A Modelling of Eutrophication in Laguna de Bay as a Tool for Rational Resource Management

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Abstract

A lake model originally developed for Shin-Nippon Meteorological and Oceanographical Consultants Co., Ltd (METOCEAN) was used with modification to simulate the water quality of Laguna de Bay. The METOCEAN model made use of the 1984 meteorological and water quality data collected from different local government agencies. Hydraulic modeling was applied to obtain basic circulation patterns which the water quality modeling was based upon. Results of the hydraulic modeling suggests that steady backflow of saltwater from Pasig River reaches deep inside the bottom layer of the lake although the lake water flows out through the Pasig River. Thus, the water quality model for Laguna de Bay focused on the unique role of the salt water intrusion in limiting phytoplankton productivity. The effect of saltwater intrusion was simplified as the change of depth of euphotic zone in the lake water estimated from the Secchi disc transparency. For simplicity and expandability of the model as a predicting tool, Secchi disc transparency was the only forcing function considered in the study.

Modelling resolution of water quality has 4 boxes horizontally and 3 levels vertically. Calibration of the water quality model was carried out by running the model repeatedly until satisfactory agreement with measured data was obtained under average wind condition (Eastern wind, 1.5 m/sec.) Other wind directions including no wind condition were also tested to see the effect of wind on water quality. Validation of the water quality model was done for 1985 to 1988 as continuing simulation from the calibration in 1984 under the average wind condition. Then simulation of the condition of the lake from 1991 to 1995 based on the 1984 data used in the calibration was tried changing only the Secchi disc transparency data.

Initial results of the water quality model differentiated conditions with and without saltwater intrusion. Without saltwater backflow, higher concentration of total inorganic nitrogen and inorganic phosphorus and low dissolved oxygen especially in the bottom layer are predicted. Under this condition, release of large amounts of nutrients in the sediments is expected to be dominant source of total inorganic nitrogen in the lake. The study is the first attempt to model the lake. The model still needs calibration and validation with measured values of recent years before adapting its usefulness as a tool for nredicting water quality of Laguna de Bay.

Introduction

Laguna de bay in the Philippines, located southeast of Manila, is used for multiple purposes such as fishery, irrigation, power generation and navigation. Recently, the lake has been considered as a source of potable water for Metro Manila by the year 2000 (Santos-Borja 1994; LLDA 1995). As such, the Philippine government is expected to the resume the operation of a hydraulic control structure (HCS) which prevents sea water intrusion from Manila Bay during the dry season as an economical method for controlling salinity in water for potable use.

Laguna de Bay is a shallow, eutrophic, and usually turbid lake. The average depth is only 2.8 m and surface area is about 900 km2. The water level rises by 1 to 3 m during the rainy season and reverts to the minimum level at the end of the dry season (Fig. 1). Since the lake's annual low level is almost the same as the mean sea level of Manila Bay, sea water may flow back to the lake at the end of the dry season depending on the hydrological condition (LLDA 1995) through the 24-km Pasig River.

While quantitative analysis of ecosystem by modeling is expected to help identify the priority use of the lake (ERMP 1993), very few models have been developed thus far. Hence, models that simulate and predict the water quality of the lake should be made if conflict of use is at stake.

To develop a water quality model for Laguna de bay, the major concern is the unique role of sea water intrusion in limiting phytoplankton productivity as it decreases lakewater turbidity by the flocculation and settling of suspended particles (Nielsen et al. 1981; Santiago 1991). However, sea water intrusion does not occur annually because the delicate hydraulic balance between the lake level and the mean sea level depends on yearly rainfall patterns. Therefore, to assess management impact such as the operation of HCS, the model should simulate the different water quality scenarios between those years with and without sea water intrusion as one continuous time series over several years. The data is then treated dynamically rather than as separately obtained steady state values because lake water quality in any given year is directly affected by the condition of the previous years.

In the present study, the effect of sea water intrusion was simplified as a change in depth of the euphotic zone in the lake water. This was based on the Secchi disc transparency readings. This was the only forcing function considered in this study which was changed every year to simulate the water quality during target period for simplicity and expandability of the model as a predicting tool. This report presents a model which simulates specifically the seasonal change of nutrients and dissolved oxygen in the Laguna de Bay during the period of 1984 to 1988. The data used in the model were collected from the Laguna Lake Development Authority (LLDA), the Southeast Asian Fisheries Development Center / Aquaculture Department in Binangonan, the River Rehabilitation

Secretariat (RRS) of the Department of Environment and Natural Resources, and other published literature. The model was then used as a management tool to assess the environmental impact of operating the HCS on the Laguna de Bay resources. The model showed a higher organic nutrient concentration and lower dissolved oxygen as the general impact on water quality of the lake.

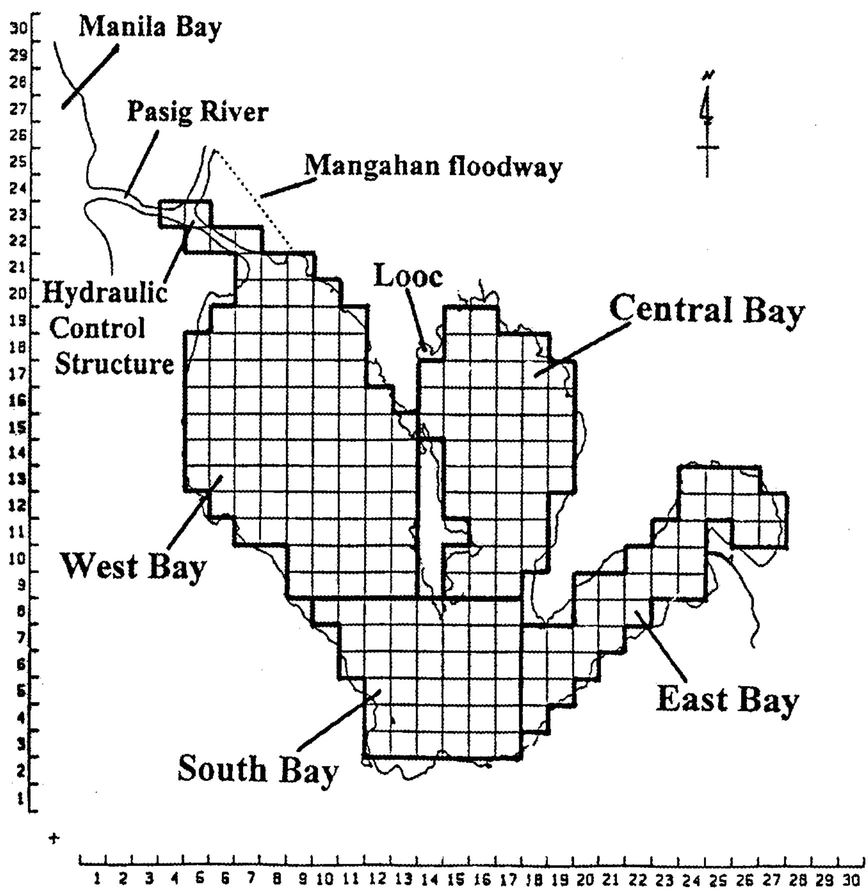

Fig. 1. **Map of Laguna de Bay showing the modeling frame used. Thick lines show the boundaries of regions used for the water quality model. (Thin lines show the computational grid for the hydrodynamic model.)**

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Methods

To simulate the water quality of Laguna de Bay, the Meteorology and Oceanographical Consultant Co., Ltd. (METOCEAN unpubl.) Lake Model was used but with modifications by the authors. The METOCEAN Lake Model basically uses the dynamic box modelling approach.

Modelling frame

The modelling frame of the Laguna de Bay's hydrodynamics, where the water quality model was based upon, consisted of 2-km interval grids filling the four boxes of water quality model (Fig. 2). The modelling frame of water quality horizontally corresponded to the distribution of major regular water quality monitoring stations maintained by LLDA and SEAFDEC for the calibration of simulated results. Both hydrodynamic and water quality models were vertically divided into three levels from surface to bottom by 1 m each to highlight stratification. The average volume flux of exchange in boxes was estimated from the hydrodynamic model, translated into monthly average to be proportional to monthly discharge to tributaries and used as input data to the water quality model.

