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WATER QUALITY MODELING OF LAGUNA DE BAY WITH EMPHASIS ON SALINITY, DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND

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ABSTRACT

Laguna de Bay is the largest and most vital inland body of water in the Philippines. The lake has been used for different purposes such as fisheries, power generation, transportation, reservoir for floodwater, water supply for irrigation, recreation, industrial cooling and potential raw water supply for drinking water. Due to population growth, deforestation, land conversion, urbanization and industrialization over the past decades, its water quality has deteriorated steadily. Conflicting uses of this water resource must be resolved to ensure the sustainable development of Laguna de Bay.

The water quality of Laguna de Bay was modeled using Delft3D software developed by WL|Delft Hydraulics of Netherlands. This work demonstrated the set-up, calibration and validation of the water quality model focusing on three state variables – salinity, dissolved oxygen and biochemical oxygen demand. The water quality data monitored by Laguna Lake Development Authority in different stations on the lake were used to calibrate and validate the model for the period 1995-1999. The model inputs consist of hydrodynamic model result for the advective transport of substances, waste load model result for the pollution loads from the watershed and other GIS-processed input data. The calibration of the water quality model in terms of salinity, dissolved oxygen and biochemical oxygen demand was satisfactory after comparing the model results and observed values.

1. INTRODUCTION

Laguna de Bay is the largest lake in the Philippines and it is located South East of Metro Manila, approximately between the co-ordinates 14°11' and 14°33' North, and 121°03' and 121°29' East (Van der Gun, 2000). Its watershed spans 14 cities and 47 municipalities located within the whole province of Laguna and Rizal, and parts of Batangas, Cavite, Quezon, and Metro Manila. The surface area of Laguna de Bay is about 900km^2 with a shoreline of 285km at 10.5m lake elevation. The average depth of the lake is 2.5m and with a maximum depth of 20m at Diablo Pass. The average volume of the lake is 2.25 billion m^3 with a retention time of 8 months (LLDA, 2005). The total area of Laguna de Bay watershed is around 3820 km^2 (Nauta, et.al., 2001). More than 100 streams flow into its drainage area, which is divided into 24 sub-basins. There is only one outlet, the 27 km Pasig River, which drains to Manila Bay (Santos-Borja and Nepomuceno, 2003).

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Laguna de Bay is classified as Class C fresh surface waters based from the DENR standard which its water is suitable for fishery, for non-contact water recreation and for industrial processes after treatment (DENR, 1990). Based from the Laguna de Bay Environment Monitor 2005, BOD concentrations in all the five lake stations which are monitored monthly consistently met the water quality criteria for Class C water from 1995 until 2004. The same is true with the DO concentration, Total Coliform concentration and Nitrate concentration. During the same period, Phosphate concentration increases during wet months (May-October) and decreases during the dry months (November-April) which may be due to flood waters and surface runoff from rivers where high levels of these nutrients accumulate during dry months. The major source of chloride in Laguna de Bay is sea water from Manila Bay which enters the lake through the Pasig River during summer months. However, the backflow episode does not happen every year.

