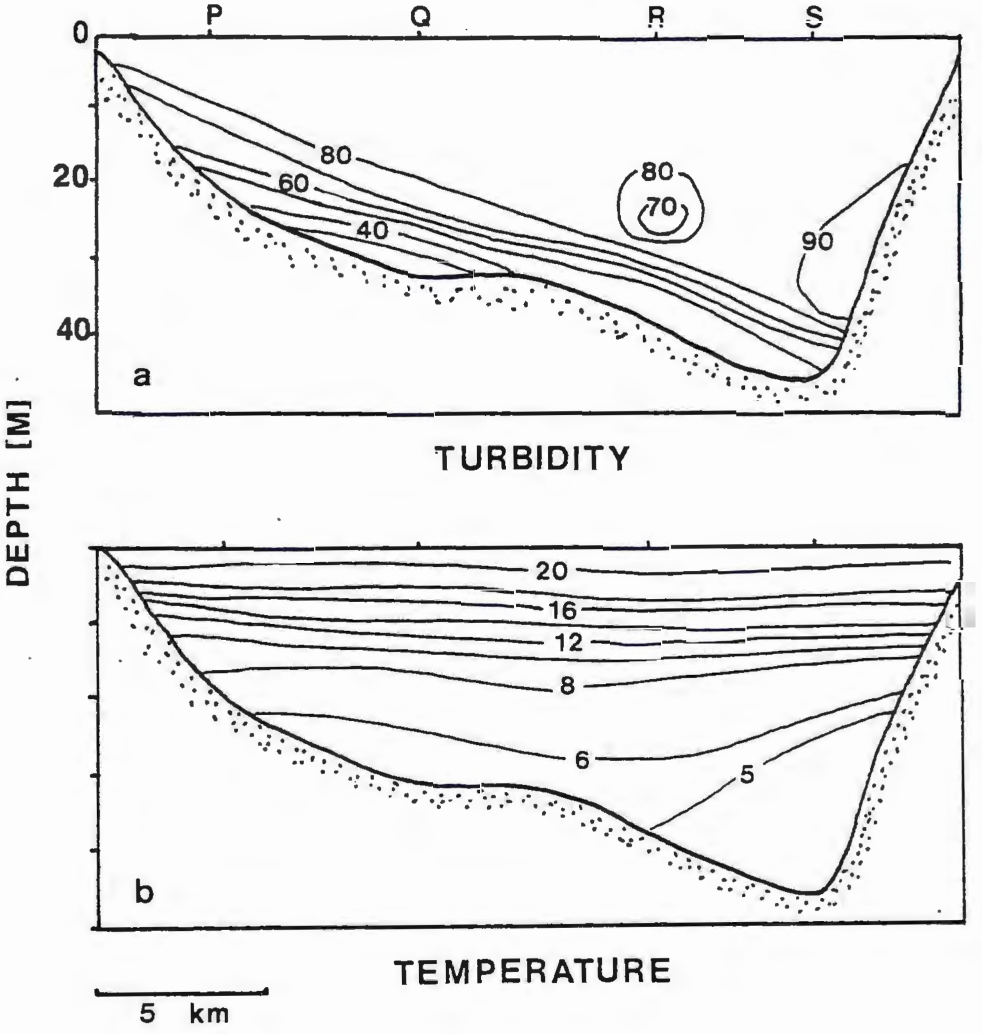


FIGURE 15ab: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) on 8/23/83. See Figure 3 for station locations.

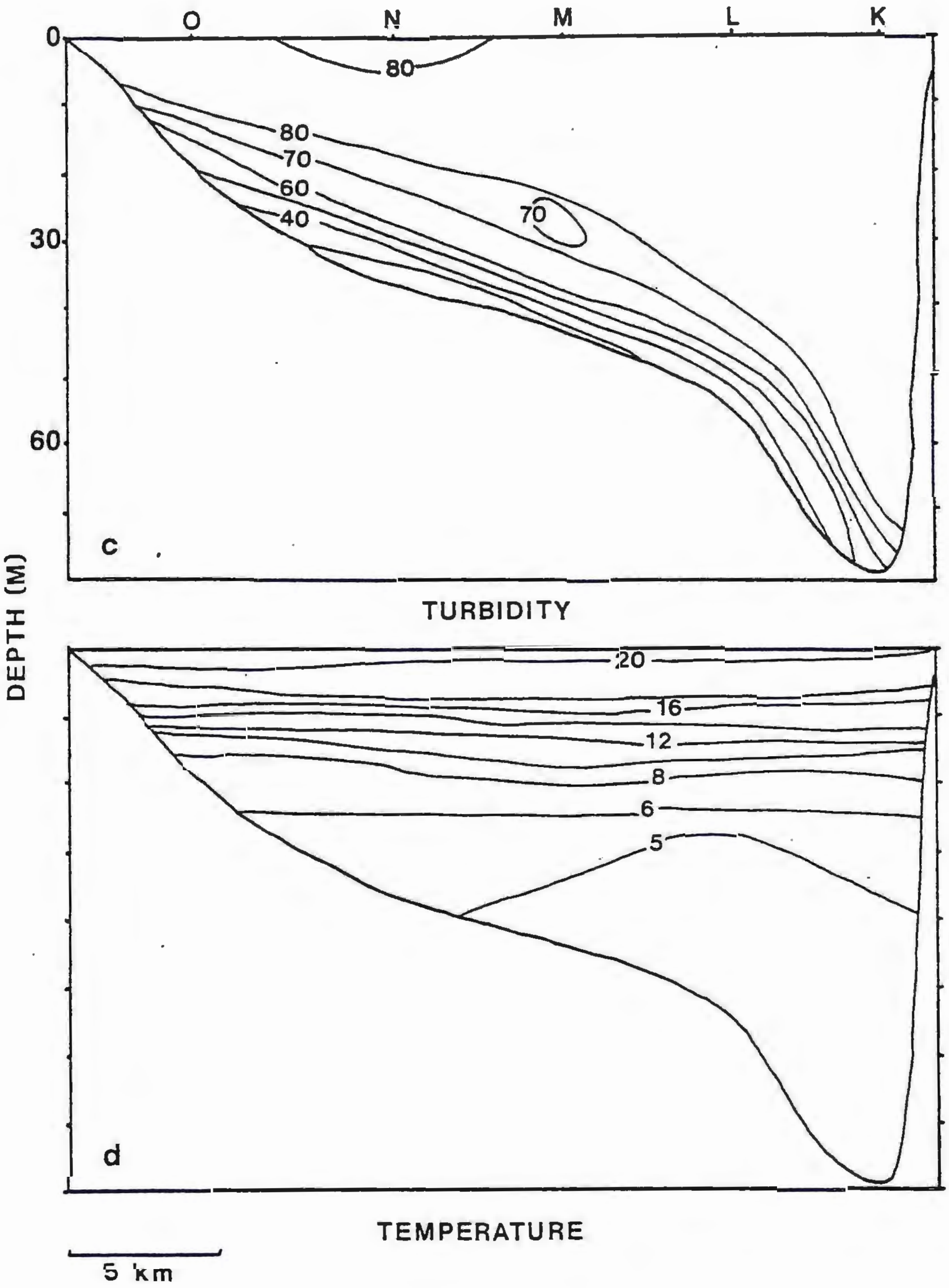


FIGURE 15cd: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) on 8/23/83. See Figure 3 for station locations.

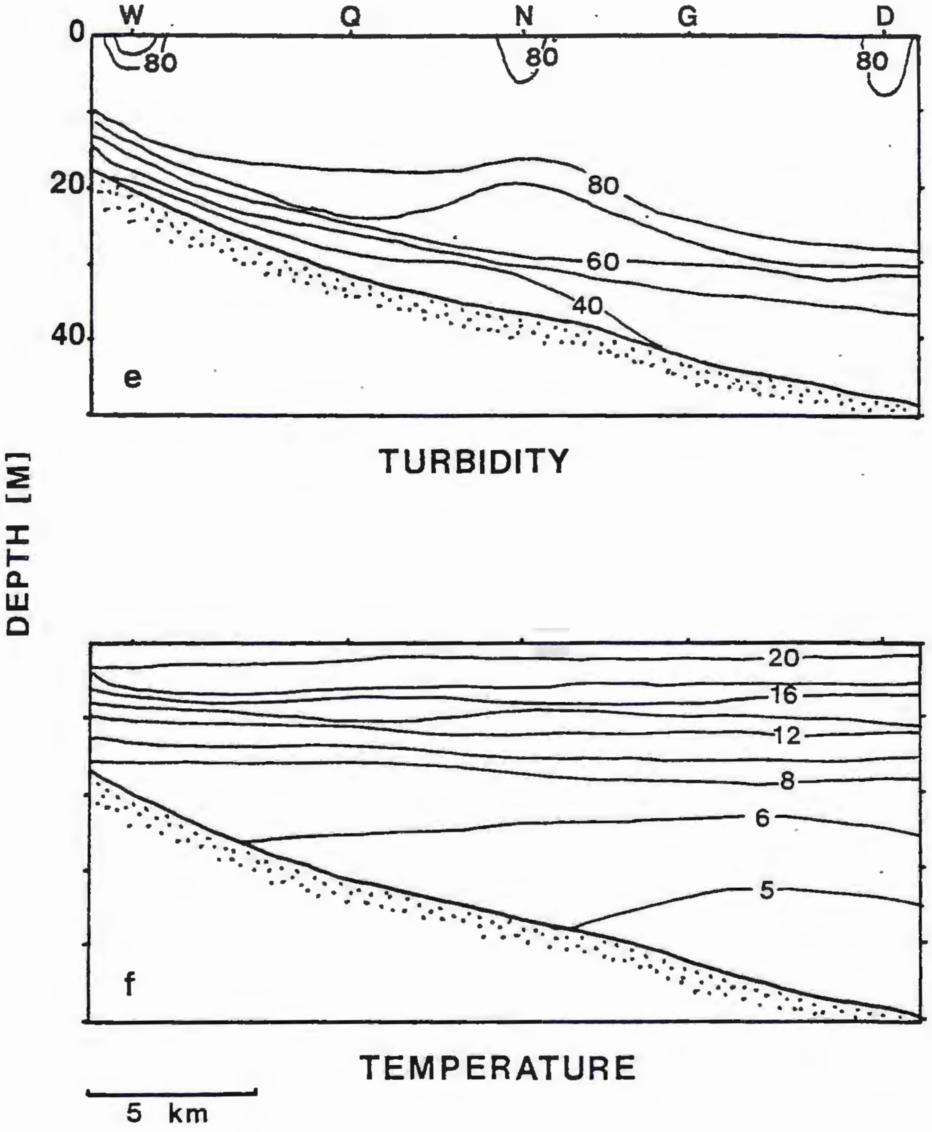


FIGURE 15ef: Cross-sectional profiles of turbidity (% transmission) and temperature (C) on 8/23/83. See Figure 3 for station locations.

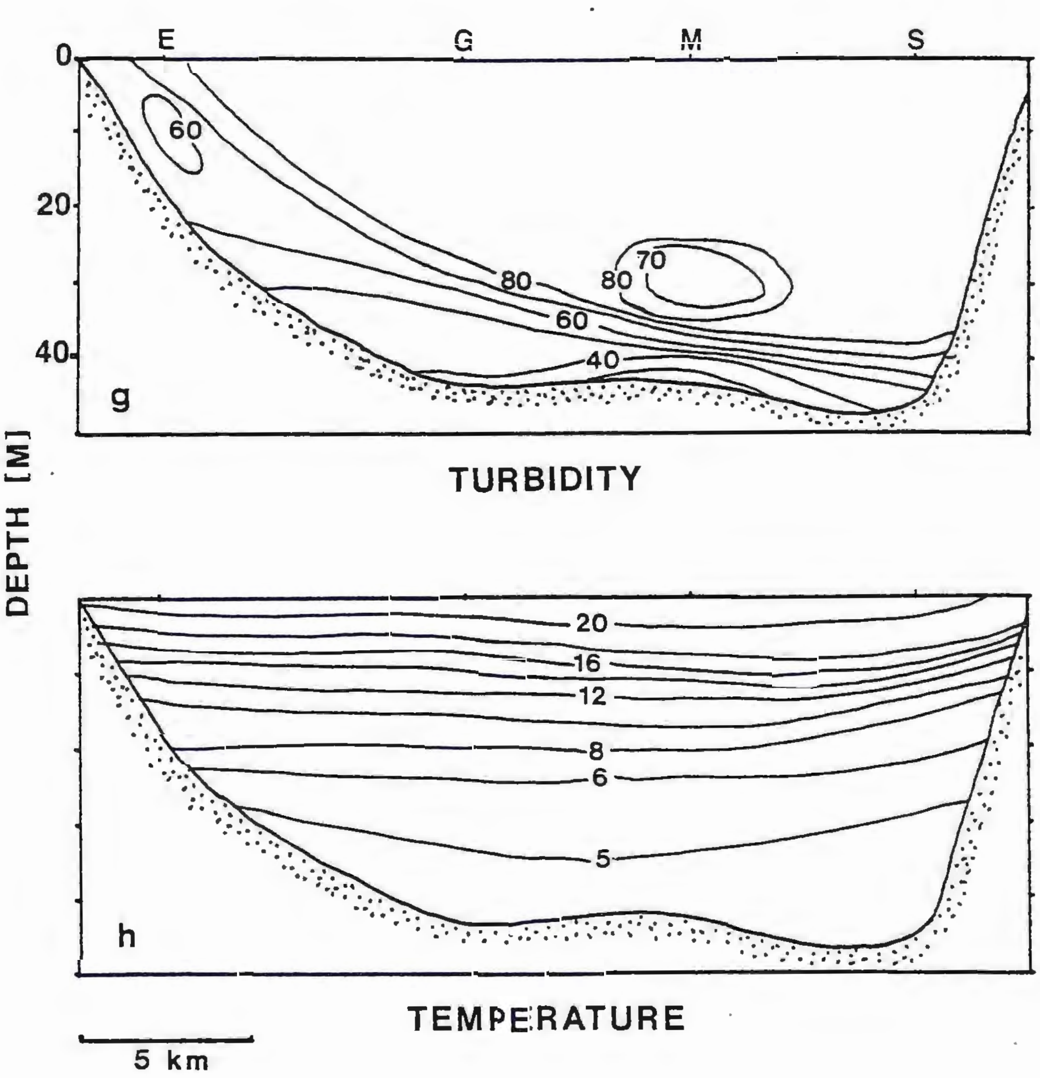


FIGURE 15gh: Cross-sectional profiles of turbidity (% transmission) and temperature (°C) on 8/23/83. See Figure 3 for station locations.

