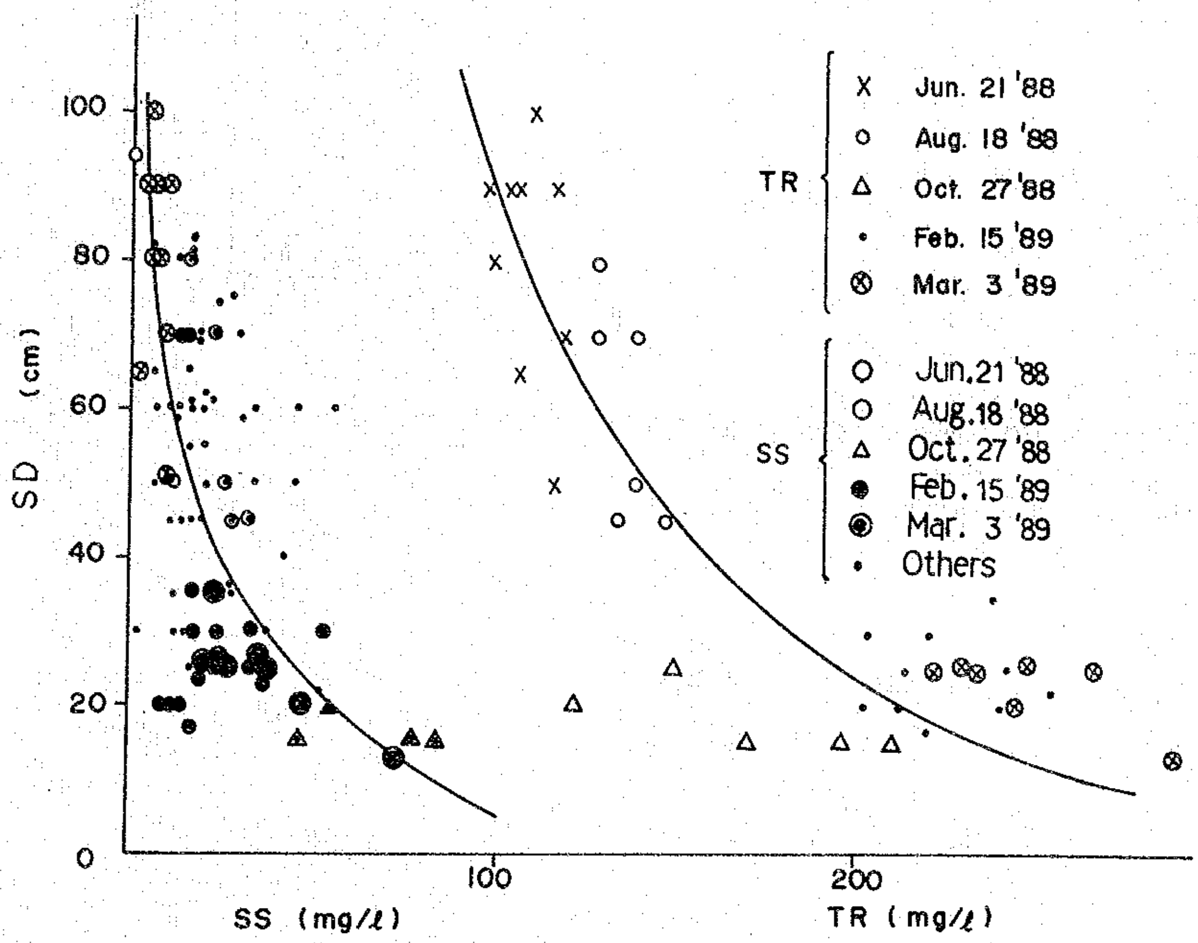

Fig. S6.4.47 Relationship between SD and SS, TR

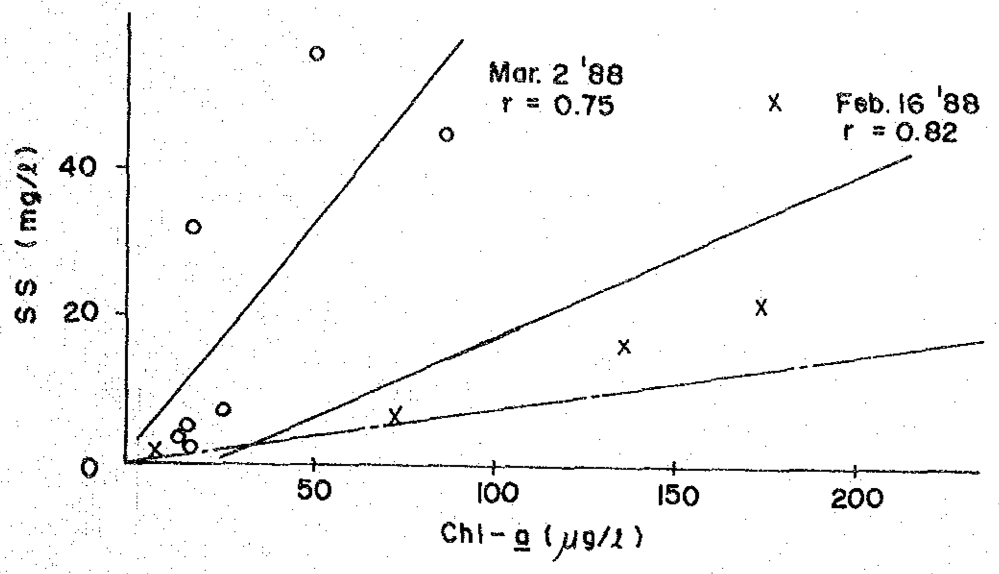

Fig. S6.4.48 Relationship between SS and Chl-a on Feb.16 and Mar.2, 1988

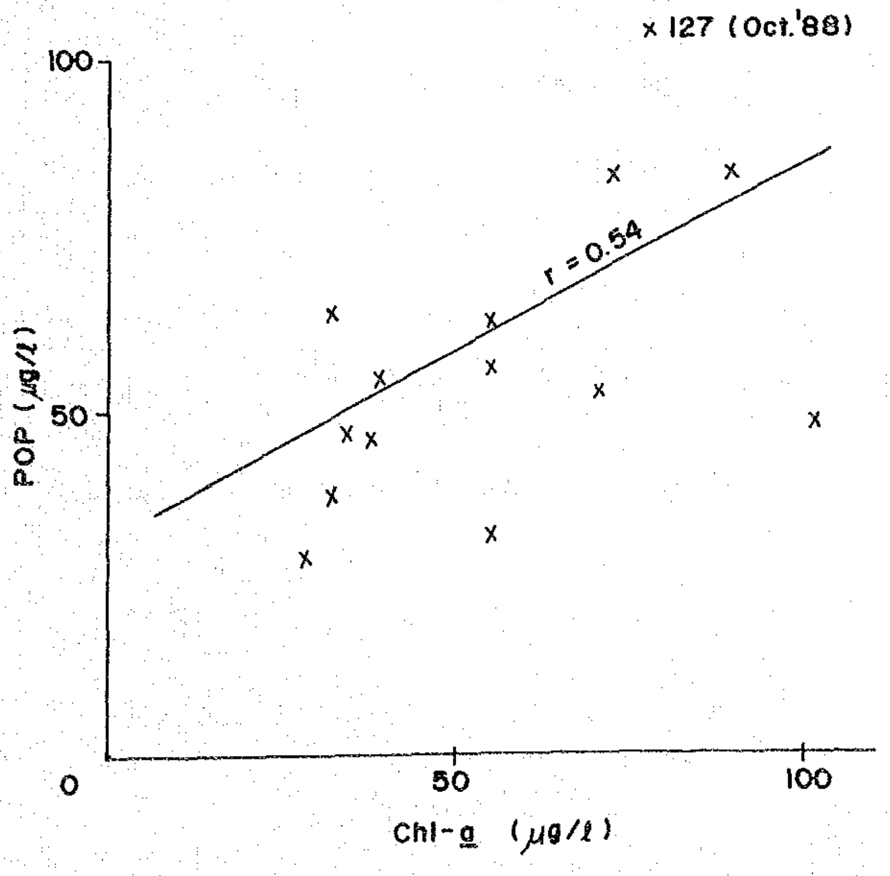

Fig. S6.4.49 Relationship between POP and Chl-a

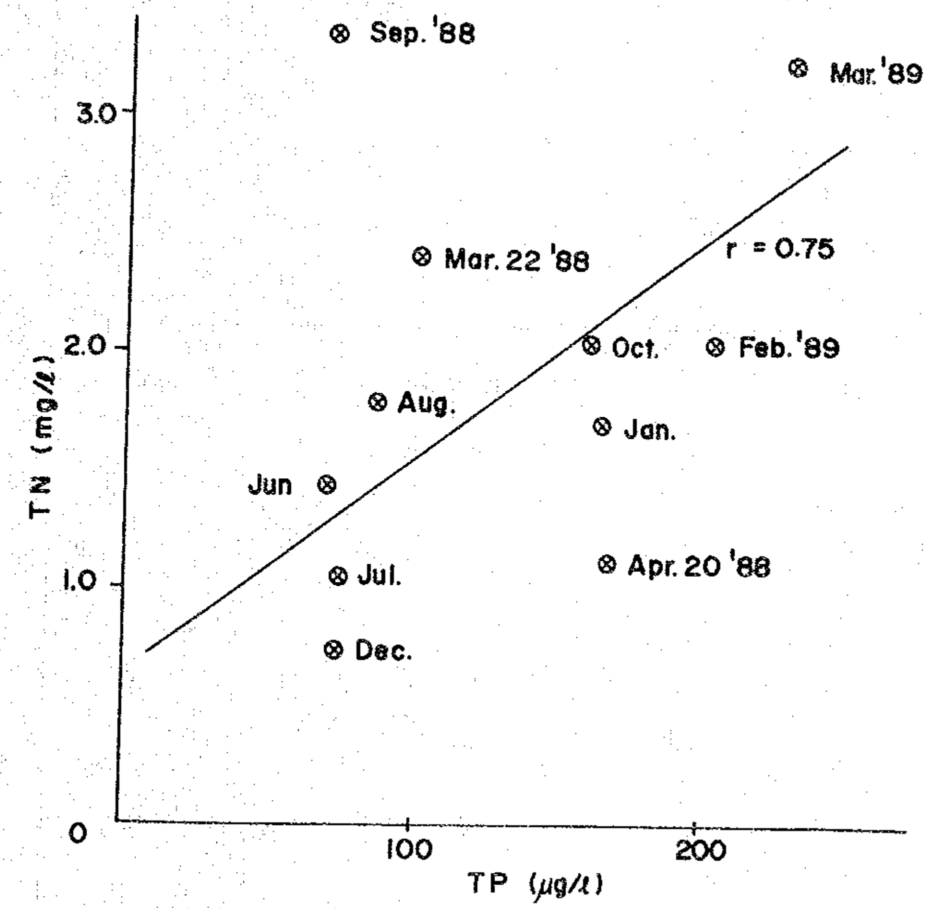

Fig. S6.4.50 Relationship between TN and TP

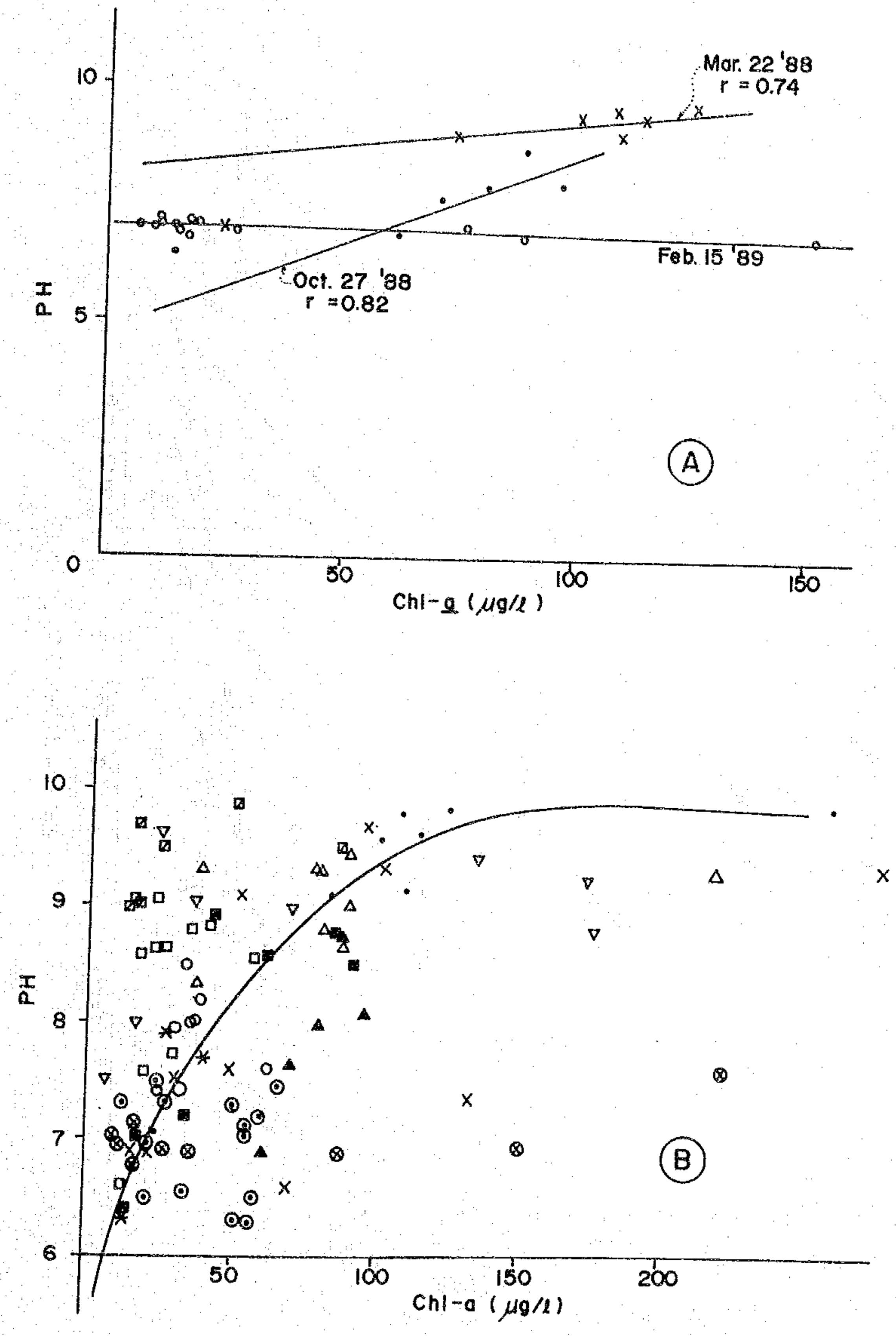

Fig. S6.4.51 Relationship between pH and Chl-a

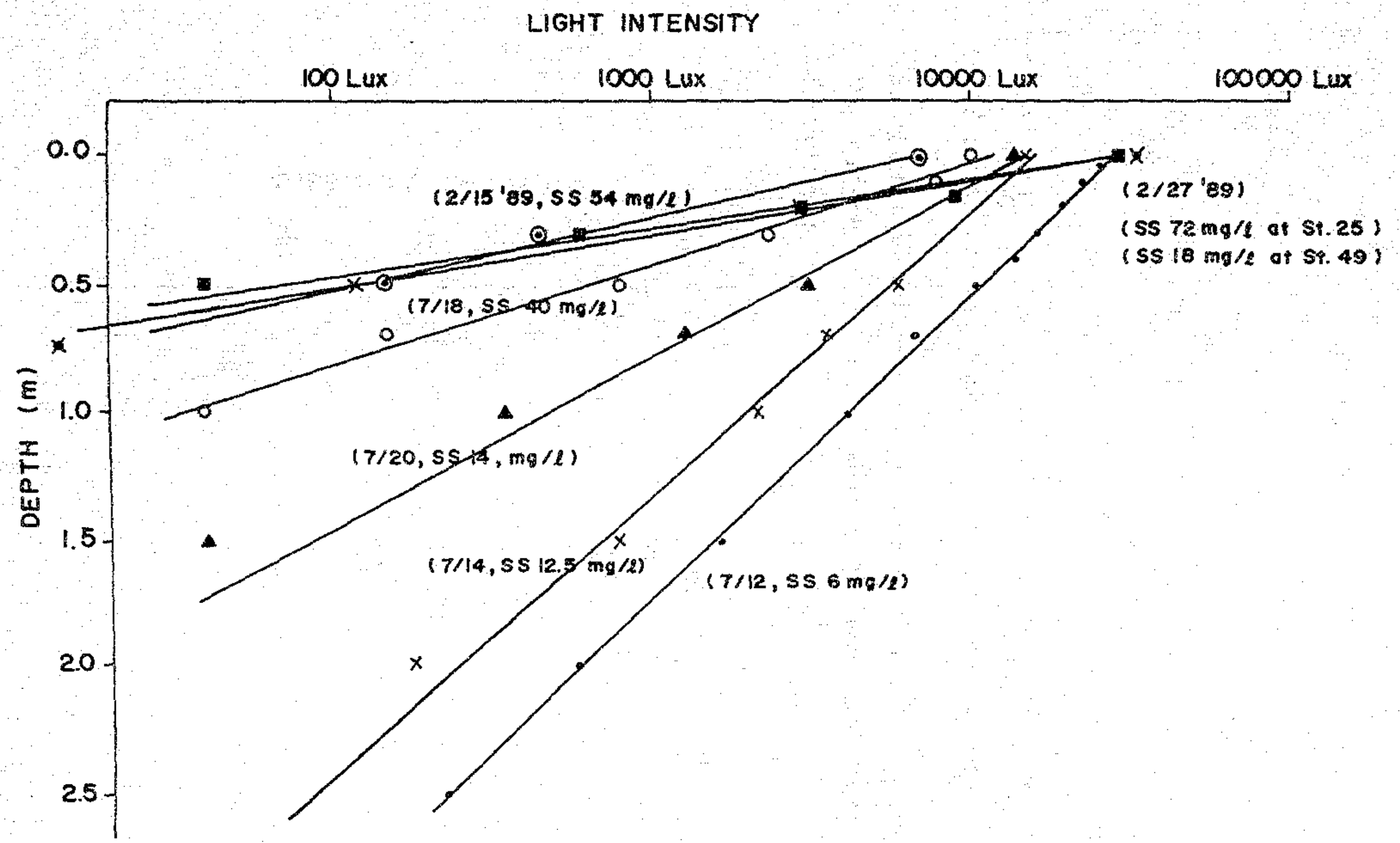