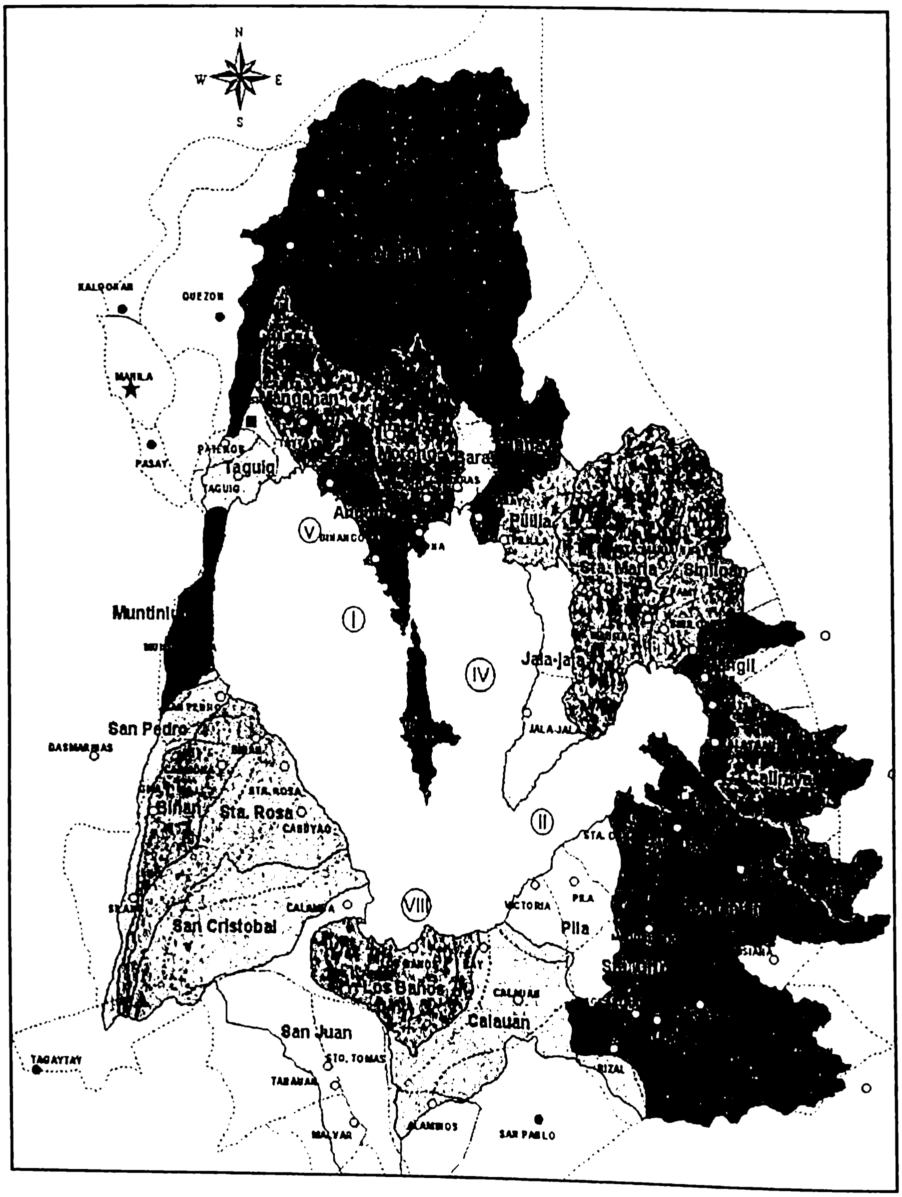

Figure 1. Laguna de Bay water quality monitoring stations

Over the recent decades, population expansion, deforestation, land conversion, urbanization, intense fisheries and industrialization have produced massive deterioration in the Laguna de Bay catchment. The resulting problems include rapid siltation of the lake, euthrophication, inputs of toxics, flooding problems and loss of biodiversity. With respect to the competing and conflicting pressures on the water resources, the Laguna Lake Development Authority (LLDA) which has the mandate over Laguna de Bay region by virtue of R.A. 4850 of 1966 needs to implement comprehensive management and development of the area. As a step towards sustainability of its current efforts, LLDA forged a partnership with The Netherlands Government for technical assistance grant toward the Sustainable Development of the Laguna de Bay Environment (SDLBE) Project implemented from 2000 until 2003 (LLDA, 2005). The project objectives included the updating of all existing knowledge and data on Laguna de Bay and the development of a decision support system (DSS). This consisted of an ArcView GIS-database linked to a state-of-the-art modeling suite, including hydrological and waste loads models for the catchment area and three-dimensional hydrodynamic and water quality model (Delft3D) linked to a habitat evaluation module for the lake (Nauta, et.al., 2001). The water quality model makes use of the output from GIS, hydrodynamic model and waste load model and by itself generates input for the ecology model.

This paper aims to demonstrate the set-up, calibration and validation of the water quality model focusing on three state variables – salinity, dissolved oxygen and biochemical oxygen demand. The water quality data monitored by Laguna Lake Development Authority in different stations on the lake were used to calibrate and validate the model for the period 1995-1999. Please refer to Figure 1 for Laguna de Bay water quality monitoring stations.

2. WATER QUALITY MODULE OF DELFT3D, DELFT3D-WAQ

Delft3D-WAQ is a 3-dimensional water quality model framework. It solves the advection diffusion-reaction equation on a predefined computational grid and for a wide range of model substances. Delft3D-WAQ allows great flexibility in the substances to be modeled, as well as in the processes to be considered. Delft3D-WAQ is not a hydrodynamic model, so information on flow fields is derived from Delft3D-FLOW hydrodynamic model. Delft3D-WAQ makes use of the hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and vertical eddy diffusivity) calculated in the Delft3D-FLOW module. A wide range of model substances is available in Delft3D-WAQ which includes salinity, decayable substances, suspended sediment, temperature, nutrients, organic matter, dissolved oxygen, BOD and COD, algae, bacteria, heavy metals and organic micro-pollutants. Delft3D-WAQ allows you to specify an even wider range of physical, (bio) chemical and biological processes (WL|Delft Hydraulics, 2003).

The Delft3D-WAQ system addresses the mass balance of each water quality variable (substance) in each computational cell. Terms included in the mass balance are:

- Advective and dispersive transport;
- Processes or reactions; and
- Sources and sinks.

The mass balance of any pollutant is given by:

$$\mathbf{C\ (t + \Delta t) = C\ (t) + transport + processes + loads} \qquad (1)$$

$C(t)$ = concentration at the beginning of the time step
$C(t + \Delta t)$ = concentration at the end of the time step
transport = changes by transport

processes = changes by physical, chemical or biological processes
loads = changes by sources (waste loads, river discharges)

Delft3D-WAQ uses the advective (or water circulation) transport calculated by the Delft3D-FLOW model. In this way, Delft3D-WAQ benefits from sophisticated modeling of the hydrodynamics in a separate module. The sources and sinks include the river discharges and water abstractions, as well as waste loads such as sewage releases. Also, boundary conditions can be considered as sources (of water) for the lake. The processes are the central part of water quality modeling which can be subdivided into physical (e.g. sedimentation, re-aeration of oxygen), chemical (nitrification, phosphate-adsorption) and biological (phytoplankton growth and mortality) processes. A detailed description of the water quality processes is available through the Delft3D-WAQ User Manual and the Delft3D-WAQ Technical Reference Manual. Some of the partial differential equations considered in Delft3D-WAQ are shown in table below.

Table 1
Summary of partial differential equations considered in Delft3D-WAQ

Advection-diffusion-reaction equation	$\frac{\partial c}{\partial t} = -v\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} + L + P$	D = dispersion (or diffusion) coefficient v = velocity c = concentration L = Discharges or 'waste loads' P = Reaction terms or 'processes'
Reaeration	$\frac{\partial (0_2)}{\partial t} = K_A \cdot (0_{2,SAT} - 0_2)$	K_A = Reaeration rate constant 0_2 = oxygen concentration $0_{2,SAT}$ = saturated oxygen
Phytoplankton (Growth)	$\frac{\partial (P)}{\partial t} = f(T)\cdot f(I)\cdot f(DL)\cdot f(N)\cdot PP_{\max}$	P = phytoplankton biomass T = temperature I = light energy DL = day length N = nutrients (N,P,Si) PP_{max} = maximum primary production
Nitrification	$\frac{\partial (NH_4)}{\partial t} = -RC_{NIT} \cdot f(T)\cdot f(0_2)\cdot (NH_4)$	NH_4 = NH_4 concentration RC_{NIT} = nitrification rate constant
Denitrification	$\frac{\partial (NO_3)}{\partial t} = -RC_{DEN} \cdot f(T)\cdot f(0_2)\cdot (NO_3)$	NO_3 = NO_3 concentration RC_{DEN}= denitrification rate constant
Sedimentation (Krone, '62)	$\frac{\partial (SS)}{\partial t} = -\mu_S \cdot (SS)\cdot (1 - \frac{\tau}{\tau_{CS}})$	SS = suspended sediment μ_S= settling velocity of suspended matter τ_{CS} = critical sheer stress for sedimentation τ = sheer stress

The dissolved oxygen concentration always seeks equilibrium with the atmosphere. In fresh water at 28°C, the equilibrium (or saturation) concentration is 7.7 mg/L. When the dissolved oxygen concentration in the water is lower than the saturation concentration, oxygen from the atmosphere replenishes the water. When the dissolved oxygen concentration in the water is higher than the saturation concentration, oxygen escapes from the water to the atmosphere. This process is called reaeration. Thus, reaeration tends to bring the dissolved oxygen concentration back to the saturation concentration. The rate of reaeration is often described by diffusive transport over a thin boundary layer between the water and the atmosphere. The assumption is made that the water at the interface with the atmosphere is saturated at all times. Then the dissolved oxygen concentration drops linearly to the concentration in the bulk water column, which is assumed to be well mixed. The rate of reaeration depends on the difference between the actual and saturated concentration and on the thickness of the boundary layer, which in turn depends on flow velocity and wind speed. Winds cause turbulence, which decreases the thickness of the boundary layer (Nolte, et.al., 2001).