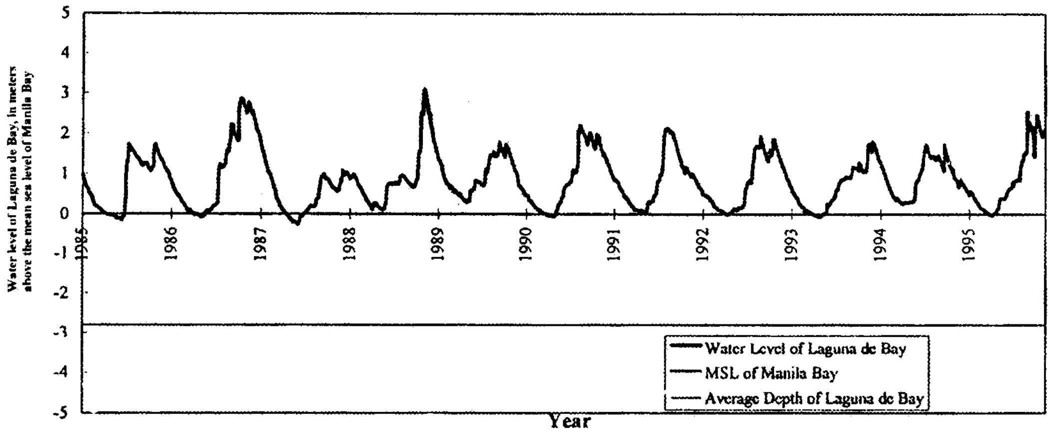


Fig 2. Water level of Laguna de Bay (Looc). The annual minimum lake level is approximately the mean sea level of Manila Bay. The annual range of rise and fall of the water level varies from about 1 to 3 m which is comparable to the average depth of the lake below the annual minimum water level. (Unpublished data from River Rehabilitation Secretariat, used with permission)

Equations

The hydrodynamic model was a combination of equations of continuity and motion as described in Table 1. Parameters used in the hydraulic model are shown in Table 2. The water quality model used six state variables. They were phosphorus (inorganic and organic), nitrogen (inorganic and organic), chemical oxygen demand (COD), chlorophyll-a, and dissolved oxygen (DO). Table 3 describes the equations used in the water quality model while Table 4 shows the water quality parameters used.

1. Equations used for the hydrodynamic model

Equation of continuity

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\left[u_1(\zeta + D_1)\right] + \frac{\partial}{\partial y}\left[v_1(\zeta + D_1)\right] - w_{12} = 0$$

$$w_{12} + \frac{\partial}{\partial x}\left(u_2 D_2\right) + \frac{\partial}{\partial y}\left(v_2 D_2\right) - w_{23} = 0$$

$$w_{23} + \frac{\partial}{\partial x}\left(u_3 D_3\right) + \frac{\partial}{\partial y}\left(v_3 D_3\right) = 0$$

Equation of motion

Level 1

$$\frac{\partial u_1}{\partial t} + u_1 \frac{\partial u_1}{\partial x} + v_1 \frac{\partial u_1}{\partial y} + w_{12} \frac{u_1 - u_2}{2(\zeta + D_1)} = f v_1 - \frac{1}{\rho_1}\left(\frac{\partial p}{\partial x}\right)_1 + A_h\left(\frac{\partial^2 u_1}{\partial x^2} + \frac{\partial^2 u_1}{\partial y^2}\right)$$

$$- \gamma_i^2 (u_1 - u_2)\frac{\sqrt{(u_1 - u_2)^2 + (v_1 - v_2)^2}}{(\zeta + D_1)} + \frac{\rho_a}{\rho_1}\gamma_a^2 W_x \frac{\sqrt{W_x^2 + W_y^2}}{(\zeta + D_1)}$$

$$\frac{\partial v_1}{\partial t} + u_1 \frac{\partial v_1}{\partial x} + v_1 \frac{\partial v_1}{\partial y} + w_{12} \frac{v_1 - v_2}{2(\zeta + D_1)} = - f u_1 - \frac{1}{\rho_1}\left(\frac{\partial p}{\partial y}\right)_1 + A_h\left(\frac{\partial^2 v_1}{\partial x^2} + \frac{\partial^2 v_1}{\partial y^2}\right)$$

$$- \gamma_i^2 (v_1 - v_2)\frac{\sqrt{(u_1 - u_2)^2 + (v_1 - v_2)^2}}{(\zeta + D_1)} + \frac{\rho_a}{\rho_1}\gamma_a^2 W_y \frac{\sqrt{W_x^2 + W_y^2}}{(\zeta + D_1)}$$

Table 1 (continued)

Level 1

$$\frac{\partial u_2}{\partial t}+u_2\frac{\partial u_2}{\partial x}+v_2\frac{\partial u_2}{\partial y}+w_{12}\frac{u_1-u_2}{2D_2}+w_{23}\frac{u_2-u_3}{2D_2}=fv_2-\frac{1}{\rho_2}\left(\frac{\partial p}{\partial x}\right)_2+A_h\left(\frac{\partial^2 u_2}{\partial x^2}+\frac{\partial^2 u_2}{\partial y^2}\right)$$

$$+\gamma_i^2(u_1-u_2)\frac{\sqrt{(u_1-u_2)^2+(v_1-v_2)^2}}{D_2}-\gamma_i^2(u_2-u_3)\frac{\sqrt{(u_2-u_3)^2+(v_2-v_3)^2}}{D_2}$$

$$\frac{\partial v_2}{\partial t}+u_2\frac{\partial v_2}{\partial x}+v_2\frac{\partial v_2}{\partial y}+w_{12}\frac{v_1-v_2}{2D_2}+w_{23}\frac{v_2-v_3}{2D_2}=-fu_2-\frac{1}{\rho_2}\left(\frac{\partial p}{\partial y}\right)_2+A_h\left(\frac{\partial^2 v_2}{\partial x^2}+\frac{\partial^2 v_2}{\partial y^2}\right)$$

$$+\gamma_i^2(v_1-v_2)\frac{\sqrt{(u_1-u_2)^2+(v_1-v_2)^2}}{D_2}-\gamma_i^2(v_2-v_3)\frac{\sqrt{(u_2-u_3)^2+(v_2-v_3)^2}}{D_2}$$

$$\frac{\partial u_3}{\partial t}+u_3\frac{\partial u_3}{\partial x}+v_3\frac{\partial u_3}{\partial y}+w_{23}\frac{u_2-u_3}{2D_3}=fv_3-\frac{1}{\rho_3}\left(\frac{\partial p}{\partial x}\right)_3+A_h\left(\frac{\partial^2 u_3}{\partial x^2}+\frac{\partial^2 u_3}{\partial y^2}\right)$$

$$+\gamma_i^2(u_2-u_3)\frac{\sqrt{(u_2-u_3)^2+(v_2-v_3)^2}}{D_3}-\gamma_b^2 u_3\frac{\sqrt{u_3^2+v_3^2}}{D_3}$$

$$\frac{\partial v_3}{\partial t}+u_3\frac{\partial v_3}{\partial x}+v_3\frac{\partial v_3}{\partial y}+w_{23}\frac{v_2-v_3}{2D_3}=-fu_3-\frac{1}{\rho_3}\left(\frac{\partial p}{\partial y}\right)_3+A_h\left(\frac{\partial^2 v_3}{\partial x^2}+\frac{\partial^2 v_3}{\partial y^2}\right)$$

$$+\gamma_i^2(v_2-v_3)\frac{\sqrt{(u_2-u_3)^2+(v_2-v_3)^2}}{D_3}-\gamma_b^2 v_3\frac{\sqrt{u_3^2+v_3^2}}{D_3}$$

Table 1 (continued)

Equation of diffusion for density

Level 1

$$\frac{\partial}{\partial t}\left[\rho_1(\zeta + D_1)\right] + \frac{\partial}{\partial x}\left[u_1\rho_1(\zeta + D_1)\right] + \frac{\partial}{\partial y}\left[v_1\rho_1(\zeta + D_1)\right] - w_{12}\rho_{12}$$

$$-\frac{\partial}{\partial x}\left[K_x(\zeta + D_1)\frac{\partial \rho_1}{\partial x}\right] - \frac{\partial}{\partial y}\left[K_y(\zeta + D_1)\frac{\partial \rho_1}{\partial y}\right] + K_z\frac{2(\rho_1 - \rho_2)}{D_1 + D_2} = 0$$

Level 2

$$\frac{\partial}{\partial t}(\rho_2 D_2) + \frac{\partial}{\partial x}(u_2\rho_2 D_2) + \frac{\partial}{\partial y}(v_2\rho_2 D_2) + w_{12}\rho_{12} - w_{23}\rho_{23}$$

$$-\frac{\partial}{\partial x}\left(K_x D_2\frac{\partial \rho_2}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y D_2\frac{\partial \rho_2}{\partial y}\right) - K_z\frac{2(\rho_1 - \rho_2)}{D_1 + D_2} + K_z\frac{2(\rho_2 - \rho_3)}{D_2 + D_3} = 0$$

Level 3

$$\frac{\partial}{\partial t}(\rho_3 D_3) + \frac{\partial}{\partial x}(u_3\rho_3 D_3) + \frac{\partial}{\partial y}(v_3\rho_3 D_3) + w_{23}\rho_{23}$$

$$-\frac{\partial}{\partial x}\left(K_x D_3\frac{\partial \rho_3}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y D_3\frac{\partial \rho_3}{\partial y}\right) - K_z\frac{2(\rho_2 - \rho_3)}{D_2 + D_3} = 0$$

ζ = water level

u_i, v_i = x, y components of the velocity in level i

$w_{i,i+1}$ = z component of the velocity between level i and level i+1

D_i = thickness of the level

f = Coriolis' parameter = $2\omega\sin(\varphi)$: ω =angular velocity of rotation of the earth,
φ =latitude