Fig. S6.4.52 Light Attenutation in the Lake Water

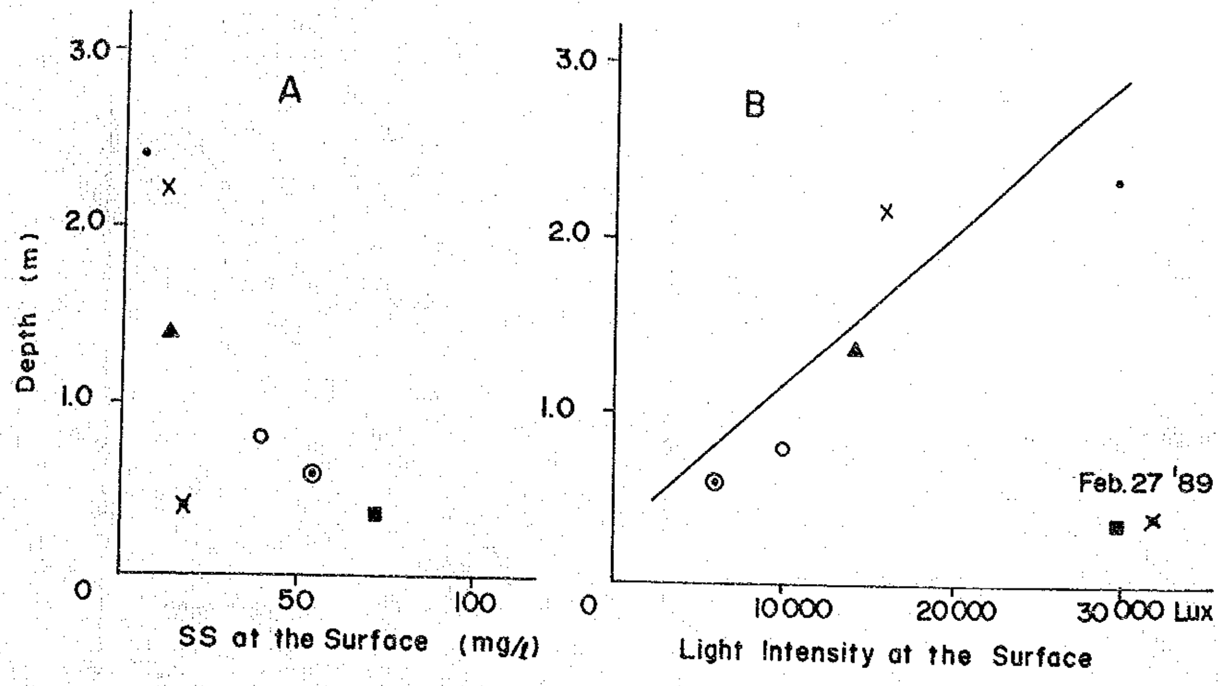

Fig. S6.4.53 Relationship between the Depth where the Light Intensity is 1% of the Surface and SS at the Surface (A), and Light Intensity at the Surface (B)

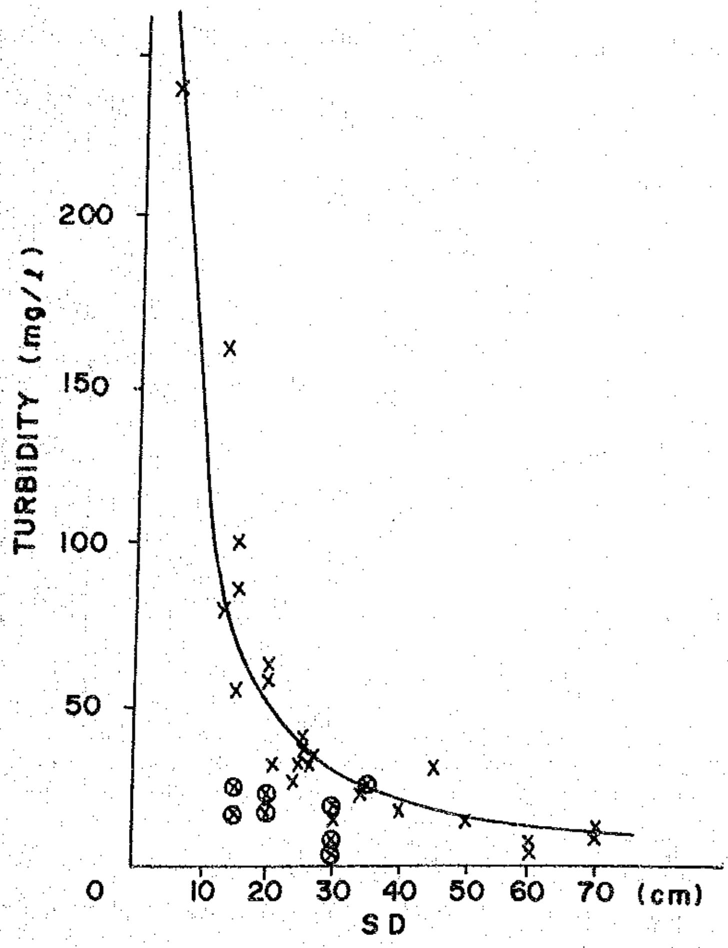

Fig. S.6.4.54 Relationship between Turbidity and SD

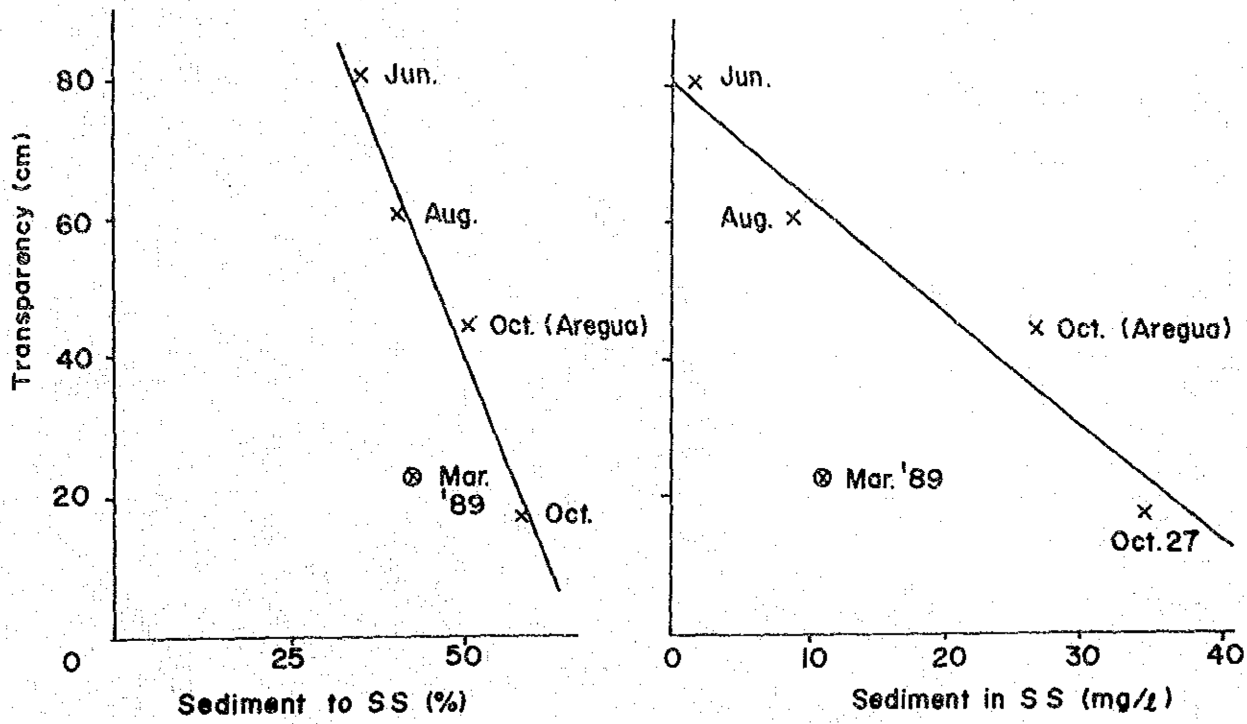

Fig. S6.4.55 Relationship between SD and the Mixing Ratio of Sediment to SS and the Sediment Content in SS

