# SEDIMENTARY PROCESSES OF BOONTON RESERVOIR

BY JACQUELINE DELU

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Professor Gail M. Ashley

and approved by

Gail M. Ashley

Alan McIntosh

Lowell A Douglas

New Brunswick, New Jersey

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# ABSTRACT OF THE THESIS

by JACQUELINE T. DELU, M. S.

Thesis Director: Professor Gail Ashley

This study of Boonton Reservoir, New Jersey and its major source of water, the Rockaway River, provides background knowledge to better understand the transportation and distribution of possible pollutants.

Rockaway River was analyzed for total organic carbon (TOC) and suspended sediment concentration. The average annual river discharge during this study was 42% lower (3.7 m /s) than that since 1940 (6.3 m /s). The suspended sediment and TOC concentration did not correlate with the river's discharge, probably because over 76% of the drainage basin is impounded. The mean TOC concentration was 7.7 ppm and the mean suspended sediment concentration was 3.6 mg/l. Both averages are similar to other river studies.

Boonton Reservoir water was analyzed for TOC and suspended sediment concentration. The mean suspended sediment concentration was 3.8 mg/l and the mean TOC was 7.5 ppm. The water was thermally stratified during the late summer and was mixed in the early winter and after the spring thaw.

Bottom samples were collected and analyzed for TOC, grain size distribution, and mineralogy. High concentrations of organic carbon were found near the river inlet and in the center of the deep northern basin. The bottom sediment had a mean TOC of 4.6% by weight while the sediment traps collected between 23-32%, suggesting most of the organic carbon reaching the bottom becomes oxidized. The mode grain-size decreases with distance from the shore. Coarse shore samples reflect-

ed wave winnowing processes. Little or no deposition occurred near the shores and in the shallow southern part of the basin because of periodic aerial exposure. The bottom sediments were a mixture of clay and sand, composed mostly of quartz, feldspars, and mica.

Two sediment traps were recovered and two cores extracted to determine the sedimentation rate in the reservoir. During the summer of 1981, the sedimentation rate was between 0.8 and 1.2 mm/yr.

ACKNOWLEDGEMENTS

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# INTRODUCTION

Recent droughts and contamination of wells by near surface pollution have focused public attention on the need to conserve and protect New Jersey's potable water supplies. Reservoirs are an important source of "fresh" water during dry periods but are susceptible to contamination from rivers carrying industrial and human wastes. An understanding of the physical processes affecting sedimentation of the reservoir will provide insights into the transportation and distribution of possible pollutants.

Boonton Reservoir has been labelled "mesotrophic" and in danger of becoming eutrophic (Wagner,1979). There are several industries located upstream which may be contributing chemical pollutants; and there have been local incidences of contamination of wells by chemical pollutants. Chemical pollutants may be entering Boonton Reservoir via the groundwater system or the Rockaway tributary system. The New Jersey Department of Environmental Protection has begun an investigation because of the danger of contamination to this potable water source. The present study will provide necessary background information for the state's chemical pollution study of Boonton Reservoir being conducted by Drexel University.

Figure 1 illustrates four major factors affecting sedimentation in Boonton Reservoir: 1)The Rockaway River provides sediment input through entrainment; 2)The atmospheric heating of the water produces stratification in the summer, mixing during turnover periods, and ice cover during the winter;

3) winds that provide surface turbulence of the water as well as erosion of the shore by waves; and 4) basin morphometry determines the textural distribution of deposited sediments. The goals of this study were to examine and describe the processes affecting sedimentation in Boonton Reservoir. Specifically the goals are the following: 1) to determine discharge variations, total organic carbon, and suspended sediment concentrations of the Rockaway River as it enters the reservoir, 2) to determine the bathymetry of the reservoir, 3) to examine spatial and seasonal temperature and dissolved oxygen variations of the reservoir; 4) to examine bottom samples from the reservoir for composition, total organic carbon, and grain size distribution; and 5) to estimate the sedimentation rate in the reservoir.

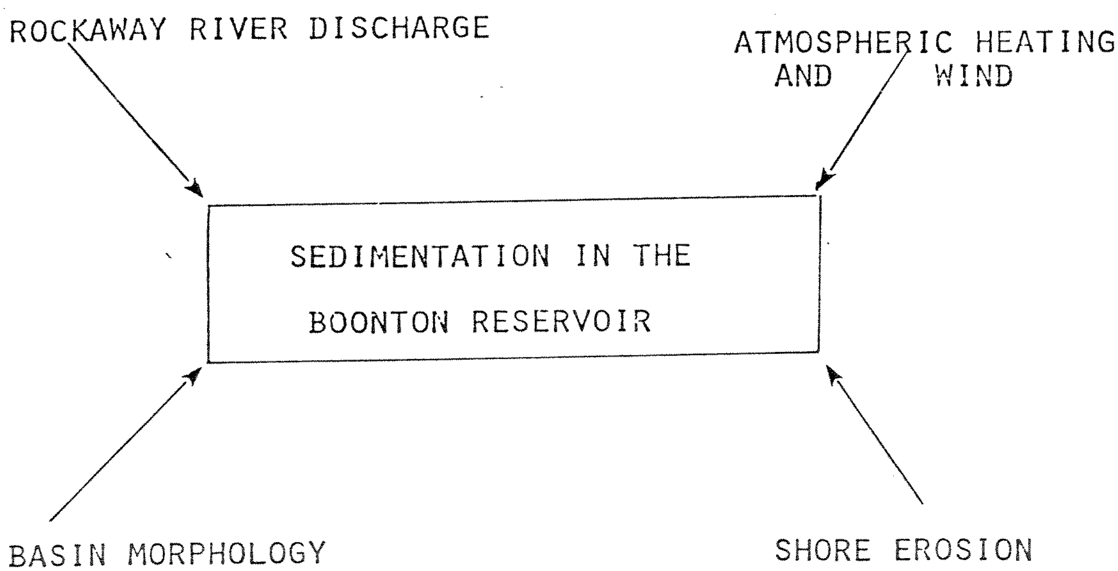



Figure 1: Four Major Factors Affecting Sedimentation in Boonton Reservoir.

# STUDY AREA

## Location

Boonton Reservoir, located in the Rockaway River drainage basin in Morris county, New Jersey, has a latitude of $40^{\circ}53'$ and a longitude of $74^{\circ}25'$ (Fig. 2). The northern half of the lake lies in the town of Boonton and the southern half is in Parsippany Troy Hills.

## Geology

The drainage basin is located in both the Highland and Piedmont physiographic provinces (Fig. 3). The Highland Province is typified by high (300 m) broad ridges and deep narrow valleys trending NE-SW (Geonics, 1979). The Highland Province contains both Precambrian crystalline and Paleozoic sedimentary rocks (Fig. 3). The Precambrian rocks consist of dark granitoid gneisses, schists and marbles. The Paleozoic rocks are folded and faulted and consist of black shales, slates, sandstones, dark limestones, arkosic quartzites and coarse quartzite conglomerates.

That portion of the drainage area containing the reservoir is located in the Piedmont Province; this area has a low undulating topography (60-120 m). The Piedmont Province in this area consists of Triassic soft red shales, sandstones, and conglomerates.

The soils formed on glacial till north of the terminal moraine. The hills are covered with a thin well drained rocky soil and exposed bedrock. The swales have a thick well drained alluvial soil. Most soils in the Rockaway River drainage basin were classified as gravelly

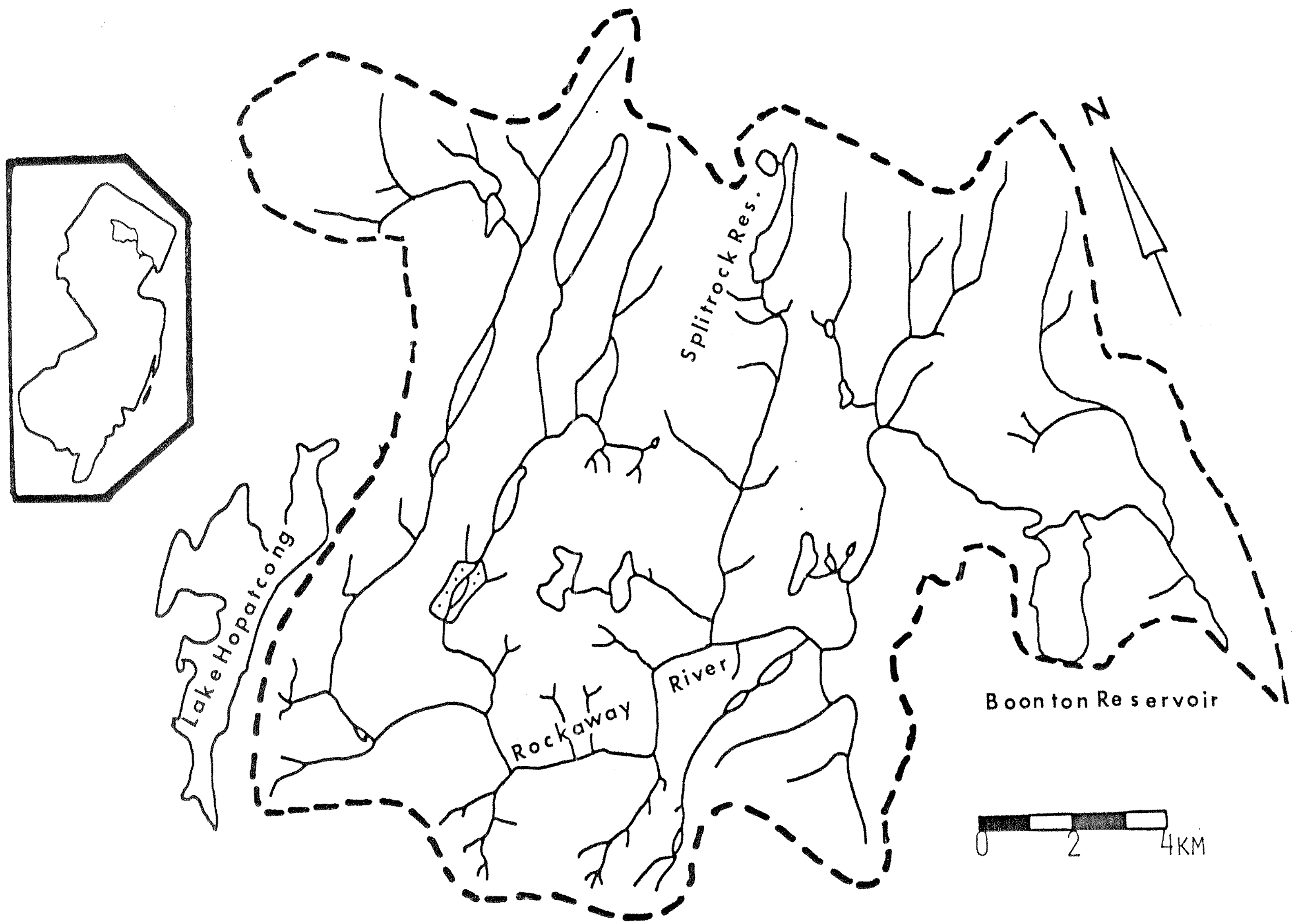



Figure 2: Map of Rockaway River Drainage Basin with Inset Showing Location of the Basin within New Jersey.

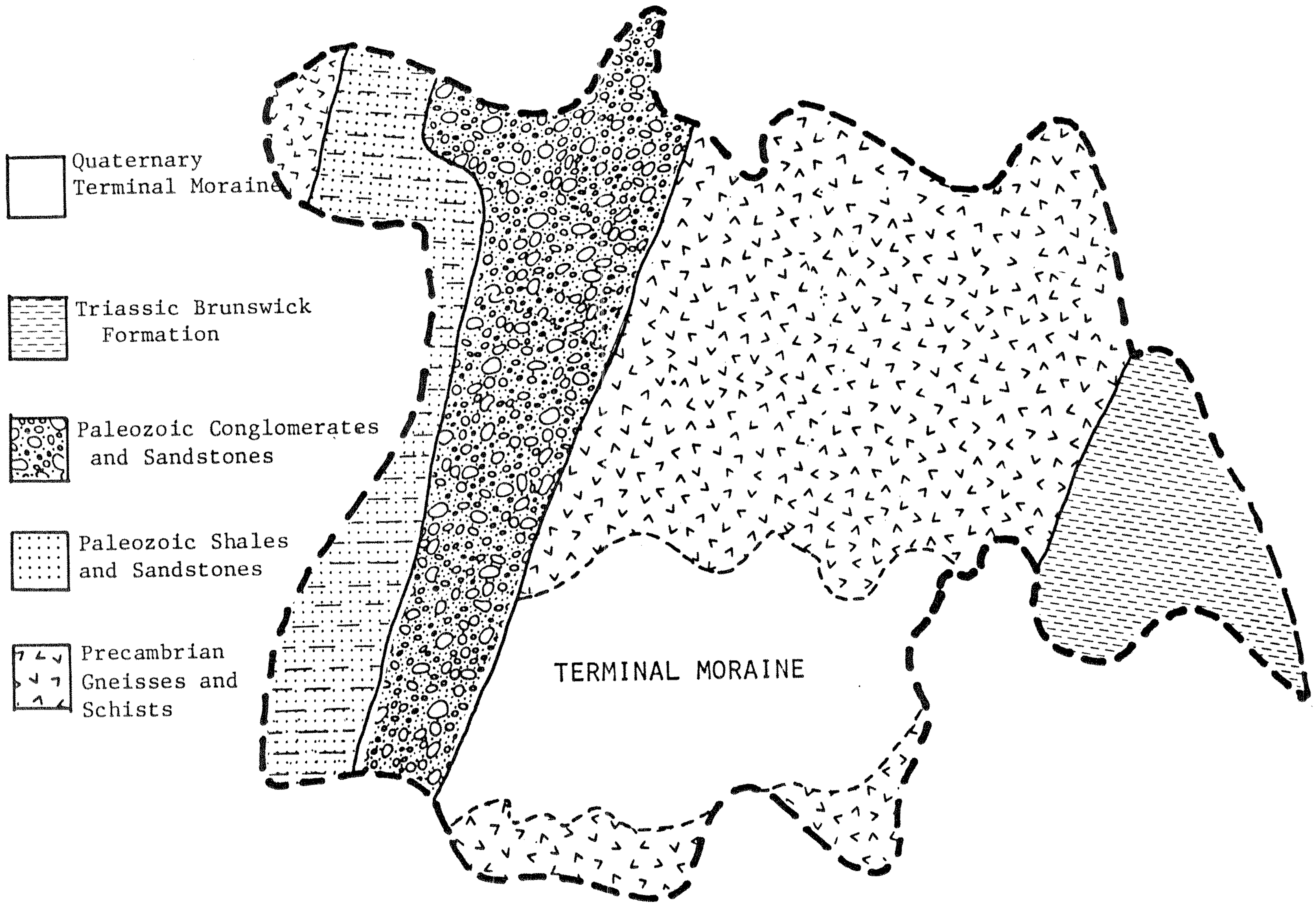



Figure 3: Geology of Rockaway River Drainage Area

or sandy loams (Caputo, 1975).

## History

In 1904 a dam was built in the Rockaway River channel by private investors. This newly formed impoundment flooded farmland. Boonton Reservoir was taken over in 1910 by the Jersey City Water Company to provide drinking water to Jersey City, Hoboken, Hackensack, West Caldwell, North Arlington and Lyndhurst, and treatment water to the Rockaway Valley Region Sewerage Authority (New Jersey Division of Water Policy and Supply, 1969). The flow into the reservoir is regulated by Splitrock Reservoir, located in the upper reaches of Beaver Brook tributary. Historically land-use was mainly for farming and mining, but today, the Rockaway River is bordered by industry and residences. The watersheds of tributaries are less populated and are occupied by forests and marshes, as well as industry and private homes.

## Climate

Winds in the Boonton area are predominantly from the northwest and the southwest (Gill and Vecchioli, 1965). During the winter air masses descend from the polar regions, while in the summer tropical air masses move northward over the southern states before reaching Boonton. These tropical air masses produce the heaviest rains. Annual precipitation is 117 cm (46 inches) with an average temperature of 10.3° C.

## Hydrology

The Rockaway River drainage basin has an area of 340 km$^2$, with 13 tributaries and over 21 impoundments. Most of the tributaries are structurally controlled and trend NE-SW. The trellis drainage pattern characteristic of the northern part of the basin (Fig. 3) changes to a dendritic pattern on quaternary glacial deposits in the southern part. These east-west trending terminal moraine deposits are an excellent near-surface aquifer because of their non-stratified and stratified sands, clays and gravels.

The valleys contain ponds and marshes, indicating a high water table. This ponding of water can be explained by clay or impermeable beds found in the unconsolidated deposits filling the low areas (Gill and Vecchioli, 1965). The Rockaway River is a major tributary to the Passaic River which drains into the Atlantic Ocean via Newark Bay (Fig. 2). USGS records show that the river's mean annual discharge is 6.3 m$^3$/s (221 cfs).

## Morphometry

Boonton Reservoir is a small oval reservoir with a surface area of 3.1 km$^2$. Its maximum depth is 30 meters (mean depth 7.6m) with a volume of 28.8 million m$^3$ at a spillway level of 93 meters (305 ft.) (Wagner, 1979). The Rockaway River enters on the northern west side of the lake approximately 1.8 km from the dam. The northern portion of the reservoir gradually deepens from 12 m to its maximum at the dam, while the southern part is flat, with an average depth of only 6 m.

# PREVIOUS STUDIES

## Geology and Hydrology

Gill and Vecchioli (1965) reported on the geography, geology, and hydrology of Morris County. The purpose of their report was to investigate the availability of groundwater in New Jersey. In Morris County groundwater is found in the unconsolidated sediments and in fractured bedrock. The largest volume of groundwater was obtained from the quaternary deposits, of which the unstratified drifts are considered to be the best aquifers. The water quality is potable with little or no treatment needed.

A water resource study by Geonics (1979) of the Rockaway Valley in Morris County identified prime aquifer zones as occurring in buried valleys. These zones of saturated sands and gravels were found to occupy ancient buried drainage channels beneath the terminal moraine. The study noted that contamination of surface waters in the upland areas could affect the groundwater in the low-lying aquifers. Near surface sediments in Boonton Township were found to be contaminated by industrial landfills and holding ponds. However, the contamination had not penetrated any groundwater sources. Sediment samples taken from Stony Brook near the airport were found to be contaminated by heavy metals above the limits set by the state of New Jersey. The report concluded that the quantity of available water was sufficient to supply Boonton for the next 40 years but that the aquifer must be protected from contamination.

Limnology

During 1978-1979 an intensive lake survey program was conducted to determine "lake dynamics and trophic conditions" (Wagner, 1979). Monthly water samples were taken from Boonton Reservoir's outlet and analyzed for physical, chemical, bacteriological and other biological parameters. It was determined that the continuation of high phosphorus loading would result in the eutrophication of the reservoir. Residential runoff accounted for 94% of the total phosphorus load. The pH, dissolved oxygen, phosphate content, coliform and bacterial counts indicated a moderate to good water quality. The reservoir showed stratification of temperature and dissolved oxygen between 7.6-12.2 m below the surface and the summer measurements indicated a deficiency in oxygen in the hypolimnion (Fig. 4). Most of the phytoplankton consisted of bluegreen algae, chlorococcalean green algae, and pollution tolerant diatoms.

The algae biomass and phosphorus data from the lake survey program indicated that the reservoir was moving from a mesotrophic to a eutrophic stage. Point sources of chemical pollution were identified as effluents and sewage from eleven industrial plants along the Rockaway River. It was concluded that much of the pollution entering the reservoir remained in the water and that because of the proximity of the Rockaway River inlet to the reservoir outlet, circulation within most of the lake was poor.

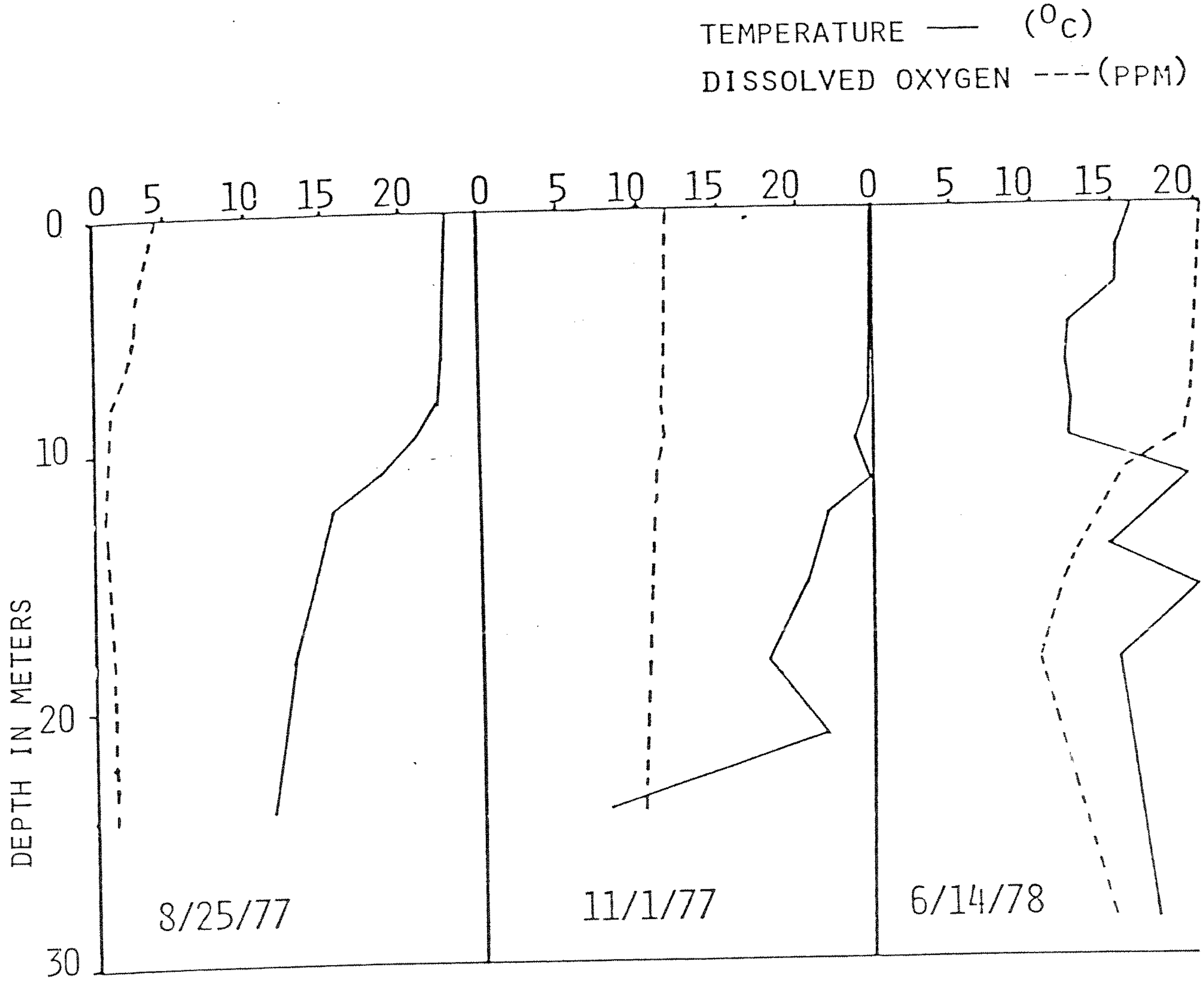



Figure 4: Temperature and Dissolved Oxygen Profiles from Boonton Reservoir (adapted from Wagner, 1979)

# METHODOLOGY

## Field Methods

### Rockaway River

Thirty water samples were collected for analysis of total organic carbon (TOC) and suspended sediment concentrations at the gauging station on the Rockaway River about 1.5 km above the reservoir (see Fig. 5). Sixteen samples were periodically collected. Thirteen samples were composites of eight hourly samples. All were collected using an open plastic gallon scoop that was dipped into the shallow (30-75 cm) river without disturbing the bottom. One water sample was collected from the bridge at the inlet to the reservoir. It was collected with a USGS DH-76 water sampler during a storm event. The sampler was lowered and raised three times to collect throughout the water column.

### Boonton Reservoir

Fourteen water samples were collected for TOC and suspended sediment concentration analyses in a boat using a Nansen water sampler. Two samples were collected from a depth of 2 meters, five samples from 4 meters, four from 8 meters and 3 from 12 meters below the water surface. Seventeen samples were collected with a bucket at the gatehouse where the water leaves the dam through a large conduit on route to the treatment plant.

Temperature and dissolved oxygen were measured in the reservoir using a YSI temperature and dissolved oxygen meter. Data was collected during the spring turnover, summer stratification and in the fall. A 15m probe extension cable was used on 3

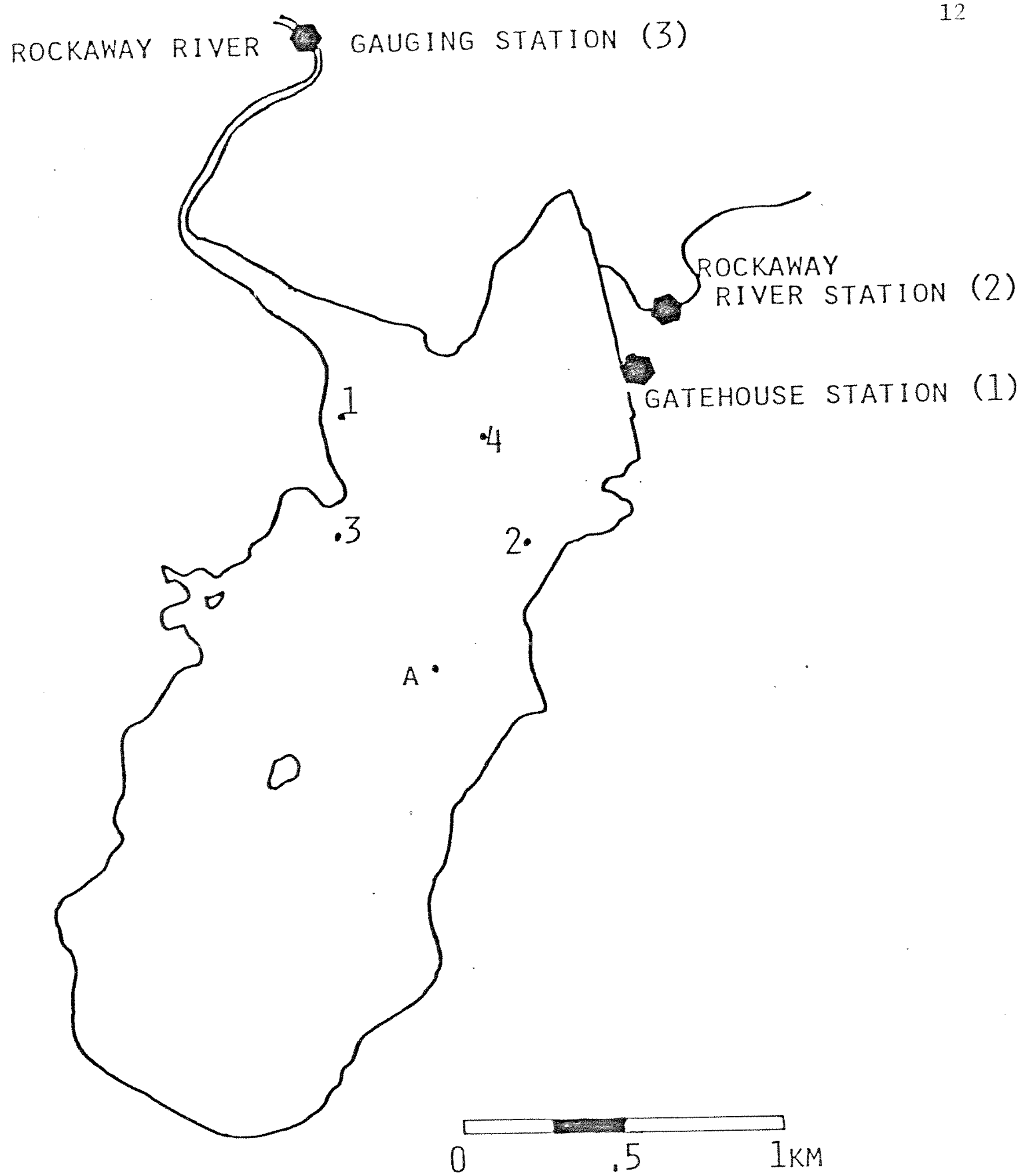



Figure 5: Water Sampling Stations ⬢ and Trap Locations •

sampling days and a 100m cable on 4 sampling days. The dissolved oxygen reading was calibrated at the water surface according to the YSI instruction manual. Measurements were taken at meter intervals.

Six bottom samples were collected from the shoreline using a shovel when the reservoir was 7.6 meters below the spillway. Five were collected from a boat using a Dietz-Lafond clam-type sampler and five using a Kahlsico screen top sediment sampler.

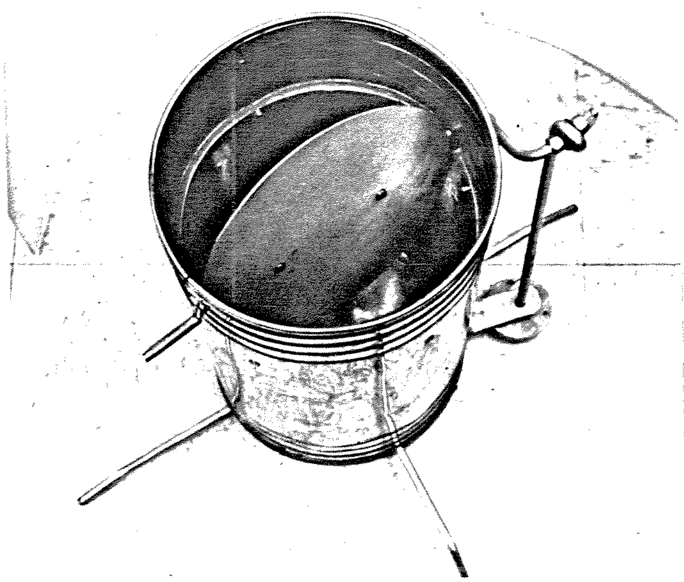
Current measurements were made from an anchored boat using a Gurley-type current meter. Velocity measurements were recorded at 30 second intervals every meter throughout the water column.

The bathymetry of the reservoir was determined with a Raytheon model DE 719AB Survey Fathometer. Twenty transects were made in the deeper portion of the lake.

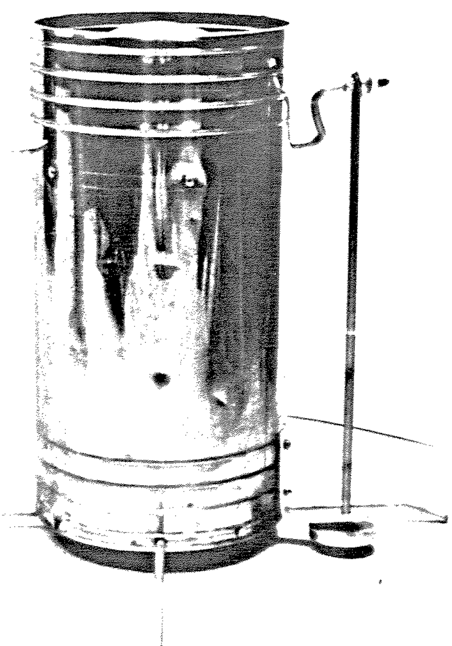
Five sediment traps were constructed and placed into the reservoir. One (A) was deposited November 13, 1980, just before the Lake Hopatcong pipeline was completed. The trap model was improved and four more were constructed. Two were placed May 27, 1981, one, June 16, 1981, and a third on July 15, 1981 (Fig. 5). These traps had mercury switches attached to a light box to indicate tilting of the trap and opening of the trap door when the cannister settled onto the bottom (Plate 1 B and C). Recovery of the traps was facilitated by the presence of yellow buoys tied to the eyelets on the cannister sides. The sediments were collected in the boat with a bilge pump and stored in gallon bottles.

Two cores were obtained from the boat near the river inlet using

A. Boonton Reservoir November 1980



B. Sediment Trap (top view)



B. Sediment Trap (side view)

Plate 1: A. Aerial Photo of Boonton Reservoir.
B,C. Sediment Trap.

a Phleger core sampler. In the laboratory each core was extracted and allowed to dry.

## Laboratory Methods

Bottom grab samples were frozen until ready for TOC analysis. Approximately ten grams were dried at 24°C and ground to a fine powder in a ball mill. Five milliliters of 5 percent HCl was added to 0.1-0.25 grams to remove any carbonate present. Each sample was then analyzed using a LECO carbon analyzer.

Water samples were analyzed for TOC using the Beckman Carbon Analyzer. Carbon dioxide was removed by bubbling nitrogen gas through the sample prior to analysis.

Grain size analysis was performed on bottom samples with sieves and a rotap in accordance with techniques described by Folk (1954). The fine fraction (less than 4 phi or 63 microns) of each sample was then analyzed using the Micromeretics Sedigraph Model 500. In addition, one sample (68.5 l) of Rockaway River water collected during a storm event was concentrated in a centrifuge and sent to Coulter Counter, Inc. for size determination.

