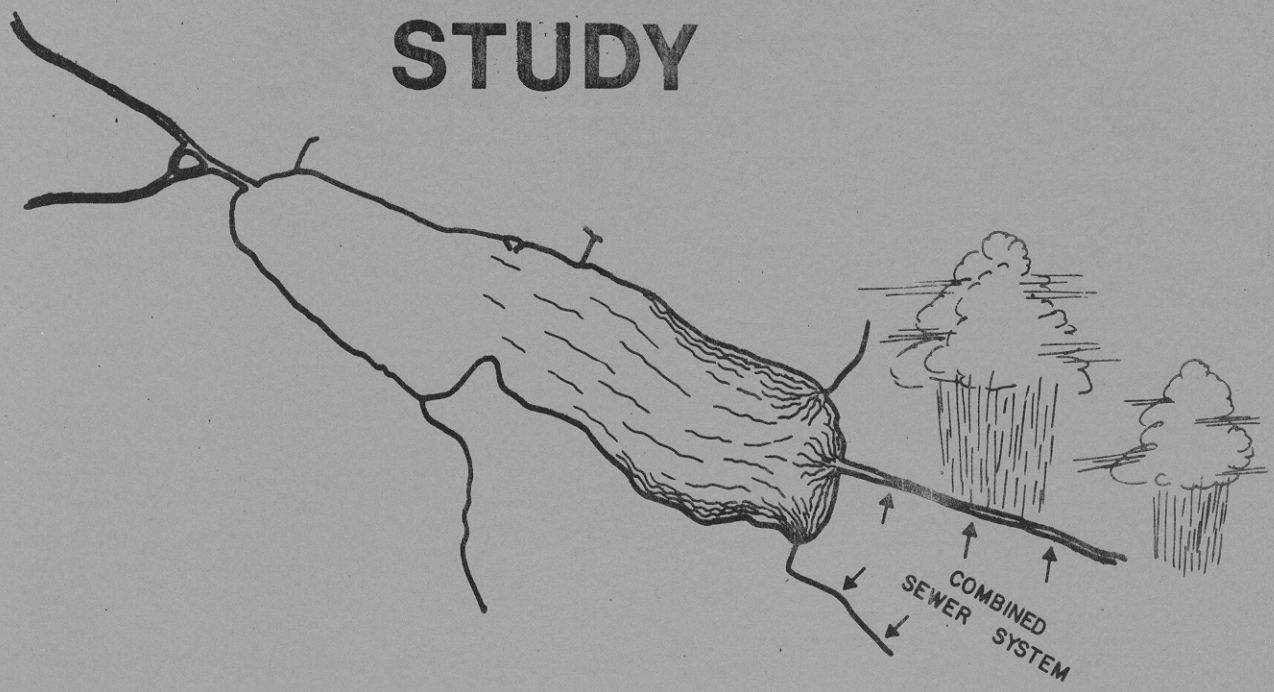
# ONONDAGA LAKE STORMS IMPACT STUDY




**Onondaga County, New York**
**Department Of Drainage and Sanitation**

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**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS
CAZENOVIA, NEW YORK · DARIEN, CONNECTICUT

**AUGUST 1979**

# REPORT ON STUDY OF THE IMPACT OF STORMS ON ONONDAGA LAKE

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August 1979

835

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

CAZENOVIA, NEW YORK DARIEN, CONNECTICUT
Reply to 10 Albany Street, Cazenovia, N.Y. 13035 (315) 655-8161

September 28, 1979

Re: Onondaga Lake Storms
Impact Study
Our File No. 835

Onondaga County Department of
Drainage and Sanitation
125 Elwood Davis Road
North Syracuse, New York 13212

Attention: Mr. John J. Hennigan, Jr., P. E., Commissioner

Gentlemen:

We are pleased to submit, herewith, our final report on the impact of storms on Onondaga Lake. This study was conducted to determine the physical, chemical, and biological response of the lake to various storm conditions. Its ultimate purpose was to provide the basis for the abatement of combined sewer overflows from the service area of the Metropolitan Syracuse Treatment Plant. The major tasks and essential findings of the study can be summarized as follows:

## Summary

Ten lake sites and all the major tributaries to the lake were monitored for various water-quality parameters prior to, during, and following each of a number of rainstorms. Each lake site was measured at two depths to represent epilimnic and hypolimnic waters. Adverse impact on lake water quality, as measured by coliform density, was observed in all five of the storms monitored. Their impact on dissolved oxygen was apparent but not significant.

These data were used as the basis for developing and calibrating a detailed mathematical model representing bacteria, dissolved oxygen, and phosphorus as the essential pollutant parameters. The model was used as a tool to predict the water-quality impact of a wide range of storm conditions.

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Under future Metropolitan Sewage Treatment Plant operating conditions, contravention of the lake's bacterial standards will occur even during such relatively moderate storms as those having less than a one-year recurrence interval. The calculated time for the lake to recover to levels of 200 fecal coliforms per milliliter is 3.5 days for a one-year storm.

On the other hand, dissolved oxygen impact will be minimal under storm conditions: A maximum deficit of 2.8 milligrams of dissolved oxygen per liter will occur under conditions of minimal reaeration and dilution for a storm as severe as one having a ten-year recurrence interval. Although this deficit in and of itself will not cause contravention of the dissolved-oxygen standards for the lake, contravention is still projected to occur in the future because of the periodic die-off of the algae standing crop. Contributions of algae-stimulating phosphorus from combined sewer overflows will be negligible when compared to future dry-weather loads from the treatment plant and non-point sources.

In order to assure the use of Onondaga Lake for contact recreation, abatement of the bacterial pollution caused by combined sewer overflows during storms will be required. Improvement of the lake with respect to fishlife and algae conditions will depend on the abatement of dry-weather point sources and upstream non-point sources.

## Acknowledgments

The success of this project is attributed to the cooperative efforts of all parties involved. Limnotech, Inc., performed the mathematical modeling of the lake. John M. Karanik, Deputy Commissioner, and Randy Ott, Project Engineer, of the Onondaga County Department of Drainage and Sanitation offered valuable comments throughout the study. John C. Byron and Steven W. Effler served as Project Manager and Project Engineer, respectively, for Stearns & Wheler.

We appreciate the opportunity to have been of service to the County of Onondaga and remain available for any questions you may have on this matter.

Respectfully submitted,

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# CHAPTER I

## INTRODUCTION

Onondaga Lake, located on the northern edge of the City of Syracuse in Onondaga County, New York, has a surface area of 11.7 square kilometers (4.5 square miles), a shoreline of 18 kilometers (11 miles), and a maximum depth of 20.5 meters (67 feet) (Figure 1). The lake, because of its proximity to the City of Syracuse and its largely undeveloped shoreline, has a great potential to the community as a recreational resource. Historically, however, the lake has acted as the receiving water for a majority of the domestic and industrial wastewaters generated in the Syracuse metropolitan area. Specifically, the following sources have contributed to the pollutant load of the lake:

1. Sewage effluents from municipal treatment facilities providing only a primary to intermediate degree of treatment.
2. Industrial wastewaters from a specialty steel manufacturer.
3. Chemical and thermal discharges from a chloro-alkali manufacturer.
4. Storm-related combined sewer overflows (CSO) from the City system.
5. Dry weather discharges from the combined sewer system.

As a result of these waste inputs, the present water quality of the lake severely limits its usefulness for recreational purposes.

A baseline limnological and engineering evaluation of the lake was performed in 1968-1969 (1). The lake was characterized at that time and still remains as a highly (culturally) eutrophic body of water. Indications of

Onondaga Lake's eutrophic state were elevated nutrient levels, character of the phytoplankton and associated activity, an extremely high rate of solids deposition, low transparency (less than 1.0 meter), and anaerobic conditions in the hypolimnion in the warmer months. Water quality standards not directly related to trophic status that are frequently contravened in the lake are fecal coliform, dissolved oxygen, and certain heavy metals.

The baseline survey was followed by a continuing lake monitoring program designed to reflect responses of the ecosystem to changes in contaminant and pollutant loading. The monitoring program, conducted since 1970, includes staggered bi-weekly sampling of the lake and the major lake tributaries (including waste effluents). In addition, an extensive lake reclamation program has been initiated which has included:

1. Construction of an industrial waste treatment plant for a local steel manufacturer.

2. Establishment of a sewer maintenance program which significantly reduced dry weather, raw sewage discharges to the lake's tributaries.

3. Diversion of treated wastes from the Ley Creek Treatment Plant to the Metropolitan Sewage Treatment Plant (MSTP) for additional treatment.

4. Construction of thermal diffusers for the cooling water discharge from a chloro-alkali industry.

5. Upgrading the MSTP to provide tertiary treatment. The facility will take chloro-alkali industrial wastes that now discharge directly to the lake and utilize them in a chemical treatment (tertiary) step for phosphorus removal. These facilities will be completed in 1979.

The completion of these projects should result in a dramatic reduction of pollutant loads, increased dissolved oxygen (DO), and slighly lower productivity in the lake. The goal of the reclamation program is to achieve lake water quality compatible with the intended "best usage" of the waters, as defined by the New York State Department of Environmental Conservation (NYSDEC). The present water quality classification of Onondaga Lake is divided between "B" and "C", as shown on Figure 1. The "B" and "C" classifications have a "best usage" of primary and secondary contact recreation (i.e., bathing and fishing), respectively.

The Onondaga Lake Storms Impact Study, funded through the 201 Facilities Plan for Onondaga County, was designed to determine the storm conditions and associated pollutant loads that could be accommodated and still maintain acceptable water quality. The study entailed three basic phases: (1) field sampling during storm conditions; (2) development of a mathematical model for predictive purposes; and (3) prediction of future conditions for evaluation of pollution abatement.

The objective of field sampling was to measure sufficient parameters to mathematically describe the critical functions within the lake consistent with federal, state and local objectives. These functions were then used to structure a model which was utilized to predict the response of the lake to future waste loads under critical environmental conditions. Once the new MSTP is completed, storm-related runoff and combined sewer overflows will be the most significant sources of pollution of the lake. The model enabled the determination of the degree of treatment required for various storm conditions.

# CHAPTER II

# FIELD SAMPLING

## ECOSYSTEM SAMPLING

### Site Selection

Selection of the tributary sampling sites was made after reviewing available monitoring data and anticipated pollutant loads associated with stormwater overflows. The locations were chosen so as to represent the final pollutant loads reaching the lake from these sources. Two exceptions were made for Onondaga Creek and Harbor Brook, where additional upstream sampling sites were selected to "bracket" the combined sewer overflows into these tributaries; this allowed a differentiation between the rural non-point runoff and the urban contribution which included the CSO's. The tributary sampling stations were established in the following locations (Figure 1):

1. Onondaga Creek
   a. Immediately upstream from the combined sewer system at Dorwin Avenue.
   b. Immediately downstream from the combined sewer system at Hiawatha Boulevard.
2. Harbor Brook
   a. Immediately upstream from the combined sewer system at Velasko Road.
   b. Immediately downstream from the combined sewer system at Hiawatha Boulevard.

3. Metropolitan Sewage Treatment Plant effluent.

4. Stream which receives a steel mill discharge.

5. Ley Creek at Park Street.

6. Cooling water discharge from the chloro-alkali industry of Allied Chemical Corporation.

7. NineMile Creek at Route 48.

8. Bloody Brook.

In the selection of the lake sampling sites, consideration was given to the following factors:

1. Proposed location of recreational areas at the northern end of the lake.

2. Results from previous circulation-model work (2), indicating that:

   a. Bacterial die-off occurs predominantly in the southern end of the lake;

   b. Mass flow tends to hug the northeastern side of the lake.

3. Present sampling location (Station 5) for the continuing Onondaga Lake Monitoring Program.

As shown in Figure 1, there were two deep-water stations, one in each of the two major basins of the lake, and eight near-shore stations, located where there was a minimum of 13 meters of water. These near-shore sampling stations were selected to represent the conditions proximate to the recreational areas. To reflect storm-related perturbations of both the epilimnetic (surface) and hypolimnetic (deep) waters, each of the ten lake stations was sampled at depths of 3 and 12 meters.

## Sampling Frequency

The frequency of sampling of the tributaries and lake was established to document the altered character of the ecosystem resulting from storms. Sampling before, during and after a storm event was required to capture the transient effects of storms. The following idealized sampling schedule was adopted initially to document the impact of a 12-hour storm:

| Sample Period | Frequency of Sampling | |
|---|---|---|
| | Lake Stations | Creek Stations |
| 12 hours prior to storm runoff | 1 | 1 |
| During 12-hour storm | 3 | 6 |
| Period following storm | 6 | 9 |

Subsequent adjustments to this schedule were based on the character of the individual storm, and field conditions and alterations based on accrued data. Because of the unpredictability of both time of occurrence and severity of storms, some pre-storm samples were missed (Storm 2) and false starts were experienced.

## Sample Preservation

Due to the unstable nature of several of the parameters, precautions were taken to inhibit sample deterioration prior to analysis. Bacteriological samples were collected in sterile containers and maintained at 4°-10°C until analysis (within 20 hours of sampling). Samples for nutrient analysis (N and P) were placed in separate containers and preserved either by refrigeration (4°-10°C) or by acidification with sulfuric acid. Both 5-day and 28-day biochemical oxygen demand ($BOD_5$ and $BOD_{28}$) analyses were initiated within 24 hours of collection. Samples for heavy metal analysis were preserved by addition of nitric acid. Heavy metals analyses were performed within the time limitations specified by the United States Environmental Protection Agency (USEPA) (3).

## ANALYSES AND MEASUREMENTS

Table 1 illustrates the methods and instrumentation utilized for making the various field measurements. Laboratory analyses of both tributary and lake samples were performed as outlined in Table 2.

TABLE 1

FIELD MEASUREMENT

LAKE

| Parameter | Method-Instrumentation |
|---|---|
| Dissolved Oxygen | DO temperature meter, YSI Model 54A, Winkler modification for standardization |
| Temperature | DO temperature meter, YSI Model 54A |
| pH | Corning pH meter, Model 610A<br>Corning pH meter, Model 10 |
| Current (direction and speed) | Endeco 110, remote reading current meter |
| Transparency | Secchi disc |

STREAM

| Parameter | Method-Instrumentation |
|---|---|
| Dissolved Oxygen | DO temperature meter, YSI Model 54A, Winkler modification for standardization |
| Temperature | DO temperature meter, YSI Model 54A |
| pH | Corning pH meter, Model 10 |
| Flow | USGS gaging stations, Metropolitan Sewage Treatment Plant records, Allied Chemical plant records |

TABLE 2

LABORATORY ANALYSES

| Parameter | Method | Instrumentation |
|---|---|---|
| Fecal Coliform | SM (4) 909C, membrane filter | |
| Fecal Streptococcus | SM 910B, membrane filter | |
| $BOD_5$<br>$BOD_{28}$ | SM 507 modified by reaeration | YSI Model 57 DO Meter |
| Suspended Solids | SM 208D | |
| Volatile Suspended Solids | | |
| Cl | SM 408B | |
| $NH_3$-N | SM 604 | Technicon Auto-Analyzer |
| Org-N | Kjeldahl-N-$NH_3$ = Org-N<br>Kjeldahl N by Automatic | Technicon Auto-Analyzer |
| $NO_2$-N | Kamphake, et al. (1967) (36) | Technicon Auto-Analyzer |
| Total Inorganic P | SM 606, following mild acid hydrolysis @ 90°C | Technicon Auto-Analyzer |
| Ortho P | SM 606 | Technicon Auto-Analyzer |
| Filtered Ortho P | SM 606, following membrane filter | Technicon Auto-Analyzer |
| Cd, Cr, Cu, Pb, Zn | SM 301A, Atomic Absorption Spectrophotometry | Perkin Elmer 360, Atomic Absorption Spectrophotometer |

SM - Standard Methods, 14th Edition.

# CHAPTER III

# METHODOLOGY

## HYDRAULIC LOAD

The hydraulic loads from the major tributaries were determined as outlined in Table 3. Flow measurements for all tributaries listed in this table are located at the point of entry into the lake. Because of the small magnitude of the stream receiving the steel mill discharge, the use of the average treatment plant flow as an estimate of the total stream flow into the lake proved to be sufficient for model calibration. In addition to the flow monitoring stations adjacent to the lake, upstream USGS gages on both Onondaga Creek and Harbor Brook were used. These upstream gages were monitored to assess the non-urban flow and pollutant concentration to the lake. Gaging station locations are shown in Figure 1.

## POLLUTANT LOADS

The pollutant loads were calculated as the product of flow and parameter concentration. A plot of these loads versus time results in a pollutograph. Ideally, both flow and concentration should be measured continually

Utilizing the appropriate paired data, total tributary loads were calculated as the area under the pollutograph. Pollutographs and total loads from the major tributaries were determined for the following pollutants: fecal coliform, fecal streptococci, biochemical oxygen demand, dissolved oxygen, organic nitrogen, ammonia nitrogen, total inorganic phosphorus, total suspended solids, volatile suspended solids, and chlorides. The pollutographs for the heavy metals were generated for Onondaga Creek, Harbor Brook and NineMile Creek.

Net loads from the East Flume and NineMile Creek were corrected for the quantity of pollutants withdrawn from the lake through cooling water used by the chloro-alkali industry. Average hypolimnetic concentrations for the storm period were utilized as the pollutant concentration withdrawn from the lake.

## METROPOLITAN SEWAGE TREATMENT PLANT BACTERIOLOGICAL DATA

During the summer of 1976, the MSTP was in the process of being upgraded from a primary to a tertiary treatment facility. Owing to the extent of construction at the existing plant site, it became necessary to select a sampling location that was both representative of the waste load that the lake received and safe and accessible for the personnel collecting the samples. Sampling points were selected following primary treatment but prior to disinfection; therefore, it became necessary to correct both bacterial and BOD loads reaching the lake.

Bench-scale studies have shown that disinfection using a high chlorine dosage and short contact time can greatly reduce the number of total coliforms present in combined sewage discharges (5). Since the effective chlorine contact time at the MSTP is also very short, generally in the range of three to four minutes, the results of these studies were applied to the MSTP discharge. The percent survival at the MSTP for the various storms is represented by the following relationships:

TABLE 4

BACTERIAL SURVIVAL FOLLOWING DISINFECTION
METROPOLITAN SEWAGE TREATMENT PLANT

| Storm No. | Chlorine Dosage (mg/l)* | Equation (5) |
|---|---|---|
| 1 and 2 | 10 | $y = 81.3e^{-1.71t}$ |
| 3 | 12 | $y = 67.6e^{-1.93t}$ |
| 4 and 5 | 11 | $y = 72.4e^{-1.82t}$ |

where: y = percent survival of fecal coliform
t = effective chlorine contact time (minutes)

*Milligrams per liter

The percent survivals as calculated from the above equations were applied to the measured fecal coliform values to generate bacteriological pollutographs for the MSTP. BOD data for the MSTP was corrected by subtracting the oxygen equivalent of chlorine applied from the BOD concentration measured.

## LAKE CIRCULATION AND WIND PATTERNS

Surface currents in lakes the size of Onondaga Lake are induced by wind and hydraulic inputs to the lake. The strength and direction of the circulation pattern depends on wind (direction and speed), frequency of change in wind, hydraulic loads, thermal gradients, and basin morphology. In small lakes, wind generally plays the predominant role in determining surface currents (6, 7).

Lake circulation patterns during the storm occurrences were measured at epilimnetic (3 meters) and hypolimnetic (12 meters) depths for the ten monitoring locations. The measurement frequency coincided with the sampling frequency of one to two measurements per station per day. Wind conditions

affecting the lake during storm occurrences were evaluated through analysis of wind direction and magnitude conditions, which were continuously monitored by NYSDEC at a station located adjacent to the MSTP.

The individual current measurements were time-averaged over the duration of the storm to obtain general current information. Time-averaged current vectors for both the 3- and 12-meter depths are shown in Figures 2 through 6 for each storm monitored. Wind conditions during the storm period are summarized by a wind rose in the lower lefthand corner of each figure. The basic circulation patterns for the storms were determined from the individual time-averaged data. The trends in epilimnetic currents are discussed below. Discussion of the 12-meter measurements are omitted since this layer did not significantly affect the recreational areas.

STORM 1 (6/22/76 - 6/26/76):

Generally strong currents were evident ($\geqslant$6 cm/sec) in the 3-meter layer, with a general counterclockwise circulation pattern (gyre) throughout the lake. The wind data partially supports the observed pattern.

STORM 2 (7/11/76 - 7/18/76):

Strong surface (3-meter) currents were demonstrated ($\geqslant$6 cm/sec). A well-defined clockwise pattern was apparent in the South Basin which is in accord with the relatively steady westerly winds at magnitudes generally exceeding 8 mph. Circulation patterns were undefined for the northern lake basin.

STORM 3 (8/5/76 - 8/11/76):

Counterclockwise gyres in both basins were evident, though the magnitudes of the resultant vectors were much smaller than in Storms 1 and 2. The current patterns generally correspond to the wind conditions.

STORM 4 (8/27/76 - 9/1/76):

Moderate currents were demonstrated. A poorly-defined counterclockwise gyre was apparent in the South Basin, with some net water transfer to the North Basin. A clockwise current pattern in the North Basin was poorly defined. The lack of current pattern definition may be associated with the generally variable wind conditions.

STORM 5 (9/15/76 - 9/21/76):

Moderate current speeds were observed in the surface layers. A counterclockwise gyre for the South Basin and a clockwise gyre for the North Basin were well defined. Wind conditions were highly variable during this storm period.

## BACTERIAL KINETICS

In order to obtain an estimate of the bacterial kinetics, a series of batch fecal coliform die-off experiments was conducted in the laboratory for four storm events. Samples for these experiments were collected from the lake's surface. Stations 7 and 8 were used since they were closest to the tributaries that receive the CSO discharges. The samples were collected 8 to 16 hours after the start of a storm. The control tanks (10-gallon glass aquaria) received normal room lighting and were maintained between 19°-23° C. Prior to the start of these investigations the tanks were allowed to acclimate to the artificial environment for approximately 12 hours. The fecal coliform analyses were conducted at least daily to sufficiently define the die-off rate. The duration of the die-off studies was dictated by the persistence of the indicator organisms. Each study was continued until less than 80 cells per 100 millimeters were measured (up to 140 hours).

The survival of the indicator organisms can be described by Chick's Law, which is expressed as follows:

$$N = N_o e^{-kt}$$

where:

$N$ = Number of organisms remaining after time (cells/100 ml)

$N_o$ = Number of organisms initially present (cells/100 ml)

$k$ = Bacterial die-off rate ($days^{-1}$)

$t$ = Incubation period (days)

$$\% \text{ Survival} = \frac{N}{N_o} \times 100$$

The bacterial die-off rate (k) at 20° C, based on data collected from all the storms, is 1.16 $days^{-1}$ (base e). The equation describing the line of "best fit" shown on Figure 7 is:

$$\% \text{ Survival} = 67e^{-1.16t}$$

The correlation coefficient for this curve is 0.96. The uniformity of the individual rates determined in the five die-off experiments (standard deviation of 0.12 $day^{-1}$) indicated that the mean value could be used for calibration of the fecal coliform model.

ORGANIC DECAY

The rate at which bacteria utilize both carbonaceous and nitrogenous material as an energy source is approximately equal to the rate at which the organisms utilize oxygen. The oxidation rates vary, depending on the ecosystem, the type of substrate (food) available, the ability of the organisms

present to utilize that particular substrate, and the presence of sufficient numbers of organisms (8, 9). An estimate of the in-lake oxidation rates can be made by in-situ measurements of BOD decay, analysis of long-term BOD ("bottle" rates), or the determination of rates through model calibration. The use of in-situ measurements is practical only when the current speed and direction are completely defined (e.g., rivers and streams). Direct measurement of decay rates is extremely difficult in lakes. Thus, "bottle" rates were used as an estimate of in-lake kinetics. Bottle deoxygenation rate constants for both carbonaceous and nitrogenous material ($K_c$ and $K_n$) were determined by applying the method of Thomas (10, 11) to the time series BOD data.

No consistent trends in the "bottle" carbonaceous or nitrogenous deoxygenation rate ($K_c$ and $K_n$) as a function of sample size were demonstrated. While these reaction rates varied slightly with location and time, these differences were not considered significant, the only exception being that the nitrogenous deoxygenation rate varied significantly between the two layers as shown in Table 5.

TABLE 5

LABORATORY DEOXYGENATION RATES (BASE e)
ONONDAGA LAKE

| Zone | Carbonaceous Rate ($day^{-1}$) | | Nitrogenous Rate ($day^{-1}$) | |
|---|---|---|---|---|
| | $K_c$ | Std. Dev. | $K_n$ | Std. Dev. |
| Epilimnion | 0.25 | 0.11 | 0.23 | 0.08 |
| Hypolimnion | * | * | 0.34 | 0.16 |

*"Bottle" rates were same for both epilimnion and hypolimnion.

The rates presented in Table 5 proved to be extremely high when calibrating the BOD-DO model. The values of $K_c$ and $K_n$, which produced results closely matching the field data, were 0.1 and 0.01 per day (base e), respectively. The discrepancy between the "bottle" and field could be attributed to either of the following:

1. The Onondaga Lake samples generally contain abnormally large quantities of algae which, when incubated in the dark, utilize oxygen for respiration. This produces a falsely high BOD and deoxygenation rate.

2. The low oxygen values in the lake, particularly in the hypolimnion, limit the rates. Since the BOD bottles are aerated prior to the test, these values would not reflect the inhibition at low DO.

# CHAPTER IV

## MODEL FRAMEWORK

It is impractical to design a sampling program with the expectation of capturing storms that would, all things being considered, represent feasible abatement goals. The probability of monitoring such storms under critical environmental conditions is even more remote. Therefore, the assessment of the impact of such a storm on water quality requires a predictive tool. A mathematical model is an expression or series of expressions which describe in mathematical terms the cause-and-effect relationship of a real event. Specifically, water quality models describe the influence of pollutant discharge on a receiving water. A model for Onondaga Lake has been developed to simulate the short-term (one to two weeks) dynamics of lake water quality in response to storm runoff for the following parameters: fecal coliform, carbonaceous and nitrogenous BOD (CBOD and NBOD), BOD, and total inorganic phosphorus (TIP).

### GENERAL THEORY

The model developed for this study is a 27-segment, three-dimensional model which predicts fecal coliform, total phosphorus, BOD, and dissolved oxygen concentrations in Onondaga Lake following storm overflows from the City of Syracuse. It includes advective and dispersive transport and mechanisms for settling, scour and chemical and biochemical reaction. The model is based on the conservation of mass, as expressed by the following equation:

$$\begin{array}{l}\text{Accumulation} \\ \text{of Mass}\end{array} = \begin{array}{l}\text{Net Input of Mass} \\ \text{from Advective} \\ \text{Transport}\end{array} + \begin{array}{l}\text{Net Input of Mass} \\ \text{from Dispersive} \\ \text{Transport}\end{array}$$

$$\pm \begin{array}{l}\text{Rate of Disappearance or Appearance} \\ \text{of Mass Due to Reaction or Sinking}\end{array}$$

or mathematically:

$$\frac{\partial C}{\partial t} = \nabla \cdot E \nabla C - \nabla \cdot UC + r$$

where:

C = Concentration (mg/l)

t = Time (day)

E = Dispersion coefficient ($m^2$/day)

U = Velocity (l/day)

r = Sources or sinks (mg/l/day)

Since a direct solution of this equation is usually not possible, the solution requires the use of finite difference approximations. This is equivalent to representing the continuous lake system as a collection of completely mixed cells that are interconnected by advective and dispersive flow. This approach does sacrifice some spatial accuracy; however, the careful segmentation of the water body to closely represent the overall circulation and mixing minimizes these inaccuracies. A more thorough treatment of the mathematical formulations is presented by Thomann (12). Consistent with the above approach, the model treats the lake as two vertical layers with 21 interconnected horizontal segments in the epilimnion and six interconnected horizontal segments in the hypolimnion (Figure 8). Measurements from U.S. Lake Survey Chart No. 180 were analyzed and used to define the morphology of Onondaga Lake and to establish the dimensions of each model cell.

The model utilizes steady-state circulation patterns and hydraulic loads and time-variable pollutant loads to simulate the lake's water quality response to stormwater discharges. The model linearly interpolates the transient pollutant loadings from tabular input data to formulate the pollutographs discharging to each model cell. Time-varying changes in flow associated with stormwater input are normally small in comparison with dispersive and

advective flow of the lake circulation pattern; therefore, the use of steady-state hydraulic loads is considered applicable. The assumption of steady-state in-lake hydraulics may, however, be invalid for major changes in lake circulation patterns caused by fluctuation in wind during the period of simulation. These variations in lake hydraulics can be roughly simulated by using stepwise changes in steady-state hydraulic patterns whenever a marked change

$$r_{f_s} = \frac{VSF}{D} \times N$$

where:

$r_{f_s}$ = Rate of loss due to settling (cells/l/day)

D = Depth (m)

VSF = Settling velocity of fecal bacteria (m/day)

N = Bacteria concentration (cells/l)

Total Phosphorus Model Kinetics

Total phosphorus is considered to be a conservative substance in the model where net changes in concentration result only from settling and sediment release or bottom scour. While only particulate forms of phosphorus settle, the non-settleable soluble organic and soluble reactive forms are converted to settleable material through biochemical processes, such as zooplankton grazing and fish predation, and chemical conversion (appatites). A model which individually describes these complex interactions was well beyond the scope of this project; therefore, the model uses a net effective settling velocity for total phosphorus which incorporates the overall removal rate in one term. The following simple kinetic expression is used to describe the rate of phosphorus loss to the sediments and sediment release of phosphorus:

$$r_p = -(VSP/D)P + SBP/D$$

where:

$r_p$ = Overall kinetic rate for total phosphorus (mg/l/day)

VSP = Average settling velocity (m/day)

D = Depth (m)

P = Total phosphorus concentration (mg/l)

SBP = Sediment release of phosphorus caused by anaerobic conditions or scour ($gm/m^2/day$)

Dissolved Oxygen Model Kinetics

The dissolved oxygen model includes kinetic expressions describing reaeration, oxidation and settling of carbonaceous and nitrogenous oxygen-demand material, algal photosynthesis and respiration, and sediment oxygen demand (SOD). The following paragraphs describe the model kinetics for each of these processes.