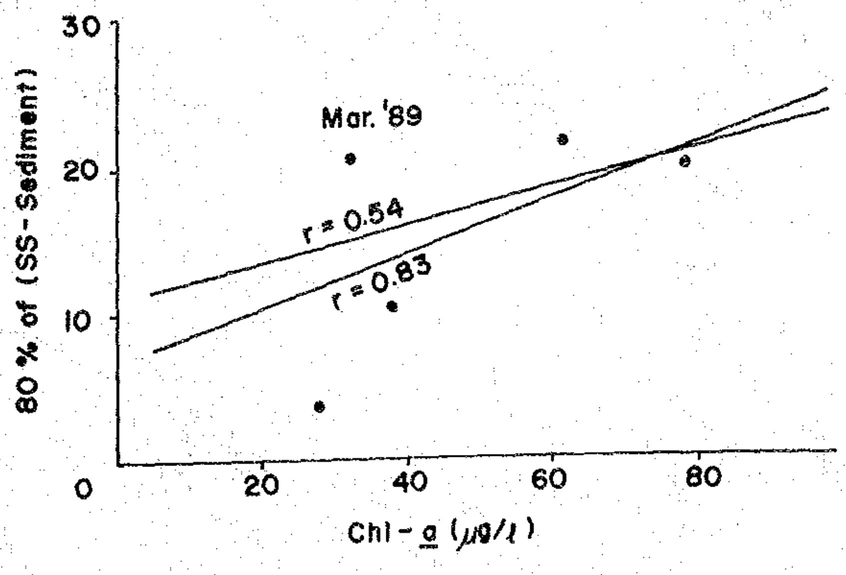

Fig. S6.4.56 Relationship between 80% of (SS-Sediment) and Chl-a

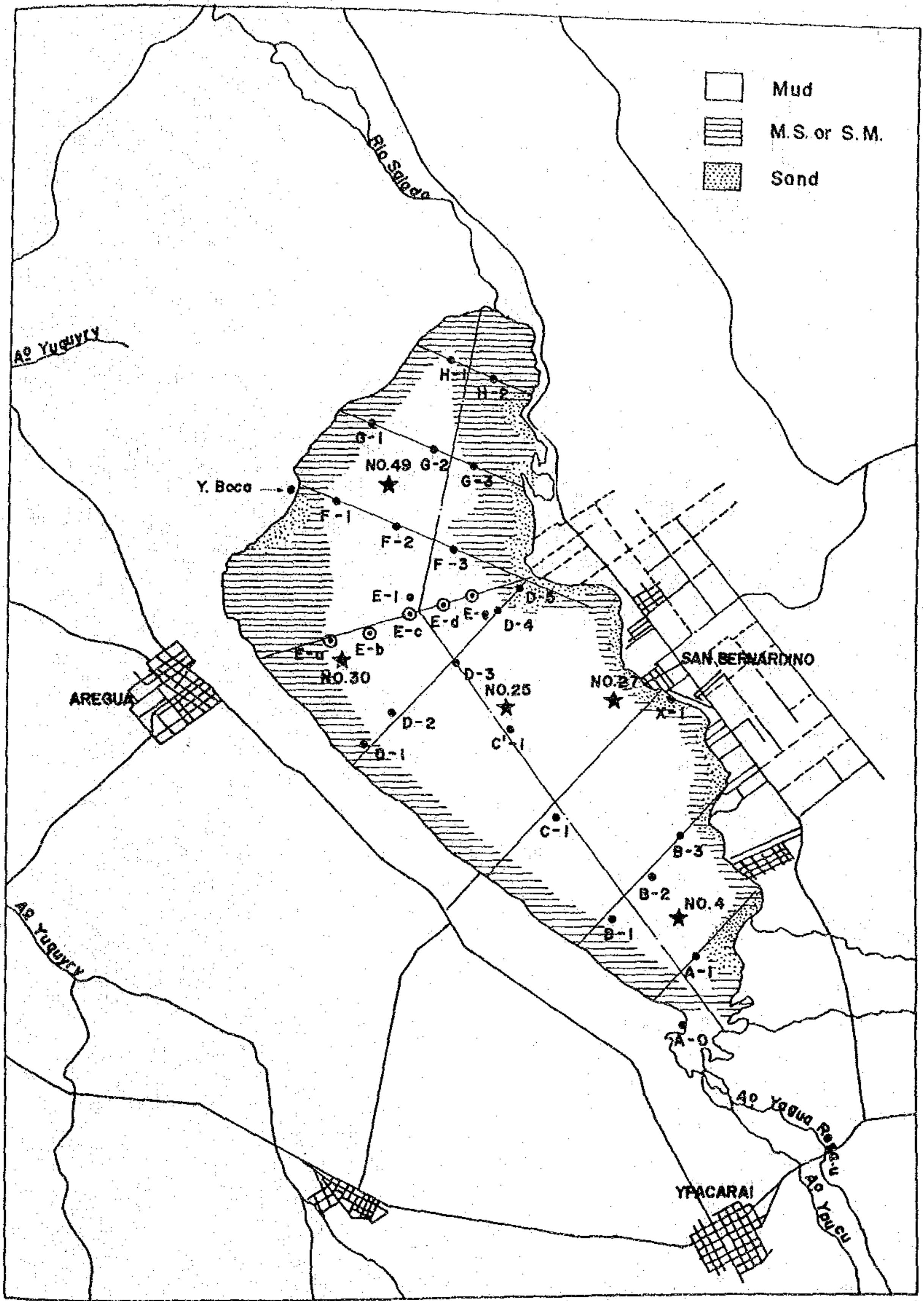

Fig. S6.5.1 Sediment Sampling Stations in the Lake

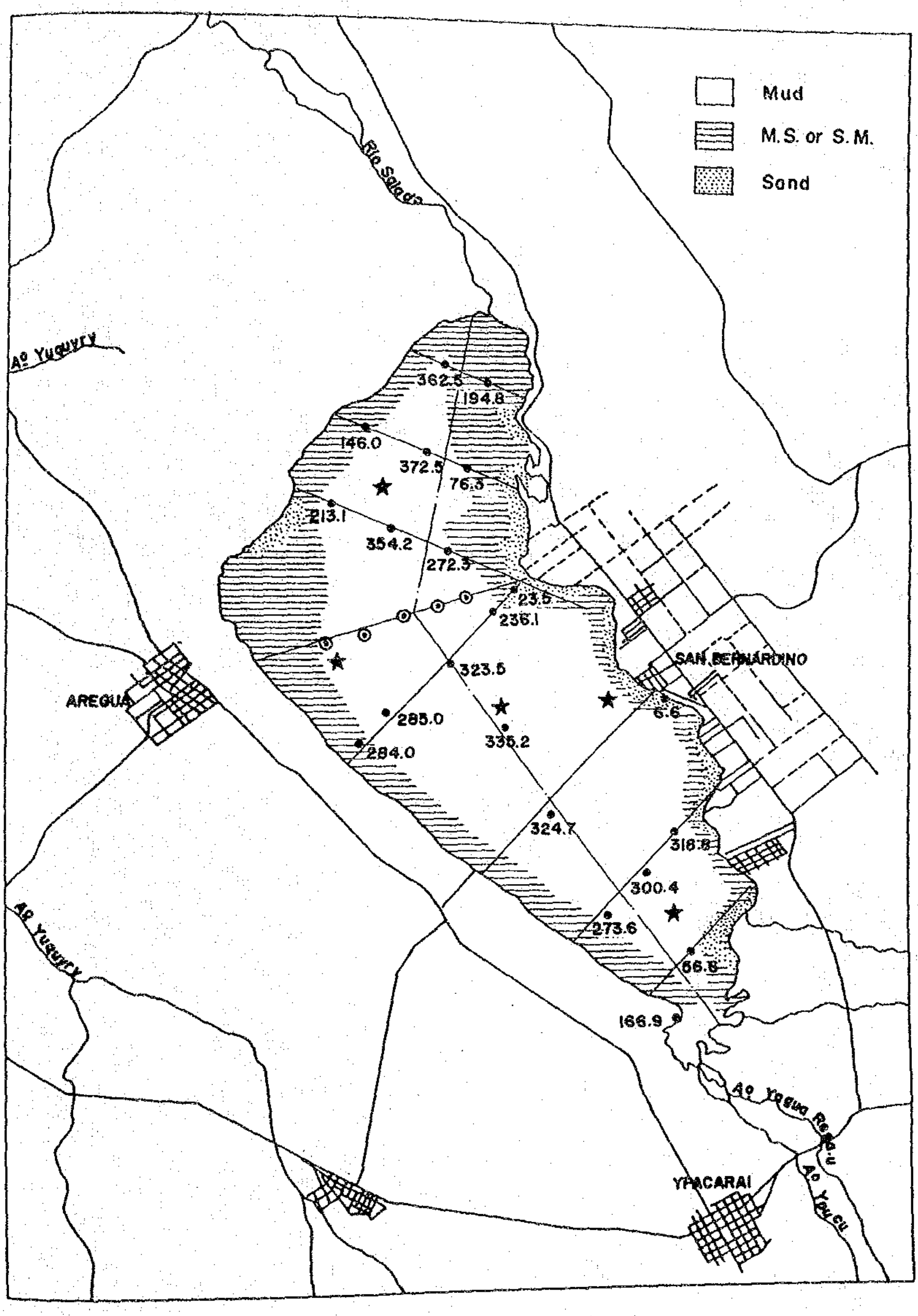

Fig. S6.5.2 Water Content of Surface Sediment in the Lake (%)

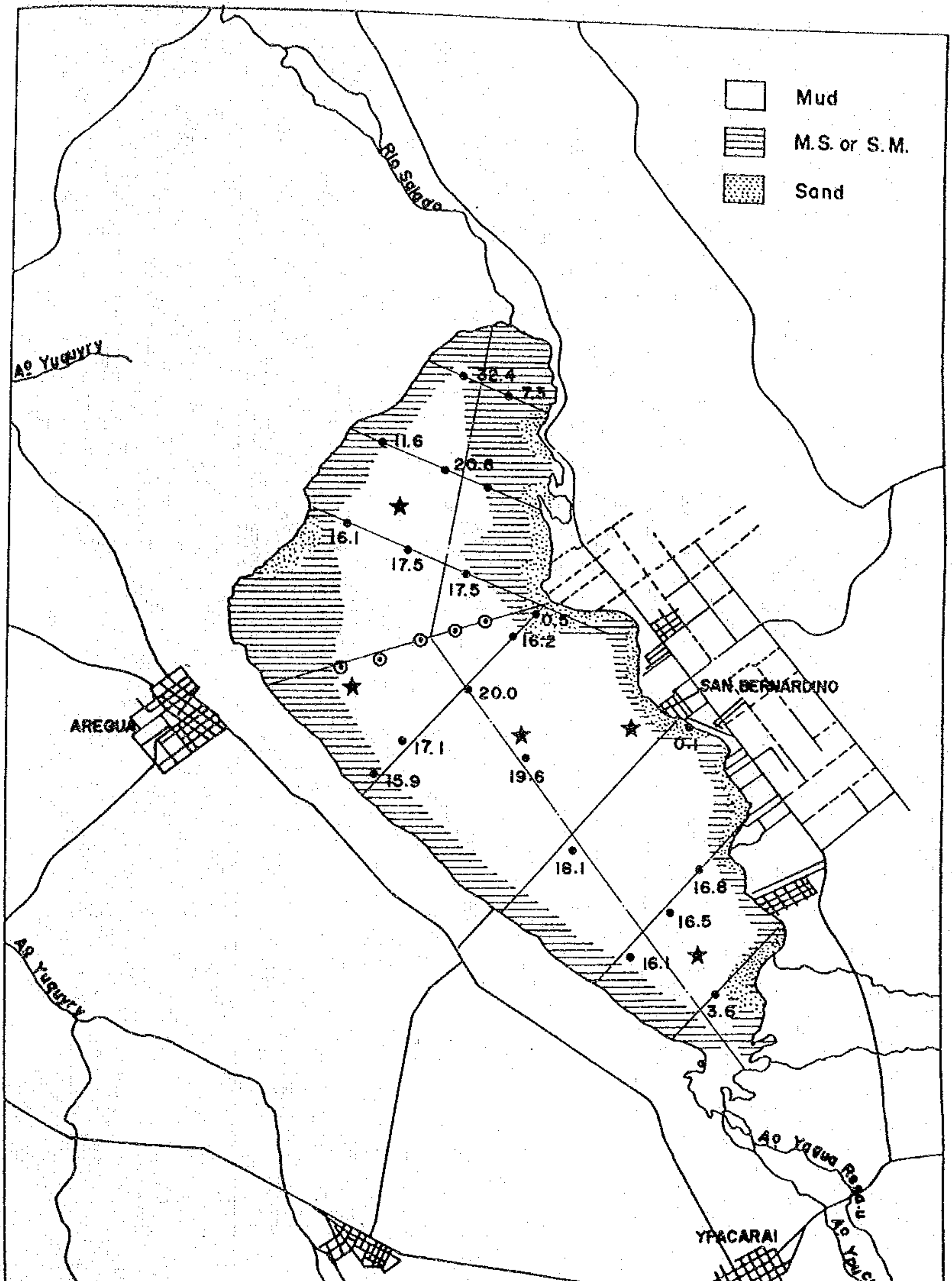

Fig. S6.5.3 Ignition Loss of Surface Sediment in the Lake (%)

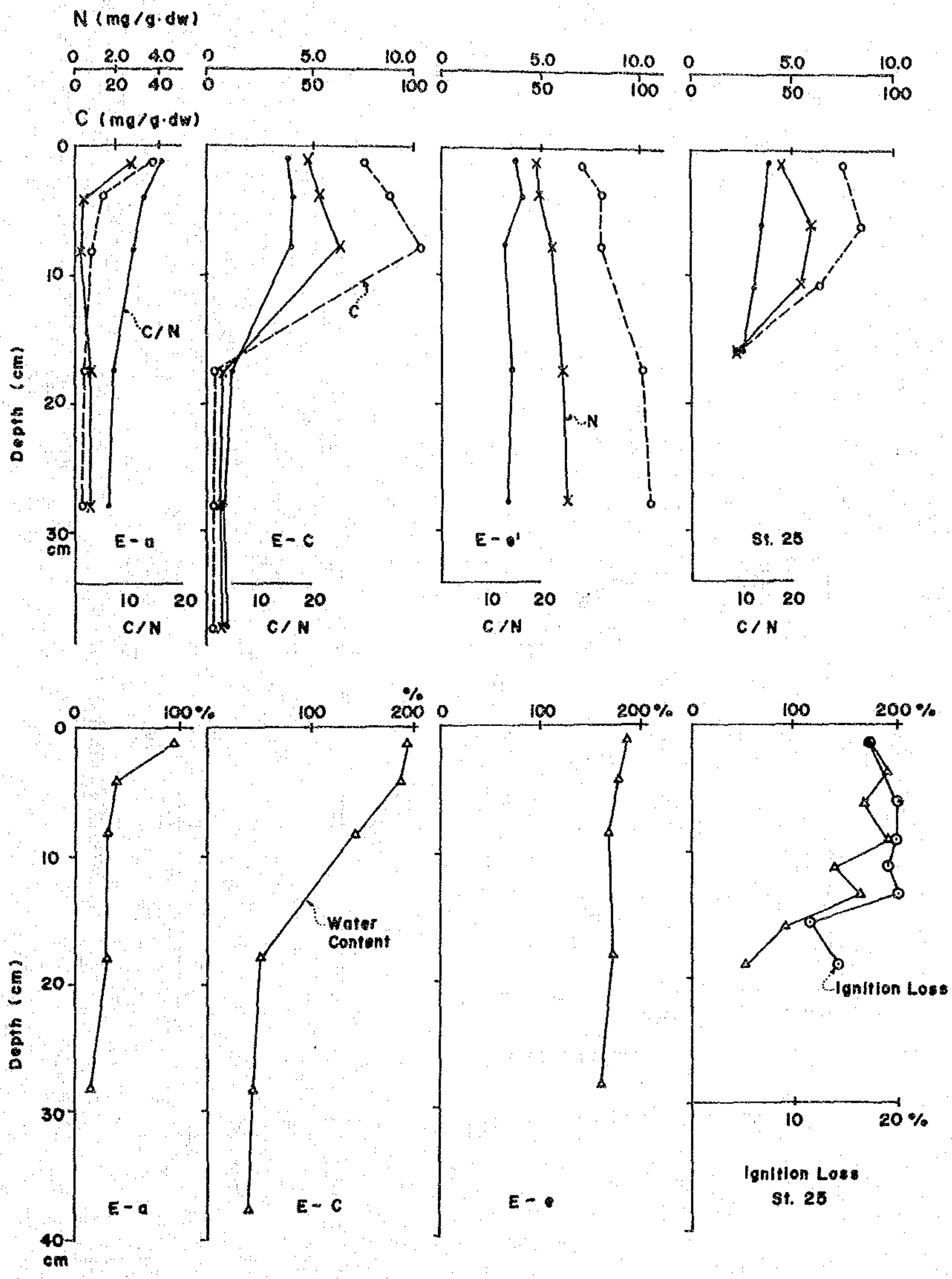

Fig. S6.5.4 Vertical Profiles of Physical and Chemical Characteristics of the Lake Sediment