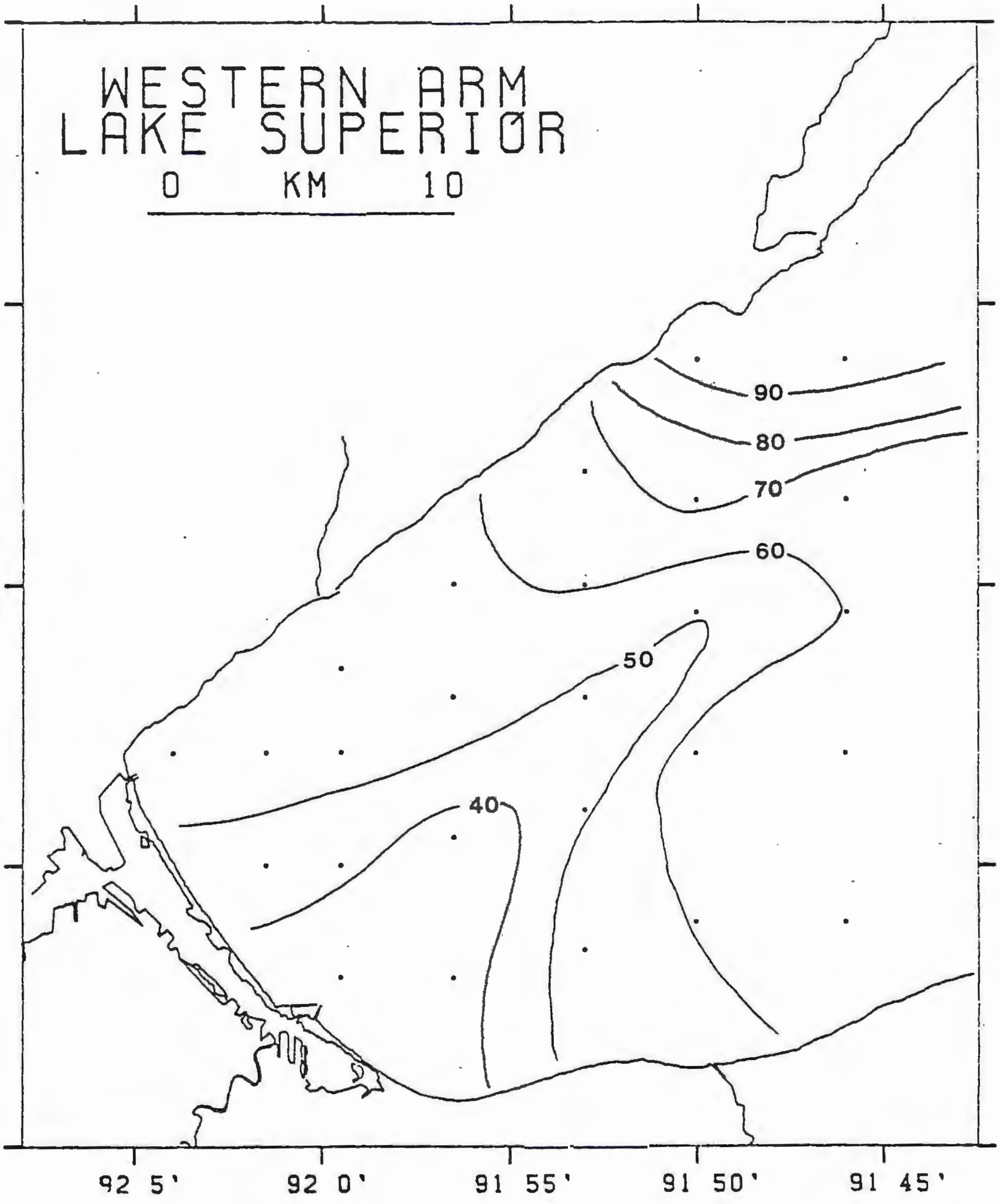


FIGURE 16: Maximum turbidity at each station (the bottom of the water column, in most cases) for 8/2/83. Contours represent isolines of percent light transmission.

between the turbid layer and the mid-depth clear water zone above.

Although the bottom turbid layer was persistent through July and August, absolute values of transmission in the layer varied with time. Suspended sediment concentration, as measured by light transmission values (always the bottom of the water column) gradually decreased until around the middle of August. It then increased, leading to a peak in turbidity (a minimum in transmission) in late August (Figure 17). This same trend is also shown by plots of suspended solid concentration over time, determined by filter analysis (Figure 18).

The bottom turbid layer weakened through the middle of September to the beginning of October. By 9/22/83 most stations had bottom turbidity values of at least 60% transmission with the exception of station G (Figure 3) which had a maximum turbidity of at least 40% transmission. The thickness of the bottom layer gradually decreased and profiles from stations 10 and 12 on 10/6/83, the last cruise of the sampling period, showed bottom turbid layers less than 5m thick.

Each turbidity profile was integrated over depth to determine the total sediment load in the water column. Transmission values were converted to concentration in mg/l using the linear regression equation and these values were then integrated over water depth to give the sediment load

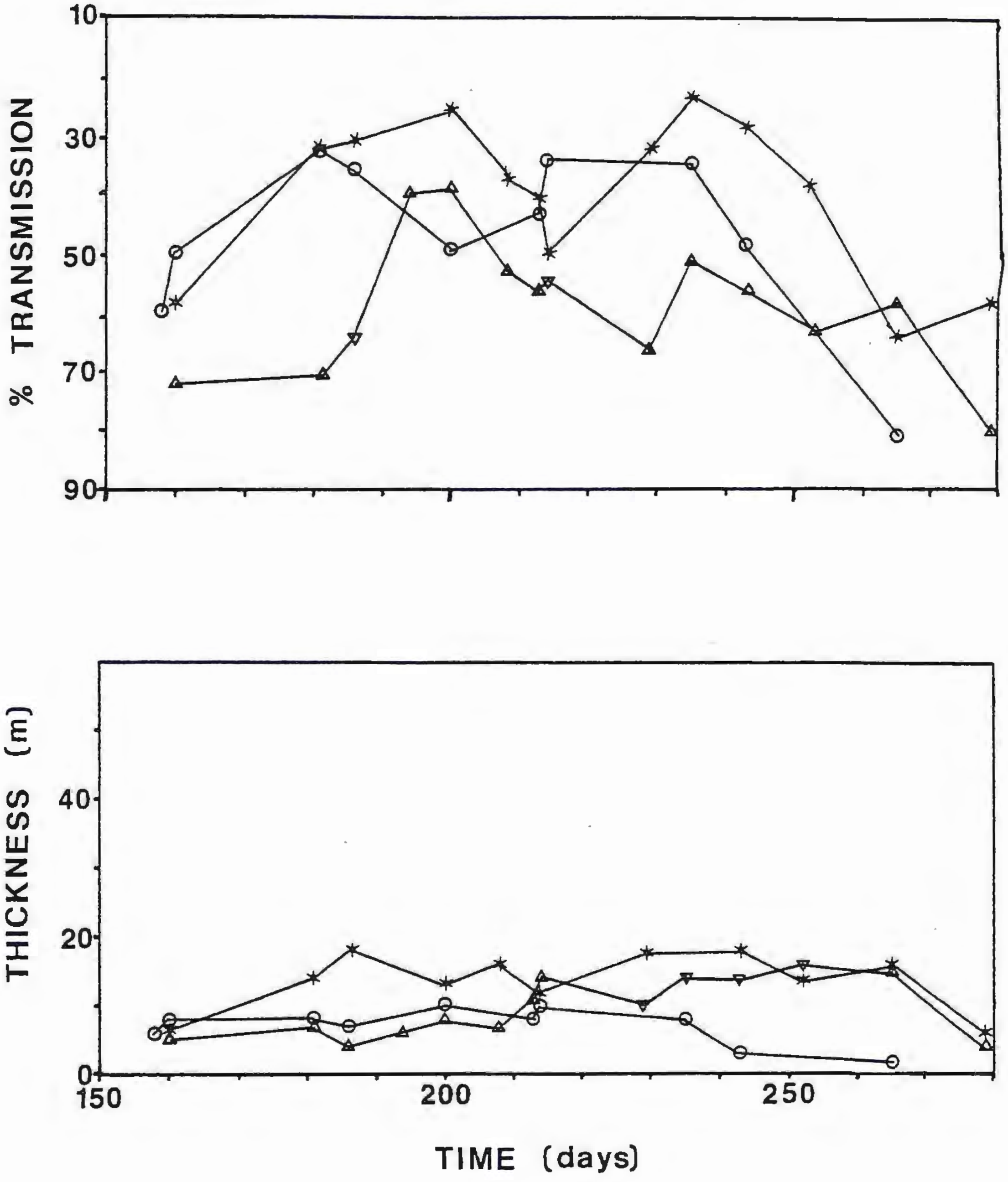


FIGURE 17: Bottom maximum turbidity (% transmission) and thickness (m) of the bottom turbid layer over time at stations 3 (o), 10 (*), and 12 (△). See Figure 2 for station locations.

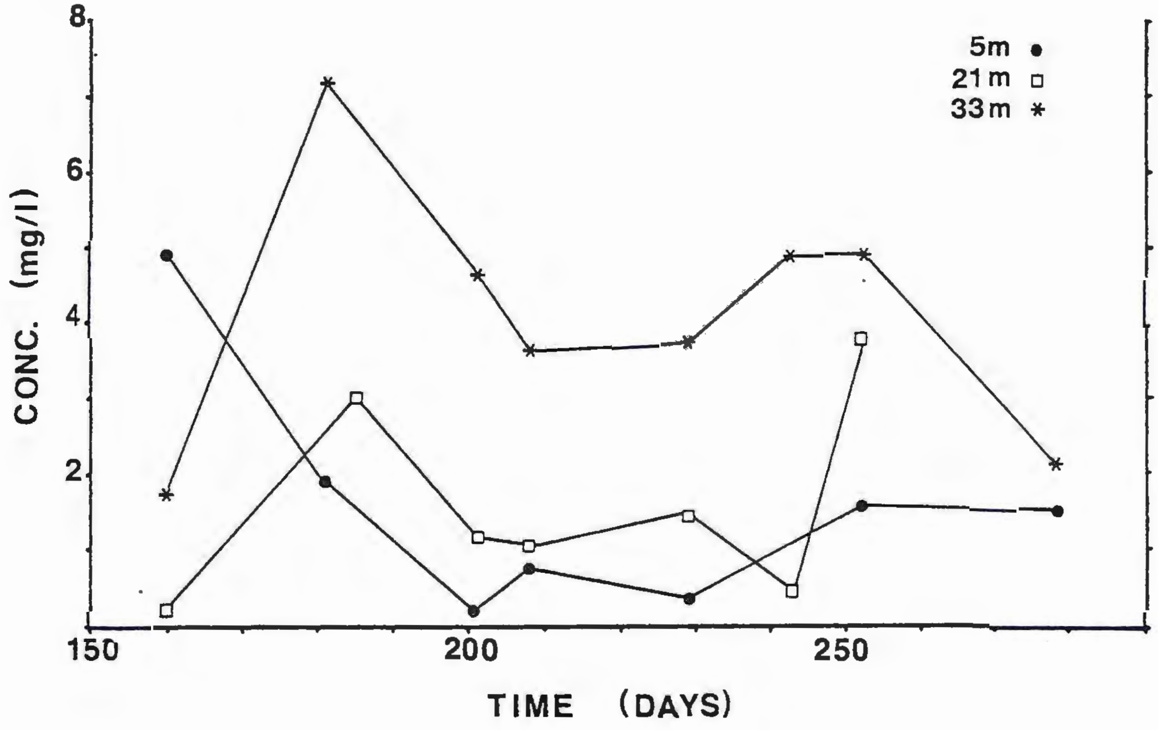


FIGURE 18: Concentration of total suspended solids in mg/l at station 10 (depths of 5m, 21m, and 33m) over time as determined by filter techniques.

in units of g/m^2. This integration was done over the entire water column and over the bottom turbid layer separately. A plot of the sediment burden of the bottom layer versus time for station 10 is shown in Figure 19. The sediment load was at its lowest value during the middle of July and increased to a high at the end of August. The integrated sediment burden for the bottom layer was plotted for each station profiled on 8/2/83 and 8/23/83 (Figure 20). These show that the maximum sediment burden for these dates was offshore along a line parallel to the lake axis and that the sediment burden decreased away from this line in all directions. This is comparable to the plots of maximum bottom turbidity for the same dates (Figure 16).

The median grain size of the entire data set collected varied over a small range of 3.6 um to 6.8 um. The majority of values were encompassed within an even smaller range, 3.6 um to 5.0 um, the coarser sized particles occurring fairly infrequently (Table A - Appendix). The suspended solids were moderately well sorted with standard deviations between .75 phi and 1.00 phi. The sample distributions were very to extremely leptokurtic with values between 2 and 3. The values of both standard deviation and kurtosis may be an artifact of analyzing a narrow grain size range (1.18 to 15.73 um or 9.7 to 6.0 phi) on the electronic particle analyzer. Any particles finer than 1 um were not counted, but they may be a statistically significant portion of the

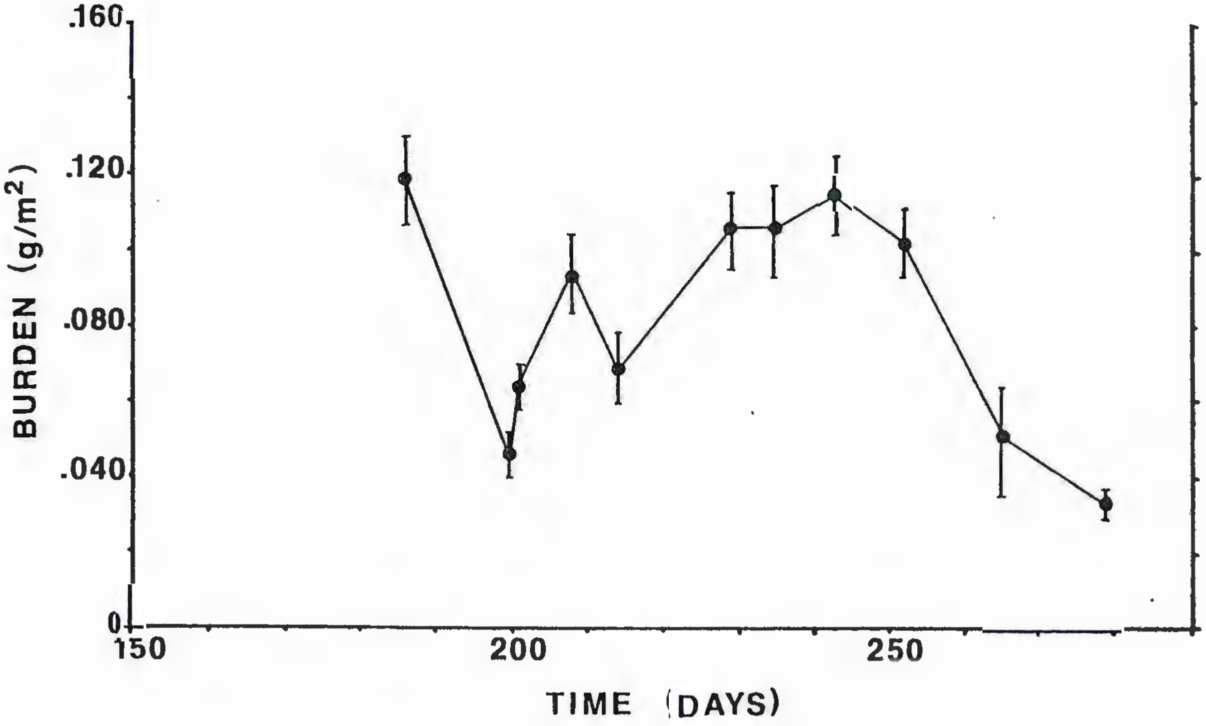


FIGURE 19: Integrated sediment burden in g/m^2 of the bottom turbid layer at station 10 over time.