CBOD occurs in both the dissolved and particulate forms and the appearance or disappearance of this material is governed by mechanisms such as settling, sediment scour, stripping, adsorption and biological oxidation. The rate of bacterial oxidation of organic carbon has been traditionally described by first-order kinetic expressions. The Onondaga Lake model uses such expressions modified by a non-linear decay coefficient to account for inhibition of biological oxidation at low dissolved oxygen concentrations (14). In addition to biochemical decay, a physical removal mechanism for settling is used in the model. The overall kinetic term for CBOD is:

$$r_{CBOD} = (k_{C_{nl}} + VSC/D)\,CBOD$$

where:

$r_{CBOD}$ = Overall kinetic rate for CBOD (mg/l/day)

$k_{C_{nl}}$ = Non-linear biological oxidation decay coefficient (1/day)

VSC = Settling velocity of CBOD (m/day)

D = Depth (meters)

CBOD = Carbonaceous biochemical oxidation demand (mg/l)

NBOD is exerted as a consequence of the bacterial oxidation of ammonia to nitrite and nitrate. All municipal and many industrial wastes contain nitrogenous material in both organic and ammonia forms. The organic component must be hydrolyzed to ammonia before biochemical oxidation can

occur. The autotrophic oxidation of ammonia to nitrite and nitrate has been described by first-order kinetic rate laws. The Onondaga Lake model uses a first-order expression of nitrification with a non-linear modification to account for inhibition of nitrification at low levels of dissolved oxygen (15). The model also uses a first-order expression to describe the settling of nitrogenous material. Both the organic and ammonia forms of nitrogen are present as dissolved and particulate matter. The particulate material, expecially organic nitrogen, can settle before it has a direct impact on the lake's dissolved oxygen resources, although ultimately this material has a potential for exerting a benthal demand. The overall kinetic expression for NBOD is given by the following equation:

$$r_{NBOD} = (k_{N_{nl}} + VSN/D)\ NBOD$$

where:

$r_{NBOD}$ = Overall kinetic rate for NBOD (mg/l/day)

$k_{N_{nl}}$ = Non-linear nitrification decay coefficient (1/day)

VSN = Settling velocity of NBOD (m/day)

NBOD = Nitrogenous biochemical oxygen demand (mg/l)

The oxygen depletion rate by organic sediments is considered constant (zero order) with inhibition at low dissolved oxygen concentration. The rate of oxygen demand due to benthal deposits (B) is defined by the following equation:

$$r_B = -\frac{B_{nl}}{D}$$

where:

$r_B$ = Oxygen uptake due to benthal demand (mg/l/day)

$B_{nl}$ = Non-linear benthal oxygen demand ($gm/m^2$/day)

Dissolved oxygen has limited solubility in water and its presence at adequate concentrations is critical to the preservation of healthy aerobic aquatic communities. Oxygen solubility in water is dependent mainly upon the partial pressure of atmospheric oxygen, temperature, and the concentration of dissolved and suspended impurities. As shown in Figure 10, the dissolved oxygen saturation concentration is dependent on the temperature and salinity of the water body (16).

Any gradient between the oxygen saturation concentration and the actual in-lake oxygen concentration causes the natural forces of gas transfer to act to restore the lake concentration to the equilibrium level. This rate of restoration is called reaeration, $r_a$, and is described mathematically as:

$$r_a = k_a(DO_S - DO)$$

where:

$r_a$ = Rate of reaeration (mg/l/day)

$k_a$ = Reaeration rate coefficient (1/day)

$DO_S$ = Dissolved oxygen concentration at saturation (mg/l)

DO = In-lake dissolved oxygen concentration (mg/l)

In lake systems, wind action on the surface of the water is primarily responsible for reaeration. Figure 11 describes the atmospheric reaction coefficient as a function of wind speed (17).

The oxidation rates for the various mechanisms discussed in this chapter are dependent on temperature and correctable using the modified Arrenhius equation. The basic equation is as follows:

$$K_T = K_{20}\theta^{(T-20)}$$

where:

$K_T$ = Corrected rate coefficient at temperature T (1/day)

$K_{20}$ = Rate coefficient at 20° C (1/day)

$\Theta$ = Rate correction factor dependent on parameter

T = Temperature (° C)

The values of $\Theta$ used in this model are presented in Table 6.

TABLE 6

TEMPERATURE CORRECTION FACTORS

| Rate Coefficient | $\Theta$ |
|---|---|
| Carbonaceous Oxygen Demand | 1.047 |
| Nitrogenous Oxygen Demand | 1.09 |
| Sediment Oxygen Demand | 1.065 |
| Reaeration | 1.0241 |

Planktonic algae and rooted macrophytes have both a beneficial and detrimental effect on the oxygen resources of natural waters. During periods of sunlight, under favorable nutrient and temperature conditions, macrophytes and algae fix carbon dioxide and produce oxygen through the process of photosynthesis. However, these plants must also constantly oxidize organic matter for energy through the process of respiration. Consequently, during prolonged periods of darkness, algal or macrophytic respiration can seriously deplete the oxygen resources of a lake. While a sophisticated phytoplankton model with nutrient cycles would be very useful for understanding the water quality dynamics in Onondaga Lake, the development of this type of model is beyond the scope of this study.

The model does, however, compute the effect of algae on the lake's dissolved oxygen budget. Algal photosynthetic oxygen production is calculated

using chlorophyll a, nutrient and incident light measurements (18, 19, 20, 21, 22) according to the following equation:

$$r_{photo} = Y(G_{p,L})(G_{p,N})(G_{p,MAX})(\text{Chl } a)$$

where:

$r_{photo}$ = Photosynthetic production of oxygen (mg/l/day)

Y = mg $O_2$/mg Chl a

$G_{p,L}$ = Light attenuation and inhibition factor (dimensionless)

$G_{p,N}$ = Nutrient limitation factor (dimensionless)

$G_{p,MAX}$ = Rate of maximum algal photosynthesis (1/day)

Chl a = Chlorophyll a concentration (mg/l)

The model predicts algal respiration using the following equation:

$$r_{resp} = -Y(k_{R_{nl}})\ \text{Chl } a$$

where:

$r_{resp}$ = Rate of oxygen depletion due to respiration (mg/l/day)

Y = mg $O_2$/mg Chl a

$k_{R_{nl}}$ = Non-linear temperature dependent respiration coefficient

Overall, the dissolved oxygen kinetics can be described by the sum of all of the individual reaction terms: $r_{CBOD}$, $r_{NBOD}$, $r_a$, $r_b$, $r_{photo}$, and $r_{resp}$.

In the model, nutrient concentrations and average daily incident light are needed to determine nutrient and light limitations on algal photosynthesis. Lake nutrient and incident light data are linearly interpolated by the model

from tabular input data to estimate the nutrient concentrations and incident light at any specific time during a simulation. The algal population is estimated from interpolated chlorophyll a concentration data. This information is combined in the model to calculate algal photosynthesis and respiration.

During photosynthesis, algae transform inorganic carbon in the form of carbon dioxide to organic carbon (cell mass). Hence, algal productivity is a source of autochthonous organic loading in the lake. The autochthonous (internal) production of CBOD is included in the model by an addition of a load equivalent to $r_{photo} + r_{resp}$. Because organic carbon is expressed as oxygen in the model, stoichiometric conversion is not required.

## MODEL CALIBRATION AND VERIFICATION

### Introduction

The interaction of the data collection and mathematical modeling phases of the project occurs during the model calibration and verification. While the general framework of the model has been based on widely-accepted relationships, the particular forcing functions, kinetics and system responses applicable to Onondaga Lake have been formulated using the actual data collected during storms. However, where field data was lacking, literature values were used.

The model calibration and verification has successfully been accomplished with data collected during Storms 2 through 5. Storm 1 was not used since its impact on the lake was not tracked for a sufficient period to reflect recovery, and laboratory dilutions on several pollutants were improperly selected, yielding inaccurate concentrations. For the remaining storms, the sampling period and dilutions used were adjusted to prevent these errors. Prior to calibrating the dynamic model with storm data, each model was calibrated in the steady-state mode versus 1975 average yearly data. This procedure aided in the initial selection of reaction coefficients and settling rates.

The Onondaga Lake model requires detailed data input for hydrology, circulation, dispersive transport, reaction coefficients, influent loads and environmental conditions. Each of these inputs must be specified for every model simulation and projection. The following paragraphs describe these inputs and the procedures used to obtain them.

Lake circulation was determined from measurements of current taken during the field surveys. Figures 12 and 13 depict simplified versions of the lake circulation patterns used for each storm simulation. For input to the model the current patterns were expressed as a net exchange of water across the interface of adjacent model cells.

The Onondaga Lake model includes transport terms for dispersive mixing. Dispersion coefficients for the model were estimated from literature on lake circulation, an assessment of observed current data to determine the extent of mixing, changes in the circulation characteristics during each survey, and thorough model calibration. The dispersion coefficients used in the model are summarized in Table 7.

Model reaction and settling coefficients were determined by a survey of literature (12, 23, 24), laboratory measurements, and through model calibration. The coefficients are summarized in Table 8. The model coefficients for deoxygenation are smaller than the rate coefficients determined in BOD bottle studies. The possible reasons for this have been discussed in Chapter III. Reaeration coefficients are not presented; these rates were based on direct model calculations using measured wind velocities (Figure 11). The fecal coliform die-away rate was determined from laboratory studies (Figure 7).

Model input data for tributary and direct discharge loads to Onondaga Lake were measured during each storm survey. The average daily and peak loading rates and percent contribution from each tributary are summarized in Tables 9 through 13 as previously discussed. The temporal variations of

TABLE 7

DISPERSION COEFFICIENTS

| Location | Dispersion Range of Coefficients ($cm^2/sec$) |
|---|---|
| Epilimnetic near shore | $2.9 - 4.6 \times 10^3$ |
| Epilimnetic mid-lake | $3.5 - 6.0 \times 10^4$ |
| Epilimnetic basin interface | $4.1 - 8.1 \times 10^4$ |
| Hypolimnetic horizontal | $8.1 - 16.2 \times 10^4$ |
| Hypolimnetic-epilimnetic vertical | $5.0 \times 10^{-1}$ |

TABLE 8

REACTION COEFFICIENTS AND SINKING RATES

| Parameter | Reaction Coefficient ($day^{-1}$)* | Near-Shore Sinking Rate (ft/day) | Mid-Lake Sinking Rate (ft/day) | Hypolimnion Sinking Rate (ft/day) |
|---|---|---|---|---|
| Fecal Coliform | 1.159 | 0.0 | 1.97 | 0.0 |
| Phosphorus | -- | 0.39 | 2.95 | 0.144 |
| CBOD | 0.10** | 0.98 | 3.28 | 0.98 |
| NBOD | 0.0115** | 0.0 | 1.67 | 0.049 |

*Base e @ 20°C

**Not corrected for non-linear kinetics

TABLE 9

SUMMARY OF TRIBUTARY POLLUTANT LOADINGS FOR STORM NO. 1

| Location (Station No.) | Average and Peak Loading Rates (Lbs/Day) | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform ($\times 10^{12}$)* | Fecal Strep ($\times 10^{12}$)* | Chlorides ($\times 10^{3}$) | BOD ($\times 10^{3}$) | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 81.1 (637.) | 15.4 (68.) | 40.7 (99.3) | 3.8 (10.2) | 510.0 (1266.) | 195.6 (491.) |
| Metro STP (4 & 5)** | 2.0 | 1.0 | 198.8 | 32.1 | 8505.6 | 1206.5 |
| Onondaga Creek (6) | 498.8 (1256.) | 25.8 (107.) | 415.1 (511.7) | 11.1 (29.0) | 1587.5 (2270.) | 296.0 (580.) |
| Harbor Brook (7) | 27.8 (87.) | 4.4 (20.) | 5.8 (26.9) | 0.9 (3.2) | 53.3 (156.) | 10.0 (45.) |
| East Flume (8) | 3.5 | 0.0 | 45.0 | 0.5 | 1827.4 | 30.2 |
| NineMile Creek (9) | *** | *** | 6071.6 (7867.0) | 45.1 (73.6) | 659.5 (4792.) | 67.9 (496.) |
| TOTAL | 613.2 | 46.6 | 6776.9 | 93.5 | 13143.3 | 1806.2 |

| Location (Station No.) | Average Percent Contribution | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform | Fecal Strep | Chlorides | BOD | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 13.2 | 33.0 | 0.6 | 4.0 | 3.9 | 10.8 |
| Metro STP (4 & 5) | 0.3 | 2.2 | 2.9 | 34.3 | 64.7 | 66.8 |
| Onondaga Creek (6) | 81.4 | 55.4 | 6.1 | 11.8 | 12.1 | 16.4 |
| Harbor Brook (7) | 4.5 | 9.4 | 0.1 | 1.0 | 0.4 | 0.6 |
| East Flume (8) | 0.6 | 0.0 | 0.7 | 0.6 | 13.9 | 1.7 |
| NineMile Creek (9) | 0.0 | 0.0 | 89.6 | 48.3 | 5.0 | 3.8 |

*Fecal coliform and fecal strep have units of cells/day.

**Measured fecal coliform and fecal strep loads have been corrected for disinfection.

***Bacterial populations in NineMile Creek are effectively disinfected by the high chlorides concentration.

( ) = peak storm-related load

TABLE 10

SUMMARY OF TRIBUTARY POLLUTANT
LOADINGS FOR STORM NO. 2

| Location (Station No.) | Average and Peak Loading Rates (Lbs/Day) | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform ($\times 10^{12}$)* | Fecal Strep ($\times 10^{12}$)* | Chlorides ($\times 10^{3}$) | BOD ($\times 10^{3}$) | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 95.4 (810.) | 8.1 (51.) | 35.1 (78.1) | 2.5 (3.8) | 410.0 (1010.) | 80.2 (181.0) |
| Metro STP (4 & 5)** | 17.2 | 7.1 | 331.9 | 54.2 | 8712.8 | 1573.3 |
| Onondaga Creek (6) | 2669.5 (5495.) | 97.9 (536.) | 316.3 (641.0) | 9.0 (23.0) | 1656.0 (4450.) | 325.2 (890.0) |

TABLE 11

SUMMARY OF TRIBUTARY POLLUTANT
LOADINGS FOR STORM NO. 3

| Location (Station No.) | Average and Peak Loading Rates (Lbs/Day) | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform ($\times 10^{12}$)* | Fecal Strep ($\times 10^{12}$)* | Chlorides ($\times 10^{3}$) | BOD ($\times 10^{3}$) | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 13.6<br>(84.) | 22.6<br>(117.) | 37.6<br>(154.) | 2.9<br>(11.0) | 350.9<br>(1522.) | 124.6<br>(732.) |
| Metro STP (4 & 5)** | .5.7 | 0.3 | 517.0 | 27.9 | 5436.8 | 904.7 |
| Onondaga Creek (6) | 796.8<br>(3343.) | 133.2<br>(633.) | 380.0<br>(575.) | 12.2<br>(23.9) | 1747.2<br>(5396.) | 337.4<br>(1091.) |
| Harbor Brook (7) | 228.8<br>(9814.) | 22.6<br>(637.) | 14.6<br>(95.3) | 1.0<br>(17.6) | 332.6<br>(2484.) | 46.5<br>(426.) |
| East Flume (8) | 9.4 | 1.4 | 62.6 | 0.3 | 6359.3 | 111.9 |
| NineMile Creek (9) | ***<br>_____ | ***<br>_____ | 6362.8<br>(11718.) | 35.7<br>(99.0) | 294.7<br>(3300.) | 84.9<br>(233.) |
| TOTAL | 1054.3 | 180.1 | 7374.5 | 80.0 | 14521.4 | 1610.0 |

| Location (Station No.) | Average Percent Contribution | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform | Fecal Strep | Chlorides | BOD | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 1.3 | 12.5 | 0.5 | 3.6 | 2.4 | 7.7 |
| Metro STP (4 & 5) | 0.5 | 0.2 | 7.0 | 34.9 | 37.4 | 56.2 |
| Onondaga Creek (6) | 75.6 | 74.0 | 5.2 | 15.3 | 12.0 | 21.0 |
| Harbor Brook (7) | 21.7 | 12.5 | 0.2 | 1.3 | 2.3 | 2.9 |
| East Flume (8) | 0.9 | 0.8 | 0.8 | 0.4 | 43.9 | 7.0 |
| NineMile Creek (9) | *** | *** | 86.3 | 44.6 | 2.0 | 5.2 |

*Fecal coliform and fecal strep have units of cells/day.

**Measured fecal coliform and fecal strep loads have been corrected for disinfection.

***Bacterial populations in NineMile Creek are effectively disinfected by the high chlorides concentration.

( ) peak storm-related load

TABLE 12

SUMMARY OF TRIBUTARY POLLUTANT
LOADINGS FOR STORM NO. 4

| Location (Station No.) | Average and Peak Loading Rates (Lbs/Day) | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform ($\times 10^{12}$)* | Fecal Strep ($\times 10^{12}$)* | Chlorides ($\times 10^{3}$) | BOD ($\times 10^{3}$) | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 30.7 (251.) | 20.2 (141.) | 30.7 (126.) | 1.8 (8.7) | 453.4 (1223.) | 122.1 (848.) |
| Metro STP (4 & 5)** | 10.8 | 9.5 | 225.4 | 64.0 | 9963.5 | 1388.2 |
| Onondaga Creek (6) | 365.7 (1077.) | 49.0 (110.) | 260.9 (757.) | 4.7 (6.6) | 1092.6 (2111.) | 166.9 (287.) |
| Harbor Brook (7) | 19.4 (74.) | 4.5 (27.) | 3.2 (12.) | 0.2 (0.6) | 49.3 (160.) | 9.8 (46.) |
| East Flume (8) | 2.1 | 2.0 | 76.2 | 2.5 | 1528.9 | 58.8 |
| NineMile Creek (9) | *** | *** | 4523.8 (7561.) | 14.4 (39.5) | 221.8 (995.) | 155.4 (358.) |
| TOTAL | 428.7 | 85.2 | 5120.3 | 87.6 | 13309.6 | 1901.2 |

| Location (Station No.) | Average Percent Contribution | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform | Fecal Strep | Chlorides | BOD | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 7.2 | 23.7 | 0.6 | 2.1 | 3.4 | 6.7 |
| Metro STP (4 & 5) | 2.5 | 11.1 | 4.4 | 73.1 | 74.9 | 75.6 |
| Onondaga Creek (6) | 85.3 | 57.5 | 5.1 | 5.4 | 8.2 | 9.1 |
| Harbor Brook (7) | 4.5 | 5.3 | 0.1 | 0.2 | 0.4 | 0.5 |
| East Flume (8) | 0.5 | 2.3 | 1.5 | 2.9 | 11.5 | 3.2 |
| NineMile Creek (9) | *** | *** | 88.3 | 16.4 | 1.7 | 4.9 |

*Fecal coliform and fecal strep have units of cells/day.

**Measured fecal coliform and fecal strep loads have been corrected for disinfection.

***Bacterial populations in NineMile Creek are effectively disinfected by the high chlorides concentration.

( ) peak storm-related load

TABLE 13

SUMMARY OF TRIBUTARY POLLUTANT
LOADINGS FOR STORM NO. 5

| Location (Station No.) | Average and Peak Loading Rates (Lbs/Day) | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform ($\times 10^{12}$)* | Fecal Strep ($\times 10^{12}$)* | Chlorides ($\times 10^{3}$) | BOD ($\times 10^{3}$) | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 1.2<br>(7.9) | 1.0<br>(10.5) | 19.9<br>(35.6) | 0.9<br>(2.8) | 214.7<br>(668.) | 38.4<br>(101.) |
| Metro STP (4 & 5)** | 10.5 | 7.9 | 207.6 | 71.4 | 11102.4 | 1647.1 |
| Onondaga Creek (6) | 282.5<br>(1423.) | 46.3<br>(363.) | 399.2<br>(1722.) | 4.9<br>(54.1) | 1275.6<br>(6258.) | 264.5<br>(1051.) |
| Harbor Brook (7) | 80.5<br>(2392.) | 6.8<br>(88.) | 3.5<br>(22.) | 0.3<br>(2.9) | 65.7<br>(736.) | 10.8<br>(98.) |
| East Flume (8) | 1.0 | 0.0 | 78.4 | 0.7 | 2077.6 | 58.0 |
| NineMile Creek (9) | ***<br>___ | ***<br>___ | 4260.8<br>(7210.) | 9.6<br>(23.3) | 0.0<br>(682.) | 21.3<br>(233.) |
| TOTAL | 375.7 | 62.0 | 4969.4 | 87.8 | 14736.0 | 2040.1 |

| Location (Station No.) | Average Percent Contribution | | | | | |
|---|---|---|---|---|---|---|
| | Fecal Coliform | Fecal Strep | Chlorides | BOD | TKN | Total Inorganic Phosphorus |
| Ley Creek (3) | 0.3 | 1.6 | 0.4 | 1.0 | 1.5 | 1.8 |
| Metro STP (4 & 5) | 2.8 | 12.7 | 4.2 | 81.4 | 75.3 | 80.7 |
| Onondaga Creek (6) | 75.2 | 74.7 | 8.0 | 5.6 | 8.7 | 13.0 |
| Harbor Brook (7) | 21.4 | 11.0 | 0.1 | 0.3 | 0.4 | 0.1 |
| East Flume (8) | 0.3 | 0.0 | 1.6 | 0.8 | 14.1 | 2.8 |
| NineMile Creek (9) | *** | *** | 85.7 | 10.9 | 0.0 | 1.0 |

*Fecal coliform and fecal strep have units of cells/day.

**Measured fecal coliform and fecal strep loads have been corrected for disinfection.

***Bacterial populations in NineMile Creek are effectively disinfected by the high chlorides concentration.

( ) peak storm-related load

loads on the various model cells were expressed as continuous pollutographs which were slightly smoothed to eliminate minor scatter in the loading data and to minimize computational expense. The hydrographs for the major tributaries during the storms monitored are presented in Figures 14 through 33. Tributary loads used in calibration of the steady-state model are presented in Table 14.

A benthal oxygen demand of 0.5 mg $O_2/m^2/day$, which had been measured in a previous study (1), was used in the model. Although this value is low compared to other polluted systems (12), the model calculations are relatively insensitive to variations in this coefficient. This insensitivity is a result of the separation of the hypolimnion and the epilimnion by the thermocline and of the short one-to-two-week duration of model simulations. Under existing lake conditions, the benthal deposits cannot exert large oxygen demands because of the extremely low oxygen concentrations in the overlying waters.

The environmental factors utilized in computing and correcting reaction coefficients and in computing the photosynthetic oxygen production and algal respiration for the various model runs are presented in Table 15. Data on wind, water temperature, secchi disc, and algal nutrient concentrations were derived from measurements made during this study. The incident light selected was based on long-term regional data (25, 26). However, the incident light was corrected for percent cloud cover as reported by the National Weather Service at Hancock International Airport in Syracuse. Model input of chlorophyll a was derived from limited data and was interpolated to provide temporal detail. Three of the four storm surveys used in calibration had chlorophyll a measurements for only a single date. Other miscellaneous non-survey measurements were used to supplement the data (27).

The Onondaga Lake model requires input of pre-storm conditions for CBOD, NBOD, dissolved oxygen, fecal coliform, phosphorus, and environmental conditions such as temperature, light, secchi disc, chlorophyll a,

TABLE 14

1975 AVERAGE DAILY INFLUENT LOADS

| | Fecal $\log_{10}$ (cells/day) | Phosphorus (lbs/day) | $BOD_5$ (lbs/day) | TKN (lbs/day) | DO (lbs/day) |
|---|---|---|---|---|---|
| Ley Creek | 9.32 | 84.2 | 3,087.7 | 705.6 | 2,160.2 |
| MSTP | 10.57 | 995.8 | 61,481.1 | 7,438.8 | 2,879.3 |
| Onondaga Creek | 10.75 | 286.4 | 7,563.6 | 1,075.2 | 10,018.0 |
| Harbor Brook | 9.35 | 17.0 | 823.1 | 121.9 | 308.0 |
| East Flume | 8.19 | 8.2 | 501.2 | 2,984.2 | 1,781.6 |
| NineMile Creek | 6.81 | 61.5 | 1,515.9 | 747.3 | 8,432.8 |
| Crucible Steel | 6.58 | 0.9 | 66.8 | 21.8 | 57.8 |

TABLE 15

ENVIRONMENTAL CONDITIONS

| | Temp. (°C) | Secchi Disc (meters) | Light Intensity (Langleys/day) | Photo-period (%/day) | Wind (km/hr) | Chl a (µg/l) | Inorg. N (mg/l) | Ortho P (mg/l) |
|---|---|---|---|---|---|---|---|---|
| Storm 2 | | | | | | | | |
| Epilimnion | 19.5-20.6 | .69-1.02 | 108-490 | 5.55 | 3.2-19.3 | 80-136 | .35-2.03 | .02-.40 |
| Hypolimnion | 15.2-15.7 | -- | -- | -- | -- | 15- 25 | 1.5 -3.12 | .01-.25 |
| Storm 3 | | | | | | | | |
| Epilimnion | 20.2-20.7 | .80-1.27 | 25-386 | 50.7 | 1.6-25.7 | 100-160 | .23-4.20 | .03-.31 |
| Hypolimnion | 15.6-15.7 | -- | -- | -- | -- | 20- 29 | 1.98-4.04 | .06-.66 |
| Storm 4 | | | | | | | | |
| Epilimnion | 20.6-21.7 | 1.40-3.01 | 10-256 | 45.2 | 1.6-18.8 | 1- 2.4 | .26-3.43 | .01-.24 |
| Hypolimnion | 16.0-17.0 | -- | -- | -- | -- | 0.6- 2.4 | 1.43-4.46 | .12-.67 |
| Storm 5 | | | | | | | | |
| Epilimnion | 18.6-19.1 | 1.58-3.71 | 20-160 | 41.0 | 3.2-19.3 | 4.5-10.0 | 1.43-3.65 | .05-.70 |
| Hypolimnion | 16.4-17.3 | -- | -- | -- | -- | 4.7-13.0 | 2.13-4.56 | .10-.75 |
| 1975 Average | | | | | | | | |
| Epilimnion | 13.3 | 0.77 | 360 | 50.8 | 12.9 | 58.6 | 2.53 | 0.15 |
| Hypolimnion | 8.0 | -- | - | -- | -- | 10.7 | 4.57 | 0.43 |

nutrients and wind. These initial water quality conditions were determined directly from the monitoring data for the calibrations and represent the first point of model output for each simulation.

The system kinetics have been established such that they closely predict the lake quality for these four storm events. The following sections describe the calibration of the fecal coliform, BOD-DO, and total inorganic phosphorus models.

## Calibration and Verification

Model calibration and verification were conducted systematically to insure the authenticity of the model in describing lake processes. As previously stated, the model was calibrated first in a steady-state mode with the average of the 1975 monitoring data. Additional calibration was performed with data from Storm 5 to provide final refinement of all model reaction coefficients. Finally, the model was verified against data from Storms 2, 3 and 4. All model simulations ultimately used the same reaction coefficients (Tables 8 and 16); however, environmental conditions, loading rates, and circulation patterns were altered consistent with the characteristics of each specific storm event.

Storm 5 was selected for model calibration because this storm had the most extensive data base and occurred during a period of steady winds and constant lake circulation. Also, photosynthesis was minimal during this period since relatively low levels of algal standing crop were present at that time.

Steady-state model calculations are compared with the average of the 1975 monitoring data in Table 17. The model results compare well with the measured lake concentrations, considering the complexities of the lake dynamics and the associated limitations of a steady-state model to describe a system with many transient processes. Two examples of these complexities

TABLE 16

DISSOLVED OXYGEN REACTION COEFFICIENTS

| Symbol | Coefficient Designation | Reaction Coefficient |
|---|---|---|
| $K_a$ | Reaeration Coefficient | * |
| Y | mg $O_2$/mg Chl a | 266 mg $O_2$/mg Chl a |
| $I_s$ | Algal Light Saturation Constant | 240 Langleys/day |
| $K_N$ | Saturation Constant - Inorganic Nitrogen | 0.015 mg N/l |
| $K_P$ | Saturation Constant - Soluble Reactive Phosphorus | 0.0025 mg P/l |

*Varies with wind speed; see Figure 11.

TABLE 17

MODEL CALIBRATION
1975 YEARLY MONITORING DATA

| Parameter | Epilimnion | | Hypolimnion | |
|---|---|---|---|---|
| | Model Calculations | Measured Data | Model Calculations | Measured Data |
| $BOD_5$* (mg/l) | 4.7 | 4.6 | 8.5 | 8.3 |
| TKN (mg/l) | 2.5 | 2.6 | 4.7 | 4.6 |
| DO (mg/l) | 8.0 | 7.0 | 1.2 | 2.2 |
| Phosphorus (mg/l) | 0.23 | 0.24 | 0.55 | 0.54 |
| Fecal (counts/100ml) | 1,540 | 2,100 | 156 | 180 |

*Corrected for algal respiration.

are the phytoplankton dynamics and the seasonal variations of dissolved oxygen concentrations.

Model calculations for Storm 5 are compared with observed data in Figures 34 through 38. The lines represent the model calculations, whereas the squares represent observed data. After hour 120, two different calculations are presented. The solid line represents model calculations using the circulation pattern defined in the previous 120 hours of simulation. The dotted line represents model predictions with a reverse pattern of circulation, as observed in the field measurement. Measurements of wind and current suggest a dramatic reversal in lake conditions between hours 100 and 120. Display of the two simulations is intended to demonstrate the effect of this change on the water quality calculations.

The model calculations for Storm 5 compare very well with the observed data. The model and data show a significant increase of fecal coliform levels in response to storm overflows. This increase is transported around the lake but decreases in intensity because of die-off and settling. With the exception of some random variations, the model and data show very little change in phosphorus and NBOD concentrations as a result of the storm load. Storm overflows appear to have only minor influence on these parameters. The CBOD model calculations and data show small increases in concentrations caused by the stormwater runoff; however, the observed increase is rapidly dispersed due to mixing processes in the lake. The model and data show a small 1 to 2 mg/l depletion of dissolved oxygen. Model sensitivity analyses have shown these changes are related primarily to phytoplankton activity and varied wind-induced reaeration and only remotely to storm runoff.

Model calculations for Storm 4 are compared with the measured data in Figures 39 through 43. The model calculations again agree closely with observed data. The model calculations and data show an initial peak of fecal coliform concentrations. These elevated concentrations travel along the path

of the lake circulation but decrease in intensity due to die-off and settling. No significant variations in phosphorus are observed except for the inherent erratic variations in the data. The observed CBOD and NBOD concentrations are slightly higher at the start of the simulation but quickly decrease and disappear due to mixing and decomposition. Dissolved oxygen depletion and recovery is observed in the data which is partially predicted by the model. Model sensitivity analyses have shown that this depletion is not due directly to the storm loading, but is rather the result of intra-lake transport of waters with very low dissolved oxygen.