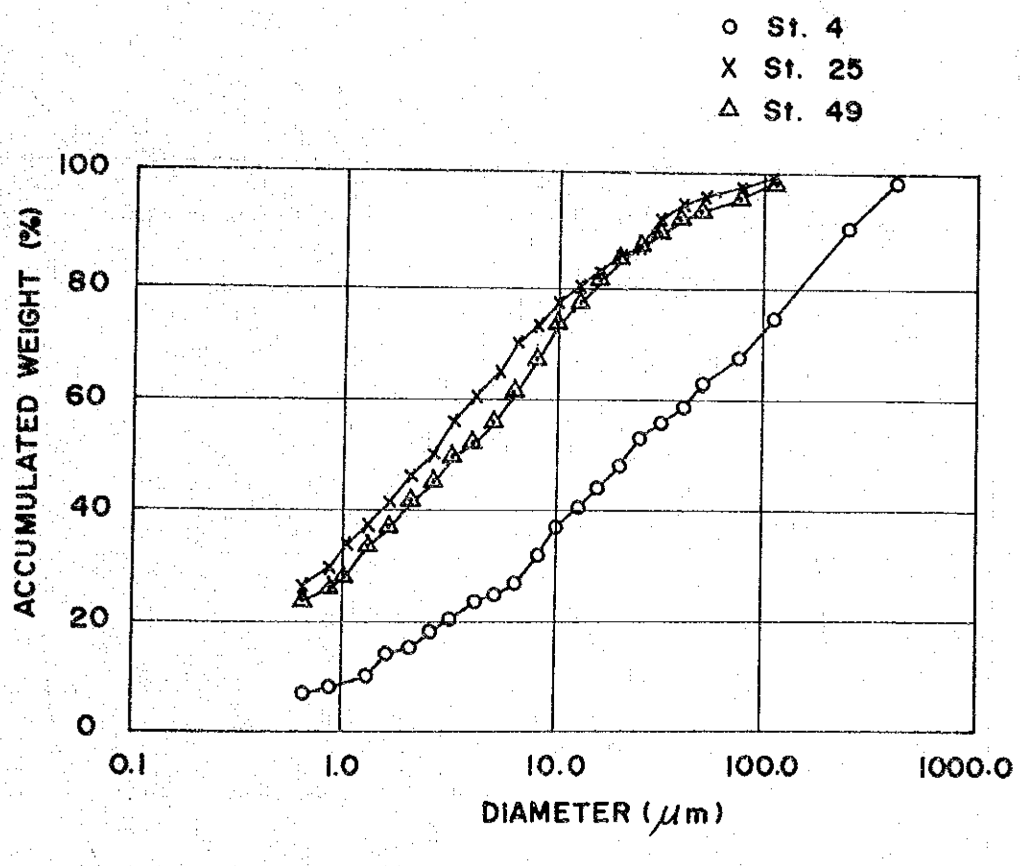

Fig. S6.5.5 Grain Diameter of the Lake Sediment

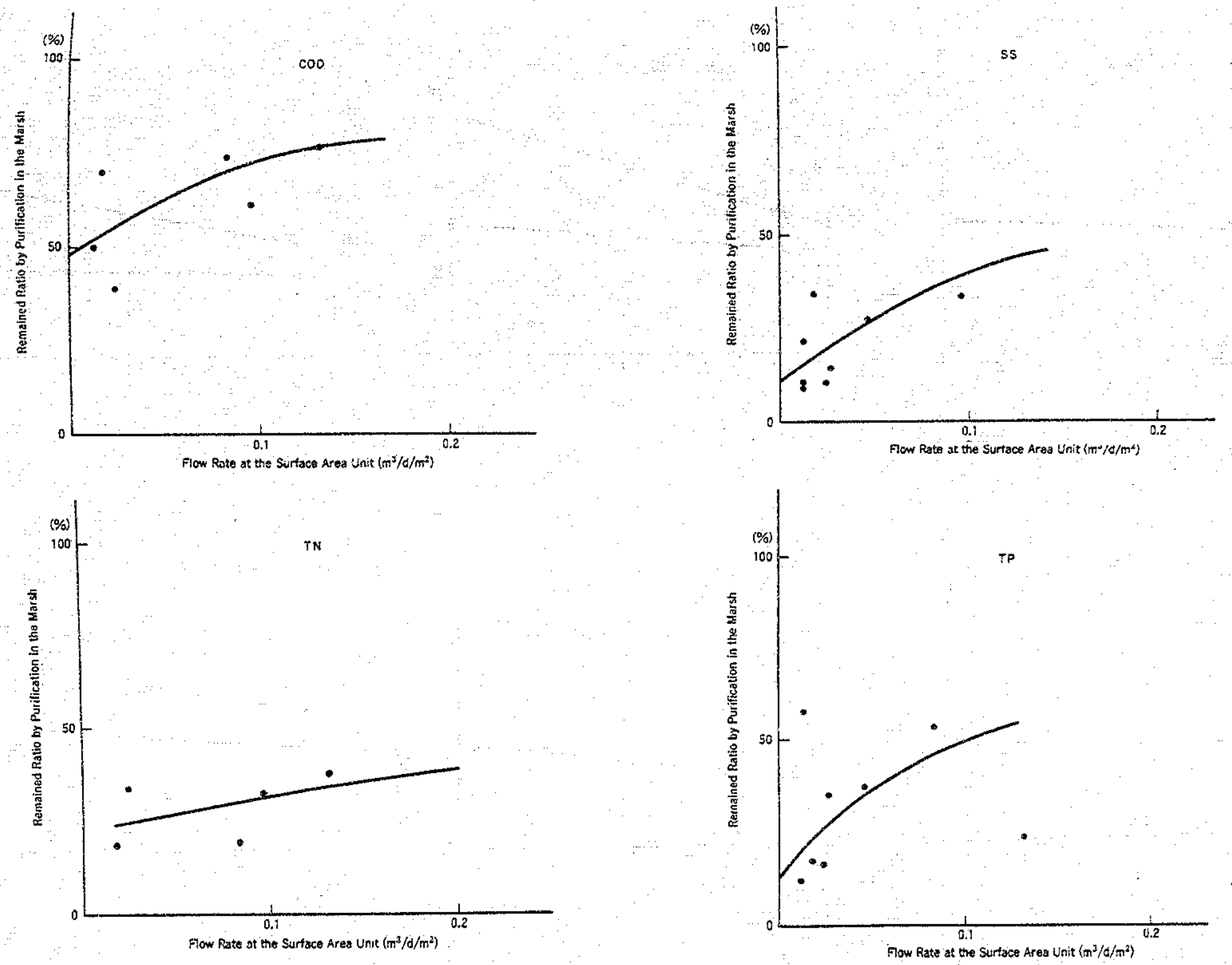

Fig. S6.6.1 Relation between Remained Ratio by Purification and Flow Rate at the Surface Area Unit in the Yuquyry Marsh

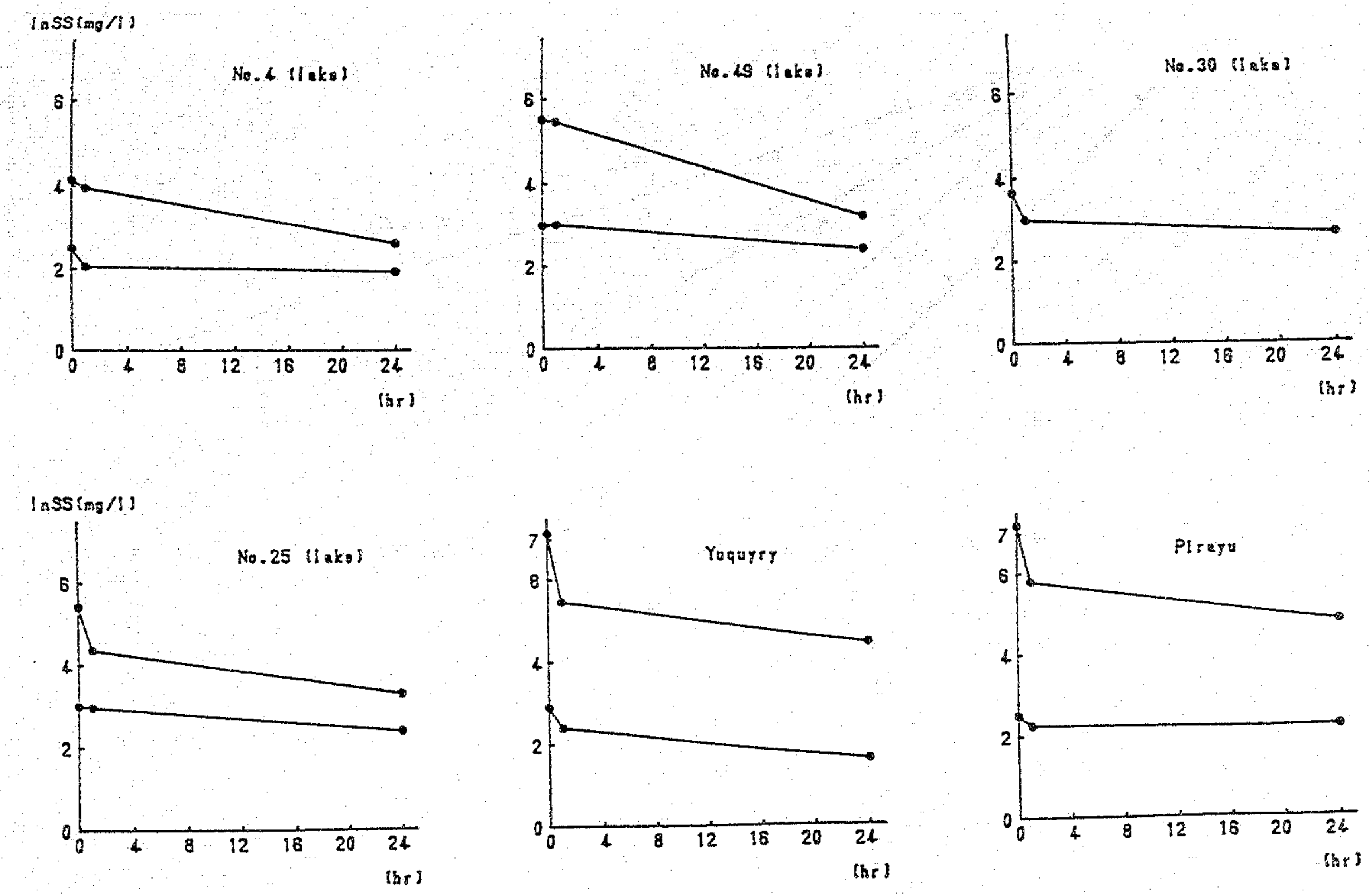

Fig. S6.6.2 Results of Experiments of Sedimentation

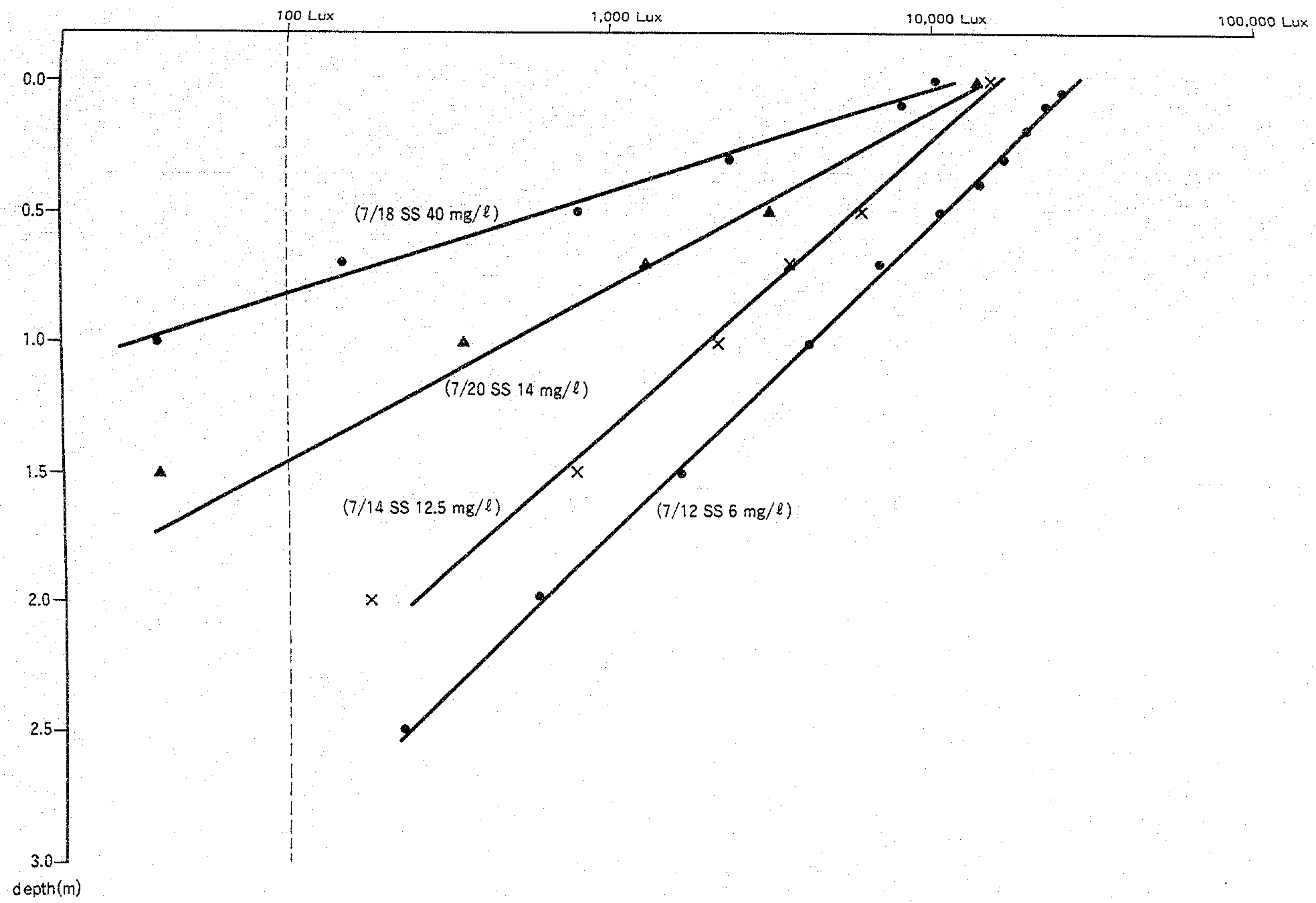

Fig. S6.6.3 Reduction of Ilumination in Lake (Place No. 30)