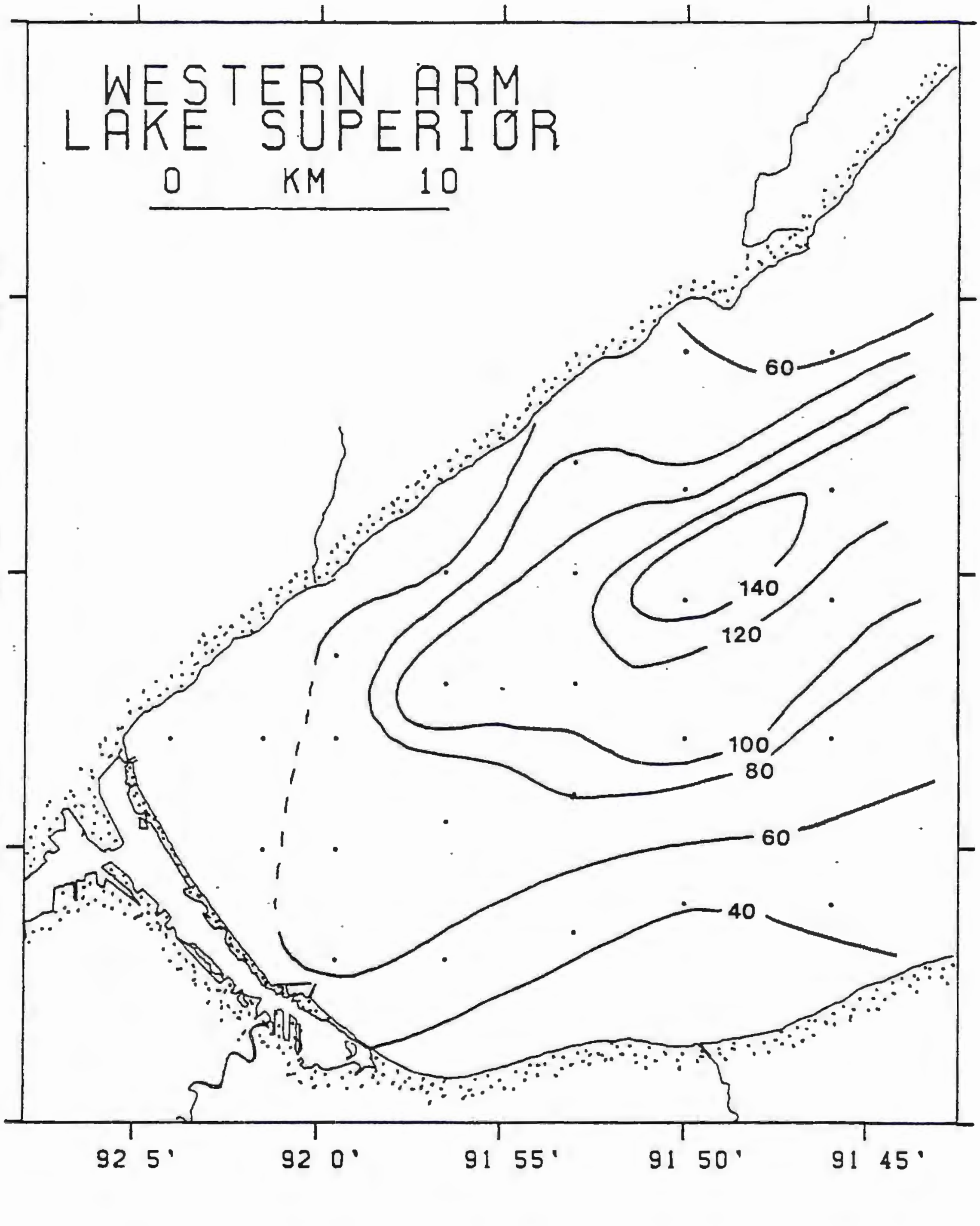


FIGURE 20a: Integrated sediment burden (mg/m^2) of the nepheloid layer at each station on 8/2/83.

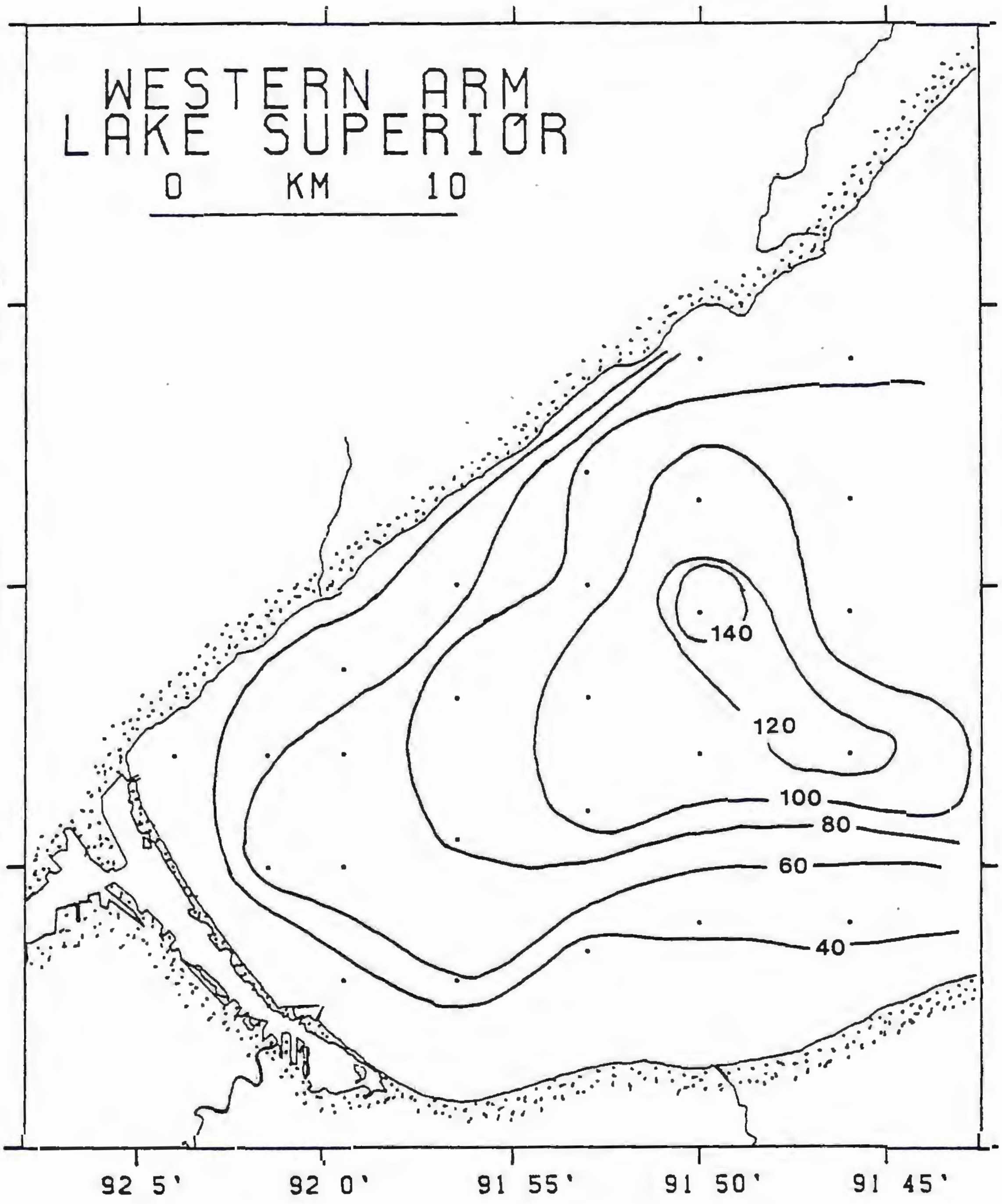


FIGURE 20b: Integrated sediment burden (mg/m^2) of the nepheloid layer at each station on 8/23/83.

grain size distribution.

In the early spring samples, taken on 5/18/83, the grain size distribution showed a distinct bimodality with peaks at about 10.0 um and 4.0 um (Figure 21). Inspection indicated that diatoms were the greater part of the coarse peak. This peak was dampened considerably in subsequent samples. In general, median grain sizes were coarser and more positively (finely) skewed in surface and mid-depth turbidity maxima and the mid-depth clear water zone than in the bottom turbid layer. Median grain sizes within the bottom layer remained constant or coarsened very slightly with depth (Figure 22). The median grain sizes in the bottom layer at stations 10 and 12 appear to be coarse in the late spring and early summer, and become finer until the end of July when they remained constant for several weeks. The median grain size at these stations began to coarsen in the last week of August; the last dates sampled show the coarsest grain sizes (Figure 23). The variations in median grain size in the upper layers do not seem to follow this same trend throughout the summer (Figure 23).

Particulate organic carbon (POC) values ranged from a high of 2.3 mg/l to zero and most values were less than 1.0 mg/l. These values corresponded to a full range from 0 to 100 % of the TSS concentrations with an overall average of 20 % for the entire water column. Percentages of POC in TSS in the surface water and bottom water were generally equal

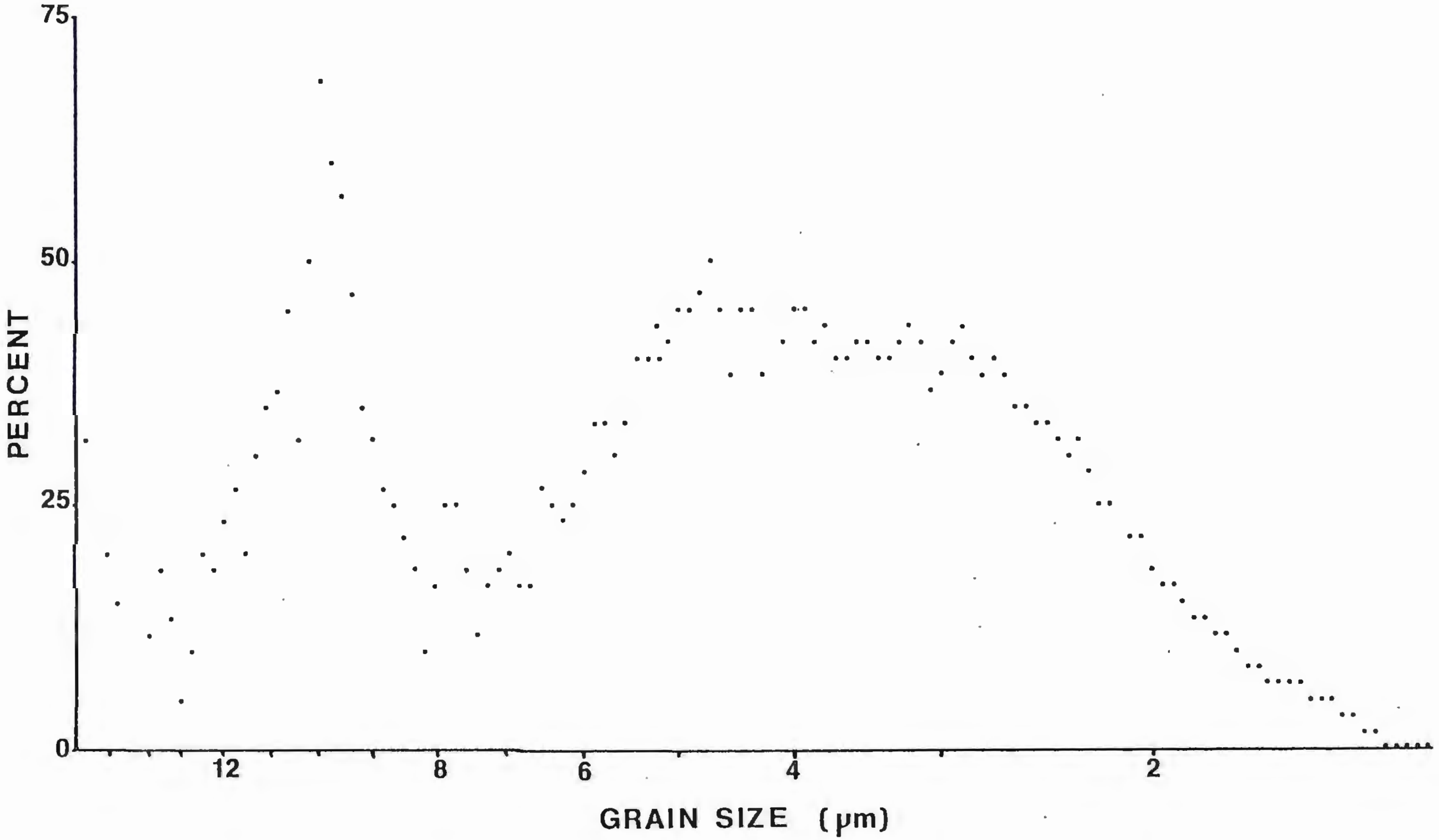


FIGURE 21a: Grain size distribution on 5/18/83 for station 1 at 2m depth, expressed as percent volume.