Model calculations for Storm 2 are compared with observed data in Figures 44 through 48. The model and data are in acceptable agreement. As usual, the model and data show significant fecal coliform dynamics. Phosphorus and NBOD concentrations display only minor variations with the data, demonstrating random scatter. CBOD concentrations are observed and predicted to increase in concentration during the survey. Analyses indicate that these increases are a consequence of internal algal production of CBOD (autochthonous load) and not a result of storm loadings. Furthermore, the increases in CBOD concentrations are not in phase with the storm loading. Autochthonous production has been estimated to be an order of magnitude greater than the Storm 2 CBOD loading. Observed and calculated dissolved oxygen concentrations increase from 3 to 4 mg/l prior to the storm to near saturation at the end of the survey. These dissolved oxygen changes are caused by variations in photosynthetic algal production and do not represent a recovery from a storm-induced depletion. The model predicts significant diurnal variations in dissolved oxygen. The frequency of sampling was insufficient to fully verify the diurnal calculations since lake samples were collected only during daylight hours.

Model calculations for Storm 3 are compared with observed data in Figures 49 to 52. Fecal coliform calculations are not presented because of a gross inconsistency between the loads and observed lake data. However,

the model and data are in acceptable agreement for NBOD, CBOD, dissolved oxygen, and phosphorus. As in the other simulations, NBOD and phosphorus show only minor changes. However, CBOD varies significantly. This variation is again in response to changes in autochthonous algal production and not storm loadings. A dramatic increase in dissolved oxygen was observed in the lake after the storm. Model sensitivity analyses have demonstrated that the decrease in dissolved oxygen is not in response to storm runoff but is caused by a small die-off of algae and reduced incident light which reduces photosynthesis but does not affect algal respiration. This simulation best exemplifies the importance of chlorophyll a and light to the dissolved oxygen resources of the lake.

In summary, the Onondaga Lake model has been calibrated and verified using five sets of lake water-quality data. The modeling analyses demonstrate that lake water quality is very sensitive to storm loads of fecal coliform; however, the lake concentrations of NBOD, CBOD, dissolved oxygen and phosphorus are much less sensitive to storm-related loads. Major variations in dissolved oxygen and CBOD are caused by changes in chlorophyll a, light, and other factors related to algal productivity. Random limnological processes and sampling inconsistencies produced minor erratic variations in the data which cannot be predicted by the model.

# CHAPTER V

## MODEL SENSITIVITY ANALYSIS

In order to demonstrate the accuracy of the calibrated Onondaga Lake model and to determine its applicability to projection of lake response under future conditions, extensive sensitivity analyses on model coefficients and environmental conditions were performed. These analyses also were conducted to investigate previous assertions concerning the relative significance to lake quality of various lake processes, such as the effect of algal productivity on the lake's dissolved oxygen levels. Steady-state and dynamic modeling analyses were used to evaluate the effect of changes in circulation, biochemical and physical removal rates, influent loads, algal productivity, and sediment oxygen demand.

Model reaction and settling coefficients for BOD, total phosphorus and fecal coliform were determined using modeling analyses and laboratory die-off studies. Verification analyses had demonstrated that these coefficients were reasonable, but the NBOD and CBOD rate coefficients used did not agree with the "bottle" rate coefficients determined from laboratory data. Model sensitivity analyses were conducted to evaluate the significance of this discrepancy. Model calculations were performed using the steady-state model to show the effect of increasing and decreasing the model rate coefficients by 25 percent. A model run was also made using the deoxygenation rate coefficients determined in the laboratory "bottle" studies (Table 5). These model calculations are compared with 1975 field (observed) data and with calibrated model calculations in Table 18. It is apparent that changes of 1.25 and 0.75 of the calibrated values have minor effects on model results, but that the "bottle" rate coefficients yield results that are grossly inconsistent with the observed data.

TABLE 18

SENSITIVITY ANALYSIS
REACTION RATES

| | 1975 Observed Data (mg/l)* | Model Results (mg/l)* | | | |
|---|---|---|---|---|---|
| | | Calibrated 1975 Model @ K=$K_{model}$ | Sensitivity Analysis | | |
| | | | K=1.25$K_{model}$ | K=0.75$K_{model}$ | "Bottle" Rates |
| Fecal Coliform | | | | | |
| Epilimnion | 2,100 | 1,540 | 1,190 | 2,010 | -- |
| Hypolimnion | 180 | 160 | 110 | 250 | -- |
| Phosphorus | | | | | |
| Epilimnion | .24 | .24 | .21 | .28 | -- |
| Hypolimnion | .54 | .55 | .56 | .56 | -- |
| $BOD_5$ (Deoxygenation) | | | | | |
| Epilimnion | 4.6 | 4.7 | 3.7 | 6.1 | 2.5 |
| Hypolimnion | 8.3 | 8.4 | 7.2 | 10.5 | 3.9 |
| TKN | | | | | |
| Epilimnion | 2.6 | 2.5 | 2.3 | 2.8 | 0.4 |
| Hypolimnion | 4.6 | 4.7 | 4.7 | 4.7 | 0.3 |
| Dissolved Oxygen | | | | | |
| Epilimnion | 7.0 | 8.2 | 8.0 | 8.6 | 3.1 |
| Hypolimnion | 2.2 | 1.2 | 0.5 | 2.3 | -6.1 |

*Fecal coliform units = cells/100ml.

Note: All concentrations apply to South lake basin. All analyses based on steady-state model projections.

Steady-state model calculations with varying fecal coliform removal rates are also given in Table 18. These results generally support the use of the die-off coefficients determined during laboratory studies.

## DEOXYGENATION RATES

Model sensitivity analyses were conducted using Storm 5 to further examine the discrepancy between model and bottle deoxygenation rate coefficients. Storm 5 was selected for these analyses because of minimum interference from algal productivity and minimal variability in wind and circulation patterns. Plots of the model output comparing the model deoxygenation and bottle rates with observed data are shown in Figures 53 through 55. Concentrations calculated using the model deoxygenation coefficients (solid line) better match the observed data than do those calculated with the bottle rates (dashed line).

It is not uncommon to observe differences between "in-situ" model reaction coefficients and laboratory bottle deoxygenation rate coefficients. There are several factors which can explain the difference for Onondaga Lake which relate to the favorable conditions under which the laboratory rates are determined. First, the laboratory studies were conducted on aerated samples, whereas the "in-situ" lake conditions often were low in dissolved oxygen. Certain bacteria (particularly nitrifiers) are very sensitive to low oxygen conditions. Second, toxic compounds may inhibit the lake bacterial processes. Dilution of lake waters and sample seeding with active bacterial cultures could produce rates much higher than true "in-situ" values. Thirdly, since the BOD bottles are incubated in the dark, the algae present respire, utilizing oxygen. This oxygen uptake produces an apparent BOD very early in the test. This factor is probably most responsible for the high "bottle" deoxygenation rates. Finally, the uptake of nitrate by algae in the lake produces organic nitrogen (NBOD) and also frees oxygen for algal respiration. The Onondaga Lake model uses net NBOD removal coefficients

that account for this process; however, laboratory bottle studies are conducted in the dark and therefore do not allow algal nutrient uptake or cell growth.

## ALGAL PRODUCTIVITY

The steady-state model sensitivity results presented in Table 19 demonstrate the importance of algal productivity levels to the lake's dissolved oxygen budget. The model internally calculates productivity using results from light-dark bottle studies and average measured values of chlorophyll a, nutrients, temperature and water transparency. An exact agreement between model calculations and data is not expected because of uncertainties in the data and the imperfect model representation of the process kinetics. However, as may be seen from the results, use of the verified model coefficients produced the best overall comparison between model and data.

TABLE 19

SENSITIVITY ANALYSIS PRODUCTIVITY
STEADY-STATE MODEL

| | Dissolved Oxygen (mg/l) | |
|---|---|---|
| | Epilimnion | Hypolimnion |
| Measured (1975 Average Yearly) | 7.0 | 2.2 |
| Calibrated Model (Average Yearly Productivity) | 8.2 | 1.2 |
| Net Productivity Increased by 25% | 9.7 | 2.7 |
| Net Productivity Decreased by 25% | 6.9 | 0.0 |

Model sensitivity calculations were also conducted for Storm 2 to demonstrate the importance of algal productivity. Model calculations which include and exclude algal productivity are compared in Figures 56 and 57.

The dashed line represents calculated concentrations assuming zero algal productivity. It is observed that without algal productivity, the model does not calculate reasonable concentrations for dissolved oxygen and CBOD. Furthermore, other model coefficients could not be adjusted within reasonable limits to compensate for the absence of productivity.

Model input for pollutant loads and lake circulation were determined from direct measurements. Continuous measurements of loads and more extensive measurements of lake circulation were impractical for this study. As a result, high frequency transient variations in these inputs could have occurred and not been observed in the data collection phase. Model sensitivity analyses have demonstrated that these variations can account for some of the observed scatter in the monitoring data.

## SEDIMENT OXYGEN DEMAND

The model coefficient for sediment oxygen demand was determined from direct measurements (1). The measured values were significantly less than benthal demands observed in other eutrophic systems. However, model sensitivity analyses have shown that the benthal oxygen demand is not important to stormwater modeling. Although the sediment oxygen demand may be very important to baseline dissolved oxygen conditions, it does not significantly affect hypolimnetic dissolved oxygen calculations during short-term model simulations at the low dissolved oxygen concentrations observed in the hypolimnion. These factors support the use of the exceptionally low sediment oxygen demands at least until increased concentrations of the hypolimnetic dissolved oxygen are realized.

Numerous other model sensitivity simulations were conducted to substantiate the model coefficients selected. The results of these sensitivity analyses demonstrate that the coefficients in the Onondaga Lake model are reasonably accurate.

# CHAPTER VI

# RESULTS

## HYDROGRAPHS

The hydrographs for the four major lake tributaries (Onondaga Creek, NineMile Creek, Ley Creek and Harbor Brook) are presented for all five storms in Figures 14 through 33. All data presented in these figures are based on provisionsal USGS gage records. Flow data for the East Flume was provided by Allied Chemical Corporation. Flows for Allied Chemical's East Flume and the remaining tributaries are presented in the "Summary of Data" found in Appendix A. The difference in response of the tributaries to the various storms observed gives an indication of both the location of the storm center and the type of drainage basin, including size, land use, and existence of CSO's.

As noted on Figures 15, 19 and 31, these hydrographs for NineMile Creek were generated from gage records at Camillus due to lack of records at the Lakeland gage. Figures 14 through 17 present the hydrographs for the four measured tributaries to Onondaga Lake for Storm 1, which occurred June 22 through 26, 1976. As may be seen from these figures, both Onondaga Creek and Harbor Brook respond very rapidly to rainfall. This response is a result of their highly urbanized drainage basins containing the major share of the Syracuse combined sewer system. The imperviousness of the urban area provides for rapid, short-lived peaks corresponding closely to the duration of a rainfall event. Ley Creek, on the other hand, responds much more slowly and over a prolonged period of time. This dampening is a result of the more pervious nature of the drainage basin. Figure 15 does not show a peak flow response by Storm 1, primarily because the recording gage at Lakeland was inoperable at the time and the flows were projected from a flow gage

approximately seven miles upstream (Camillus, New York). It is apparent from the results that rainfall did not occur in the upland drainage basin; nevertheless, these data provided the necessary input to the model.

The hydrographs for Storms 2 and 3, which occurred July 12 through 17, 1976, and August 5 through 11, 1976, are presented in Figures 18 through 25. The response of Onondaga Creek is a combination of abrupt changes resulting from the combined sewer overflow discharges and a gradual increase in baseline flow from the upland portion of the drainage basin. Harbor Brook, on the other hand, due to its small drainage area, responds primarily to its combined sewer overflow discharges. Both Nine Mile Creek and Ley Creek reflect the influence of upland drainage areas. Both these streams respond very gradually to storms, even though a portion of the Ley Creek drainage basin receives combined sewer overflows.

The hydrographs for Storm 4, August 26 through September 1, 1976, are presented in Figures 26 through 29. The brunt of the storm was felt on the east side of Syracuse, as evidenced by the dramatic response of Ley Creek to the rainfall; the other tributaries responded only marginally.

Monitoring for Storm 5 extended from September 15 through 22, 1976. Its hydrographs are summarized in Figures 30 through 33. Onondaga Creek, Harbor Brook and Ley Creek all show a three-peaked response to the rainfall. Both Onondaga Creek and Harbor Brook had an extremely short-lived response, indicating that the rainfall occurred primarily within the drainage area of the combined sewer system and was not an areawide storm affecting the upland drainage basins. Ley Creek shows the same three peaks dampened, as in previous storms, by the pervious nature of the drainage basin. The flow in NineMile Creek again did not respond to the storm, probably because the flows were generated from the gage at Camillus and did not reflect the true conditions in the lower drainage basin immediately above Lakeland.

## POLLUTANT LOADS

Tables 9 through 13 summarize the pollutant loadings of the major tributaries for Storms 1 through 5. The average loading rate in terms of pounds per day is calculated over the entire period for which sampling was conducted and reflects baseline as well as storm-related pollutant loads. The peak rates are instantaneous measurements and provide an indication of the storm-related CSO discharge. The loading rates for both the East Flume and Nine-Mile Creek were corrected for the background water quality of Onondaga Lake which served as the source for industrial cooling water. Loading rates were not included for Bloody Brook or the "steel mill" stream since their impact on the lake as a whole was relatively mnior, which is not to say that these inputs, especially Bloody Brook's, do not have localized impact on the lake. Such impact was not within the purview of this study, but owing to the proximity of this discharge to potential recreation areas, it will have to be studied prior to lake use.

The loadings for the various storms demonstrate a consistent pattern in terms of percent contribution of certain constituents; this can be attributed in large part to the influence of dry weather loads. The Metropolitan Sewage Treatment Plant is by far the major contributor of oxygen-demanding materials and nutrients and will continue in this role until construction of the advanced waste treatment facility is completed. Once this facility is placed in operation, Onondaga Creek will become the most significant contributor of these pollutants during storm periods. Onondaga Creek currently provides the major input of bacteriological contaminants, ranging from 67 to 85 percent of the total input for the storms monitored. During the severe storm periods, NineMile Creek supplied a surprisingly high amount of BOD, ranging from 30 to 48 percent of the total contribution, which is attributed to the impact of infiltration/inflow on several upstream treatment facilities. The East Flume is a consistent contributor of total kjeldahl nitrogen (TKN) during dry weather as well as storm periods.

The individual loadings are further discussed later in this chapter.

## BACTERIAL CONTRIBUTIONS

### Measured Results

Ideally, the suitability of a body of water for contact recreation should be determined by testing for the entire range of waterborne pathogens, but this type of testing program is prohibitive because of the number of possible pathogenic organisms, the time requirements of the tests, and the complex laboratory techniques required. To expedite the analytical process, several procedures have been developed which test for bacteria whose presence has been correlated to the presence of pathogens (Appendix B). The two most commonly-used tests for indicator organisms are the total coliform (TC) and fecal coliform (FC) determinations. Since the TC group includes soil bacteria (28), their presence does not necessarily signify fecal contamination or the presence of pathogens, hence TC is generally considered a poor indicator of human pathogens. The FC group, however, has been shown to correlate well with fecal contamination from warm-blooded animals. This group in itself does not distinguish between human and animal sources of pollution. The ratio of fecal coliform to fecal streptococci (FS) has been used (29) effectively to distinguish the source of the fecal contamination. It has been proposed that the ratios be interpreted as shown in Table 20.

TABLE 20

SIGNIFICANCE OF FECAL COLIFORM TO FECAL STREPTOCOCCI RATIOS

| Fecal Coliform to Fecal Streptococci Ratio | Origin of Contamination |
|---|---|
| > 4.0 | Human |
| 0.7 - 4.0 | Combined human and animal |
| < 0.7 | Non-human contamination |

A further discussion of the bacteriological significance of the various indicator organisms is presented in Appendix B.

Table 21 depicts the FC/FS ratios for the major tributaries to Onondaga Lake. These ratios represent the average values observed during each of the storms monitored. For Onondaga Creek and Harbor Brook, data are presented for both the station above the combined sewer overflow system and the station at the mouth of the tributary. Instantaneous FC/FS ratios for Dorwin Avenue (not shown) indicate that at certain times, upstream contamination was contributed from human sources; however, on the average, the human contribution from upstream is minimal. The data collected at Spencer Street, downstream of the urban sources, show that on the average the contribution of bacteria is primarily from human sources; this is true for values sampled before, during and after a storm.

The upstream data presented for Harbor Brook indicate that human bacterial contamination usually is present. Harbor Brook, just prior to entering Onondaga Lake, generally contains high levels of fecal coliform and high FC/FS ratios, indicating predominantly human contamination.

The average FC/FS ratios for Ley Creek indicate that the bacterial contribution comes primarily from animal sources. Analysis of the individual data within the storm, however, does indicate that at times the contribution can be primarily human, which is to be expected with any stream receiving discharges from combined sewer overflows. NineMile Creek, due to its brackish nature, is an effective "disinfectant" and at the present time both fecal coliform and fecal streptococci concentrations entering the lake are negligible. In the future, however, when a high percentage of the inorganic salts will be diverted from NineMile Creek, the bacterial contribution from upstream may become significant.

Tables 9 through 13 present the average daily and instantaneous peak FC and FS loads measured in the major tributaries. These tables show that

TABLE 21

AVERAGE FC/FS RATIO*
FOR ONONDAGA LAKE TRIBUTARIES

| Tributary | FC/FS Storm No. 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Onondaga Creek | | | | | |
| Upstream-Dorwin Avenue | 1.7 | 3.3 | 0.8 | 1.3 | 2.0 |
| Downstream-Spencer Street | 19.3 | 27.3 | 6.1 | 7.5 | 6.1 |
| Harbor Brook | | | | | |
| Upstream-Velasko Road | 0.05 | 15.3 | 3.2 | 2.7 | 3.1 |
| Downstream-Hiawatha Boulevard | 6.4 | 20.2 | 9.2 | 4.4 | 11.8 |
| Ley Creek | 5.26 | 11.8 | 0.6 | 1.5 | 1.3 |
| NineMile Creek | -- | -- | -- | -- | -- |
| No. of Days/Storm | 3.2 | 6.6 | 7.3 | 4.1 | 7.5 |

*Ratio of areas under pollutographs for entire period monitored.

Onondaga Creek is the major contributor of fecal coliforms to Onondaga Lake. The contribution from this source represents between 75 and 93 percent of the fecal coliforms discharged to the lake, based on average loadings over the entire period monitored. On a peak basis, Onondaga Creek is also the major contributor of coliforms because of its highly urbanized lower drainage basin and the number of combined sewer overflows it receives. Ley Creek and Harbor Brook are also major contributors of fecal coliforms to the lake. Ley Creek discharges large quantities of bacteria primarily during storms, but Harbor Brook can, at times, discharge large quantities of bacteria during dry-weather periods.

In summary, the primary contributors of human fecal contamination to Onondaga Lake are Onondaga Creek and Harbor Brook. Both these tributaries are contaminated primarily from discharges located within the City. During several storms, however, significant human contamination was noted from upstream sources. As shown in Tables 8 through 12, Ley Creek can be a major contributor of fecal coliform, but the FC/FS ratios generally indicate animal contamination except during the more severe storm periods.

## Fecal Coliform Model Projections

The utility of a receiving water model is demonstrated by its ability to project ecosystem responses to pollutant loads under critical environmental conditions. Of importance to such projections is selection of appropriate critical temperatures and critical conditions of pollutant transport. In the case of fecal coliforms, the organisms persist longer at low temperatures than at high ones; therefore, the temperature used for the Onondaga Lake model was only 20°C (68°F). Historical monitoring records compiled over the previous eight years showed that the epilimnetic temperature generally exceeded 20°C during the recreation season. Rapid transport, which generally occurs at high wind speeds, is also critical to fecal coliform projections since it may allow bacteria to reach proposed recreation areas before significant die-off occurs.

In the case of Onondaga Lake, wind speed did not correlate well with circulation patterns; therefore, the selected transport velocity was the maximum prolonged current measured during this study. The value used for the in-lake transport of fecal coliform was 6.3 miles/day (11.8 cm/sec). Along with this high-speed current, a low dispersion coefficient was used which maintained the peak slug of bacteria from the combined sewer system intact as it was transported around the lake. Under these severe conditions, the coliform peak was transported to the recreational (Class "B") zone within a ten-hour period following the storm.

The total pollutant load on the lake is comprised of both dry-weather and wet-weather components. The wet-weather component was determined through a detailed combined sewer overflow study (30), and the resulting wet-weather loads are summarized in Table 22. The dry-weather components were determined through analysis of historical monitoring data (2, 27, 31). The dry-weather fecal coliform loads are listed in Table 23.

A loading curve which defines the in-lake response to a particular waste discharge was formulated for fecal coliforms. Figure 58 shows that discharges exceeding $2.5 \times 10^4$ cells/day violate standards in the epilimnion of the contact recreation zone. As shown on this figure, two orders of magnitude of reduction of all wet-weather discharges associated with a one-year, two-hour storm are required to maintain Class "B" standards in the area proposed for contact recreation.

## DISSOLVED OXYGEN BALANCE

It is difficult to interpret the observed fluctuations of dissolved oxygen without the aid of a mathematical model. Because so many factors enter into the oxygen balance, it is difficult by observation to determine quantitatively which sources are contributing to the oxygen depletion at any particular time. The factors influencing the sag for Onondaga Lake include:

TABLE 22

WET-WEATHER POLLUTANT LOAD

| Tributary | Flow (mgd) | Influent Load (lbs/day) Carbonaceous BOD | Ammonia Nitrogen | Organic Nitrogen | Total Inorganic[2] Phosphorus | Fecal Coliform[3] |
|---|---|---|---|---|---|---|
| ONE-YEAR, TWO-HOUR STORM | | | | | | |
| Onondaga Creek | 182.4 | 138,200. | 3,790. | 2,110. | 480. | 13.0 |
| Ley Creek | 48.0 | 16,600. | 120. | 310. | 58. | 7.2 |
| Harbor Brook | 28.8 | 19,400. | 130. | 365. | 48. | 3.2 |
| TWO-YEAR, TWO-HOUR STORM | | | | | | |
| Onondaga Creek | 330.7 | 250,700. | 6,850. | 3,795. | 870. | (4) |
| Ley Creek | 72.5 | 24,900. | 180. | 470. | 87. | (4) |
| Harbor Brook | 50.2 | 34,000. | 225. | 635. | 87. | (4) |
| TEN-YEAR, TWO-HOUR STORM | | | | | | |
| Onondaga Creek | 548.6 | 415,500. | 11,355. | 6,308. | 1,426. | (4) |
| Ley Creek | 154.3 | 53,200. | 387. | 1,011. | 185. | (4) |
| Harbor Brook | 68.6 | 46,300. | 113. | 864. | 113. | (4) |

(1) Wet weather pollutant loads and flow for the 1-, 2- and 10-year storms were applied at these rates over 5, 5.5 and 7 hours, respectively.

(2) Due to the long-term effect of phosphorus loads, average daily wet weather loads were entered into the steady state model.

(3) Units = $10^{15}$ cells/day.

(4) The impact of these loads was not modeled since dramatic effects were noted at a much lower loading level.

TABLE 23

DRY-WEATHER POLLUTANT LOADS

| Tributary | Flow (mgd) | Influent Load (lbs/day) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Carbona-ceous BOD | Ammonia Nitrogen | Organic Nitrogen | Dissolved Oxygen | Total Inorganic Phosphorus(1) | Fecal Coliform(2) |
| MSTP(3) | 80.0 | 5,000. | -- | 6,670. | 1,335. | 665. | 0.60 |
| Onondaga Creek | 100.0 | 5,170. | 590. | 785. | 2,000. | 248. | 65.20 |
| Ley Creek | 28.0 | 1,775. | 320. | 110. | 1,070. | 183. | 1.81 |
| Harbor Brook | 10.0 | 1,510. | 145. | 110. | 250. | 88. | 29.20 |
| NineMile Creek | 123.0 | 4,190. | 820. | 550. | 1,760. | 131. | 0. |
| Allied Chemical East Flume | 56.0 | 735. | 1,350. | 500. | 1,600. | 7. | 0.54 |
| Crucible Steel | 0.4 | 65. | 10. | 5. | 40. | 4. | 0.006 |
| TOTALS | 397.4 | 18,445. | 3,235. | 8,730. | 8,055. | 1,326. | 97.36 |

(1) Average daily loading rate based on yearly monitoring data; not dry weather loads.
(2) Units = ($10^{12}$ cells/day)
(3) Loads based on tertiary treatment at Metropolitan Sewage Treatment Plant.
(4) 1 kg = 2.2 lbs.

1. Organic material, both nitrogenous and carbonaceous, discharged directly to the lake from tributaries.

2. Oxygen added to the lake through photosynthetic production.

3. Oxygen removed from the lake through photosynthetic respiration.

4. Oxygen added to the lake through reaeration (which is not added at a constant rate and is dependent on wind speed).

5. Oxygen depletion as a result of organic loads contributed from algal die-off (autochthonous load).

Because of these complicating factors, the observed dissolved oxygen fluctuations could not be explained without the aid of mathematical modeling.

## Dissolved Oxygen Model Projections

The environmental conditions which produce critical in-lake dissolved oxygen concentrations are converse to the critical conditions which produce maximum fecal coliform impact. The maximum impact on DO occurs when temperatures are high, minimizing the saturation of oxygen in water and maximixing the rate of organic decay as a result of oxidation by microorganisms. For Onondaga Lake, a maximum temperature of 25°C (77°F) was selected, based on eight years of monitoring data (2, 27, 31). The maximum epilimnetic temperature recorded during this period was approximately 25°C.

Wind speed enters directly into the dissolved oxygen model as the primary driving force for both transportation and reaeration (17). Figure 11, described previously, shows the relationship between wind speed and reaeration. In order to determine a realistically low wind speed, six years of local wind records were analyzed to determine the speed to be used for predictive purposes. The average monthly minimum seven-consecutive-day

wind speed was selected for use in the Onondaga Lake model since it was considered to represent realistic, critical conditions; the value used was 3.9 miles per hour (6.4 kilometers per hour). The in-lake transport velocity used in the predictive dissolved oxygen model was 1.1 miles per day (2.1 cm/sec). Since the dissolved oxygen goal is uniform for the entire lake, the transport speed enters into the critical conditions only insofar as it influences dilution. The lower the speed, the less dilution provided. The transport velocity of 1.1 miles per day corresponds closely to the time-averaged velocities observed in Storms 3, 4 and 5.

The dry-weather background loads utilized to project their impact on the dissolved oxygen concentration in Onondaga Lake are presented in Table 23. The transient wet-weather loads from the CSO's which were superimposed on the continuous dry-weather loads are presented in Table 22. Table 24 shows that the impact of even a ten-year return-period storm is minimal as far as dissolved oxygen is concerned. Assuming a circulation pattern which would produce no mixing or dilution (plug flow), the maximum lake dissolved oxygen deficit was 2.8 mg/l (Cell 1). This indicates that storm-induced loads have minimal effect on the DO of Onondaga Lake.

Based on the above findings, it was suspected that the controlling mechanism of the dissolved oxygen balance in the lake is presently, and will be in the future, the sudden die-off of algae (autocthonous load). As may be seen from Figure 59, the pre-storm dissolved oxygen conditions observed during the summer of 1976 closely parallel the pre-storm chlorophyll a concentrations. A die-off of 145 micrograms per liter chlorophyll a occurred between Storms 3 and 4. During this period the measured epilimnetic dissolved oxygen decreased by 8 mg/l. Since large algal die-offs are not uncommon for Onondaga, the impact of these fluctuations under estimated future conditions was investigated. Once the tertiary treatment facility is placed in service, it is projected that the remaining phosphorus load will

support a standing crop of 86 µg/l of chlorophyll a (32). The dissolved oxygen model was utilized to predict a die-off of this magnitude over a two-week period. The results of this model run produced a decrease in dissolved oxygen between 8 and 10 mg/l (Figure 60). Thus, algal die-off will be the major factor influencing dissolved oxygen in the lake, new point-source loadings notwithstanding.

## TOTAL PHORPHORUS

Due to the conservative nature of total phosphorus, the impact of phosphorus loads on Onondaga Lake was evaluated on an average basis. Table 23 presents the anticipated future average daily total phosphorus loads on Onondaga Lake once the MSTP is completed. These loads do not include the combined sewer overflow component. The average daily component from the combined sewer system is 12.7 pounds per day, which is less than 1 percent of the total of 1,326 pounds per day that the lake receives.

In order to evaluate the impact of the phosphorus loads on in-lake phosphorus concentrations, the steady-state model was run for the following two input conditions:

1. Average daily total inorganic phosphorus loads presented in Table 23, based on monitoring data, including projected phosphorus reductions at the MSTP.
2. Superimposing the CSO component (12.7 pounds per day) on the average daily loads presented in Table 23. Table 25 presents the results of these model runs.

As may be seen from Table 25, the 1 percent increase in load caused by combined sewer overflows produces approximately a 1 percent change in the in-lake concentrations. Since these wet-weather loads produce such a minute change in the lake's water quality, wet-weather treatment for phosphorus removal has not been considered in the final abatement plan.

TABLE 24

PROJECTED IMPACT OF WET-WEATHER LOADS
ON ONONDAGA LAKE

| | Pre-Storm | Storm Recurrence Interval 1 Year | 2 Years | 10 Years |
|---|---|---|---|---|
| FC (cells/100 ml)* | 120 | $10^4$ | ** | ** |
| TOR (days)*** | - | 3.3 | ** | ** |
| DO Deficit (mg/l) | 0 | 0.39 | 0.48 | 0.90 |
| TOR (days)*** | - | Negl. | 2.97 | 4.37 |

*Occurring in epilimnion of contact recreation zone.
**Not modeled since dramatic effects were noted with much more frequent storms. Two additional model runs were performed for storms occurring more frequently than once per year to define the loading curve (Figure 58).
***TOR (time of recovery) is the time required for the lake's water quality to return to ±5 percent of the background value.

TABLE 25

AVERAGE ANNUAL PHOSPHORUS CONCENTRATIONS
IN ONONDAGA LAKE

| Loading Condition | South Basin (mg/l) Epilimnion | Hypolimnion | North Basin (mg/l) Epilimnion | Hypolimnion |
|---|---|---|---|---|
| Average Daily: Without CSO Component | 0.221 | 0.508 | 0.204 | 0.495 |
| Average Daily: With CSO Component | 0.223 | 0.513 | 0.206 | 0.500 |

## SUSPENDED SOLIDS IN TRIBUTARIES

The increase in suspended solids resulting from storm-related runoff causes aesthetic deterioration of water quality, accelerates solids deposition, and provides a potential source of benthal oxygen demand.

The major sources of solids in Onondaga Lake are the chemical discharges via NineMile Creek, algal cell mass, non-point runoff from upland areas, and contributions of urban runoff (both CSO and non-point source).