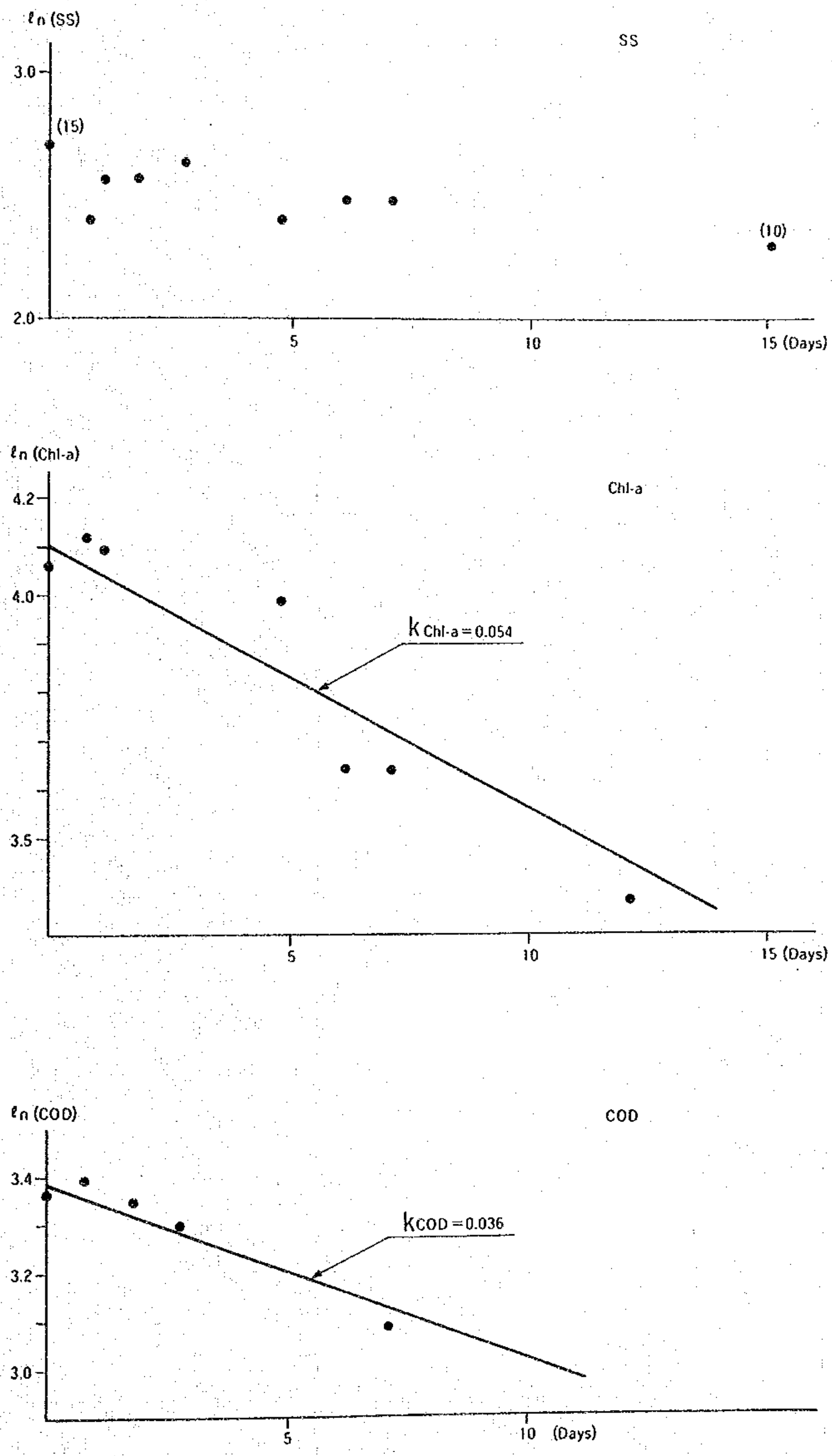

Fig. S6.6.4 Decomposition Velocity of COD, Chl-a, SS

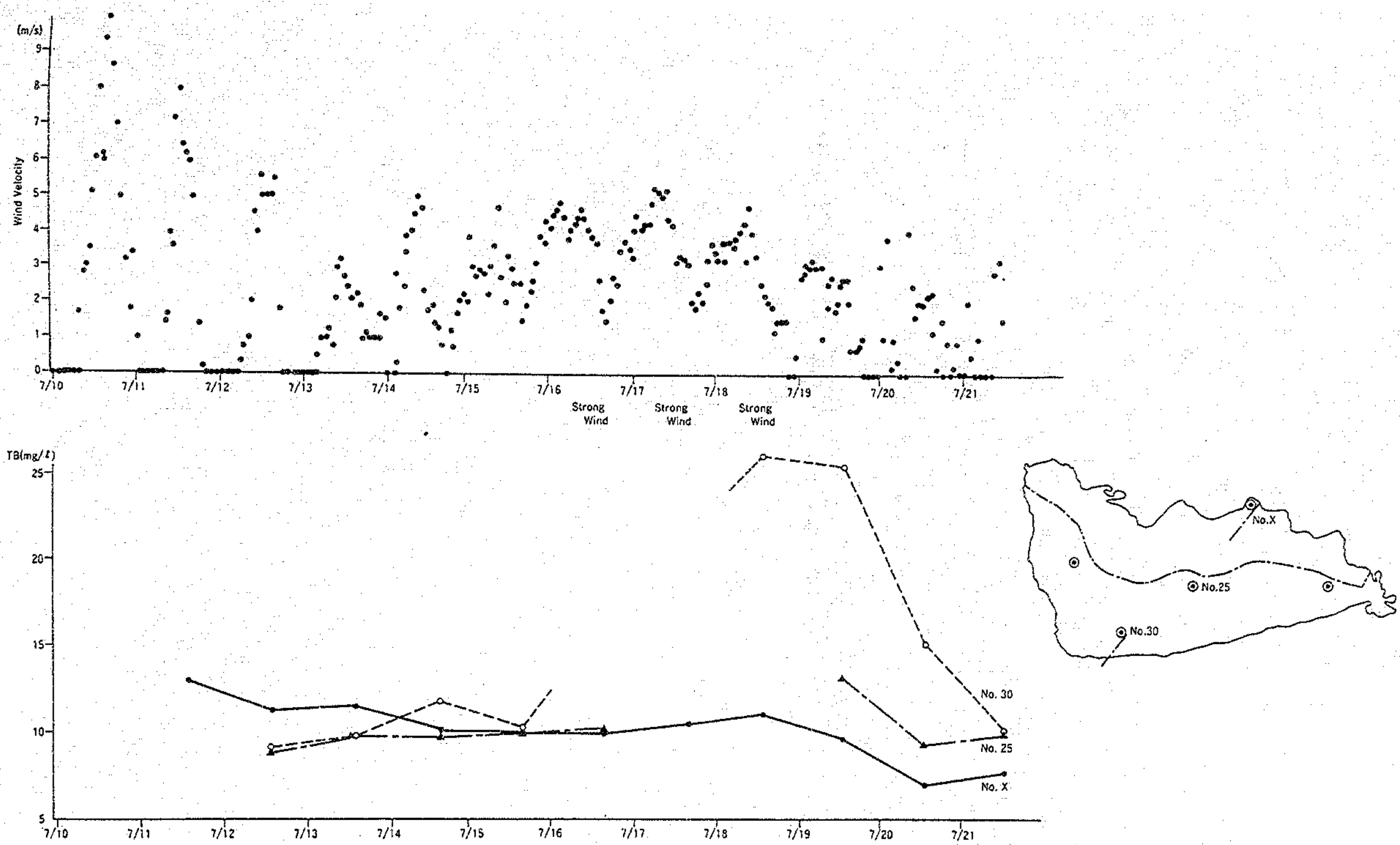

Fig. S6.6.5 Relation between Wind Velocity and Turbidity

SUPPORTING REPORT Ⅶ

WATER POLLUTION SIMULATION

WATER POLLUTION SIMULATION

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CHAPTER I

COMPOSITION OF POLLUTION SIMULATION

1.1 Objectives of Analysis through Pollution Simulation

In general, the quality of water in lakes is affected by a complex combination of factors such as (i) hydrological and meteorological factors, (ii) characteristics of the basin and inflow load, (iii) topography of the lake and (iv) changes in the lake due to biological, chemical and hydraulic phenomena. In pollution simulation, systems analysis is performed using a comprehensive numerical model of the microcosm that consists of factors such as the circulation of water, inflow of pollutant load into the lake, biological and chemical changes in the lake and circulation of matters including the ecosystem of the lake.

The aim of the analysis through pollution simulation is as follows.

① Clarification of quantities and mechanisms of pollutant contribution from pollution sources

② Forecasts on future water quality in the event of no measures being taken to control the pollution

③ Comparison of alternative plans for improvement of water quality (The elements of lake water pollution are shown in Fig. S7.1.1.)

1.2 Procedure of Analysis using Numerical Model

The procedure of the analysis using numerical models is shown in Fig. S7.1.2.

1.3 Aim and Details of Analysis

The aim and the details of analysis through simulation are shown in Tab. S7.1.1.

1.4 Basic Composition of Water Pollution Model

The inputs for the water pollution model of Lake Ypacarai will consist of the reaction constants of phenomena including inflow water volume, inflow load, meteorological phenomena and changes in the lake, on the basis of which, variation in lake water quality is calculated. This model will be

composed of those of the balance of water in the lake, of the inflow load from the basin, and of the variation of water quality in the lake.
The basic constitution of water pollution is shown in Fig. S7.1.3.

The inputs for the water balance model are the volume of inflow from the rivers, precipitation on the lake, evaporation from the lake surface, water intake from the lake and water level (water volume) of the lake. The model is used for calculating the discharge from the rivers, water retention time in the lake and its turnover.

The inputs for the inflow load model are rainfall in the basin, load generation conditions (land use, topography, etc.) for non-point sources, and load generated by point sources. The model is used for calculating the water volume and the load flowing into the lake.

The water quality variation model is used to quantitatively express changes in load flowing into the lake resulting from sedimentation, decomposition, generation, advection, dispersion, ellusion, and stirring up of the lake bottom material.

CHAPTER II

STRUCTURE ESTABLISHMENT OF NUMERICAL MODEL

2.1 Characteristics of Water Pollution in Lake Ypacarai

Phenomena and reactions shown in Fig. S7.2.1 illustrate the pollution mechanism of Lake Ypacarai.

【1】Principal Causes of Water Pollution

The principal causes of water pollution in Lake Ypacarai are as follows.

(1) Soluble organic matter which do not easily decompose such as humic acid flowing into and remaining in the lake

(2) Algae produced through eutrophication, and dead algae

(3) Remnant of deposit stirred up from lake bed by wind

【2】Factors affecting Water Quality

Simultaneous occurrences, or occurrences on their own, of the above-mentioned three principal pollution causes are responsible for worsening the correlation between the measured values of water quality indicators.

Persistent soluble organic matter is responsible mainly for variation in the D-COD values. Factors involved are the rainfall and runoff, inflow load and retention time.
Production and disintegration of algae result in variation of values for P-COD, D-COD, Chl-a and SS. Factors involved include concentrations of nitrogen and phosphorus, water temperature, solar radiation, flow velocity and retention time.
Disturbance of the lake bed results in variation of the P-COD and SS values. Factors involved include wind and flow velocities, quality of lake bed and depth of water.

【3】Changes in Outward Appearance of Water

The three causes mentioned above also contribute towards variation in the outward appearance of the water. Pollution due to eutrophication turns the water green, and the increase in the residue of persistent organic matter turns the water liver-brown, while the disturbance of the deposit on the lake bed turns the colour of the water blackish.

【4】 Horizontal Distribution

There are no outstanding specificities in the horizontal distribution of pollutants and the whole area can be thought to constitute a single body of water. Average water quality values will be used in the verification of the model.

【5】 Vertical Distribution

The depth of the water being small, there is no stratification due to variation in water temperature. Although there are slight variations in the values, among others, for DO according to varying depths, as in the case for horizontal distribution, there are no outstanding specificities in the vertical distribution of pollutants. The model will be of a single stratum.
Variation in the quantity of light reaching various depths, however, is clearly observed. Hence, water quality greatly affects the water depth at which production takes place. Average water quality values will be used in the verification of the model.

【6】 Temporal and Seasonal Variation of Water Quality

Degree of change in water quality due to disturbance of botto deposit varies greatly with wind and shows hourly variation. pH and DO values show periodic daily variation. The rate of production of algae due to eutrophication varies with seasons, increasing in summer when the water temperature is high and decreasing in winter when the water temperature is low.

【7】 Residue of Inflow Load

COD values in Lake Ypacarai remain high throughout the year, even when there is no algae production nor disturbance of deposit on the lake bed. This is thought to be due to the inflow load which remains in the lake. In other words, it is thought that there is a high proportion of organic matter which do not decompose easily, such as humic acid, among the organic matter in the inflow load.

【8】 Thermal Stratification of the Lake Water

The depth of the water being too small for the water to resist being mixed by the stirring action of the wind, stratification due to variation in water temperature is not observed even in summer. From the point of view of stratification due to water temperature, too, the lake may be considered as consisting of a single vertical stratum.