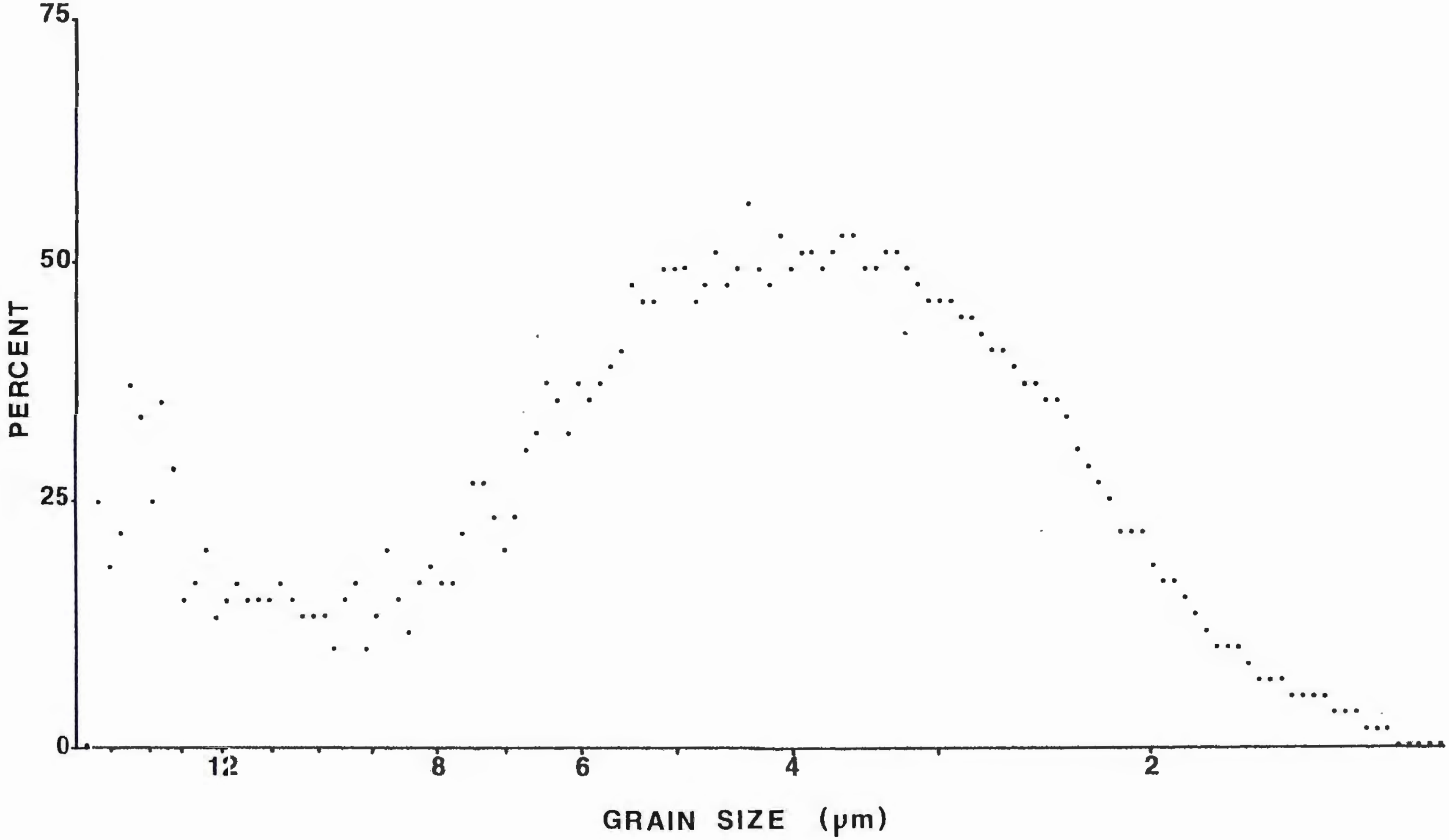


FIGURE 21b: Grain size distribution on 7/5/83 for station 10 at 21m depth, expressed as percent volume.

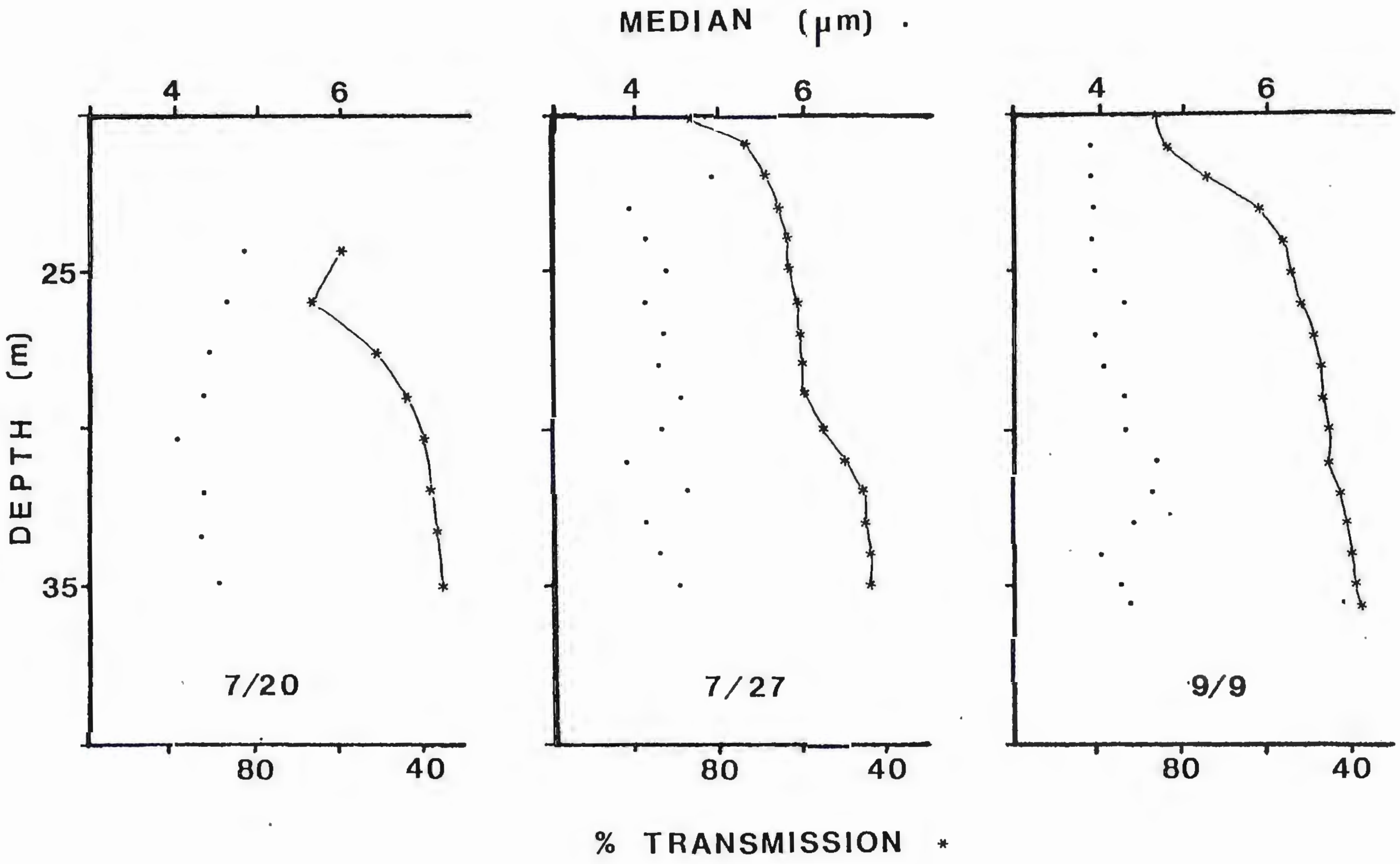


FIGURE 22: Changes in median grain size with depth in the bottom turbid layer at station 10 on 7/20/83, 7/27/83, and 9/9/83.

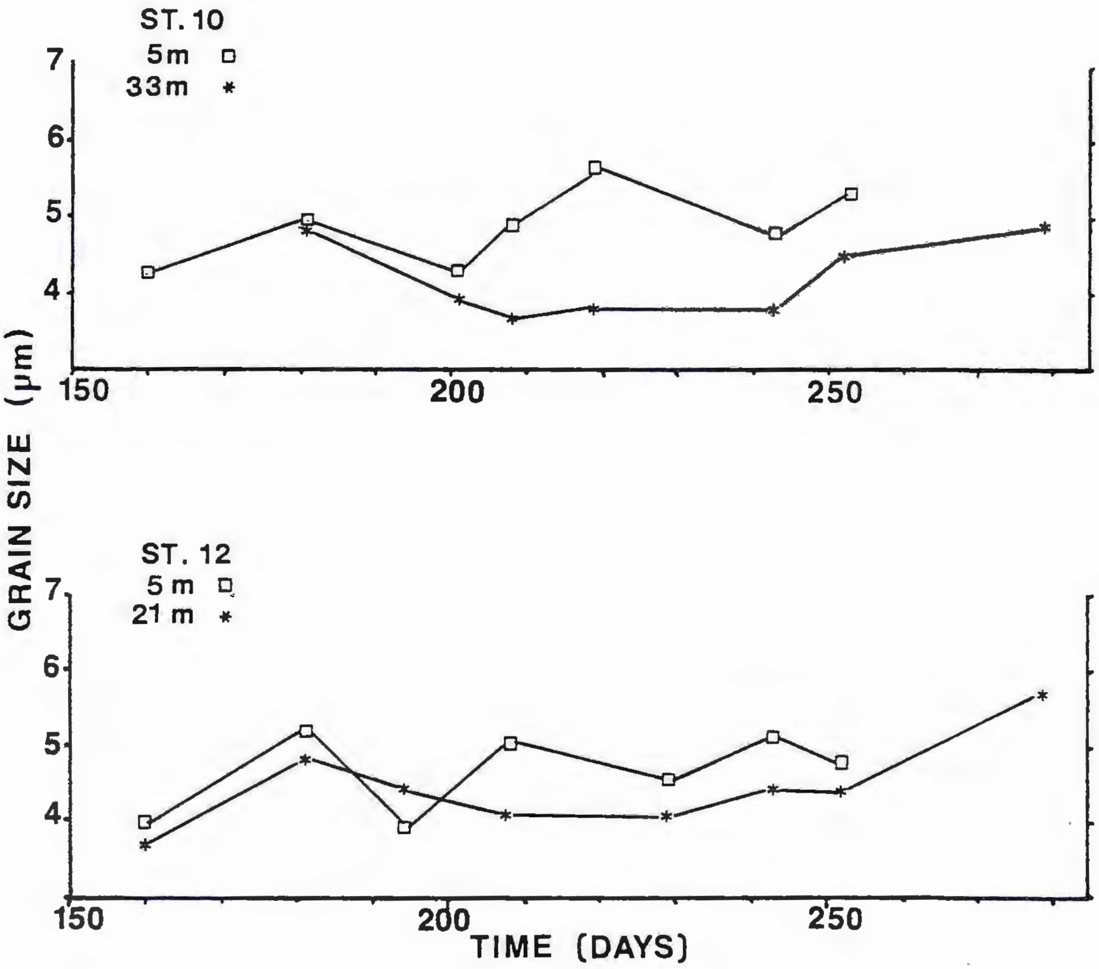


FIGURE 23: Change in median grain size over time at stations 10 and 12 in surface (□) and bottom (*) waters.

during the spring and early summer (up to about 6/30/83) at the large majority of stations and dates sampled. Percent POC in the surface waters stayed high throughout the summer averaging 29%, while in bottom waters,it fell to an average of 10%. A singularly high value of POC occurred at station 10 on 7/20/83 where it increased to about 1 mg/l over the average to a high of 1.7 mg/l or about 39 % (Table B - Appendix). Data from 7/20/83 also show that at station 10 the fraction of organic carbon in TSS in the bottom turbid layer decreased with depth (Table B - Appendix).

Concentrations of chlorophyll-a ranged from 0.0 to 15.8 ug/l and were consistently higher in the surface waters than at the mid-depth clear zones and bottom turbid layers at all stations sampled. Station 3 had the highest chlorophyll-a concentrations, by as much as 50%, for all samples on any given day. Concentrations at stations 10 and 12 (Table C - Appendix) varied throughout the sampling period but no peaks or consistent trends seemed apparent. The sampled dates are far enough apart, however, to possibly mask any consistent changes in chlorophyll-a concentrations through time.

Phaeophytin concentrations were consistently low for both surface and bottom layers typically as low as 0.4 ug/l. Phaeophytin was about 11% of the chlorophyll-a concentrations on the average and in some cases within the nepheloid layer was as high as 36%. The only exceptionally high phaeophytin concentrations occurred at station 3 on

6/9/83 and 7/5/83 in the surface water layer. Concentrations were 1.1 and 0.8 ug/l, respectively. These high concentrations occur simultaneously with the lowest transmission values seen at any depth through the entire sampling period, below 10% and 0%, respectively (Table C - Appendix).

DISCUSSION

Distribution

The distribution studies revealed new aspects of the suspended solids in the lake. Surface suspension events such as the red clay plume of the Nemadji River are well known but the existence of persistent bottom turbidity in Lake Superior had not previously been measured. The project provided substantial evidence for the existence of a well-developed persistent bottom layer of suspended solids in the western arm of Lake Superior.

A large amount of suspended material enters the western arm during snowmelt and spring runoff (Sydor 1975). Sources for this material are the suspended load of runoff, wave erosion along the red clay bluffs and resuspension of very fine-grained sediments deposited during winter. The majority of the suspended load coming into the lake is distributed as a surface plume observed in the spring that then must settle through the water column before the lake is well stratified.

Thermal stratification in Lake Superior begins during late spring or early summer. The increased stability of the water column with stratification probably acts as a barrier for the bottom water motion due to winds. Suspended solids, no longer dispersed throughout the water column, begin to settle and accumulate as a distinct nepheloid layer near the lake floor. With continued stratification the surface waters become 'uncoupled' from the bottom waters. This occurred near the end of May and early June in 1983.