As shown in Table 26, the major contributor of total suspended solids is NineMile Creek, which consistently discharges in escess of 200,000 pounds per day to the lake's northern basin. These solids, comprised primarily of calcium precipitates, are discharged by the chloro-alkali industry. During storms there is an increased discharge of solids which may be caused by two factors related to the industrial operation: Rainfall on the surface area of the waste beds to which the industry discharges can result in a greater volume of overflow from the waste beds, carrying with it a greater quantity of calcium precipitate; the higher stream flow may cause a scouring of the creek bottom, which also is comprised of calcium precipitates. For the five storms monitored during the summer of 1976, the volatile fraction of this source ranged from 8.6 percent to 16.8 percent (Table 27). It should be noted that the volatile solids test does not provide a true indicator of organics present, but rather reflects the breakdown of the calcium precipitates at the elevated temperature (550°C) used during this analysis (3).

Table 28 compares the contribution of solids from upstream sources to the total load that the lake receives from Onondaga Creek and Harbor Brook. As previously discussed, the upstream locations are situated above the City's combined sewer system and the downstream stations are located below the last CSO discharge, close to the point of discharge to the lake. As may be seen from these tables, the average and peak suspended solids load from upstream sources generally exceeds the load at the mouth of Onondaga Creek,

TABLE 26

TRIBUTARY LOADS OF TOTAL SUSPENDED SOLIDS
TO ONONDAGA LAKE

| Tributary | Total Suspended Solids Loading Rate (Lbs/Day) Storm No. 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Onondaga Creek | 45,380 | 55,170 | 25,790 | 20,330 | 11,120 |
| NineMile Creek | 236,740 | 262,840 | 236,330 | 126,140 | 200,680 |
| Ley Creek | 75,730 | 18,760 | 56,960 | 37,720 | 3,440 |
| Harbor Brook | 1,240 | 1,200 | 1,730 | 280 | 770 |
| | 359,090 | 337,970 | 320,810 | 184,470 | 216,010 |

| | % Contribution Storm No. 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Onondaga Creek | 12.6 | 16.3 | 8.0 | 11.0 | 5.1 |
| NineMile Creek | 65.9 | 77.8 | 73.7 | 68.4 | 92.9 |
| Ley Creek | 21.1 | 5.6 | 17.8 | 20.4 | 1.6 |
| Harbor Brook | 0.3 | 0.4 | 0.5 | 0.2 | 0.4 |
| | 99.9 | 100.0 | 100.0 | 100.0 | 100.0 |

TABLE 27

TRIBUTARY LOADS OF VOLATILE SUSPENDED SOLIDS*
TO ONONDAGA LAKE

| Tributary | Volatile Suspended Solids (Lb/Day) | | | | |
|---|---|---|---|---|---|
| | Storm No. | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| Onondaga Creek | 15,029 (33.1%) | 17,031 (30.9%) | 7,521 (29%) | 3,981 (19.6%) | 3,565 (32%) |
| NineMile Creek | 36,292 (15.3%) | 25,368 (9.7%) | 20,399 (8.6%) | 21,169 (16.8%) | 20,293 (10.1%) |
| Ley Creek | 25,869 (34.2%) | 2,435 13%) | 3,364 (5.9%) | 6,075 (16.1%) | 1,060 (30.8%) |
| Harbor Brook | 552 (44.5%) | 258 (21.5%) | 317 (18.3%) | 111 (39.6%) | 124 (16.1%) |
| | 77,742 | 45,092 | 31,601 | 31,336 | 25,042 |
| | % Contribution | | | | |
| | Storm No. | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| Onondaga Creek | 19.3 | 37.8 | 23.8 | 12.7 | 14.2 |
| NineMile Creek | 46.7 | 56.3 | 64.6 | 67.6 | 81.0 |
| Ley Creek | 33.3 | 5.4 | 10.6 | 19.4 | 4.2 |
| Harbor Brook | 0.7 | 0.6 | 1.0 | 0.4 | 0.5 |
| | 100.0 | 100.1 | 100.0 | 100.1 | 99.9 |

*Volatile suspended solids (VSS)
Note: ( ) = % volatile.

TABLE 28

COMPARISON OF SOLIDS CONTRIBUTION
FROM RURAL AND URBAN SOURCES

| Tributary | Storm No. | Suspended Solids Load (Lbs/Day) | | | |
|---|---|---|---|---|---|
| | | Upstream Location | | Downstream Location | |
| | | Avg. | Max. | Avg. | Max. |
| Onondaga Creek | 1 | --<br>-- | --<br>-- | --<br>-- | --<br>-- |
| | 2 | 179,000<br>(11,700) | 642,000<br>(51,000) | 55,200<br>(17,000) | 163,300<br>(75,300) |
| | 3 | 80,600<br>(6,700) | 435,000<br>(34,900) | 25,800<br>(7,500) | 79,800<br>(22,900) |
| | 4 | 53,900<br>(4,800) | 299,000<br>(34,300) | 20,300<br>(4,000) | 65,600<br>(12,900) |
| | 5 | 11,200<br>(1,800) | 33,100<br>(8,200) | 11,200<br>(3,600) | 110,000<br>(15,000) |
| Harbor Brook | 1 | --<br>-- | --<br>-- | --<br>-- | --<br>-- |
| | 2 | 1,385<br>(235) | 17,700<br>(1,890) | 1,200<br>(260) | 1,850<br>(1,210) |
| | 3 | 1,990<br>(190) | 33,300<br>(2,850) | 1,730<br>(320) | 37,570<br>(2,400) |
| | 4 | 540<br>(100) | 1,020<br>(540) | 280<br>(110) | 860<br>(390) |
| | 5 | 470<br>(100) | 860<br>(260) | 770<br>(120) | 22,700<br>(2,420) |

Note: Values in ( ) are VSS.

indicating that sedimentation occurs along the creek within the City limits. This observation is supported by the fact that periodic dredging is required along the creek. The average volatile suspended solids loads are generally slightly greater downstream, which reflects the CSO discharges.

## HEAVY METALS IN TRIBUTARIES

Heavy metals are prominent among the materials which can cause toxicity in aquatic ecosystems and have only rarely been monitored in previous storm (CSO) impact studies (33). The highly urbanized and industrialized character of the Onondaga Lake drainage basin and the lake's history of high heavy metal concentrations (1, 2, 27, 31) dictated the need for an assessment of storm-related loading conditions.

Table 29 presents various water quality standards for the heavy metals analyzed during this study. The New York State Standards are presently applicable to Onondaga Lake, but a revision of these criteria is currently being contemplated. Proposed New York State revisions are more stringent than those recommended by USEPA; however, as a result of public concern over the social and economic impact of the proposed standards, they have been withdrawn pending further evaluation. Since the USEPA has published a recent guide (28) to be considered by the individual states when formulating water-quality standards and New York State has yet to adopt a complete set of heavy metals standards, the USEPA recommended criteria were used in the following sections to evaluate the potential effects of the various metals concentrations.

Heavy metal loadings increased over dry-weather loadings in all tributaries during the monitoring storms. In general, the heavy metal concentrations found in the major tributaries did not fluctuate with increased runoff, and no correlation between flow and loading rate was discernible. Table 30 summarizes the heavy metal data from NineMile Creek, Onondaga Creek and Harbor Brook.

TABLE 29

SUMMARY OF WATER QUALITY STANDARDS
FOR HEAVY METALS

| Parameter | New York State | | USEPA (28) Recommended Criteria for Water Quality** (mg/l) |
|---|---|---|---|
| | Drinking Water Stds.* (mg/l) | Class B & C Water Quality Stds. (mg/l) | |
| Cadmium | 0.01 | 0.3 | 0.012 |
| Chromium | 0.05 | -- | 0.1 |
| Copper | 1.0 | 0.2 | 0.04*** |
| Lead | 0.05 | -- | 5.0*** |
| Zinc | 5.0 | 0.3 | 0.08*** |

*Identical to USEPA recommended criteria for drinking water.
**Based on data from waters similar to Onondaga Lake.
***Based on 96-hour tolerance limit (TL50) of fathead minnows.

TABLE 30

SUMMARY OF TRIBUTARY METALS DATA
STORMS IMPACT STUDY

| Parameter | USEPA Recommended Criteria (mg/l)(28) | Tributary Concentration (mg/l) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Onondaga Creek | | | Harbor Brook | | | NineMile Creek | | |
| | | Peak | Mean | Standard Deviation | Peak | Mean | Standard Deviation | Peak | Mean | Standard Deviation |
| Cadmium | 0.012 | 0.020 | 0.010 | 0.012 | 0.020 | 0.008 | 0.004 | 0.095 | 0.055 | 0.018 |
| Chromium | 0.1 | 0.050 | 0.020 | 0.012 | 0.100 | 0.037 | 0.030 | 0.075 | 0.039 | 0.013 |
| Copper | 0.04 | 0.070 | 0.019 | 0.010 | 0.062 | 0.019 | 0.010 | 0.210 | 0.060 | 0.027 |
| Lead | 5.0 | 0.160 | 0.049 | 0.030 | 0.130 | 0.062 | 0.028 | 0.560 | 0.324 | 0.103 |
| Zinc | 0.08 | 0.511 | 0.081 | 0.097 | 1.457 | 0.137 | 0.211 | 1.450 | 0.208 | 0.254 |

## Cadmium

Cadmium is an extremely toxic, naturally-occurring metal which has been reported to be present in only a small percentage of the waters of the United States (28). Its presence in natural waters is generally at a very low concentration - less than 1 µg/l (28). Comparisons of the cadmium data (Table 30) with the various water quality standards (Table 29) show that peak concentrations measured in Onondaga Creek and Harbor Brook violate the USEPA recommended criteria, but the mean concentrations do not exceed these levels. NineMile Creek is the major contributor of cadmium to the lake; the mean concentration in NineMile Creek far exceeds the recommended maximum concentration of .012 mg/l.

## Copper

The peak concentrations of copper measured in each of the tributaries exceed the USEPA recommended standards. On the average, the measured concentrations in Onondaga Creek and Harbor Brook were well below the recommended criteria. The mean concentrations of copper in NineMile Creek, on the other hand, violated the USEPA standard throughout the study.

## Lead and Chromium

The USEPA recommended concentrations for lead and chromium were never exceeded throughout the study.

## Zinc

Both the existing New York State Water Quality Standards and USEPA recommended criteria are violated in all of the major tributaries of Onondaga Lake.

## HEAVY METALS IN THE LAKE

The peak concentrations of cadmium (Table 31) in Onondaga Lake exceeded the USEPA recommended levels for all storm periods monitored. The magnitude of these peak concentrations relative to the mean indicates that the peaks could be random fluctuations of the data. The extremely high peak concentration (0.067 mg/l) measured during Storm 5 is so radically different from the other storms that it may have resulted from the disturbance of the flocculent sediment layer. Mean concentrations measured during the storm periods were approximately equal to the USEPA recommended maximum level (0.012 mg/l) for the entire summer. The annual monitoring program (34) shows the cadmium concentrations generally remain at this level for the entire year.

The peak concentrations of both chromium (Table 32) and copper (Table 33) periodically exceed the recommended standards for brief periods. However, the mean concentrations, which reflect their prolonged impact, were never observed to violate standards. The lead concentration (Table 34) throughout the lake remained well below the recommended standard for measurements.

The peak concentrations of zinc (Table 35) in both the epilimnion and hypolimnion greatly exceeded the recommended standard, and the mean concentrations occasionally exceeded the standard. During Storm 5, a dramatic increase in the lake's zinc concentration was observed. This peak occurred for a two-day period and then subsided. A corresponding peak in the tributary loads was not observed, but the sampling frequency used may not have been adequate to capture the peak load. This dramatic peak (an order of magnitude increase at some stations) resulted from a storm of relatively low intensity (Storm 5), whereas such an increase was not observed for the more severe storms (Storms 2 and 3). For this reason, it is speculated that the peaking of zinc concentration during Storm 5 was the result of a direct discharge and

not necessarily related to the storm. Review of the historic data shows that the magnitude of this peak is not unusual and appears to occur periodically. It is probable that these peaks occur occasionally but are undetected by the bi-weekly monitoring program.

TABLE 31

SUMMARY OF CADMIUM DATA
ONONDAGA LAKE

| Storm No. | Concentration (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Epilimnion | | | | Hypolimnion | | | |
| | Mean | Std. Dev. | Peak | N* | Mean | Std. Dev. | Peak | N* |
| 1 | 0.010 | 0.002 | 0.016 | 55 | 0.012 | 0.002 | 0.017 | 52 |
| 2 | 0.011 | 0.003 | 0.020 | 88 | 0.012 | 0.004 | 0.020 | 89 |
| 3 | 0.013 | 0.004 | 0.025 | 121 | 0.015 | 0.004 | 0.024 | 118 |
| 4 | 0.013 | 0.010 | 0.021 | 83 | 0.014 | 0.003 | 0.021 | 70 |
| 5 | 0.015 | 0.003 | 0.024 | 96 | 0.016 | 0.006 | 0.067 | 87 |

TABLE 32

SUMMARY OF CHROMIUM DATA
ONONDAGA LAKE

| Storm No. | Concentration (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Epilimnion | | | | Hypolimnion | | | |
| | Mean | Std. Dev. | Peak | N* | Mean | Std. Dev. | Peak | N* |
| 1 | 0.027 | 0.009 | 0.060 | 54 | 0.029 | 0.009 | 0.050 | 52 |
| 2 | 0.036 | 0.012 | 0.080 | 88 | 0.038 | 0.013 | 0.080 | 88 |
| 3 | 0.020 | 0.010 | 0.050 | 121 | 0.023 | 0.012 | 0.050 | 118 |
| 4 | 0.015 | 0.014 | 0.093 | 83 | 0.015 | 0.008 | 0.068 | 70 |
| 5 | 0.014 | 0.006 | 0.046 | 96 | 0.015 | 0.011 | 0.104 | 86 |

*N = Number of data points in set.

TABLE 33

SUMMARY OF COPPER DATA
ONONDAGA LAKE

| Storm No. | Concentration (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Epilimnion | | | | Hypolimnion | | | |
| | Mean | Std. Dev. | Peak | N* | Mean | Std. Dev. | Peak | N* |
| 1 | 0.011 | 0.002 | 0.020 | 54 | 0.010 | 0.000 | 0.015 | 52 |
| 2 | 0.018 | 0.005 | 0.040 | 88 | 0.020 | 0.005 | 0.040 | 89 |
| 3 | 0.019 | 0.004 | 0.032 | 119 | 0.020 | 0.006 | 0.061 | 119 |
| 4 | 0.026 | 0.009 | 0.069 | 83 | 0.026 | 0.007 | 0.052 | 70 |
| 5 | 0.021 | 0.007 | 0.044 | 96 | 0.022 | 0.006 | 0.033 | 87 |

TABLE 34

SUMMARY OF LEAD DATA
ONONDAGA COUNTY

| Storm No. | Concentration (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Epilimnion | | | | Hypolimnion | | | |
| | Mean | Std. Dev. | Peak | N* | Mean | Std. Dev. | Peak | N* |
| 1 | 0.077 | 0.025 | 0.130 | 53 | 0.097 | 0.030 | 0.160 | 52 |
| 2 | 0.096 | 0.042 | 0.300 | 88 | 0.104 | 0.037 | 0.200 | 89 |
| 3 | 0.085 | 0.030 | 0.160 | 120 | 0.097 | 0.029 | 0.160 | 118 |
| 4 | 0.085 | 0.024 | 0.180 | 83 | 0.103 | 0.020 | 0.160 | 70 |
| 5 | 0.089 | 0.021 | 0.130 | 95 | 0.088 | 0.025 | 0.140 | 87 |

*N = Number of data points in set.

TABLE 35

SUMMARY OF ZINC DATA
ONONDAGA LAKE

| Storm No. | Concentration (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Epilimnion | | | | Hypolimnion | | | |
| | Mean | Std. Dev. | Peak | N* | Mean | Std. Dev. | Peak | N* |
| 1 | 0.031 | 0.012 | 0.070 | 54 | 0.030 | 0.015 | 0.080 | 52 |
| 2 | 0.085 | 0.128 | 0.750 | 88 | 0.064 | 0.065 | 0.520 | 89 |
| 3 | 0.050 | 0.034 | 0.205 | 119 | 0.047 | 0.027 | 0.150 | 116 |
| 4 | 0.051 | 0.038 | 0.288 | 83 | 0.035 | 0.021 | 0.170 | 70 |
| 5 | 0.111 | 0.173 | 1.130 | 96 | 0.095 | 0.151 | 0.949 | 87 |

*N = Number of data points in set.

# CHAPTER VII

## CONCLUSIONS

1. Bacterial water-quality standards in Onondaga Lake are violated frequently as a result of wet-weather discharges. All storms sampled in this study showed fecal coliform levels in the northern basin in excess of NYSDEC Class "B" water-quality standards. Individual concentrations as high as 50,000 cells/100 ml were measured in the northern basin.

2. The allowable fecal coliform load for the lake is $2.5 \times 10^{14}$ cells/day in order to avoid exceeding a lake concentration of 200 cells/100 ml. This allowable load was determined from model projections at the critical environmental conditions selected for the study, and it includes both point and non-point sources of pollution.

3. Overflows from the combined sewer system are primarily responsible for the elevated levels of coliform bacteria in the lake. However, wet-weather contributions of bacteria to Onondaga Creek upstream of the combined sewer system were observed to exceed the allowable load for the lake during one storm. This observation indicates that bacterial contributions upstream of the City of Syracuse must be reduced to insure that water-quality standards are met.

4. Based on predictions of the calibrated fecal coliform model, untreated overflows resulting from a one-year, two-hour storm will result in a maximum fecal coliform concentration of greater than 11,000 cells/100 ml in the northern basin. It is predicted that a storm of this magnitude will cause water-quality standards to be violated for a period in excess of three (3) days. Thus, abatement of bacterial pollution will be required to assure the use of Onondaga Lake for contact recreation.

5. Unless dry-weather discharges of bacteria into Onondaga Creek and Harbor Brook are reduced, it is possible that these loads alone could cause contravention of the Class "B" standards in the lake.

6. Wet-weather discharge of organic material (carbonaceous and nitrogenous BOD) causes only minor depletions of dissolved oxygen in the lake. At the critical environmental conditions selected for the DO model, a ten-year, two-hour storm produces only a 2.8 mg/l deficit in dissolved oxygen.

7. Once the upgraded Metropolitan Sewage Treatment Plant is placed in operation, low levels of oxygen in Onondaga Lake will be a result of the abrupt die-off of algal biomass. A die-off over a two-week period equivalent to projected dry-weather concentrations of chlorophyll a can result in an oxygen deficit of 8 to 10 mg/l.

8. Abrupt algal die-offs of approximately 140 micrograms per liter over a two-week period were observed. These die-offs produced dramatic decreases in dissolved oxygen levels (> 8 mg/l).

9. Contributions of total phosphorus from the combined sewer overflows are negligible when compared to the anticipated future average daily loads. This component comprises less than 1 percent of the average daily load. Model runs demonstrated that the CSO discharges increase the average phosphorus concentration of the lake's epilimnion by only 0.002 mg/l, or by approximately 1 percent. With the lake receiving the phosphorus loads anticipated once the MSTP is completed, average in-lake concentrations are expected to be approximately 0.1 mg/l.

10. NineMile Creek is currently the major contributor of suspended solids to Onondaga Lake. This tributary was observed to contribute between 65 and 93 percent of the total suspended solids load. Onondaga Creek and Ley Creek also contributed significantly to the total suspended solids reaching the lake during the five storms monitored. Harbor

Brook, primarily by virtue of its low flow, contributed negligible quantities of solids (<0.5% of the total solids load).

11. For the majority of the storms, the suspended solids reaching the lake from Onondaga Creek and Harbor Brook were less than those contributed from non-point sources upstream of the City. However, the volatile suspended solids entering the lake from these two sources were generally slightly greater than those contributed from the upland areas.

12. In contrast to the consistently high load from NineMile Creek (approximately 200,000 pounds per day), the average daily loads contributed from the other sources during the storm periods represented only a small fraction of the total solids reaching the lake.

13. The heavy metals concentrations in Onondaga Lake are not greatly influenced by wet-weather discharges.

14. The cadmium concentrations in Onondaga Lake continuously fluctuate around the USEPA recommended standard of 0.012 mg/l.

15. The USEPA recommended criterion for zinc is periodically violated in Onondaga Lake.

16. Except for an occasionally high concentration, Onondaga Creek and Harbor Brook meet the recommended criteria for heavy metals.

17. NineMile Creek continually contains concentrations of cadmium, copper and zinc in excess of the USEPA's recommended levels.

18. The rural non-point contribution of BOD and TKN to both Onondaga Creek and Harbor Brook generally represents in excess of 25 percent of the total load contributed to the lake by these tributaries. The non-point contribution of total phosphorus to Onondaga Creek and Harbor Brook accounts for 27 and 16 percent, respectively, of the total load discharged by these tributaries to the lake.

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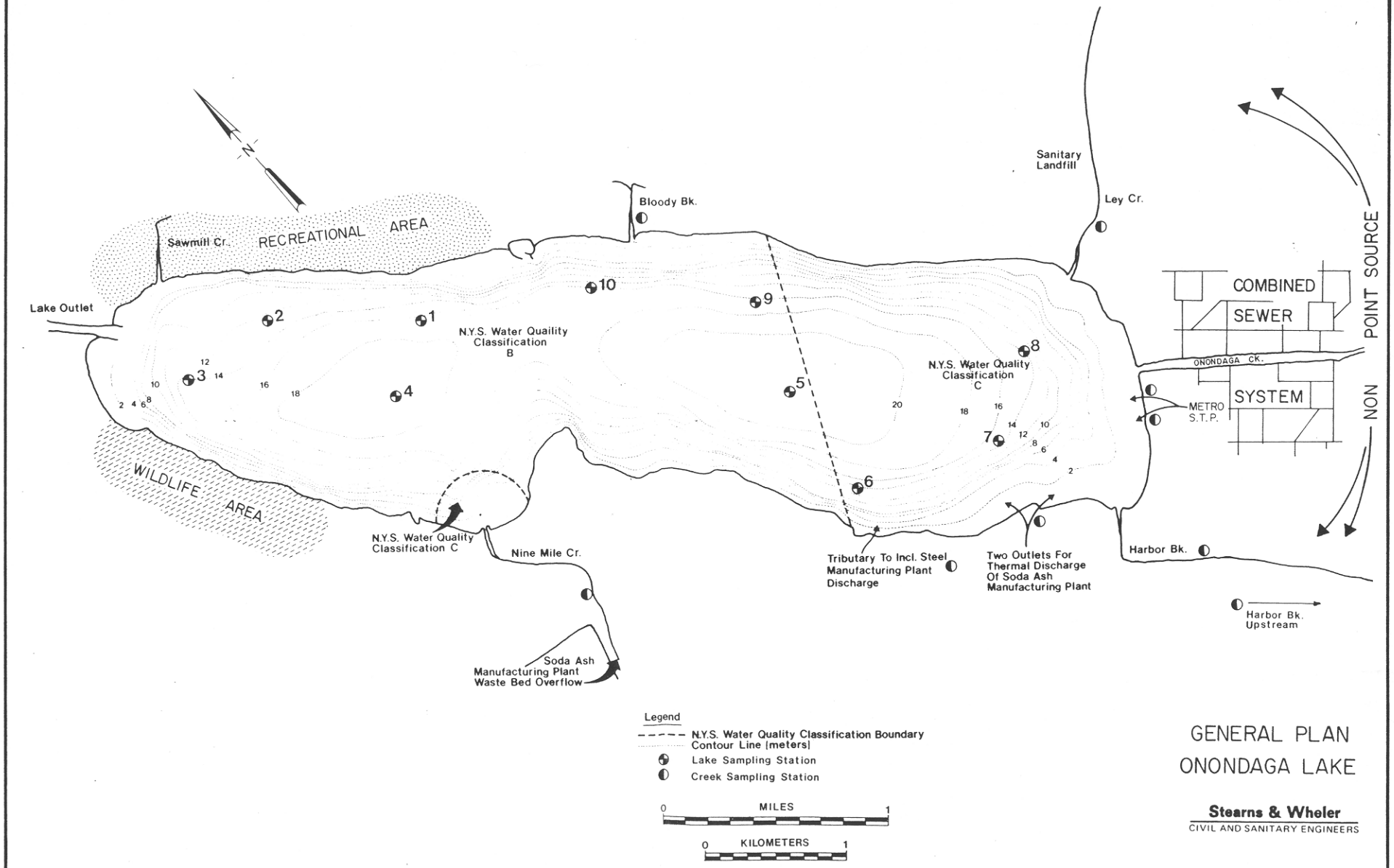
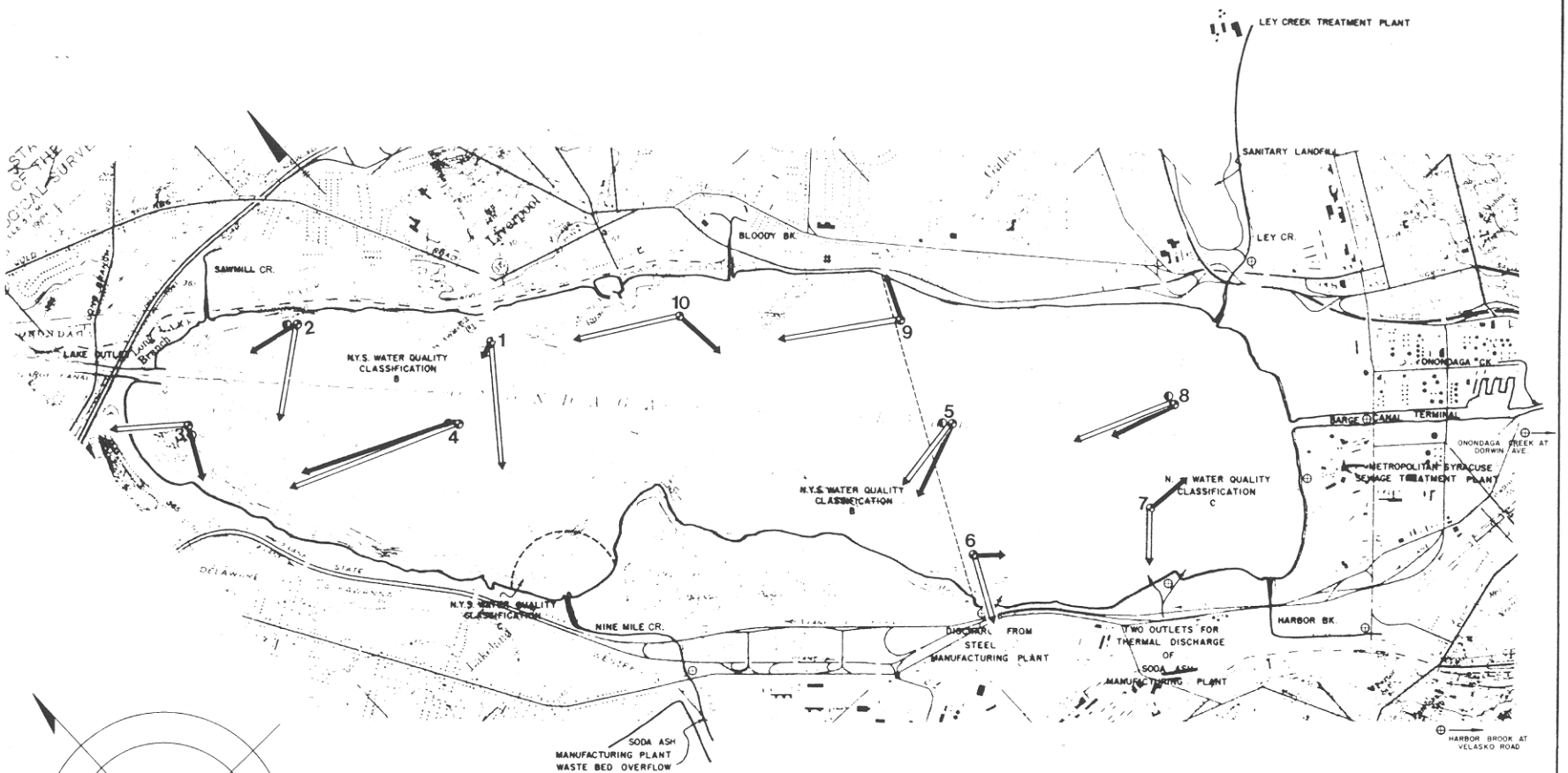
FIGURE 1