【9】 Euphotic Zone

Disturbance of the lake bed greatly alters the amount of light penetrating the water in the lake, causing variation in the depths at which algae are produced. Values for the depths at which the algae are produced need to be altered using the coefficient for the reduction in the quantity of light as a function of SS.

【10】 Purification in Swamps

Inflow load is purified in the swamps and enters the lake at an almost constant concentration. Calling the water quality of the influent rivers Co and the quality of the discharge from the swamps Ca, two ways of thinking are possible, either that Ca is in proportion with Co (i.e. Ca/Co = k) or that there is no correspondence between the two. The results of the water quality survey suggests the latter, but the samples measured may be affected by back water from the lake and in the latter way of thinking, the purification capacity of the swamps is determined as being infinite. For these reasons, two models, each taking in either way of thinking, need to be prepared.

【11】 Settlement

SS component of the inflow load, deposit disturbed from the lake bed and dead algae all settle at the bottom of the lake. The SS component of the inflow load contains a high proportion of colloidal particles, while the particles of the deposit stirred up are small, resulting in a slow rate of settlement. The rate will need to be determined through experiments. The rate of settlement of algae in the lake is thought to be around 0.02 to 0.10 m/day as generally reckoned.

【12】Elution

Elution of COD, nitrogen and phosphorus generated by decomposition of organic matter in the deposit on the lake bed is observed. Elution rate needs to be determined through experiments. Factors involved include the quality of the deposit and the water temperature. Elution rate increases with organic content of the deposit, and with water temperature.

【13】Production

Concentrations of nitrogen and phosphorus are high and algae are being actively produced in the euphotic zone. Factors involved include water temperature, concentrations of nitrogen and phosphorus and depths of euphotic zone. Cyanophyceae are the predominant type of algae in summer and even in winter cyanophyceae make up approximately 50% of all the algae produced, meaning that the production of algae is greatly affected by water temperature.

【14】Disturbance of Bottom Deposit

Bottom deposit is disturbed by the generation of shear due to winds. The phenomenon is not limited to several times a year but is thought to occur whenever there are winds of 3 to 5 m/s.

【15】Denitrification

The low TN concentration in the lake water compared to that in the influent rivers suggests occurrence of denitrification. Since the main body of the lake is permanently in an aerobic state, it is thought that most of the denitrification occurs in the swamps.

【16】Convection and Dispersion

Convection and dispersion are thought to keep the water quality of the lake more or less uniform.

【17】Decomposition

Decomposition of organic matter is due to bacteria. In general, dead algae decompose at a rate of 2 to 8% per day. Decomposition of persistent organic matter in the inflow load is thought to be slow.

【18】 Direct Precipitation

The quality of rainwater is used as the quality of the inflow water due to direct precipitation.

2.2 Selection of Models and Calculation Pollution Indices

【1】 Selection of Models

Material circulation model will be adopted, as, besides eutrophication, the disturbance of the bottom deposit by wind due to the shallowness of the water constitutes a major cause of water pollution in Lake Ypacarai. In the material circulation model, three models for calculating the balance of inflow and outflow of water, for calculating the inflow load into the lake, and for representing the intra-lake matter transformation are used for calculations of mass balance including the changes of water quality and matter within the lake.
A classification of lake water quality predictions models is shown in Table S7.2.1.

【2】 Selection of Calculation Pollution Indices

According to the analyses of the characteristics of water quality in Lake Ypacarai, matters that constitute the principal elements of water quality in the lake are represented by 5 indicators: COD, nitrogen, phosphorus, Chl-a and SS. These 5 indicators will be used in calculations.
The constitution of water pollution matters is shown in Table S7.2.2.

2.3 Determination of Chronological and Spatial Factors for Inflow Load Model

【1】 Calculation Indices

The 4 indices of COD, TN, TP and SS will be used.

【2】 Chronological Factors

In considerations of the inflow load, since the quality of water in the inflow rivers shows great variation between times of fine weather and of rain, and the quality varies every day, the input of precipitation will be made daily. Calculation models of inflow load will also be determined by the day. Calculations will be made separately for inflow load during fine weather and for discharge due to precipitation during rainfall.

【3】 Spatial Factors

The lake basin will be divided into 4 areas according to the manner in which the study data have been compiled.
Basin division is shown in Fig. S7.2.2.

2.4 Determination of Chronological and Spatial Factors for Model of Water Balance in the Lake

【1】 Calculation Index

One index consisting of water quantity will be used.

【2】 Chronological Factors

Since the inputs of precipitation and water level (flow) of the rivers are compiled daily, the inputs and calculations will be made every day.

【3】 Spatial Factors

The basin will be divided into 4 areas according to the manner in which the study data have been compiled. The lake itself will be treated as a single area, as the water quality (E.C) shows no significant horizontal variation and there is little vertical stratification. The swamps will be treated separately.
Basin division is shown in Fig. S7.2.2. A chart illustrating the water balance model is shown in Fig. 7.2.3.

2.5 Determination of Chronological and Spatial Factors for Intra-Lake Matter Transformation Model

【1】 Calculation Indices

The 5 indices of COD, TN, TP, SS and Chl-a will be used.

* COD will be used in the overall evaluation of water quality.

* SS will be used in the evaluation of the turbidity of water in the lake.

* In determination of the turbidity, colours (brown or black) will not be differentiated as these are difficult to distinguish.

* Analyses of SS due to algae and SS in turbid water will be carried out considering the Chl-a and the SS in algae to be in proportion with each other.

* Chl-a will be used in evaluation of eutrophication.

* 5 items of COD, TN, TP, SS and Chl-a will be used simultaneously in calculations of water quality.

* Composition of COD, TN and TP will be considered according to types. The relationship between these is as follows.

$$COD = D\text{-}COD + P\text{-}COD$$
$$TN = D.TN\,(IN + DON) + PON$$
$$TP = D.TP\,(IP + DOP) + POP$$

【2】 Chronological Factors

Changes in water quality will be calculated every five days on the basis of the data on daily load calculated using he inflow load model, and the data on the daily inflow and outflow of water calculated using the water balance model. Calculations will only be made every five days since there is insufficient data on the changes of water quality in the lake and estimations are used in reaction equations and constants.

【3】 Spatial Factors

* Lake Ypacarai will be treated as a single body of water as horizontal distribution of water quality is uniform. Calculated average water quality means the ratio between the pollutant load in the lake and the lake volume.

* In the absence of stratification because of the shallowness of the water, the lake will be considered to consist of a single stratum.

* Since the euphotic zones vary greatly with turbidity, reactions related to production of phytoplanktons will be handled in two strata.

* Swamps will be treated as being a part of the lake, and reactions in the swamps will be noted separately.

The complete combination model treats the lake as a single water body of a single stratum. Swamps are treated separately.

Fig. S7.2.4 shows the spatial structure of the intra-lake matter transformation model.

CHAPTER III

PREPARATION AND VERIFICATION OF INFLOW LOAD MODEL

3.1 General

【1】 Calculation Indices

The 4 indices of COD, TN, TP and SS will be used.

【2】 Concept of Model

* Runoff of water and pollutants will be treated as separate phenomena and calculations concerning them made separately.

* Runoff of water will be divided into the following 3 categories, as shown in Fig. S7.3.1.

* In calculations of pollutant runoff, pollutant load stored within the basin during ordinary levels of water will be thought to be discharged during floods.

【3】 Chronological Factors

In consideration of the inflow load, since the quality of water in the inflow rivers shows great variation between times of fine weather and of rain, and the quality varies every day, the input of precipitation will be made daily. Calculation models of inflow load will also be determined every day. Calculations will be made separately for inflow load during fine weather and for discharge due to precipitation during rainfall. The period under consideration is from 1st March 1988 to 30th January 1989.

【4】 Spatial Factors

The basin will be divided into 4 areas according to the manner in which the study data have been compiled.
Dealing with the inflow load covers the inflow up to the marsh zone.
The marsh zone is handled by lake water quality fluctuation calculations.
An inflow contamination load model is shown in Fig. S7.3.2.

3.2 Basic Equations for Inflow Load Model

The following equation will be used as the basic equations for the inflow load model and calculations will be carried out for each block.

$L = L1 + L2$ (7-3)
$Q = Qa + Qr + Qb$ (7-4)

where,

L : inflow load into lake (kg/day)

L1 : inflow load in fine weather (kg/day)

L2 : inflow load during rain (kg/day)

Q : inflow water into lake (m^3/day)

Qa : inflow water at normal water level (m^3/day)

Qr : discharge due to rain (m^3/day)

Qb : artificial discharge (m^3/day)

* Equations for Inflow Load

$$L = L1 + L2 \quad (7\text{-}5)$$

$$L1 = LE.KIE + LD.KID \quad (7\text{-}6)$$

$$L2 = (LD(1\text{-}KID) + LE(1 - KIE) + LM\ \Delta T - 1)\cdot f_2(Ro) \quad (7\text{-}7)$$

$$LM\ \Delta T = [\{LE(1 - KIE) + LD(1 - KID) + LM\ \Delta T - 1\}(1 - K1)] \quad (7\text{-}8)$$

where,

L : inflow load (kg/day)

L1 : inflow load in fine weather (kg/day)

L2 : inflow load during rain (kg/day)

LE : discharge load from point sources (kg/day)

KIE: inflow rate of discharged load from point sources in fine weather (-)

LD : discharge load from non-point sources in fine weather (kg/day)

KID : inflow rate of discharged load from non-point sources in fine weather (-)

LM : cumulative load remaining in block (kg)

f2 : function for correlation between rate of inflow of remnant load due to rain, and precipitation (-)

K1 : rate of decomposition and disappearance of cumulative remnant load (ℓ/day)

Ro :precipitation minus quantity of ineffective rain (mm/day)

* Equations for Inflow Water

$$Q = Qa + Qr + Qb \qquad (7\text{-}9)$$

$$Qa = QA.AA.QX.86400 \qquad (7\text{-}10)$$

$$Qr = (R - RA).AA.K2.10^{-3} \qquad (7\text{-}11)$$

$$Qb = QB.K3 \qquad (7\text{-}12)$$

where,

Q : inflow water from rivers (m^3/day)

Qa : inflow water at normal water level (m^3/day)

Qr : outflow water due to rain (m^3/day)

Qb : inflow load from artificial discharge (m^3/day)

QA : standard specific discharge (m^3/sec.km^2)

AA : area of block (km^2)

QX : coefficient for seasonal variation of standard specific discharge (-)

R : precipitation (mm/day)

RA : ineffective precipitation (mm/day)

K2 : rate of stormwater discharge into lake (-)

QB : artificial discharge calculated from basic units (m^3/day)

K3 : runoff rate of artificial discharge into lake (-)

3.3 Inputs and Constants for Inflow Load Model

3.3.1 Precipitation

Precipitation in each block will be calculated by using the Thiessen polygon method from the locations of the six observatories within the basin. Daily precipitation will be used for inputs.
This is shown in Table S7.3.1.

3.3.2 Seasonal Variation Coefficient of Standard Specific Discharge

This is shown in Table S7.3.2.

3.3.3 Constants Related to Flow

This is shown in Table S7.3.3.

3.3.4 Constants Related to Load

1) Discharge Rate of Load from Point Sources at Normal Water Level
This is shown in Table S7.3.4.

2) Discharge Rate of Load from Non-Point Sources at Normal Water Level
This is shown in Table S7.3.5.

3) Rate of Decomposition and Disappearance of Remnant Load
This is shown in Table S7.3.6.

4) Functions for Runoff of Stormwater
This is shown in Table S7.3.3.

3.4 Calculation Results

Calculation results are shown in Figures S7.3.4, S7.3.5 and S7.3.6.

3.4.1 Annual Flow of Influent Rivers March 1988 - February 1989

This is shown in Table S7.3.7.

3.4.2 Annual Inflow Load

This is shown in Table S7.3.8.

CHAPTER IV

PREPARATION AND VERIFICATION OF MODELS FOR WATER BALANCE AND FOR MATTER TRANSFORMATION IN THE LAKE

4.1 Basic Equations for of Water Balance Model of a Lake

[1] Mechanism of Water Balance Model

This is shown in Fig. S7.4.1 and Fig. S7.4.2.

[2] Basic Equations of Water Balance Model

Using measured values for inflow from rivers, water levels of the lake and precipitation, water intake and coefficient for monthly evaporation as inputs, evaporation from the lake surface is calculated from the relation between the water level and the volume of the lake by multiplying the variation in the water level of the lake and the area of the lake by the evaporation coefficient. Discharge to outflowing rivers is calculated at the same time.

$$\frac{dV}{dt} = I_A + R \cdot A - E \cdot A - Ic - Qout \qquad (7\text{-}1)$$

$$\frac{dV}{dt} = A \cdot (\Delta H_T - \Delta H_{T-1}) \qquad (7\text{-}2)$$

where,

Qout : discharge to rivers

IA : inflow from rivers

R : precipitation

A : area of lake

Ic : water intake

ΔV : variation in volume of lake

$H\Delta_T$: water level of lake (at time of calculation)

$H\Delta_{T-1}$: water level of lake (at time of previous calculation)

4.2 Basic Equations for Intra-Lake Matter Transformation Model

【1】 Basic Mechanism of the Model

The 5 indices of COD, TN, TP, Chl-a, and SS will be used in the model for intra-lake matter transformation, which will be an integrated model taking the euphotic zones into account.
The matter transformation model is shown in Fig. S7.4.3.