In Delft3D-WAQ, reaeration is formulated according to the following equation:

$$\mathbf{f_{Reaeration} = Rc_{Reaeration} * (C_{Saturation} - C_{Actual})} \qquad (2)$$

$f_{Reaeration}$ = Reaeration flux ($gO_2/m^3/d$)
= f (Temperature, Flow velocity, Wind speed)
= Reaeration rate constant (d^{-1})
$Rc_{Reaeration}$
$C_{Saturation}$ = Saturation concentration (gO_2/m^3)
C_{Actual} = Actual concentration (gO_2/m^3)

There are two main sources of dissolved oxygen in the aquatic environment: the atmosphere being the first and primary production as the second. Oxygen in the water column is consumed by the decay of organic matter, respiration of biota (both aquatic flora and fauna) and oxidation of reduced substances.

The overall mass balance for dissolved oxygen:

$$\mathbf{\Delta O_2/\Delta t = loads + transport + reaeration + net\ primary\ production - mineralization - nitrification + denitrification} \qquad (3)$$

The processes that may increase the oxygen concentration in the water column are primary production by photosynthesis, reaeration over the atmosphere-water interface (in case of undersaturation), uptake of nitrate by algae and denitrification. While the processes that can decrease the oxygen concentration in the water column are respiration of algae, reaeration (in case of oversaturation), decay of organic material in the water column, sediment oxygen demand and nitrification.

Biochemical Oxygen Demand (BOD) is a parameter that is often used to estimate the quantity of organic matter present in a water body. Biochemical oxygen demand is the sum of carbonaceous and nitrogenous oxygen demand. This oxygen demand is determined by standard methods that measure the oxygen consumption of a filtered sample during laboratory incubation within a period of time (usually 5-days at 20°C in the dark). To obtain meaningful results the samples must be diluted in such a way that adequate nutrients and oxygen will be available during the incubation (WL|Delft Hydraulics, 2003).

In Delft3D-WAQ, the mass balances for carbonaceous BOD_5 (CBOD5):

$$\mathbf{\Delta CBOD_5/\Delta t = loads + transport - settling - mineralization} \qquad (4)$$

The mineralization of carbon detritus consumes oxygen at a molar ratio of 1:1, equivalent to a ratio of 32/12 g O_2 to 1 g C. For detritus carbon (DetC), the mineralization flux in the water column is given by:

$$\mathbf{f_{mineralization} = K_d * K_T^{(T-20)} * C} \qquad (5)$$

$f_{mineralization}$ = mineralization flux (g/m^3/d)
K_d = mineralization rate constant (1/d)
K_T = temperature coefficient (-)
T = temperature (°C)
C = Det C concentration (g/m^3)

While the formulation for settling is given by:

$$\mathbf{f_{sedimentation} = V_s * C * Psed} \qquad (6)$$

$f_{sedimentation}$ = sedimentation flux (g/m^3/d)
V_s = settling velocity of suspended matter (m/d)
C = concentration of suspended matter (g/m^3)
Psed = probability for sedimentation

3. METHODOLOGY

A prerequisite for setting up a successful water quality model is a good understanding of the system. Therefore, the key processes in Laguna de Bay need to be identified. One should realize that a model only reflects what is known about the system that is modeled. Only by identifying the key processes and by including them in the water quality model, the model will be able to describe the system more accurately. Data needed for a water quality model consists of data for model input on the one hand and data for model calibration and verification on the other hand. For example, wind speed is an important input parameter in several processes (e.g. re-aeration, sedimentation and erosion). This makes accurate data on wind speed a necessity for a reliable water quality model. These data are also used in the calibration and validation of the water quality model. By comparing the model result with the observed concentration, the goodness of fit is assessed. The model calibration is concluded when the model result reproduces the observations satisfactorily. Subsequently, the model simulation is repeated for a second independent year with the same model settings. Initial conditions can vary based on monitoring data of that specific year. The validation stage is successful when the model succeeds in reproducing the observations of the independent year without changing the process parameters. At that point, the model has been shown to adequately describe the water quality of Laguna de Bay (Nolte, et. al., 2001).

The water quality model of Laguna Lake was set-up using the water quality module, Delft3D-WAQ, of the state-of-the-art Delft3D software. The Delft3D-WAQ User Manual and Delft3D-WAQ Technical Reference Manual were the main references in setting up the water quality model for Laguna de Bay. The setting up of any simulation software requires knowledge on the theoretical background of water quality processes, knowledge on the operation of the software and understanding the numerical and mathematical formulations used in water quality modeling.

Basically, the steps in water quality modeling using Delft3D-WAQ are:

1. Coupling of the hydrodynamic model with the water quality model Result from Delft3D-FLOW hydrodynamic model is converted into format suitable for Delft3D-WAQ water quality model. If it is necessary to reduce simulation computational time, the computational grid from the hydrodynamic model is aggregated using Delft3D grid editor, DIDO.
2. Define the substances with their processes to be included in the simulation by creating a substance file using Process Configuration Tool (PCT).
3. Define a water quality simulation input file using the results of the previous steps. Specify the dispersion coefficients, simulation time, initial and boundary conditions, process parameter settings, numerical option, waste loads and output variables.
4. Run the simulation.
5. Compare the simulation results with the monitored data using Delft-GPP.

Generally, the results from the Delft3D-FLOW hydrodynamic model; the Delft-WLM waste load model, and; the spatial data from GIS constitute the three main inputs to the water quality model Delft3D-WAQ. Because these three sets of input come from simulations done by other specialists, there is a need to convert these into a format that can be read by the water quality model. Output of the hydrodynamic model is converted first before incorporating it into the water quality model. The same is done with the waste load model output which is converted using a simple program into time series format.

For calibration and validation, the output of the water quality model is compared with the monitored water quality data which are stored in the Laguna Lake water quality database, Delft-HYMOS. In comparing the model result with the monitored water quality data, the goodness of fit is assessed. Commonly, the measured data and the model results were graphed together and compared visually to assess the goodness of fit. The model calibration is concluded when the model result reproduces the monitored values satisfactorily. Finally, the output of the water quality model is post-processed as input data into the Ecology Model to determine the suitability of lake water for different uses.

3.1 Hydrodynamic input

Since the transport of substances through a water body is an important term in any water quality model, the Delft3D water quality model (Delft3D-WAQ) is based on the result of the hydrodynamic simulation with Delft3D-FLOW. The hydrodynamic model generates a communication file, which fully describes the schematization of the lake (e.g. grid sizes, etc.) and the flow of water through the lake. Subsequently, this communication file can be imported by the water quality module, accurately defining transport.