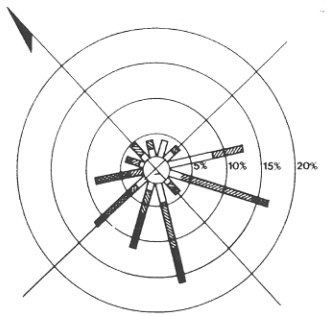



GENERAL PLAN
ONONDAGA LAKE

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

FIGURE 2




WIND ROSE
6/22/76 – 6/26/76

0–4 MPH
4–8
8–12
OVER 12

LEGEND

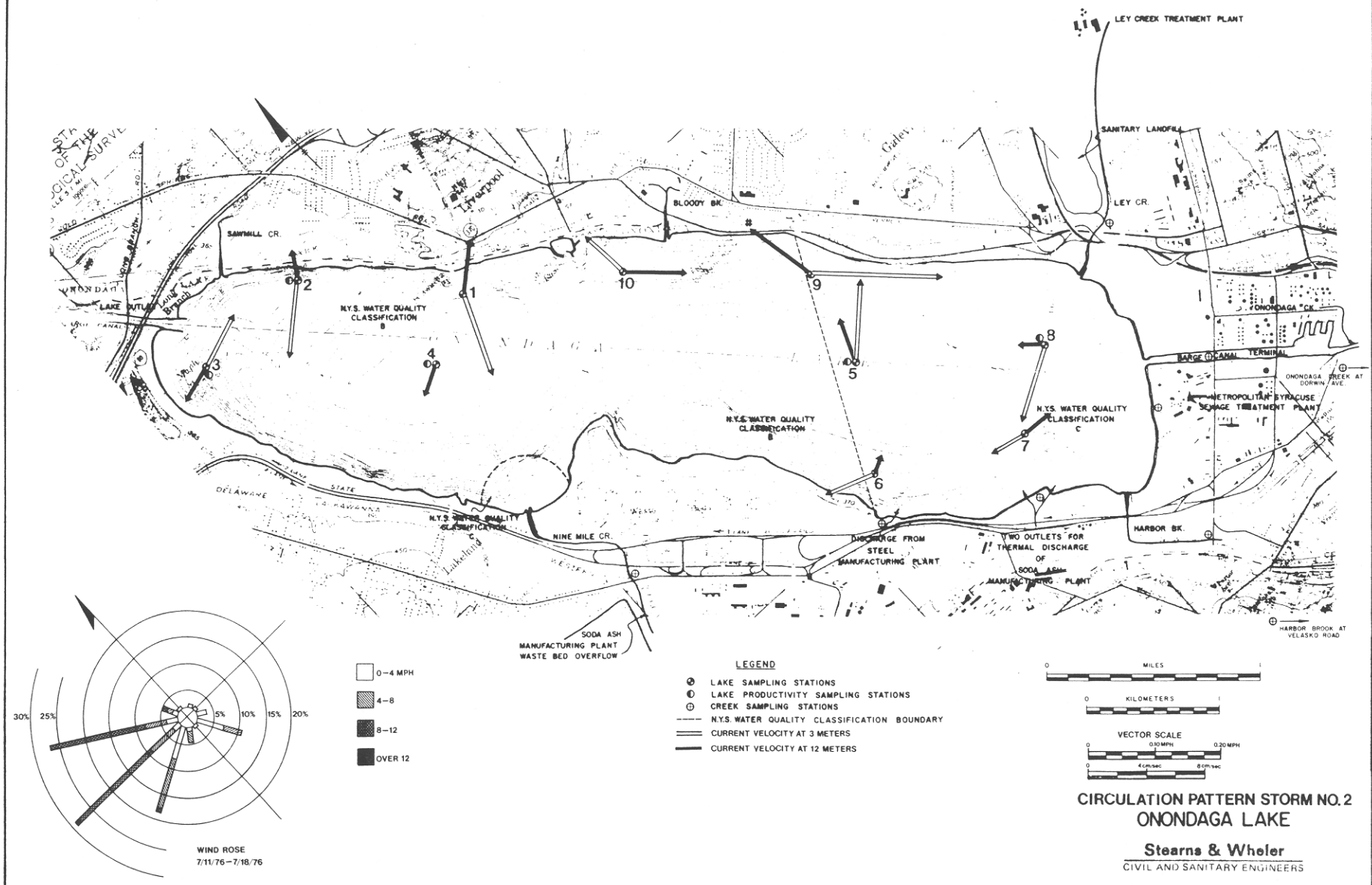
- LAKE SAMPLING STATIONS
- LAKE PRODUCTIVITY SAMPLING STATIONS
- CREEK SAMPLING STATIONS
- N.Y.S. WATER QUALITY CLASSIFICATION BOUNDARY
- CURRENT VELOCITY AT 3 METERS
- CURRENT VELOCITY AT 12 METERS

0 MILES 1
0 KILOMETERS 1
VECTOR SCALE
0 0.10 MPH 0.20 MPH
0 4 CM/SEC 8 CM/SEC

# CIRCULATION PATTERN STORM NO.1
# ONONDAGA LAKE

Stearns & Wheler
CIVIL AND SANITARY ENGINEERS

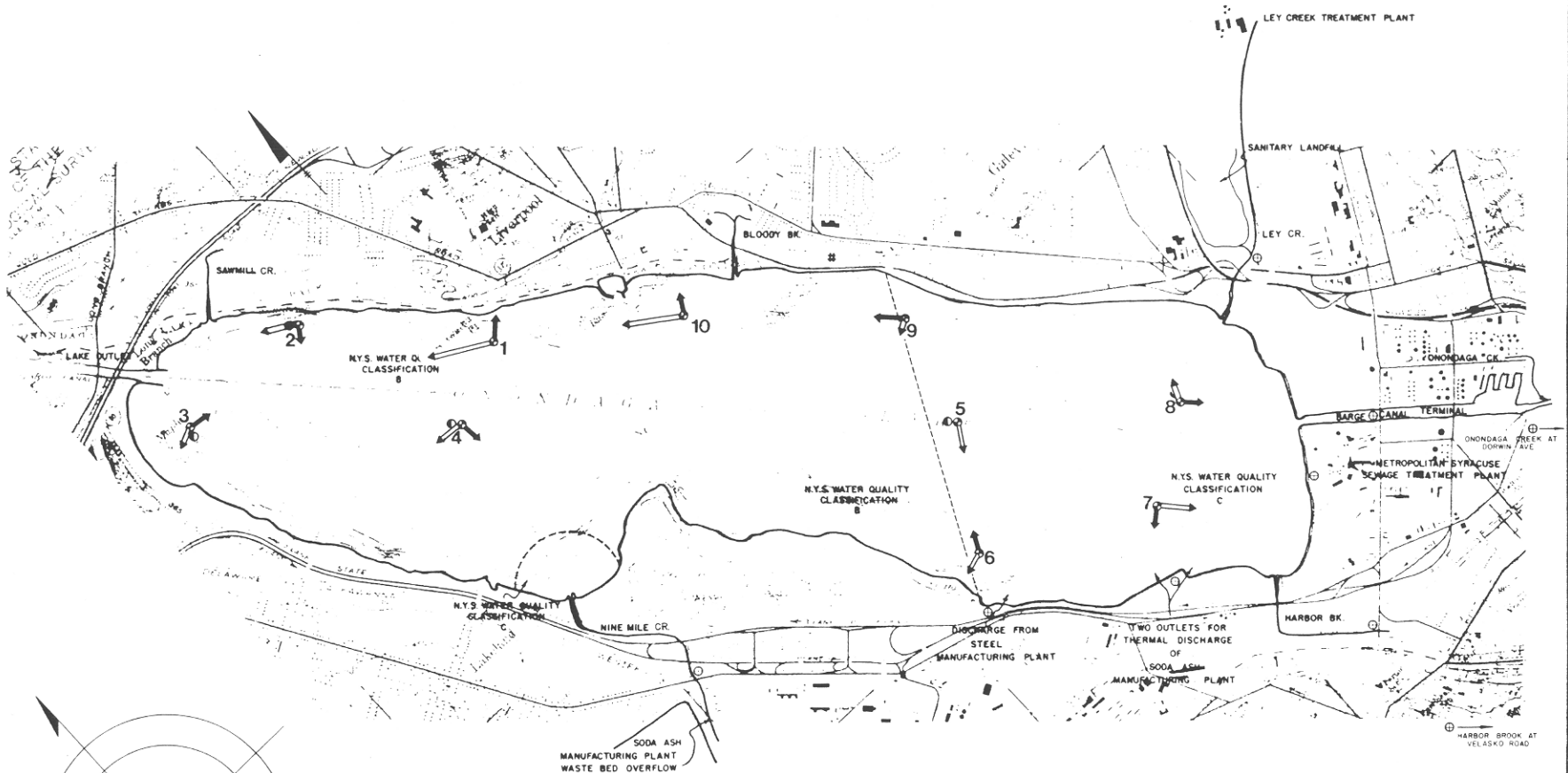
FIGURE 3

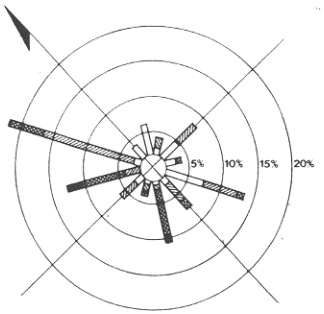



## CIRCULATION PATTERN STORM NO. 2
## ONONDAGA LAKE

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

FIGURE 4




WIND ROSE
8/5/76 – 8/11/76

0–4 MPH
4–8
8–12
OVER 12

LEGEND

- LAKE SAMPLING STATIONS
- LAKE PRODUCTIVITY SAMPLING STATIONS
- CREEK SAMPLING STATIONS
- N.Y.S. WATER QUALITY CLASSIFICATION BOUNDARY
- CURRENT VELOCITY AT 3 METERS
- CURRENT VELOCITY AT 12 METERS

0 MILES 1

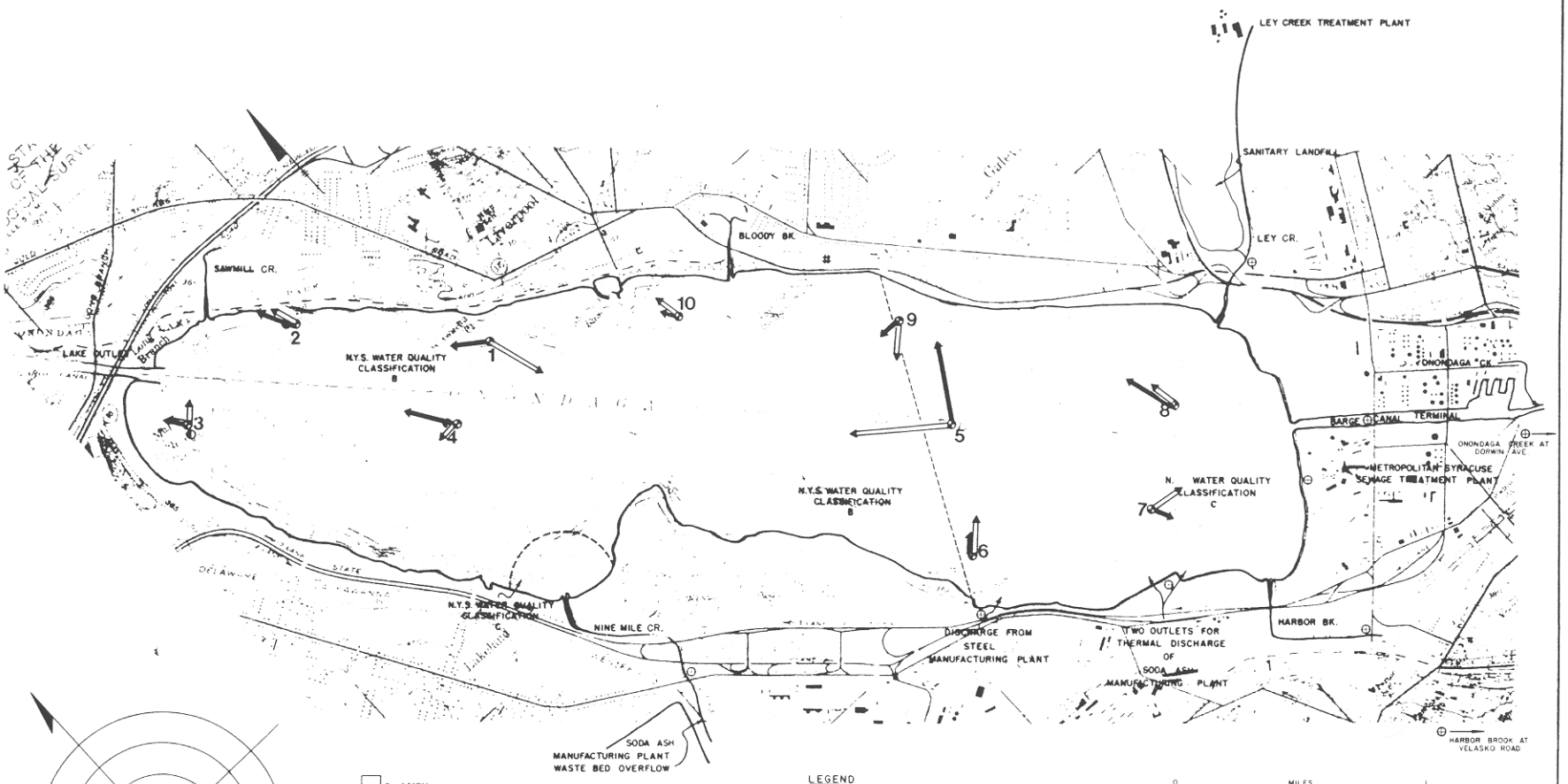
0 KILOMETERS 1

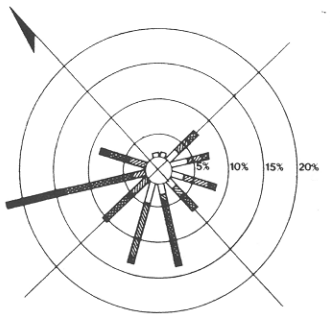
VECTOR SCALE
0 0.10 MPH 0.20 MPH
0 4 CM/SEC 8 CM/SEC

# CIRCULATION PATTERN STORM NO. 3
# ONONDAGA LAKE

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

FIGURE 5




WIND ROSE
8/27/76 – 9/1/76

0–4 MPH
4–8
8–12
OVER 12

LEGEND

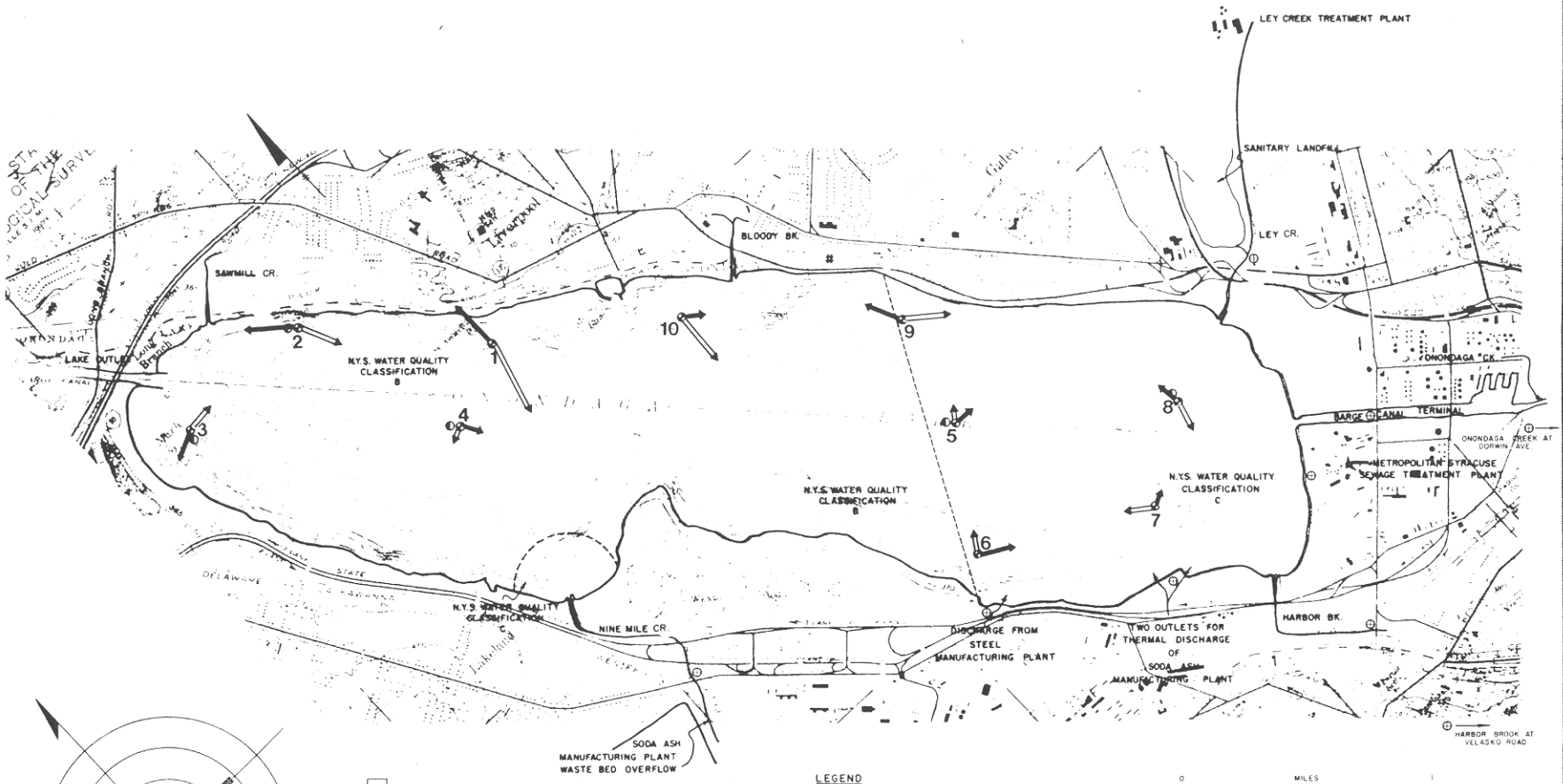
- LAKE SAMPLING STATIONS
- LAKE PRODUCTIVITY SAMPLING STATIONS
- CREEK SAMPLING STATIONS
- N.Y.S. WATER QUALITY CLASSIFICATION BOUNDARY
- CURRENT VELOCITY AT 3 METERS
- CURRENT VELOCITY AT 12 METERS

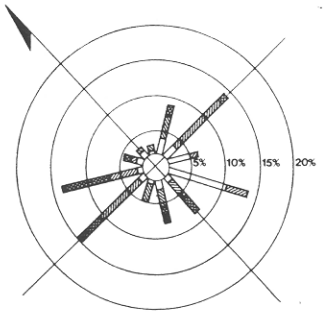
0 MILES 1
0 KILOMETERS 1
VECTOR SCALE
0 0.10 MPH 0.20 MPH
0 4 CM/SEC 8 CM/SEC

# CIRCULATION PATTERN STORM NO. 4
## ONONDAGA LAKE

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

FIGURE 6




WIND ROSE
9/15/76 – 9/21/76

0–4 MPH
4–8
8–12
OVER 12

LEGEND

- LAKE SAMPLING STATIONS
- LAKE PRODUCTIVITY SAMPLING STATIONS
- CREEK SAMPLING STATIONS
- N.Y.S. WATER QUALITY CLASSIFICATION BOUNDARY
- CURRENT VELOCITY AT 3 METERS
- CURRENT VELOCITY AT 12 METERS

0 MILES 1

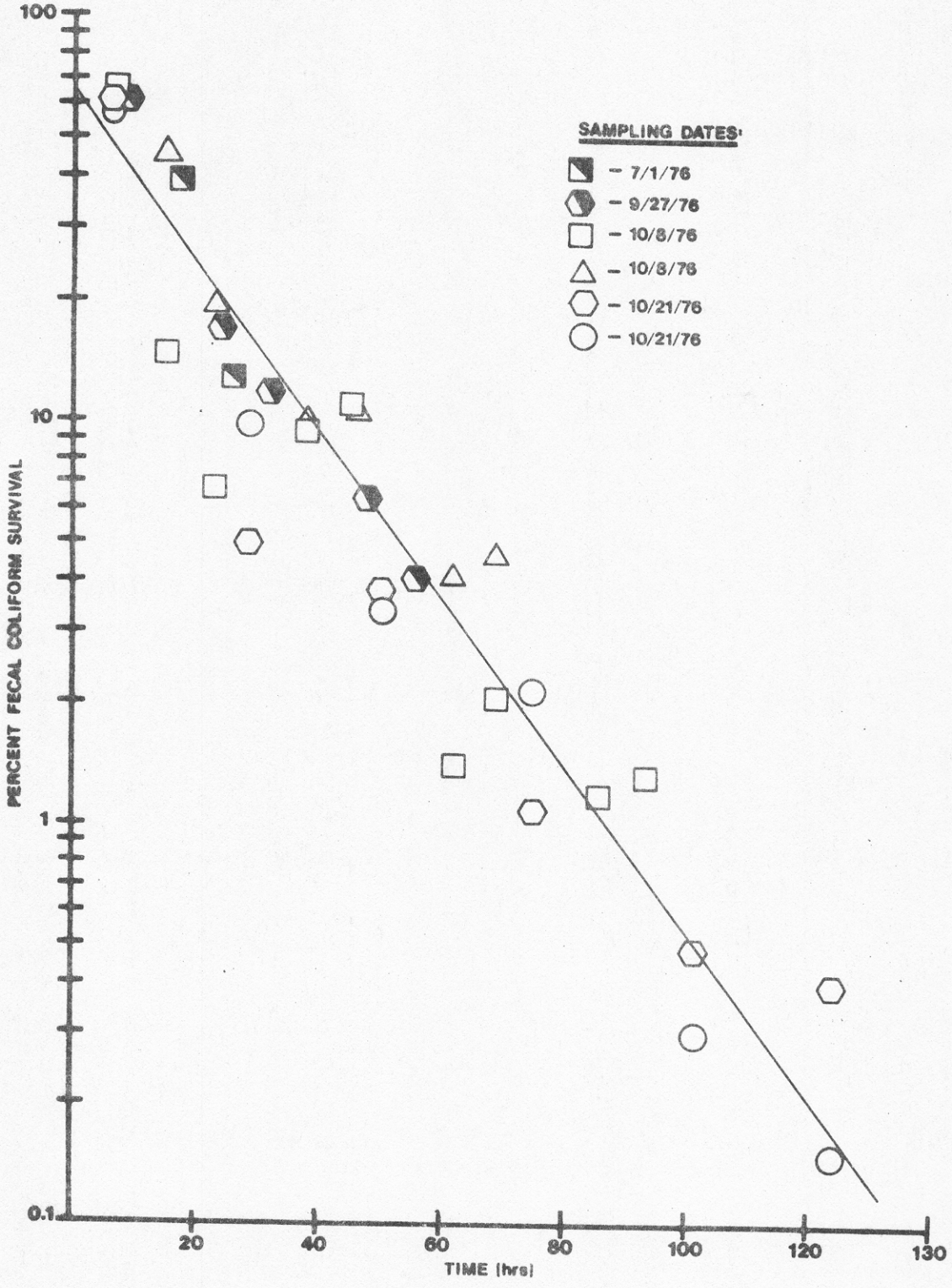
0 KILOMETERS 1

VECTOR SCALE
0 0.10 MPH 0.20 MPH
0 4 CM/SEC 8 CM/SEC

# CIRCULATION PATTERN STORM NO. 5
# ONONDAGA LAKE

**Stearns & Wheler**
CIVIL AND SANITARY ENGINEERS

FIGURE 7




FECAL COLIFORM DIE-OFF

K&E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO MADE IN U.S.A.



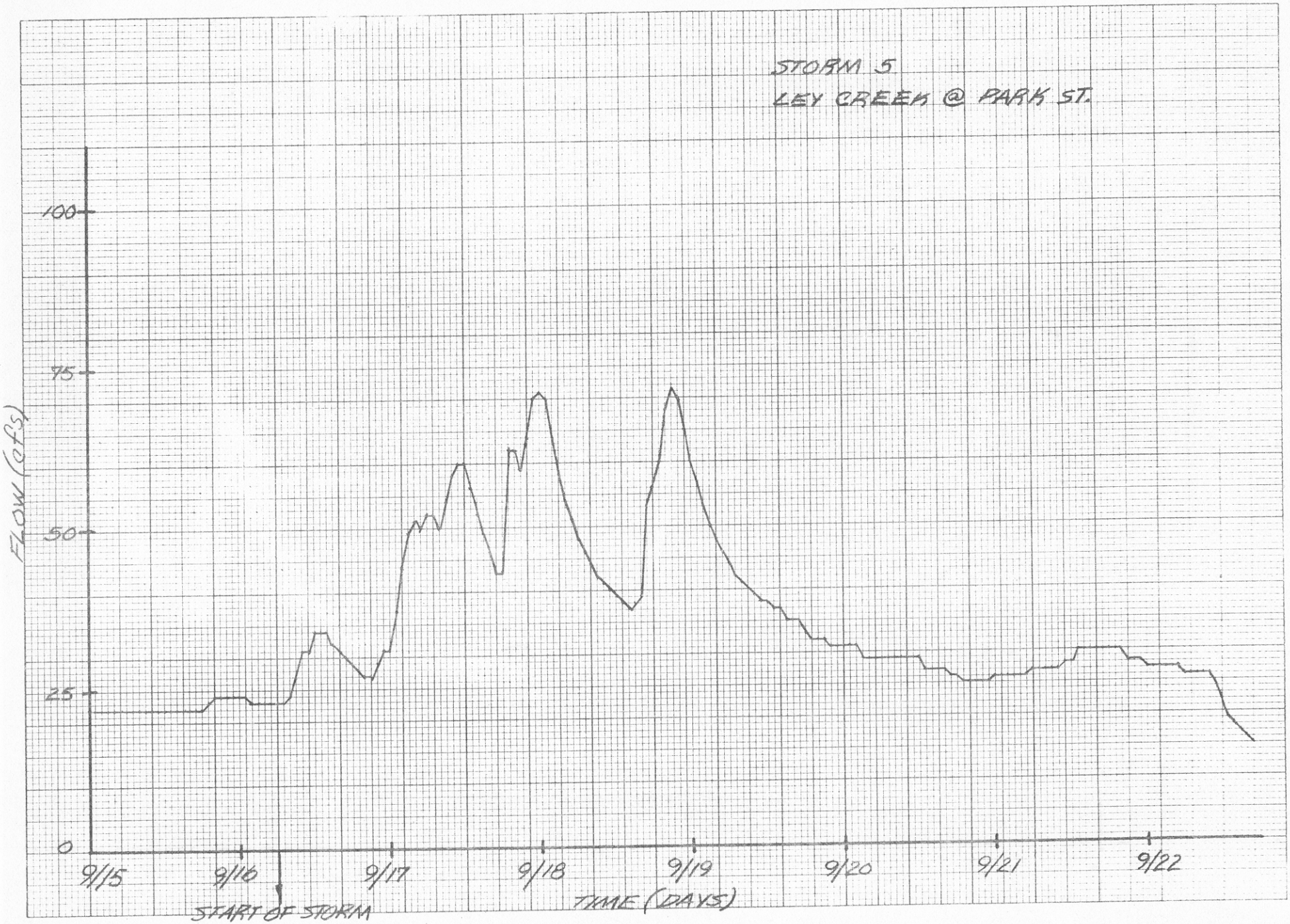
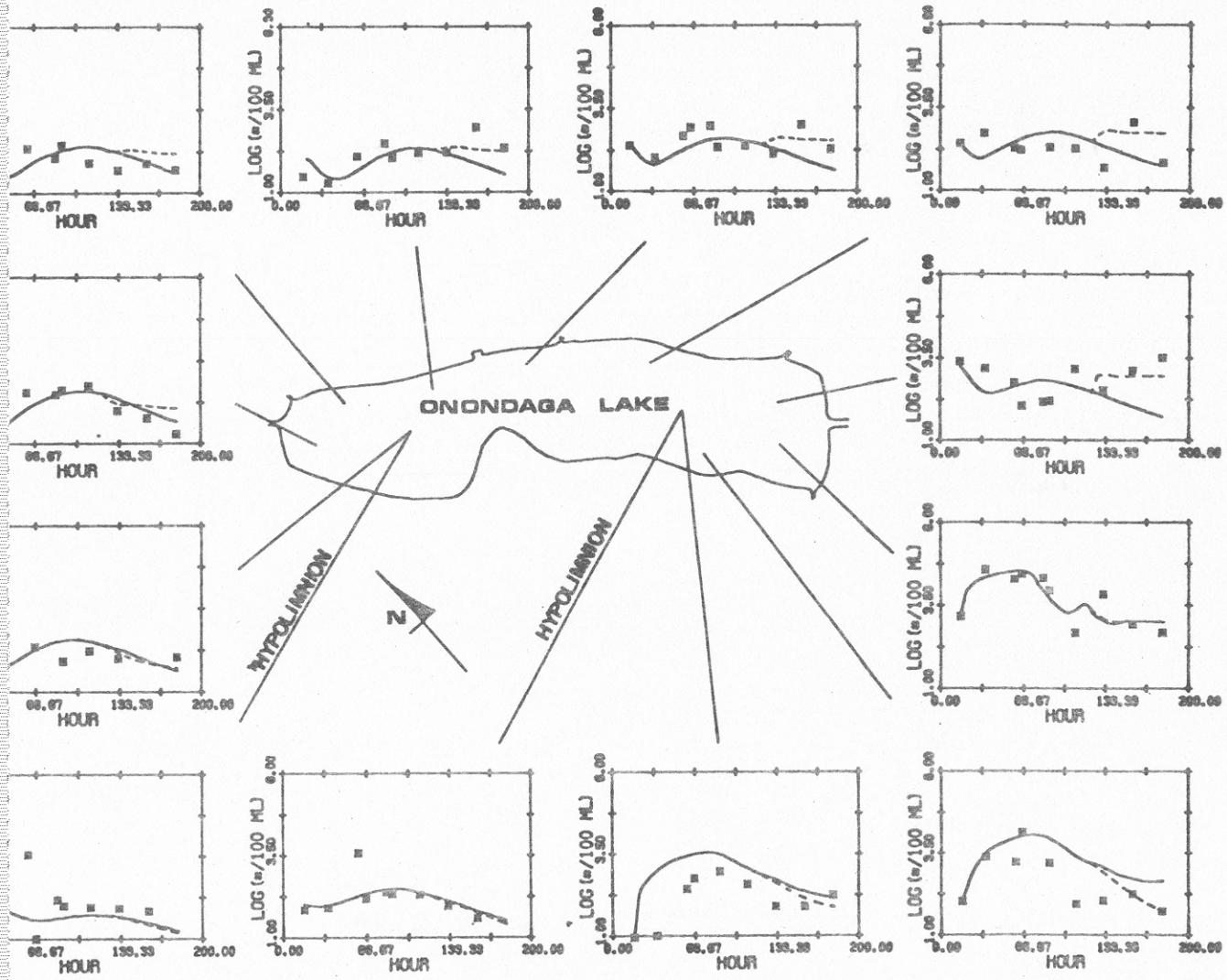
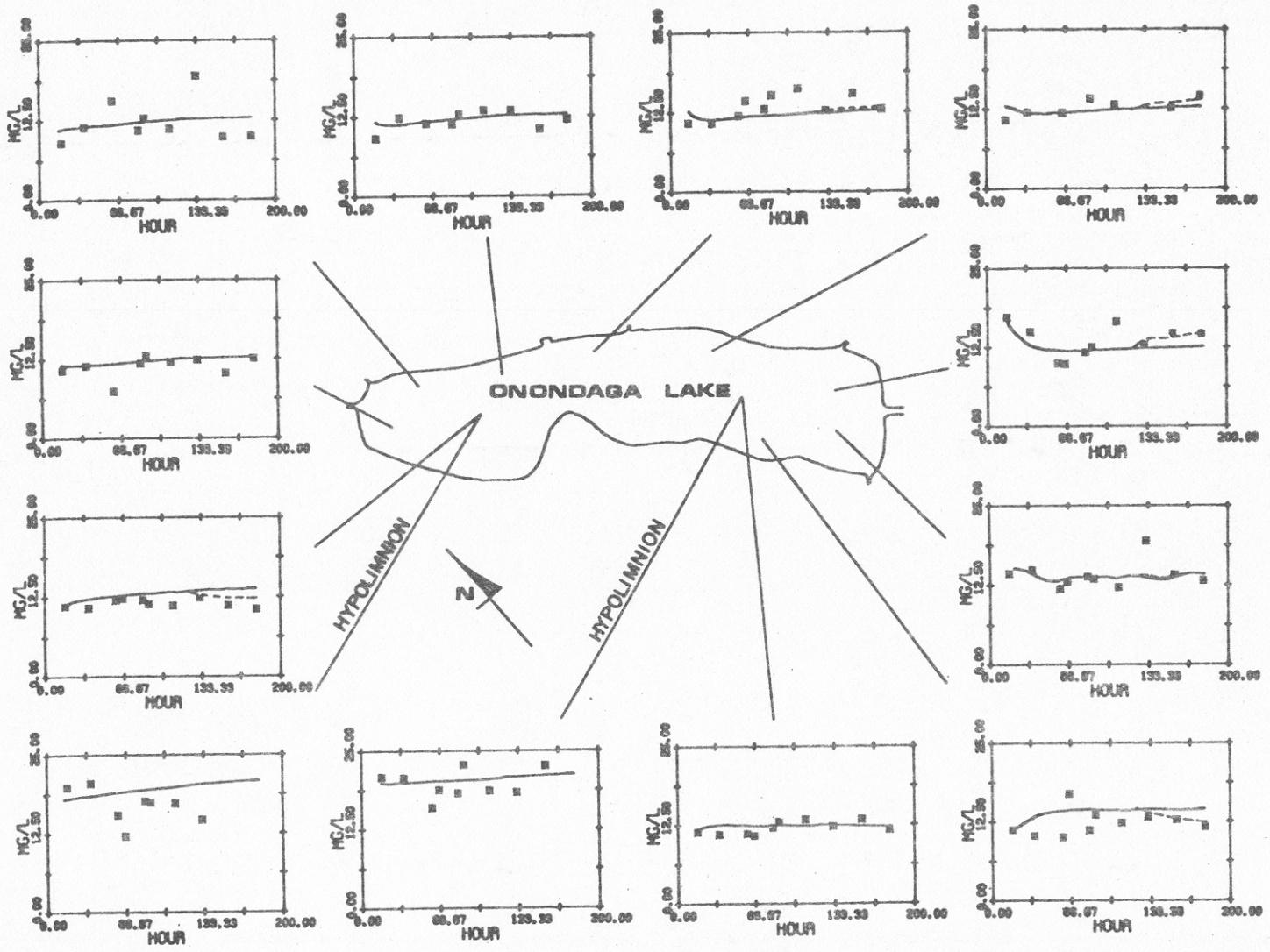