ρ_i = density of the lake water in level i

p = pressure, $\left(\frac{\partial p}{\partial x}\right)_i = g\rho_1\frac{\partial \xi}{\partial x} + g\frac{\partial}{\partial x}\left(\sum_{n=1}^{i-1}\rho_n D_n\right) + \frac{1}{2}g\frac{\partial}{\partial x}\rho_i D_i$

A_h = eddy viscosity

γ_i^2 = internal friction constant

ρ_a = density of the air

γ_a^2 = surface friction constant

W_x, W_y = x, y component of the wind velocity

γ_b^2 = bottom friction constant

K_x, K_y = eddy diffusivity

$\rho_{i,i+1}$ =density of the lake water transported between level i and level i+1: if $w_{i,i+1} > 0$ then $\rho_{i,i+1} = \rho_{i+1}$, if $w_{i,i+1} < 0$ then $\rho_{i,i+1} = \rho_i$

g = gravitational acceleration

Table 2. Parameters used in the hydrodynamic model

Parameter	Values	References
ω	7.29×10^{-11} rad / s	NAO, 1996
φ	14.3°	center of Laguna de Bay
A_h	$10000\,cm^2/s$	based on Horie, 1980
γ_i^2	0.0013	based on Horie, 1980
ρ_a	$1.3 \times 10^{-3} g/cm^3$	NAO, 1996
γ_a^2	0.0016	based on Horie, 1980
γ_b^2	0.0026	Horie, 1980
K_x, K_y	$10000\,cm^2/s$	based on Horie, 1980
g	$9.8\,m/s^2$	NAO, 1996

Table 3. Equations used for the water quality model

Inorganic phosphorus

$$\frac{d\,PO_4}{dt} = -V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})} f(I)f(T)Chla\,\alpha_P h + V_P\,O\text{-}P\,h + \beta Chla\,\alpha_P h$$
$$+ R_{PO_4} + S_{PO_4}(PO_4^{UP} - PO_4)$$
$$+ J_{IN}PO_4 - J_{OUT}PO_4 + \frac{dfv}{DH}(PO_4^{UP} + PO_4^{low} - 2PO_4)$$

Inorganic nitrogen

$$\frac{d\,TIN}{dt} = -V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})} f(I)f(T)Chla\,\alpha_P\alpha_N h + V_P\,O\text{-}N\,h + \beta Chla\,\alpha_P\alpha_N h$$
$$+ R_{TIN} + S_{TIN}(TIN^{UP} - TIN)$$
$$+ J_{IN}TIN - J_{OUT}TIN + \frac{dfv}{DH}(TIN^{UP} + TIN^{low} - 2TIN)$$

Phytoplankton

$$\frac{d\,Chla}{dt} = V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})} f(I)f(T)(1-\gamma)Chla\,h - m_P\,Chla\,h + \beta Chla\,h$$
$$+ S_{Chla}(Chla^{UP} - Chla)$$
$$+ J_{IN}Chla - J_{OUT}Chla + \frac{dfv}{DH}(Chla^{UP} + Chla^{low} - 2Chla)$$

organic phosphorus

$$\frac{d\,O\text{-}P}{dt} = V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})} f(I)f(T)\gamma\,Chla\,\alpha_P h + m_P\alpha_P h$$
$$+ V_P O\text{-}P h + S_{O\text{-}P}(O\text{-}P^{UP} - O\text{-}P)$$
$$+ J_{IN}O\text{-}P - J_{OUT}O\text{-}P + \frac{dfv}{DH}(O\text{-}P^{UP} + O\text{-}P^{low} - 2O\text{-}P)$$

organic nitrogen

$$\frac{d\,O\text{-}N}{dt} = V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})} f(I)f(T)\gamma\,Chla\,\alpha_P\alpha_N h + m_P Chla\,\alpha_P\alpha_N h$$
$$+ V_N O\text{-}N\,h + S_{O\text{-}N}(O\text{-}N^{UP} - O\text{-}N)$$
$$+ J_{IN}O\text{-}N - J_{OUT}O\text{-}N + \frac{dfv}{DH}(O\text{-}N^{UP} + O\text{-}N^{low} - 2O\text{-}N)$$

Table 3 (continued)

Chemical oxygen demand

$$\frac{d\,COD}{dt} = V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})}f(I)f(T)\gamma\,Chla\,\alpha_P\alpha_{COD}h + m_P\,Chla\,\alpha_P\alpha_{COD}h$$
$$+ V_{COD}COD + S_{COD}(COD^{up} - COD) + R_{COD}$$
$$+ J_{IN}COD - J_{OUT}COD + \frac{dfv}{DH}(COD^{up} + COD^{low} - 2COD)$$

Dissolved oxygen

$$\frac{d\,DO}{dt} = V_{max}\frac{PO_4\,TIN}{(PO_4 + K_{PO_4})(TIN + K_{TIN})}f(I)f(T)(1-\gamma)Chla\,\alpha_{DO}\alpha_P h - \beta\,Chla\,\alpha_{DO}\alpha_P h$$
$$- V_{COD}COD\frac{\alpha_{DO}}{\alpha_{COD}} + R_{DO}$$
$$+ J_{IN}DO - J_{OUT}DO + \frac{dfv}{DH}(DO^{up} + DO^{low} - 2DO)$$

$f(I)$ = growth limitation due to light = $(I/Iopt)\exp(1-I/Iopt)$: I = average light intensity of the level, Iopt = optimum light intensity
$f(T)$ = growth limitation due to temperature = $(T/Topt)(\exp(1-T/Topt))^2$: T = water temperature of the level, Topt = optimum temperature
PO_4 = inorganic phosphorus
TIN = total inorganic nitrogen
Chla = chlorophyll-*a*
O-P = organic phosphorus
O-N = organic nitrogen
COD = chemical oxygen demand
DO = dissolved oxygen
PO_4^{up} = inorganic phosphorus of the upper level
TIN^{up} = inorganic nitrogen of the upper level
$Chla^{up}$ = chlorophyll-a of the upper level
$O\text{-}P^{up}$ = organic phosphorus of the upper level
$O\text{-}N^{up}$ = organic nitrogen of the upper level
COD^{up} = chemical oxygen demand of the upper level
DO^{up} = dissolved oxygen of the upper level
PO_4^{low} = inorganic phosphorus of the lower level
TIN^{low} = inorganic nitrogen of the lower level
$Chla^{low}$ = chlorophyll-a of the lower level
$O\text{-}P^{low}$ = organic phosphorus of the lower level
$O\text{-}N^{low}$ = organic nitrogen of the lower level
COD^{low} = chemical oxygen demand of the lower level
DO^{low} = dissolved oxygen of the lower level
K_{PO_4} = half saturation constant of phosphorus
K_{TIN} = half saturation constant of nitrogen
J_{IN} = incoming volume flux (computed by hydrodynamic model)
J_{OUT} = outgoing volume flux (computed by hydrodynamic model)
dfv = vertical eddy diffusivity
h = thickness of the level
DH = distance between levels
Vmax = maximum growth rate of phytoplankton
α_P = phosphorus/chlorophyll-a ratio in phytoplankton
α_N = nitrogen/phosphorus ratio in phytoplankton
α_{COD} = chemical oxygen demand/phosphorus ratio in phytoplankton
α_{DO} = dissolved oxygen demand/phosphorus ratio in phytoplankton
$S_{O\text{-}P}$ = sedimentation rate of particulate organic phosphorus and dissolved organic phosphorus

Table 3 (continued)

$S_{O\text{-}N}$ = sedimentation rate of particulate organic nitrogen and dissolved organic nitrogen
S_{COD} = sedimentation rate of particulate chemical oxygen demand and dissolved chemical oxygen demand
S_{Chla} = sedimentation rate of phytoplankton
V_P = decomposition rate of phosphorus
V_N = decomposition rate of nitrogen
V_{COD} = decomposition rate of chemical oxygen demand
m_P = mortality of phytoplankton
β = respiration rate of phytoplankton
γ = excretion/photosynthesis ratio of phyoplankton
R_{PO_4} = release rate of inorganic phosphorus from sediment
R_{TIN} = release rate of inorganic nitrogen from sediment
R_{COD} = release rate of chemical oxygen demand from sediment
R_{DO} = release or consumption rate of dissolved oxygen by sediment

Table 4. Parameters used in the water quality model

Symbol	Value	Reference
Iopt	4000 lux	calibration
Topt	30°	calibration
K_{PO_4}	0.005 mg/L	based on Matsuoka et al., 1986
K_{TIN}	0.038 mg/L	based on Matsuoka et al., 1986
Vmax	3.63 /day	Matsuoka et al., 1986
α_P	1.0	unpublished METOCEAN data
α_N	7.2	Redfield et al., 1963
α_{COD}	63.5	unpublished METOCEAN data
α_{DO}	143.0	Redfield et al., 1963
$S_{O\text{-}P}$	0.1 m/day	calibration
$S_{O\text{-}N}$	0.1 m/day	calibration
S_{COD}	0.1 m/day	calibration
S_{Chla}	0.1 m/day	calibration
V_P	0.050exp(0.0693T) /day[a]	calibration
V_N	0.050exp(0.0693T) /day[a]	calibration
V_{COD}	0.005exp(0.0693T) /day[a]	calibration
m_P	0.050 1/day	calibration
β	0.010exp(0.0693T) /day[a]	based on WHO/LLDA, 1978
γ	13.5%	based on Jorgensen et al., 1991
R_{PO_4}	0.00015 mg/cm^2 /day	Holdren, 1981
R_{TIN}	0.0012 mg/ cm^2 /day	Holdren, 1981
R_{COD}	0.0024 mg/ cm^2 /day	calibration
R_{DO}	0.0000 mg/ cm^2 /day	calibration

[a] T=temperature (°C)

Boundary condition for the hydrodynamic model

Depth. Bathymetry data was digitized from the chart of Laguna de Bay published by the Philippines Coast and Geodetic Survey in 1983 and interpolated into the computational grid shown in Fig. 1.