The hydrodynamic model of Laguna de Bay was set-up using an orthogonal curvilinear grid. A curvilinear grid allows for a high resolution in the specific area of interest with lower resolution in areas of less importance. Furthermore, a curvilinear grid can follow the land boundary outline by a single grid line. Initially, the design of the curvilinear grid for Laguna de Bay aimed at covering the entire lake area below the 12.5 m contour. In this study, the hydrodynamic grid was extended from the 12.5 to the 15-meter elevation line. The resulting computational grid is shown below (Figure 2).

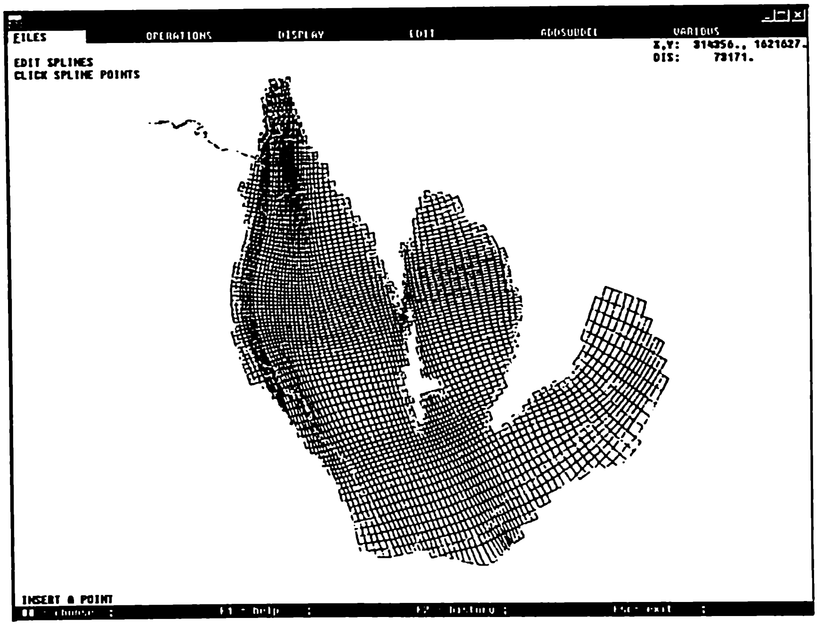

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Figure 2. Curvilinear grid of Laguna de Bay created using in the hydrodynamic model, Delft3D-FLOW (Hydrodynamic Model, LLDA)

The results of hydrodynamic model (water level) concluded that the 3D hydrodynamic schematization (1x1 original grid and 10 layers) and the 2D aggregated of the 3D hydrodynamic simulation (1x1 original grid and 1 layer) are in good agreement as shown below (Figure 3). Although inconsistencies were observed, these were considered to be relatively minor. It is concluded that a 2D aggregation of the 3D hydrodynamic simulation is allowed, since the loss in detail is minimal (Van der Kaaij, et.al, 2001).

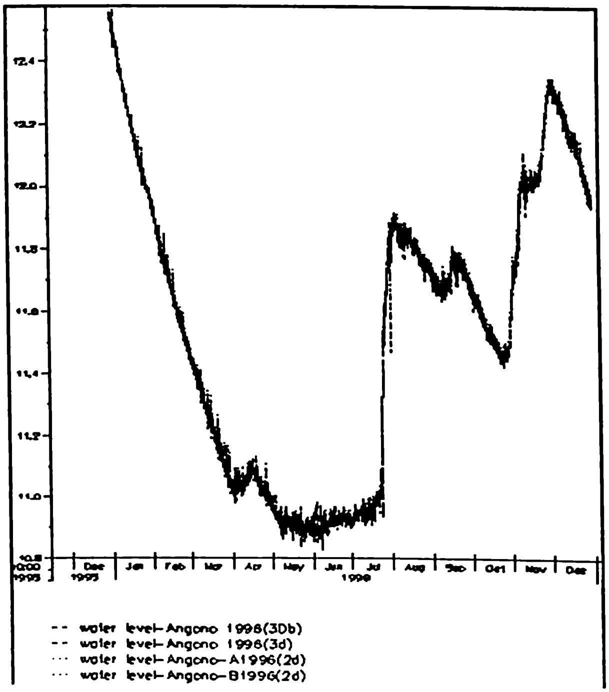

Figure 3. Comparison of water level simulation results at Angono station using a depth-averaged (2d) and 3d mode computation

As part of the hydrodynamic simulations, the saltwater intrusion in Laguna Lake was included. Figure 4 compares the computed salinity for 1995 at LLDA measurement station 1 (West Bay). The computed salinity at this station is comparable with the measurements. Visually, the result gives a very good agreement in terms of observed and computed salinity (Van der Kaaij, et.al, 2001).

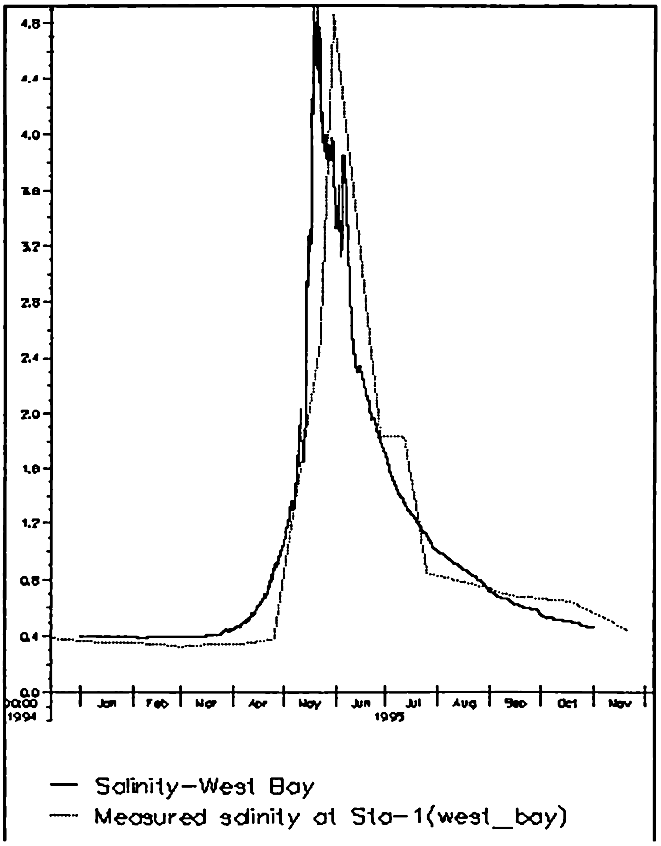

Figure 4. Comparison of hydrodynamic model result and actual salinity concentration at Station I (West Bay)

One of the advantages of the Delft3D-WAQ model is its ability to aggregate the communication file. Aggregation means the reduction of the number of segments in the model. The main purpose of applying an aggregation is to reduce the computation time during water quality simulation. For example, by reducing the number of segments by 50% the computation time is roughly halved. A 2x2 aggregation of the communication file is allowed without losing essential information. The benefit is the gain in computation speed, decreasing the computation time for a single year from approximately 8 hours to only 2 hours. Thus, a horizontal aggregation of 2x2 can be applied when time is a factor.