Mineralogy of the coarse fraction was determined with a dissecting microscope (maximum magnification = 45x). The size fraction finer than 2 microns was separated by centrifugation on an International No. 2 centrifuge. Five milliliters of this clay fraction were treated with citrate-bicarbonate-dithionite to remove free iron oxides (Kunze, 1965). The iron-free samples were saturated with 1N magnesium acetate-magnesium chloride solution (Whittig, 1965). Saturated samples were mounted with preferred orientation onto glass slides, air dried and x-rayed on a Siemans Kristalloflex 700 diffractometer. Three samples were heated overnight in the presence of ethylene glycol at 80° C and x-rayed to detect expansion by smectites. Then they were heated for 1 hour at 500°C and x-rayed again to check for the presence of chlorite.

Suspended sediment was collected with a vacuum pump system by passing a measured amount of water through a pre-weighed Millipore filter (pore size 0.45 microns). The filters were then air dried and reweighed to determine suspended sediment concentration. Portions of these filters were examined using the Scanning Electron Microscope (SEM). Organics were not removed.

Porosity was determined for the trap sediments by extracting three 20 ml aliquots from the slurries. The aliquots were then dried and weighed. The average dry weight per milliliter was multiplied by the total slurry volume to determine the total weight of sediments in each trap. The dry weight volume of the sediments divided by the volume of the trap slurry is equal to the porosity. The total dry weight of sediments was divided by the number of days the traps were in the reservoir to give the g/day sedimentation rate.

## Data Analysis

Grain size data were analyzed using a Fortran program (Sedstat, Kane and Hubert, 1963). This program provided statistical parameters such as mean grain size, sorting, kurtosis, and skewness using the method of moments. Textural classification of the sediment was determined using the gravel-sand-mud ternary diagram from Folk (1957).

Regression analyses were performed using the Minitab program written by Thomas A. Ryan, Jr. of Pennsylvania State University. Total organic carbon, mean grain size, standard deviation, discharge, suspended sediment concentation, percent sand, silt and clay and depth data were compared. The Minitab program provided T-ratios for determining the significance values of the correlations.

# RESULTS

## Rockaway River

### Discharge Variations

The average daily river discharge during the study period (October 1980-October 1981) was 3.7 $m^3/s$, with a maximum of 47.8 $m^3/s$ in May and a minimum of 0.104 $m^3/s$ in February (USGS, 1981). For the days on which suspended sediment samples were collected, the river had a mean discharge of 3.36 $m^3/s$, a maximum of 16.6 $m^3/s$ (February) and a minimum of 0.92 $m^3/s$ (August) (Table 1). When comparing the monthly mean discharges during this study with the long term monthly means for 1940-1981 (Fig. 6), it is obvious that this study was conducted during a dry period. Figure 6 is a hydrograph showing that, normally, the Rockaway River produces a peak flow winter through spring. However, during this study the winter high flow did not occur. Rockaway River's average annual discharges for 1940-1981 also illustrate how low 1980 and 1981 discharges were compared to the past and how variable discharge has been especially since 1960 (Fig. 7). Even though the mean annual discharge was below average, the mean suspended sediment concentration and mean total organic carbon values did not differ greatly from the USGS samples collected at the same station between 1975 and 1978 (Fig. 8).

Splitrock Reservoir (at the head of Beaver Brook tributary) (Fig. 3) is regulated and normally contributes 0.001 $m^3/s$ to the Rockaway River drainage (Table 2) (G. Plastoris, pers. comm.). During 1980 and the early part of 1981, Splitrock Reservoir discharge was increased to as high as 1.1 $m^3/s$. It is not known

Table 1: Data for Water Samples from Rockaway River Gauging Station

| Date | Discharge ($m^3/s$) | Susp. Sed. (mg/1) | Susp. Sed. (kg/day) | TOC ppm |
|---|---|---|---|---|
| 9/12/80 | 1.19 | 1.7 | - | - |
| 10/16/80 | 1.42 | 3.1 | 380.2 | - |
| 1/23/81 | 1.76 | 2.9 | 440.6 | - |
| 2/23/81 | 16.59 | 5.8 | 8320.3 | - |
| 6/16/81 | 2.85 | 2.9 | 717.1 | - |
| 6/26/81 | 3.99 | - | - | - |
| 7/6/81 | 7.19 | 3.2 | 1986.8 | 8.3 |
| 7/7/81 | 4.82 | 3.5 | 1457.6 | 10.0 |
| 7/8/81 | 3.68 | 2.0 | 635.7 | 7.5 |
| 7/9/81 | 3.07 | 2.4 | 635.9 | 10.0 |
| 7/20/81 | 1.62 | 3.5 | 489.9 | 4.3 |
| 7/21/81 | 4.47 | 7.7 | 2973.1 | 4.3 |
| 7/22/81 | 3.99 | 3.5 | 1205.8 | 9.0 |
| 8/3/81 | 1.14 | 1.6 | 157.5 | 4.5 |
| 8/4/81 | 1.09 | 1.2 | 113.6 | 5.5 |
| 8/5/81 | 1.09 | 2.9 | 274.6 | 5.5 |
| 8/18/81 | 1.09 | 6.4 | 606.0 | 12.5 |
| 8/19/81 | 0.96 | 6.0 | 499.2 | 10.0 |
| 8/20/81 | 0.92 | 5.4 | 429.4 | 9.5 |
| 9/10/81 | 2.06 | - | - | - |
| 1/5/82 | 35.26 | 230 | (collected at the bridge above the delta) | |
| 4/15/82 | | 2.2 | | - |

Table 2: Splitrock Reservoir Discharge

| Date | Discharge ($m^3/s$) |
|---|---|
| 9/1/80 - 9/18/80 | 0.7 |
| 9/20/80 - 9/30/80 | 0.15 |
| 10/1/80 - 10/10/80 | 0.21 |
| 10/11/80 - 10/25/80 | 0.88 |
| 10/26/80 - 11/26/80 | 0.44 |
| 11/27/80 - 12/1/80 | 0.21 |
| 12/2/80 - 12/31/80 | 0.04 |
| 1/29/81 - 2/3/81 | 1.10 |

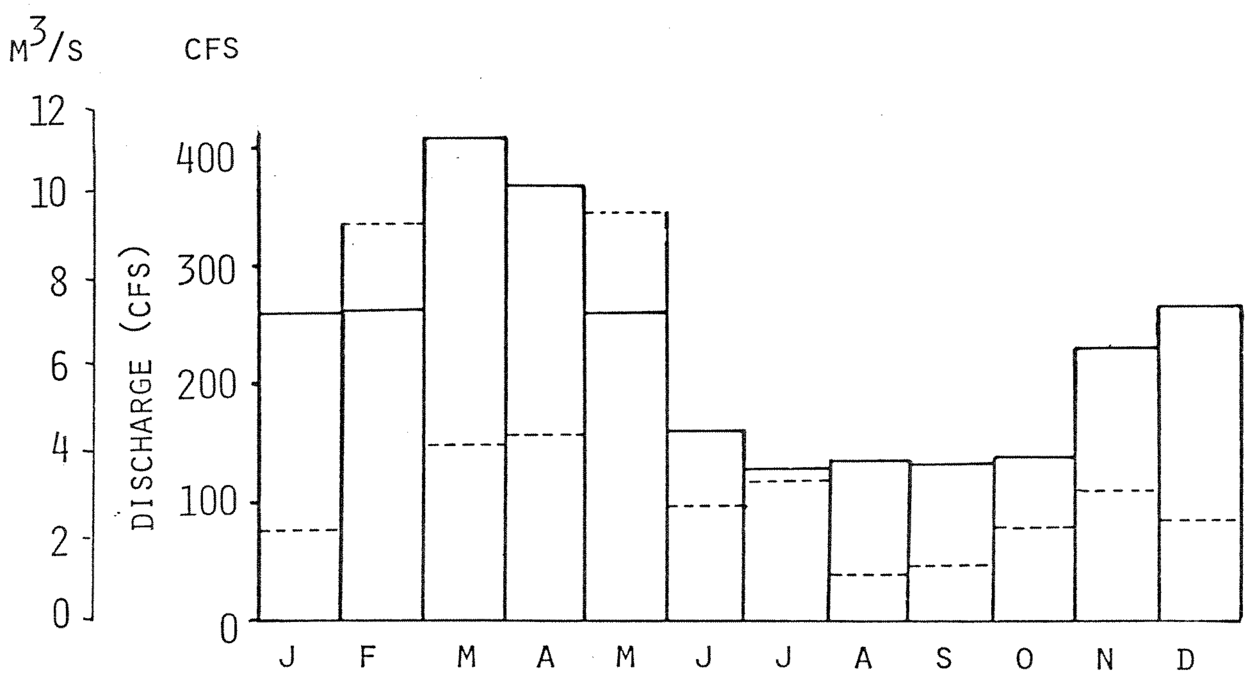



Figure 6: Long Term Monthly Mean Discharge from Rockaway River;
1940 - 1981 (——) 1980-1981 (---)

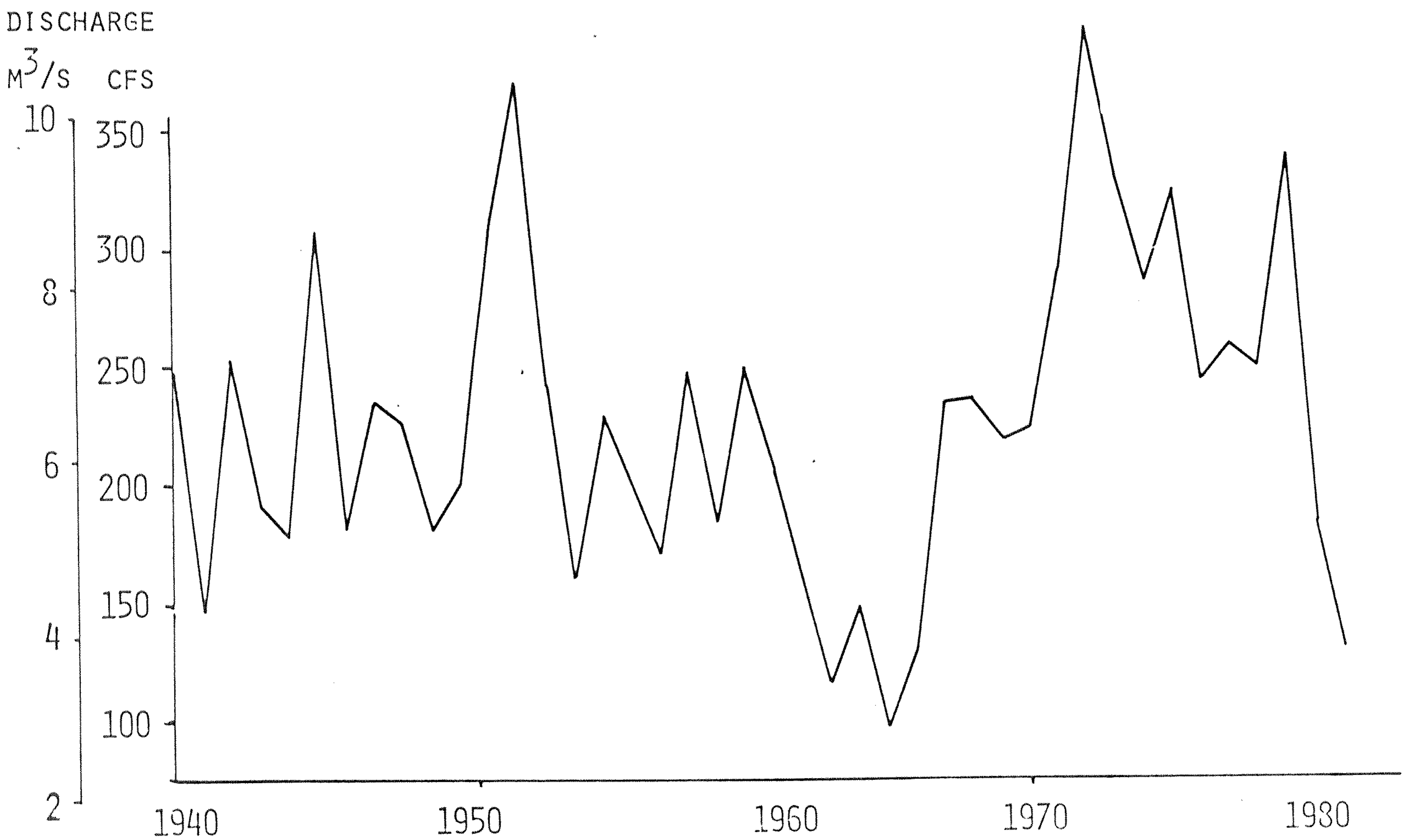



Figure 7: Rockaway River Mean Annual Discharge (Laskowski, 1970; USGS, 1981)

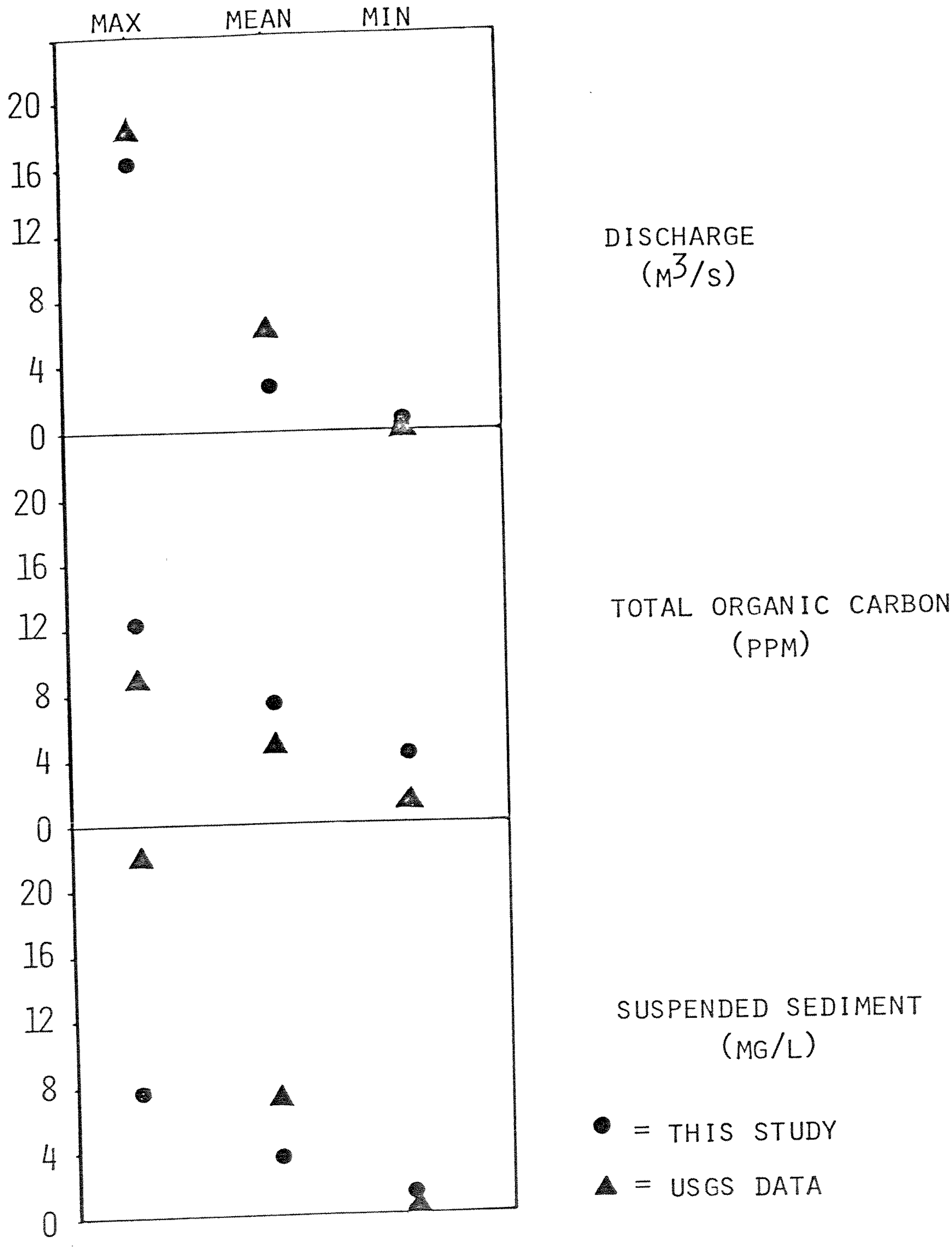



Figure 8: Comparison of Discharge, Total Organic Carbon and Suspended Sediment Found During This Study with That Found by the USGS Between 1975-1978.

what proportion of this runoff travels the length of the tributary to reach the Rockaway River.

Suspended Sediment Load

The average suspended sediment concentration in the Rockaway River during the study was 3.65 mg/l (n=18), with a maximum of 7.7 mg/l (July) and a minimum of 1.2 mg/l (August). The mean suspended sediment concentration for samples taken during this study differed slightly from those samples taken by the USGS between 1975-1978 (Fig. 8). The maximum concentration was lower than the USGS data for this study period.

Rockaway River total suspended load delivered to the reservoir has been calculated for each day that samples were taken (Table 1). The mean was 1254.3 kg/day, with a maximum of 8320.3 kg/day and a minimum of 113.6 kg/day. During 1975, nine monthly samples collected by the USGS had a mean of 5263.9 kg/day with a maximum of 12623.3 kg/day and a minimum of 435.5 kg/day. In 1976 only seven samples were collected, with a mean of 2643.6 kg/day, a maximum of 5167.7 kg/day and a minimum of 513.8 kg/day. Seven samples in 1977 had a mean of 1670.9 kg/day, a maximum of 3941.1 kg/day and a minimum of 110.1 kg/day. The USGS seven samples for 1978 had a mean of 3280.9 kg/day, a maximum of 11989.6 kg/day and a minimum of 408.6 kg/day. The mean suspended sediment concentration collected by the USGS between 1975-1978 was 7.1 mg/l, with a maximum of 22 mg/l and a minimum of 1 mg/l.

The size distribution of the suspended sediment collected during a storm was determined by Coulter Counter (Fig 9 and

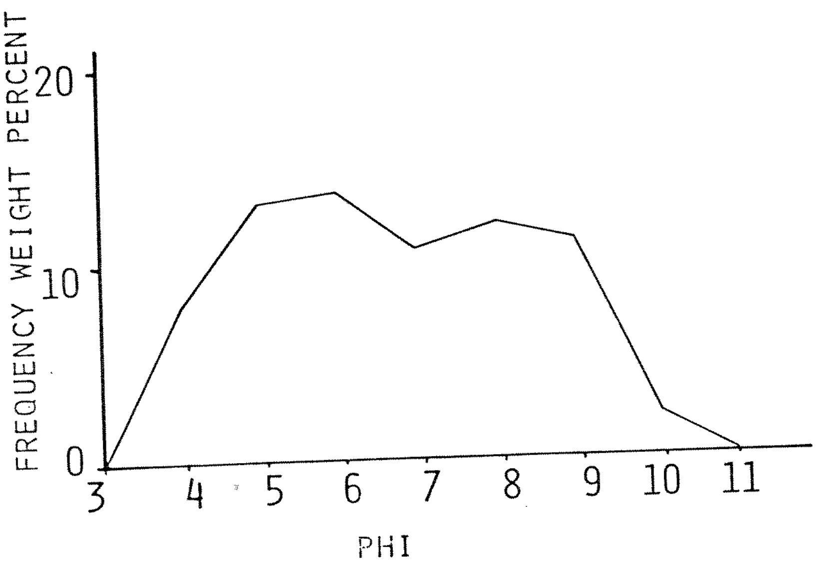



Figure 9: Coulter Counter's Size Analysis of Suspended Sediment Collected from Rockaway River During Rainstorm 9/10/81

Table 3). The mean particle size was 9.6 microns (6.8 phi) with a standard deviation of 3.24 microns (well sorted).

Total Organic Carbon in River Water

The mean total organic carbon (TOC) value for the Rockaway River was 7.76 ppm (n=13), with a maximum of 12.5 ppm (August) and a minimum of 4.3 ppm (July). The minimum TOC value was obtained for two different discharges (1.6 $m^3/s$ and 4.5 $m^3/s$). No correlation was found between TOC and discharge (r=0.07), nor between TOC and suspended sediment (r=0.29). There was very little difference between the TOC values from this study and the USGS samples (Fig. 8).

The USGS data for discharge, total organic carbon and suspended sediment from 3/75 to 8/78 are shown in Table 4. The mean TOC was 5.4 ppm, with a maximum of 9.2 ppm and a minimum of 1.6 ppm. There was no correlation between suspended sediment and discharge (r=-0.27) nor between TOC and discharge (r=-0.27).

Scanning Electron Microscope

Scanning electron microscope photographs were made of filtered suspended sediment from the Rockaway River above the reservoir. Plate 2 A-C shows flocculated clay, mica sheets and a diatom. Below the reservoir the Rockaway River is very shallow and full of organic debris. Plate 2D shows a *Navicula* diatom from the river below the dam. *Navicula* is known to be pollution tolerant. (pers. comm. Marianne Foote) The river samples contained many *Navicula* species.

Table 3: Rockaway River Storm Suspended Sediment Size Distribution

| Phi | Diameter (microns) | Cumulative % |
|---|---|---|
| 11 | 0.50 | 100.0 |
| | 0.63 | 99.9 |
| | 0.79 | 99.4 |
| 10 | 1.00 | 98.5 |
| | 1.26 | 96.5 |
| | 1.59 | 93.8 |
| 9 | 2.00 | 89.5 |
| | 2.52 | 83.9 |
| | 3.17 | 78.4 |
| 8 | 4.00 | 72.9 |
| | 5.04 | 66.9 |
| | 6.35 | 60.9 |
| 7 | 8.00 | 55.5 |
| | 10.08 | 50.2 |
| | 12.70 | 44.4 |
| 6 | 16.00 | 37.9 |
| | 20.16 | 31.4 |
| | 25.40 | 25.2 |
| 5 | 32.00 | 19.0 |
| | 40.32 | 12.4 |
| | 50.80 | 7.0 |
| 4 | 64.00 | 3.5 |
| | 80.63 | 1.2 |
| | 101.59 | 0.0 |
| 3 | 128.00 | 0.0 |

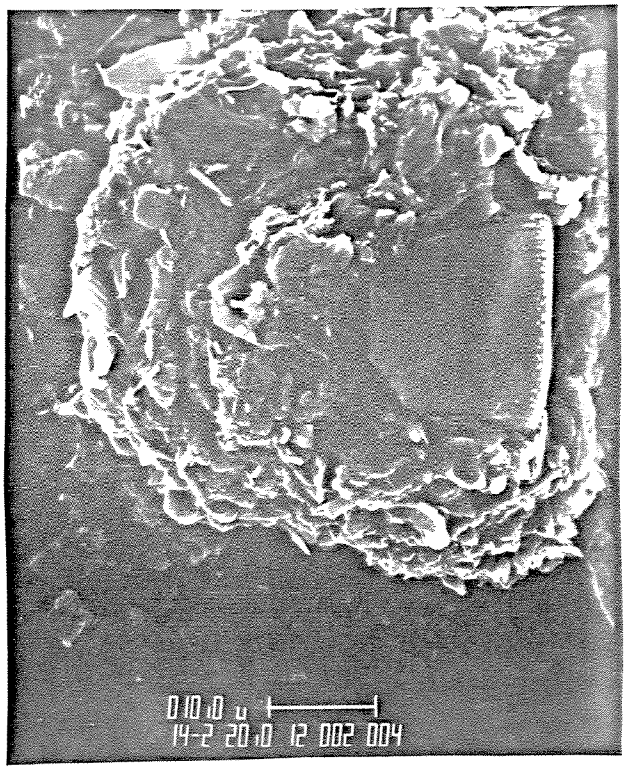
Mean 9.58 microns
Mode 34.14 microns

Median 10.15 microns
Standard Deviation 3.24 microns

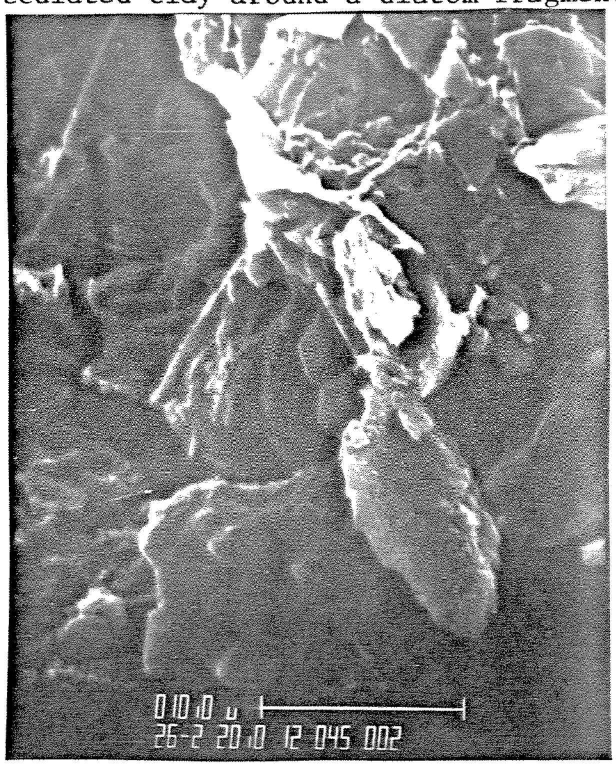
Table 4: Rockaway River USGS Data (NJDEP, 1980)

| Date | Discharge $m^3/s$ | Susp. Sed. mg/1 | TOC ppm | Susp. Sed. kg/day | Average Susp. Sed. per day for the year |
|---|---|---|---|---|---|
| 3/75 | 6.65 | 3 | 7.2 | 1725.0 | |
| 4 | 10.62 | 10 | 3.3 | 9175.7 | |
| 5 | 14.75 | 9 | 5.1 | 11473.3 | |
| 6 | 13.28 | 11 | 5.4 | 12623.3 | 5263.9 kg/day |
| 7 | 2.69 | 8 | 6.7 | 1859.6 | |
| 8 | 3.54 | 5 | 4.5 | 1529.3 | for 1975 |
| 9 | 2.52 | 2 | 8.1 | 435.5 | |
| 10 | 4.93 | 16 | 6.8 | 6812.0 | |
| 11 | 10.08 | 2 | 4.1 | 1742.2 | |
| 3/76 | 8.33 | 3 | 2.6 | 2158.1 | |
| 4 | 3.57 | 2 | 3.6 | 616.6 | |
| 5 | 4.93 | 4 | 3.2 | 1703.0 | |
| 6 | 8.49 | 6 | 6.7 | 404.3 | 2643.6 kg/day |
| 7 | 2.72 | 22 | 8.2 | 5167.7 | |
| 8 | 5.95 | 1 | 5.7 | 513.8 | for 1976 |
| 9 | 3.99 | - | - | - | |
| 11 | 5.07 | 9 | 2.6 | 3941.9 | |
| 2/77 | 1.27 | 1 | 5.9 | 110.1 | |
| 4 | 8.89 | 2 | 5.3 | 1536.6 | |
| 5 | 2.58 | 16 | 6.7 | 3562.6 | |
| 6 | 2.89 | 13 | 5.1 | 3244.5 | |
| 8 | 0.65 | 9 | 6.0 | 506.5 | 1670.9 kg/day |
| 9 | 2.07 | 7 | 4.2 | 1250.3 | for 1977 |
| 10 | 2.44 | 15 | 5.9 | 3156.4 | |
| 11 | 18.32 | - | 9.2 | - | |
| 2/78 | 9.12 | 8 | 1.6 | 6303.1 | |
| 4 | 13.59 | 1 | - | 1174.5 | |
| 5 | 4.73 | 1 | 4.3 | 408.6 | |
| 6 | 3.68 | 6 | 7.0 | 1908.5 | 3280.9 kg/day |
| 7 | 1.81 | 3 | 5.1 | 469.8 | for 1978 |
| 8 | 9.91 | 14 | 7.9 | 11989.6 | |
| 9 | 2.75 | 3 | 3.7 | 712.0 | |

1975-1978 Mean = 3214.8 kg/day

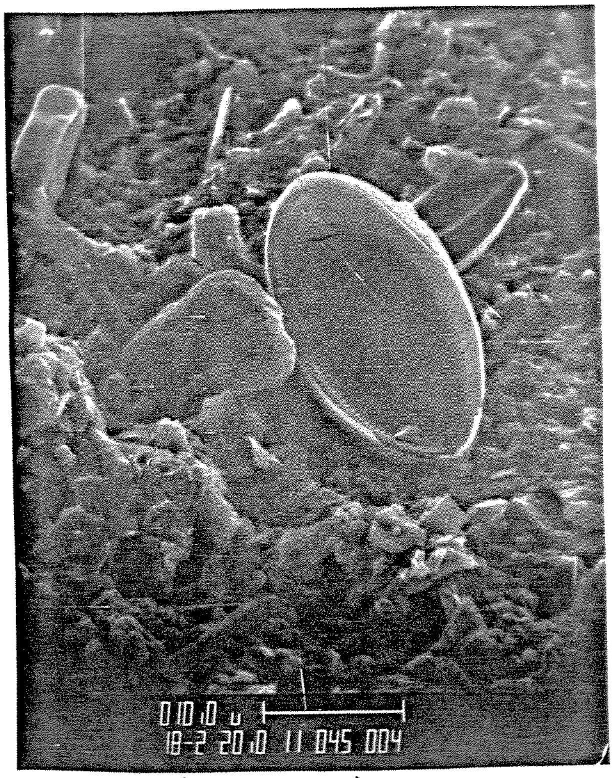


A. Flocculated clay around a diatom fragment.



B. Mica Sheets.

Plate 2: A,B. Clay SEM Photographs from the Rockaway River.



C. Coccaneis (placentula).

D. Navicula (in river below dam).

Plate 2 cont'd: C,D. Diatom SEM Photographs from above the Reservoir and Below the Dam.

Bathymetry

Twenty-one sonar traverses were made in the northern half of the reservoir (Fig. 10). Using these data a bathymetric map was constructed (Fig. 11). Contour intervals of 20 feet were used in order to correlate it with an 1898 topographic map. The two maps were superimposed by matching the contour lines, the center island, and river channel. The differences between the two maps are the result of errors in converting meters to feet, inaccuracies of map-making prior to 1900, and land excavation during dam construction. Six cross-sections of the reservoir bottom topography revealed the location of the drowned river channel and a tributary channel (Figs. 12-15). The northern deep portion of the lake is a basin with relief. The maximum depth is 30.5 m (100 feet) at the northern end with an average depth of 17 meters. The southern half of the reservoir averages 6.5 meters deep.