Wind. Four wind directions (E, SE, SW, NE) were evaluated to obtain representative wind conditions based on records from three meteorological stations (Manila, Quezon City, Los Baños) near the lake. Records from 1961 to 1994 for Manila and Quezon City were gathered from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) while Los Baños records from 1977 to 1990 were collected from the University of the Philippines in Los Baños. Eastern wind conditions, recorded in Los Baños, the nearest station to the lake, was used as an average wind direction for the model. The average wind speed recorded at Los Baños was applied to all wind directions. On the other hand, a no wind condition was tested as an extreme case for calm weather.

Volume of inflow. The 1984 average volume of inflow for nine major tributaries based on the hydrobiological data of LLDA (unpubl.) was used in the hydrodynamic model. Volume of back flow from Pasig River and volume of diverted flow through Mangahan (Fig. 2) were not considered.

Tide. The tide in Manila Bay is diurnal (NAMRIA 1996). Water elevation by tidal force was computed using Eq. 1 as a boundary condition at the lower end of the Pasig River shown in Fig. 2.

$$\zeta = A\cos\left(2\pi \frac{t}{T}\right) \qquad (1)$$

where ζ is the water elevation, A = 27 cm (NAMRIA, 1996), t is time in hour, T = 24 hrs.

Boundary condition for the water quality model

Pollution load. Monthly pollution load in 1984 (Fig. 3) was estimated from the discharge and water quality measurements of parameters for the nine major tributaries mentioned in the volume inflow. The total phosphorus (TP), total nitrogen (TN) and COD in the lake in 1984 were 740, 2100, 23000 tons, respectively. Pollution load from Pasig River back flow, Mangahan floodway (Fig. 1), and other industrial, agricultural, domestic sources were not considered.

Water elevation. Water elevation was simulated using a year-long average curve based on records at Looc in Central Bay (Fig. 1) from the average of a 10-year (1985 to 1994) data on water elevation.

Transparency. The model linked transparency (from Secchi disc readings) to light intensity and corresponding limiting effect on growth. Transparency was converted as the depth of the euphotic zone to calculate average light intensity for each level. Here, the depth of the euphotic zone was defined as the depth in which light intensity is one percent of the surface. Moreover, it was assumed that the euphotic zone was correlated to transparency as seen in equation 2.

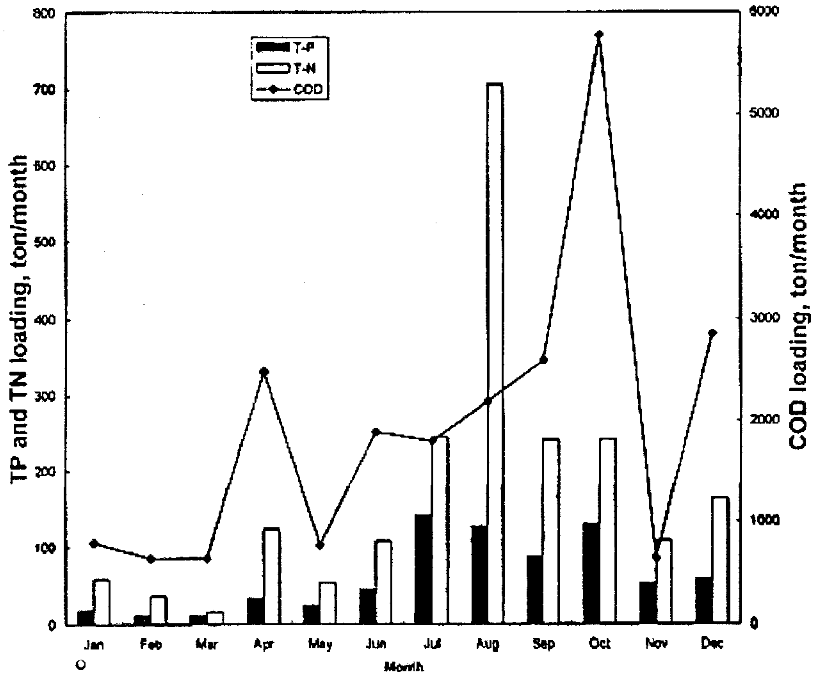


Fig. 3. Total pollution load in Laguna de Bay for 1984

$$\text{depth of euphotic zone} = 2.5 \times \text{transparency} \qquad (2)$$

Monthly data of transparency (Fig. 4, 5) as measured by SEAFDEC (unpublished) and LLDA (ERMP 1993) were used in Eq. 2.

Dissolved oxygen concentration. The saturated DO concentration was used as the upper limit. No super saturation of DO was included in the model for simplicity.

Radiation. Daily global radiation measured by PAGASA in Quezon City in 1984 was converted to monthly surface light intensity.

Temperature. The monthly data of water temperature in 1985 (LLDA 1984) were used for all the water levels uniformly. The vertical profile of water temperature was not included in the monitoring protocol recommended by the Philippine government.

Calibration and validation of the water quality model

Calibration of the water quality model was carried out for 1984 by running the model repeatedly until it agrees satisfactorily with the measured data given an average Eastern wind condition of 1.5 m/s. Other wind directions including no wind case were also tested to see the effect of wind to the water quality.

Validation of the water quality model was done under average wind conditions for the 1985 to 1988 data as a continuous simulation from the calibration in 1984. Here, transparency was the only forcing function used to induce changes in water quality year after year. All other forcing functions inputted for 1984 were applied periodically without any changes. All parameters calibrated for 1984 were used for the 1985 to 1988 data.

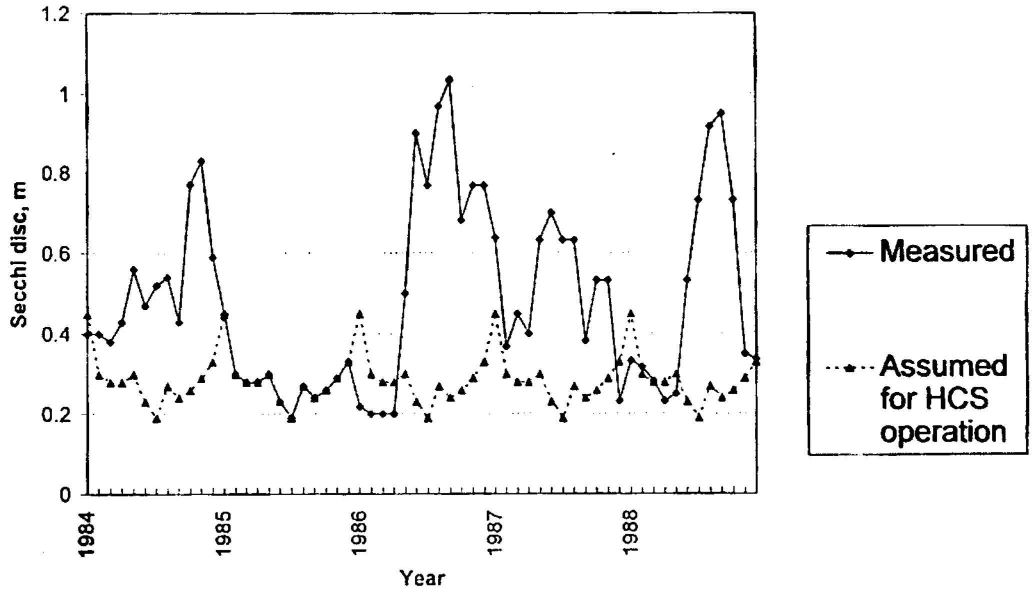


Fig. 4. Average transparency for the whole lake from 1984 to 1988. (Source: unpublished data from LLDA and SEAFDEC, used with permission.)