FIGURE 33



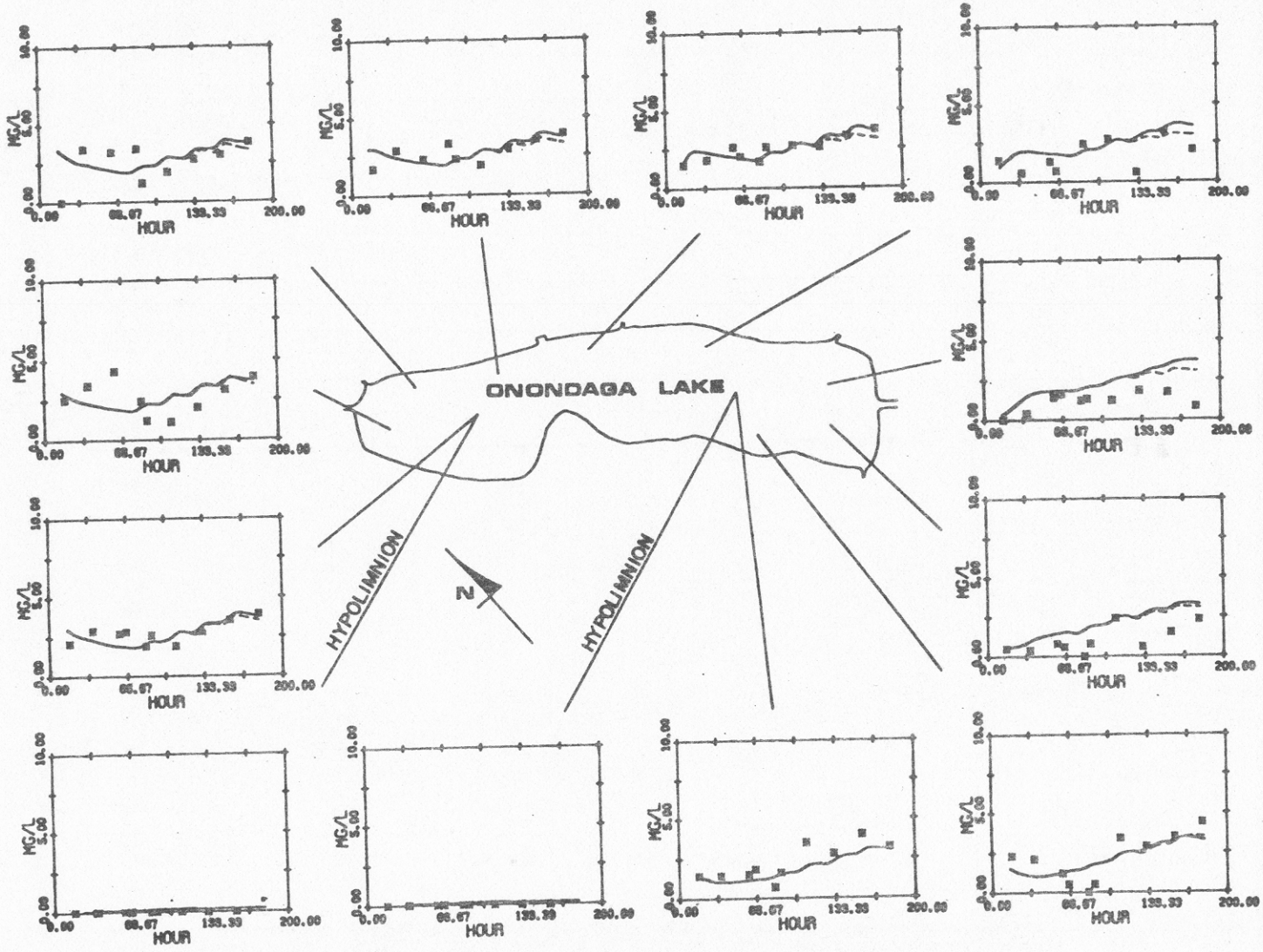

FECAL COLIFORM MODEL SIMULATION: STORM 5

FIGURE 34



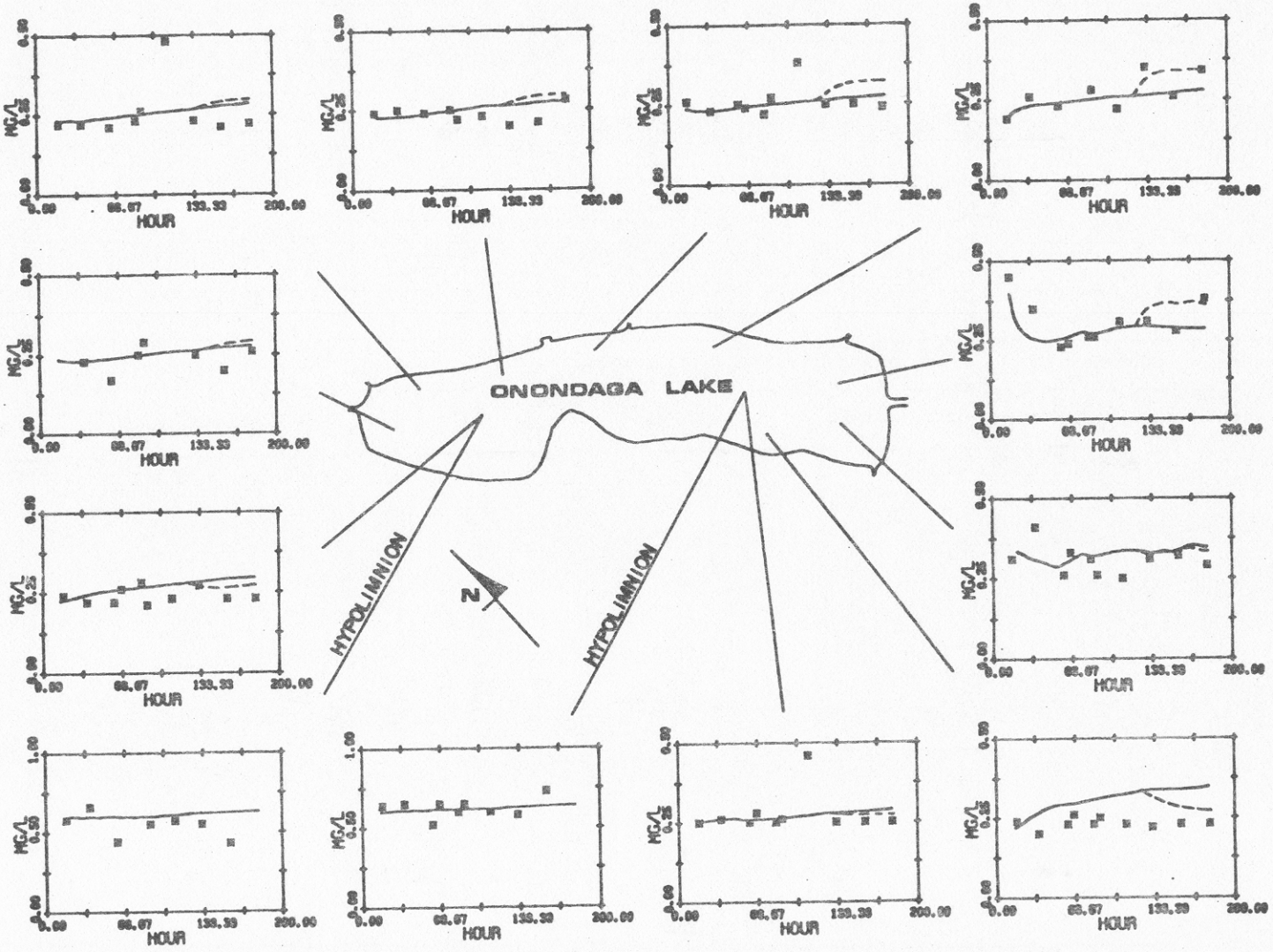

NBOD MODEL SIMULATION: STORM 5

FIGURE 36




DISSOLVED OXYGEN MODEL SIMULATION: STORM 5

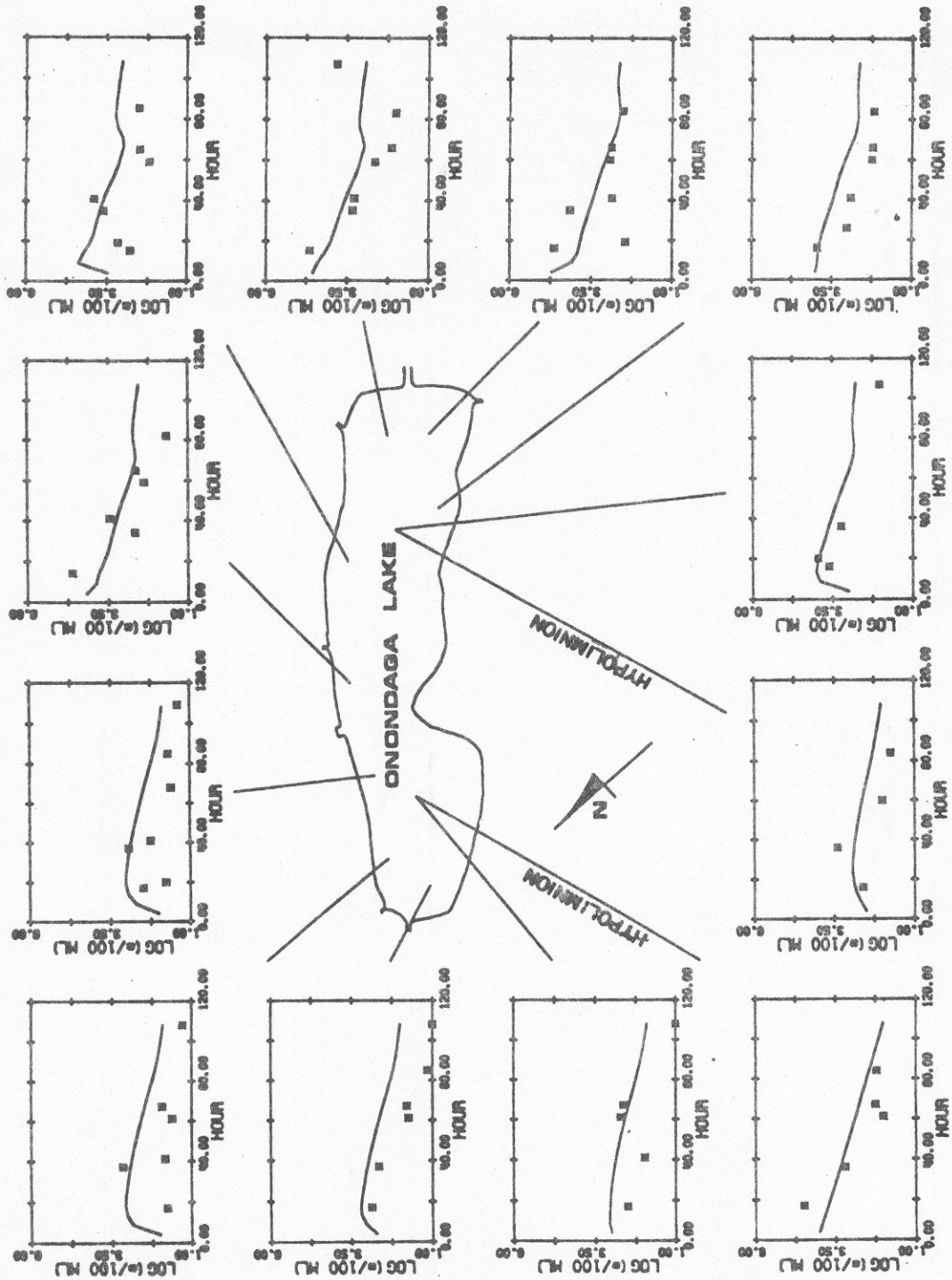
FIGURE 37



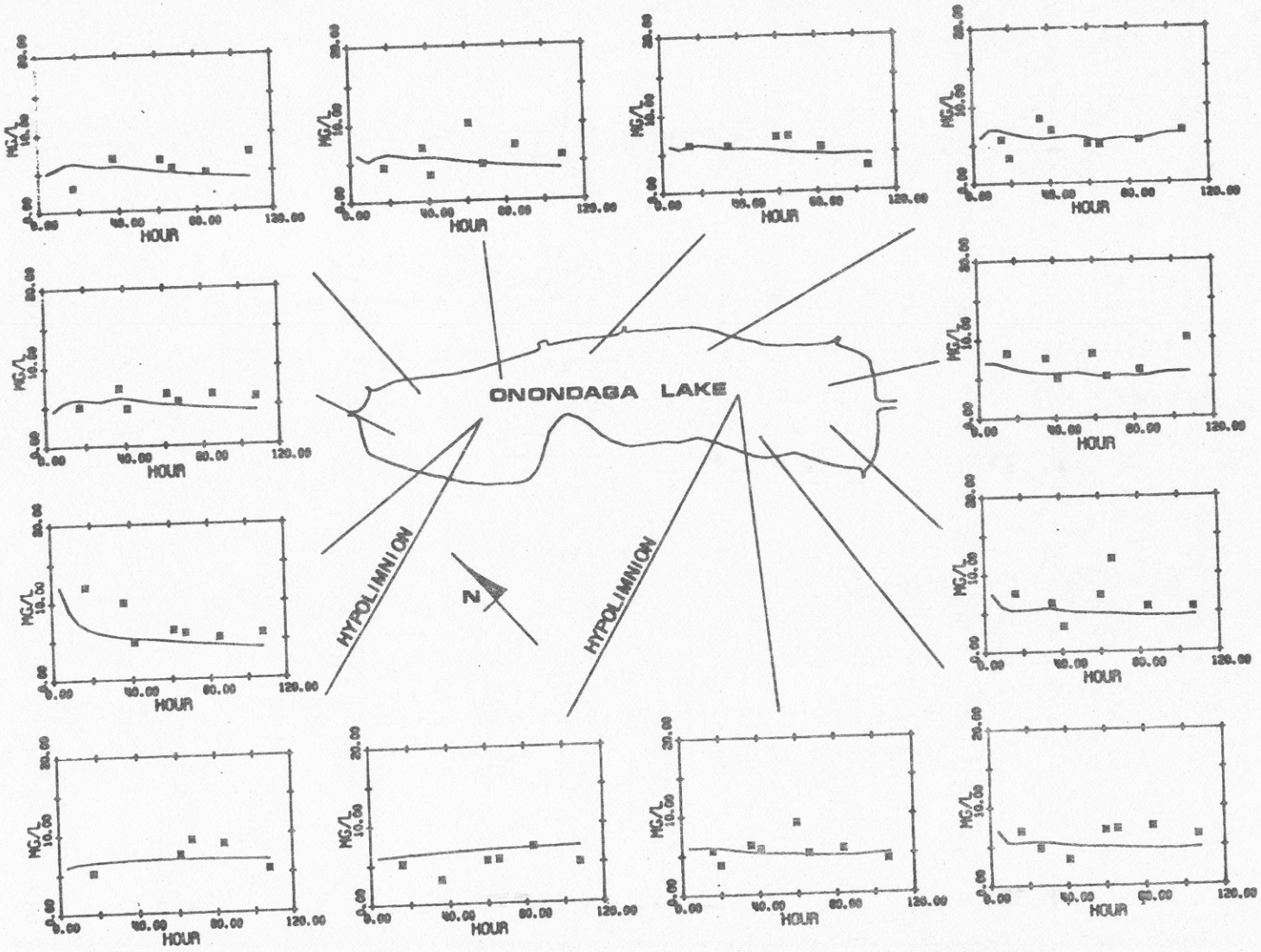

TOTAL PHOSPHOROUS MODEL SIMULATION: STORM 5

FIGURE 38

FIGURE 39

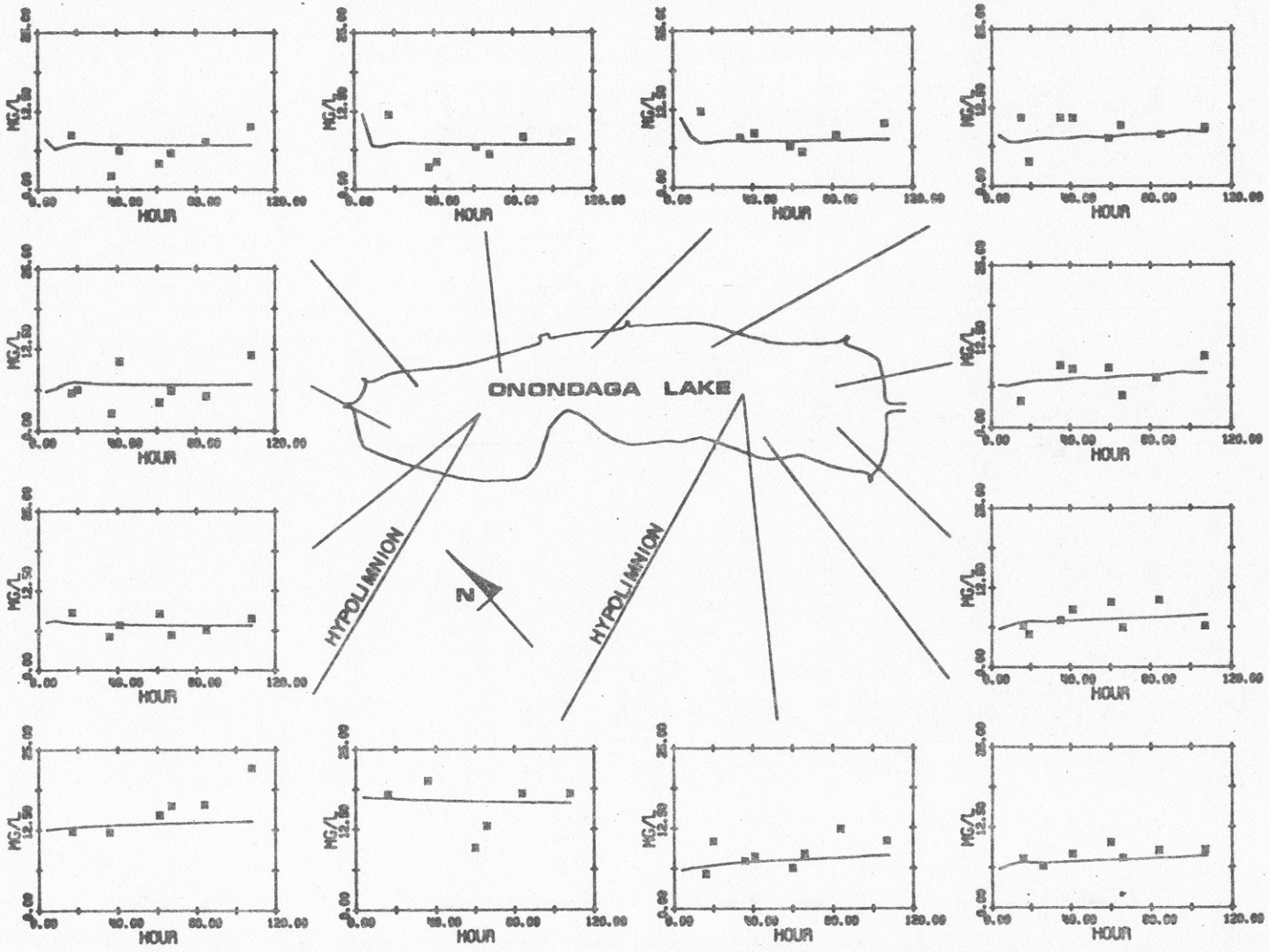



FECAL COLIFORM MODEL SIMULATION: STORM 4



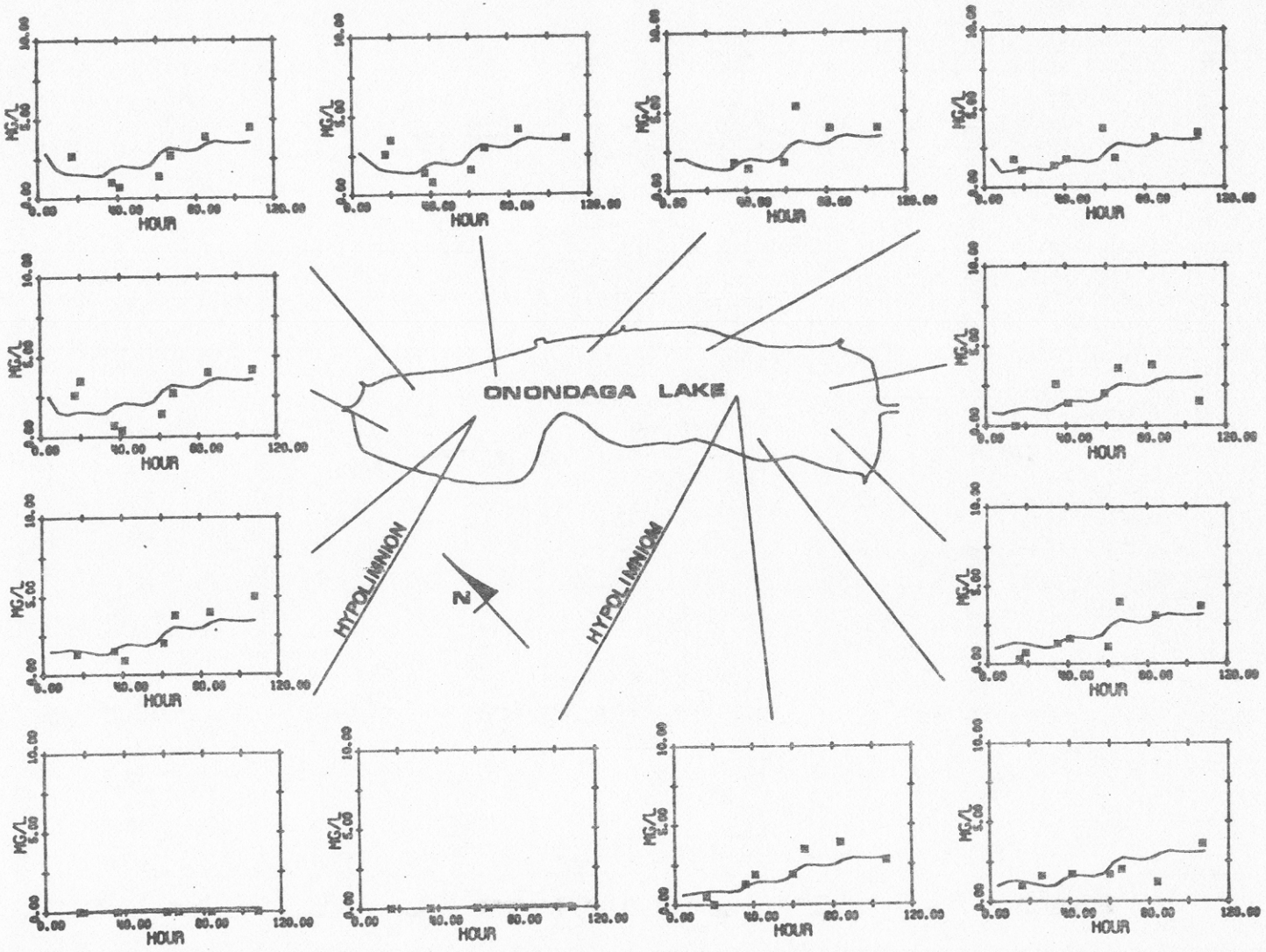

CBOD MODEL SIMULATION: STORM 4

FIGURE 40



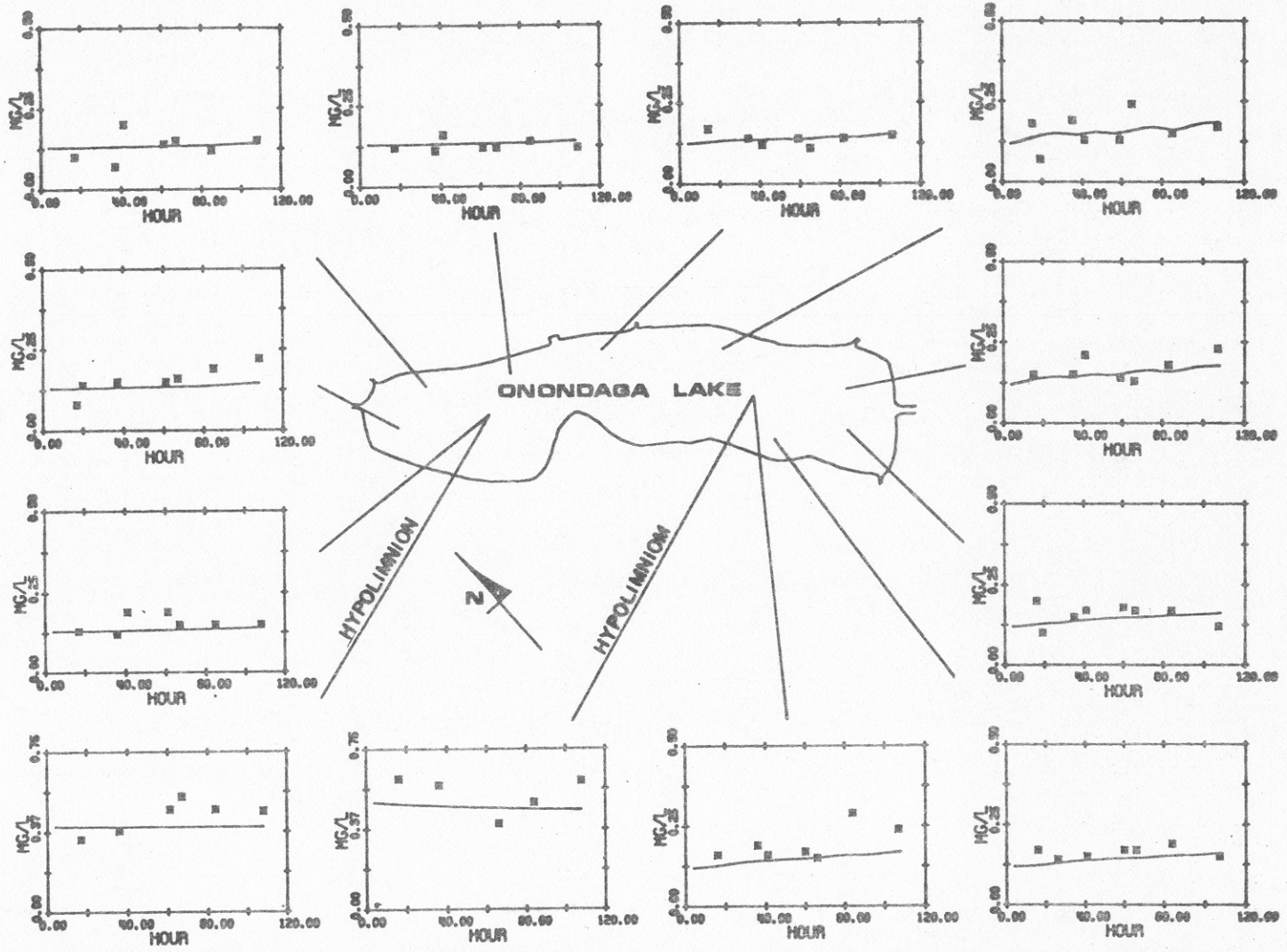

NBOD MODEL SIMULATION: STORM 4

FIGURE 41




DISSOLVED OXYGEN MODEL SIMULATION: STORM 4

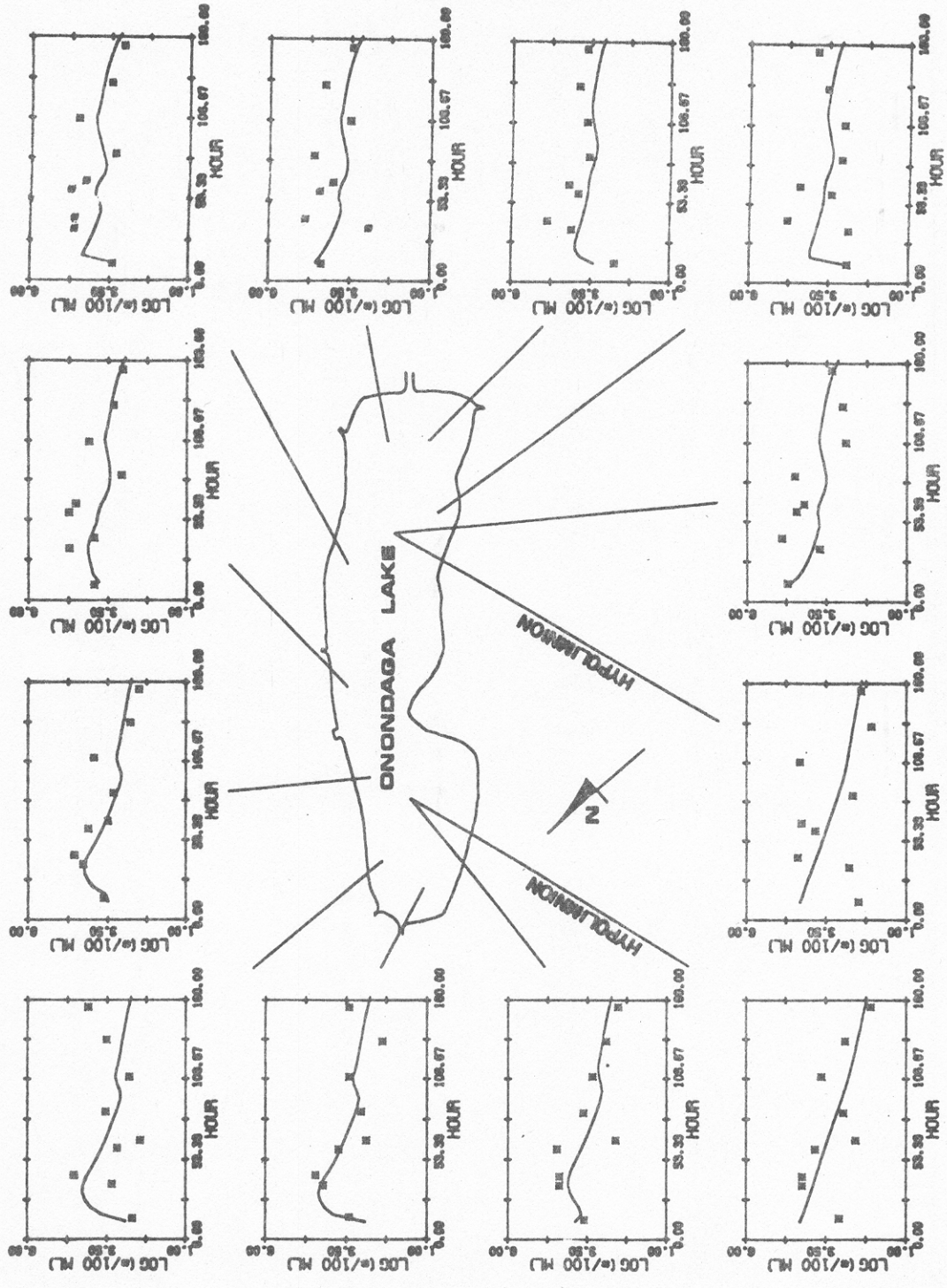
FIGURE 42



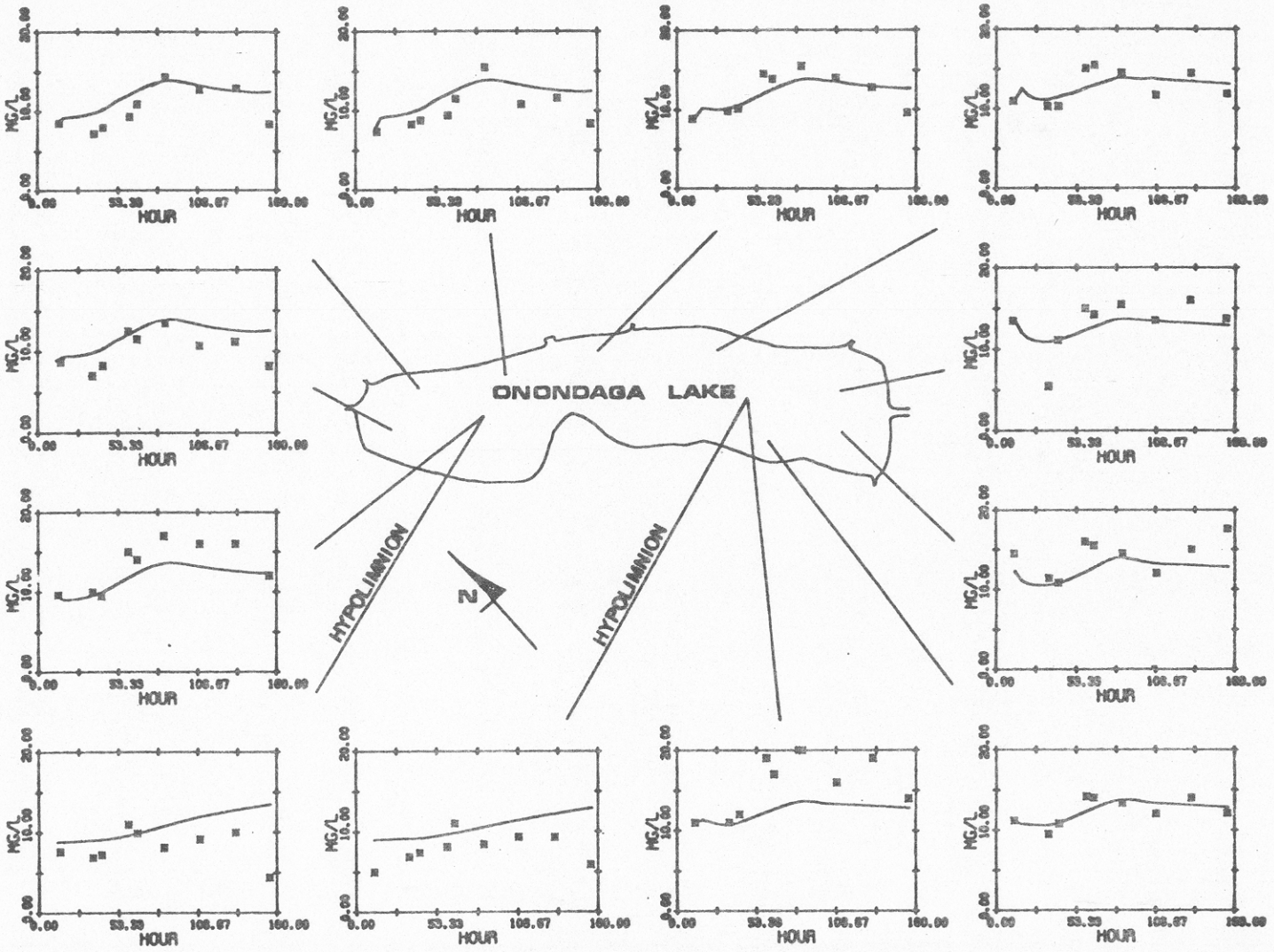

TOTAL PHOSPHOROUS MODEL SIMULATION: STORM 4