Physical Limnology

Figures 15-18 show the temperature and dissolved oxygen measurement locations and profiles. (Table 5 appendix) In addition, Figures 17 and 18 show the contoured values for temperature and dissolved oxygen. The coldest temperature of 5$^{\circ}$C was recorded during March 1982. However, water temperature was not measured while the reservoir was frozen during January and February. The warmest temperature recorded was 26.5$^{\circ}$C during June 1981. During March 1982 the temperature decreased only slightly with depth, indicating the waters were well mixed following the melting of

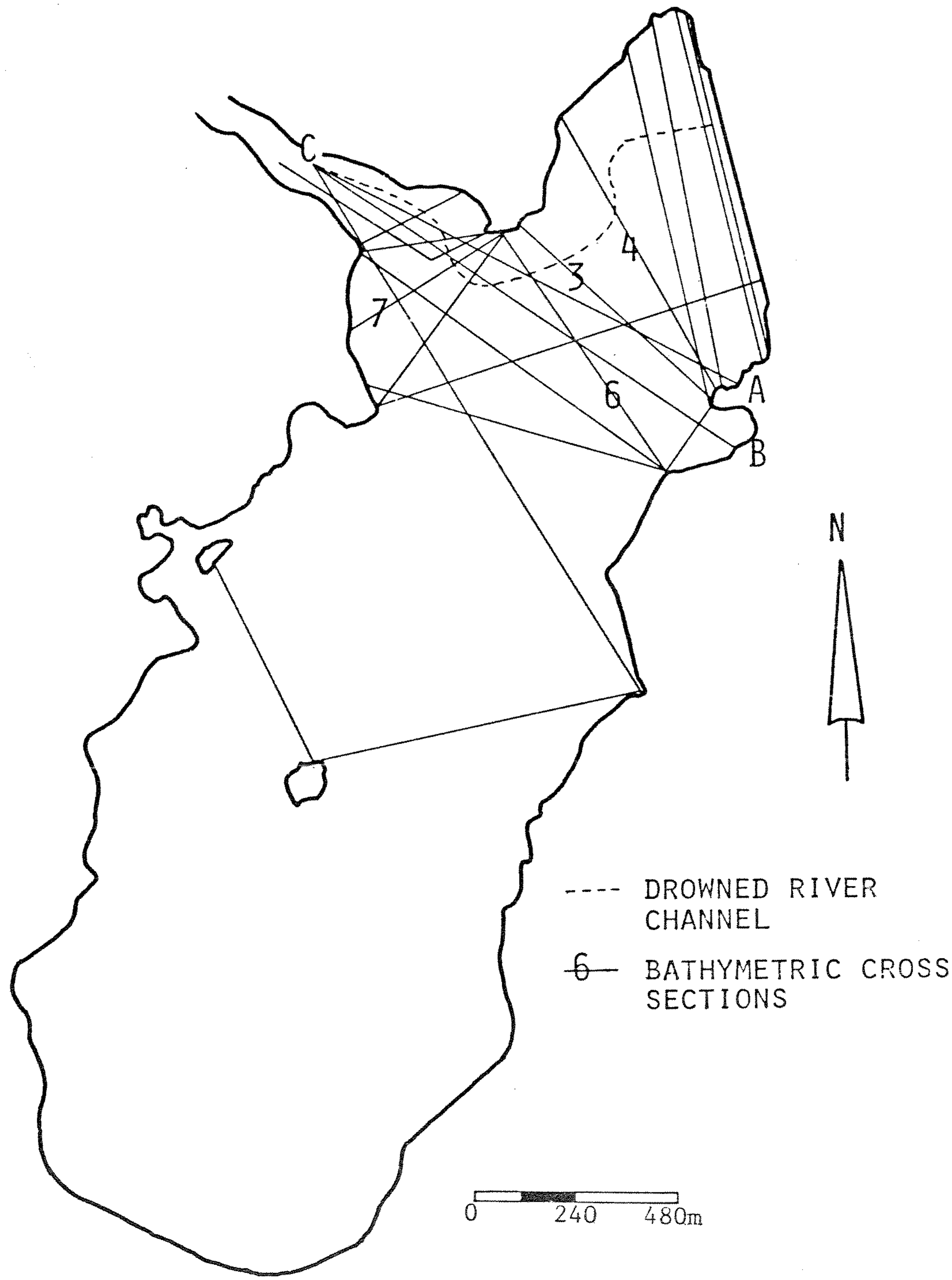



Figure 10: Bathymetric Traverses

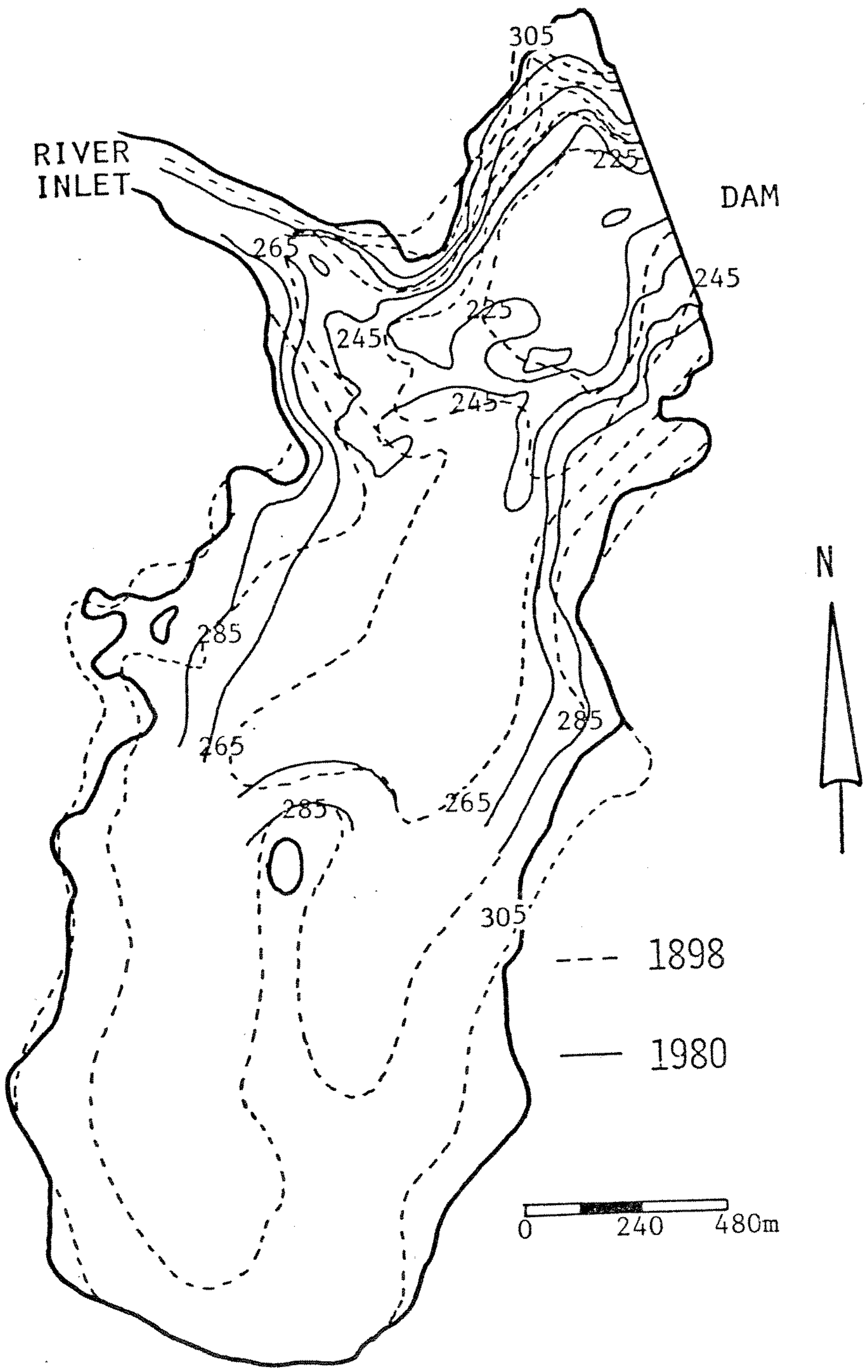



Figure 11: Bathymetric Map of Boonton Reservoir in Elevation Above Sea Level; 20 Foot Contour Intervals

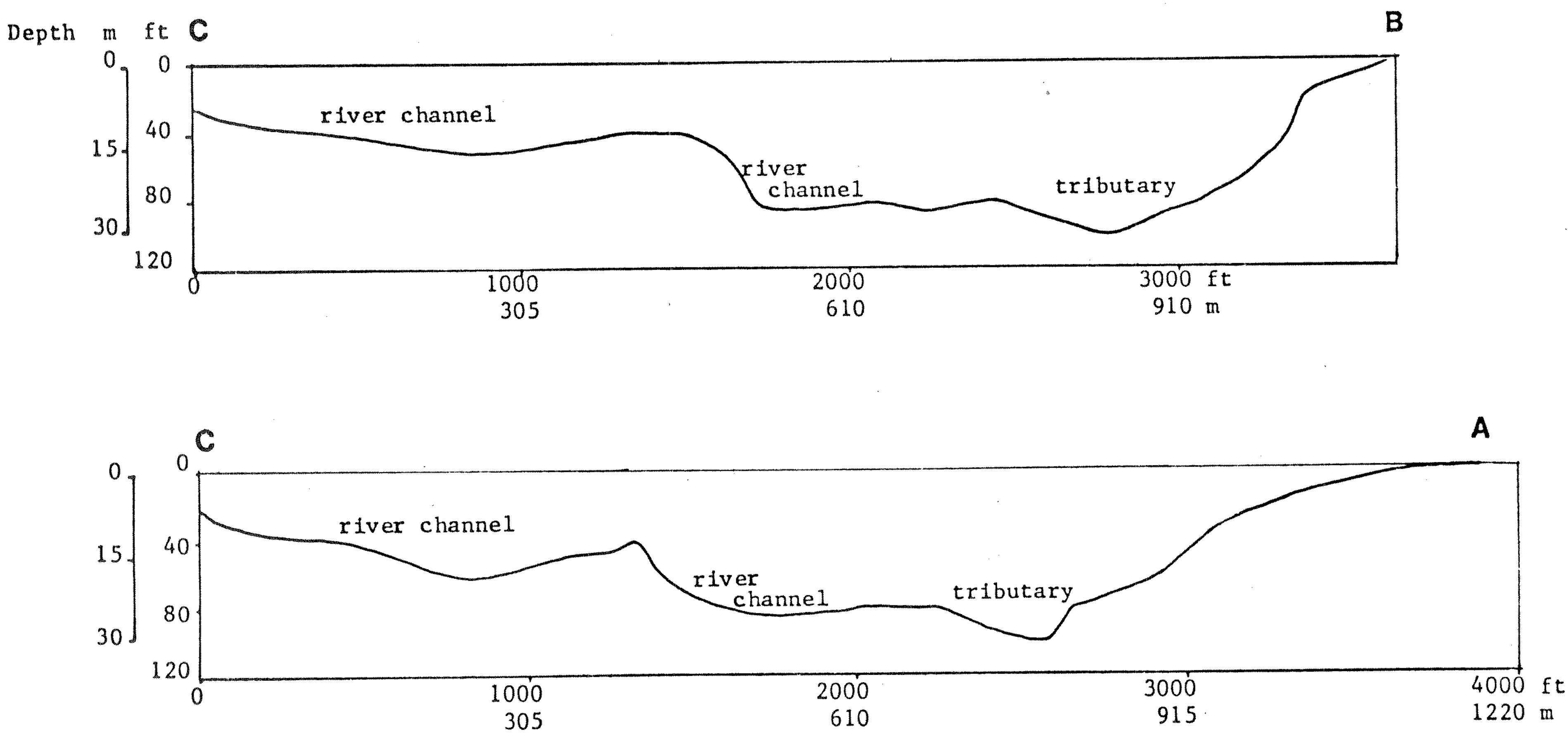



Figure 12: Bathymetric Cross Sections CB and CA

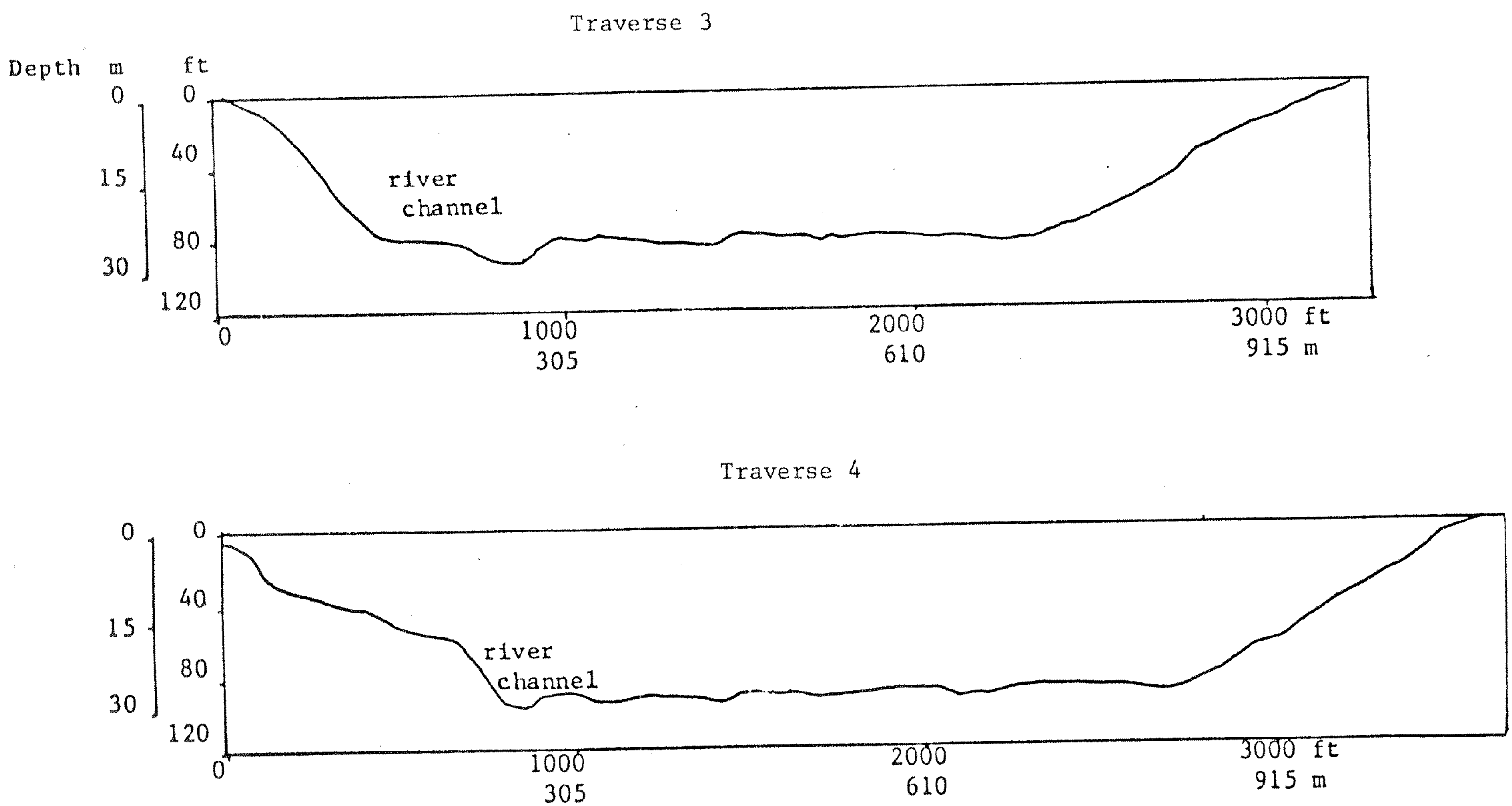



Figure 13: Bathymetric Cross Sections of Traverse 3 and 4

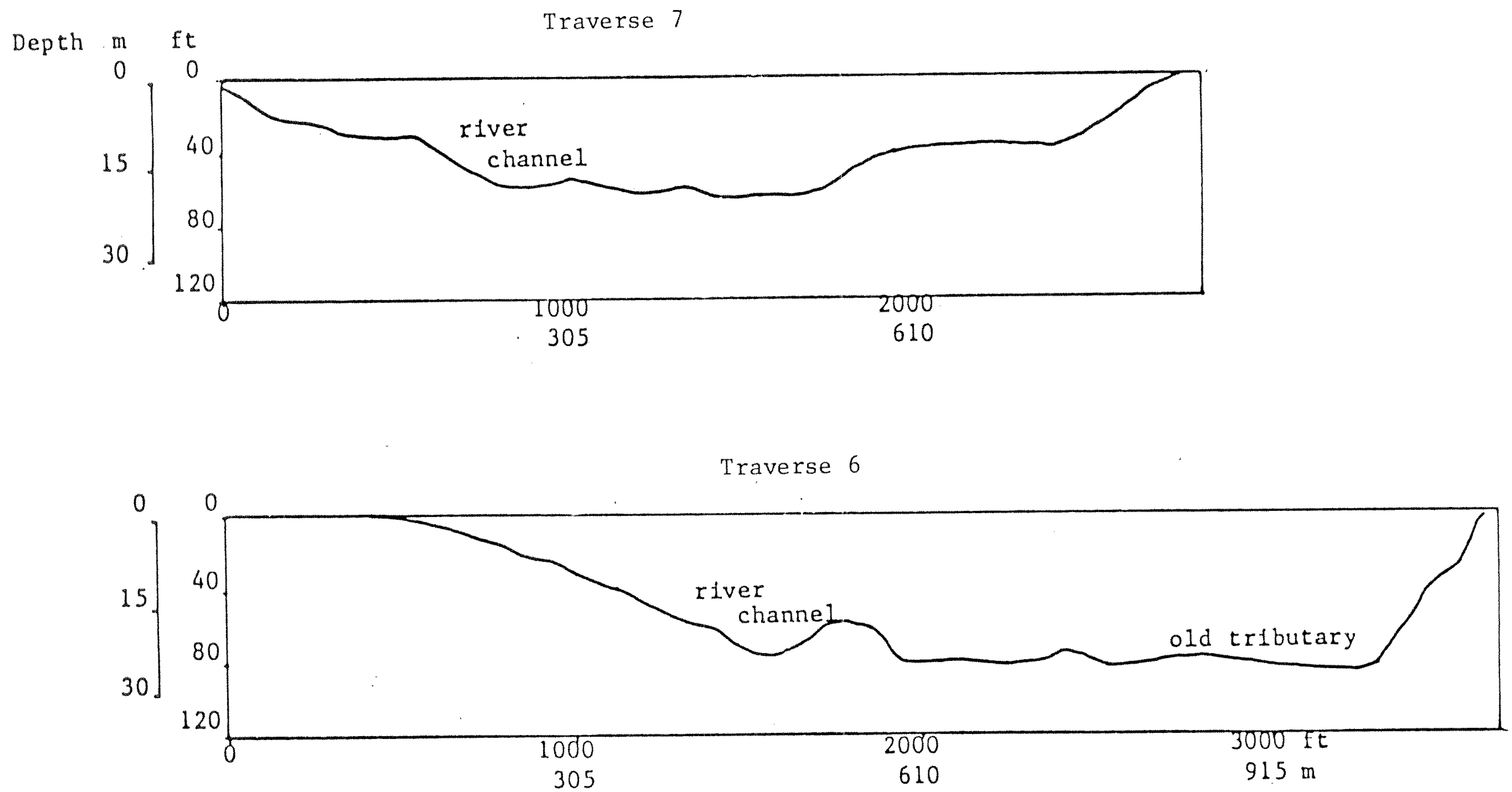



Figure 14: Bathymetric Cross Sections of Traverse 6 and 7

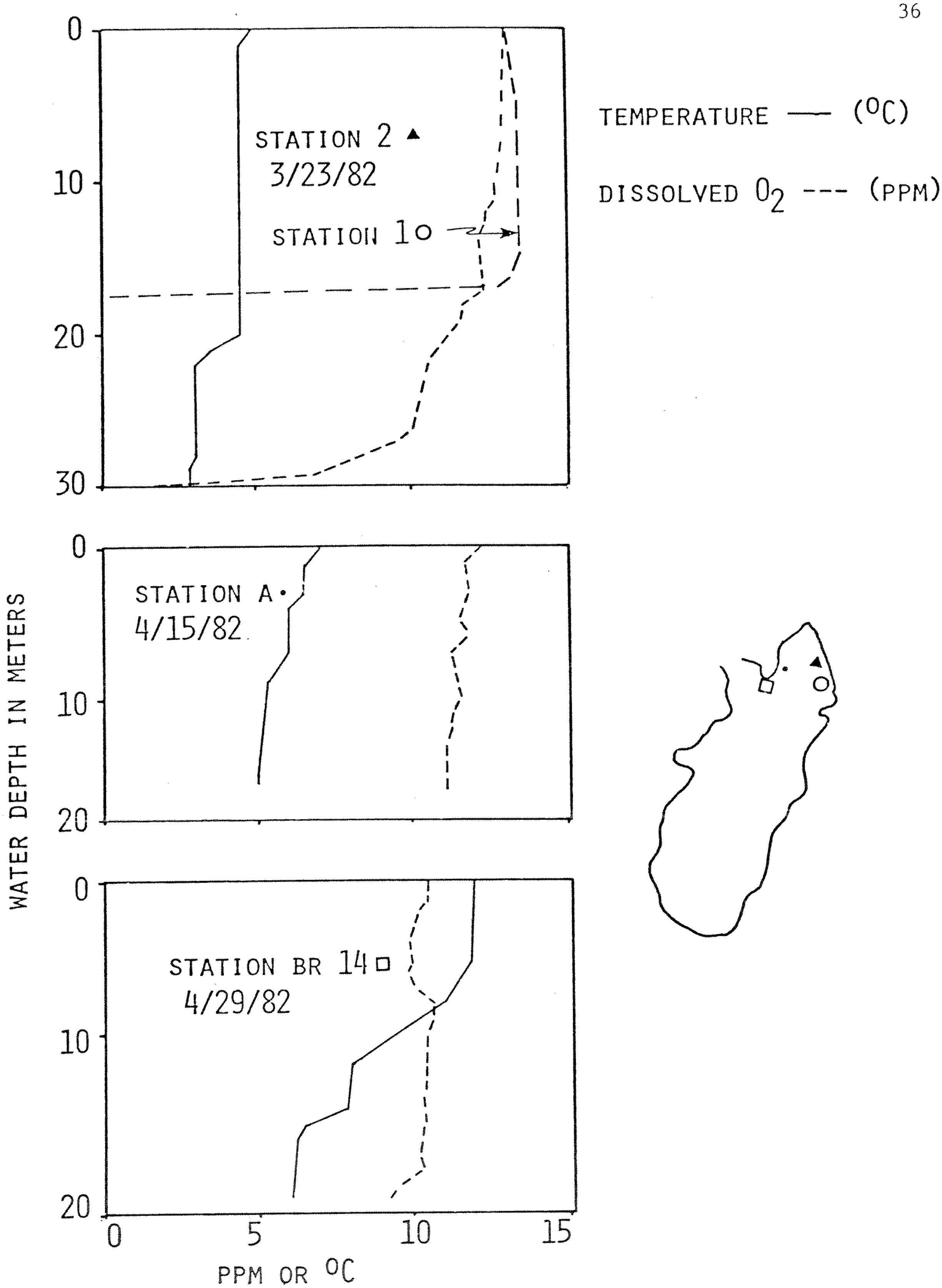



Figure 15: Temperature and Dissolved Oxygen Profiles During Mixing Period in the Spring

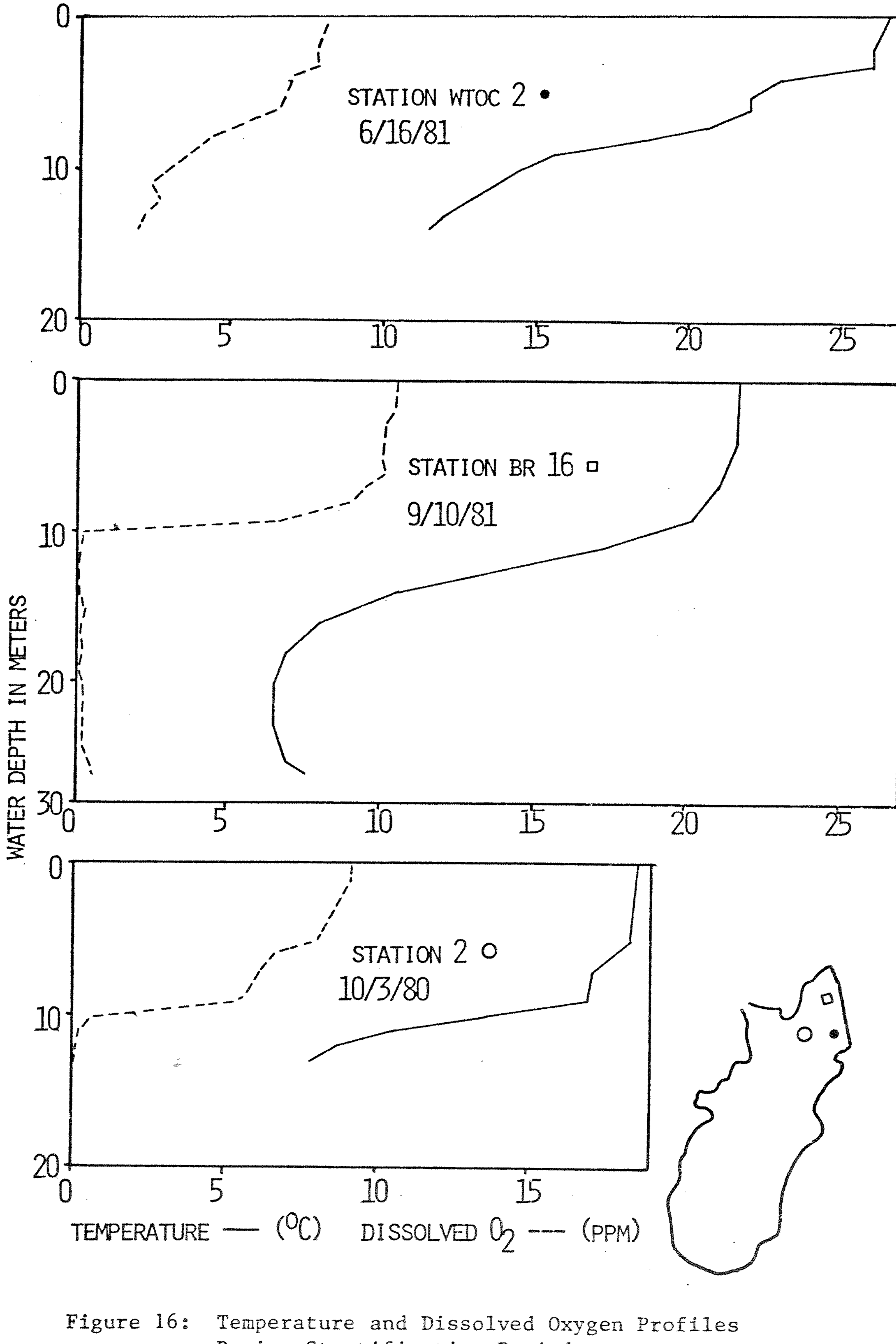



Figure 16: Temperature and Dissolved Oxygen Profiles During Stratification Period

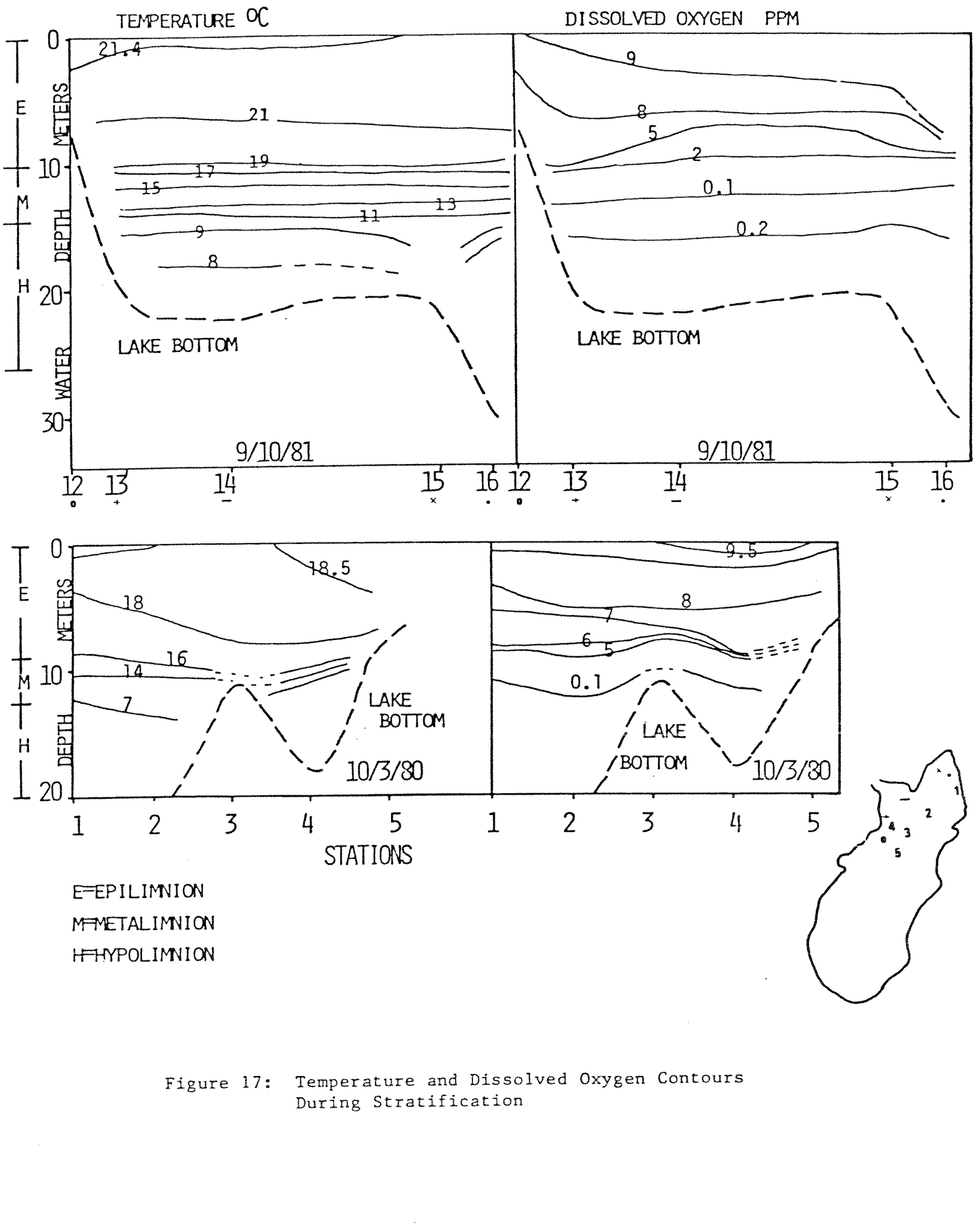
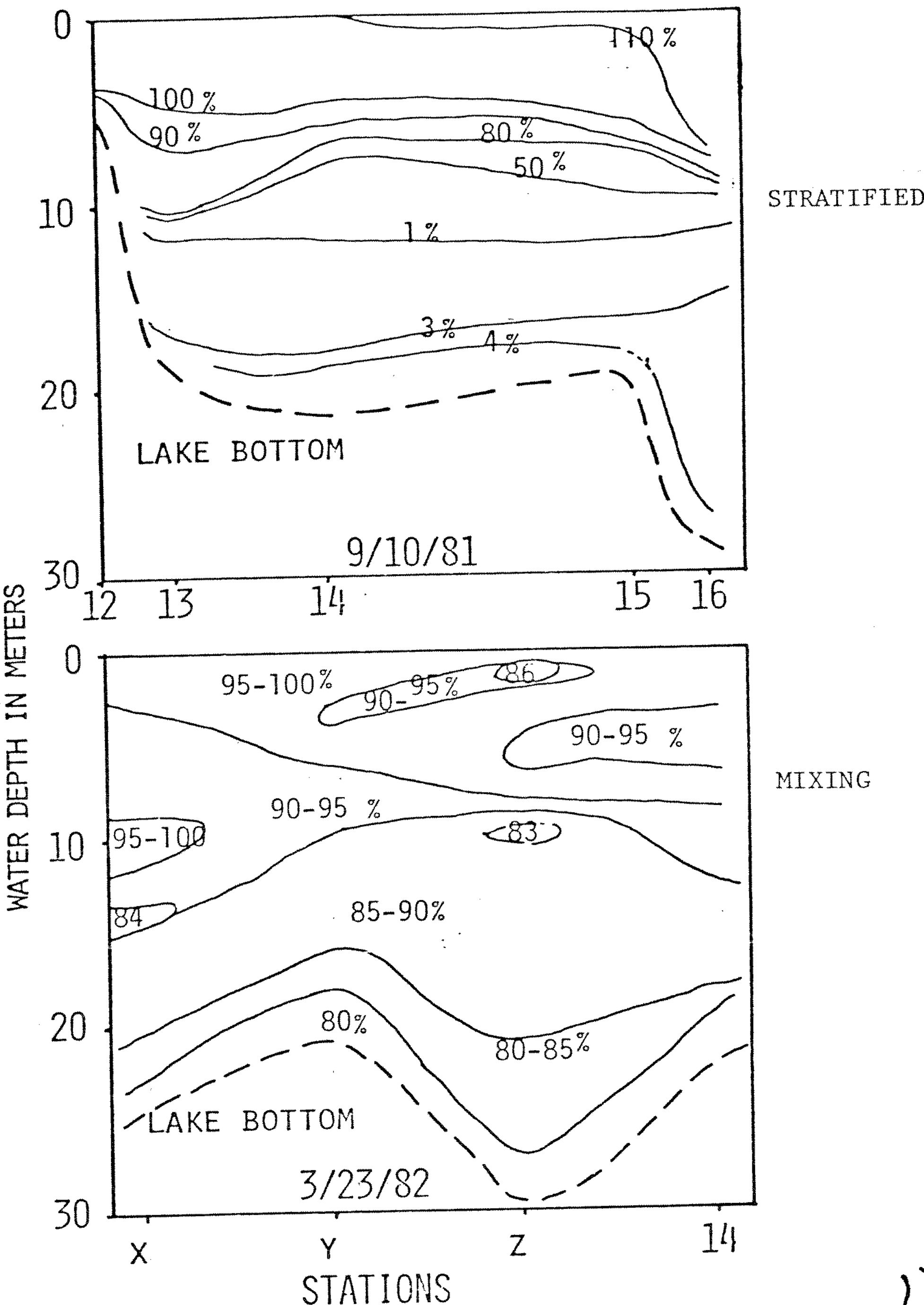



Figure 17: Temperature and Dissolved Oxygen Contours During Stratification



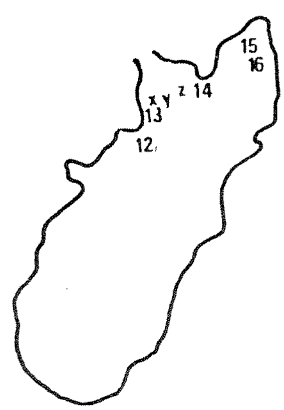




Figure 18: Percent Oxygen Saturation Contours During Stratification and Mixing

the ice cover (Fig. 15). During June 1981, it was apparent that layers of uniform temperature were forming. The temperature ranged from 26.5°C at the surface to 11.5°C at the 14 meter mark (Fig. 16). Three layers were apparent at depths of 0-4 meters, 4-7 meters and 10-14 meters. The temperatures for September 1981 indicated that the reservoir had formed a mixed layer near the surface (epilimnion), a middle layer with a steep temperature gradient (metalimnion) and a non-mixed bottom layer (hypolimnion) (Fig. 17). In the deeper waters the temperature increased slightly perhaps due to groundwater seepage. The fall thermocline was pronounced in October 1980 and also in September 1981. Although the October surface temperature was slightly colder (18.9°C) than in September (22°C) the thermocline was in the same position (10m).