The concurrent growth of the thermal stratification and the bottom turbidity can be seen in Figure 4. The stratification was very weak on 5/18/83 and turbidity at the lake floor was essentially non-existent. The majority of the suspended solids seemed to be coming from the Wisconsin shoreline (Figure 9). Stations 2, 3, and 5 in Figure 9, directly off the Superior entry, show elevated concentrations of suspended solids in the surface water. This turbidity is probably due to river runoff.

By 6/7/83, however, stratification was stronger and there was a distinct bottom layer of turbidity. At this point, stratification had developed enough to effectively separate surface and bottom waters (Figure 10). River or harbor inputs, showing as surface turbidity at station 3, were separated from bottom turbidity by a zone of clearer water. The two zones of turbidity are due to different processes. Warmer river water, meeting and overriding colder lake water, probably caused the surface turbidity. Intensified stratification allowed the continued build-up of suspended solids in the bottom layer.

The last significant amount of suspended solids from the river runoff entered the western arm as a result of a major storm on 7/2/83 - 7/4/83. The storm dropped nearly 8 cm of precipitation and maintained high wind speeds (averaging 10 - 15 m/s and including tornados in northern

Wisconsin near the lake shore) over the three day period preceding a cruise on 7/5/83. Sampling on 7/5/83 took place at least 30 hrs after the peak of precipitation on 7/3/83 (6.8 cm) and transmission values at station 3 near the Superior harbor entry were as low as 0% (filtering gave concentrations of 50 mg/l). The peak in suspended load of the Nemadji has been recorded as occurring within 12 hrs of the peak in precipitation (Sydor 1975). This suggests that the turbidity input from the Nemadji River as sampled on 7/5/83 was probably the tail-end of the total suspended load entering the lake as a result of the storm. A substantial amount of material probably entered the lake before sampling took place. This is supported by the fact that high surface turbidity, with less than 45% transmission, extended nearly 10 km into the lake (Figure 11a). The sharp concentration gradient within the surface turbidity plume contrasted greatly with the diffuse, more gentle gradient in the bottom layer (Figure 11). The two zones were separated by almost 10 m of relatively clear water (60% - 70% transmission). A similar type of surface plume was profiled off the mouth of the Grand River in Lake Michigan although probably under normal weather conditions (Chambers and Eadie 1981). This plume diminished to background lake concentrations within only 1 - 2 km of the river mouth.

After strong stratification was established, there was apparently little or no net sediment moved out of the western arm. This is suggested by the gradual increase in the integrated sediment burden with continued stratification for both the entire water column and the bottom layer alone until around 8/23/83 (Figures 4 and 19). The increase in the sediment load was augmented by the lessening in the average strength and duration of winds over the same period (Figure 6) and perhaps by the thermal stratification which was fully developed during this time. An average particle, 4.0 um diameter and density = 2.65 g/cm^3, would take about 12 days to settle through 8 m (the thickness of the bottom layer) in 6° C water using Stokes Law of settling velocity. The period of increased sediment burden, however, took place over about 30 days. This indicates that during this period there was sufficient turbulence to prevent the suspended particles from settling out completely and they remained suspended although concentrated closer to the bottom of the water column.

A period of relatively quiet conditions in the hypolimnion probably was enforced because of low average winds and intense stratification and yet the sediment burden in the bottom layer increased. The specific mechanism responsible for this persistent suspension of particles in the bottom layer is uncertain. One possible reason for the increased sediment burden and persistent turbidity during the summer could simply be the addition of suspended solids from a fairly constant source. One such source may be the harbor area. Maps of the transmission at the bottom of the water column at each station profiled on 8/2/83 and 8/23/83 (which is also the minimum transmission value for the entire water column) show that turbidity decreases away from station W at the Superior entry (same as station 3) along a line parallel to the axis of the lake and to either side of this line (Figure 16). The area of minimum transmission was oriented downslope, perpendicular to bathymetric contours. These data suggest a source in the harbor, perhaps the Nemadji River. Surface turbidity for these two days plotted in the same manner, shows uniform transmission values of greater than 80%. This may indicate the presence of a density flow at depth, i.e. suspended material moving out of the Superior entry at depth and flowing into the lake parallel to its axis as far as 25 km from the harbor mouth.

Dominik et.al. (1983) found that Rhône River water entering Lake Geneva in summer months descended below the lake surface as a discrete stream and preserved its identity for as far as 30 km from the Rhône mouth. The waters flowed at a density equilibrium depth determined by temperature and the amount of dissolved and particulate matter. Rhône water is colder and more dense than water in Lake Geneva because of its glacial origin (Dominik et al. 1983). The temperature of the Nemadji is much closer to that of Lake Superior than that of the Rhône is to that of Lake Geneva.

A similar plot of the integrated sediment burden of the bottom layer at each station shows that the greatest load within the layer is in an area at least 10 km from either shoreline and 20 km from the Superior entry (Figure 20). This type of sediment load pattern could be due to a density flow coming out of the harbor entry whose initial velocity is relatively fast and which decreases as the flow moves offshore. The existence of the density flow could be substantiated by current meter measurements in the western arm.

Chambers and Eadie (1981) pointed out that the bottom layer in Lake Michigan seemed to initiate at the approximate depth of the thermocline. They postulated that the layer was supplemented throughout the summer by sediment resuspended at this boundary by the impingement or 'rubbing' of the thermocline as it came against the shallow shelf area of Lake Michigan. Oscillatory currents associated with the breaking internal waves could add suspended sediment to the nepheloid layer during the summer months.

The feasibility of this mechanism of suspending sediments for the marine environment has been examined both experimentally and in the field by Southard and Cacchione (1972) and Cacchione and Southard (1974). They found that for a small scale, two-layer model, internal waves did initiate sediment movement as they shoaled on a gently sloping bottom. The waves broke abruptly at a point invariably downslope of the original position of the two-layer interface. At the point of breaking, sediment was thrown violently into suspension, transported initially upslope and subsequently downslope by a return current between breakers. Cacchione and Southard (1974) then made some limited field observations off the New England coast in order to check the validity of applying the model to the marine shelf environment. They found that comparisons between predictions of incipient sediment movement and mean grain sizes present on the shelf off New England suggested that internal waves of the size known to be present in the oceans would move the bottom sediment found on the shelf. It is possible that this internal wave mechanism could be applied to Lake Superior as well.

Erodable clays along the Wisconsin shoreline certainly constitute a readily available source of fine-grained sediment to the adjacent lake floor. Cross-sections for 7/19/83, 8/2/83, and 8/23/83 show the thermocline abutting the relatively gentle slope of the Wisconsin shore. In some cases, the bottom turbidity initiates where the slope and thermocline meet (e.g. cross-section 15gh, 22ab) and in others, bottom turbidity occurs some meters below this interface (e.g. 5 - 7 m below: 14ab, 15cd; 10 - 15 m below: 13cd). For all cases, the minimum transmission (i.e. maximum turbidity) does not occur at the same depth as the thermocline/slope interface.

The presence of seiche or internal wave motion has been described for Lake Superior and substantiated with field observations (Mortimer, 1974). Carlson (1982) measured currents at various depths near Isle Royale, north of the western arm region of Lake Superior. He found that while oscillatory currents, associated with internal waves, measured near the lake floor (240m) did not appear strong enough to initiate erosion, currents measured at mid-depth (120m) did appear strong enough (greater than 30 cm/s). He suggested that these current speeds have strong implications about the stability of recent sediments at depths of less than 120m, assuming a correlation with sediments of Lake Erie which began to erode at 20.5 to 25.0 cm/s. These implications are equally true for the recent sediments in the western arm where the mean water depth is less than 100m.

Several other lines of evidence can be examined for other indications of local resuspension. One method is to investigate the change in type and abundance of diatoms with depth. This is discussed later. A second method is to examine changes in grain size with depth. Simple settling of sediment in water should produce an increase in grain size with depth. A size gradient should exist for all but very small grain sizes.

On three occasions during the sampling period, 7/20/83, 7/27/83, and 9/9/83, water samples were taken every 1 or 1.5 m for grain size distribution analyses. Figures 22 shows median grain size for each sample plotted against depth in the layer. These plots all show a slight increase with depth in the bottom 2 - 3m but nearly uniform grain size throughout most of the nepheloid layer. This suggests that the energy available to keep the particles in suspension was adequate enough to prevent much size segregation by settling.

A first estimate of the magnitude of energy needed for maintaining suspension can be obtained from the concentration gradient within the bottom layer as shown by several workers (e.g. Inman 1968, Blatt et al. 1980). When vertical velocity fluctuations are greater than or equal to settling velocities, particles are held in suspension. The shear velocity (U*) is about equal in magnitude to the root mean square of the vertical velocity fluctuations (Blatt et al., 1980). U* can be determined from concentration gradients by using the equation (following Inman 1968):

$$Nz/No = (Z/Zo)^{-w/aU^{*}k} \qquad (4)$$

where: Zo = reference height measured positive upwards (= 1m)
Z = height above the bottom
Nz = concentration at height z
No = concentration at reference height
w = settling velocity
k = von Karman's constant (= .4)
a = dynamic viscosity proportionality constant (= 1)

The proportionality constant (a) relates the eddy viscosity of sediment mixing to that of water mixing. It was chosen to equal unity because the sediment suspension is relatively dilute and consists of very fine particles. By taking the log of both sides and rearranging, the equation becomes:

$$U^* = -w/ak \frac{(\log Z/Zo)}{(\log Nz/No)} \qquad (5)$$

For a 4.0 um diameter particle in 5° C water, this becomes:

$$U^* = 2.4 \times 10^{-3} \frac{(\log Z/Zo)}{(\log Nz/No)} \qquad (6)$$

U* can now be calculated from the slope of the plot of (log) height above the bottom versus (log) concentration. The concentration values were taken from turbidity profiles (volts) and converted to concentration (mg/l). Table 2 shows first estimate U* values calculated for the bottom turbid layer at station 10 from 6/9/83 to 10/6/83 ranging from 1.0 x 10^{-3} cm/s to 4.0 x 10^{-3} cm/s. These U* values reflect the magnitude of energy needed to keep particles (4 microns and at 5° C) in suspension. The value of mean velocity at 100 cm above the bed (U_{100}) can be calculated from the equation (Sternberg 1972):

$$Uz = 5.75\, U^* \log(z/z_o) \qquad (7)$$

where: z_o = roughness length (= 0.01 to 0.1 m)
z = height above the bed
Uz = mean velocity at height z
U* = shear velocity
k = von Karman's constant (= 0.4)

This equation assumes that z_o is much smaller than z. The values for z_o of 0.01 to 0.1 m were chosen as reasonable roughness lengths based on work by Sternberg (1972). The values of U* calculated from concentration gradients yield U_{100} values of 0.01 to 0.07 cm/s for the range of z_o values

DATE	DAY NO.	U* (x 10^{-3} cm/s)
7/05/83	186	2.16
7/19/83	200	1.37
7/27/83	208	3.17
8/02/83	214	1.14
8/17/83	229	1.32
8/23/83	235	2.19
8/31/83	243	1.67
9/09/83	252	2.84
9/22/83	265	1.61
10/6/83	279	2.86

TABLE 2. Shear velocity (U*) for the bottom turbid layer at station 10. See Figure 2 for station location.

given in equation (7).

The low values of the estimated shear velocity are much lower than critical U* values calculated for the erosion of marine muds. For example, Young and Southard (1978) found critical U* values ranging from .25 to .45 cm/sec for *in situ* muds affected by normal tidal bottom currents in Buzzards Bay, Mass. These values of U* yield corresponding U_{100} values of 6.7 cm/s and 12.0 cm/s, respectively. These values are at least 3 orders of magnitude greater than the shear velocities calculated in this study. The calculations indicate that very little energy is needed to maintain the suspended sediments in Lake Superior.

The magnitude of energy needed can also be estimated from resuspension rates. Fukuda and Lick (1980) state that the entrainment rate (resuspension rate) will equal the net sediment flux plus the deposition rate. This can be formulated as:

$$R = q_s + D \qquad (8)$$

where: R = resuspension rate
q_s = net sediment flux
D = deposition rate

in units of $g/m^2/s$.

This equation was used to estimate a resuspension rate for the suspended solids in the nepheloid layer from 8/2/83 to 8/31/83 (Figure 27). The increase in the sediment load (.04 g/m^2) over this period (30 days) is the net sediment flux ($q_s = 1.54 \times 10^{-8}$ $g/m^2/s$). A 4 um particle, in 6°C water, will settle 25m, or 69 % of the water column at station 10, in 30 days using Stokes Law of settling. Assuming uniform distribution throughout the water column and an average sediment load of .14 g/m^2 (from Figure 19), the deposition rate, D, equals 9.7×10^{-2} g/m^2 / 30 days or 3.74×10^{-8} $g/m^2/s$. The resuspension rate using equation (8) is then 5.3×10^{-8} $g/m^2/s$.

Fukuda and Lick (1980) report resuspension rates for sediments in Lake Erie of 1.0 to 1.0×10^{-4} g/m^2s. The resuspension rate calculated for Lake Superior is orders of magnitude smaller. This illustrates that little energy is needed to maintain the net sediment load of the bottom layer throughout the summer.

Many different processes could be acting to supply the small amount of activity needed for the maintenance of the bottom turbid layer. Because the U_{100} values and resuspension rates are so low, events such as wind-driven bottom currents, surface waves, and internal waves may well supply enough energy to maintain the system even though their initial energy is considerably diminished at depth.

The significance of the amount of suspended solids in the nepheloid layer can be illustrated by comparison with yearly sedimentation rates for the western arm. The average sediment load in the nepheloid layer was about 8.0×10^{-5} $g/cm^2/y$ if this entire amount of material settles on the bottom at the end of the summer stratification.

Mass sedimentations rates of 9×10^{-3} to 1.5×10^{-1} $g/cm^2/y$ have been reported for the western arm based on palynological studies and ^{210}Pb geochronology (Maher 1977; Evans et al. 1981; and Scholz, in prep.). The amount of sediment added to the bottom if the nepheloid layer settled is two orders of magnitude less than the amount that accumulates yearly in the western arm. This indicates that while the summer turbid bottom layer has a much higher concentration than the rest of the water column, the loadings it provides to the lake floor are insignificant compared to the year as a whole.

Sydor (1975) reported the the suspended load for the Nemadji River spring runoff (4/3/75 - 5/7/75) as 4×10^2 to 13×10^3 metric tons per day. A sediment load for the western arm can be calculated by multiplying the average sediment burden ($.14\ g/m^2$) as determined by this study by the surface area ($5.4 \times 10^7\ m^2$). This yields a sediment load of 7 metric tons. A comparison of spring runoff versus summer water column loading indicates that the spring runoff load makes a much greater contribution to the sediment budget for the western arm.