FIGURE 43

FIGURE 44

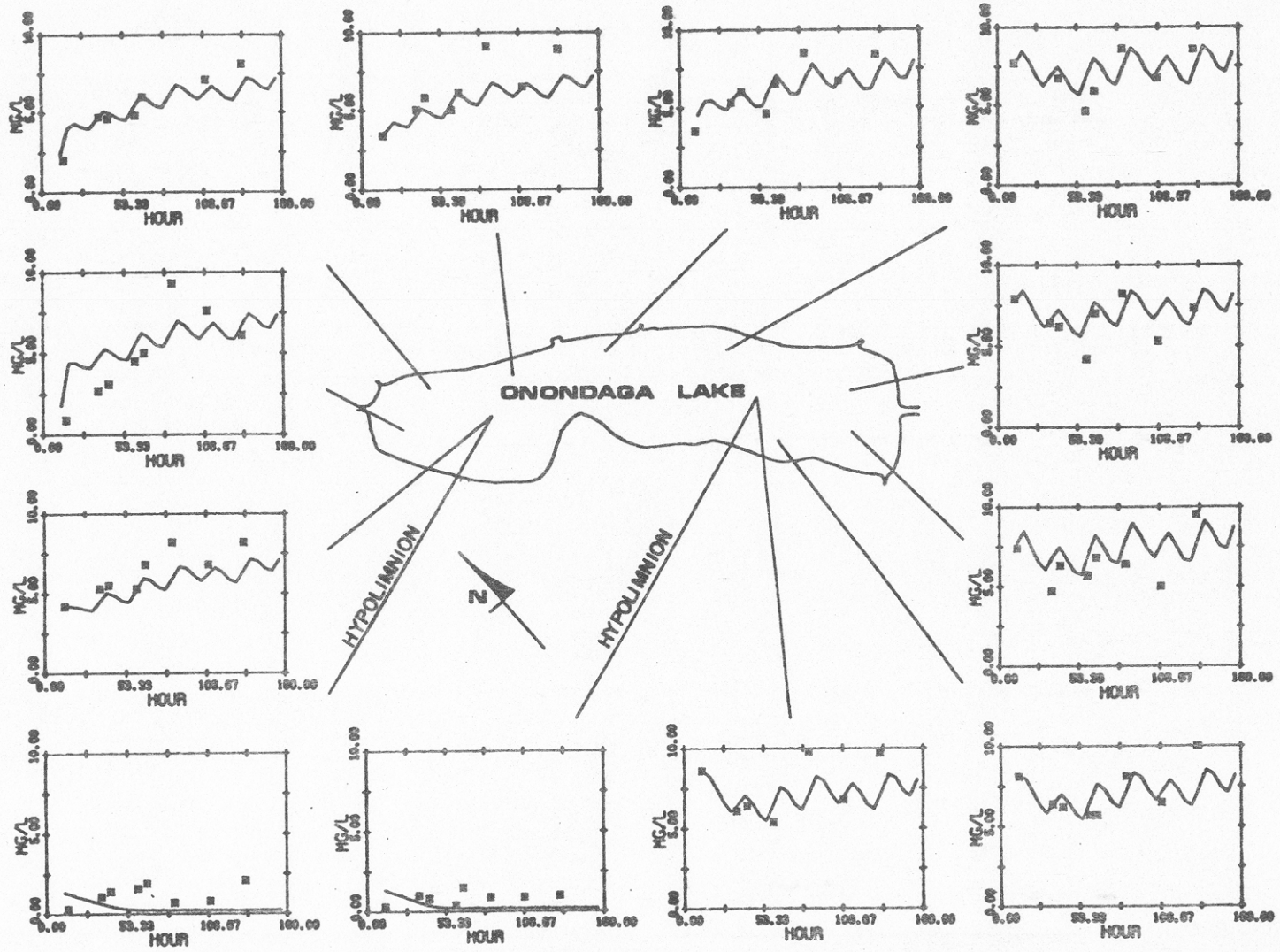



FECAL COLIFORM MODEL SIMULATION: STORM 2




CBOD MODEL SIMULATION: STORM 2

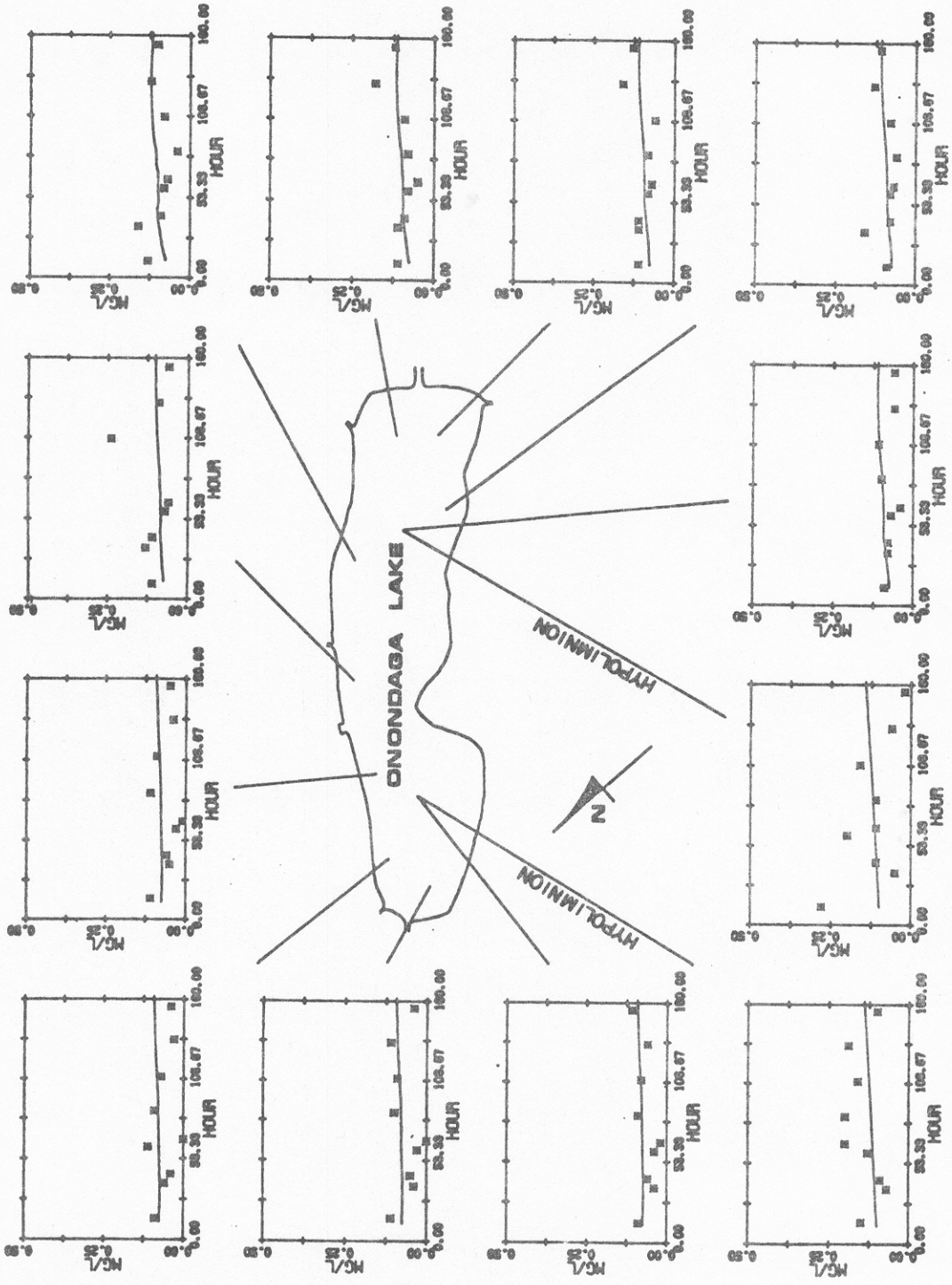
FIGURE 45



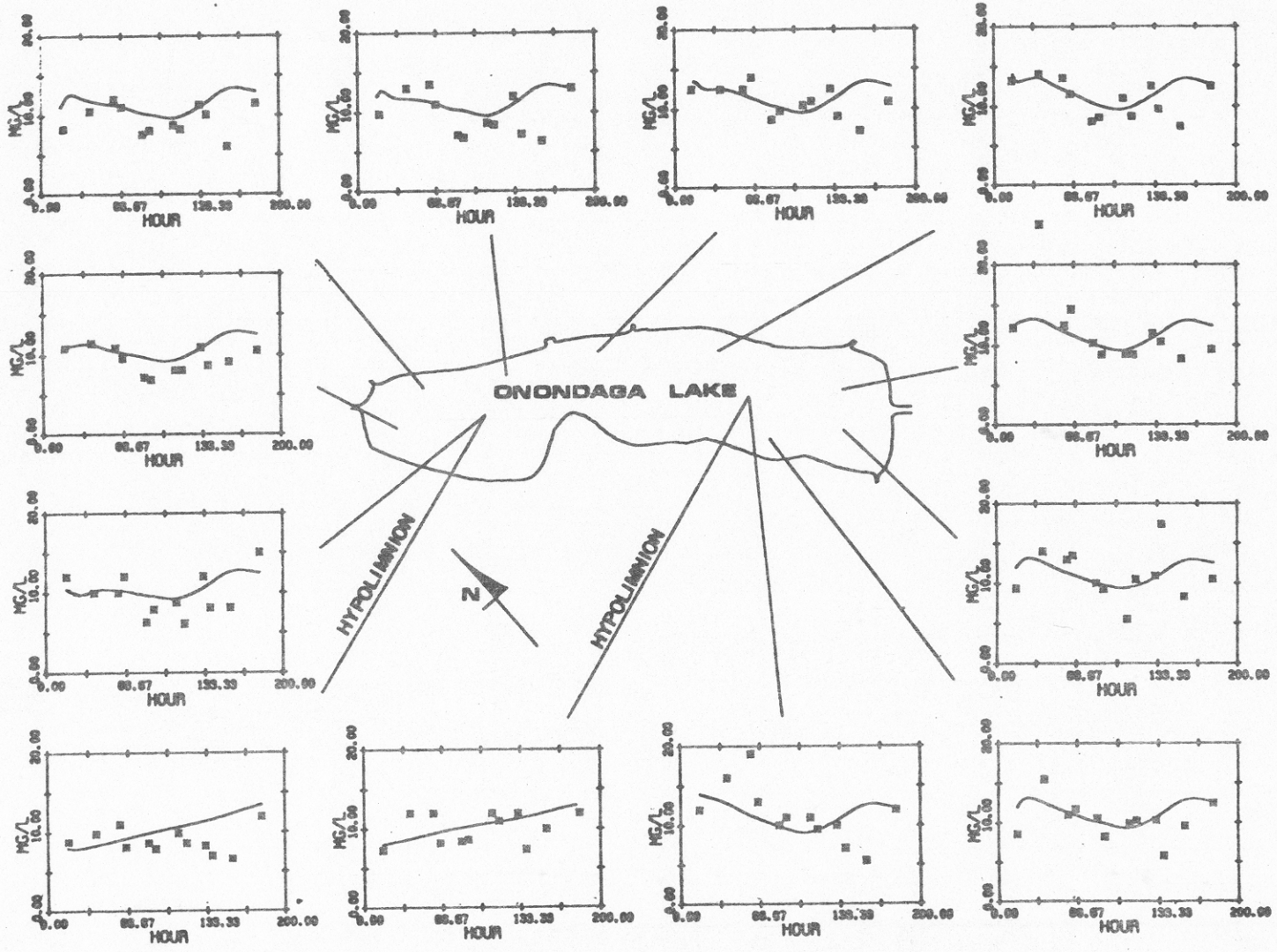

DISSOLVED OXYGEN MODEL SIMULATION: STORM 2

FIGURE 47

FIGURE 48

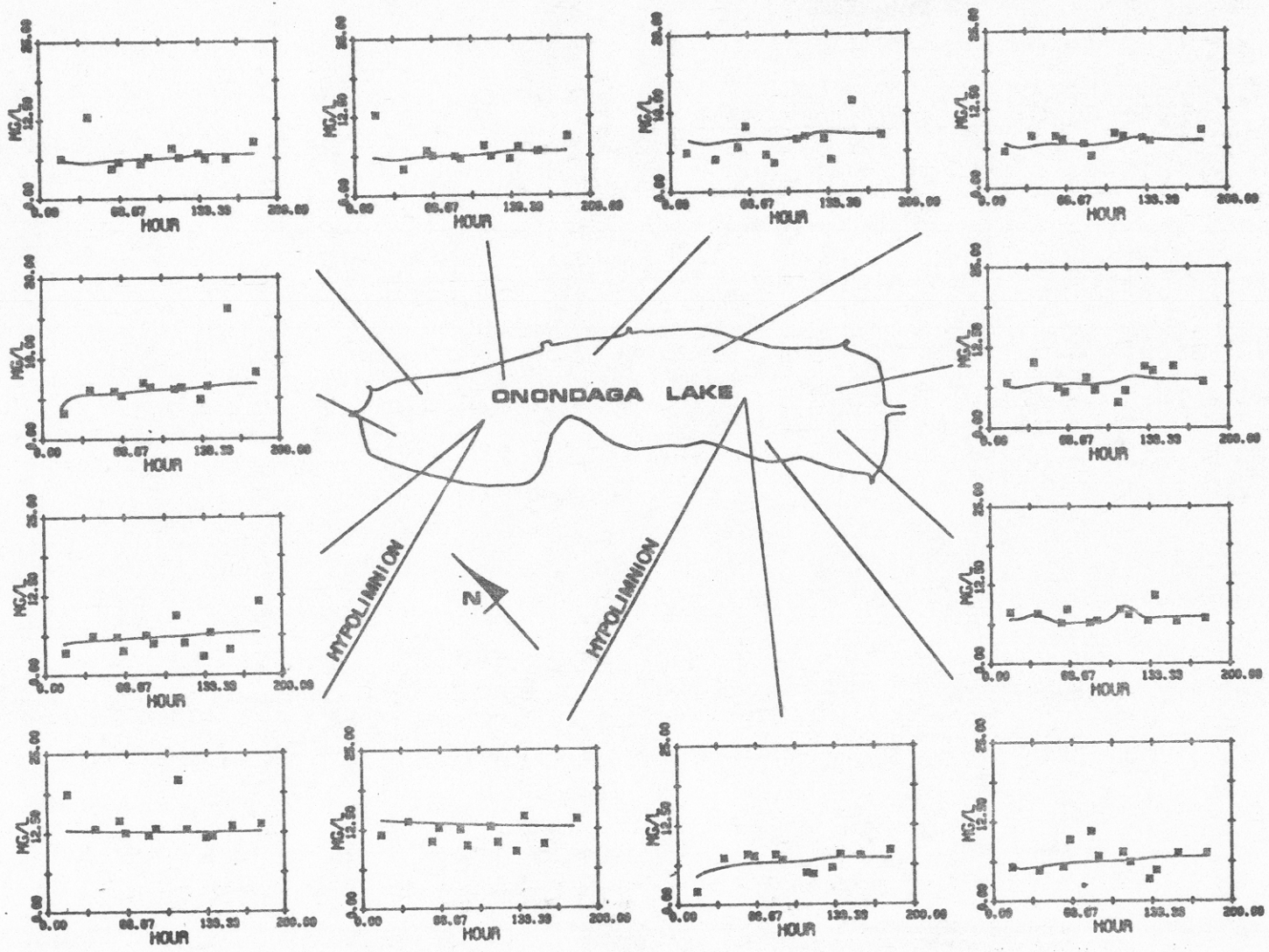



TOTAL PHOSPHOROUS MODEL SIMULATION: STORM 2



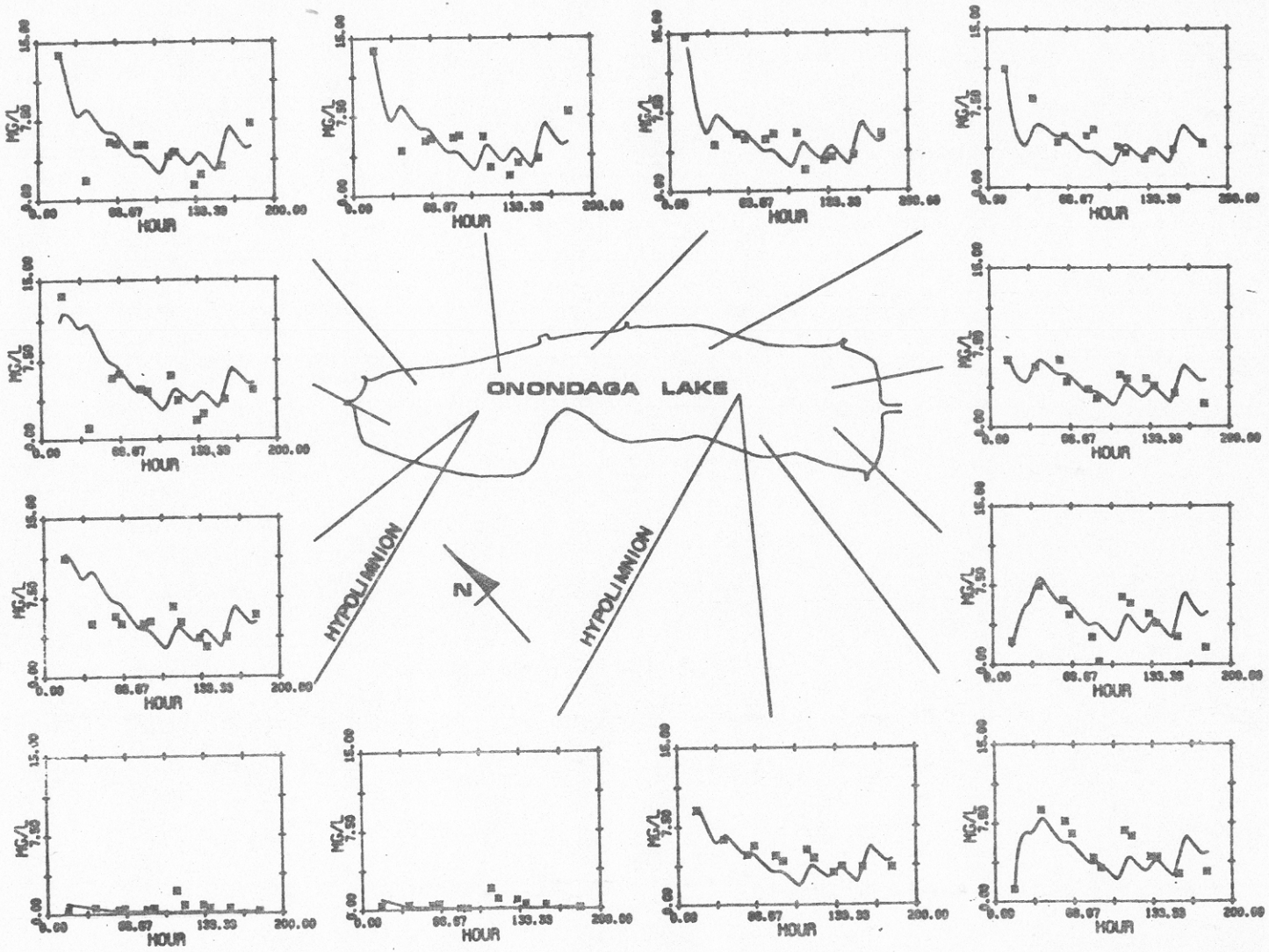

CBOD MODEL SIMULATION: STORM 3

FIGURE 49



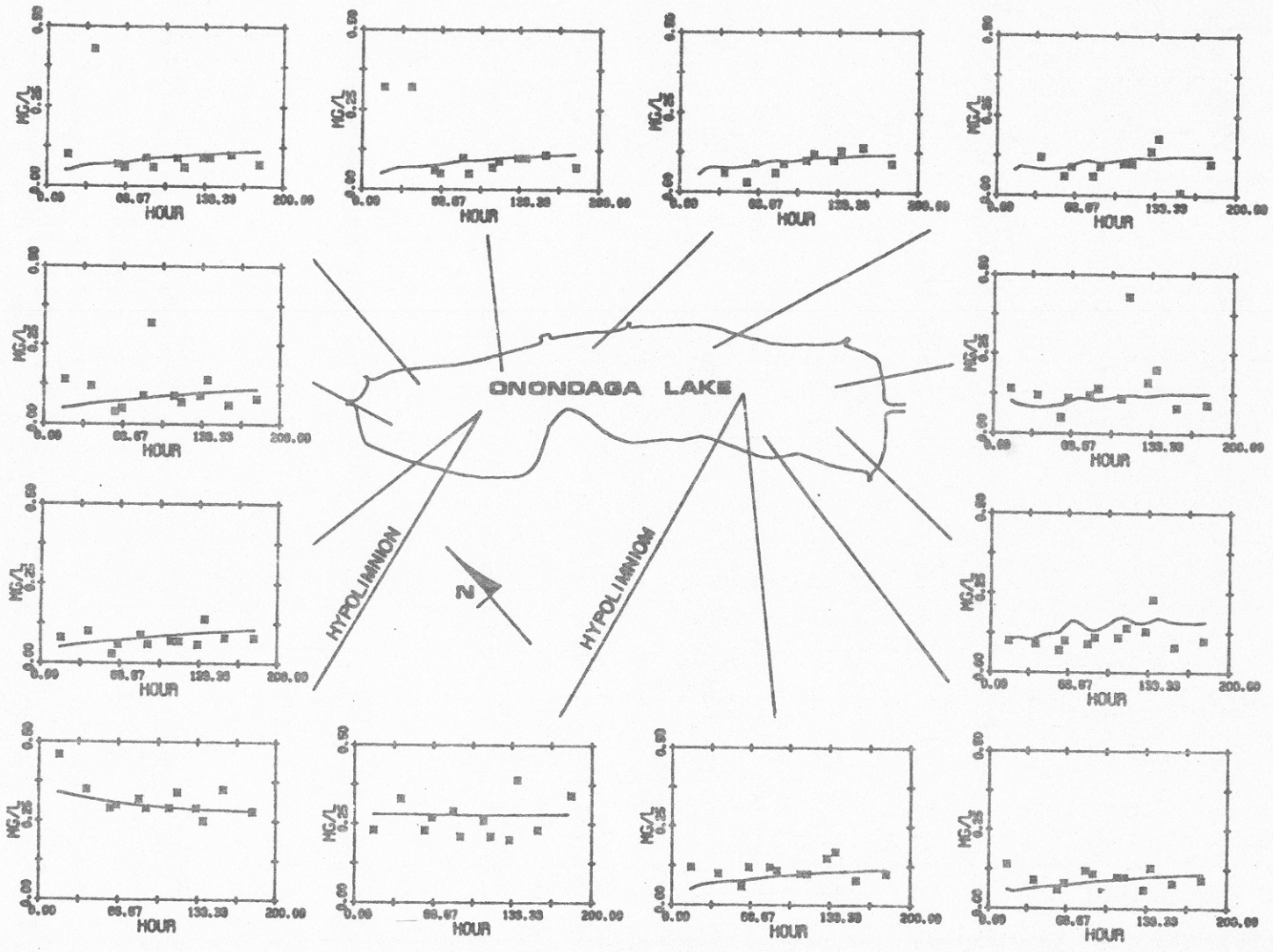

NBOD MODEL SIMULATION: STORM 3

FIGURE 50



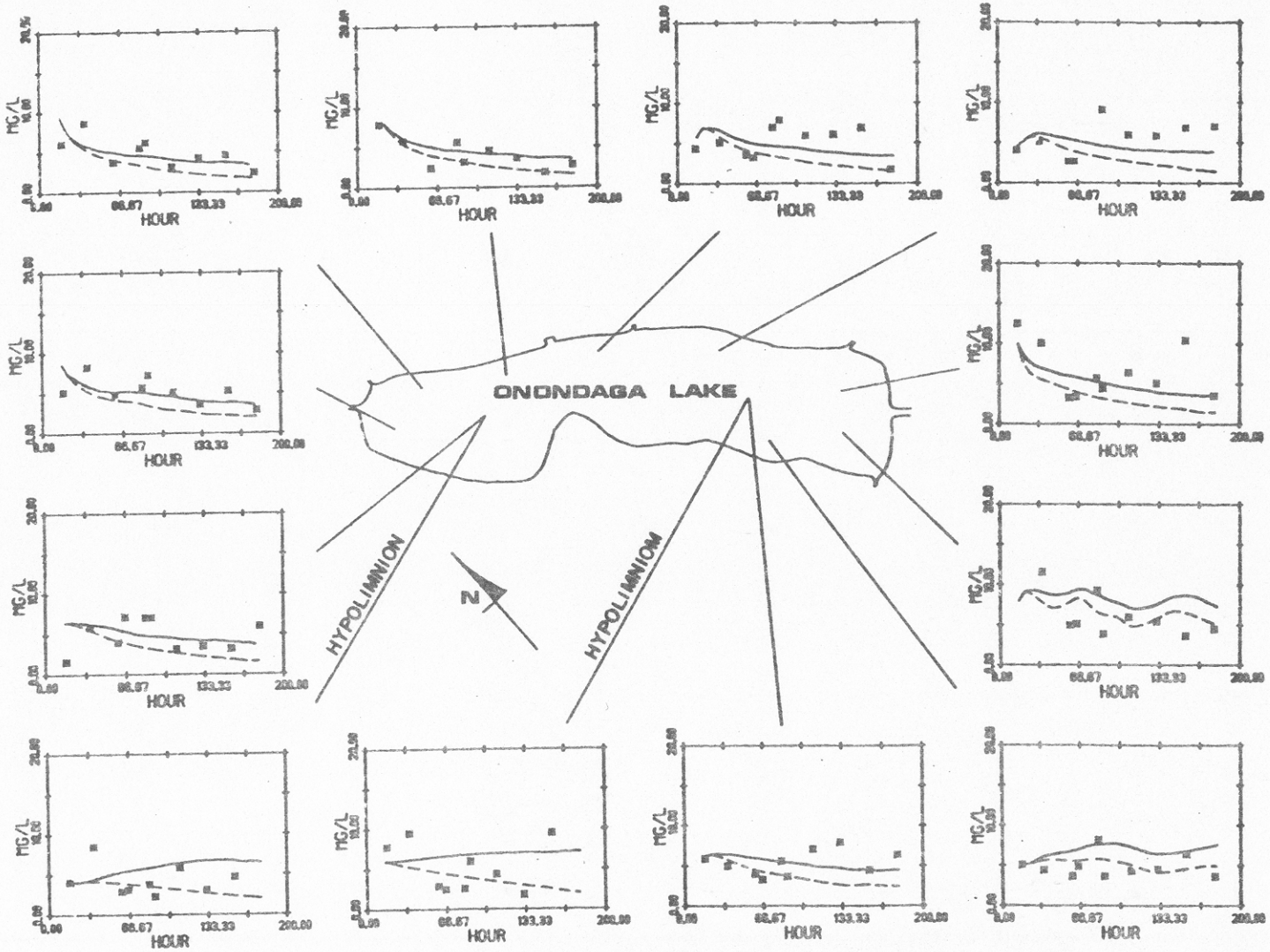

DISSOLVED OXYGEN MODEL SIMULATION: STORM 3

FIGURE 51



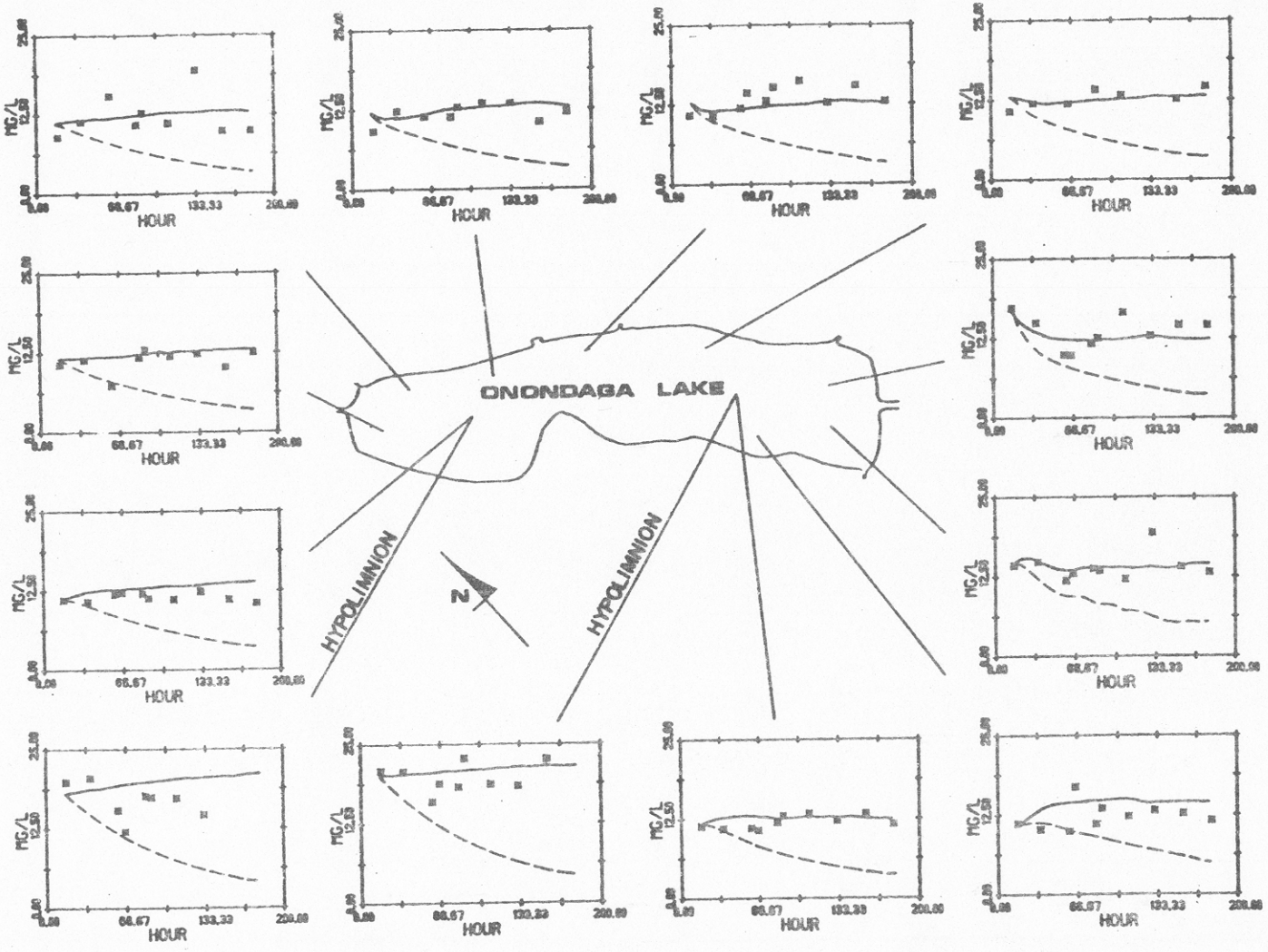

TOTAL PHOSPHOROUS MODEL SIMULATION: STORM 3

FIGURE 52



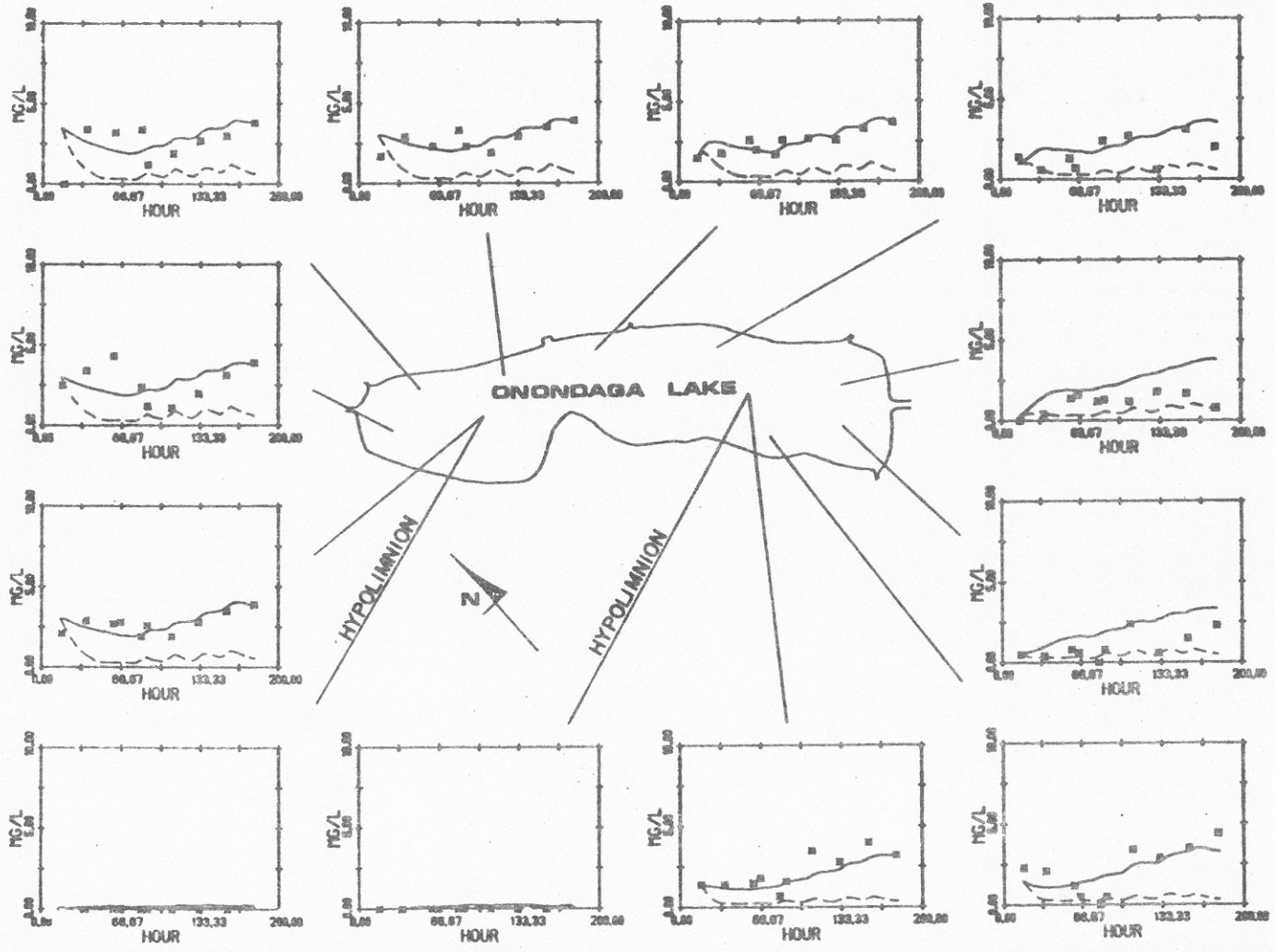