The dissolved oxygen at the surface was highest during March 1982 with 13 ppm at a temperature of 5°C (105% saturation) and was lowest during June 1981 with 8.1 ppm at a temperature of 26.5°C (102% saturation). However, no measurements were taken during ice cover. Unless covered by ice, the surface waters are well aerated due to constant winds. Prevailing winds blow from the NW between April and October and from the SW through the winter and spring (Gill and Vecchioli, 1965). The fetch is the length of the lake (approximately 2 km) and can create waves of up to 30 cm high.

Current measurements were made at stations BR 12, BR 13, BR 14, BR 15, and BR 16 on 9/10/81 (Fig. 26). There was no measurable current throughout the water column. However, Arnold Wicklund (Drexel University) reported that during a storm event on May 12, 1981, the river was able to transport dissolved copper sulfate as a tracer from the reservoir inlet to the treatment plant in approximately 14 hours. A hydrograph of this storm is in Figure 19. (Note the initial peak discharge associated with the rain and the second peak discharge associated with groundwater influx.) With a discharge of 47.8 $m^3/s$ (1690 cfs), this would represent a velocity of 2 cm/s assuming a channelized and undisturbed flow to the dam.

Water Samples

Twenty-two water samples were taken by boat and seventeen were collected at the gatehouse between 11/80 and 4/82 (Fig. 20). The maximum suspended sediment concentration was 14.5 mg/l and the minimum was 1.2 mg/l, with a mean of 3.83 mg/l (Table 6). Suspended sediment concentration measurements between 12/8/80 and 1/4/81 from the Jersey City Water treatment plant had a maximum of 45 mg/l, a minimum of 3 mg/l with an average of 14.2 mg/l. The water collected by the treatment laboratory was withdrawn from the conduit in the gatehouse.

The suspended sediment concentration in the reservoir had little correlation with the Rockaway River discharge between 7/6/81 and 8/20/81 (r= -0.05).

Nineteen samples of Boonton Reservoir water were tested for TOC (Table 6). The mean concentration was 7.5 ppm, with a maximum of 12.5 ppm and a minimum of 5 ppm. There are no data for suspended sediment or TOC from the reservoir prior to this study.

During July and August of 1981, TOC and suspended sediment were measured in water entering and leaving the reservoir. The TOC entering the reservoir from the Rockaway River averaged 1.85 x

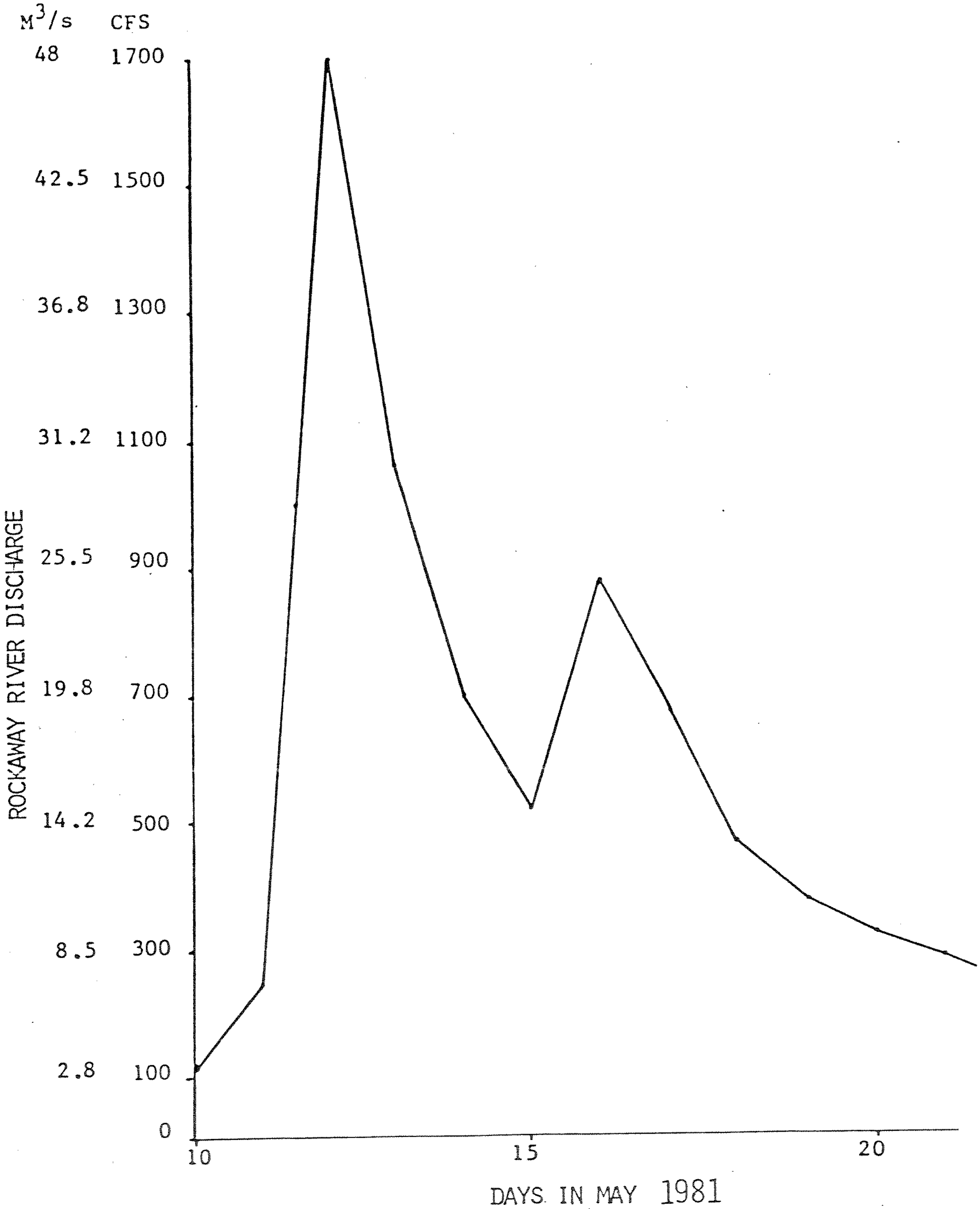



Figure 19: May 11, 1981 storm Hydrograph

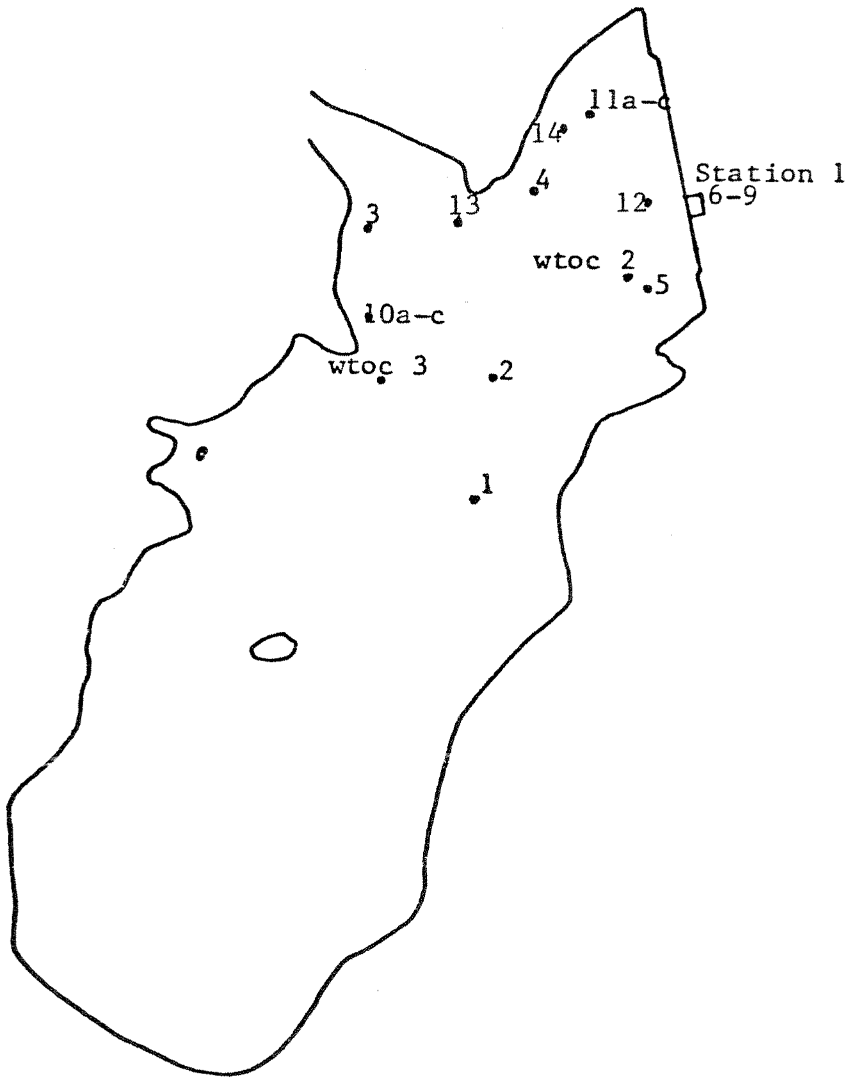



Figure 20: Water Sample Locations in Boonton Reservoir

Table 6: Boonton Reservoir Water Samples



| Date | Sample # | Sus. Sed. (mg/1) | TOC (ppm) | Location |
|---|---|---|---|---|
| 11/17/80 | BRW 1 | 5.9 | - | reservoir - 2m below surface |
| " | BRW 2 | 4.9 | - | " " |
| " | BRW 3 | 4.6 | - | " " |
| " | BRW 4 | 5.5 | - | " " |
| " | BRW 5 | 5.4 | - | " " |
| 2/23/81 | BRW 6 | 5.9 | - | dam gatehouse |
| 5/18/81 | BRW 7 | 3.9 | - | " " |
| 5/27/81 | WTOC 1 | lost | - | Trap 1 |
| 6/16/81 | BRW 8 | 2.1 | - | dam gatehouse |
| 6/26/81 | WTOC 2 | - | 34 | reservoir (contaminated) |
| 6/17/81 | WTOC 3 | - | 32 | Trap 3 (contaminated) |
| 7/6/81 | Station 1 | 2.2 | 12.5 | dam gatehouse |
| 7/7/81 | " | 2.0 | 10.5 | " " |
| 7/8/81 | " | 1.5 | 7.5 | " " |
| 7/9/81 | " | 1.7 | 7.5 | " " |
| 7/20/81 | " | 2.0 | 6.5 | " " |
| 7/21/81 | " | 2.0 | 6.5 | " " |
| 7/22/81 | " | 2.4 | 6.5 | " " |
| 8/3/81 | " | 2.6 | 6.5 | " " |
| 8/4/81 | " | 2.3 | 5.0 | " " |
| 8/5/81 | " | 1.2 | 6.5 | " " |
| 8/18/81 | " | 7.2 | 7.7 | " " |
| 8/19/81 | " | 7.0 | 8.5 | " " |
| 8/20/81 | " | 6.5 | 8.0 | " " |
| 9/10/81 | BRW 10a | 5.5 | 5.5 | BR 13 - 2m below surface |
| " | BRW 10b | 1.2 | 7.0 | BR 13 - 4 m below surface |
| " | BRW 10c | 2.1 | 7.5 | BR 13 - 8m below surface |
| " | BRW 11a | 1.3 | 8.5 | BR 15 - 2m below surface |
| " | BRW 11b | 2.1 | 7.0 | BR 15 - 4m below surface |
| " | BRW 11c | 2.1 | 7.5 | BR 15 - 8m below surface |
| 3/23/82 | BRW 12a | 3.7 | - | reservoir - 4m below surface |
| " | BRW 12b | 3.5 | - | " 8m below surface |
| " | BRW 12c | 14.5 | - | " 12m below surface |
| " | BRW 13a | 3.2 | - | " 4m below surface |
| " | BRW 13b | 3.2 | - | " 8m below surface |
| " | BRW 13c | 2.8 | - | " 12m below surface |
| 4/15/82 | BRW 14a | 4.5 | - | " 4m below surface |
| " | BRW 14b | 4.1 | - | " 12m below surface |
| 4/29/82 | BRW 15a | 5.2 | - | reservoir surface |
| " | BRW 15b | 3.9 | - | dam gatehouse |

Table 6 cont'd



| Date | Suspended Sed. (mg/1) | Date | Suspended Sed. (mg/1) |
|---|---|---|---|
| 12/8/81 | 45 | 1/4/82 | 5 |
| 12/10/81 | 20 | 1/6/82 | 17 |
| 12/14/81 | 18 | 1/11/82 | 14 |
| 12/16/81 | 3 | 1/13/82 | 9 |
| 12/18/81 | 6 | 1/18/82 | 15 |
| 12/21/81 | 3 | 1/20/82 | 16 |
| 12/28/81 | 3 | 1/22/82 | 18 |
| 12/30/81 | 15 | 1/25/82 | 20 |

Table 7: Data for Mass Balance of Total Organic Carbon in the Reservoir between July and August 1981.

TOC into Reservoir

| Date | Discharge ($m^3/s$) | TOC (ppm) | TOC (g/day x $10^6$) |
|---|---|---|---|
| 7/6/81 | 7.2 | 8.3 | 5.20 |
| 7/7 | 4.8 | 10.0 | 4.15 |
| 7/8 | 3.7 | 7.5 | 2.40 |
| 7/9 | 3.1 | 10.0 | 2.70 |
| 7/20 | 1.6 | 4.3 | 0.59 |
| 7/21 | 4.5 | 4.3 | 1.70 |
| 7/22 | 3.9 | 9.0 | 3.10 |
| 8/3 | 1.1 | 4.5 | 0.43 |
| 8/4 | 1.1 | 5.5 | 0.52 |
| 8/5 | 1.1 | 5.5 | 0.52 |
| 8/18 | 1.1 | 12.5 | 1.20 |
| 8/19 | 0.96 | 10.0 | 0.83 |
| 8/20 | 0.92 | 9.5 | 0.75 |
| | | average | = $1.85x10^6$ g/day |

| | TOC Leaving via Spillway | | TOC Leaving via Treatment Plant | | |
|---|---|---|---|---|---|
| Date | Q ($m^3/s$) | TOC (ppm) | Q ($m^3/s$) | TOC (ppm) | TOC (g/dayx$10^6$) |
| 7/6/81 | 4.6 | 9.0 | 2.86 | 12.5 | 6.7 |
| 7/7 | 3.3 | 9.0 | " | 10.5 | 5.2 |
| 7/8 | 1.4 | 7.0 | " | 7.5 | 2.9 |
| 7/9 | 0.9 | 7.5 | " | 7.5 | 2.4 |
| 7/20 | 0.4 | 9.5 | " | 6.5 | 1.9 |
| 7/21 | 0.3 | 6.5 | " | 6.5 | 1.8 |
| 7/22 | 0.3 | 7.5 | " | 6.5 | 1.8 |
| 8/3 | 0.2 | 7.5 | " | 6.5 | 1.8 |
| 8/4 | 0.2 | 6.5 | " | 5.0 | 1.4 |
| 8/5 | 0.2 | 6.5 | " | 6.5 | 1.7 |
| 8/18 | 0.2 | 6.5 | " | 7.7 | 2.1 |
| 8/19 | 0.2 | 5.5 | " | 8.5 | 2.2 |
| 8/20 | 0.2 | 8.5 | " | 8.0 | 2.2 |
| | | | | average | = $2.6x10^6$ g/day |

Q = discharge
Discharge data from USGS, NJ Water Resources, 1981)

$10^6$g/day (Table 7). The TOC leaving the reservoir via the spillway and the gatehouse (treatment plant outlet) averaged 2.6 x $10^6$g/day. The higher TOC values in water leaving the reservoir may have originated as organic matter from the growth of phytoplankton within the reservoir. Shore runoff was considered negligible because of the oxidation of organic matter exposed to air and the low volume of runoff into the reservoir. To estimate the amount of organic material produced in the reservoir water, an equation was used:

$$Q_{rr} C_{toc} + G = Q_{sp} C_{toc} + Q_{tp} C_{toc} + S_{toc}$$

$C_{toc}$ = concentration of total organic carbon in the water

$Q_{sp}$ = discharge of the reservoir over the spillway of the dam

$S_{toc}$ = total organic carbon incorporated into sediments at the the bottom of the reservoir

$Q_{rr}$ = discharge of the Rockaway River into the reservoir

The left side of the equation represents the influx of organic carbon into the reservoir. This influx is from two sources: TOC from the Rockaway River and growth of organisms within the reservoir. The right side of the equation represents outflow of organic carbon from the reservoir. These carbon sinks are: TOC in the waters leaving the reservoir at the treatment plant conduit and at the spillway, and carbon settling to the bottom of the reservoir.

Solving for $G = Q_{tp} C_{toc} + Q_{sp} C_{toc} + S_{toc} - Q_{rr} C_{toc}$. Data for the right side of the equation was calculated to be (Table 7,8&9):

$Q_{tp} C_{toc} + Q_{sp} C_{toc} = 2.6 \times 10^6$ g/day

$S_{toc} = 0.92 \times 10^6$g/day (negligible)

$Q_{rr} C_{toc} = 1.8 \times 10^6$g/day

Table 8: Sediment Trap Calculations for Sedimentation Rate and Amount of Organic Matter

TRAP 1

5.03g(dry weight of a 20ml aliquot)

5.03g/20ml = 0.25g/ml

0.25g/ml x 214ml (total sediment volume in trap) = 53.5g (total dry weight of sediment in trap)

0.25g/2.65g/cc x 100 = 9.4% volume is due to dry sediment

100% - 9.4% = 90.6% porosity

53.5g/132 days = 0.405 g/day were deposited in the trap

0.405g/day / 452.4 $cm^2$ (area of trap bottom) = 8.95 x $10^{-4}$g/$cm^2$-day

8.95 x $10^{-4}$g/$cm^2$-day x 365 x $10^4$ = 3266.7g/$m^2$-yr

3266.7g/$m^2$-yr / 0.934 (% non-organic matter) x 0.046 (% organic carbon in bottom sediments) x 0.77 x $10^6$ $m^2$ (sedimented area of the reservoir) / 365 = 0.92 x $10^3$ g/day organic matter retained in the bottom sediments.

OR

16.5cc (volume of organic matter with 0 porosity)

16.5 cc / 1g/cc (density of organic matter) / 132 days / 452.4 $cm^2$ x 0.77 x $10^{10}$ $cm^2$ = 2.1 x $10^6$ g/day (production of organic matter)

2.1 x $10^6$ g/day / 1.72 = 1.2 x $10^6$ g/day of carbon produced

organic matter / 1.72 = organic carbon (Thomas, 1969; Schoettle and Friedman, 1973)

TRAP 4

2.3 g (dry weight of a 20 ml aliquot)

2.3g/20ml - 0.115 g/ml

0.115g/ml x 202 ml (total sediment volume in trap) = 23.3 g

0.115g/ml / 2.65g/cc x 100 = 4.3% volume due to dry sediment

100% - 4.3% = 95.7% porosity

23.3g / 84 days = 0.276g/day were deposited in the trap

0.276g/day / 452.4 $cm^2$ = 6.1 x $10^{-4}$ g/$cm^2$-day

6.1 x $10^{-4}$ g/$cm^2$-day x 365 x $10^4$ = 2226.5g/$m^2$-yr

2226.5 g/$m^2$-yr / 0.934 x -.046 x 0.77 x $10^6 m^2$ / 365 = 0.63 x$10^3$g/day (this is the amount of organic carbon deposited in the trap)

OR

15.2 cc (amount of organic matter with 0 porosity)

15.2cc / 1g/cc (density of organic matter) = 15.2 g

15.2g / 84 days / 452.4 $cm^2$ x 0.77 x $10^{10}$ $cm^2$ = 3.08 x $10^6$g/day

3.08 x $10^6$g/day / 1.72 = 1.8 x $10^6$ g/day organic carbon deposited in the trap.

Table 9 : Rockaway River Suspended Sediment Entering and Leaving Boonton Reservoir from June through August 1981.

| Date | g/day Entering $\times 10^6$ | g/day Leaving $\times 10^6$ | Residual g/day $\times 10^6$ |
|---|---|---|---|
| 7/6 | 1.99 | 0.87 | 1.12 |
| 7/7 | 1.46 | 0.57 | 0.89 |
| 7/8 | 0.64 | 0.23 | 0.41 |
| 7/9 | 0.64 | 0.13 | 0.51 |
| 7/20 | 0.49 | 0.07 | 0.42 |
| 7/21 | 2.97 | 0.05 | 2.92 |
| 7/22 | 1.21 | 0.06 | 1.15 |
| 8/3 | 0.16 | 0.06 | 0.10 |
| 8/4 | 0.11 | 0.05 | 0.06 |
| 8/5 | 0.28 | 0.03 | 0.25 |
| 8/18 | 0.61 | 0.17 | 0.44 |
| 8/19 | 0.49 | 0.16 | 0.33 |
| 8/20 | 0.43 | 0.15 | 0.28 |

Average residual sediment is $0.68 \times 10^6$ g/day

$0.68 \times 10^6 \times 365 \times 1/1.4_a\text{g} \times 1/.77_b \times 10^{10}\ \text{cm}^2 \times 10\text{mm/cm} = 0.23\ \text{mm/yr}$

a. 1.4 g/cc is the average density found by Sherman (1953) for floccules in Lake Mead. 1.2 g/cc is the average density found for a floccule of 90% porosity containing particles of 2.65 g/cc.

b. $0.77 \times 10^{10}\ \text{cm}^2$ is the area of the sedimented portion of Boonton.

Thus a minimum value for TOC production in the reservoir is about $0.8 \times 10^6$ g/day.

The TOC concentrations of water samples from the reservoir do not correlate with the suspended sediment concentrations (r=0.01). There was poor correlation between the TOC of the reservoir and the TOC of the Rockaway River during composite sampling (r=0.48).

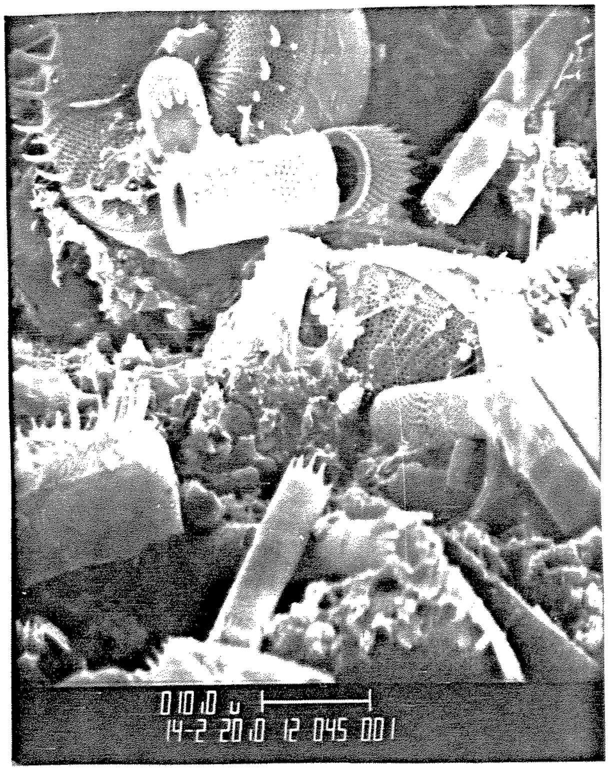
## Scanning Electron Microscope

Suspended sediments trapped onto Millipore filters were examined with the SEM. (Plate 3) Diatoms and diatom fragments composed between 20-30% of the particulate matter. Occasional floccules ranging from 5-7 phi (40-50 microns) were found, but the majority of the matter appeared to be small granules and flakes of clay-sized sediment.

## Bottom Sediments

Table 10 presents statistical parameters for the 16 bottom samples as well as TOC and sand:silt:clay ratios. The correlation coefficients for depth, % sand, %silt, % clay, mean size, and standard deviation are in Table 11. Frequency weight percent size distributions for the bottom samples and the material collected in the traps are in Figure 21 and 22. Sample locations are in Figure 23. The bottom sample size distribution graphs are grouped into subenvironments according to their location within the reservoir basin (Fig.24).

The highest correlation (r=0.98) was between the percent clay and the mean size (Ø). The percent sand had high negative correlations with mean size (r=-0.97), and percent clay (r=-0.95). Sorting




A. Melosira granulate and Stephanodiscus


B. Fragilaria

Plate 3: Planktonic Diatoms from Boonton Reservoir
Photographed with a Scanning Electron Microscope


C. Cyclotella

Plate 3 continued

Table 10: Bottom Sediment Statistics and Total Organic Carbon

| Sample | Mean Size ø | Stnd. Dev. r=ø | Sand:Silt:Clay % | Wt. % C | Depth m |
|---|---|---|---|---|---|
| BR 1 | 3.60 | 3.58 | 76.3:14.7:9 | 2.1 | 3.3 |
| BR 2 | 3.89 | 3.88 | 67:13:20 | 2.5 | 3.3 |
| BR 3 | 5.62 | 3.80 | 41.5:28:30.5 | 1.5 | 3.3 |
| BR 4 | 5.67 | 3.56 | 49:22.7:27.4 | 0.1 | 8.2 |
| BR 5 | 7.47 | 3.20 | 14:40:46 | 0.2 | 8.2 |
| BR 6 | 3.77 | 3.64 | 60:26:14 | 0.1 | 8.2 |
| BR 7 | 8.06 | 3.06 | 11:36:53 | 5.8 | 13.7 |
| BR 8 | 8.38 | 2.33 | 0:49:51 | 6.8 | 12.2 |
| BR 9 | 8.92 | 3.06 | 9:27:64 | 6.4 | 10.7 |
| BR 10 | 8.96 | 2.31 | 0:40:60 | 5.4 | 12.2 |
| BR 11 | 7.36 | 3.01 | 22:38:40 | 3.2 | 7.6 |
| BR 12 | 8.76 | 3.04 | 10:32:58 | 3.6 | 9.2 |
| BR 13 | 8.94 | 2.70 | 2:39:59 | 5.5 | 16.7 |
| BR 14 | 8.82 | 2.85 | 5:38.5:56.6 | 6.0 | 18.3 |
| BR 15 | 9.78 | 2.63 | 1:27:72 | 5.2 | 18.3 |
| BR 16 | 9.86 | 2.67 | 1.5:25:73.5 | 5.7 | 24.4 |

Folk's Textural Classification

| | |
|---|---|
| BR 1 | Silty Sand |
| BR 2,6 | Muddy Sand |
| BR 3-5,7,11 | Sandy Mud |
| BR 8-10, 12-16 | Mud |

Table 11: Correlation Coefficients for Boonton Reservoir Bottom Sediment Composition and Statistical Parameters

| | Depth m | TOC % | Sand % | Silt % | Clay % | Mean Size∅ | Sorting r |
|---|---|---|---|---|---|---|---|
| Depth | | 0.68 | -0.64 | 0.60 | 0.82 | 0.80 | -0.74 |
| TOC | | | -0.72 | 0.38 | 0.75 | 0.76 | -0.71 |
| Sand | | | | -0.75 | -0.95 | -0.97 | 0.88 |
| Silt | | | | | 0.50 | 0.60 | -0.71 |
| Clay | | | | | | 0.98 | -0.81 |
| Mean Size | | | | | | | -0.81 |

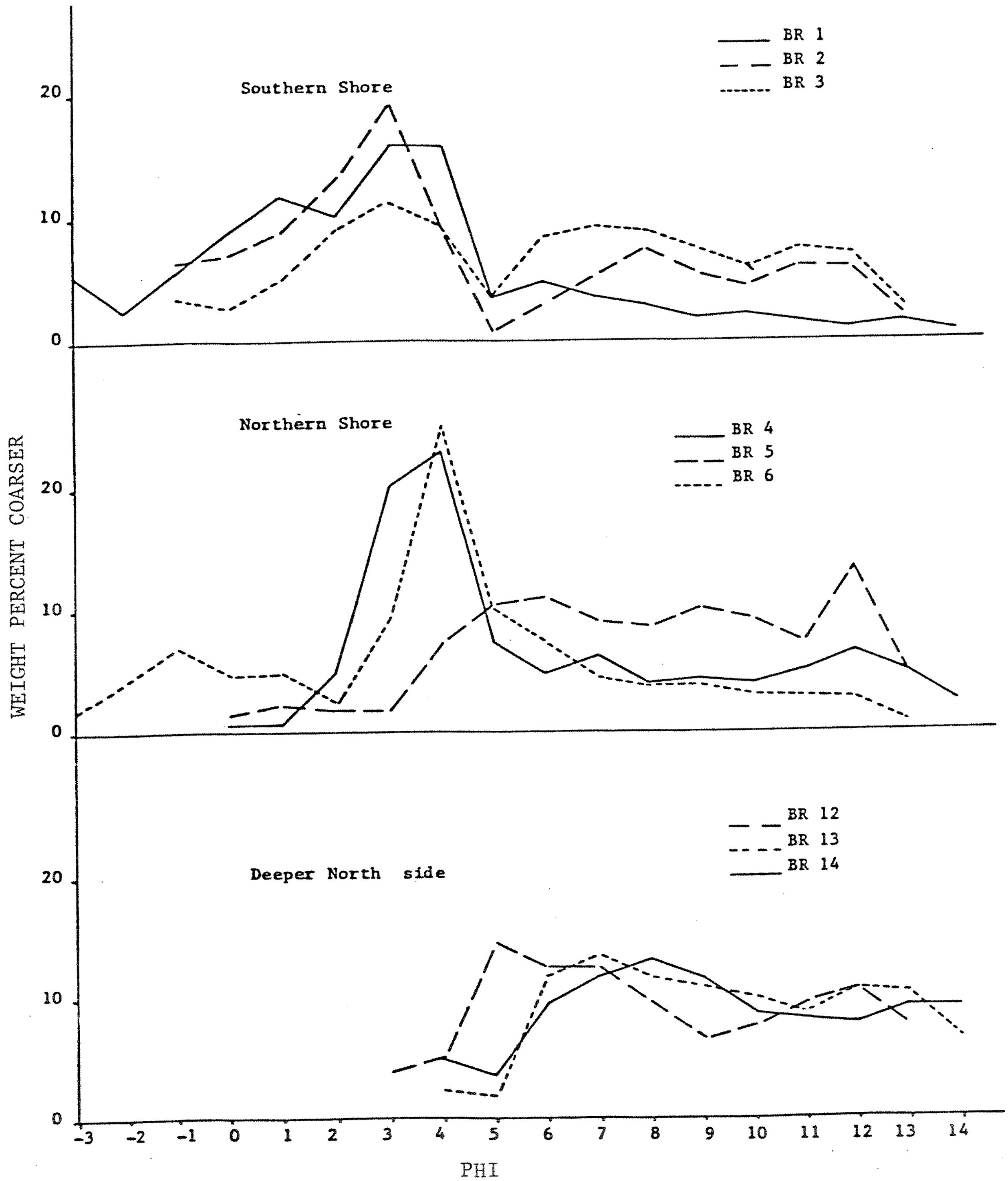



Figure 21 Size Frequency Graphs of Bottom Samples; Locations in Figure 23.

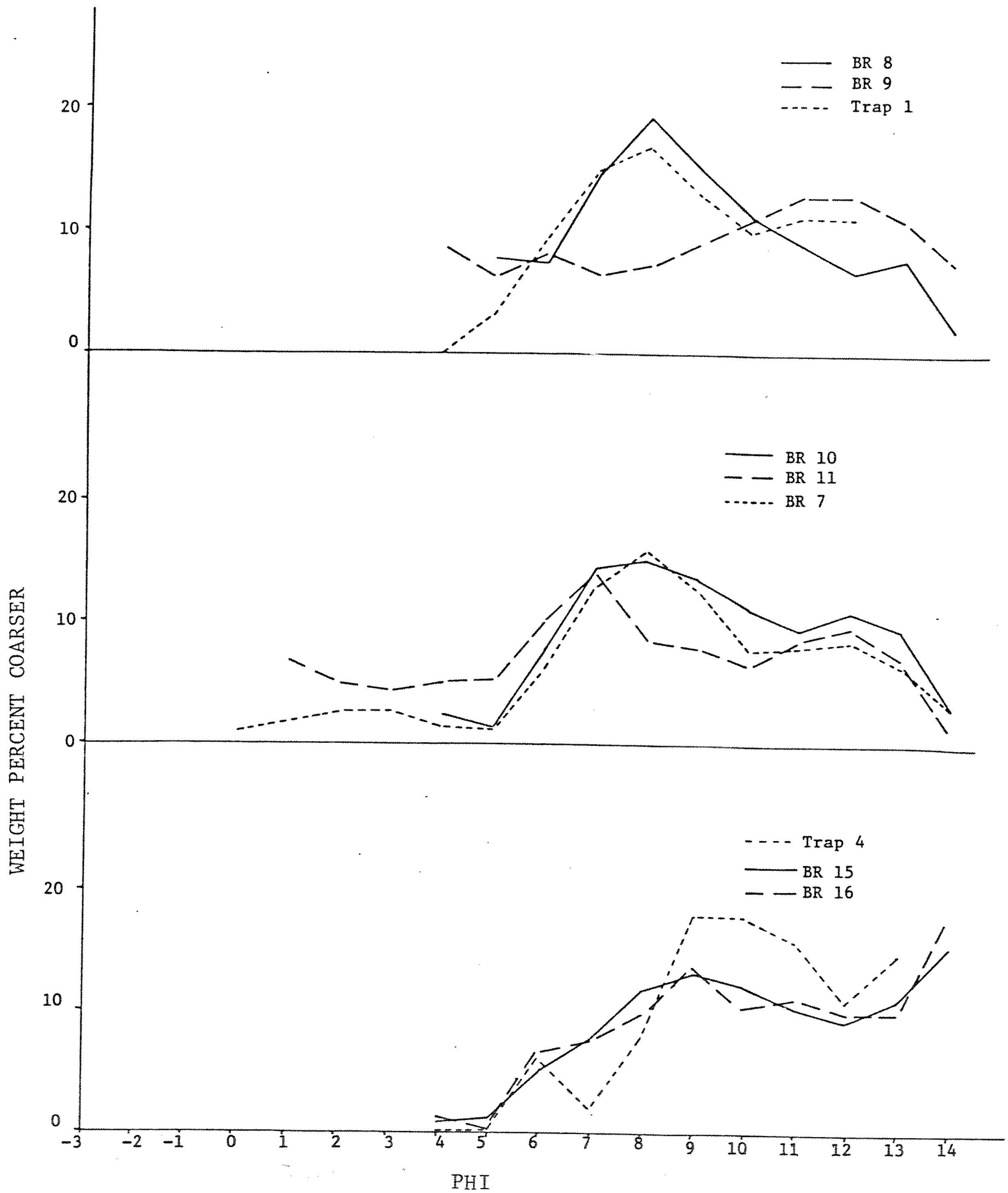



Figure 22: Size Frequency Graphs of Bottom Samples; Locations in Figure 23.