3.2 Meteorological forcing data

Data for wind speed and direction were taken from the only available station with detailed information. Due to the absence of sufficient wind data at a lake base station, hourly wind speed and wind direction from the Ninoy Aquino International Airport (NAIA) were used.

The length of the path traversed by a given wind over a water surface is represented by the fetch. The longer the path of the wind over the water surface, the higher the waves and the higher the shear stress. In sheltered areas waves are (much) lower than in open waters. Because of the topography of the Laguna de Bay watershed, a constant fetch is not appropriate in the water quality model. A procedure was formulated to create a segment function for Delft3D-WAQ. The segment function contains a time-dependent valüe for the fetch for every segment.

To determine the distance to the shoreline use is made of the GIS. For each computational cell, a line is drawn in 18 directions: 20°, 40°, 60°, 80°... 340° and 360°. Then, the length of the line from the center of the computational line to the intersection with the shoreline is determined as shown in Figure 5. Subsequently, the table generated by the GIS is converted to the segment function. The actual wind direction is compared with the tabulated values and the actual fetch is determined for every segment (Nolte, et. al., 2001).

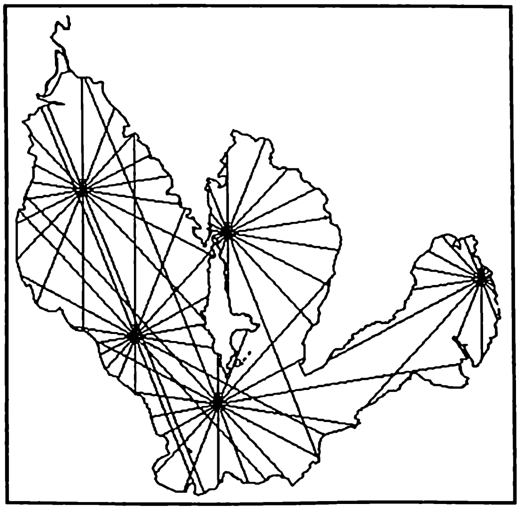

Figure 5. An illustration of fetch applied in the water quality model

Long-term average water temperatures were applied based on the Laguna de Bay monitoring program observations. Linear interpolation is applied between given dates and the water temperature in Laguna de Bay used in the model is shown below (Table 2).

Table 2
Water temperature applied in the model

Date	Temperature	Date	Temperature
January 1	24.8 °C	July 1	34.0 °C
February 1	26.8 °C	August 1	30.5 °C
March 1	27.0 °C	September 1	30.5 °C
April 1	30.6 °C	October 1	30.7 °C
May 1	32.0 °C	November 1	28.5 °C
June 1	33.6 °C	December 1	27.3 °C

3.3 Waste load input

Waste loads by domestic, industrial and agricultural sources are calculated by the Waste Load Model. The Laguna de Bay watershed area is divided into 24 sub-basins. In the set-up of the Waste Load Model each sub-basin was attributed one waste load. WLM calculates the total annual load in kg/y.

The waste load has been applied as a constant load, i.e. a constant amount per time (g/s). This arises from the assumption that most waste is generated by domestic and industrial sources and that this waste generation is continuous.

Since the water quality model includes more substances than are provided for in the Waste Load Model, assumptions were made on the distribution of the loads per substance. The output from the Waste Load Model and conversion to input for the Water Quality Model is summarized below (Table 3).

Table 3
The waste load model results used in the water quality model

Output from the Waste Load Model	Load (kg/y except coliforms in MPN/y)	Use in Water Quality Model
Ammonia	7.075E+6	90% NH4, 10% DetN
Nitrate	7.672E+6	NO3
Total phosphorus	2.997E+6	70% PO4, 30% AAP
Biochemical Oxygen Demand	6.630E+7	(×12 gC/32 gO_2) DetC
Chemical Oxygen Demand	1.170E+8	--
Chloride	1.218E+8	Salinity
Total coliforms	3.657E+15	Tcoli
Total Suspended Solids	1.274E+8	50% IM1, 50% IM2
Oil	2.286E+5	dTR1
Cadmium	3.710E+2	Cd
Copper	3.727E+4	Cu
Zinc	5.619E+4	Zn
Lead	2.750E+4	Pb

3.4 Calibration and Validation

General settings of the 1995 calibration calculation are mentioned in the table below. This is a year with a backflow period in the months of April to June. The Initial Conditions are the initial water quality situation of the lake and the Boundary Conditions are the water quality situation of the Pasig River.

Table 4
Initial and boundary conditions for 1995

Parameter Name	Initial conditions (Laguna de Bay)	Boundary conditions (Pasig river)
Salinity (g/kg)	0.34	34
Oxygen (g/m^3)	7	3
Detritus Carbon (g C /m^3)	0.5	0.5

The validation of the water quality model of Laguna de Bay was done for 1996. Additional validation of the model was performed for 1997, 1998 and 1999.

4. RESULTS AND DISCUSSIONS

The water quality in Laguna de Bay was simulated for the years 1995 up to and including 1999. Using LLDA water quality data, model results were compared visually with the observed data gathered from monitoring stations on the Laguna de Bay.

4.1 Salinity

During the period of 1995-1999, only 1996 have no backflow and 1997 has limited backflow. In contrast, 1998 saw a prolonged period of backflow. The initial value for salinity used in 1995 simulation was 0.34 ppt and then 1996 simulation used the last value simulated in 1995. This exercise was also applied in the succeeding simulation years, 1997-1999. Using Delft-GPP, a time series plot (from *.his file) of simulated salinity concentration (broken line) is compared with observed salinity data (solid line) from 1995 until 1999 at Station V which is located nearest to the mouth of Pasig River as shown in Figure 6.