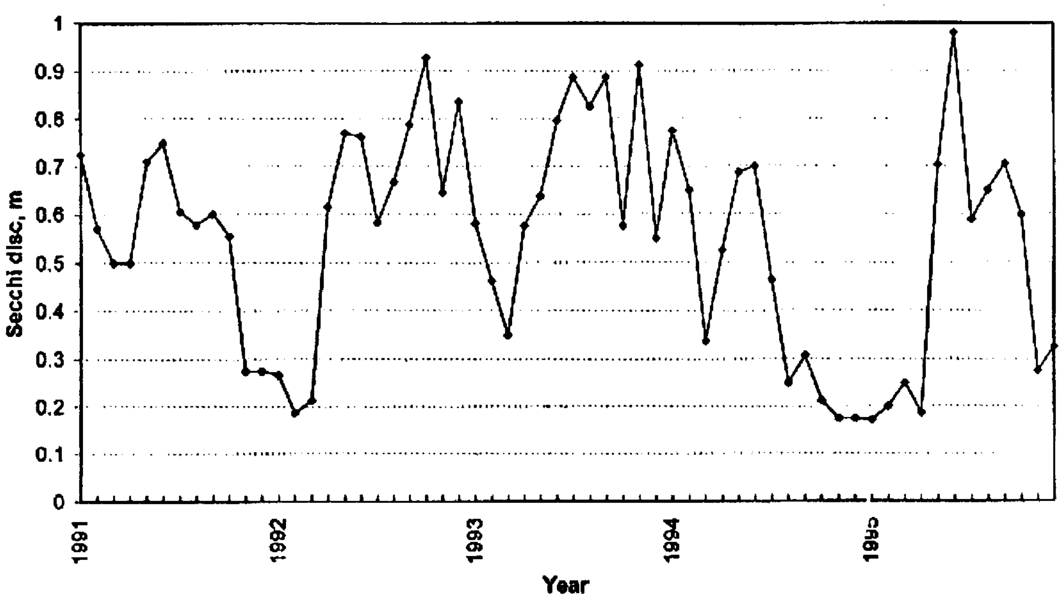


Fig. 5. Average transparency for the whole lake from 1991 to 1995. (Source: unpublished data from LLDA and SEAFDEC, used with permission.)

Application of the water quality model

Two applications of the water quality model were tried. The first application was an impact assessment on the water quality of the lake if HCS was fully operational from 1984 to 1988. HCS operation was suspended during this period. The impact of closing the HCS was focused on low transparency caused by no sea water intrusion. The model used the transparency data of 1985 repeatedly through 1984 to 1988 because the transparency of 1985 was the actual record of the year without sea water intrusion (Santiago 1991). Although HCS was designed not only for preventing sea water intrusion but also for preventing any pollution load from Pasig River to the Lake, this simplification worked as a good approximation.

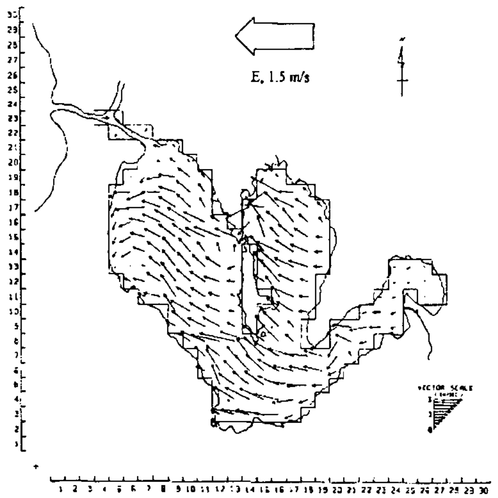
The second application was the simulation of the recent condition of the lake from 1991 to 1995 based on the 1984 input data used in the calibration updating only the transparency.

Results and Discussion

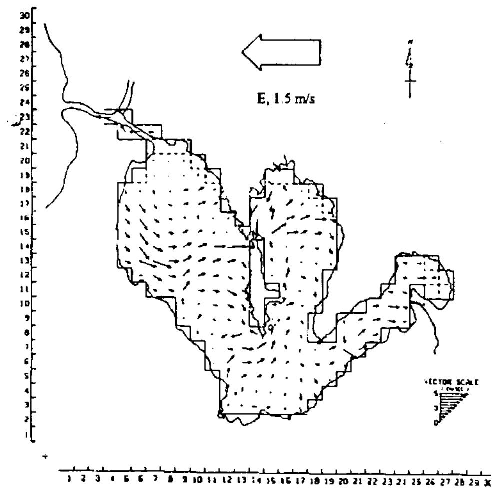
Circulation pattern using the hydrodynamic model

An example of the circulation pattern obtained by the hydrodynamic model is shown in Fig. 6. Surface water was directly dragged by eastern wind and flowed toward west or northwest. On the other hand, the middle and bottom level of the water showed an inverse pattern. This vertical shear in velocity was a common characteristic in all wind directions tested in the study. Even a no wind case showed similar vertical shear driven by the inflow from tributaries with velocity lower than those under windy cases (Fig. 7).

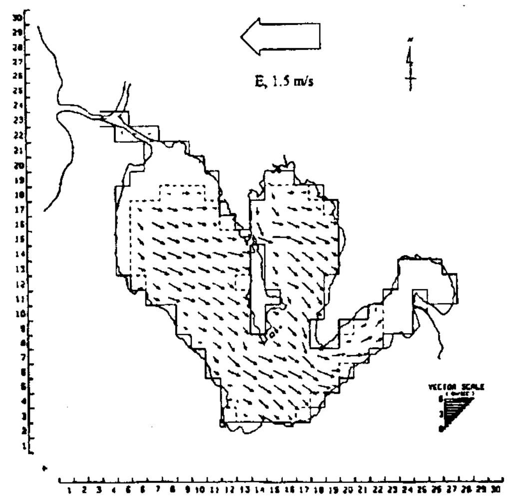
Data on circulation patterns actually measured in the lake was unavailable; hence, a comparison with the simulated pattern was not possible. However, chloride (Cl) data in the year with sea water intrusion could be regarded as a tracer of the water movement because the only source of Cl in the Lake is the back flow from Pasig River. In 1990, Cl showed a sharp rise in the West Bay at a station near the Pasig River (Fig. 8) as back flow commenced. The increase of Cl then progressed in the center of West Bay, Central Bay, South Bay, and East Bay with a time lag of several months. The chloride concentration gradually decreased due to some dilution. The net circulation pattern which just concentrates to the Pasig River could not explain this trend in Cl transport. This indicates that there is a different mechanism to transport Cl constantly from Pasig River to other areas in the Lake. This mechanism is probably the significant vertical shear of the velocity shown in the simulated circulation patterns. Good agreement of the calibration and validation of water quality also indirectly supported the accuracy and closeness of the simulated circulation pattern to the actual pattern.



surface



middle



bottom

Fig. 6. Examples of the circulation patterns at the surface, middle and bottom levels with easterly winds at 1.5 m/s

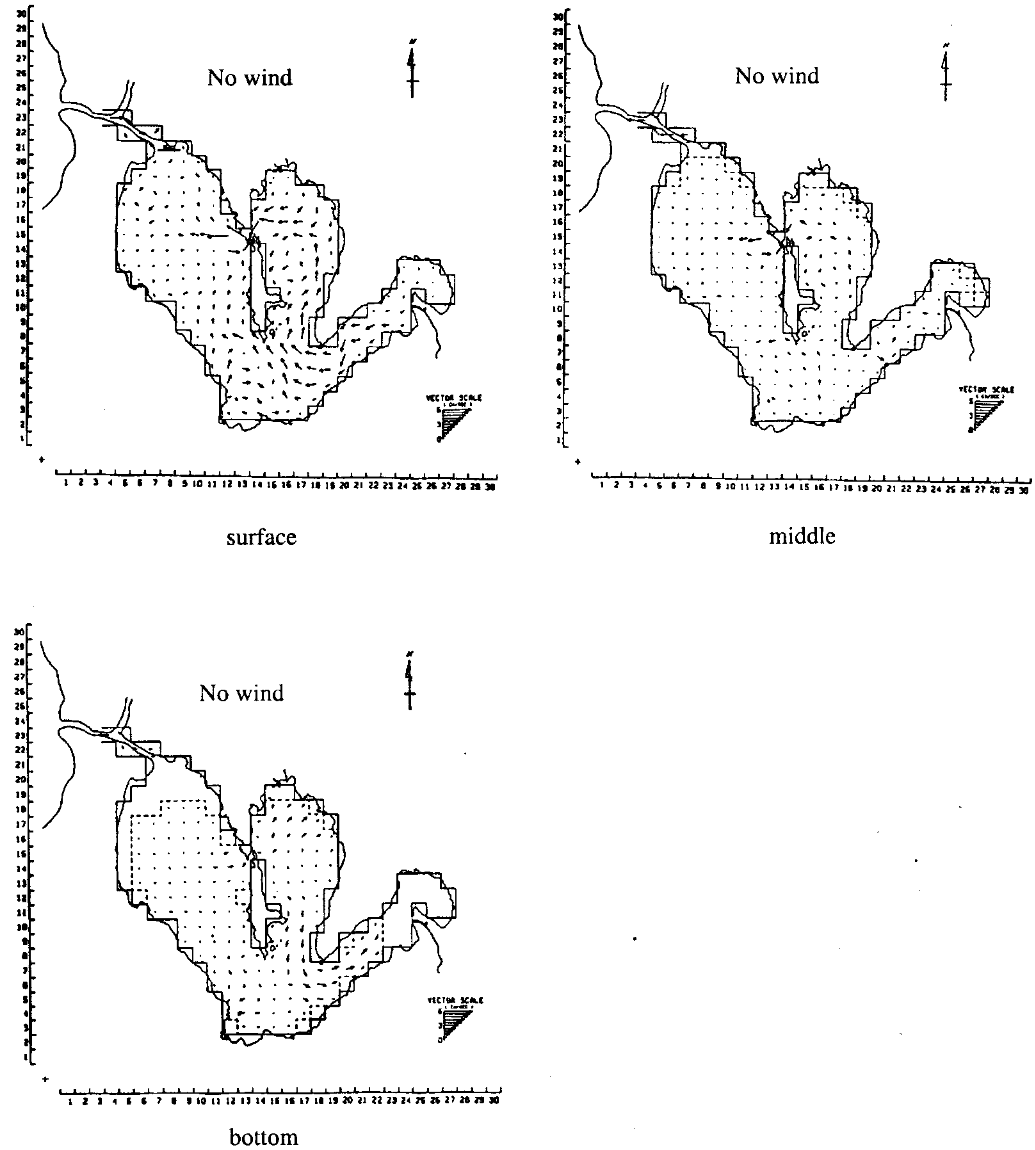


Fig 7. Examples of the circulation patterns in Laguna de Bay at the surface, middle and bottom levels with no wind