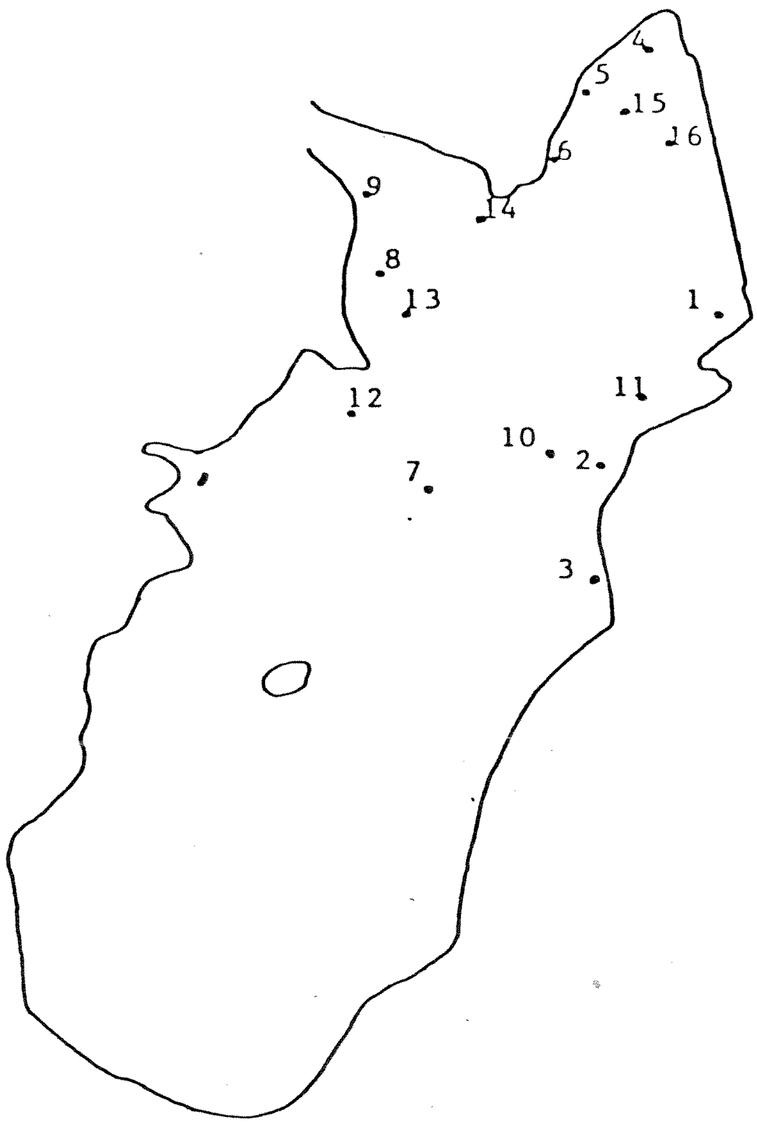



Figure 23: Bottom Sample Locations.

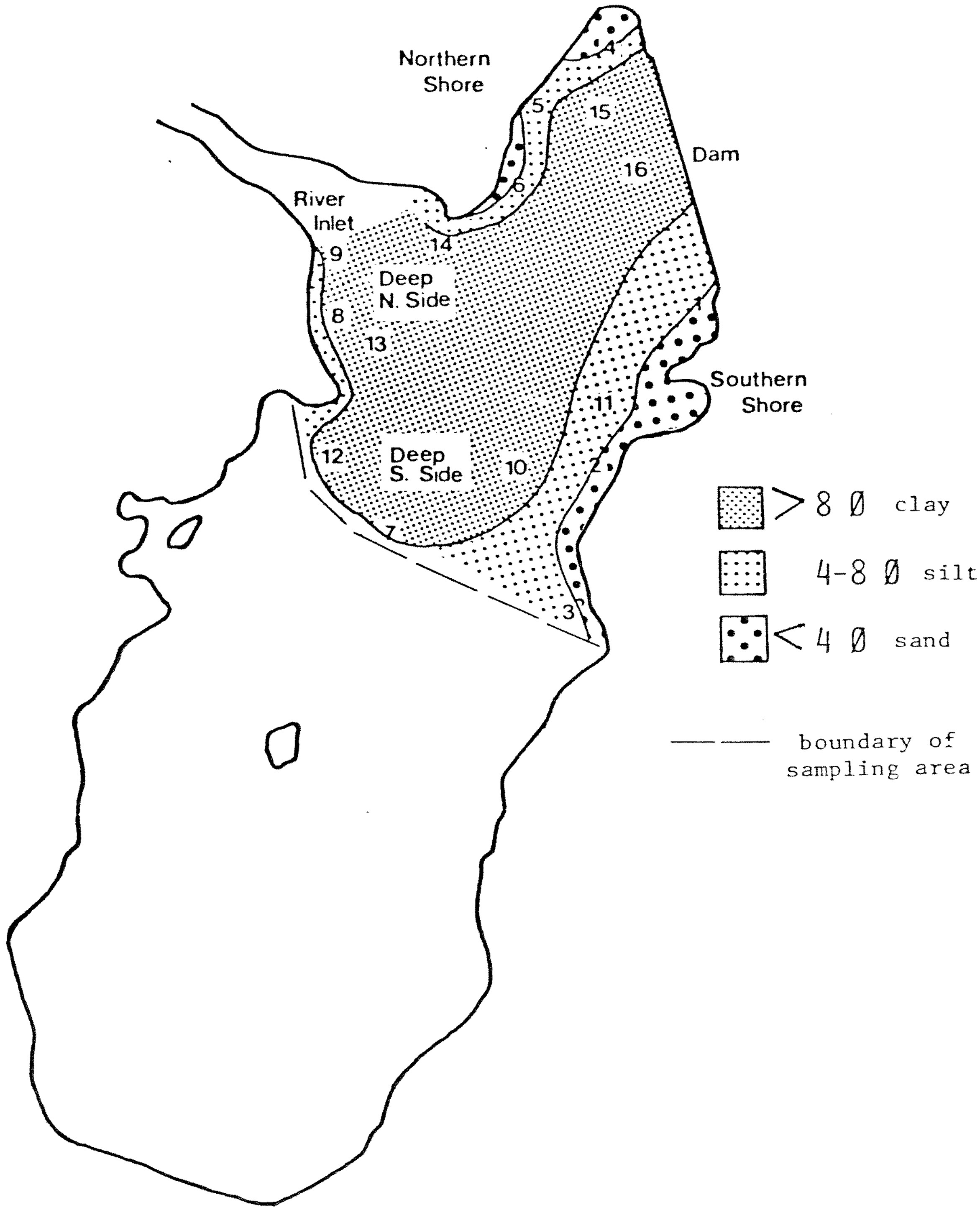



Figure 24: Mean Size of Bottom Samples Contoured for Boonton Reservoir

had a high positive correlation with percent sand (r=0.88) and a high negative correlation with the mean size (r=-0.81).

The total organic carbon (TOC) values for these bottom samples ranged from 6.8% for BR 8 to 0.1% for BR 4, with a mean of 3.8% (Table 10). The organic carbon was primarily associated with the fine particles found to settle in the deeper parts of the reservoir. It was positively correlated with percent clay (r=0.75), depth (r= 0.68), mean grain size (high phi values show high TOC values) (r= 0.76), and sorting (r=0.71). These correlations are to be expected because organic matter is believed to be adsorbed onto the very fine particles transported and deposited in the areas of lowest energy or deepest water (Hyne, 1978; Drever, 1982). Because sorting is slightly better in the deepest part of the reservoir then in the shallow near-shore areas, it also correlates well with the percent organic carbon (r=0.71).

Figure 25, a ternary diagram plotting TOC against percent sand, silt, and clay, shows a cluster of samples with high TOC (4-7%) corresponding to 50-70% clay. The low and medium TOC values are found in samples containing 40-60% clay. The proportion of clay to silt appeared to be nearly constant, while the sand content was variable. Samples BR 4, BR 5, and BR 6 were not included when TOC values were correlated because their low values represented exposure of the lake bottom prior to sampling.

Organic matter comprises a large percentage of the bottom sediments collected in the sediment traps. The sediments in Trap 1 contained 45% organic matter and Trap 4, 64% organic matter. In contrast, as discussed above, grab samples of bottom sediments

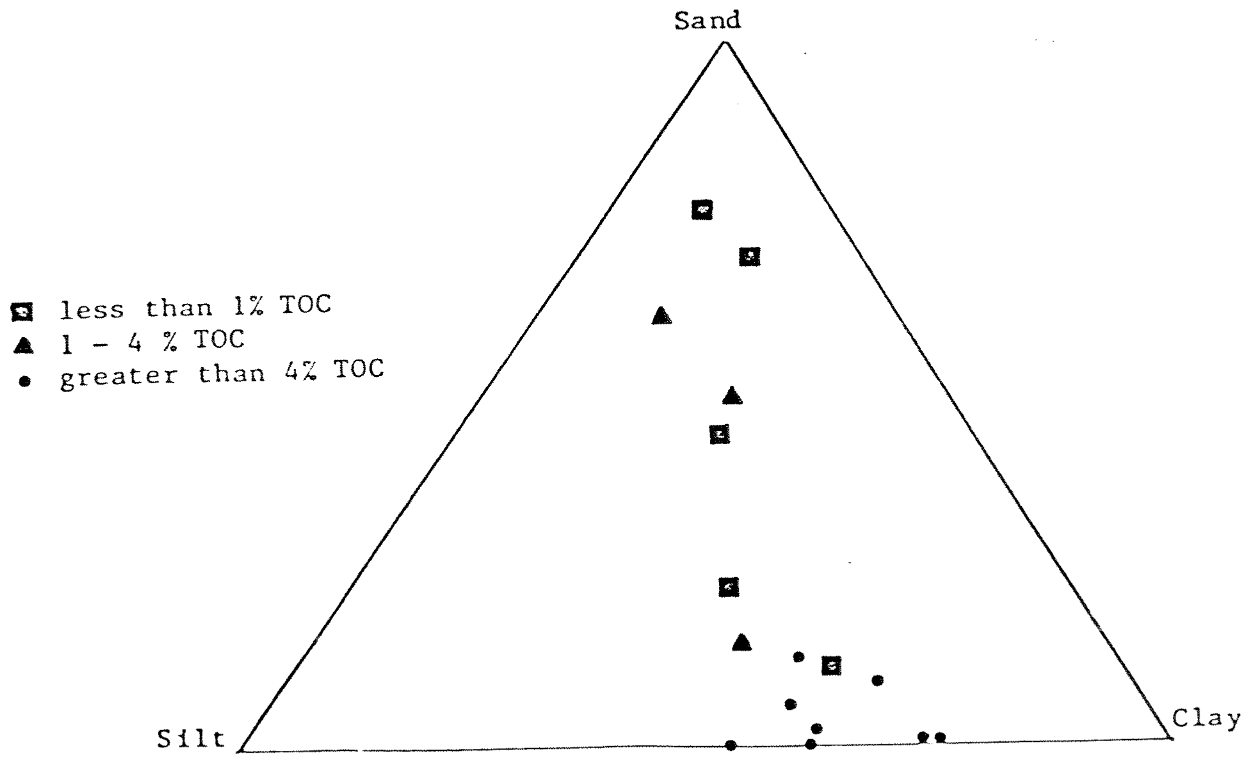



Figure 25: Ternary Diagram of Percentage of Sand, Silt, Clay and TOC in Bottom Samples.

show much lower TOC values.

The coarse fraction of the bottom sediments contained plutonic and metamorphic clasts. The plutonic clasts consisted of quartz, feldspar, and muscovite, with smaller amounts of hornblende. The hornblende showed alteration to chlorite. Some quartz showed yellow iron staining. There were filings of fine magnetite in the coarse and fine fractions. The metamorphic clasts consisted of meta-quartz, with feldspar matrix and small amounts of muscovite. There were also meta-sandstone clasts.

X-ray analysis of the fine fraction showed chlorite, muscovite, a small amount of smectite and possibly some kaolinite. The chlorite appeared to be interlayered with a mica. Feldspar, amphibole and calcium carbonate were also identified. An x-ray diffractogram typical of the lake sediments is in Figure 26.

The coarse fraction consisted primarily of quartz and feldspars from the gneisses and glacial till. Magnetite probably came from the metamorphic Precambrian gneisses (Sims, 1958). The fine fraction (less than 4 phi) had a large percentage of muscovite easily seen with the naked eye. Filters containing suspended sediment from a storm runoff showed more mica flakes than fine quartz sand grains. The fine fraction has its source in the weathering of metamorphic rocks and glacial till. Chlorite in the clay fraction was present because of weathered mafics such as hornblende. Because kaolinite is masked by chlorite during x-ray analysis, it is dificult to positively identify. However, because of the abundance of feldspars, kaolinite is probably present. During glycolation, a 17 Å peak indicated a small amount of smectite. Smectite is to

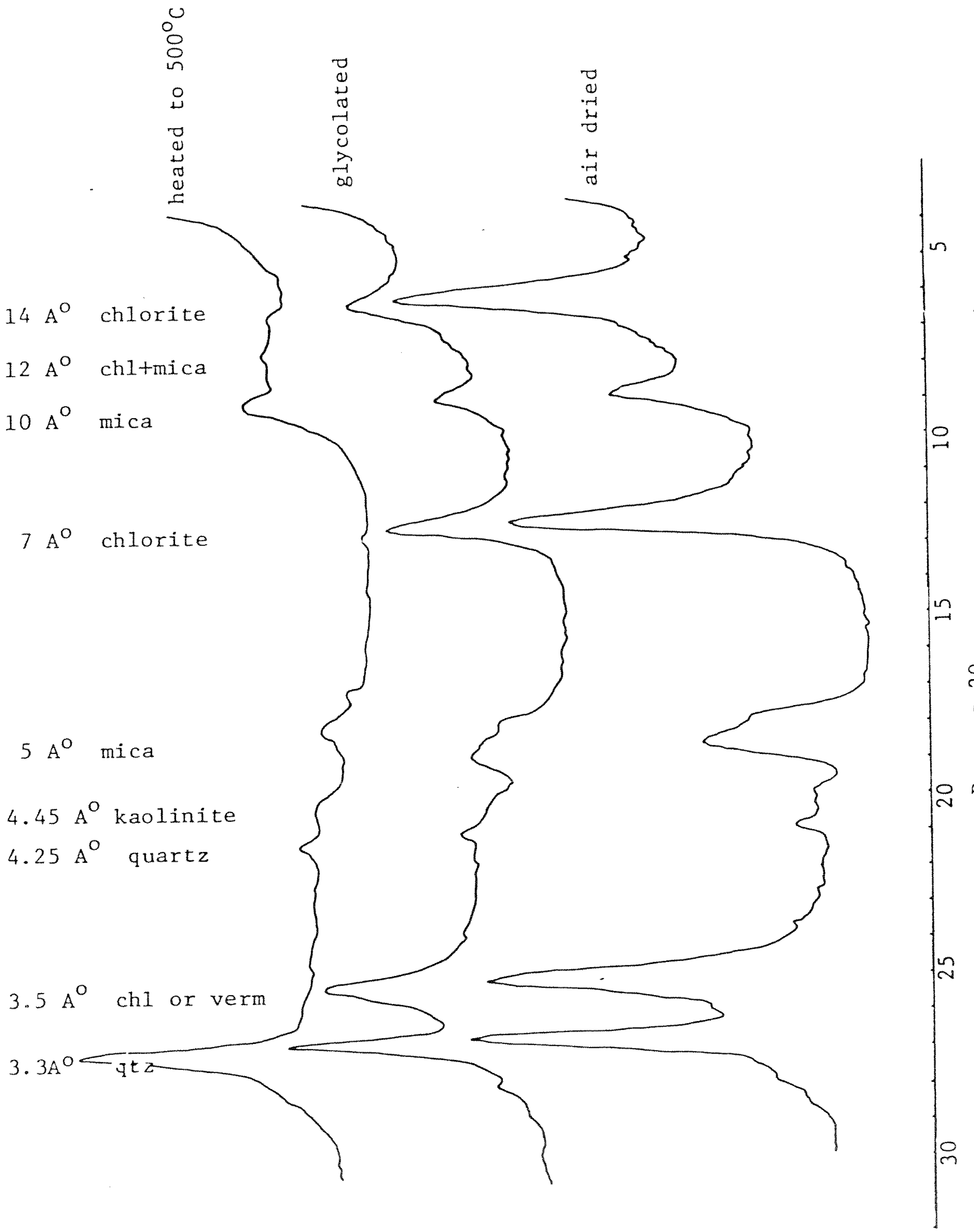



Figure 26: X Ray Diffractogram of Trap 4 Sediment

be expected where there is an abundance of cations (Mg, Fe, Ca) as well as aluminum and silica. L. Douglas (1971) has shown that hydrogen peroxide treatment for the removal of organics may have dissolved some of the smectite during analysis.

Sedimentation Rates

Two of the five sedimentation traps were recovered: #1 and #4. (Fig. 27). The sediments from Trap 1 had 90.6% porosity, while Trap 4 had 95.7% porosity. The sedimentation rate for Trap 1 was $8.9 \times 10^{6}$ g/cm$^{2}$-day, and for Trap 4 was $6.1 \times 10^{6}$ g/cm$^{2}$-day (Table 8). When determining the area of the reservoir in which sedimentation occurs, it was assumed that the deeper northern end nearest the river inlet would acquire most of the sediment. The area of this northern portion was measured to be 0.77 km$^{2}$ (Fig. 27). Using this area and Trap 1's sedimentation rate it was calculated that 1.2 mm/yr ($6.9 \times 10^{6}$ g/day) of dry sediment are being deposited whereas using Trap 4's rate, about 0.84 mm/year ($4.7 \times 10^{6}$ g/day) are being deposited. Trap 1 had a higher sedimentation rate because it was nearest to the river. Both values should represent areas of maximum sedimentation rates because both traps were situated near the river inlet and in deep water (15.1-21m).

The total suspended sediment load entering the reservoir via the Rockaway River ranged from a maximum of $2.97 \times 10^{6}$ g/day to a minimum of $0.011 \times 10^{6}$ g/day with the average being $1.25 \times 10^{6}$ g/day (Table 1 & 9). The average residual suspended sediment of $0.68 \times 10^{6}$ g/day corresponded to a sedimentation rate of 0.23 mm/year (Table 9). The USGS monthly data for 3/75 - 8/78 showed a maximum of $1.3 \times 10^{6}$ g/day

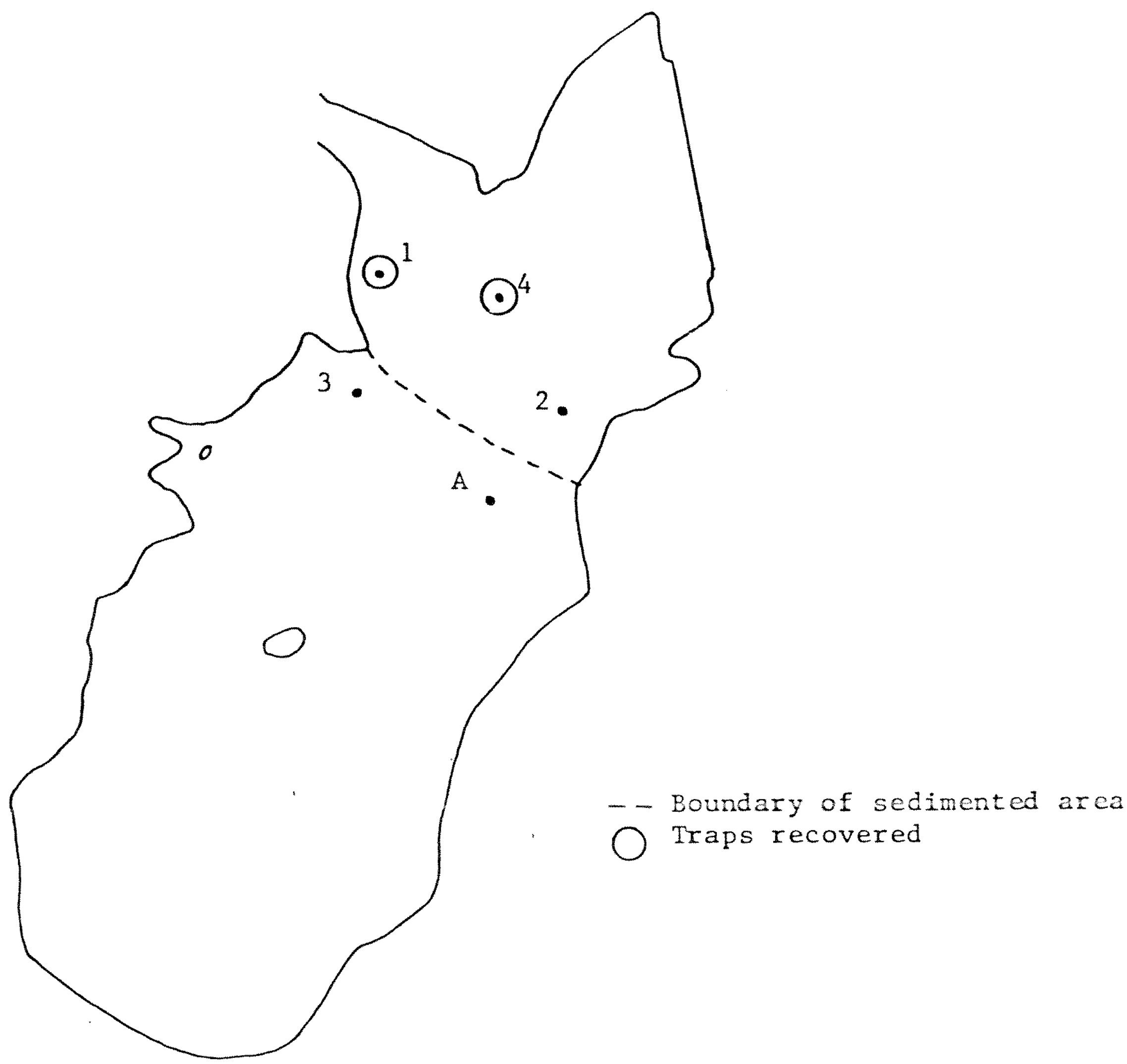



Figure 27: Trap Locations and Location of Lake Area Believed to Receive Most of the Transported Sediment.

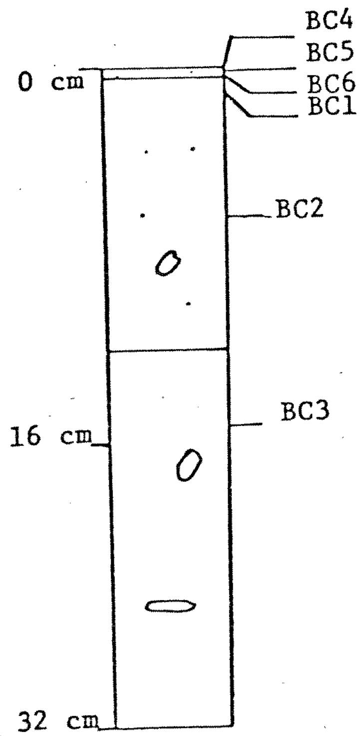
a minimum of 0.5 x $10^6$ g/day and an average of 3481.2 kg/day (Table 4). The USGS data corresponded to a sediment input of about three times the amount found during this study.

Cores 1 and 2 were extracted from near the river inlet. The descriptions can be found in Figure 28. It was difficult to distinguish, in Core #1, the pre-lake soil from the lake deposits. Dark brown color and high TOC content indicated that the uppermost 2.5 cm of the core was probably reservoir sediments. Based on the fact that the dam was built in 1904, this thickness indicates a sedimentation rate of 0.3 mm/yr. Coring was unsuccessful in three other locations of the reservoir because submerged hard objects (building foundations?) were encountered.

## Dating Lake Sediments

When bottom samples BR 7 and BR 8 were tested for CS 137, only 24±7 picoCuries and 19±6 picoCuries, respectively ,were obtained. These values represent 0.6 ± 0.2 pC/g which is an expected background level; thus, it was not possible to utilize Cs 137 for dating the core.

## CORE 1



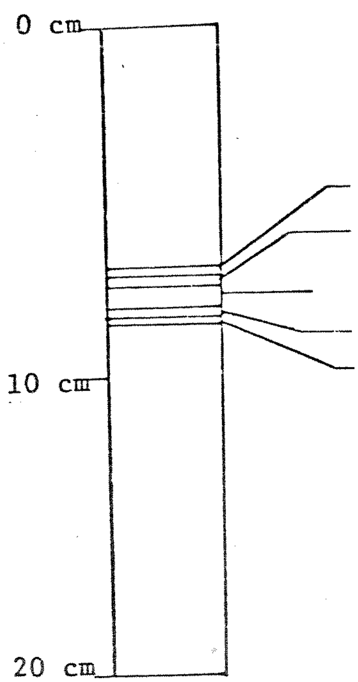

2.5 cm of dark brown (when wet) unconsolidated clay and silt with 5% coarse grains of sand. When dry the color is 2.5 YR 7/2 on the Munsell color chart.

12 cm of dark brown (when wet)clay and silt. When dry the color is 10 YR 7/3 on the Munsell color chart. Contains a few yellow oxidized (?) spots and only a few coarse sand grains.

18 cm of yellow tan (when wet) clay with some light brown spots. 10 YR 7/3 when dry. Approximately 1% coarse sand grains.

| TOC (weight %) | |
|---|---|
| BC1 | 1.7 |
| BC2 | 2.0 |
| BC3 | 0.7 |
| BC4 | 5.4 |
| BC5 | 5.9 |
| BC6 | 2.2 |

## CORE 2




Dark brown (when wet) very fine sand and mud with leaves and twig pieces.

0.5 cm of yellow brown (wet) fine sand.
1 cm of black silty clay with sulfurous smell. (sapropel)
1.3 cm of yellow brown laminated fine sand.
0.7 cm of sapropel
1 cm of yellow brown fine sand.

Lower part of core is all sapropel.

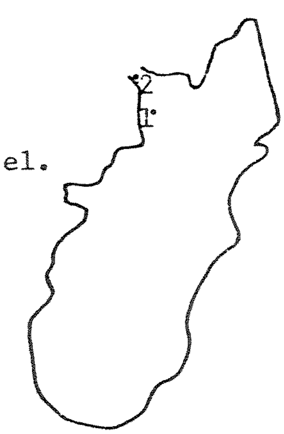



Figure 28: Boonton Reservoir Core Descriptions

# DISCUSSION

## Rockaway River

### Discharge Variations

The average monthly mean discharge for this study period (1.05 $m^3/s$) was only 1/6 of that for the period of 1940-1981. This dry period began in the summer of 1980 and continued through December 1981. The suspended sediment concentration measured during this study was low when compared to the only other available long term data (USGS data from 1975-1978). There was no correlation between the river discharge and its suspended sediment concentration as has been seen in other river studies (Gregory and Walling, 1973), nor was there a correlation between the discharge and suspended sediment concentration for the USGS data. The lack of correlation between discharge and suspended sediment may be due to the fact that 76.5% of the drainage basin is impounded. Two hundred and sixty $km^2$ of the Rockaway drainage system has lakes, reservoirs and ponds that trap sediment before it can be transported into the Rockaway River. The areas of the drainage basin that are not impounded are found along the Beaver Brook tributary and along Rockaway River's main channel (Fig. 29).

Storm events can transport large volumes of sediment into the reservoir. During a high discharge event on January 5, 1982 (43 $m^3/s$), the suspended sediment concentration of a water sample collected in the delta area was 280 mg/l. This concentration is more than 70 times the mean river concentrations found during this study. Such high flows are capable of resuspending deltaic sediments and depositing them in the reservoir. During the lake's low stands,

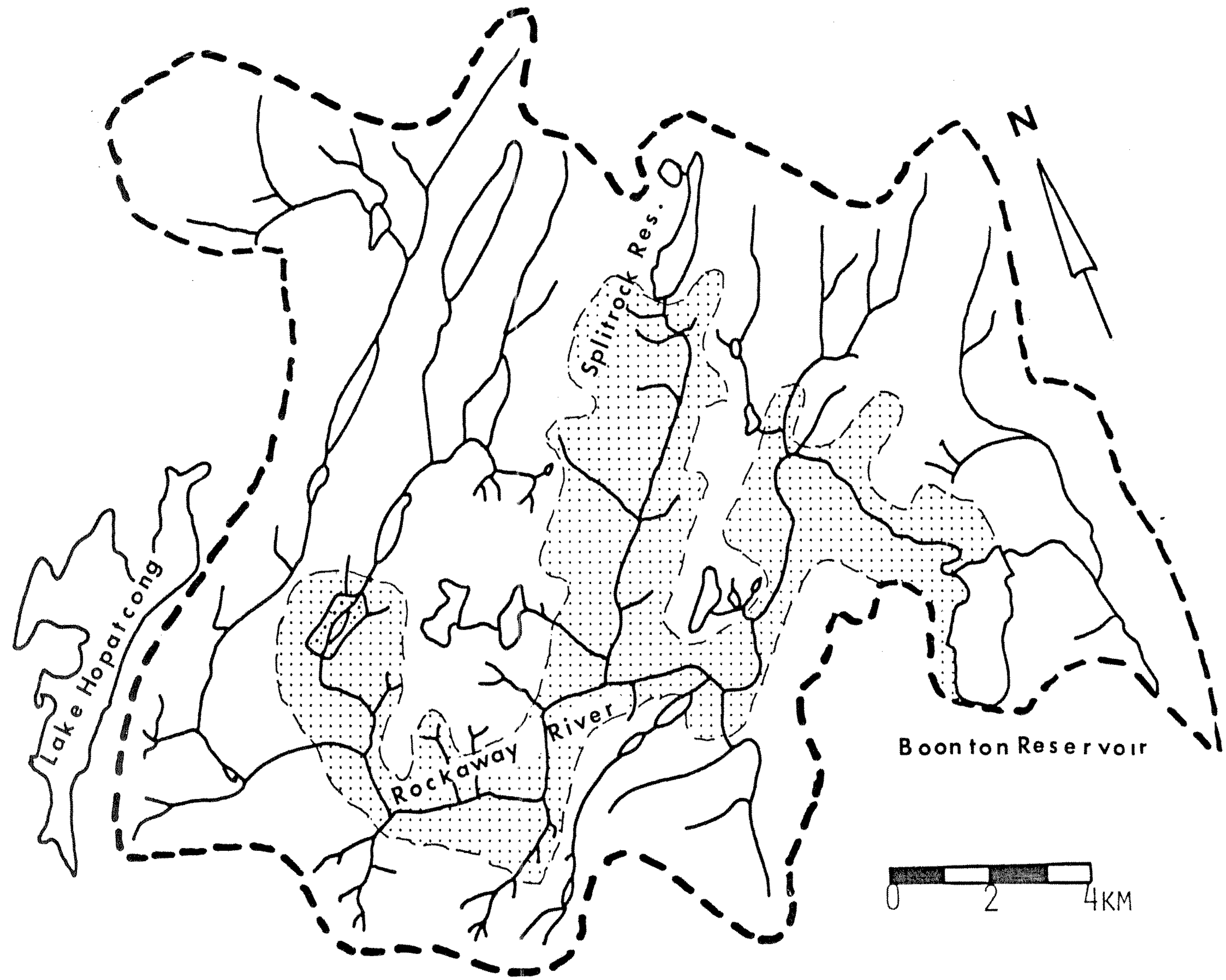



Figure 29: Stipled Area is Rockaway River Drainage Not Impounded.

the river erodes channels into the exposed delta. Channels approximately one meter deep and two meters wide were observed following a rain on October 26, 1980, which produced that month's maximum discharge of 10.5 $m^3/s$ (Plate 4). Multiple layers of organic rich oozes and leaf mold could be seen exposed in the channel banks. The presence of channels suggest that scoured deltaic sediments were transported further into the lake during this storm.