The fall overturn of Lake Superior occurred concurrently with the disappearance of the bottom layer in late summer/early fall. The results indicate that the lake cooled from summertime highs while the bottom layer diminished in strength and thickness. The concentration gradient within the bottom layer became more erratic. In 1983, this breakup occurred between 9/22/83 and 10/6/83.

With increased water movement, the suspended solids become more evenly dispersed throughout the water column. As in spring, higher wind speed and duration augment the circulation and suspended sediment is again able to leave the western arm and move into other areas of the lake. This is illustrated by the decrease in the integrated sediment burden for the entire water column as shown in Figure 19.

The results of the distribution studies point to a need for continued work with a turbidity/temperature profiling system. Was the 1983 summer nepheloid layer typical or did the unusual temperatures of June, July, and August, the warmest on record at the Duluth Intl. Airport, allow it to develop to a degree not usually seen in the lake? Did the nepheloid layer occur outside of the western arm? Continued work with a profiling system could help determine the turbid layer's uniqueness, i.e. its tendency to reoccur from year to year or its presence in regions of the lake other than the western arm. It could also help clarify the relationship between the thermocline's behavior and suspended solids, and help monitor the suspended load input from rivers due to runoff or storm activity.

Composition

The median grain size of the suspended solids in the western arm averaged about 4.0 um (8.0 phi) which was finer than the mean grain size of the surface sediments as found by Thomas and Jaquet (1975) for the western arm (3 - 7 phi). The surface sediments were poorly to very poorly sorted with standard deviations of greater than 1 to 4 phi. The suspended solids as found in this study were moderately sorted but this may be an artifact of the electronic particle analyzer. The good correlation between skewness and median grain size found by Thomas and Jaquet (1975) for the surface sediemnts held true for the suspended sediments also.

A bimodal grain size distribution of the suspended sediment in late spring probably represents the tail-end of the spring algal bloom. Microscopic inspection of the late spring particulates indicated that the coarser fraction of material producing the 10 micron peak was diatoms.

The POC percent of the total suspended solids in the nepheloid layer generally decreased with depth at most stations during the summer. The concentration of POC (mg/l) in the nepheloid layer, however, increases with depth. This indicates that although the absolute amounts of POC in the layer are highest near the lake floor, they are overwhelmed by much greater amounts of inorganic material and contribute less to the total composition.

The average percentage POC in the suspended solids of the bottom turbid layer was about 10%. Johnson et al. (1982) found that surface sediments in the western arm of the lake had about 2-3% organic carbon. These values suggest that at least 7-8% of the organic material in the suspendeded solids must be degraded at the sediment-water interface or in the mixing layer before incorporation into the permanent sediment record.

Munawar and Munawar (1978) classify Lake Superior as oligotrophic to ultra-oligotrophic based on biomass and phytoplankton assemblages. El-Shaarawi and Munawar (1978) report typical chlorophyll-a concentrations (corrected for phaeophytin) of about 0.6 to 1.3 ug/l. Concentrations of chlorophyll-a found in this study were of the same magnitude but slightly higher (Table C, Appendix). Relatively higher concentrations of chlorophyll-a in the surface waters simply reflect the optimal zone for primary productivity. Concentrations were also slightly higher in spring and early summer, probably due to the spring algal bloom.

The concentrations of phaeophytin for 6/9/83 and 7/5/83 at station 3 are relatively high. This is probably due to heavy spring runoff and runoff due to storms. The phaeophytin concentrations and the exceptionally low transmission values for the same period, indicate a greater amount of organic debris than the lake normally carries.

The results of identification and enumeration of diatom species are comparable to earlier studies, although the diatom study was only a limited survey. The most commonly occurring diatom species in the suspended matter are for the

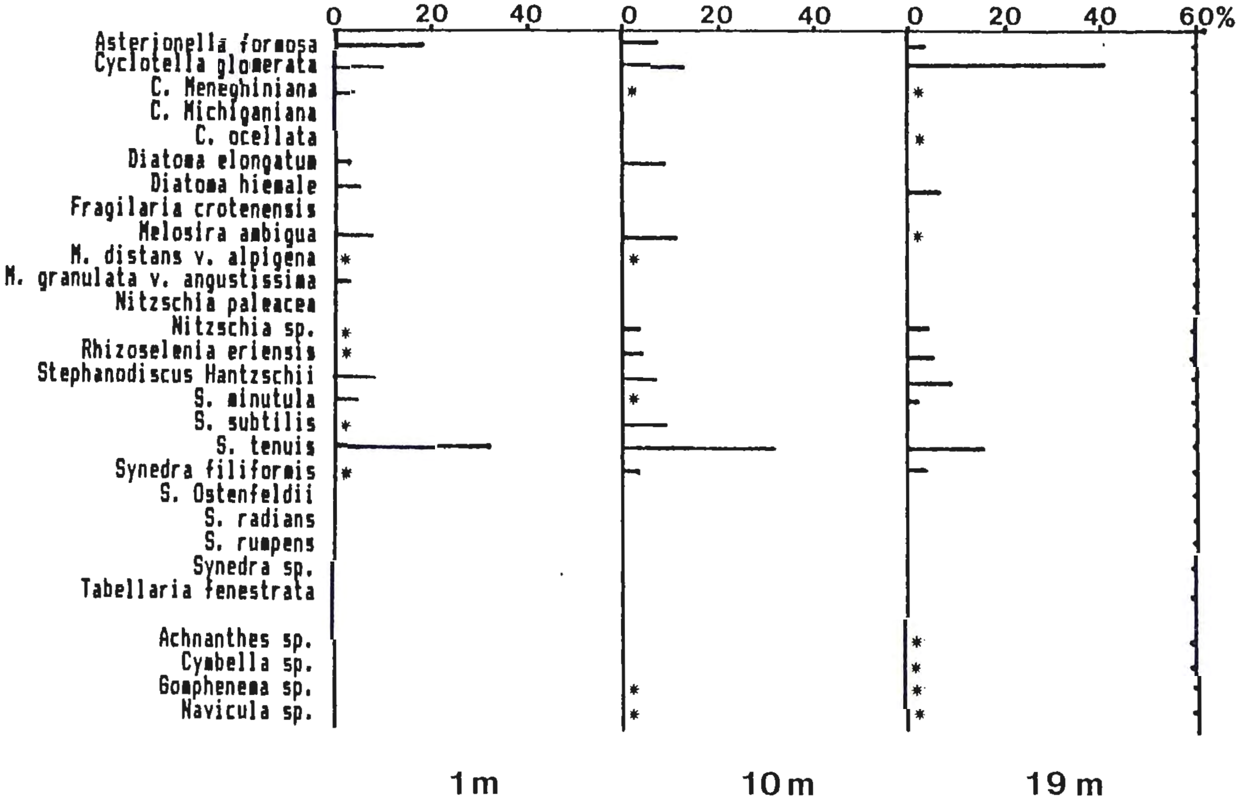


FIGURE 24: Percent of total abundance of common diatoms (at 1m, 10m, and 19m) at station 3 on 6/9/83. Stars indicate diatom species identified but at less than 1%.

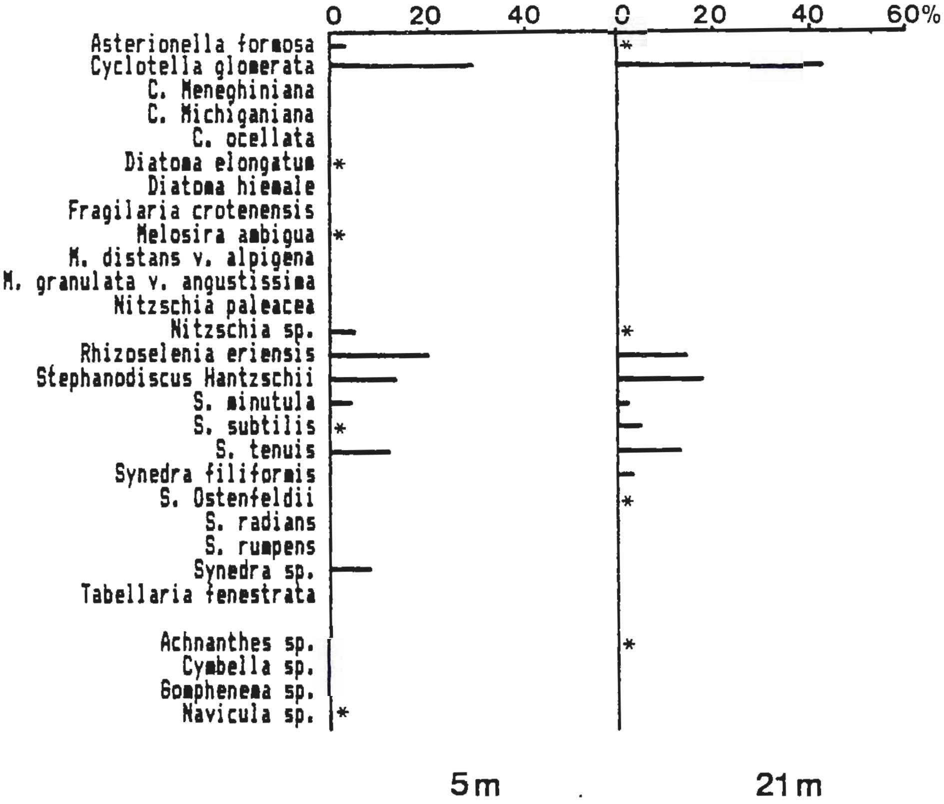


FIGURE 25: Percent of total abundance of common diatoms (at 5m and 21m) at station 10 on 6/9/83. Stars indicate diatom species identified but at less than 1%.

most part the same as those studied in more detail by Munawar amd Munawar (1978), and Stoermer and Kreis (1978). They also compare with the common diatom species in Lake Superior bottom sediments as described by Thayer (1981). The succession of species over time is also comparable to that reported by Munawar and Munawar (1978). For example, figures 25 - 28 show that in 1983, *Asterionella formosa* was present in low amounts in early summer and increased to more than 30% of the population by 9/9/83. *Tabellaria fenestrata* was absent in spring and early summer but appeared consistently in samples taken after 7/19/83, though still in low numbers. Munawar and Munawar (1978) noted an increase in *A. formosa* and *T. fenestrata* in late summer and a peak in early fall in the western arm of Lake Superior.

The results of the diatom study also indicated the potential usefulness of diatoms as tracers of specific water masses and as evidence for resuspension. The species *Melosira ambigua*, *Melosira granulata* v. *angustissima*, and *Stephanodiscus tenuis* are considered to be pollution indicators in that they favor highly eutrophic environments (Stoermer and Yang 1970; Stoermer and Ladewski 1976). In Lake Michigan they were generally restricted to harbor waters (Stoermer and Yang 1970). Figure 29 shows the decrease in these three species with distance from the Superior entry on 6/9/83. It is also interesting to note that *Rhizoselenia eriensis* shows the opposite trend.

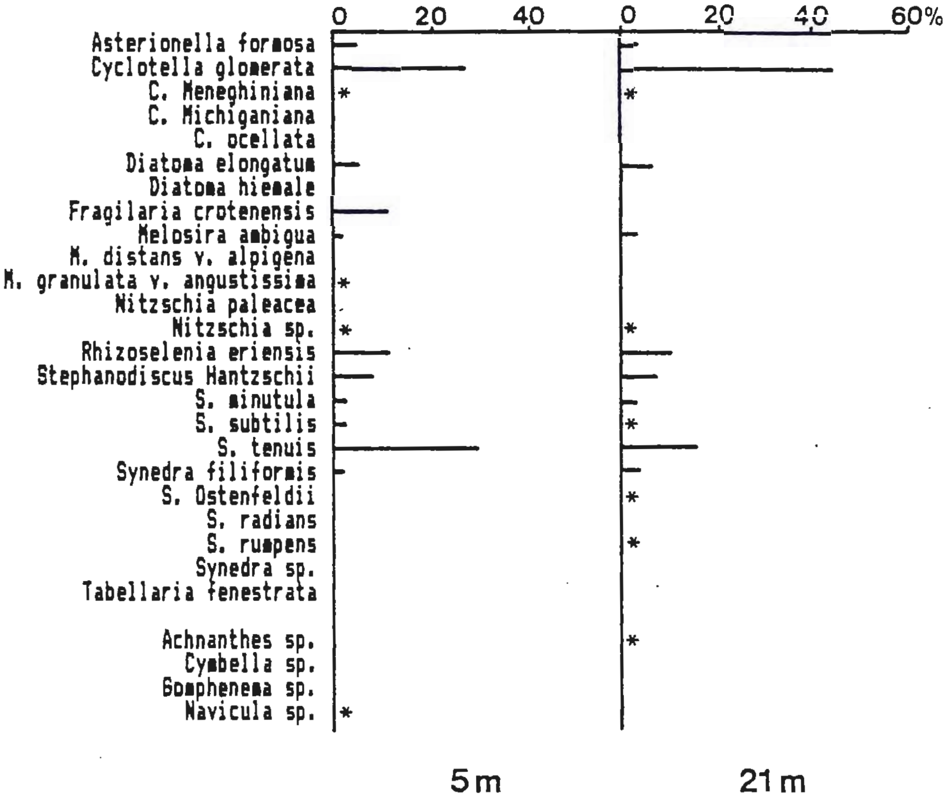


FIGURE 26: Percent of total abundance of common diatoms (at 5m and 21m) at station 12 on 6/9/83. Stars indicated diatom species identified but at less than 1%.