【2】 Basic Equations for the Model

(TN)

$$\frac{d}{dt}(C_N \cdot V) = \underbrace{Q_I \cdot C_{IN} \cdot Ka}_{\text{(inflow)}} - \underbrace{Q_O \cdot C_N}_{\text{(outflow)}}$$

$$- \underbrace{C_N \cdot \beta \cdot V \cdot K_C \cdot \frac{1}{Z}}_{\text{(settlement)}} + \underbrace{Kd\,(\theta_2)^{T-20} \cdot A}_{\text{(elution)}} + \underbrace{Ke \cdot fs\,(W \cdot Z)\,A}_{\text{(disturbance)}}$$

(TP)

$$\frac{d}{dt}(C_P \cdot V) = \underbrace{Q_I \cdot C_{IP} \cdot Ka}_{\text{(inflow)}} - \underbrace{Q_O \cdot C_P}_{\text{(outflow)}} - \underbrace{C_P \cdot \beta \cdot V \cdot K_C \cdot \frac{1}{Z}}_{\text{(settlement)}}$$

$$+ \underbrace{Kd\,(\theta_2)^{T-20} \cdot A}_{\text{(elution)}} + \underbrace{Ke \cdot fs\,(W \cdot Z)\,A}_{\text{(disturbance)}}$$

(COD)

$$\frac{d}{dt}(C_C \cdot V) = \underbrace{Q_I \cdot C_{IC} \cdot Ka}_{\text{(inflow)}} - \underbrace{Q_O \cdot C_C}_{\text{(outflow)}} - \underbrace{C_C \cdot V \cdot Kf\,(\theta_3)^{T-20}}_{\text{(decomposition)}}$$

$$- \underbrace{C_P \cdot \beta \cdot V \cdot K_C \cdot \frac{1}{Z}}_{\text{(settlement)}} + \underbrace{Kd\,(\theta_2)^{T-20} \cdot A}_{\text{(elution)}} + \underbrace{Ke \cdot fs\,(W \cdot Z) \cdot A}_{\text{(disturbance)}}$$

$$+ \underbrace{Ca \cdot \delta \cdot V}_{\text{(production)}}$$

(Chl-a)

$$\frac{d}{dt}(Ca \cdot V) = Qa \cdot V \cdot Kf(\theta)^{T-20} - Ca \cdot V \cdot K_C \cdot \frac{1}{Z} - Q_O \cdot Ca$$

(decomposition) (settlement) (outflow)

$$+ Ca \cdot \frac{f_6(Tr)}{Z} \cdot V \cdot K_P \cdot f7(T) \cdot \frac{S}{M_S + S} \cdot \frac{IN}{M_N + IN} \cdot \frac{I_P}{M_P + I_P}$$

(production)

(SS)

$$\frac{d}{dt}(C_S \cdot V) = Q_I \cdot C_{IS} \cdot Ka - Q_O \cdot C_S - C_S \cdot V \cdot K_C \cdot \frac{1}{Z}$$

(inflow) (outflow) (settlement)

$$+ Kef_5(W, Z)\,A + Ca \cdot \lambda \cdot V$$

(disturbance) (production)

where

C_{IN} : concentration of inflow IN (mg/ℓ)

C_{IP} : concentration of inflow IP (mg/ℓ)

C_{IC} : concentration of inflow COD (mg/ℓ)

C_{IS} : concentration of inflow SS (mg/ℓ)

Q_I : volume of inflow (m³/day)

Q_O : volume of outflow (m³/day)

C_N : TN concentration in lake (mg/ℓ)

C_P : TP concentration in lake (mg/ℓ)

C_C : COD concentration in lake (mg/ℓ)

Ca : Chl-a concentration in lake (mg/ℓ)

Cs : SS concentration in lake (mg/ℓ)

Ka : coefficient for remnant due to settlement at river mouths (-)

Kc : coefficient for velocity of settlement (1/day)

Kd : coefficient for elution from lake bed ($mg/m^2 \cdot day$)

Ke : coefficient for disturbance of lake bed (mg/m^2)

Kp : coefficient for rate of production (1/day)

f_5 (W, Z) : function for influence of wind and depth of water in disturbance of lake bed

f_6 (Tr) : function for calculation of euphotic zone using values for transparency

f_7 (T) : function for effect of temperature on production of algae

T : water temperature (°C)

θ_2 : temperature constant for elution rate

θ_3 : temperature constant for decomposition rate

α : proportion of IN in lake

β : proportion of particulate matter

δ : coefficient for conversion of Chl-a into COD

λ : coefficient for conversion of Chl-a into SS

Z : average water depth (m)

F : wind velocity (m/s)

S : solar radiation ($cal/cm^2/day$)

M_S : Michaelis constant for solar radiation

M_N : Michaelis constant for IN

M_P : Michaelis constant for IP

4.3 Inputs and Constants for Models of Water Balance and Master Transformation

4.3.1 Inputs for Model for Calculation of Water Balance in Lake

【1】 Precipitation

Precipitation on the lake surface was calculated from the precipitation observed on land by using the Thiessen polygon method.

【2】 Quantity of Inflow

Data given in calculations on inflow load were used.

【3】 Evaporation from Lake Surface

The average evaporation over the past 10 years measured at Caacupe was multiplied by 0.8.

【4】 Water Level of Lake

Water gauge at San Bernardino and records of water levels in the past were used.

【5】 Change in Volume of Lake

The area of the lake was taken as being constant (59.6 Km^2) and this value was multiplied by the changes in the water level.

【6】 Water Intake

Monthly intake of water at San Bernardino during 1987 was used.

【7】 Quantity of Outflow
Calculated from values in 【1】 ~ 【6】

4.3.2 Inputs for the Model for Calculation of Intra-Lake Matter Transformation

(i) Production

$$(Chl\text{-}a)\,P = \mu\,max \cdot f_{(T)} \cdot f_{(I)} \cdot f_{(N)} \cdot \frac{s \cdot V}{z}$$

【1】 Water Temperature and Solar Radiation

Average value of 5 days of measurement data

【2】 Maximum Capacity for Propagation μ max = 0.41

【3】 Function Dependent on Water Temperature

$$f_{(T)} = \frac{T}{Ts} \{\exp(1 - \frac{T}{Ts})\}^2$$

Optimum water temperature (Ts) was taken to be 27°C on the basis of measurement data.

【4】 Function Dependent on Illumination Intensity

$$f_{(I)} = \frac{I}{Is + I}$$

Solar radiation was used for I in place of intensity of illumination. The standard solar radiation (Is) was taken to be 400 cal/cm^2/day.

【5】 Function Dependent on Nutrient Salt Concentration

$$f_{(N)} = \frac{C_{IN}}{K_m^N + C_{IN}} \cdot \frac{C_{IP}}{K_m^P + C_{IP}}$$

Semi-saturation constant: $K_m^N = 0.15$, $K_m^P = 0.012$

Since there is sufficient IN and IP and there is little chance of their supply being short, fixed values were adopted for nutrient salts, using yearly water quality averages (IN = 0.38 mg/ℓ, IP = 0.025 mg/ℓ).

【6】 Depth of Euphotic Zone (S)

Values twice those for transparency were adopted. Measurement data on transparency from regular surveys were converted into values for 5 days periods.

【7】 Coefficient for Conversion of Chl-a Values into Values for COD and SS in Algae

(i) COD / Chl-a = 130
SS / Chl-a = 130

(ii) Decomposition

$D = (C \cdot V) \cdot K \cdot \theta^{T-20}$

	Reaction Coefficient (Kf)	Temperature Coefficient (θ)
Chl-a	0.054	1.024
COD	0.028	1.08

(iii) Elution from Lake Bed

$E = Kd \cdot A \cdot \theta^{T-20}$

	Reaction Coefficient (Kd)	Temperature Coefficient (θ)
COD	660	1.08
TN	8	1.03
TP	0.45	1.08

(iv) Index of Disturbance of Lake-bed Deposit

$M = A \cdot f(w, z) \cdot Ke$

Disturbance of deposit on the lake bed will be treated as a function of wind velocity and water depth and the following equation was used.

$f(w,z) = Ke \cdot (2 \cdot w)2\ /z$

where,

w : average wind velocity (m/s)

z : average water depth (m)

Ke : constant

The constant Ke was determined as follows from the observation results on the quantity of settlement taking as basis the proportions of components.

Disturbance Speed Constant

Item	Disturbance Speed ($mg/m^2/day$)
SS	500
COD	370
TN	6.5
TP	0.55

(v) Settlement

$$Se = Kc \cdot \frac{(C \cdot V)}{Z}$$

Item	Settlement Speed (m/d) Kc
SS	0.17
COD	0.16
N	0.03
P	0.05
Chl-a	0.02

Note: Based on on-site tests.

Where, V : Volume of lake
C : Concentration
Z : Average depth

(vi) Other Conversion Coefficients

1) Rate of Purification in Swamps

The following equations were used for the rate of purification in the swamps of the Yuquyry River.

$$f_N(x) = 0.218 + 1.11 \cdot x - 1.23 \cdot x^2$$

$$f_P(x) = 0.127 + 4.93 \cdot x - 10.3 \cdot x^2$$

$$f_{COD}(x) = 0.48 + 3.32 \cdot x - 9.09 \cdot x^2$$

$$f_{SS}(x) = 0.11 + 4.07 \cdot x - 10.0 \cdot x^2$$

where,

x : 5 day average load per surface area ($m^3/d/m^2$)

f : proportion of residue after purification
$x < 0 < 0.2$

Rate of purification for swamps of the Pirayu River was taken to be nil, as their effect in purification is not clear.

2) Settlement around River Mouths

When rainfalls exceed 40 mm in 5 days, a half of the SS inflow load is reckoned to settle around the river mouths. As for other items, river mouth settlement is not considered.

3) Proportion of Particulate Matter

From the survey results,

PON/TN = 0.44

P.TP/TP = 0.53

P.COD/COD = 0.33

4) Coefficient for Conversion of Chl-a into SS and COD

COD/Chl-a = 130

SS/Chl-a = 130

5) Water Quality of Direct Precipitation

Data gathered and analysed at San Lorenzo were used.

TN = 1.26 mg/ℓ

TP = 0.010 mg/ℓ

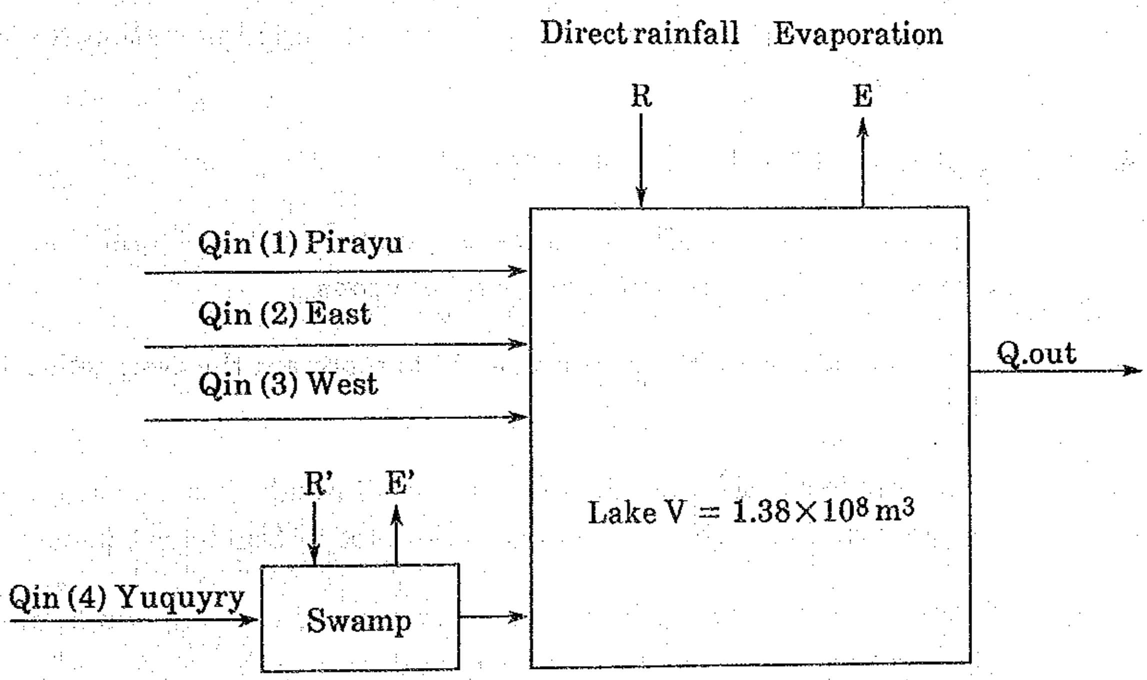
SS and COD were considered as being nil in the precipitation.

4.4 Simulation of Water Quality in Lake Ypacarai

4.4.1 Calculation Results on Balance of Water

The results of calculations with Qout as an unknown quantity are as shown below.

<u>Annual Water Balance at the Lake (1988.3 ~ 1989.2)</u>



Item	Numerical Value
Lake Area	$59.6\ km^2$
Lake Volume	* $1.38 \times 10^8\ m^3$
Direct Rainfall	$0.88 \times 10^8\ m^3$ (1,479 mm)
Evaporation	$0.91 \times 10^8\ m^3$ (1,529 mm)
Qin Total	$3.30 \times 10^8\ m^3$
Qout Total	$3.28 \times 10^8\ m^3$

* Remarks 1988.3 ~ 1989.2 Average value

Number of rotation of water in the lake

The number of rotations of water on the lake (total Qin/lake volume) is 2.4 times a year.

4.4.2 Results of Calculations for Simulation of Water Quality

The results of calculations for simulation of water quality are shown in Fig. S7.4.4.

The dots plotted with ranges on either side represent averages of all the data taken on the lake and their range. (Since it was thought inappropriate to have the values for COD, SS and Chl-a represented by single measurement data, average values were taken for these.)

For TN and TP, vertical average values at sampling station No.25 were used.

4.4.3 Evaluation of Results

* Production greatly affects the water quality of the lake and that in turn is affected by the extent of the euphotic zone.

* Decomposition of Chl-a can be thought to represent the destruction of algae.

* Conversion of SS into dissolved matter through decomposition is thought to be included in the values represented by that for settlement.

* Disturbance increases in winter when there are strong winds, and elution in summer when the water temperature is high.

* The proportion of the inflow load increases during floods, ranging between 15% and 50% of the load generated in the lake.

* Production and decomposition tempo is high, however, this is thought to be due to the fact that the water temperature, sunlight amount and nutrient salts are all effective.

CHAPTER V

WATER QUALITY FORECASTS

5.1 Analysis of Pollution Causes using Mathematical Models

Calculations were made on 4 cases to analyse the importance of related factors (COD, SS Fig. S7.5.1).

5.1.1 Cases

Case 1

The inflow load is reduced by a half.

Case 2

The average IN and IP concentrations in the lake are reduced by a half.

Case 3

The course of Yuquyry River is altered, but the water level of the lake is kept as at present.

Case 4

The production rate in the lake is reduced to nil. (Since most of the inflow COD load is thought to be persistent, the decomposition rate of COD was put at 0.01/day.)

5.1.2 Results

In Cases 1 to 3, the values for the pollutants are only slightly reduced and there is little overall effect on the water quality of the lake.

The results of calculations on Case 4 indicate the importance of the rate of production in the lake. The increase in concentration during winter (July to September) is due to the disturbance of the lake bed.