The suspended sediment in the Rockaway River (at the gauging station) during a storm (with a discharge of 2.06 $m^3/s$) on 9/10/81 contained a small percentage (27%) of clay-sized particles and a low suspended sediment concentration (approximately 7 mg/l). Coulter Counter's analysis of the suspended sediment size distribution indicated no particles finer than 11 phi and only 4.7% coarser than 4 phi. Because the sample was only mechanically dispersed it is assumed that the results of this size analysis were similar to those found in the Rockaway River under normal flow conditions. This analysis seems to indicate that those particles finer than 11 phi found in the reservoir bottom sample analyses must have been borne by the river as floccules or were produced in the reservoir. However, more high discharge water samples must be collected at the gauging station to accurately determine the particle size range carried by the Rockaway River.

Storm events are also responsible for creating lake level fluctuations. During a storm on February 21, 1981, a discharge of 33.4 $m^3/s$ resulted in a 2.6 meter rise in lake level by February 23 (Plastoris, pers. comm.). This rise represented a volume increase of 29 percent. Water level rises following storms or water

Plate 4: Storm Channels cut into the Delta Area of Boonton Reservoir.

level drops due to dry periods can contribute sediment to the reservoir via wave erosion at the shorelines. This sediment input is balanced by the increase in basin volume along the shores. Thus, there is no net sediment volume change of the reservoir as a whole.

## Total Organic Carbon in River Water

Organic carbon is found in rivers in particulate and dissolved forms. Gruner (1922; as cited in Sholkovitz, 1976) found that the concentration of dissolved organic carbon in river waters was about 10 times greater than the particulate form. The world average dissolved organic carbon found in rivers is 10 mg/l (Sholkovitz, 1976). Sholkovitz studied four rivers in Wigtownshire, Scotland draining peaty soils and found that dissolved organic carbon averaged 4.1 to 13.5 mg/l. Maier et al. (1973) found in the major Minnesota rivers receiving residential and industrial inputs, average TOC (particulate and dissolved) values to be between 5 and 29 mg/l.

The Rockaway River TOC values of 1.5 - 12.5 mg/l found in this study and 1.6 - 9.2 mg/l, as found by the USGS (1975 - 1978), fall well within the ranges found in the river studies discussed above. However, unlike Maier's, studies there was no correlation between Rockaway River discharge and TOC. It is believed that because the river is bordered by industry and residential areas, the TOC values could reflect man's input wastes as well as natural sources. For example, Maier et al. (1973) found that urban and industrial areas around the St. Louis River had increased organic carbon values.

There was good correlation between the Rockaway River total organic carbon and the suspended sediment concentration (r=0.69) if one data point is disregarded (Fig. 30). (This sample showed a very low TOC with a very high suspended sediment concentration because it was collected near shore runoff.) A correlation is expected because some of the organic carbon occurs as suspended particulate matter in the water.

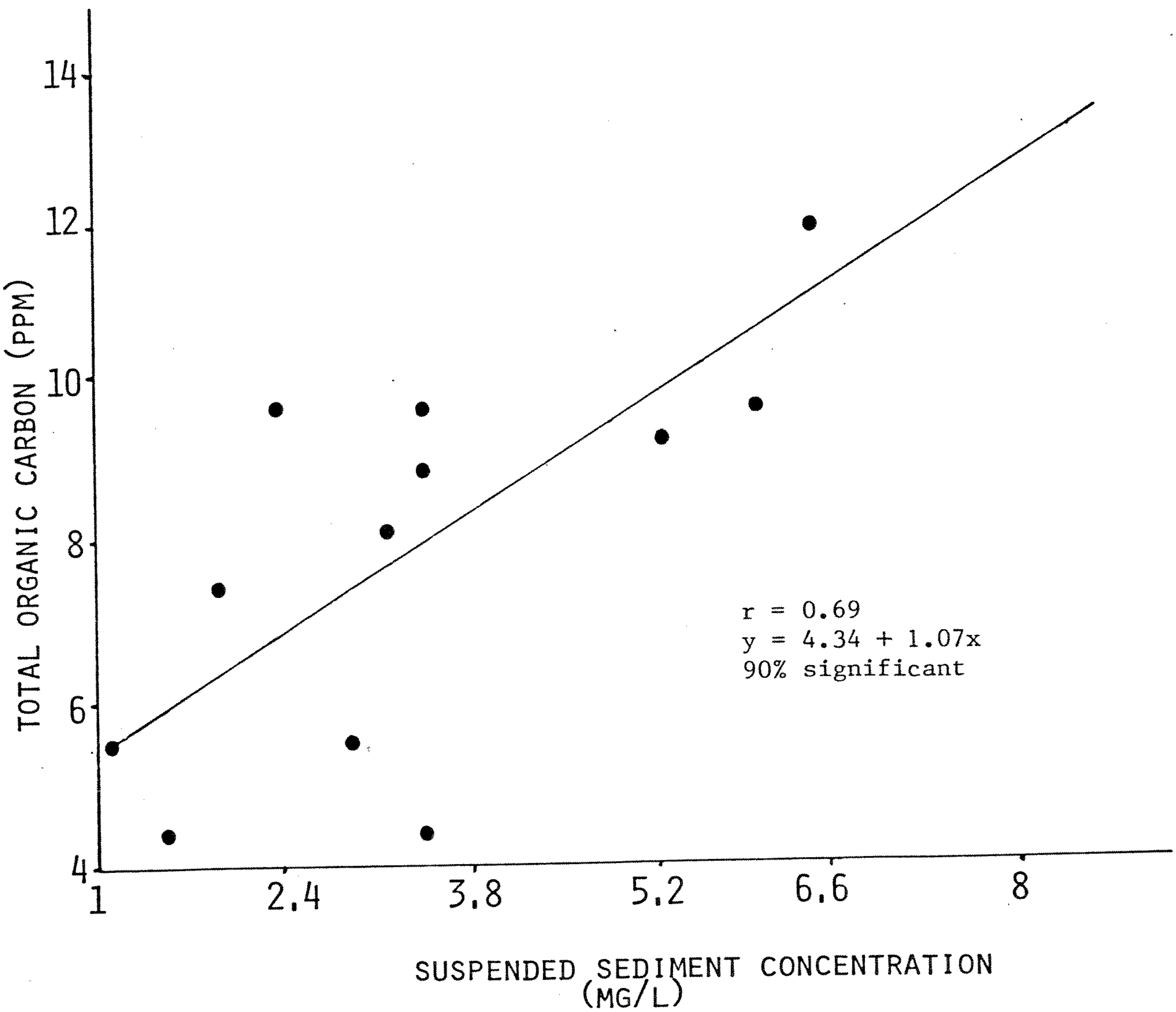



Figure 30: Correlation of Rockaway River Suspended Sediment versus Total Organic Carbon

# Boonton Reservoir

## Physical Limnology

Boonton Reservoir can be classified as a temperate lake by Yoshimura (1936; as cited by Hutchinson, 1975, p. 437). The surface temperatures are above $4^{o}$C in the summer, below $4^{o}$C in the winter and it has large seasonal temperature variations. Boonton Reservoir is a dimictic system with mixing in the early spring and in the early winter.

The reservoir is typically covered with ice in January and February. During the spring, soon after the ice cover has melted, the water is easily mixed by the wind. Ruttner (1964) explains that heat is easily transferred through the water column because of the homogeneous character of the water temperature and density.

Figure 18 illustrates the reservoir's percent saturation of dissolved oxygen during mixing. The values for percent saturation at different temperatures were determined using tables from Truesdale et al. (1955). Figure 18 also illustrates the percent saturation during stratification. During stratification the percent saturation decreases with depth while during mixing the percent saturation varies with depth.

Station 13 and Station X in Figure 18 showed an increase in oxygen at a depth of 10 meters. Because the river channel is not near this location, and since this increase in oxygen occurred during both mixing and stratification, it can be assumed that seepage occurs from the basin slope. It is also possible that during stratification cold water seepage from the lake basin slopes could be responsible for the slight increase in oxygen seen at the bottom of the lake in

Figure 18. Groundwater seepage is common in the area, as evidenced by a spring observed on the shore near Station 16 when the water level had dropped 7.6 meters.

The dissolved oxygen measured in the upper 10 meters at station 16 was higher than all other stations measured that day (Fig. 18.) This station is located near the dam and just southeast of the spillway. As the wind sends waves up against the dam, the oxygenated water may be forced to downwell.

As the surface temperatures increase, the density of the water decreases and more energy is needed to transfer heat. The wind acting on the low density water near the surface results in horizontal mixing and the formation of layers of mixed waters over unmixed cool water. It is during this time that multiple thermoclines can form (Fig. 15). These planes of maximum temperature gradients form quickly on very hot days and represent boundaries between layers of different densities (Ruttner, 1964).

## Stratification

As layers of warmer, less dense water continue to deepen by mixing, they will reach an equilibrium depth where the deeper cold dense water acts as a barrier. The upper mixed layer is called the epilimnion (Fig. 18). During the daytime the winds and solar heating provide energy for horizontal mixing. During the night as the water releases heat the cooler particles sink and convection currents can cause a temporary breakup of the stratification (Hutchinson, 1959). The dissolved oxygen is high in the upper mixed layer.

The metalimnion is the middle cooler layer with the steepest temperature gradient. Its depth depends on the wind velocity and fetch. The dissolved oxygen decreases here because this layer is below the effective depth of photosynthesis and mixing (Ruttner, 1964). There is also an accumulation of oxidizable materials raining from the surface lowering the oxygen content of the water.

The deepest layer of cold water is where little mixing occurs except for turbulent shore or river inflows. The hypolimnion, as this layer is called, is anoxic in Boonton Reservoir during the late summer (Fig. 17). The processes affecting the concentration of the dissolved oxygen are temperature (low temperature contains more dissolved oxygen), sedimentation rate of organics (bacterial oxidation of organic matter on the lake bottom depletes dissolved oxygen), and depth (the deeper the water the less chance for oxygen diffusing from the surface (Ruttner, 1964).

The most important process affecting the dissolved oxygen in the hypolimnion of Boonton Reservoir is the growth of algae. The growth of algae is dependent on many factors such as temperature, light and nutrients. A lake which is rich in nutrients (eutrophic) could have a large algae population and as a result an anoxic hypolimnion. The accumulation of unoxidized organic material and anaerobic bacteria could render the water unpalatable due to the production of noxious gases such as hydrogen sulfide, ammonia and carbon dioxide.

Ruttner (1964) illustrated how the temperature and dissolved oxygen profiles differ for oligotrophic and eutrophic (nutrient rich) lakes (Fig. 31). Oligotrophic lakes such as Lake Constance (Fig. 31) show a gradual step-like decrease in temperature with a constant

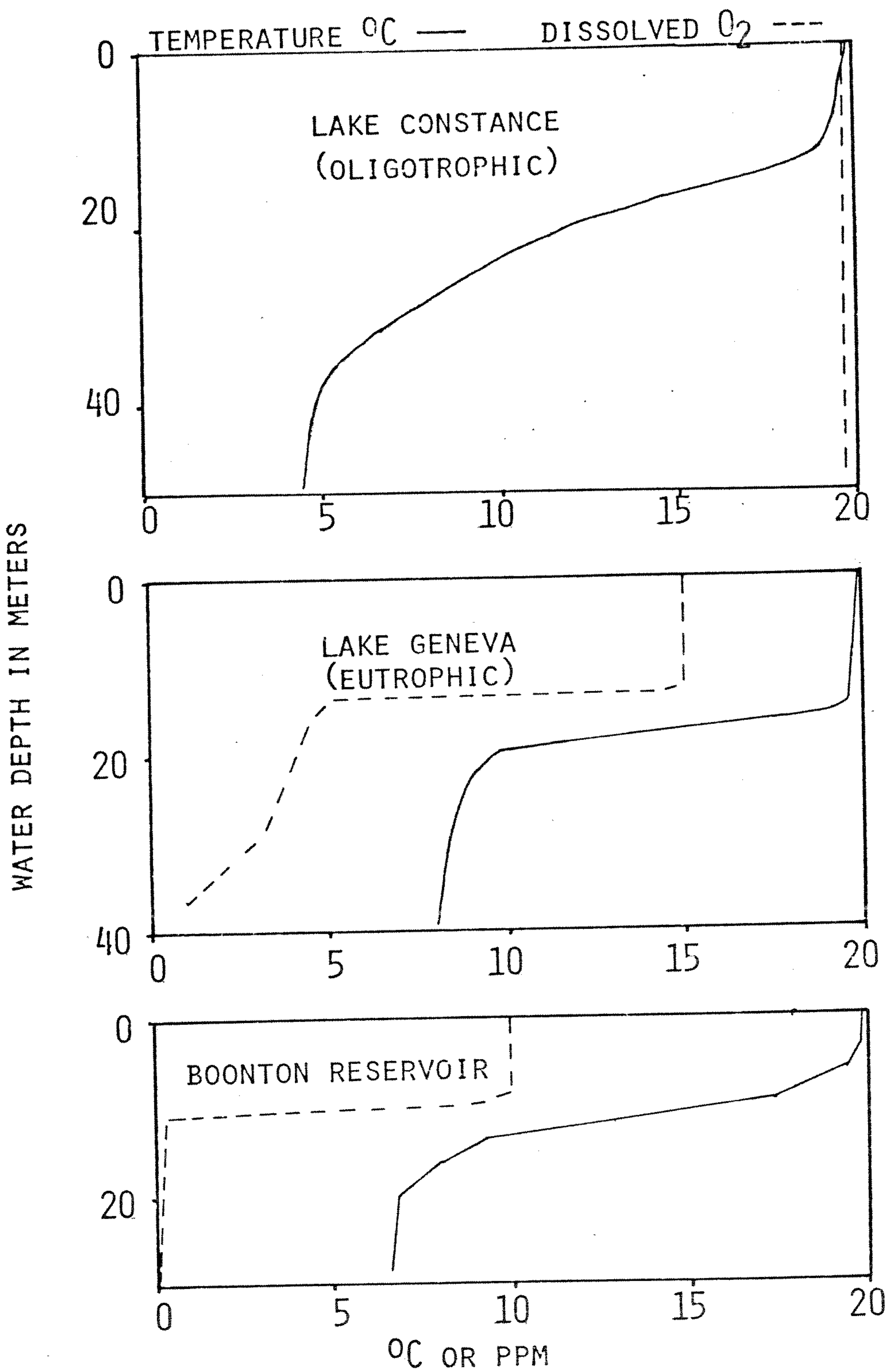



Figure 31: Temperature and Dissolved Oxygen Profiles of Oligotrophic and Eutrophic Lakes Compared to Boonton Reservoir (adapted from Ruttner, 1964)

concentration of dissolved oxygen with depth. Eutrophic lakes exhibit a sharp break in temperature and dissolved oxygen at the thermocline (Fig. 31). Boonton Reservoir profiles resemble that of the eutrophic lakes.

During the early winter as the surface temperature decreases and the density difference between the epilimnion and the metalimnion decreases, mixing occurs (Fig. 5). The epilimnion increases in thickness until stratification disappears (Hutchinson,1975). Winter mixing brings dissolved oxygen to the hypolimnion and can also redistribute bottom sediments (Davis, 1968; Serruya, 1977).

Even though data were not collected when the lake was frozen, it is assumed that during January and February when the surface waters freeze and decrease in density a weak stratification will form (Lerman, 1978). The ice on the surface decreases the heat loss, while preventing wind from further cooling the waters. In fact, there can be an increase in heat of the water mass through solar radiation and bottom sediment conduction (Lerman, 1978). During early spring when the ice has melted, the lake mixes again as the warmer bottom waters rise in response to ice melting and blowing winds. Thus the cycle of mixing and stratification begins anew.

The development of a metalimnion can have an effect on the settling of suspended sediments and on the river circulation as it enters the reservoir. The effect of stratification on particle settling is discussed in a later section.

If the river density is less than that in the reservoir because of higher temperatures or lower suspended sediment concentrations, the discharge will flow above the thermocline (Serruya, 1974). This type of overflow is expected during the summer when the stratification has been established. However, during the spring, shortly after a major flow event, temperature and dissolved oxygen measurements taken near the river inlet did not detect any continuity in the river flow as it entered the reservoir (Fig. 17). More detailed temperature and dissolved oxygen measurements taken after stratification has been established would be needed to detect this type of flow.

The absence of stratification in the late fall and winter would allow the river inflow to either disperse evenly during average discharge or create turbid bottom flow in response to storm events that produce high suspended sediment loads. However, when the lake freezes over and the bottom temperature is much lower than the river, discharge must ride above the bottom unless it is carrying a large suspended load. During these times of still water and little stratification more sediment would settle out of suspension and thus not reach the treatment plant intake.

Water Samples

Sources of suspended sediment in the reservoir include erosion from the watershed and the shore, biological production and man's activities along the drainage basin waterways. In the lake the suspended material, or seston as it is termed by Hutchinson (1967), is composed of organic and inorganic materials. The organic component is important in the identification of nutrient sources and in the estimation of sedimentation rate of organics and their associated pollutants.

Organic material is classified by Hutchinson (1967) as allochthonous or autochthonous. Allochthonous material is derived from land vegetation and autochthonous material is derived from decomposition of lake biota . Birge and Juday (1934) found that phytoplankton represented a primary source of organics in lakes. Manny and Wetzel (1973) found another source of organics to be groundwater seepage.

The seston concentrations in the surface waters of the reservoir were low during the summer sampling period (1-7 mg/l). Samples taken by the Jersey City treatment plant during December 1981 and January 1982 had a higher range of concentrations (1-45 mg/l). There was no correlation between Rockaway River suspended sediment and Boonton Reservoir suspended sediment, indicating that other factors within the reservoir influenced the formation of seston. Possible factors include seasonal variation in seston production, trophic condition of the lake as shown by Pennington (1974), addition of nutrients to the lake by man's activities upstream, and resuspension of bottom sediments during the mixing period of the lake waters. Continuous sampling of seston for at least one year should be completed and correlated with weather data and chronology of man's activities upstream to gain an understanding of origin and final deposition of organic materials.

## Total Organic Carbon

As with the suspended sediment concentration, the total organic carbon in the reservoir did not correlate with either the discharge nor the TOC of the river. Unlike the Rockaway River, suspended sediment concentration in Boonton Reservoir did not correlate with Boonton Reservoir TOC (Fig. 32). Many samples showed variable amounts of TOC with low suspended sediment concentrations. The variability of the TOC may be due to fluctuations in its dissolved component. Dissolved organic carbon is derived from the decay of organic matter and organic pollutants entering the water system.

Three samples showing a high suspended sediment concentration (about 7 mg/l) were collected from an open conduit where fast moving reservoir water left the dam. The turbulent water was able to carry more sediment than the still waters of the reservoir. The source of the sediment could be dirt falling into the open conduit or algae growing on its walls.

The minimum value of $0.8 \times 10^6$ g/day of organic carbon produced in the reservoir is probably accurate for the summer months in 1981. The discharge data for the Rockaway River entering the reservoir and water spilling out of the reservoir was provided by USGS gauging stations ($Q_{rr}$ & $Q_{sp}$). The discharge data from the reservoir to the treatment plant was provided by the Jersey City watershed supervisor. These data are assumed to be consistent and accurate. Water samples for TOC analyses were collected at the same time and analyzed with the same techniques. The value for TOC settling into the bottom sediments was chosen as a minimum value calculated from the material in the sediment traps (Table 8). Thus, it is evident that the reservoir biota contributes to the organic carbon found in the reservoir water.

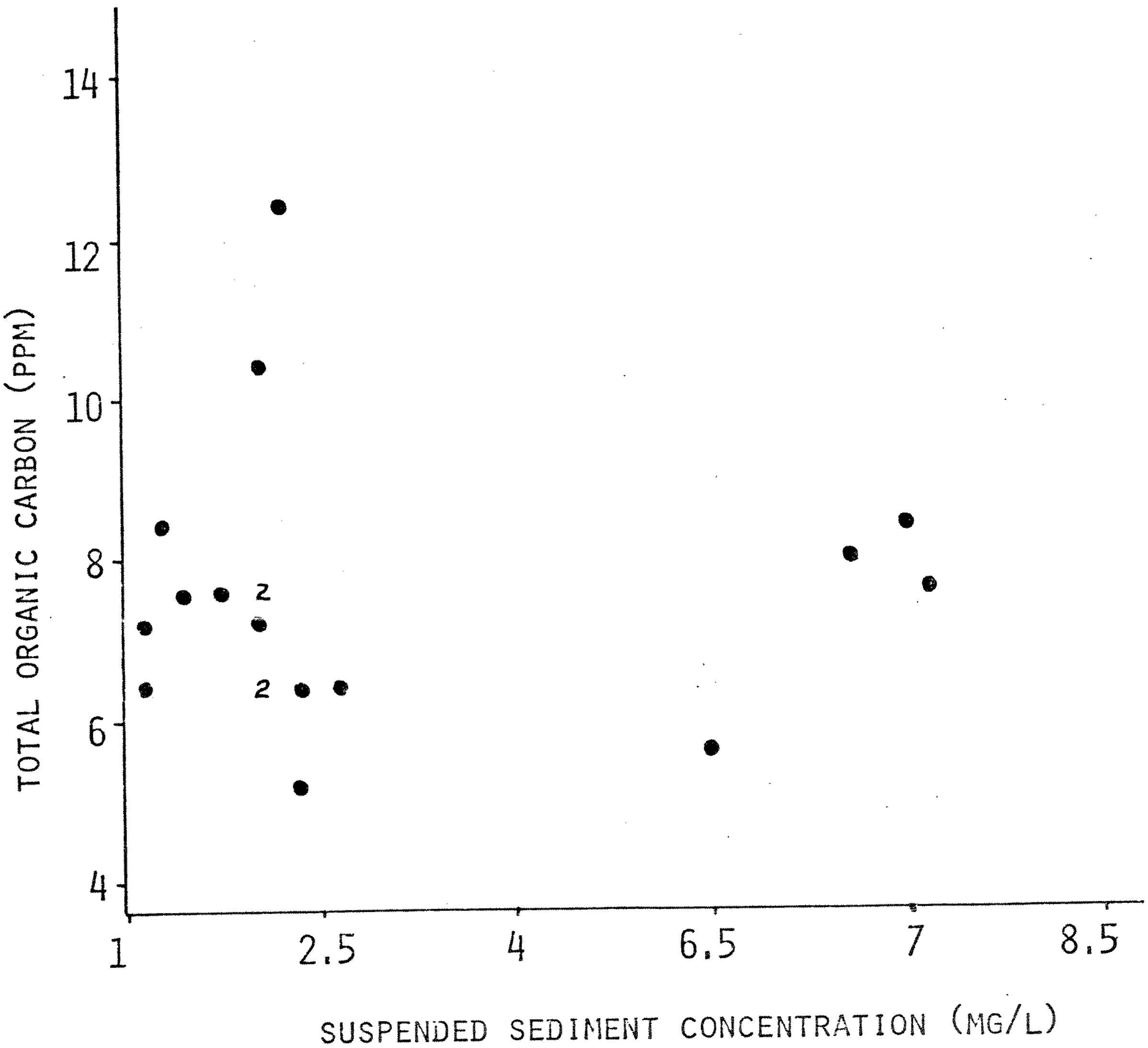



Figure 32: Boonton Reservoir Suspended Sediment Concentration versus Total Organic Carbon

Bottom Sediments

Sediments are transported into the reservoir by the river and are carried by horizontal, vertical (gravity), and turbulent forces to finally settle on the bottom or pass through the reservoir via the spillway or treatment plant intake tower. The distribution of the sediments depends on currents in the reservoir, particle size distribution of the sediment load entering the reservoir, the reservoir geometry and the water level fluctuations in the reservoir. The ability of a reservoir to retain the sediment load has been shown by Brune (1953) to be a function of the capacity-inflow ratio. Brune developed a curve that relates the percentage of sediment trapped to the ratio of reservoir capacity to the annual inflow (Fig. 33). According to Brune's curve, Boonton reservoir has a trap efficiency of 87-95%. The lower percentage refers to the efficiency if the sediment load is mostly colloidal and dispersed fine sediments. During average discharge this low efficiency value holds because the Rockaway River brings sand only during high discharge.

Wiebe and Drennan (1973) have described three zones of deposition for a reservoir: upper, intermediate and lower. The upper zone is the zone of delta formation. The intermediate zone has the fine silts and clays and colloids from the river wash load carried mainly by wave action. The lower zone holds the redeposited silts and clays eroded from the shores. Boonton reservoir has a unique distribution of its sediments because of its geometry. The river enters the reservoir after flowing over gentle falls and turning sharply southward into an arm-like appen-

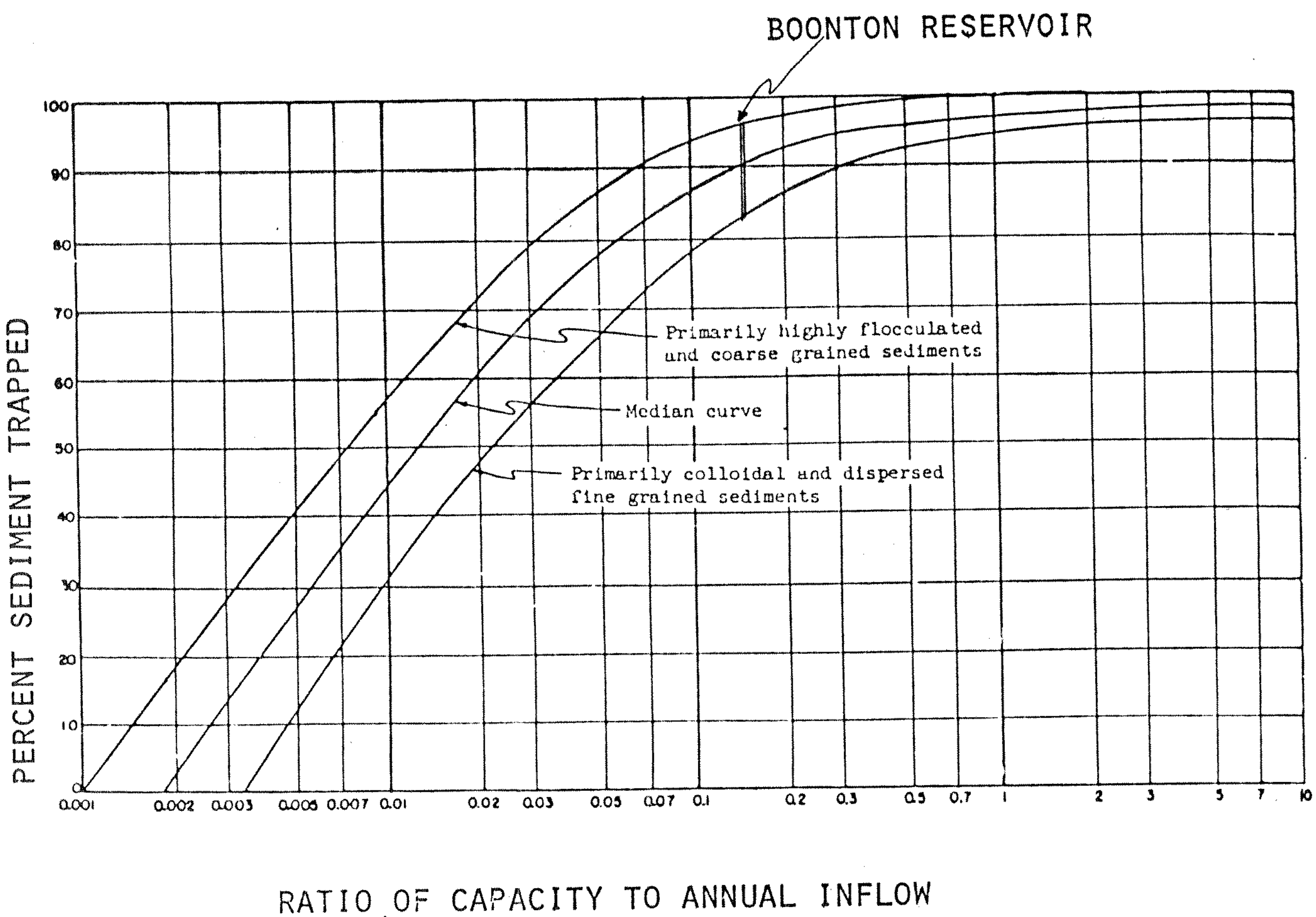



Figure 33: Trap Efficiency Graph for Reservoirs (adapted from Brune, 1944).

dage of the reservoir. Most of the sediment load is dropped here as the velocity suddenly drops, forming a delta (Fig. 34). This material is mostly coarse sands and organic rich silty clays (sapropel) deposited in coarsening upward sequences as seen in a core taken near the bridge (Fig. 27b). However, when the lake lowers during periods of low discharge, the river cuts channels into the exposed delta and moves the sediments closer to the reservoir (Plate 4). This area of deposition corresponds to Wiebe and Drennan's upper zone of deposition.

The reservoir's deeper northern portion nearest the river inlet is the site of deposition of silts and clays from the river and from shore erosion. This area of deposition corresponds to Wiebe and Drennan's lower zone of deposition. The Wiebe and Drennan intermediate zone is well developed where the waves have resuspended material from the shore. It is not well developed at the inlet area.

The shallow southern portion of the reservoir and the shores are areas of non-deposition. Here the waves and shallow water circulation leave behind sand, cobbles, and pebbles. Although the southern portion was never sampled, it was exposed for observation from September 1980 until early November 1980 and little deposition was indicated. A small intermittent stream on the western shore was judged to contribute insignificant amounts of sediment (Fig. 34).