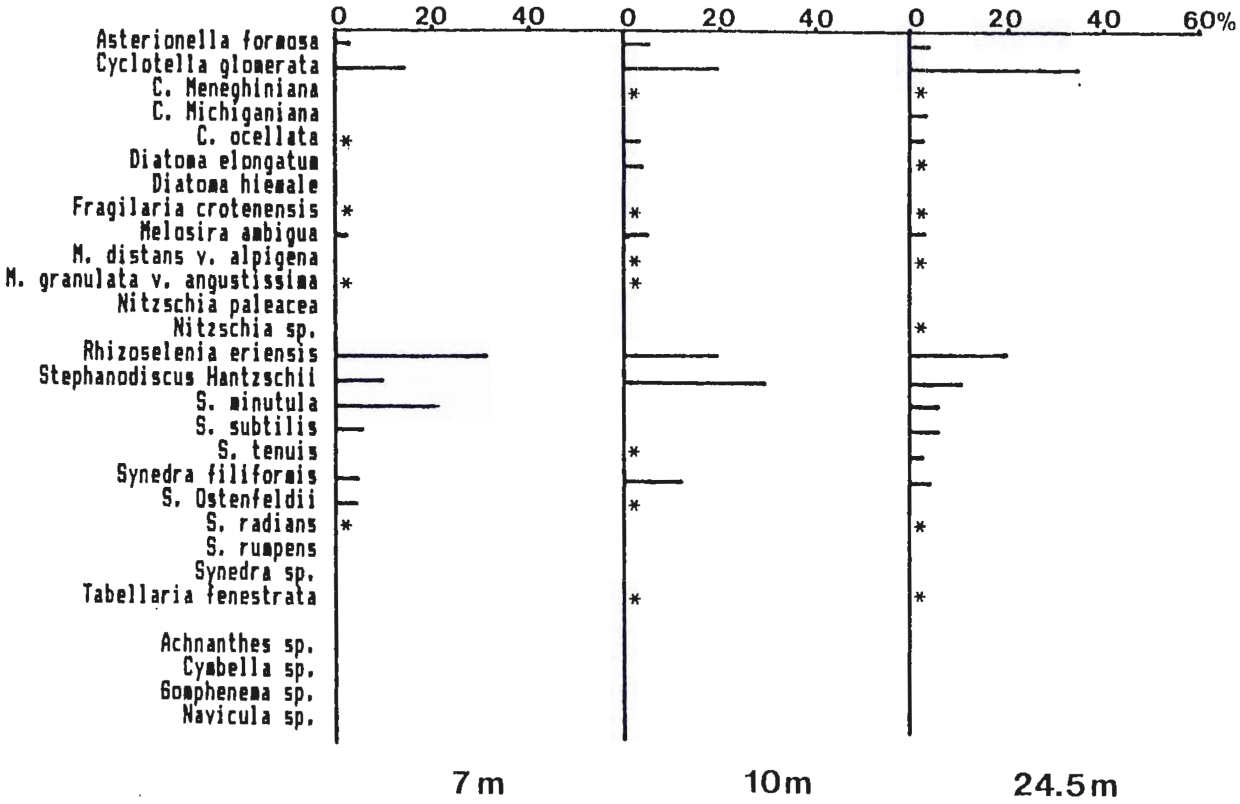


FIGURE 27: Percent of total abundance of common diatoms (at 7m, 10m, 24.5m, 27.5m, 32m, 35m) at station 10 on 7/20/83 (continued on next page). Stars indicate diatom species identified but at less than 1%.

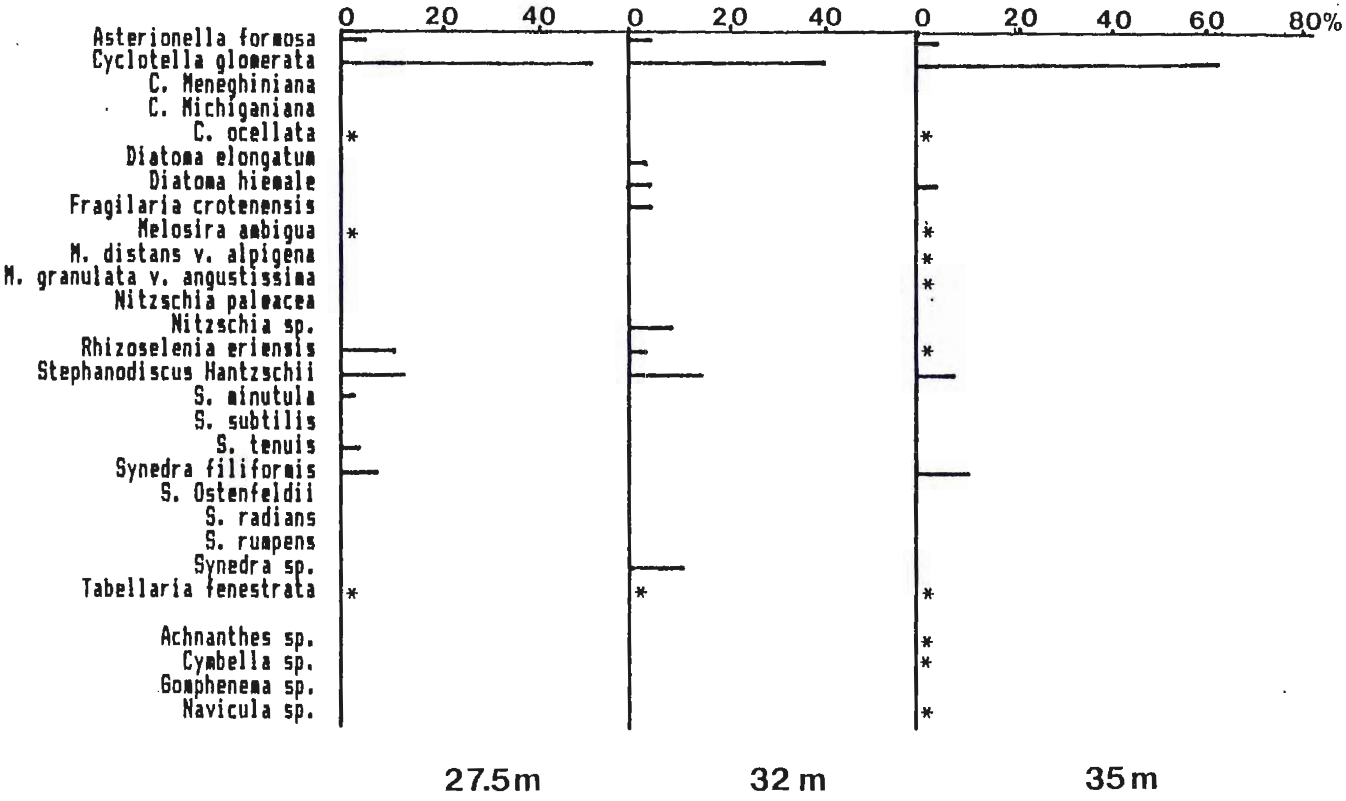


FIGURE 27 (cont.):

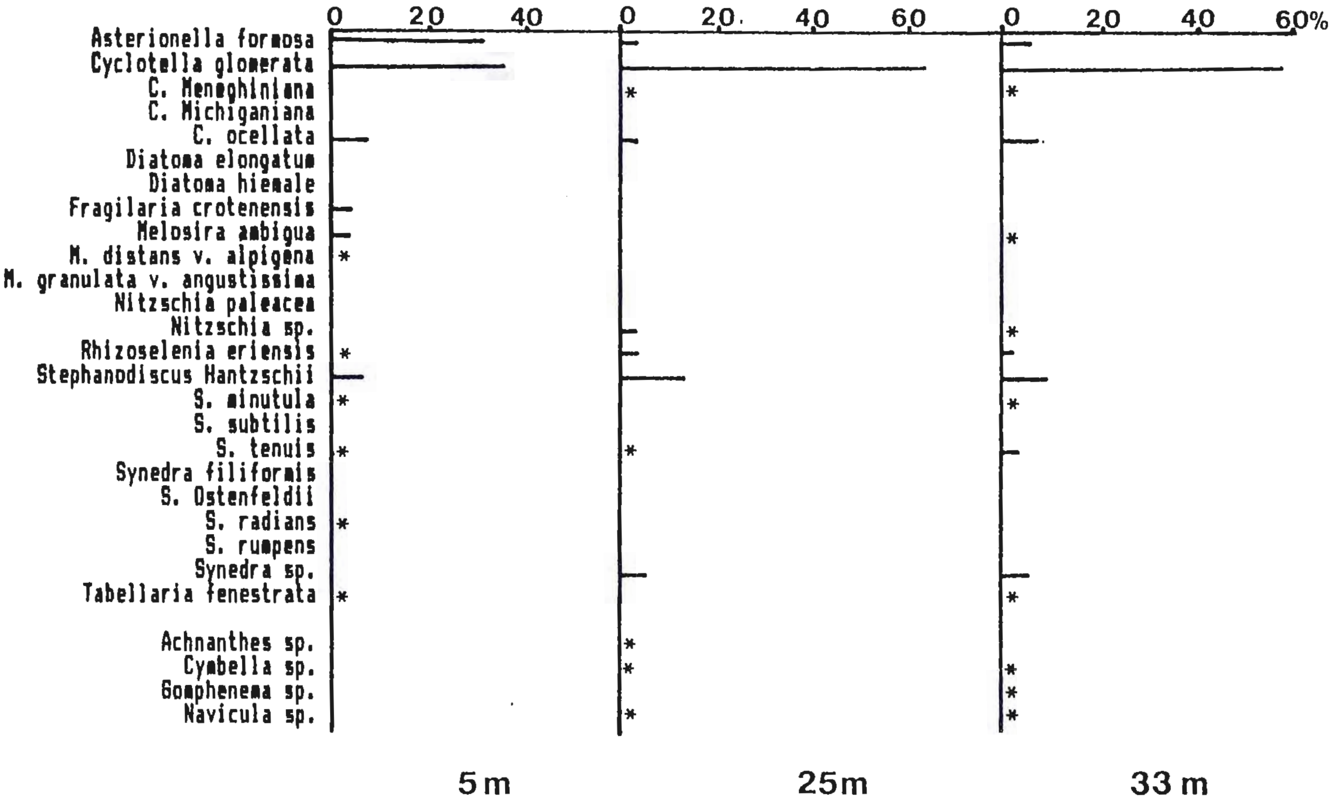


FIGURE 28: Percent of total abundance of common diatoms (at 5m, 25m, and 33m) at station 10 on 9/9/83. Stars indicate diatom species identified but at less than 1%.

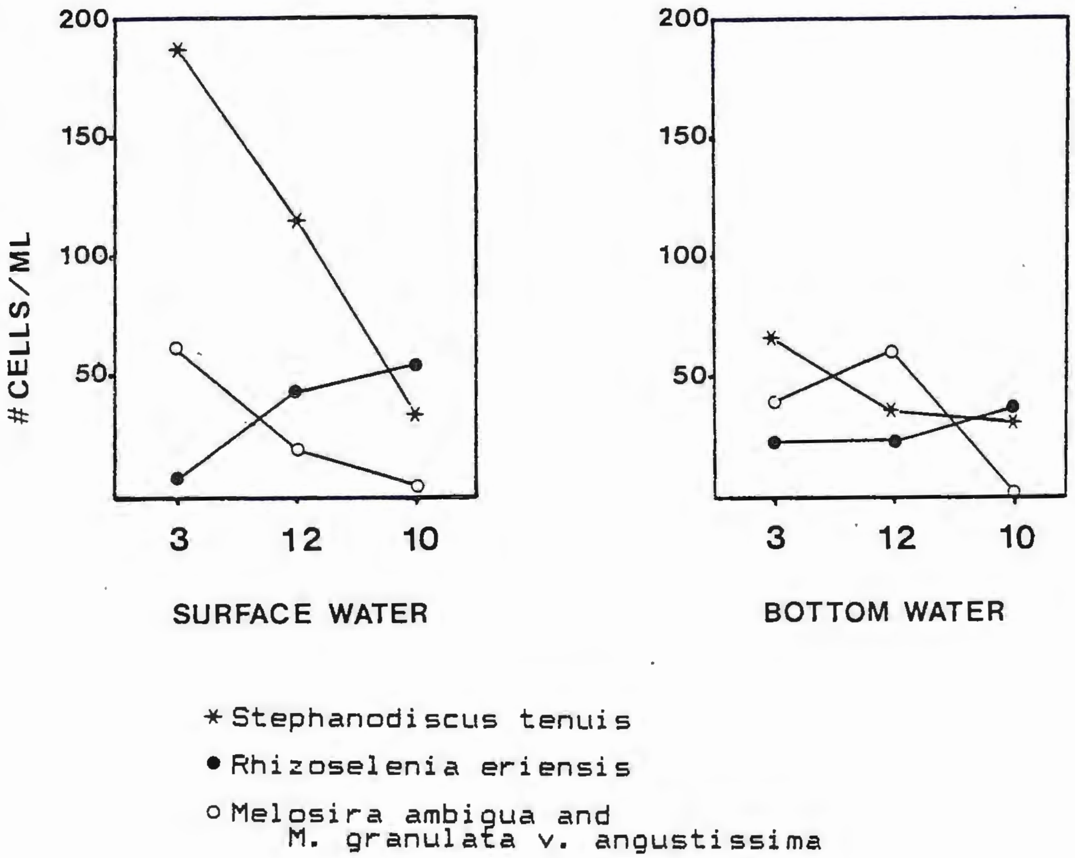


FIGURE 29: Change in diatom species with distance from the harbor, i.e. station 3 - near harbor, station 10 - intermediate, station 12 - open lake, in both surface and bottom waters.

Stoermer and Ladewski (1976) found this species generally restricted to offshore waters and intolerant of advanced eutrophication in Lake Michigan. The changes in these four diatom species may reflect the influence of harbor water dispersing into the lake.

The change over depth of the species *Cyclotella glomerata* could indicate local resuspension (Figure 30). The ecology of this species is uncertain but it is considered by some to be a benthic species in Minnesota lakes (Thayer 1981). If it is benthic, then the increase in its percent abundance with depth in the bottom turbid layer would logically result from resuspension. Other genera which are generally considered to be benthic dwellers, e.g. *Cymbella* sp., *Achnanthes* sp., appeared only in the samples taken from 1 - 8m above the bottom, never in samples taken from surface or mid-depth water. The presence of these diatoms in the upper reaches of the bottom turbid layer suggest that a significant portion of the suspended solids was resuspended bottom material.