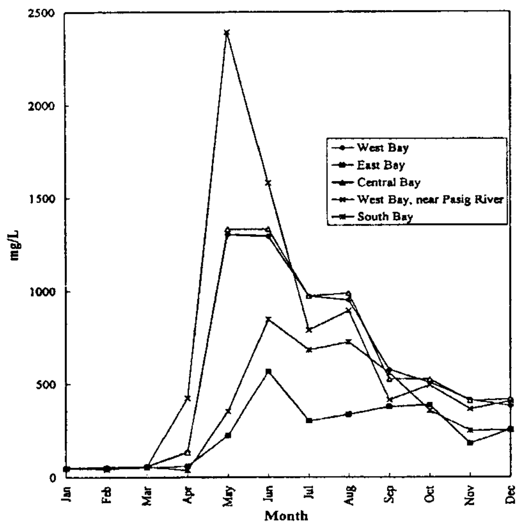


Fig 8. Chloride concentrations in Laguna de Bay in 1990. (Unpublished data from LLDA, with permission)

Calibration and validation of the water quality model

Calibrated and validated results for TIN, IP, and DO of the water quality model are seen in Figures 9, 10 and 11 respectively as a continuous simulation from 1984 to 1988. As a first approximation for the aforementioned water quality parameters the simulated results showed good agreement with measured data. The results also suggested a stratification of all water quality parameters. Poor agreement between simulated results and measured data is shown in the late 1985 and the beginning of 1988.

Results of 1984 under different wind conditions are summarized in Table 5. Stratification was clear for NE and no wind conditions. Least stratification was obtained under SE wind condition. An example of the stratification of DO is shown in Fig. 12.

Table 5. Wind effect on water quality

Wind Condition	West Bay	South Bay	Central Bay	East Bay
No wind	H	H	H	H
E	M	H	M	H
SE	L	M	L	M
SW	M	M	M	L
NE	H	L	H	H

H - high stratification; M - medium stratification; L - low stratification

Although this model did not consider the input of pollution from Pasig River back flow, Mangahan floodway, and other known sources and although the only forcing function change year after year was transparency, it succeeded to simulate the measured water quality from 1984 to 1998 as a first approximation (Fig. 9, 10 and 11).

The poor agreement of TIN (the actual data was higher than the simulated results) in late 1985 was probably due to the additional pollution load triggered by the heavy rain after dry months that year (Fig. 13) and was not caused by the ignored pollution load from Pasig River. The lake level was already more than 1 m higher than the annual low lake level at the end of June (Fig. 2). Therefore, no back flow could have happened in July to cause the sharp rise of the measured TIN. The measured TIN increase, if caused by the back flow, should have happened in June at the time of the lowest lake level.

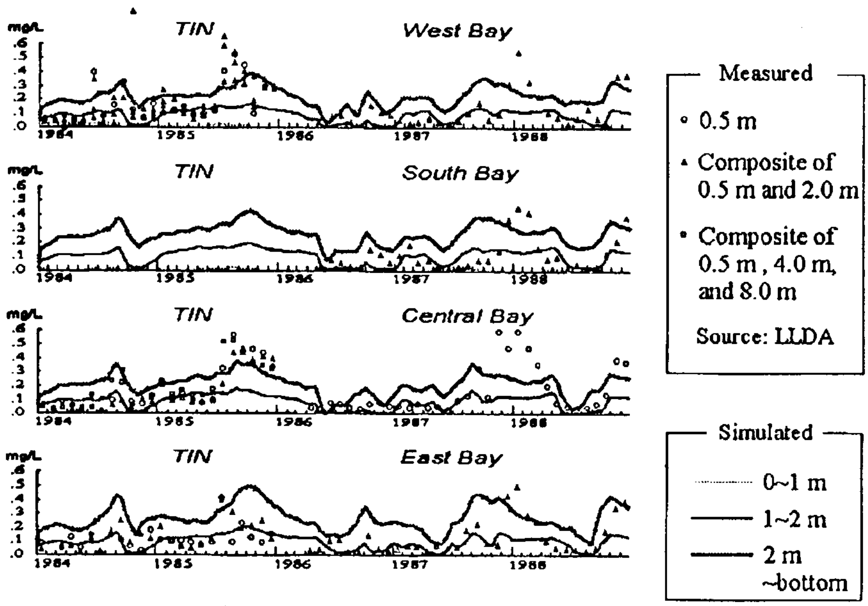


Fig 9. Model calibration and validation of inorganic nitrogen in the different areas of Laguna de Bay

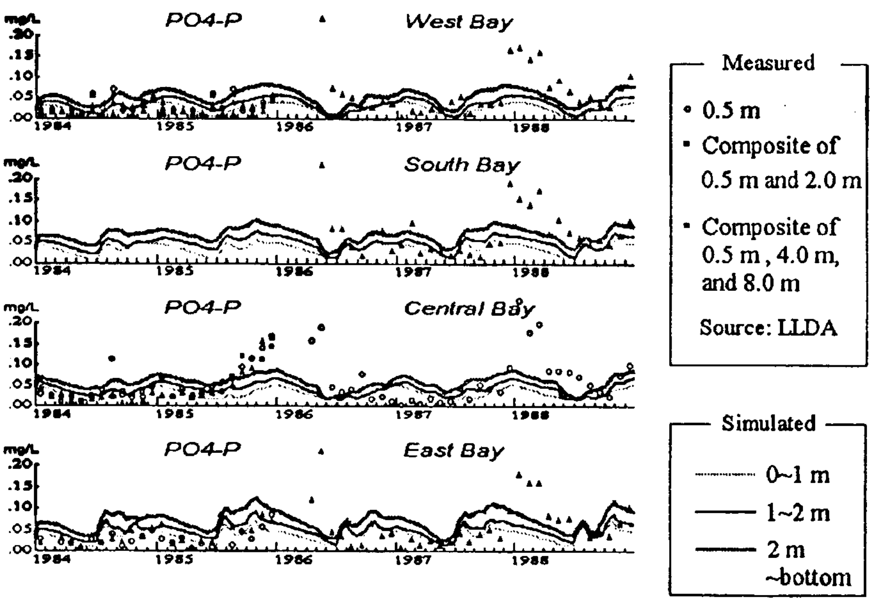


Fig 10. Model calibration and validation of inorganic phosphorus in the different areas of Laguna de Bay

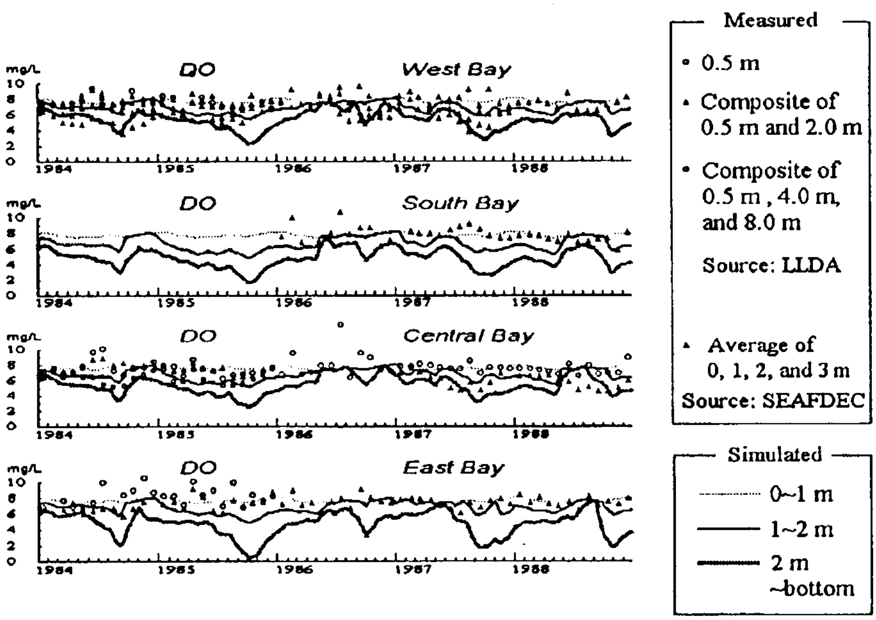


Fig 11. Model calibration and validation of dissolved oxygen in the different areas of Laguna de Bay