The prevailing northwest wind direction during the winter and the southwest winds in the spring and summer are the probably cause for the paucity of 5 phi particles found on the southern shore (Fig. 35). The fetch is also longer when the winds blow from these

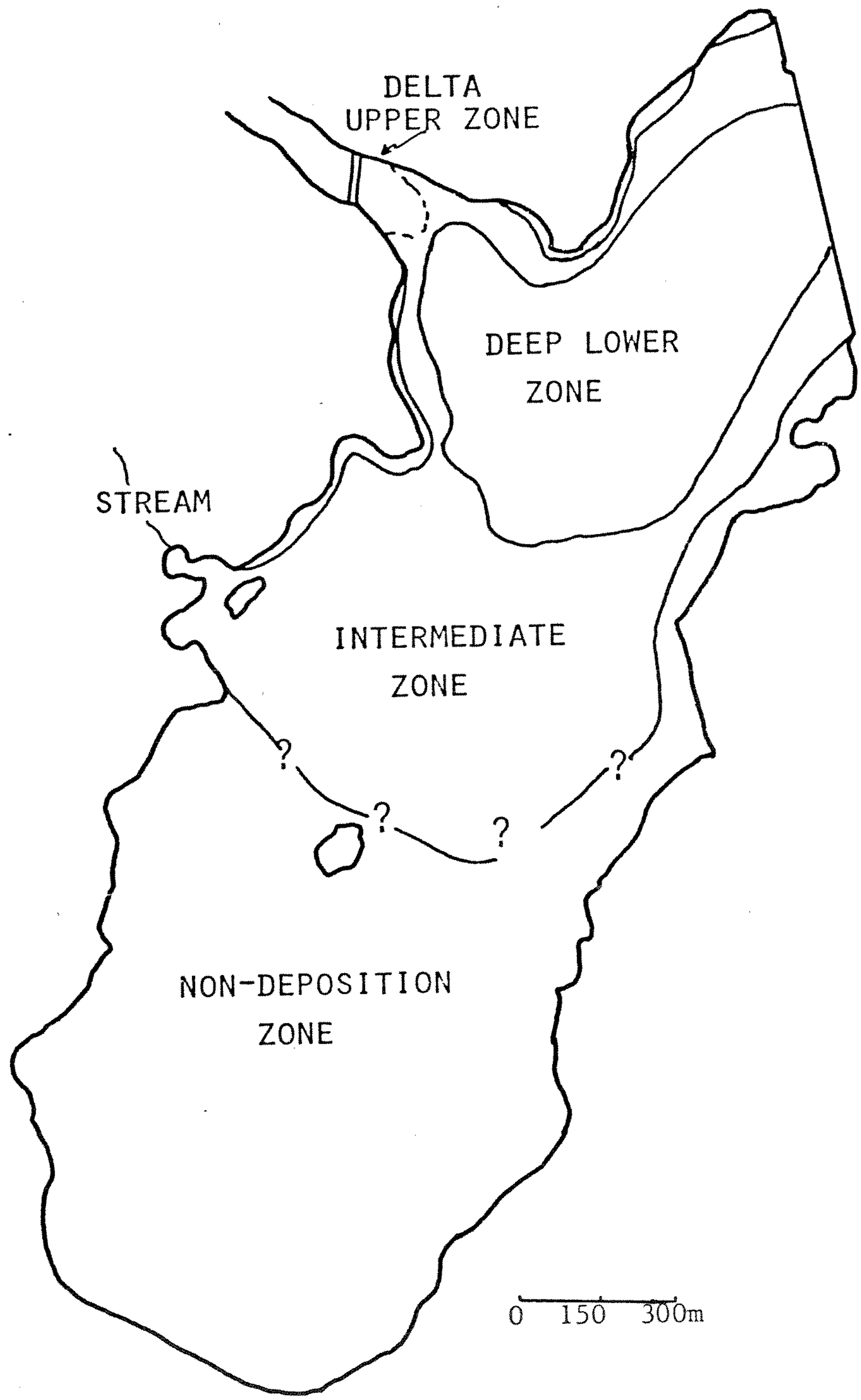



Figure 34: Depositional Zones in Boonton Reservoir

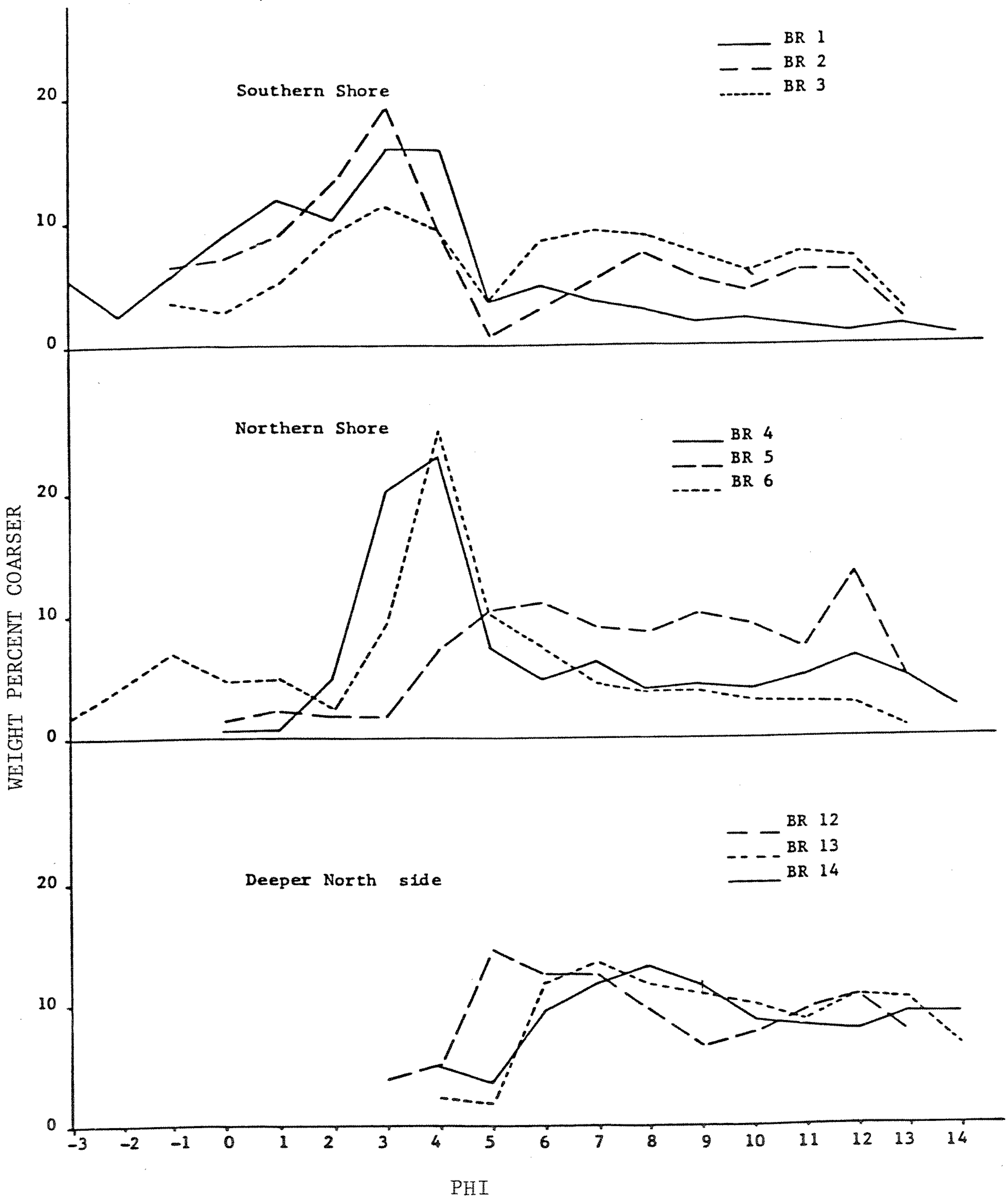



Figure 35 : Size Frequency Graphs of Bottom Samples; Locations in Figure 23.

directions than if a southeastwind blew toward the northern shore. In this area, wind-related waves are able to winnow out the silt -sized particles, while the cohesive clays and heavy sands remain (Fig. 36). The mode for this shore is 3 phi (0.125 mm).

On the northern shore sample BR 5 has a large percentage of fines because it was collected just below a small stream running down the shore-face from the woods. The mode for these samples was 4 phi (0.0625 mm).

Near the river inlet samples BR 8 and BR 9 appeared to be mirror images (Fig. 36). Samples from Trap 1 were similar to those from BR 8 because their locations were similar. The coarsest sample, BR 8, is farther away from the river but nearer to the sloping shore. Perhaps BR 9, which was nearest the delta, received the fine particles on a regular basis. BR 8 was probably receiving the coarser particles from shore runoff and erosion. Evidence in support of this explanation would be the observations of isolated coarse sand grains at the top of Core #1 taken near the BR 8 location.

BR 12 does not fit into any subenvironment, perhaps because it was collected from the outside of the sampler, resulting in the loss of some fines (Fig. 35). However, no other sample had such a high percentage of silts. The silts may have come from shore runoff, while the fines could have come from the river and the shore.

BR 13 and 14 in the deeper north side appeared similar to BR 7, 10 and 11 (Fig. 35). All of these samples were taken at intermediate distances between the shores and the lake center. It is possible that these locations were receiving sediment from both the river and the shores. Their modes are at 7-8 phi (0.0078-0.0039 mm).

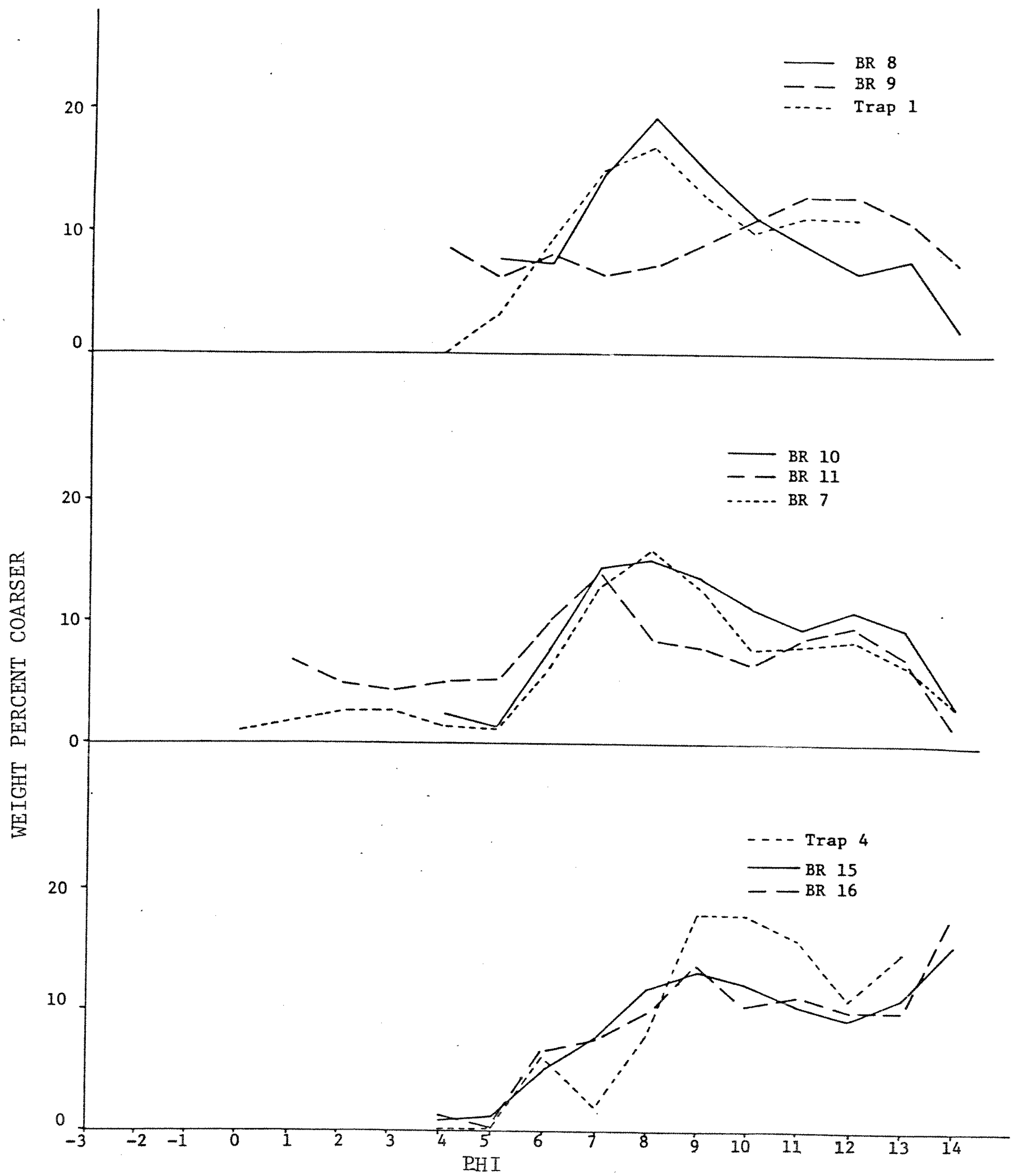



Figure 36: Size Frequency Graphs of Bottom Samples; Locations in Figure 23.

The finest samples, with modes of 14 phi, were found near the dam. Here the water is deepest (30 m) and quietest and only the smallest sized particles are able to be transported and allowed to settle. The large percentage of particles finer than 13 phi were probably deposited as floccules, as will be discussed in a later section.

Total Organic Carbon in Sediments

Carbon is found as organic matter and carbonate sediments in the bottom samples. The organic portion consists of plant and animal material. The carbonates (approximately 1% of the bottom samples) originated in the Paleozoic marbles and limestones.

Values for the percentage of organic carbon in other lakes are variable: Kemp et al. (1974) found that the top 1-2 cm of bottom samples from Lakes Huron, Erie and Ontario contained 2.3-6.3% organic carbon. Thomas et al. (1972 a ) found that in Lake Ontario organic carbon ranged from 0.46% near shore to 3% in the basins. Hyne (1978) noted that high values for organic carbon were 10-40% as found in small lakes such as Lake George and Lake Champlain. Low values of 1-3% were found in large lakes such as Lake Victoria, Lake Baikal and the Black Sea. Most lakes averaged 5% organic carbon.

Boonton Reservoir organic carbon values ranged from 0.1% near shore to 5.7% in the basin and 6.8% near the river inlet. The lowest values (0.1-0.2%) were due to subaerial exposure prior to sampling. Discounting these exposed samples, the mean TOC was 4.6% for the bottom samples.

From the organic carbon measurements and Core #2 (collected in the river inlet), it appeared that a fine clay-sized organic rich (sapropel) material is being constantly flushed into the reservoir. This organic material could be coming from the deposition and decomposition of woody and leafy material along the river and lake shores. Pieces of twigs and leaves have been observed in core #2 and layers of organic rich matter were observed in the channel walls cut into the delta following a storm. Boonton Reservoir appears to have two areas of deposition of organic matter; the river inlet and the deep basin. The inlet carbon may be dominated by allochthonous organic debris and the basin may be the final resting place for autochthonous biological material.

Authochthonous production of organic material in the reservoir has been discussed previously in the results section. It was calculated that approximately 0.8 x $10^6$g/day of organic carbon was produced in the reservoir. This figure compares well with organic carbon deposition rates calculated for the traps. The deposition rate for Trap 1 was estimated to be 1.2 x $10^6$g/day and for Trap 4, to be 1.8 x $10^6$g/day. (Table 8 ). These values are three orders of magnitude greater than the value of organic carbon calculated as preserved in the bottom sediments . Therefore, much of the organic matter must be oxidized before being incorporated into bottom sediments.

The location of organic rich sediments is important in the identification of possible pollutants (Schoettle and Friedman, 1973; Shimp et al., 1971) such as heavy metals (Pita and Hyne, 1975), since pollutants are associated with organic matter.

Bottom Sediment Textural Relationships

Relationships between textural characteristics of bottom samples reflect the physical processes of sedimentation. Correlation coefficients for depth, total organic carbon, percent sand, silt and clay, mean size and sorting are tabulated in Table 11. According to Folk (1965) correlation coefficients greater than 0.5 are geologically significant.

Although the mean size of the bottom samples correlated negatively with the sorting (r=-0.81), a T-test indicated the correlation was not significant at the 95% confidence level. The lack of correlation can best be explained by the model of Folk and Ward (1957) (Fig. 37 inset) showing that sediments occur naturally as mixtures of a gravel, a sand and a clay population and form a sinusoidal curve when the standard deviation and mean size are plotted. This study revealed a mixture of sand and clay population. The gravel population was absent because sampling did not include the shore nor the shallow end of the lake.

The sand population had a mean range of 3.5-5.5 phi and the clay population, between 7-9 phi. The sand population represents the shore's inherited grain sizes and winnowing by wave action, while the clay population represents fine sediment brought in by the river or washed into the basin from shore runoff. Thus the clay represents redeposited and transported material, while the sand population represents the material left behind.

Figure 37 also shows poor sorting in the shore samples where different hydraulic regimes interact (Fig. 37). These shore samples

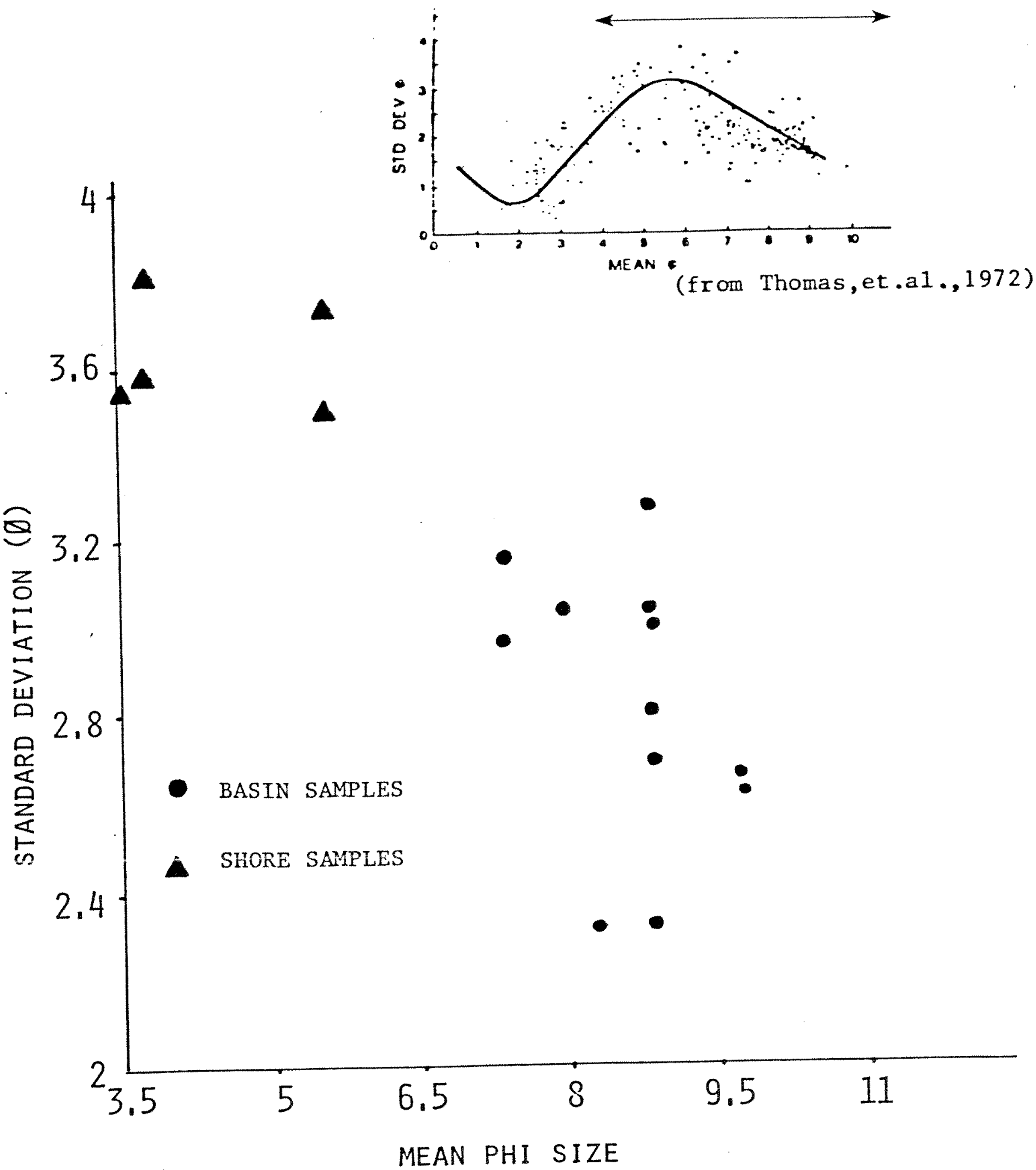



Figure 37: Boonton Reservoir Bottom Sediment Mean Size (Ø) versus Sorting (Standard Deviation in Phi units)

reflect wave action, runoff, and changes in water level, as well as quiet bottom sedimentation when the reservoir is full.

Organic carbon in the bottom sediments were positively correlated with clay size, depth and mean grain size (Fig. 38). These relationships have also been shown in lake studies by Schoettle and Friedman (1973), R. L. Thomas (1969), and Thomas et al. (1972a). Sedimentation variations within a lake are primarily controlled by the depth of the water and the distance from shore. Organic matter is of low density and fine particle size so that it tends to settle where water turbulence is low and oxidation is slow. Jenne and Wahlberg (1968) have found that organic molecules can adsorb readily to smaller particles having large surface area to weight ratios. Thus organic carbon is associated with clay-sized particles that settle in deep waters.

Thomas et al. (1972b) showed offshore trends in Lake Ontario bottom sediments on a ternary diagram of sand, silt and clay. Figure 39 is an adaptation of Thomas' figure with Boonton Reservoir's samples included. Findings from Boonton Reservoir agree with the fining offshore trend found by Thomas. In addition, Figure 40 illustrates the similar offshore trends for silt, sand, clay, mean size, and standard deviation seen in bottom samples. Those physical processes that act in large lakes appear to play a similar role in Boonton Reservoir. Wind, thermal circulation and hydraulic forces distribute the sediments and suspended sediments in this small reservoir as they would in a large lake.

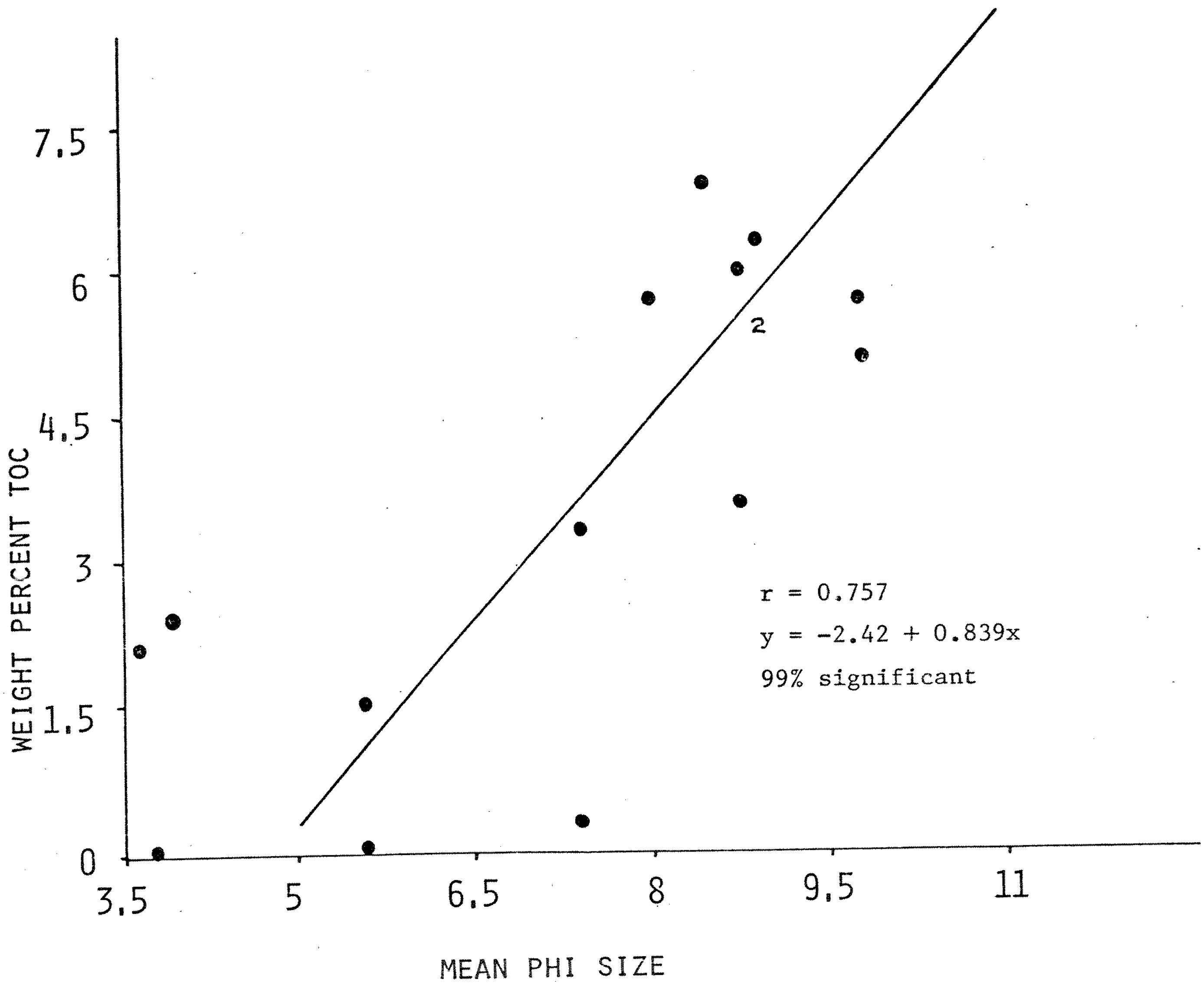



Figure 38: Boonton Reservoir Total Organic Carbon versus Mean Size of Bottom Samples

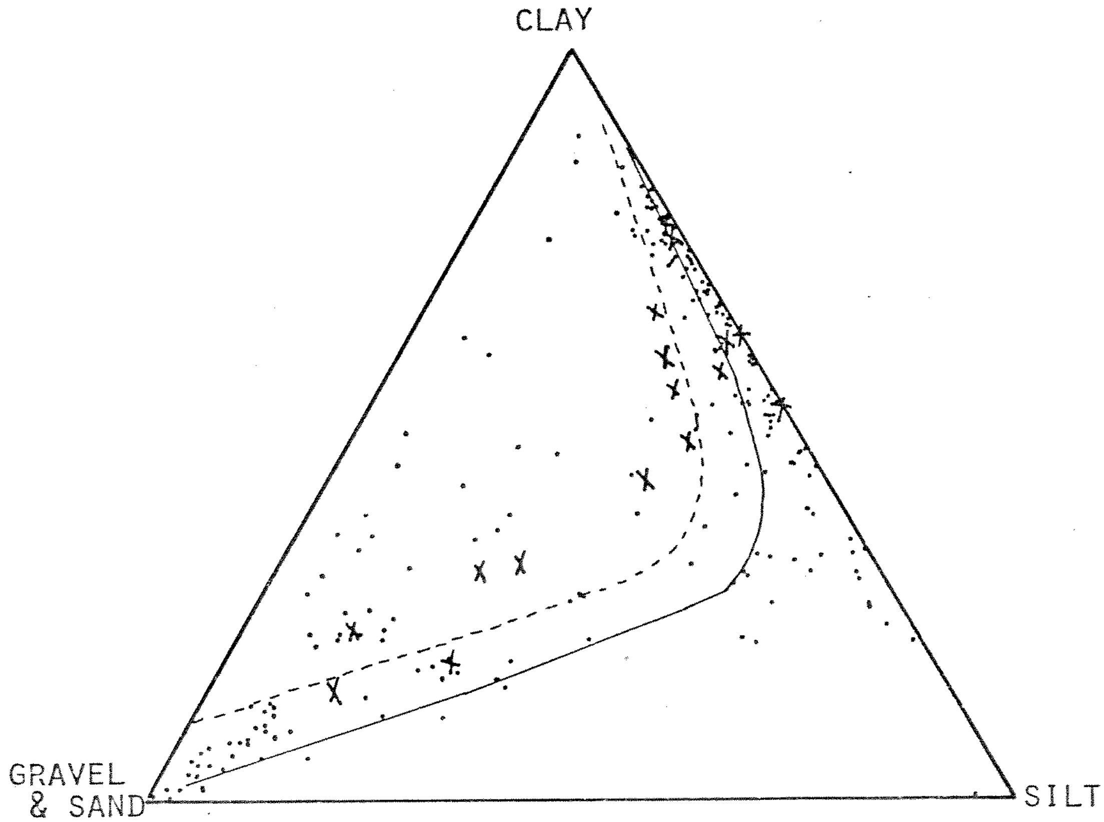



Figure 39: Sand Plus Gravel, Silt and Clay Ternary Diagram Including Boonton Reservoir Samples (X). Curve Shows Trend from Sand Population Near Shore to the Clay Population in the Basin. (Thomas et al., 1972a)

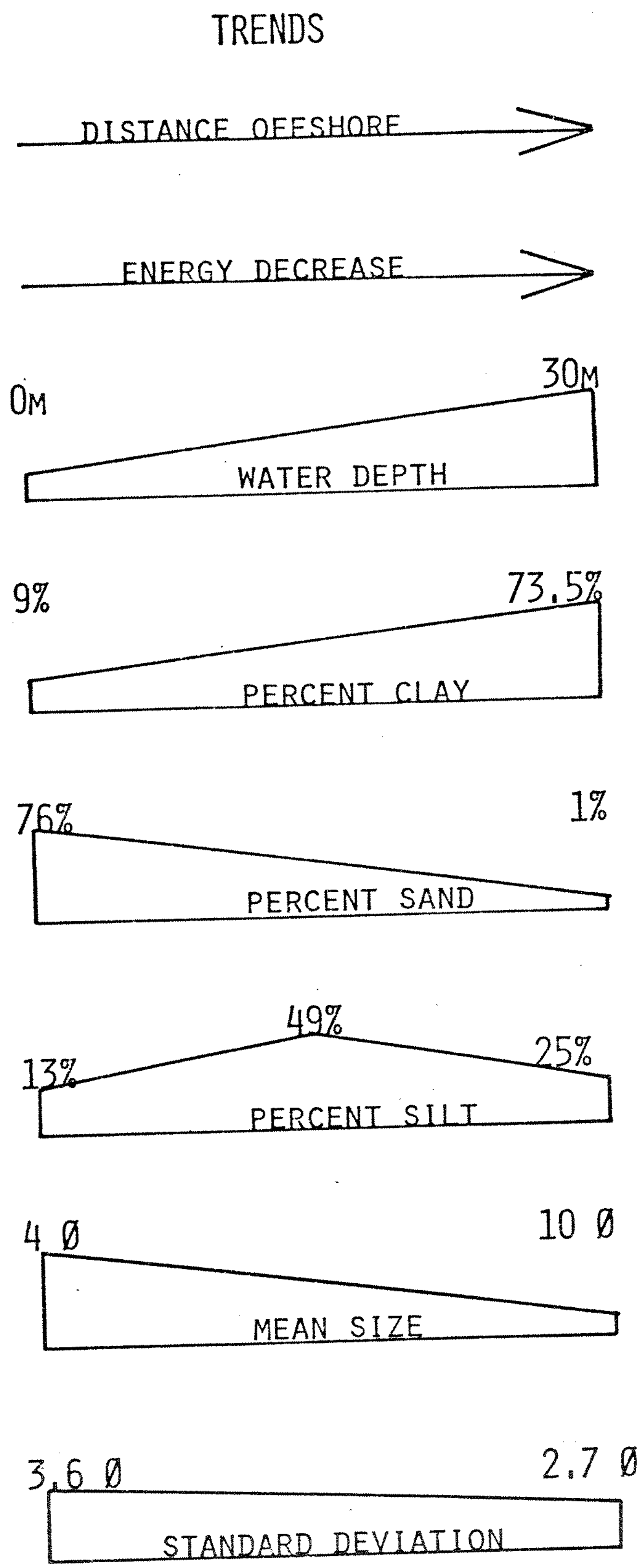



Figure 40: Offshore Textural Trends for Boonton Reservoir Bottom Samples

Sedimentation Rate

The sedimentation rate of a lake reflects the environmental conditions in the drainage basin as well as the lake itself. (Kemp et al., 1974) Environmental conditions such as climate, vegetation, urbanization and eutrophication affect the amount of sediment deposited in a reservoir. The trapping efficiency of a reservoir, as described by Brune (1953), is controlled by the capacity of the reservoir, the amount of inflow, the shape of the reservoir, and the type of outlets. A secondary factor affecting Boonton Reservoir's sedimentation rate is the presence of many upstream impoundments. Many of these ponds and reservoirs were built after Boonton Reservoir. Sedimentation may have been greater before all of the impoundments were completed.

Sedimentation rates for lakes of the world range from 0.1-10 mm/yr or 100-1000 g/$m^2$ (Lerman, 1978). Brune (1953) listed a range of 20-2190 g/$m^2$-yr for 41 reservoirs in the United States. Boonton Reservoir's calculated sedimentation rate is greater than 2190 g/$m^2$-yr. Yet the figures for those reservoirs may not be accurate today because of increased nutrient additions by man. Pennington's (1974) studies of Lake Windermere in the English Lake District have shown a doubling of the sedimentation rate since 1954. Urbanization may be part of the cause of this increase. More runoff from residential and industrial areas with less infiltration could result in increased sediment input. In addition, Pennington found that eutrophic lakes produced more organic matter and that the sedimentation rate of seston is affected by seasonal changes in the thermal conditions of the lake. Thomas (1972) and

Kemp et al. (1974) have found that sedimentation rate is affected by the depth of basins within Lakes Huron, Erie and Ontario. The sedimentation rate is greater and less variable in deep basins.

Boonton Reservoir's sedimentation rate has been studied by analyzing a core, calculating river suspended sediment entering and leaving the reservoir, and sediment trap accumulations. For reasons described below, the most accurate estimation is believed to be from the trap data.

Observations of color differences and high total organic content in core #1 indicated approximately 2.5 cm of compacted lake deposits above the pre-reservoir soil surface. This represents a sedimentation rate of 0.3mm/yr or 800 $g/m^2$-yr. However, this sedimentation rate is not considered accurate because it was difficult to identify the boundary between the lake deposits and the underlying soil and because sampling for total organic carbon in the core could only be done at centimeter intervals in order to obtain a sample large enough for testing with the LECO carbon analyzer.

Suspended sediment entering and leaving the reservoir between 7/6/81 and 8/20/81 (samples every other week) has been tabulated in Table 6. The average residual suspended sediment was found to be 679.7 kg/day or 320 $g/m^2$-yr. This value does not accurately represent annual suspended sediment accumulations in the reservoir because 1) sampling was done for only two months out of the year, 2) suspended sediment leaving the reservoir was derived from not only the Rockaway River but also from shore erosion and organic production. Shore erosion and organic production of suspended sediment was not measured. Thus, the residual suspended sediment represents a minimum value for suspended sediment deposited in the reservoir.

Shore erosion in the form of terraces was observed in the fall of 1980 as the water level receded. They were approximately 5 cm high by 2 cm wide. The perimeter of the reservoir in the northern half of the reservoir is 3 km . The formation of terraces could represent a volume of 3 cubic meters (10 g/m$^2$) of sediment eroded from the shores and deposited in the reservoir each time the level changes. The lake level changed frequently, especially during the low flows of summer. During October 1980, the lake level dropped 8 meters and approximately two terraces were formed per 30 centimeters of water level decrease. The sediment volume eroded would have been approximately 540 g/m$^2$, a substantial amount of sediment. Thomas (1972) indicated that 45% of Lake Ontario sedimentation was derived from shore erosion.

Sedimentation rates calculated from the traps set in Boonton Reservoir have certain limitations: 1) it is not known how much seston may have entered the traps during their deployment, 2) it is not known how much seston was contributed to the traps by organic production on the trap walls. However, these sedimentation rates are believed to be valid because the shape and size of the trap have been selected for accuracy. According to Gardner (1980a&b) cylindrical shapes trap particles at a rate closest to the controlled sedimentation rate in a flume. He also found that cylinders with a height to width ratio of 2.3 were the most accurate and that a ratio of greater than 3 would trap a greater percentage of fines.