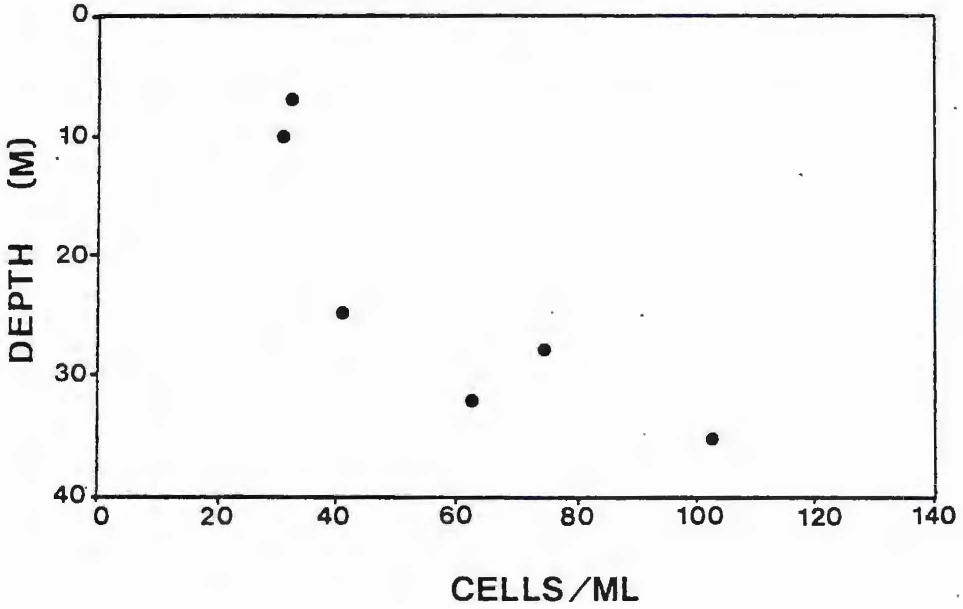


FIGURE 30: Change in abundance of *Cyclotella glomerata* with depth in the water column at station 10 on 7/20/83.

SUMMARY

Spring and storm runoff of the Nemadji River often produces surface turbidity plumes that extend as far as 10 km into the lake. Thermal stratification begins during late spring/early summer in Lake Superior. During this time, solids suspended throughout the water column begin to accumulate near the lake floor. The increased turbidity in this bottom nepheloid layer is concurrent with the growth of thermocline stability. Fall overturn in Lake Superior occurs concurrently with the disruption of the nepheloid layer and more uniform distribution of the suspended solids throughout the water column.

The total sediment load of the bottom turbid layer increased from middle to late summer during the period of the most stable, and strongest, thermal stratification. Plots of the maximum turbidity in the water column at each station indicate that the increase in the sediment load may be due to additions of suspended material brought into the lake by density flows originating in the Duluth-Superior Harbor and flowing out into the lake at depth. The increase in sediment burden may also be due to sediment resuspended by oscilllatory currents associated with internal wave or seiche activity.

The magnitude of energy needed to keep particles in suspension in the nepheloid layer is negligible. U* values calculated from concentration gradients within the nepheloid layer indicated that U_{100} values, i.e. mean velocities 100 cm above the bottom, were only on the order of 0.01 to 0.07 cm/s. Resuspension rates were estimated at 5.3 x 10^{-3} $g/cm_2/yr$. The low U_{100} values and resuspension rates indicate that very little energy is needed to maintain the nepheloid layer.

The nepheloid layer is a significant feature of the summer water column. The amount of sediment loadings represented by the nepheloid layer, however, is insignificant when compared to yearly loadings to the lake floor. Spring runoff provides a much greater contribution to the yearly sediment budget for the western arm.

Median grain sizes within the nepheloid layer remained constant with depth. The median grain size of the suspended solids as a whole were much finer grained than modern surface sediment on the lake floor.

Particulate organic carbon (POC) concentrations decreased with depth. The percent of POC in the suspended solids was 7 - 8% greater than the percent of POC in the modern surface sediments.

Chlorophyll-a and phaeophytin values were typically on the order of 1 - 3 ug/l and 0.4 ug/l, respectively, and were comparable to values found in earlier studies. The concentrations found are typical of an oligotrophic to ultra-oligotrophic system.

The identification of diatom species assemblages and the enumeration of individual diatom species in this study are comparable to earlier studies. Plots of species abundance against distance from the harbor entry indicate a potential usefulness for diatoms as tracers for specific water masses.

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APPENDIX

TABLE A. Grain size statistics

DATE	STATION	DEPTH	MEDIAN	KURT.	SKEWN.	ST. DEV.
		(m)	(phi units)			
5/18/83	5	5	7.35	1.89	.37	.90
	7	1	7.20	1.96	.58	.90
6/07/83	1	1	7.90	1.91	.11	.90
		18	7.75	1.86	.12	.93
	2	1	7.74	1.81	.11	.93
		18-A	7.68	1.84	.33	.95
		18-B	7.38	1.96	.73	.99
	3	1	7.86	2.04	-.10	.86
		18	7.73	1.96	.05	.90
	4	1	7.55	1.92	.42	.92
	5	0	7.86	1.79	-.03	.94
6/09/83	3	1	7.26	2.22	-.04	.82
		10	7.89	1.92	.00	.90
		19	7.84	2.18	-.12	.86
	10	5	7.88	1.79	.11	.96
		21	7.87	1.79	-.01	.95
	11	5	7.94	1.88	.04	.93
		15	7.86	2.03	.26	.88
	12	5	7.68	1.81	.05	.96
		21	8.08	2.07	-.16	.90
6/27/83	2	1	7.78	2.01	-.08	.89
	3	1	7.77	1.96	.11	.89
		15	7.82	2.00	.26	.87
	10	10	7.72	1.80	.13	.96
6/30/83	10	10	7.66	1.92	.51	.93
		29	7.75	2.21	.08	.82
		33	7.71	2.39	.03	.77
	12	10	7.59	1.86	.47	.94
		25	7.69	1.90	.52	.92
7/05/83	1	3	7.95	2.07	-.05	.87
		19	7.50	2.13	.38	.84
	2	4	7.72	1.95	.36	.90
	3	0	8.07	3.02	-.33	.65
	4	2	7.89	1.97	.29	.88
	10	15	7.82	2.00	.20	.88
		21	7.83	2.42	-.19	.80
	11	2	7.93	1.82	.05	.95
		18	7.86	1.94	.09	.91
7/13/83	4	3	7.91	1.90	.14	.91
		20	7.87	1.80	.18	.94
		40	8.06	2.27	-.25	.85
	11	3	7.98	2.23	-.01	.83
		10	8.12	2.38	-.36	.85
	12	3	7.99	2.08	-.12	.86
		20	7.81	2.09	.11	.85
7/20/83	10	7	7.86	2.14	-.05	.86

DATE	STATION	DEPTH	MEDIAN	KURT.	SKEWN.	ST. DEV.
7/20/83	10	10	7.70	1.85	.14	.93
		24	8.06	1.84	-.09	.95
		26-A	8.13	2.07	-.08	.89
		26-B	7.73	1.71	.32	.98
		27	8.11	2.00	-.35	.94
		29	8.06	2.38	-.39	.86
		30	8.08	2.67	-.54	.80
		32	8.00	2.51	-.24	.79
		33	8.00	2.46	-.19	.79
		35	7.90	2.28	-.35	.84
7/26/83	10	5	7.68	2.48	.32	.77
		20	7.78	1.93	.07	.91
		21	7.66	1.86	.09	.92
		22	7.74	2.29	.03	.79
		23	8.17	2.67	-.63	.83
		24	8.11	2.50	-.31	.80
		25	8.06	2.27	-.17	.85
		26	8.06	2.56	-.44	.81
		27	8.07	2.46	-.32	.82
		28	8.04	2.48	-.44	.84
		29	8.00	2.38	-.22	.83
		30	8.10	2.39	-.42	.87
		31	8.22	2.95	-.44	.74
		32	8.02	2.23	-.13	.87
		33	8.09	2.78	-.50	.79
		34	7.98	2.68	-.19	.75
		35	8.03	2.43	.10	.78
	12	5	7.64	2.47	.13	.75
		15	7.71	2.09	.21	.87
		26	7.94	2.13	-.06	.87
8/17/83	10	5	7.47	2.30	.37	.80
		25	8.02	2.86	-.62	.80
		33	8.04	2.76	-.41	.77
	12	3	7.78	2.29	-.01	.81
		15	7.72	2.44	.20	.78
		25	7.93	2.44	-.23	.80
8/31/83	3	1	7.54	2.07	.34	.86
		10	7.78	2.29	-.01	.81
		17	7.92	2.81	-.42	.73
	10	5	7.70	1.91	.15	.92
		10	7.77	2.35	-.10	.80
		22	7.90	2.55	-.20	.78
		33	8.05	2.40	-.24	.81
	11	5	7.47	2.50	.50	.75
		17	7.90	2.43	.26	.77
	12	5-A	7.59	2.19	.23	.82
		5-B	7.61	2.28	.30	.81
		21	7.82	2.57	-.26	.74
		26-A	7.77	2.50	-.25	.77
		26-B	7.84	2.62	-.26	.75

DATE	STATION	DEPTH (m)	% POC	POC MG/L
8/31/83	10	22	>100	.16
		33	8	.41
	11	17	13	.17
	12	21	13	.19
9/09/83	10	5	40	.60
		25	10	.37
	12	5	19	.31
		14	6	.15
		25	6	.16
10/6/83	10	10	26	.35
		30	11	.16
		33	7	.16
		35	4	.21
	12	15	16	.30
		27	10	.21

TABLE B. Organic carbon

DATE	STATION	DEPTH (m)	% POC	POC (mg/l)
6/27/83	2	1	20	1.0
	3	1	25	1.5
		15	21	1.0
6/30/83	1	10	28	.8
	10	10	24	.9
		29	10	.9
		33	7	.9
	12	10	34	.6
		25	90	.4
7/05/83	1	3	7	.5
		19	4	.1
	2	1	23	.3
	3	0.5	5	1.7
	4	2	16	.3
	10	15	17	.3
		21	--	0.0
	11	2	12	.5
		18	7	.2
7/13/83	4	3	54	1.5
		20	70	1.6
		40	33	1.4
	11	3	41	1.6
		10	24	1.3
	12	3	68	2.1
		20	81	1.7
		28	6	2.9
7/20/83	10	24.5	82	1.6
		26	55	1.5
		27.5	63	1.2
		29	40	2.0
		30.5	27	2.2
		32	18	1.6
		33.5	20	1.7
		35	16	1.5
7/27/83	10	5	>100	.52
		22	15	.15
		33	7	.25
	12	6	52	.79
		15	58	.16
		26	17	.23
8/17/83	10	5	>100	--
		25	8	.13
		33	7	.33
	12	3	40	.32
		15	54	.14
		25	10	.15
8/31/83	3	10	31	.76
		17	8	.24

DATE	STATION	DEPTH	MEDIAN	KURT.	SKEWN.	ST. DEV.
9/09/83	10	5	7.56	2.14	.34	.84
		20	7.87	2.59	.05	.73
		21	8.00	2.49	-.21	.78
		22	8.01	2.69	-.17	.74
		23	7.97	2.53	-.41	.80
		24	8.00	2.65	-.18	.77
9/09/83	10	25	7.97	2.58	-.37	.77
		26	7.82	2.27	.08	.81
		27	7.96	2.46	-.39	.80
		28	7.92	2.29	-.19	.83
		29	7.83	2.48	-.19	.77
		30	7.82	2.28	-.11	.80
		31	7.71	2.26	.34	.81
		32	7.73	2.34	.00	.78
		33	7.79	2.43	.00	.75
		34	7.95	2.45	-.38	.81
		35	7.84	2.44	-.06	.76
	12	5	7.70	2.96	.02	.64
		14	7.89	2.40	.19	.77
		25	7.82	2.44	.13	.74
10/6/83	10	30	7.58	2.44	.31	.75
		33	7.68	2.34	.13	.78
		36	7.82	2.43	-.14	.76
	12	15	7.58	2.27	.29	.79
		27	7.46	2.17	.49	.84

TABLE C. Chlorophyll-a and Phaeophytin

DATE	STATION	DEPTH (m)	CHLPHYLL-A (ug/l)	PHPHYTN (ug/l)	% PHPHYTN
5/18/83	5	1	2.3	---	
	7	1	1.6	---	
6/07/83	1	1	6.4	0.2	3.1
	2	1	3.4	0.1	2.9
		18	3.6	0.2	5.6
	3	1	5.8	0.2	1.3
		18	3.8	0.3	7.9
	4	1	1.6	0.2	12.5
	5	1	1.8	0.1	5.6
6/09/83	3	1	8.9	1.1	12.4
		10	7.1	0.4	5.6
		19	2.7	0.3	11.1
	10	5	3.9	0.1	2.6
		21	2.0	0.2	10.0
	11	5	4.2	0.3	7.1
		15	2.2	0.1	4.5
	12	5	3.8	0.2	5.3
6/27/83	2	1	6.8	0.1	1.5
	3	1	5.8	0.6	10.3
		15	6.7	0.6	9.0
6/30/84	1	10-A	4.3	0.2	4.7
		10-B	3.3	0.1	3.0
	10	10	5.0	0.4	8.0
		29	2.6	0.7	26.9
		33-A	3.6	0.6	16.7
		33-B	2.6	0.3	11.5
	12	10	3.6	0.3	8.3
		25	3.0	0.1	3.3
7/05/83	1	3	6.2	0.3	4.8
		19	3.3	0.3	9.1
	2	4	5.2	0.3	5.8
	3	.5	9.6	0.8	8.3
	4	2	3.4	0.2	5.9
	10	15	3.4	0.3	8.8
		21	3.0	0.4	13.3
	11	2	6.8	0.3	4.4
		18-A	4.2	0.7	16.7
		18-B	5.3	0.2	3.8
7/13/83	4	20	1.9	---	
		40	4.5	0.6	13.3
	11	3	3.5	---	
		10	3.7	---	
	12	3	5.3	---	
		20	2.5	0.1	4.0
7/27/83	10	5	5.4	---	
		22	1.6	0.2	12.5
		33	1.4	0.3	21.4

DATE	STATION	DEPTH (m)	CHLPHYLL-A (ug/l)	PHPHYTN (ug/l)	% PHPHYTN
7/27/83	12	6	5.8	---	
		15	1.8	0.4	22.2
		26	1.9	0.1	5.3
8/17/83	10	5	2.5	---	
		25	1.3	0.3	23.1
		33	1.8	0.4	22.2
	12	3	4.9	0.5	10.2
		15	1.8	0.3	16.7
		25	1.4	0.1	7.1
9/09/83	10	5	4.7	---	
		25	1.1	0.4	36.4
		33	1.2	0.4	33.3
	12	5	3.9	---	
		14	1.7	0.2	11.8
		25	1.1	0.3	27.3
10/6/83	10	10	2.2	0.1	4.5
		30	1.1	0.2	18.2
		33	1.3	0.2	15.4
		36	2.9	0.2	6.9
	12	15	5.2	---	
		27	3.5	0.2	5.7

--- undetected concentrations