It is thought that the minimal effect of Case 2 is due to the fact that there is more than enough IN and IP in the lake.

5.2 Estimation of Annual Increase in Settlement of Bottom Deposit

The annual settlement of SS, excepting that amount disturbed from the lake bed, is 123 × 10^6 kg/year, which divided by the area of the lake (53 km^2) gives the value of 2300 g/m^2 of SS.

The rate of settlement is greatly affected by the level of compaction (= water content).

Water content (W) of the deposit at the centre of the lake is 190% at the surface and 50% at 20 cm below the surface (samples taken in July 1988).

With true specific density Gs = 2.5 and degree of saturation Sr = 100%,

void ratio e = Gs.W/Sr = 1.25 to 4.75

For dry density (γd),

γr = Gs/(1 + e) = 1.11 to 0.435 g/cm^3

Annual increase in settlement is, therefore,

$$d = \frac{SS \cdot 10^3}{\gamma d \cdot 10^6} \left(\frac{g\, m^2}{g\, m^3}\right) = 2.1 \sim 5.3 \text{ mm/year}$$

i.e. the increase will be 5.3 mm/year using the surface density, and 2.1 mm/year using density at 20 cm below surface.

These values, however, do not take into account the reduction in the volume of the deposit due to decomposition.

5.3 Annual Pollutant Balance

From the results of the annual calculations, the pollutant balance is shown in FIg. S7.5.2.

5.4 Determination of Calculations Conditions for Forecasts

【1】 Forecast Year - 2010

【2】 Calculation Index - COD

【3】 Hydrological and Meteorological Inputs

It is hypothesised that the conditions during the period from 1st Mach 1988 to 28th February 1989 will be repeated every year.

【4】 Future Conditions

* Case 1 - The inflow load will increase at a rate of 2% per year.

* Case 2 - As the quality of the deposit at the lake bed will deteriorate in accordance with change in Case 1, the elution rate of COD will increase at a rate of 2% per year.

5.5 Results of Calculations for Forecasts

These results are shown in Fig. S7.5.3.

CHAPTER VI

CONCLUSIONS

1) Due to the fact that pollutant load induced by human activities within the Yuquyry River basin is purified when passing through the marshes, the Lake is relatively untouched by this load.

2) Due to the fact that production and decomposition rates are high, the lake water quality is affected quite a bit. The reason for this is that there is sufficient light, water temperature is high and nutrient salts concentrations are high.

3) The reason why the concentration of nutrient salts is high is because that in the inflowing rivers is high. It is believed that the reason NP concentrations in inflowing rivers are generally high is because organic NP, which are stored in the basin, are decomposed by the generally high temperature and then, due to this decomposition, easily outflow. However, the details are not yet clear.

4) The water replacement ratio in the lake is low at about 2-3 times a year and the water doesn't flow in and out very often.

5) Most of the inflowing particle matters settle by the process of inflow, thus, the lake is not affected by these matters.

6) The influences of sludge are the stirring up and the elution in the lake. Elution, as the sludge is generally in favorable conditions and although the water depth is shallow, does not have a large effect on the lake. The stirring up phenomenon could not be studied sufficiently, although the investigation was conducted with the thought that this is caused by the wind and waves. There could be other factors involved (for example, convection) besides the wind and waves, however this is not clear at this point, therefore the elucidation should be postponed until the next investigation.

7) The reason why the concentrations of COD and SS are high is because of the algae and its dead matters. The reason why parts of the lake water look black frequently is because a portion of the organic matters carbonizes over the course of decomposition.

CHAPTER VII

FUTURE TOPICS

7.1 Problems in Water Quality Simulation

Although calculations can be made for forecasts and analyses on the causes of pollution through simulation, there still remain the following problems.

【1】 Material balance equations are used in expressing various phenomena at present but there are difficulties in applying these equations to items that decrease through decomposition (e.g. COD, Chl-a).

【2】 Since transformation of matter from one form into another is used as a principal indicator, rate of reaction becomes an important factor. For some items, however, the rate of reaction cannot be determined through experiments, and there are items for which only rough data can be obtained (e.g. AGP test).

【3】 There is often a lack of input data and data on water quality for use in calculations for simulation. (e.g. Only monthly data on water quality can be used in calculations made for 5 day periods.)

【4】 Because difficult-to-apply special advanced techniques are required for survey and analysis, the analysis results do not always reflect true facts.

【5】 Purification experiments may be more effective than analyses through calculations.

Under such circumstances, it is thought to be necessary to make improvements on the reliability of the calculation results by increasing the accuracy of the model constants through further survey.

7.2 Direction for Measures against Pollution

The simulation here should be regarded as being no more than a hypothesis. The following points, however, may be made from the calculation results.

Measures to reduce the amount of algae in the lake will be the most important element in the actions to be taken to curb the pollution in the lake.

Since there are still too many points of uncertainty to allow implementation of measures for the lake as a whole, one possible course of action is to carry out experiments by segregating the body of water around the water intake for the purification plant at San Bernardino. (Algae are often responsible for causing obstacles to filtration and turning the water odorous in the process of water treatment.)

These experiments might include the following.

【1】 a. Contact oxidation using fixed beds

【2】 b. Sprinkling algicides such as copper sulphate

ANNEX

Appendix

Surveys and Tests for Examination of Model Constants

A.1 Phenomena Affecting Water Quality in Lake

The following are the factors that affect the water quality in lakes.

① Purification and settlement in swamps

② Elution from bottom deposit

③ Disturbance of bottom deposit

④ Settlement

⑤ Production

⑥ Decomposition

⑦ Denitrification

Of these, item ⑦ may be ignored at Lake Ypacarai, as the bottom deposit is constantly in an aerobic state.
The above is shown in Table S7.A.1.

A.2 Purification in Swamps

(1) Data on the swamps of the Yuquyry and Pirayu rivers (See Table S7.A.2).

(2) Mechanism of Purification in Swamps

Water is thought to be purified in the swamps through the operation of the mechanism as described below.

① SS and Turbidity

Attachment to root hair of aquatic plants and filtration by aquatic plants

② Organic Matter

Purification and decomposition due to actions of microorganisms around the aquatic plants

③ Purification of Nitrogen

Conversion into gas through denitrification and dispersion into the atmosphere

④ Purification of Phosphorus

Phosphorus, mainly in particle form, removed through same reaction as in case of SS and turbidity

(3) Water Channels in Swamps

Yuquyry River flows into the lake in 4 channels after passing through the swamps. The waterways forms a complex system of channels in the swamps.

The area of the swamps is smaller on the Pirayu River and the water channels there are easier to distinguish.

(4) Purification Rate, Purification Residue and Water Area Load

The purification rate in the swamps is thought to be relative to the water area load (= water flow per unit area $m^3/d/m^2$).

The average water area load over 5 day periods on Yuquyry River and their relationship with COD, SS, TN and TP are shown in Fig. S7.A.1.

A.3. Test for Elution of Nitrogen, Phosphorus and COD from Bottom Deposit

Elution rates of nitrogen, phosphorus and COD from the bottom deposit were obtained through laboratory tests.

(1) Test Method

A sample of the deposit was collected using an Ekman Berge sampler at sampling station No. 25 in July 1988. The sample taken was placed at the bottom of a bucket, distilled water was added, and an elution test was carried out under aerobic conditions. The tests were carried out at 2 temperatures of 20 °C and 30 °C.

(2) Analyses

Analyses were carried out on COD, nitrogen and phosphorus dissolved in the water.

(3) Calculation of Elution Rate

$$KR = (Cn - Co) \times Vn \times \frac{10000}{A} \times \frac{1}{n} \cdots\cdots\cdots (1) \quad N, P$$

$$KR = (Cn - Co10^{-kn}) \times Vn \times \frac{10000}{A} \times \frac{1}{n} \cdots\cdots\cdots (2) \quad COD$$

* for deposit decomposition constant for COD, K = 0.03

where,

KRn : daily elution (mg/m2.day)

Co : concentration (on day 0) (mg/ ℓ)

Cn, Cn + 1 : concentration on days “n” and “n + 1” (mg/ ℓ)

Vn, Vn + 1 : water quantity on days “V” and “V + 1” (ℓ)

A : area of experiment (cm^2)

n, (n + 1) - (n): period subject to calculation (days)

(4) Results

(See Table S7.A-3).

A.4. Survey on Disturbance of Bottom Deposit

Disturbance of the bottom deposit due to wind is the phenomenon whereby the deposit at the bottom of shallow lakes is stirred up by the wind. In this phenomenon, most of the deposit stirred up will settle again when the wind ceases but a part of it may be dissolved while suspended in the water. Disturbance due to winds may be expressed using the following equations.

$$Kv = f(F)$$

$$Kz = f(Kv)$$

where,

Kv : quantity of deposit disturbed

F : force of wind

Kz : quantity of deposit dissolved in water

Measurements were taken on the disturbance of deposit due to wind on Lake Ypacarai in July 1988. The results are shown in Fig. S7.A.2.

There was a particularly large increase in turbidity at Point No. 30 between 18th and 19th July.

A.5. Observation of Settlement Rate

① Survey Method

Measurements were taken by placing a collector (diameter: 24 cm) at Point No. 25 (total depth: 2.9 m) at a depth of 2 m and changing the collector every 24 hours. This collector is shown in Fig. S7.A.3.

After measuring the quantity of water in the collectors, analyses were carried out to determine the quantities of SS, COD, D-COD, K-N, D-K-N, T-P and D-TP. Values for P-COD, P-K-N and P-T-P were calculated from the results of the analyses.

② Survey Results

Quantity of settled matter was calculated from the test results on particulate matter using the following equation.

$$M = Ca \times \frac{V}{1000} \times \frac{1}{A} \times \frac{1440}{T}$$

where,

M : quantity of settlement ($mg/m^2.day$)

Ca : concentration in collector (mg/ ℓ)

V : quantity of water in collector (mℓ)

A : area of collector (m^2), A = 0.0452

T : collection time (min.)

This is shown in Table S7.A.4.

③ Calculation of Settlement Velocity

Daily settlement rate and settlement velocity of SS are calculated using the following equations.

$$Ur = \frac{M}{Cs \cdot H \cdot 1000} \qquad U = Ur \cdot H$$

where,

Ur : settlement rate (l/d)

U : settlement velocity (m/d)

H : depth at which collector was placed (m) H = 2.0

M : quantity of settlement ($mg/m^2/d$)

Results are shown in Table S7.A.5. Because of the nature of the experiment, values for SS disturbed from the bottom may be included, creating a certain amount of error in the said values.

Values for COD, nitrogen and phosphorus calculated in the same way as for SS are shown in Table S7.A.6.

A.6. Laboratory Tests for Settlement

Reduction in concentration of pollutants in ater due to settlement of particulate matter normally shows a logarithmic curve.

Samples were taken from the lake water, water in the influent rivers and their beds and settlement was observed over a period of 24 hours in a measuring cylinder for two cases, when the deposit was mixed and when it was not.

The results are shown in Fig. S7.A.6.

The decrement rate in the settlement of SS in water for water containing deposit is high (0.02 to 0.07 l/hr) in relation to that of water not containing deposit (0.001 to 0.02 l/hr).

A.7. Survey on Decrement of Intensity of Illumination in Water

Rate of production in the lake is affected by the depth of the euphotic zone and the vertical distribution of light.

The results of the survey on decrement of intensity of illumination carried out using underwater illumination photometers are shown in Fig. S7.A.5.

TABLES

Table S7.1.1 Numerical Value Model Objectives and Content

Objectives	Description
Analysis of Degree of Contribution to Present Pollution	• Water balance and rotation • Inflow pollutant load by river • Transmission phenomenon of lake water quality • Lake water quality by contributors • Estimation of seasonal change characteristics
Predictions of Future Lake Water Quality	• Long term estimation of present condition
Test Calculation of Effects of Implementation of Water Quality Improvement Measures	• Effects of each water quality improvement measure

Table S7.2-1 Classification of Lake Water Quality Prediction Model

Model Name	Description	Objective Phenomena for Analysis	Seasonal Fluctuation Reappearances
Vollenweider Model	Based on a black box statistical analysis of the lake ecosystem water quality fluctuations	Eutrophication	No
Ecosystem Model	Analysis of the lake water quality fluctuation within the ecosystem	Eutrophication	Yes
Matter Circulation Model	Analaysis of the lake water quality fluctuation focussing on water balance and matter circulation	Eutrophication and other causes	Yes

Table S7.2.2 Constitution of Water Polutant Matters of Lake Ypacarai

Pollutant Matters	Participating Matters	Calculation Index	Remarks
Remaining Matters from Inflow Load	–	COD	There is thought to be an abundance of humic acid of varying forms and organic matters which do not decompose easily
Internally produced algae and their remains	Nitrogen Phoshorous	Chl－a	As an eutrophic lake, there is abundant phytoplankton and its remains
Matter in stirred-up sludge	Sludge	COD SS	Inorganic (clay and silt) and organic matters within sludge are stirred up and float

(Note 1) Data for investigation of disease-related bacteria by numerical model are inexistent.

(Note 2) Iron and Mn caused colors could be considered, but this phenomenon is not clearly understood.

Table S7.3.1 Weighted Coefficient by Thiesen Method

Basin block	Observation point	PARAGUARI	PIRAYU	YPACARAI	SAN BERNARDINO	AREGUA	SAN LORENZO
I	PIRAYU	0.23	0.55	0.22	0	0	0
II	EAST	0	0	0.23	0.77	0	0
III	WEST	0	0	0.43	0.08	0.49	0
IV	YUQUYRY	0	0	0.18	0	0.40	0.42
V	LAKE	0	0	0.03	0.56	0.41	0

Table S7.3.2 Coefficient for Seasonal Variation of Standard Specific Discharge

		1988										1989
		3	4	5	6	7	8	9	10	11	12	1
I	PIRAYU	1	2.5	2.0	1.4	0.81	0.69	0.69	0.75	0.94	0.94	0.81
II	EAST	1	2.2	1.5	1.4	1.1	0.8	0.7	0.7	0.9	0.9	0.8
III	WEST	1	2.2	1.5	1.4	1.1	0.8	0.7	0.7	0.9	0.9	0.8
IV	YUQUYRY	1	1.9	1.7	1.4	1.2	0.96	0.75	0.71	0.92	0.92	0.83

Based on the monthly flow observation resuts from the Pirayu and Yuquyry Basins. As for the remainting East and West Coast, based on on-site investigations, summarized values have been input.