The trap used in this study had a height to width ratio of 2.05.

Trap #1 sediments represented an accumulation of 1.2 mm/yr ($3266\ g/m^2$-yr) and Trap #4 represented 0.84 mm/yr ($2226\ g/m^2$-yr). These calculations were performed with dry sediment weight and zero porosity. These sedimentation rates have been calculated over the area of the deep, northern portion of the reservoir. It is believed that because of the river's location near the dam and the predominant wind directions, suspended sediment is not able to disperse into the shallow southern end. A sedimentation rate of 3266-2226 $g/m^2$-yr or 1 mm/yr is believed to represent a maximum sedimentation during the summer in the northern portion of Boonton Reservoir because of the proximity of the traps to the river inlet.

Cesium 137 was not employed as a technique for calculating sedimentation rates because the sediments contained only small quantities. Krishnaswami and Lal (1979) pointed out that bioturbation is an important factor in radioisotope distribution in sediments. Boonton Reservoir has fresh water bivalves that may redistribute the Cesium 137, thus eradicating any peak value that would correspond to the onset of nuclear testing.

## Circulation and Particle Transport

The circulation of suspended sediments in the reservoir is dependent upon temperature of the river and reservoir, the density of the water and sediment particles, and river discharge variations (Wiebe & Drennan, 1973; Serruya, 1974). Figure 41 shows the settling time and depths for particles 7-10 phi as calculated using Stoke's Law. The calculations were made with the following assump-

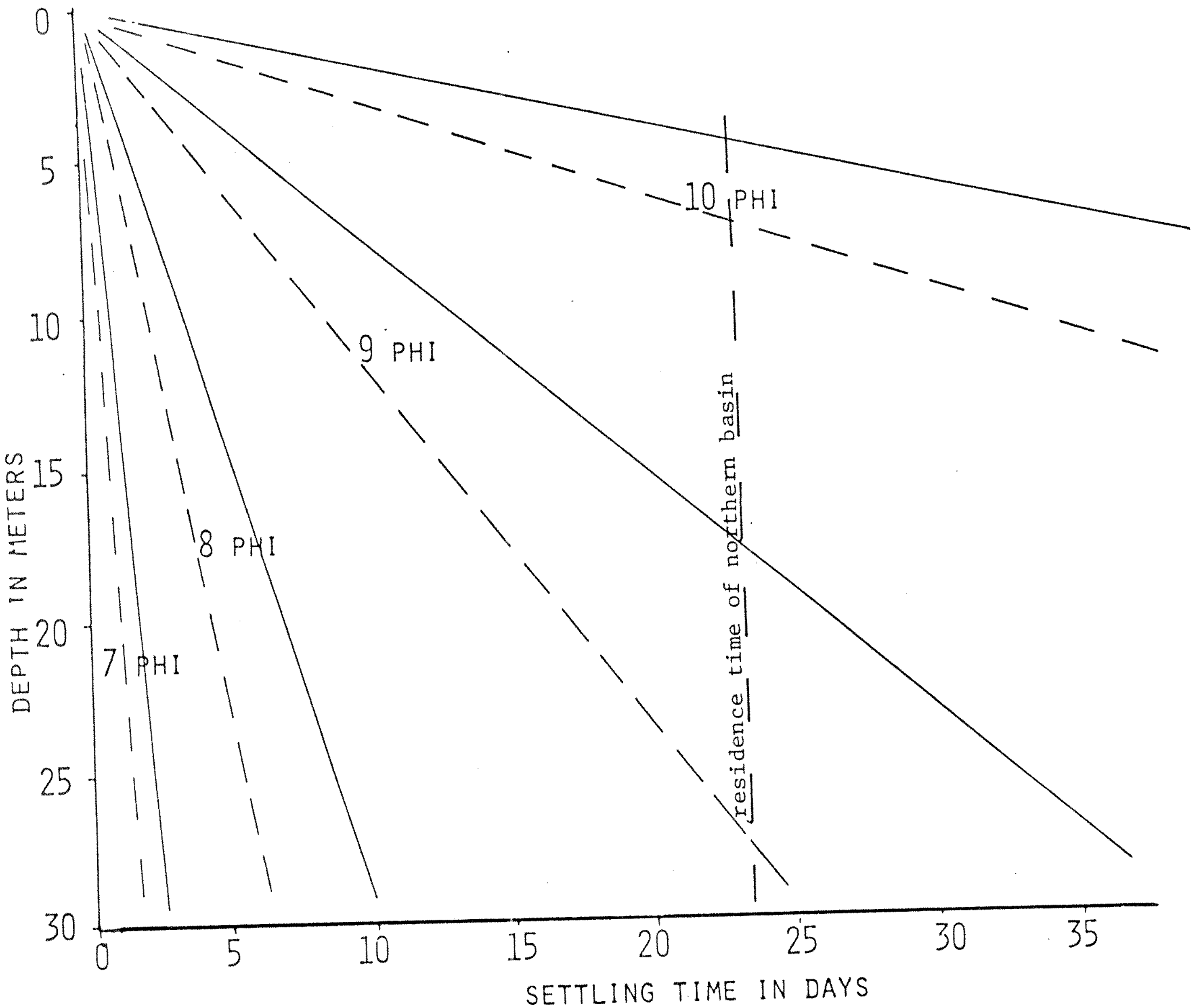



Figure 41: Settling Time for Clay-Sized Particles in Boonton Reservoir for 4.5°C (——) and 20°C (---).

tions: 1) particles were 2.65 g/cm$^3$, 2) the water temperature was homogeneous; and 3) there were no currents in the reservoir. If one considers the residence time of the whole lake basin as 52 days (Wagner, 1979), the 10 phi and finer sized particles will never settle. If one considers sedimentation from the river discharge occurring only in the northern portion of the reservoir with a volume of 13.3 x $10^6$m$^3$(average depth of 17 m), then the residence time is reduced to about 24.2 days. If this is true, particles 9 phi and finer will not settle. However, the size distributions of bottom sediments record particles finer than 9 and 10 phi. This finding provides evidence that particles finer than 9 phi form floccules that can settle to the bottom. The average size of the floccule seen on the SEM is between 6-7 phi (approximately 8-15 microns). Using Sherman's (1953) density calculation of 1.5 g/cm$^3$ for 6-7 phi floccules made up of particles 3 microns in diameter, the settling time would be between 1 and 5 days. Three microns was chosen because it represents the moment mean size for those bottom samples found in the deeper portions of the reservoir.

Stratification in the reservoir can have an effect on the settling of suspended sediment. If a settling particle with a density of 2.65 g/cm$^3$ encounters a 10$^\circ$C difference while passing from the epilimnion to the metalimnion, its velocity, according to Stoke's Law, would decrease by 25 percent. This temperature gradient can be seen during stratification in Boonton Reservoir. However, if one considers that a large percentage of the particles suspended in the lake are floccules, then a density of 1.5 g/cm$^3$ could be used in the calculations (Sherman, 1953). The settling velocities would be 1/3 of those for particles and thus might be affected to a greater degree by epilimnetic circulation.

During high discharge the river flow may be channelized in the lake. A transport time across the lake of 14 hours during high discharge was measured by A. Wicklund using copper sulfate dropped into the river inlet. The volume of water brought into the reservoir during this event was calculated to be $2.4 \times 10^6$ $m^3$, while the volume of the northern end of the reservoir is $13.3 \times 10^6$ $m^3$. This high flow was not sufficient to displace the entire volume of the northern end and yet copper sulfate was detected as coming out of the dam after 14 hours. The flow from the river inlet must have been channelized near the surface and directed toward the dam. This channelized flow creates an effective residence time shorter than the normal residence time. This type of circulation is important in the understanding of the distribution of suspended sediment within the reservoir. More studies similar to this one should be done during additional storm events, as well as during normal river flow. During events like these, all particles 7 phi and finer would be transported to the treatment plant. The laboratory technicians at the Jersey City Water Treatment Plant have noted the higher concentrations of suspended sediment during rainstorms (verbal communication, Al Dzydzora).

In order to better describe the circulation in Boonton Reservoir, detailed temperature and dissolved oxygen measurements should be made throughout the water column at least every other day during a rainy season and every other week during seasonal changes of the thermal stratification. The measurements should be taken along traverses paralleling the dam. It has been observed in other studies (Gilbert, 1973), that the thermocline can become depressed or partially destroyed during a high river discharge. In addition, the dissolved oxygen record should indicate where the oxygenated river water enters the reservoir. The location of the intake to the treatment plant 7.6 meters below the water surface is very near the thermocline during the late summer and thus could act to draw the warm river's discharge above the thermocline resulting in a short effective residence time.

Another means to study the reservoir circulation would be to take transmissivity measurements near the river inlet to detect over-, inter- or under-flow. Transmissivity could also provide more information concerning suspended sediment concentrations in the water column when the lake is stratified.

A more complex method of determining the circulation would be to deposit copper sulfate at the river inlet or in the shallow southern end of the reservoir. Samples every two or four hours would be taken in the lake, at the gatehouse and at the spillway to determine residence time and circulation pattern. It is important to remember that such an experiment is dependent upon the river discharge, reservoir thermal stratification and wind direction.

# CONCLUSIONS

## Rockaway River

The Rockaway River mean annual discharge has been variable since records began in 1940. Discharge has ranged from 105.6 $m^3/s$ to 27.4 $m^3/s$. The average daily discharge during this study was low (3.7 $m^3/s$) compared to past records.

Rockaway River water samples collected during this study had suspended sediment concentrations (mean = 3.65 mg/l) and total organic carbon values (mean =7.76 mg/l) similar to those contained in past records. No correlation was found between suspended sediment concentration and river discharge nor between TOC and discharge. The average suspended sediment load during this study was $1.25 \times 10^6$ g/day.

Suspended sediment from a storm of moderate intensity (2.1 $m^3/s$) was devoid of sand and contained less than 30% clay-sized particles. The lack of sand and the lack of correlation between discharge and suspended sediment can be explained by the presence of many impoundments in the Rockaway River drainage system. Over 75% of the drainage area contains reservoirs, lakes, or ponds which act as sediment traps.

Suspended sediment from the Rockaway River as seen with the SEM is composed of floccules, mica, diatoms and biota parts.

## Boonton Reservoir

Boonton Reservoir has summer stratification, winter and spring mixing and has an ice cover during January and February. During stratification the hypolimnion is anoxic. During mixing the lake is at least 80% saturated with dissolved oxygen. It is considered to be a mesotrophic reservoir because of its low concentration of dissolved oxygen during the summer and high biological production within the lake.

During this study, the total organic carbon in the reservoir averaged 7.5 ppm. Algal production during the summer is high and can contribute approximately 1 x 10  g/day to the bottom sediments.

The composition, distribution and rate of deposition of Boonton Reservoir sediments reflect the Rockaway River input and lake processes. The mineralogy reflects the Precambrian gneisses and schists and Pleistocene glacial drift found in the drainage basin. The total organic carbon found in the bottom grab samples was comparable to other lake studies (3.8%). Production by lake biota contribute much organic carbon but negligible amounts are incorporated into the sediments.

The distribution of bottom sediments showed trends with depth. As hydraulic energy decreases offshore, the percentage of sand decreases, and clay and organic carbon increase. The sorting is poor throughout the basin yet increases slightly toward the center of the basin.

The sediments are a mixture of a sand and clay population. The sand population represents lag deposits winnowed by the wind and waves near the shore. The clay population is represented by the fine sediments deposited in the deep basin by settling of suspended particles.

Sediments are distributed in three zones of deposition: 1) the deltaic zone with coarse sands to silts interlayered with organic rich silts and clays, 2) the intermediate zone with silts and clays redistributed from the river and shores, and 3) the deep lower zone where fine suspended sediment with modes of 14 phi settled. Boonton Reservoir has a zone of non-deposition near the shores where waves winnow the fines and in the shallow areas that are repeatedly exposed during lake fluctuations.

Total organic carbon is associated with clay and silts and thus was found to increase in bottom sediments as the depth increased. There were two zones of organic deposition: 1) the inlet where allochthonous organics concentrated and 2) the basin where autochthonous organics settled. Bottom sediments contained an average of 4.6% total organic carbon. The total organic carbon found to settle in the sediment traps was 45-64% because the matter had not been incorporated into bottom sediments where bottom fauna could oxidize it.

The rate of deposition as determined by two traps was 0.84 - 1.2 mm/yr. This is comparable to other large lake studies. The trapping efficiency of Boonton Reservoir is 83-95%. Deposition of sediments probably occurs mostly in the northern deep end of the reservoir because the shallow end has no significant input of sediment.

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# APPENDIX

Table 5: Temperature and Dissolved Oxygen Measurements from Boonton Reservoir

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station 1 -- Center of Dam - October 3, 1980 | | |
| 1 | 18.9 | 9.1 |
| 5 | 18.4 | 6.5 |
| 10 | 16.4 | 3.0 |
| 14.5 | 7.8 | 0.0 |
| 12 | 7.8 | 0.1 |
| 10 | 10.0 | 0.0 |
| 5 | 17.8 | 7.4 |
| 6 | 17.2 | 6.6 |
| 7 | 17.2 | 6.4 |
| 8 | 17.2 | 6.1 |
| 10 | 14.0 | 0.4 |
| 11 | 8.2 | 0.1 |
| 12 | 7.1 | 0.1 |
| 14 | 6.7 | 0.1 |
| Station 2 -- 100m from Center of Dam | | |
| 0 | 18.5 | 9.2 |
| 1 | 18.5 | 9.2 |
| 5 | 18.4 | 8.1 |
| 6 | 17.8 | 6.6 |
| 7 | 17.1 | 6.2 |
| 8 | 17.0 | 5.9 |
| 9 | 16.9 | 5.5 |
| 10 | 13.5 | 0.6 |
| 11 | 10.5 | 0.2 |
| 12 | 8.8 | 0.1 |
| 13 | 7.8 | 0.1 |
| Station 3 -- Center of Reservoir in Front of Inlet | | |
| 0 | 18.2 | 9.5 |
| 1 | 18.2 | 9.5 |
| 5 | 18.1 | 8.2 |
| 7 | 18.1 | 7.2 |
| 8 | 18.1 | 6.8 |
| 9 | 18.0 | 0.2 |
| 10 | 18.0 | 0.2 |
| Station 4 -- Closer to the Inlet than Station 3 | | |
| 0 | 18.5 | 9.7 |
| 5 | 18.5 | 8.1 |
| 8 | 18.0 | 7.3 |
| 9 | 17.5 | 6.9 |
| 10 | 14.7 | 0.3 |
| 11 | 10.5 | 0.1 |
| Station 5 -- Near the Island | | |
| 0 | 19.0 | 9.5 |
| 5 | 18.9 | 7.8 |

Table 5: continued

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station BR 14a -- May 18, 1981 | | |
| 0 | 16.0 | 9.9 |
| 1 | 16.5 | 10.0 |
| 2 | 16.2 | 10.0 |
| 3 | 16.0 | 9.4 |
| 4 | 16.0 | 9.0 |
| 5 | 15.5 | 8.7 |
| 6 | 15.0 | 8.2 |
| 7 | 15.0 | 7.8 |
| 8 | 15.0 | 7.6 |
| 9 | 14.0 | 7.4 |
| 10 | 13.0 | 7.0 |
| 11 | 12.5 | 6.8 |
| 12 | 12.0 | 6.8 |
| 13 | 11.5 | 6.7 |
| 14 | 11.2 | 6.4 |
| Station 1 -- Near the Dam - June 16, 1981 | | |
| 0 | 26.5 | 8.1 |
| 2 | 23.0 | 7.8 |
| 3 | 22.5 | 7.2 |
| 4 | 22.0 | 7.0 |
| 5 | 21.0 | 6.3 |
| 6 | 20.5 | 5.7 |
| 7 | 19.0 | 4.7 |
| 8 | 16.5 | 3.8 |
| 9 | 15.0 | 3.7 |
| 10 | 14.5 | 3.0 |
| 11 | 13.5 | 2.8 |
| 12 | 13.0 | 3.0 |
| 13 | 12.5 | 2.6 |
| 14 | 12 | 1.9 |
| Station 2 -- June 16, 1981 | | |
| 0 | 26.5 | 8.1 |
| 2 | 26.0 | 7.8 |
| 3 | 26.0 | 7.8 |
| 4 | 23.0 | 7.0 |
| 5 | 22.0 | 6.7 |
| 6 | 22.0 | 6.5 |
| 7 | 20.5 | 5.4 |
| 8 | 18.5 | 4.2 |
| 9 | 15.5 | 3.6 |
| 10 | 14.5 | 3.0 |
| 11 | 13.8 | 3.4 |
| 12 | 13.0 | 3.6 |
| 13 | 12.0 | 3.2 |
| 14 | 11.5 | 3.0 |

Table 5: continued

| Depth (m) | Temperature ($^{o}C$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station BR 12 -- Between the Island and Northern Shore - Sept. 10,1981 | | |
| 0 | 21.9 | 9.0 |
| 1 | 21.9 | 8.9 |
| 2 | 21.9 | 8.8 |
| 3 | 21.8 | 8.8 |
| 4 | 21.5 | 7.5 |
| Station BR 13 -- Near Inlet and Northwest Shore | | |
| 0 | 21.8 | 9.2 |
| 1 | 21.8 | 9.0 |
| 2 | 21.6 | 9.0 |
| 3 | 21.5 | 8.9 |
| 4 | 21.4 | 8.9 |
| 5 | 21.2 | 8.6 |
| 6 | 21.1 | 8.2 |
| 7 | 21.0 | 7.8 |
| 8 | 20.5 | 7.3 |
| 9 | 20.0 | 7.5 |
| 10 | 19.3 | 7.4 |
| 11 | 17.8 | 2.2 |
| 12 | 14.9 | 0.1 |
| 13 | 13.2 | 0.1 |
| 14 | 10.9 | 0.1 |
| 15 | 9.8 | 0.1 |
| 16 | 8.9 | 0.2 |
| 17 | 8.7 | 0.4 |
| Station BR 14 -- Center of Inlet | | |
| 0 | 21.8 | 9.4 |
| 1 | 21.7 | 9.2 |
| 2 | 21.7 | 9.1 |
| 3 | 21.6 | 9.0 |
| 4 | 21.3 | 8.8 |
| 5 | 21.3 | 8.4 |
| 6 | 21.1 | 7.8 |
| 7 | 20.9 | 5.1 |
| 8 | 20.7 | 4.0 |
| 9 | 20.0 | 3.2 |
| 10 | 19.0 | 0.7 |
| 11 | 17.6 | 1.0 |
| 12 | 14.8 | 0.1 |
| 13 | 13.0 | 0.1 |
| 14 | 10.9 | 0.1 |
| 15 | 9.1 | 0.2 |
| 16 | 8.3 | 0.2 |
| 17 | 7.9 | 0.2 |
| 18 | 8.0 | 0.4 |
| 19 | 8.1 | 0.6 |

Table 5: continued

| Depth (m) | Temperature ($^{o}C$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station BR 15 -- Near Spillway and North Shore - Sept. 10, 1981 | | |
| 0 | 21.7 | 9.5 |
| 1 | 21.6 | 9.4 |
| 2 | 21.6 | 9.4 |
| 3 | 21.5 | 9.1 |
| 4 | 21.5 | 9.0 |
| 5 | 21.3 | 8.9 |
| 6 | 21.2 | 8.3 |
| 7 | 21.0 | 6.5 |
| 8 | 20.9 | 5.6 |
| 9 | 20.3 | 5.1 |
| 10 | 19.4 | 0.2 |
| 11 | 18.0 | 0.1 |
| 12 | 15.7 | 0.1 |
| 13 | 13.0 | 0.1 |
| 14 | 10.9 | 0.1 |
| 15 | 9.9 | 0.2 |
| 16 | 9.5 | 0.3 |
| 17 | 9.5 | 0.4 |
| Station BR 16 -- In Front of Dam | | |
| 0 | 21.7 | 10.4 |
| 1 | 21.7 | 10.5 |
| 2 | 21.6 | 10.4 |
| 3 | 21.6 | 10.2 |
| 4 | 21.6 | 10.2 |
| 5 | 21.4 | 10.0 |
| 6 | 21.3 | 10.2 |
| 7 | 21.0 | 9.5 |
| 8 | 20.7 | 9.0 |
| 9 | 20.2 | 6.5 |
| 10 | 18.8 | 0.2 |
| 11 | 17.2 | 0.1 |
| 12 | 14.8 | 0.1 |
| 13 | 12.9 | 0.1 |
| 14 | 10.5 | 0.2 |
| 15 | 9.2 | 0.3 |
| 16 | 8.0 | 0.2 |
| 17 | 7.5 | 0.2 |
| 18 | 6.9 | 0.2 |
| 19 | 6.7 | 0.1 |
| 20 | 6.5 | 0.2 |
| 21 | 6.5 | 0.2 |
| 22 | 6.5 | 0.2 |
| 23 | 6.5 | 0.2 |
| 24 | 6.8 | 0.2 |
| 25 | 6.9 | 0.2 |
| 26 | 7.5 | 0.5 |

Table 5: continued

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station 1b -- Intake Tower - March 23, 1982 | | |
| 0 | 5 | 13.0 |
| 1 | 4.5 | 13.2 |
| 2 | 4.5 | 13.3 |
| 3 | 4.5 | 13.4 |
| 4 | 4.5 | 13.5 |
| 5 | 4.5 | 13.4 |
| 6 | 4.5 | 13.5 |
| 7 | 4.5 | 13.6 |
| 8 | 4.5 | 13.4 |
| 9 | 4.5 | 13.4 |
| 10 | 4.5 | 13.5 |
| 11 | 4.5 | 13.4 |
| 12 | 4.5 | 13.6 |
| 13 | 4.5 | 13.5 |
| 14 | 4.5 | 13.5 |
| 15 | 4.5 | 13.6 |
| 16 | 4.5 | 13.5 |
| 17 | 4.5 | less than 1 |
| Station 2 -- Near Spillway - March 23, 1982 | | |
| 0 | 5 | 13.1 |
| 1 | 4.5 | 12.8 |
| 2 | 4.5 | 13.1 |
| 3 | 4.5 | 13.1 |
| 4 | 4.5 | 12.9 |
| 5 | 4.5 | 13.0 |
| 6 | 4.5 | 12.9 |
| 7 | 4.5 | 12.9 |
| 8 | 4.5 | 12.8 |
| 9 | 4.5 | 12.7 |
| 10 | 4.5 | 12.6 |
| 11 | 4.5 | 12.6 |
| 12 | 4.5 | 12.3 |
| 13 | 4.5 | 12.3 |
| 14 | 4.5 | 12.2 |
| 15 | 4.5 | 12.3 |
| 16 | 4.5 | 12.4 |
| 17 | 4.5 | 12.4 |
| 18 | 4.5 | 11.7 |
| 19 | 4.5 | 11.6 |
| 20 | 4.5 | 11.3 |
| 21 | 3.5 | 10.9 |
| 22 | 3.0 | 10.5 |
| 23 | 3.0 | 10.2 |
| 24 | 3.0 | 10.2 |
| 25 | 3.0 | 10.1 |
| 26 | 3.0 | 10.0 |
| 27 | 3.0 | 9.5 |
| 28 | 3.0 | 8.3 |
| 29 | 2.8 | 7.7 |
| 30 | 2.8 | less than 1 |

Table 5: continued

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station 3 -- Near River Inlet - March 23, 1982 | | |
| 0 | 5.0 | 12.8 |
| 1 | 5.0 | 12.0 |
| 2 | 4.5 | 12.2 |
| 3 | 4.5 | 12.4 |
| 4 | 4.5 | 12.4 |
| 5 | 4.5 | 12.4 |
| 6 | 4.5 | 12.4 |
| 7 | 4.5 | 12.2 |
| 8 | 4.0 | 12.0 |
| 9 | 4.0 | 11.8 |
| 10 | 4.0 | 11.8 |
| 11 | 4.0 | 11.8 |
| 12 | 4.0 | 11.6 |
| 13 | 4.0 | 11.2 |
| 14 | 3.8 | 11.1 |
| 15 | 3.8 | 10.7 |
| 16 | 3.5 | 10.7 |
| 17 | 3.4 | 10.5 |
| 18 | 3.3 | 10.5 |
| 19 | 3.2 | 10.1 |
| 20 | 3.2 | 10.1 |
| 21 | 3.2 | 10.0 |
| 22 | 3.0 | 9.5 |
| 23 | 3.0 | 9.8 |
| 24 | 3.0 | 6-7.8 |
| Station 4 -- Opposite River Inlet - March 23, 1982 | | |
| 0 | 5.0 | 12.5 |
| 1 | 4.8 | 12.4 |
| 2 | 4.5 | 12.2 |
| 3 | 4.5 | 12.2 |
| 4 | 4.5 | 12.2 |
| 5 | 4.4 | 12.4 |
| 6 | 4.4 | 12.2 |
| 7 | 4.2 | 12.4 |
| 8 | 4.5 | 12.5 |
| 9 | 4.3 | 12.2 |
| 10 | 4.3 | 12.3 |
| 11 | 4.3 | 12.2 |
| 12 | 4.3 | 12.2 |
| 13 | 4.0 | 12.3 |
| 14 | 4.0 | 11.8 |
| 15 | 4.0 | 11.5 |
| 16 | 3.5 | 11.2 |
| 17 | 3.5 | 10.7 |
| 18 | 3.3 | 11.0 |
| 19 | 3.5 | 10.5 |
| 20 | 3.5 | 10.0 |
| 21 | 3.0 | 9.1 |
| 22 | 3.0 | 7.5 |
| 23 | 3.0 | 6.2 |
| 24 | 3.0 | 6.1 |

Table 5: continued

| Depth (m) | Temperature ($^{o}C$) | Dissolved $O_2$ (ppm) |
|---|---|---|
| Station A --North Shore, Near River Inlet - April 15, 1982 | | |
| 0 | 7.0 | 12.2 |
| 1 | 6.5 | 11.6 |
| 2 | 6.5 | 11.7 |
| 3 | 6.5 | 11.8 |
| 4 | 6.0 | 11.6 |
| 5 | 6.0 | 11.4 |
| 6 | 6.0 | 11.6 |
| 7 | 6.0 | 11.2 |
| 8 | 5.5 | 11.5 |
| 9 | 5.3 | 11.4 |
| 10 | 5.2 | 11.6 |
| 11 | 5.2 | 11.3 |
| 12 | 5.2 | 11.3 |
| 13 | 5.0 | 11.1 |
| 14 | 5.0 | 11.1 |
| 15 | 5.0 | 11.1 |
| 16 | 5.0 | 11.0 |
| Station B -- Center of Basin - April 15, 1982 | | |
| 0 | 7.0 | 12.2 |
| 1 | 6.5 | 12.0 |
| 2 | 6.8 | 11.8 |
| 3 | 6.2 | 11.8 |
| 5 | 5.8 | 11.5 |
| 7 | 5.8 | 11.4 |
| 9 | 5.5 | 11.5 |
| 11 | 5.5 | 11.6 |
| 13 | 5.3 | 11.5 |
| 15 | 5.2 | 11.4 |
| 17 | 5.1 | 11.4 |
| Station C -- Near Bridge - April 15, 1982 | | |
| 0 | 9.5 | 11.2 |
| 2 | 9.0 | 10.9 |
| 3 | 8.4 | 10.6 |
| 4 | 8.0 | 10.5-11.0 |
| 5 | 7.0 | 11.2 |
| 6 | 6.7 | 11.6 |
| 7 | 6.0 | 11.4 |
| 8 | 6.0 | 10.9 |
| 9 | 5.7 | 11.1 |
| 10 | 5.5 | 11.2 |
| 11 | 5.4 | 11.2 |
| 12 | 5.2 | 11.1 |
| 13 | 5.2 | 10.9 |
| 13.5 | 5.0 | 10.7 |

Table 5: continued

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) | % Saturation |
|---|---|---|---|
| Station BR 14 -- River Inlet - April 29, 1982 | | | |
| 0 | 12.0 | 10.4 | 100 |
| 1 | 12.0 | 10.4 | 100 |
| 2 | 12.0 | 10.2 | 98 |
| 3 | 11.8 | 10.0 | 95 |
| 4 | 11.8 | 9.8 | 93 |
| 5 | 11.8 | 9.9 | 94 |
| 6 | 11.5 | 9.8 | 94 |
| 7 | 11.3 | 10.0 | 94 |
| 8 | 11.0 | 10.4 | 97 |
| 9 | 9.8 | 10.6 | 96 |
| 10 | 9.4 | 10.4 | 94 |
| 11 | 8.5 | 10.4 | 92 |
| 12 | 8.0 | 10.4 | 91 |
| 13 | 8.0 | 10.4 | 91 |
| 14 | 7.8 | 10.2 | 89 |
| 15 | 7.8 | 10.3 | 89 |
| 16 | 6.5 | 10.3 | 86 |
| 17 | 6.2 | 10.3 | 86 |
| 18 | 6.2 | 10.1 | 86 |
| 19 | 6.1 | 10.2 | 86 |
| 20 | 6.0 | 9.3-10.0 | 77-83 |
| 21 | 6.0 | 9.2 | 76 |

Table 5: continued

| Depth (m) | Temperature ($^{o}$C) | Dissolved $O_2$ (ppm) | % Saturation |
|---|---|---|---|
| Station Z -- River Inlet - April 29,1982 | | | |
| 0 | 12.8 | 9.8 | 96 |
| 1 | 12.0 | 9.0 | 86 |
| 2 | 12.0 | 9.9 | 95 |
| 3 | 12.0 | 10.0 | 96 |
| 4 | 11.8 | 10.0 | 95 |
| 5 | 11.7 | 10.0-9.8 | 94 |
| 6 | 11.5 | 10.0 | 95 |
| 7 | 11.0 | 10.2 | 96 |
| 8 | 10.8 | 10.2 | 95 |
| 9 | 10.0 | 9.7 | 89 |
| 10 | 9.2 | 9.2 | 83 |
| 11 | 8.2 | 10.3 | 90 |
| 12 | 8.0 | 10.1 | 89 |
| 13 | 8.0 | 10.2 | 89 |
| 14 | 8.0 | 10.2 | 89 |
| 15 | 7.5 | 10.4 | 90 |
| 16 | 7.0 | 10.4 | 88 |
| 17 | 6.8 | 10.3 | 87 |
| 18 | 6.8 | 10.3 | 87 |
| 19 | 6.8 | 10.2 | 86 |
| 20 | 6.3 | 10.3 | 87 |
| 21 | 6.2 | 10.2 | 85 |
| 22 | 6.1 | 10.2 | 85 |
| 23 | 6.0 | 10.2 | 85 |
| 24 | 5.8 | 10.0 | 82 |
| 25 | 5.5 | 10.1 | 83 |
| 26 | 5.2 | 10.0 | 81 |
| 27 | 5.0 | 10.0 | 81 |

Table 5: continued

| Depth (m) | Temperature ($^oC$) | Dissolved $O_2$ (ppm) | % Saturation |
|---|---|---|---|
| Station Y -- River Inlet - April 29, 1982 | | | |
| 0 | 13.0 | 10.0 | 98 |
| 1 | 12.5 | 9.9 | 96 |
| 2 | 12.2 | 10.2 | 98 |
| 3 | 12.0 | 9.6 | 92 |
| 4 | 12.0 | 10.0 | 96 |
| 5 | 12.0 | 9.9 | 95 |
| 6 | 11.8 | 10.2 | 97 |
| 7 | 11.0 | 9.9 | 93 |
| 8 | 10.5 | 10.2 | 94 |
| 9 | 10.0 | 10.1 | 92 |
| 10 | 9.2 | 9.7 | 87 |
| 11 | 8.8 | 10.0 | 89 |
| 12 | 8.0 | 10.2 | 89 |
| 13 | 7.8 | 10.1 | 88 |
| 14 | 7.1 | 10.2 | 87 |
| 15 | 6.9 | 10.1 | 87 |
| 16 | 6.5 | 10.1 | 85 |
| 17 | 6.2 | 9.0 | 82 |
| 18 | 6.0 | 9.6 | 79 |
| Station X -- River Inlet - April 29, 1982 | | | |
| 0 | 13.0 | 10.0 | 98 |
| 1 | 12.8 | 9.8 | 96 |
| 2 | 12.2 | 10.2 | 98 |
| 3 | 12.2 | 10.0 | 96 |
| 4 | 12.0 | 9.8 | 94 |
| 5 | 12.0 | 9.5 | 91 |
| 6 | 12.0 | 9.7 | 93 |
| 7 | 12.0 | 9.7 | 93 |
| 8 | 12.0 | 9.7 | 93 |
| 9 | 11.0 | 10.2 | 96 |
| 10 | 11.0 | 10.2 | 96 |
| 11 | 10.3 | 10.4 | 96 |
| 12 | 9.3 | 10.4 | 94 |
| 13 | 8.7 | 10.3 | 91 |
| 14 | 8.0 | 9.6 | 84 |
| 15 | 7.9 | 10.2 | 89 |
| 16 | 7.5 | 10.2 | 88 |
| 17 | 7.0 | 10.4 | 88 |
| 18 | 7.0 | 10.2 | 87 |
| 19 | 6.8 | 10.2 | 86 |
| 20 | 6.5 | 10.4 | 87 |
| 21 | 6.0 | 10.1 | 84 |
| 22 | 5.5 | 9.8 | 80 |