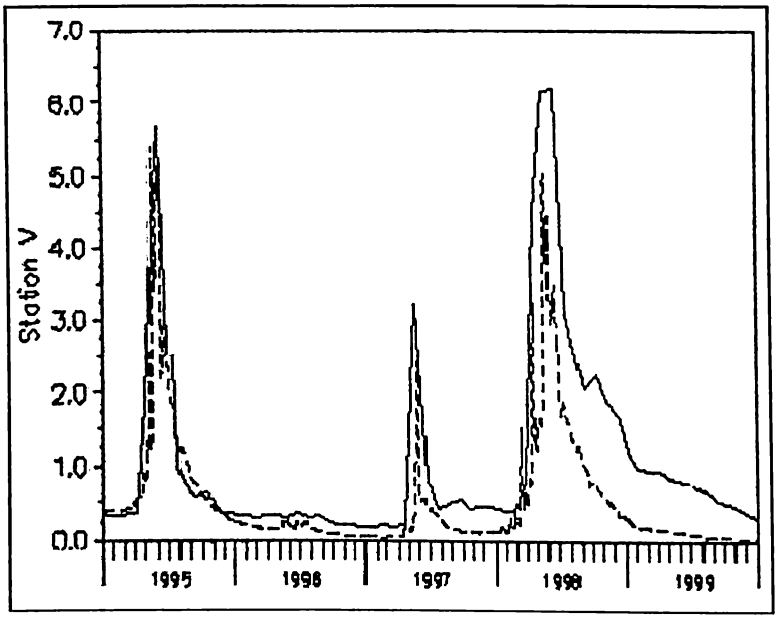

Figure 6. Time series of simulated (broken line) and observed (solid line) salinity concentration at Station V

The 1995 salinity intrusion was reproduced very well. The salinity concentrations for 1996, 1997 and 1998 were slightly underestimated. For 1999, salinity concentration is considerably underestimated which is due to low initial value. So it was decided to use the observed salinity values in the lake as initial values for 1996, 1997, 1998 and 1999 simulations. The model results from 1995 until 1999 using new initial values are presented in Figure 7. In the figure, the modeled salinity concentration (in broken line) is compared with observed salinity data (in solid black line) at Station V. Now, the salinity concentration for 1996 reproduced very well. For 1997 and 1998, the peaks were not reached and the salinity concentration in the last few months of the years was underestimated. The salinity concentration for 1999 was reproduced reasonably well.

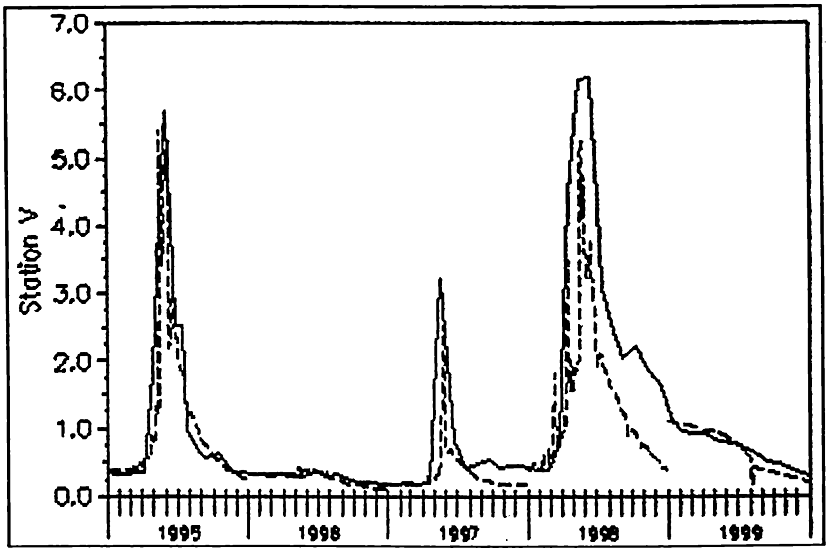

Figure 7. Time series of simulated (broken line) and observed (solid line) salinity concentration at Station V with new initial values

In general, the simulated salinity from 1995 until 1999 is comparable with the observed values. The results give a better agreement in terms of observed and simulated salinity concentration when the initial values used in the simulation are based on actual data. Since the salinity concentrations are reproduced well by the model, the advective transport (by Delft3D-FLOW) and dispersion through the Pasig River is assumed to be described correctly by the model.

4.2 Dissolved Oxygen

The simulated dissolved oxygen (solid line) compared with observed dissolved oxygen values (noline x) at Station V and I are shown in Figure 8. Relatively little variation in the observed dissolved oxygen concentration can be seen, and agreement between model and observed values is good. Simulated dissolved oxygen concentration at other monitoring stations on the lake also exhibit the same comparison with the observed values.