SENSITIVITY ANALYSIS ON CBOD REMOVAL RATES: STORM 5

FIGURE 53



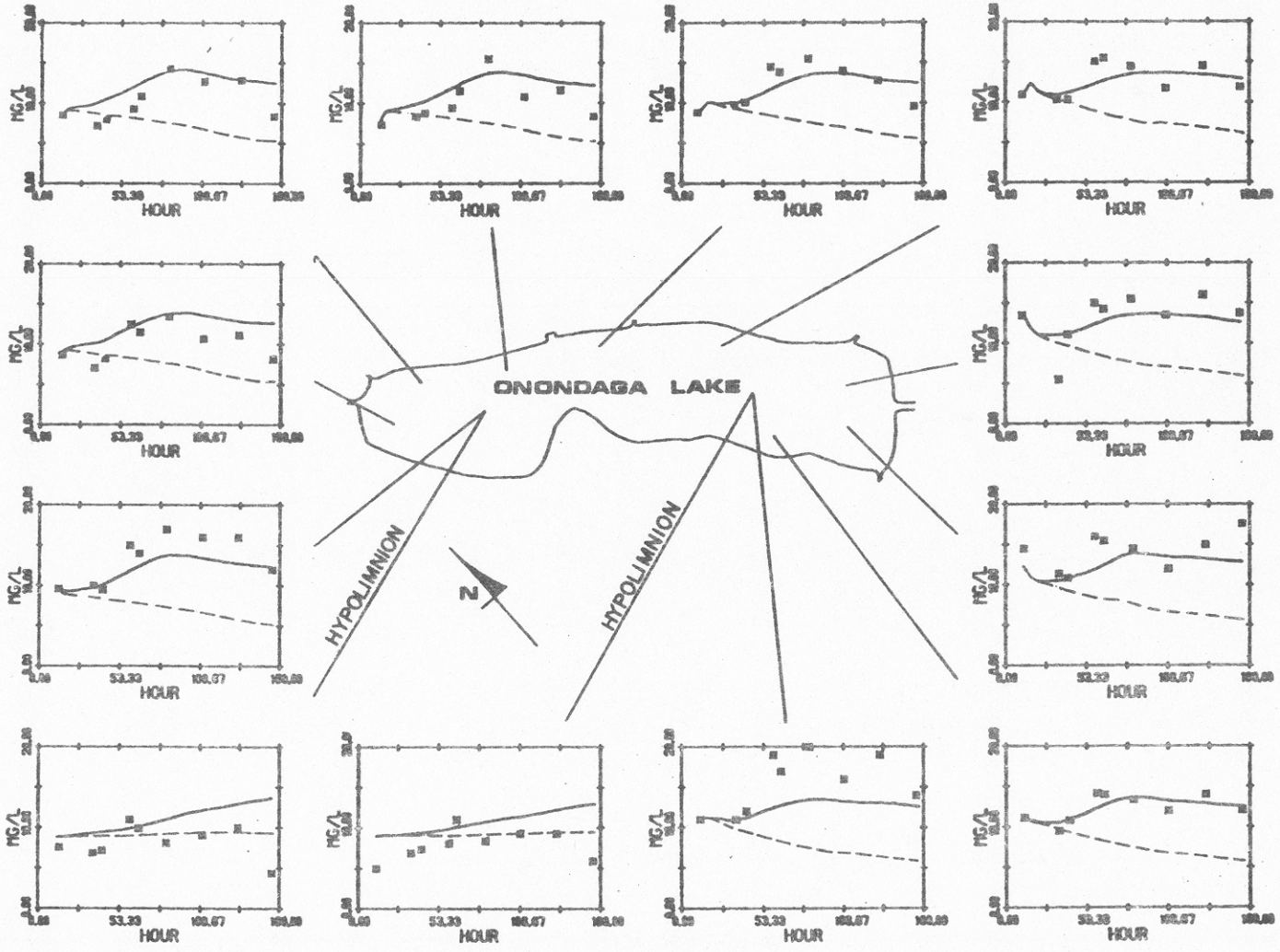

SENSITIVITY ANALYSIS ON NBOD REMOVAL RATES: STORM 5

FIGURE 54



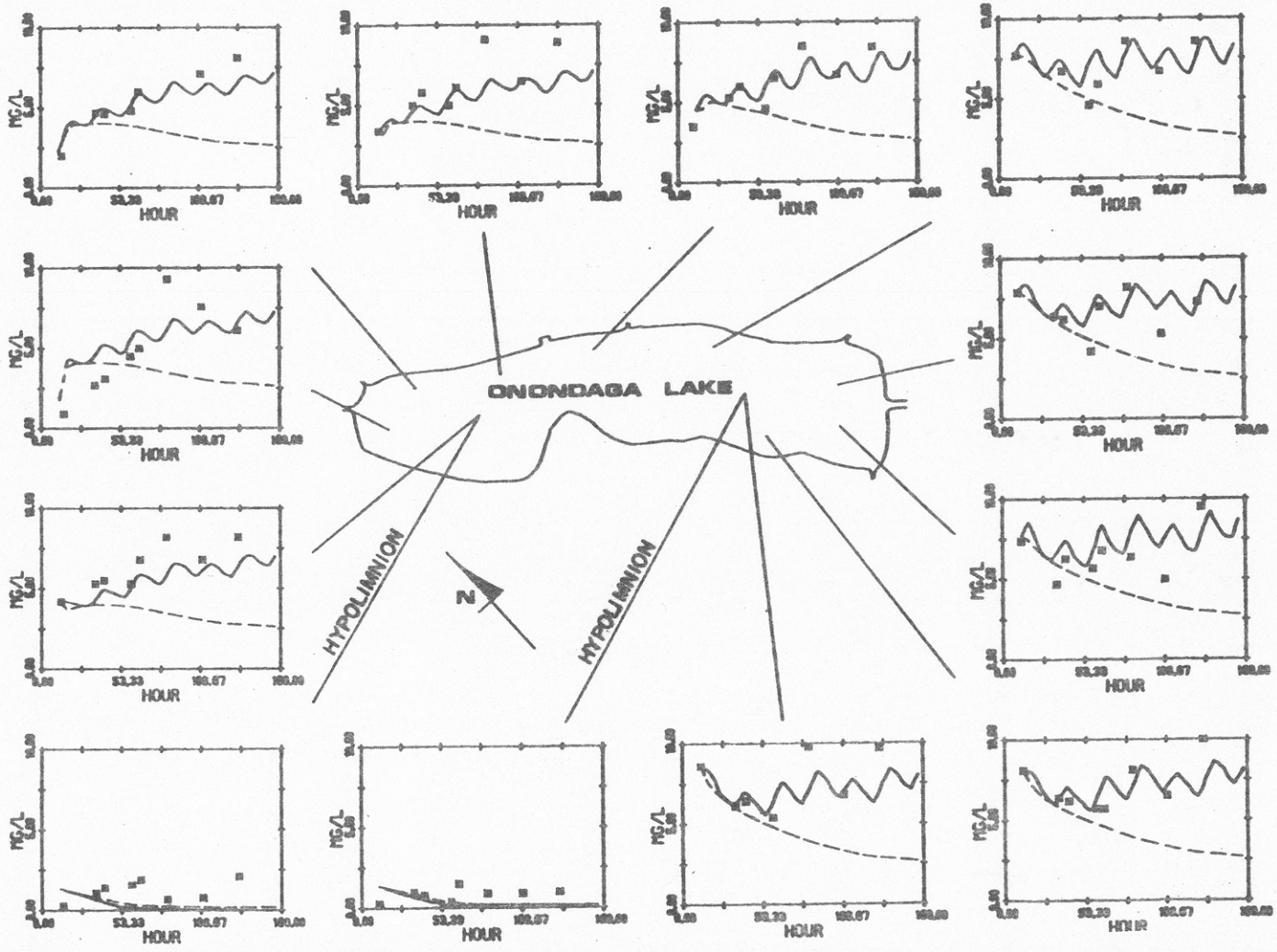

SENSITIVITY ANALYSIS EFFECT ON DISSOLVED OXYGEN CONCENTRATION: STORM 5

FIGURE 55



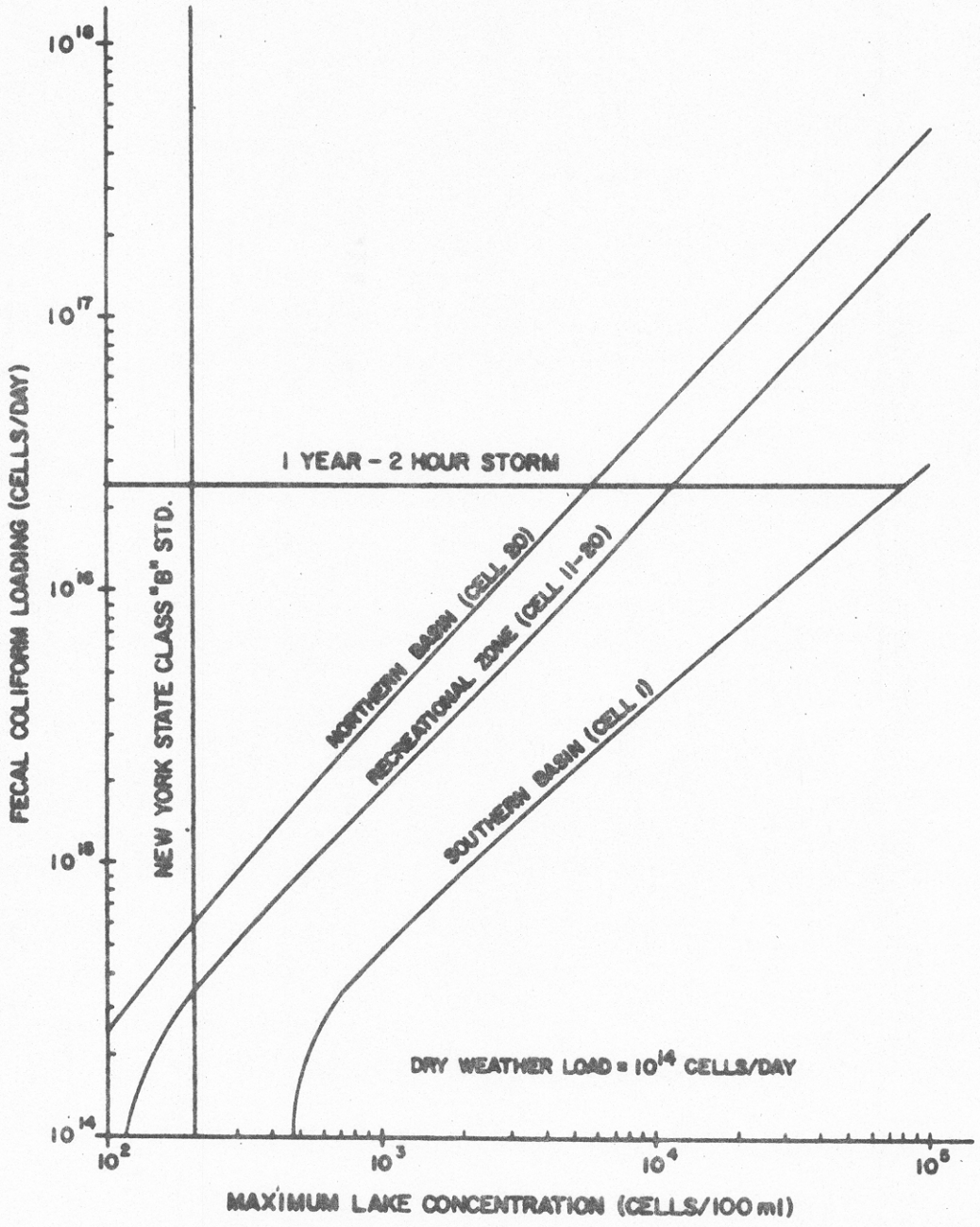

SENSITIVITY ANALYSIS EFFECT ON CBOD CONCENTRATION
OF VARYING ALGAL PRODUCTIVITY: STORM 2

FIGURE 56



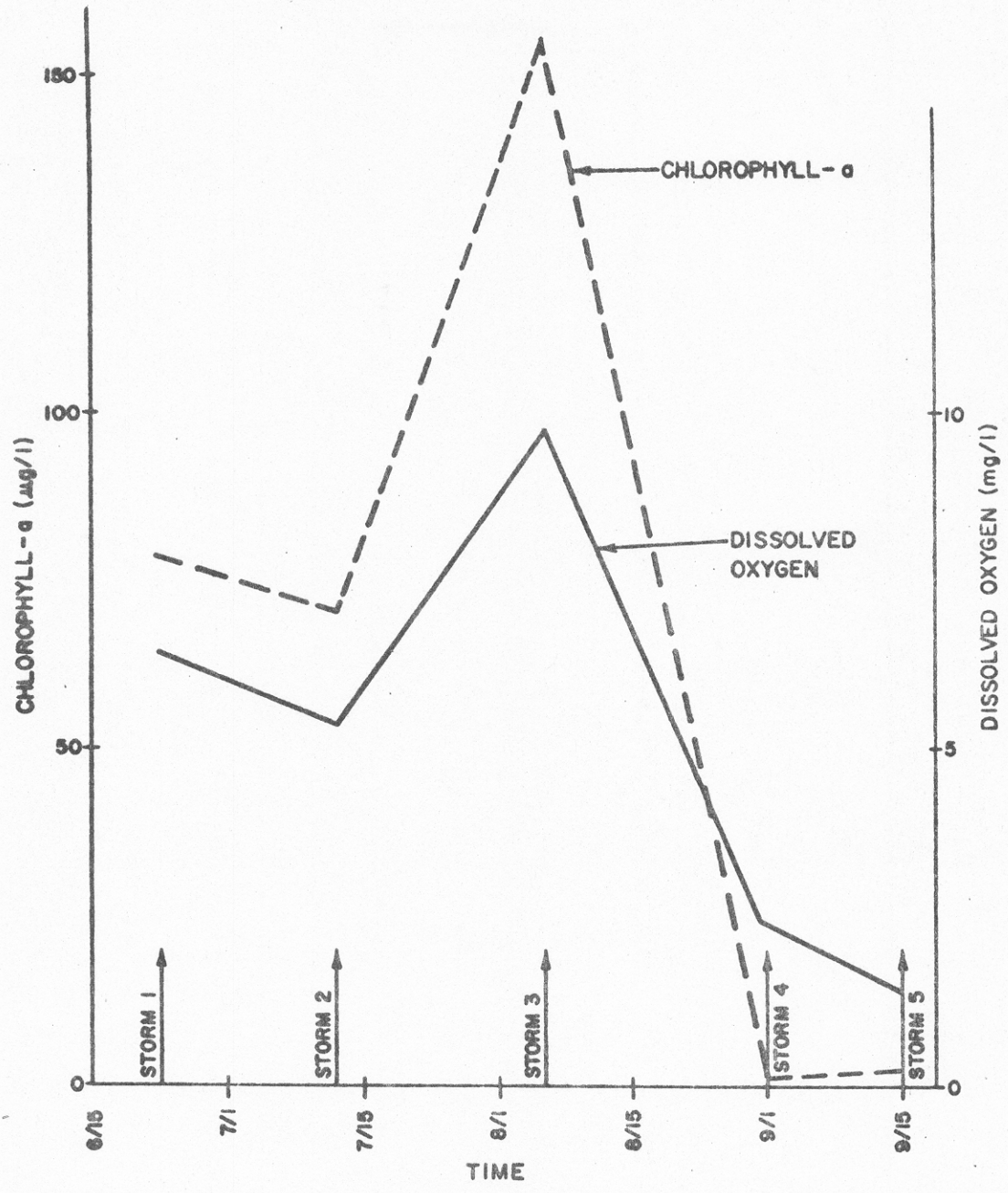

SENSITIVITY ANALYSIS EFFECT ON DISSOLVED OXYGEN
OF VARYING ALGAL PRODUCTIVITY: STORM 2

FIGURE 57

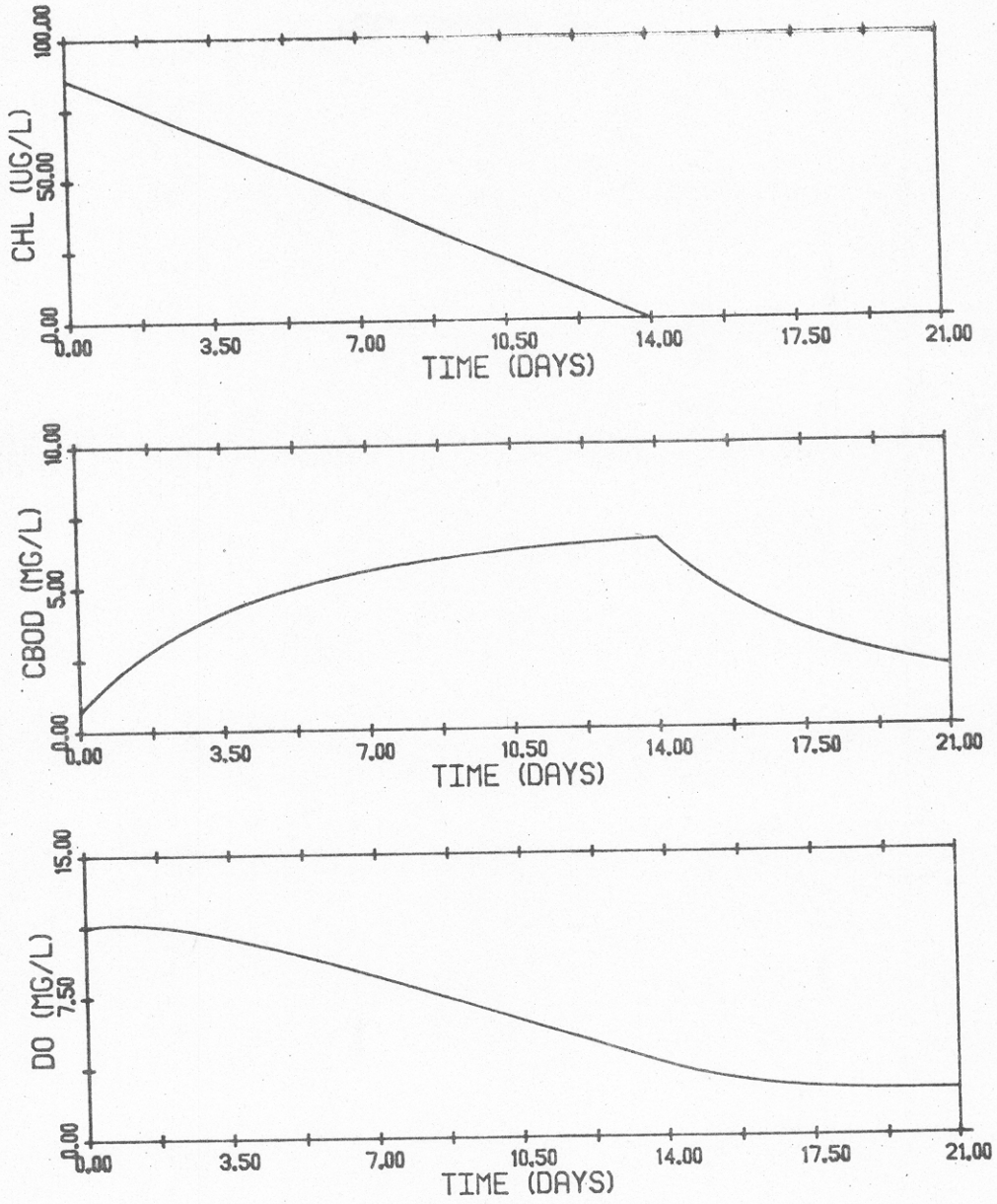



FECAL COLIFORM LOADING CURVE FOR
EPILIMNION OF ONONDAGA LAKE

FIGURE 59




EPILIMNION DISSOLVED OXYGEN TRENDS
COMPARED WITH ALGAL STANDING CROP
ONONDAGA LAKE, NEW YORK




MODEL SIMULATION OF CHLOROPHYLL DIEOFF