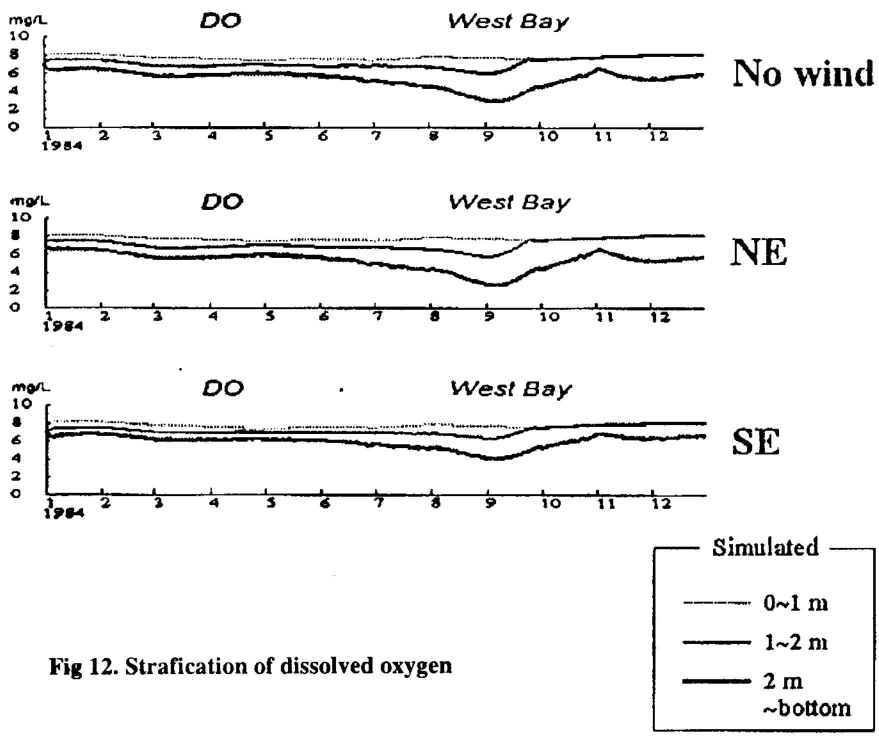


Fig 12. Strafication of dissolved oxygen

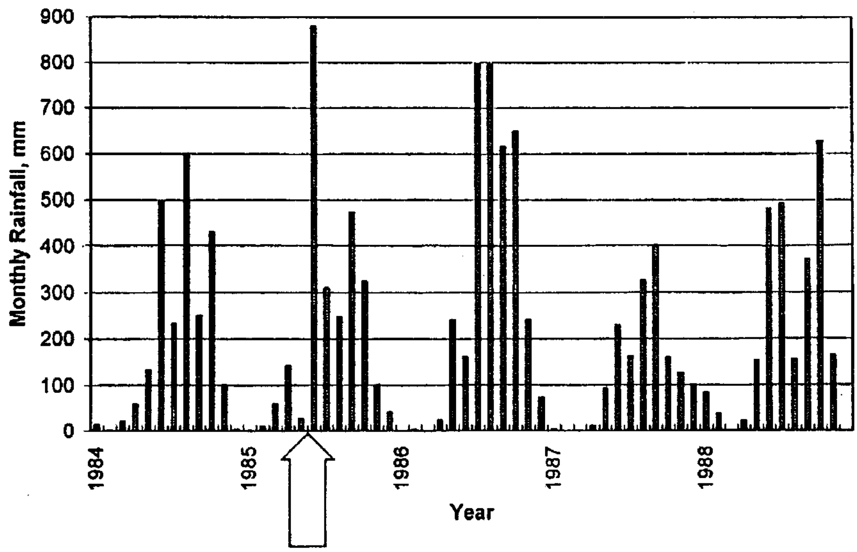


Fig 13. Monthly rainfall in Laguna de Bay region from 1984 to 1988. (Source: PAGASA)

The poor agreement of TIN in early 1988 is hard to explain, but one possibility was the accelerated release of TIN from the bottom sediment after an anaerobic condition of the overlying water prevailed for a period of time (about one month) (Wetzel 1984). Simulated DO in late 1987 (Fig. 11) showed a low DO in the bottom layer which suggested the probability of anaerobic condition of the overlying water in the bottom occurring before the sharp rise of measured TIN in early 1988. Even under aerobic conditions, the amount of total nutrients released in the model based on Holdren (1981) was comparable to the amount of the total external pollution load from tributaries. The total releases were 460 and 3700 tons/yr for inorganic P (IP) and inorganic N (IN), respectively, while the external pollution loads were 740 and 2100 tons/yr. Therefore, if the release rate becomes several times larger under anaerobic condition, it can greatly influence the TIN concentration in the lake. Similar poor agreement of IP in early 1988 was also found (Fig. 10) and can be explained by the same mechanism of TIN.

Application of the water quality model of an environmental scenario

An application of the water quality model to the situation without sea water intrusion was shown in Figures 14, 15 and 16 for TIN, IP, and DO, respectively. The results showed higher TIN and IP, and lower DO compared with a sea water intrusion situation every year. Higher TIN and IP were the results of lower consumption by phytoplankton because of light limitation. The same mechanism was found in 1985 (Fig. 9, 10) because no sea water intrusion occurred. Although HCS was designed not only for preventing sea water intrusion but also for preventing pollution from Pasig River to Laguna de Bay, it is not expected to lower the concentrations of at least the nutrients because nutrients will remain and possibly at higher concentrations even if HCS is operated. The low DO shown by the model will induce the higher release of nutrients from the bottom sediments in the lake which are bound under aerobic condition. The operation of HCS may not achieve the reduction of pollution in the lake but, on the contrary increase nutrients available in the lake ecosystem.

Application of the water quality model to a recent condition

The water quality model was applied for the years 1991 to 1995 as shown in Figures 17, 18 and 19 for TIN, IP and DO, respectively. Simulated results of TIN and DO generally agree with the measured data except in the beginning of 1992 and 1995 and at the end of 1995. Simulated results of the IP, however, had relatively poor agreement with the measured data. Poor agreement of TIN and IP at the beginning of 1992 and 1995 and at the end of 1995 was preceded by low DO. This supports the hypothesis of accelerated release of nutrients from bottom sediments stated earlier.