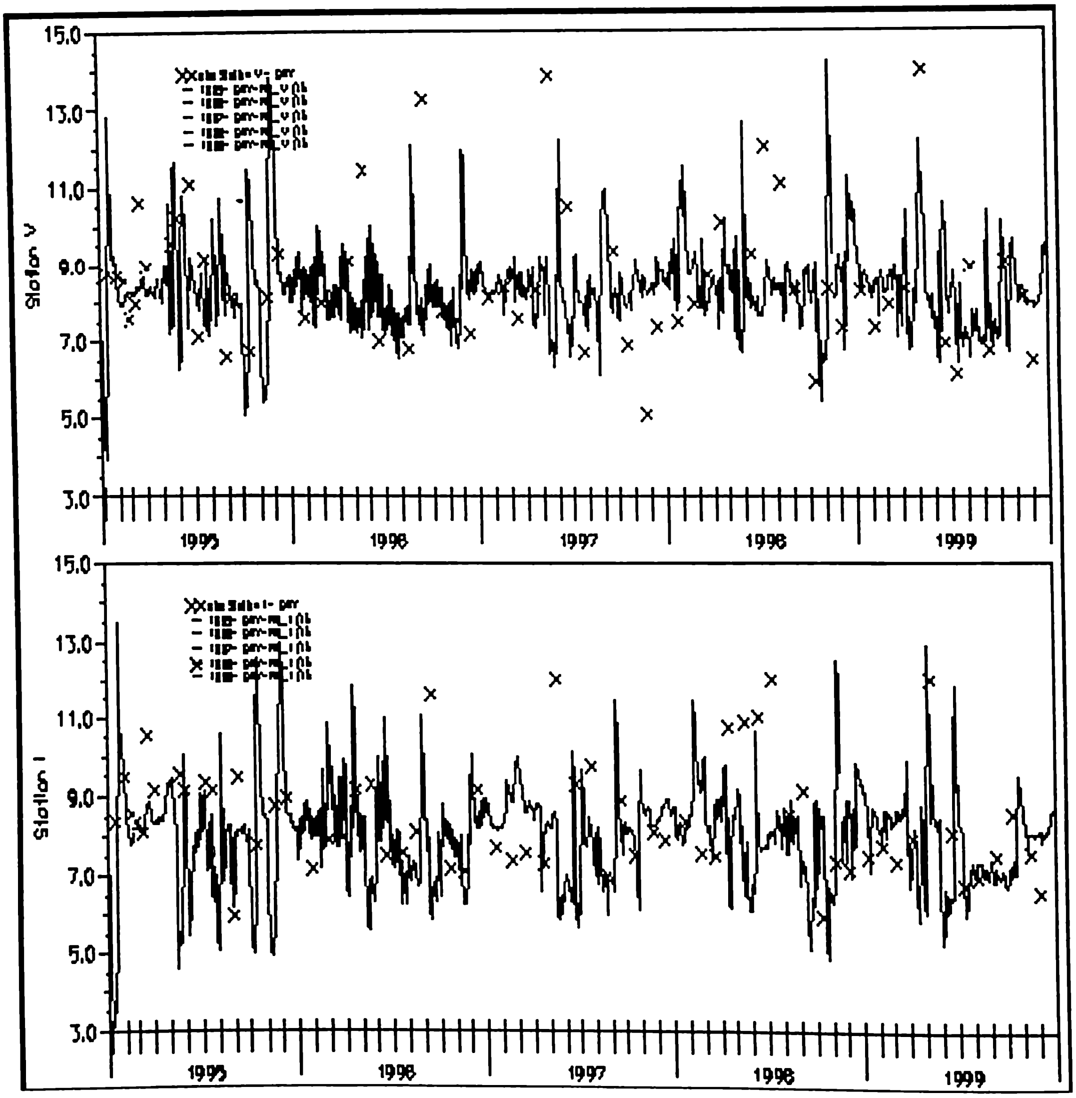

Figure 8. Time series of simulated (solid line) and observed (no line x) dissolved oxygen concentration (mg/L) at Station I (below) and V (above)

The range of natural variability in the lake oxygen concentrations is reproduced reasonably well by the model. The exact timing of the high and low concentrations is not reproduced. Partly this is caused by the daily variations of oxygen concentrations in the field that are compared to daily averaged concentrations in the model. Further, this may be caused by the mixing in the lake driven by unrealistic wind forcing. In a shallow lake like Laguna de Bay, wind speed is the main contributor to the reaeration rate. As shown in Figure 9, the variability of wind speed during the period of 1995-1999 is also similar to the variability of simulated dissolved oxygen concentration in the lake. The simulated dissolved oxygen concentration can still be improved if lake-based wind data becomes available or by establishing a wind model for Laguna de Bay. Also due to the shallowness of the Laguna, the dissolved oxygen concentration is close to saturation. Note that none of the monitoring locations is close to a major river discharge.

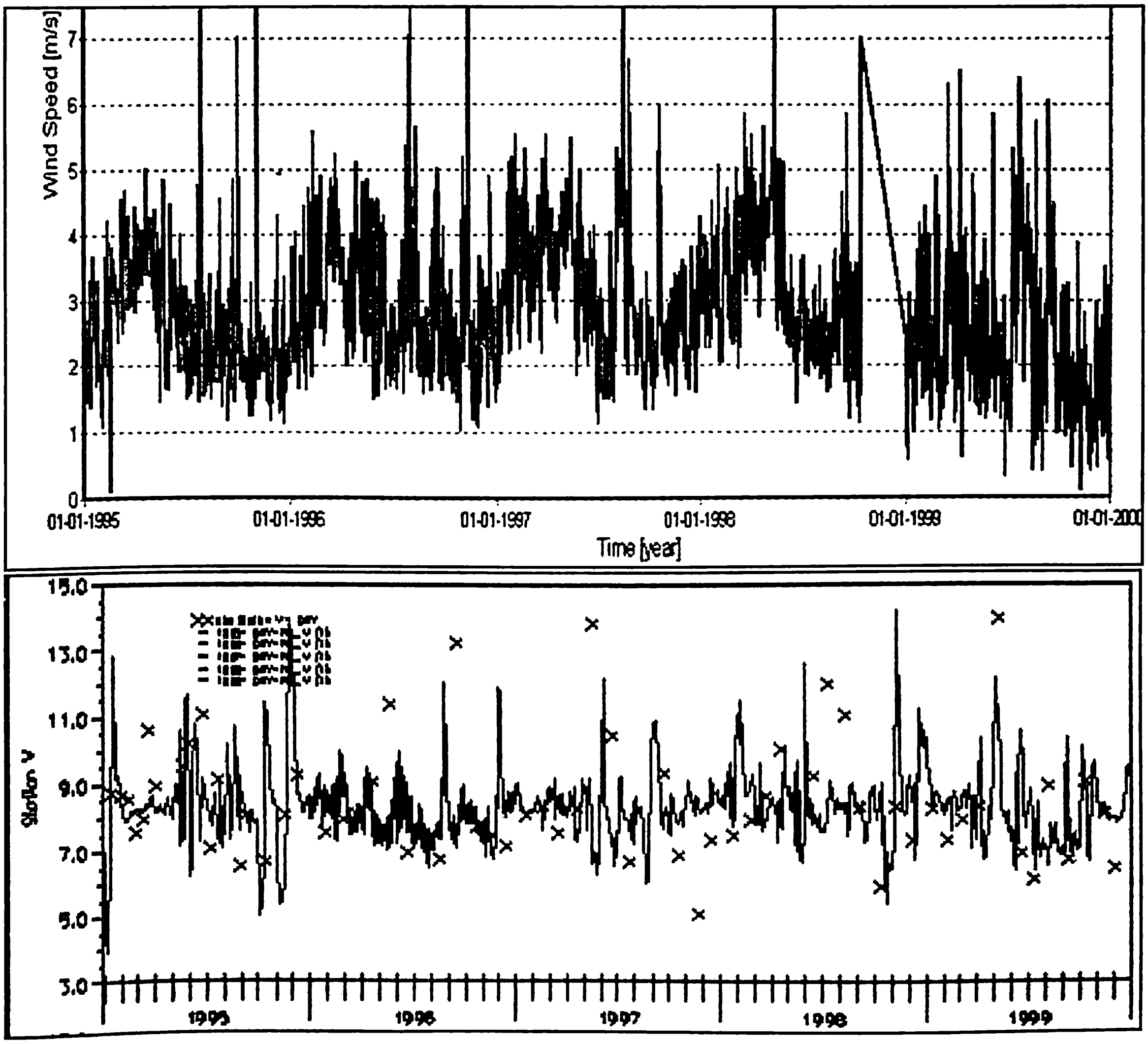

Figure 9. (Above) Time series of daily wind speed from NAIA station, m/s;
(Below) Time series of simulated (solid line) and observed (no line x)
DO (mg/L) at Station V for the period 1995-1999

4.3 Biochemical Oxygen Demand

The comparison of model results for BOD5 (no line x) with the observed BOD5 values (solid line) at Station I, V and VIII is shown in Figure 10. In general, the comparison of simulated BOD5 concentration with the observed values is reproduced reasonably well but some of the peaks were not reproduced.