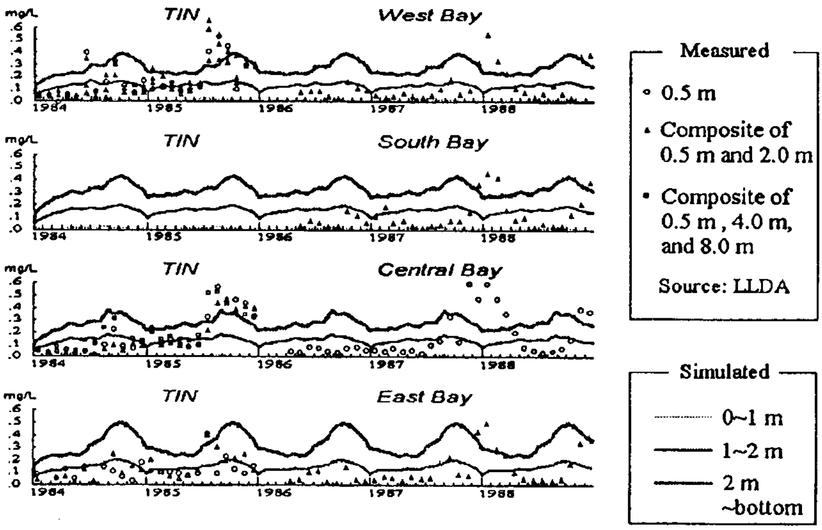


Fig 14. Application: Inorganic nitrogen without sea water intrusion

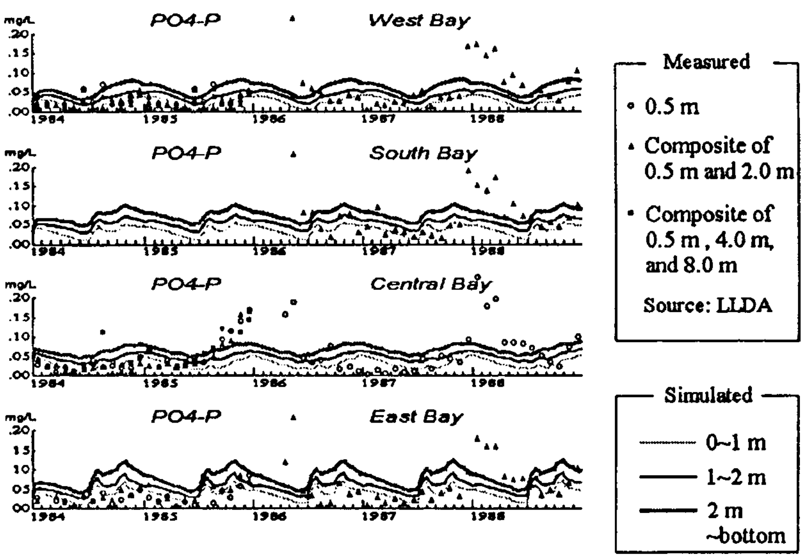


Fig 15. Model application: Inorganic phosphorus without seawater intrusion

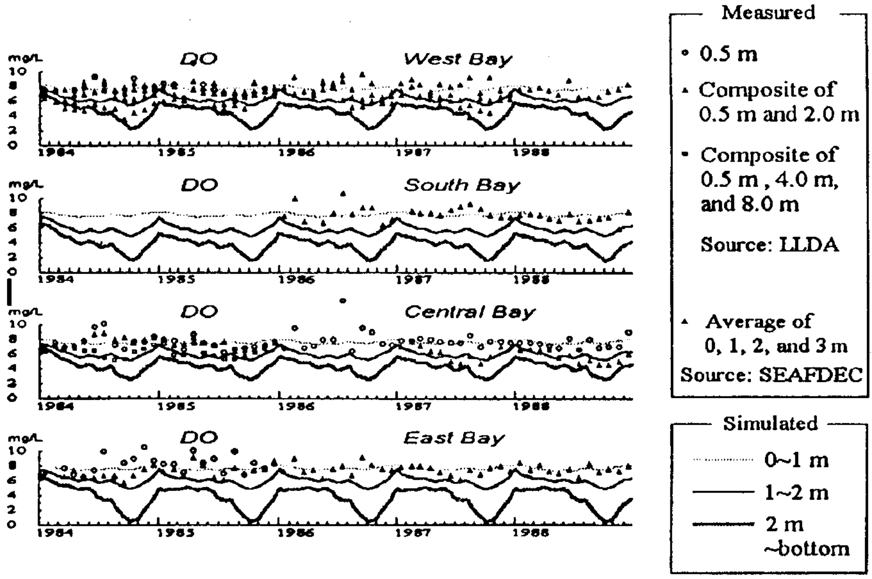


Fig 16. Model application: Inorganic phosphorus without seawater intrusion

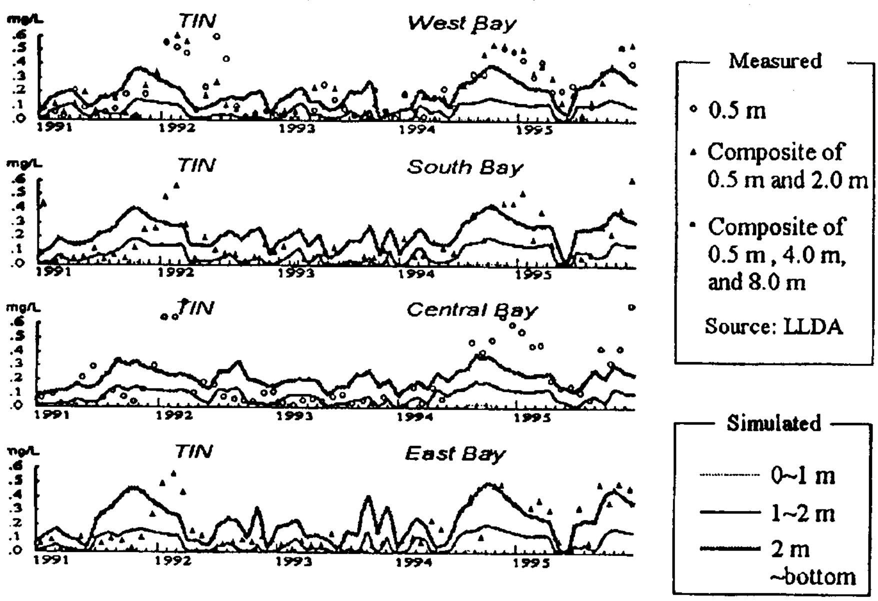


Fig. 17. Model application: Inorganic nitrogen for recent conditions (1991 to 1995)

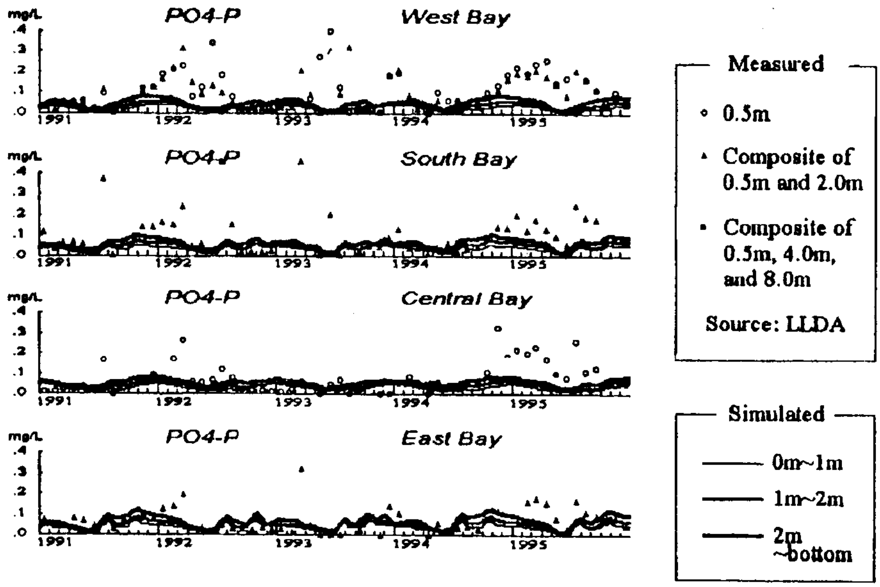


Fig. 18. Application: Inorganic phosphorus for recent conditions (1991 to 1995)

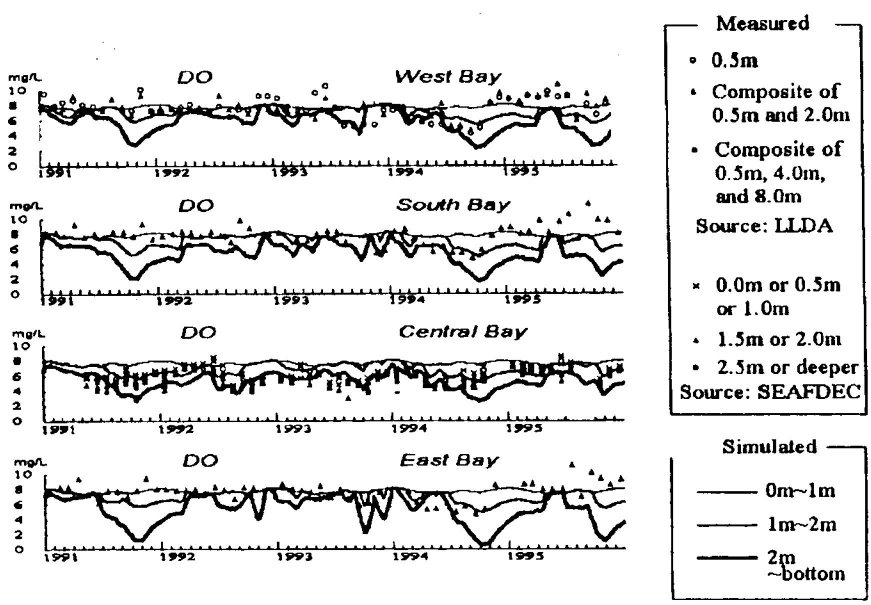


Fig. 19. Application: Dissolved oxygen for recent conditions (1991 to 1995)
Conclusion

Conclusion

The model with light intensity as the major forcing function could simplify the simulation of the dynamic change of inorganic nutrients and dissolved oxygen in Laguna de Bay.

Major prediction errors of nutrients were probably due to the accelerated release of the nutrients from bottom sediments under anaerobic condition since most of them were preceded by low DO in the water column. Therefore, as the model suggested, the HCS must be operated to prevent backflow which results in lower DO and higher nutrient level caused by light limitation during photosynthesis and additional nutrient release from bottom sediments.

Recommendation

There is a need to verify this model as a tool for future rational resource management. The authors recommend the monitoring of nutrient release rates from the bottom sediments of the lake under aerobic and anaerobic conditions. This is a major potential source of pollution load which may even exceed the external loading. In the present study, release rates under aerobic condition were assumed to be constant based on the experiment by Holdren (1981). The increase in measured concentration of nutrients after an episode of low dissolved oxygen suggests a rapid change of release rates.

To update this model, it is necessary to calibrate it with at least yearlong data of updated pollution load. The pollution load should be estimated from water quality and discharge of tributaries which covers at least the same items and the same sampling frequency (monthly) used in 1984.

To refine the model further, pollution load brought in through the back flow of Pasig River, the Mangahan floodway and aquaculture wastes should be taken into account. Biological parameters shown in Table 4 should be replaced by measured values rather than the calibrated values used in this study.

Acknowledgements

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