It is assumed that all organic material (detritus carbon) is subjected to degradation in the lake. Even in the waste load input, the BOD generated by waste load model is converted into detritus carbon as organic loading into the lake. In the initial calibration runs, the simulated BOD5 concentration was overestimated compared to the observed values. So the rate of mineralization or decay of detritus carbon (RcDetC) was adjusted progressively in the model and after having satisfactory result, it was also validated in the succeeding years. In Figure 10, the agreement between observed values and simulated BOD5 concentration is relatively good. The simulated BOD5 levels at the monitoring stations are within the magnitude of the observed values. Some of the high and the low observed values were not reproduced which maybe caused by the yearly constant organic loading from the sub-basins. Despite of the high organic load into the system, they do not influence much on the simulated BOD5 concentration at stations away from the discharge points. The change in the simulated BOD5 concentration at the monitoring stations is sensitive to the mineralization of detritus carbon in the lake which also comprise of phytoplankton biomass.

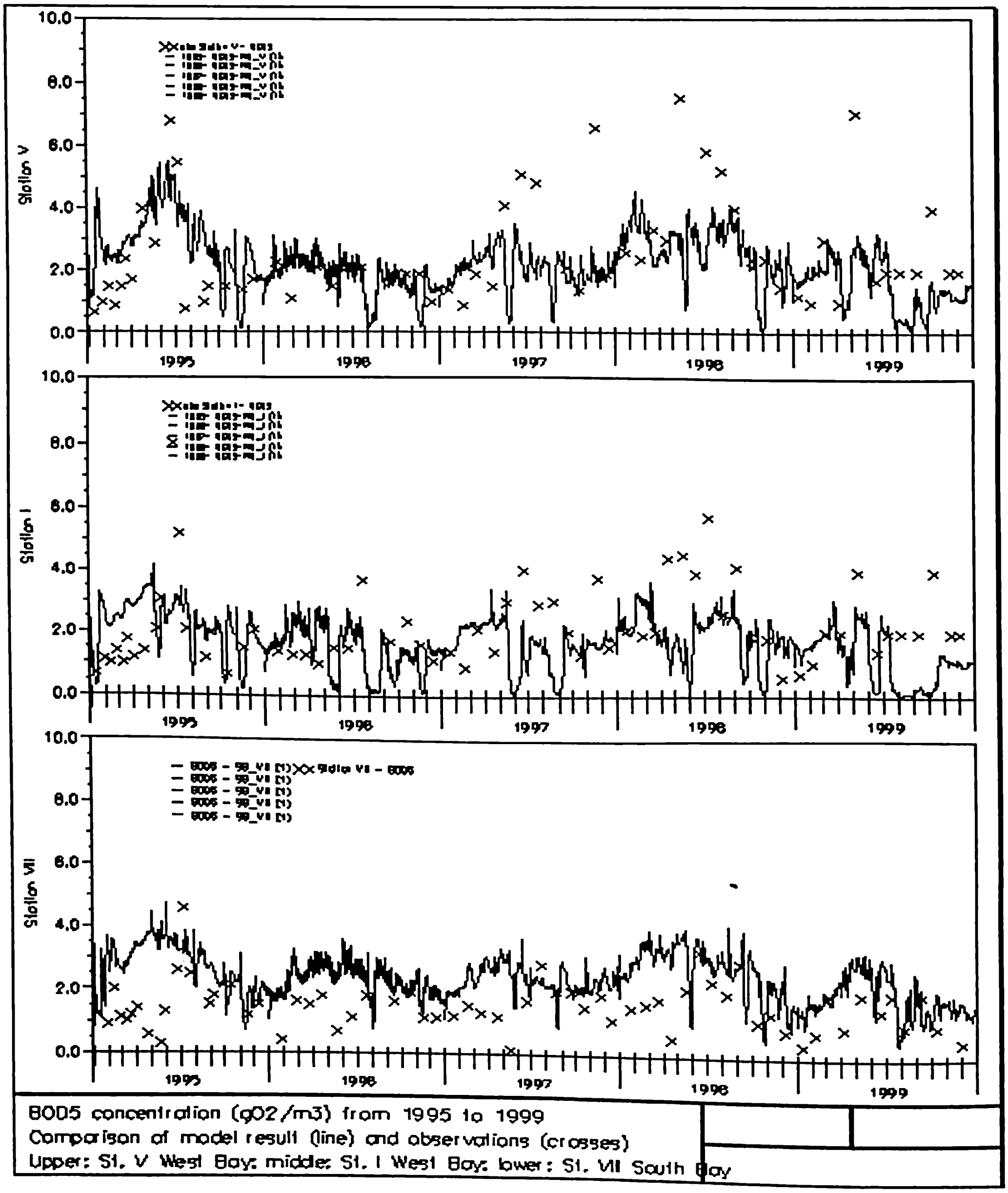

Figure 10. Time series of simulated (solid line) and observed (no line x) BOD concentration at Station I (below), V (above) and VIII (below)

5. CONCLUSIONS AND RECOMMENDATIONS

The water quality modeling was able to simulate the water quality processes and steering condition in Laguna de Bay where the trends in salinity, dissolved oxygen and BOD were reproduced satisfactorily. Laguna de Bay shows a much more dynamic behavior than in the water quality model based on the comparison with water quality monitored data.

Environmental assessment of Laguna de Bay using water quality modeling is useful in providing decision makers the impacts and benefits of likely future scenarios but the model result should only be considered over a one year period because it can not predict the exact concentration at specific location and time. The Laguna de Bay water quality model could be used to confirm some hypothesis on the lake's behavior as well as provide recommendations on the proper siting and schedule of water quality sampling on the lake.

The water quality modeling of Laguna de Bay can be still improved by resolving some uncertainties due to the lack of lake-based wind data, constant waste load and irregular sampling time on Laguna de Bay. Updating the meteorological inputs to the water quality model by establishing wind monitoring stations on the lake can provide the model more realistic input data on the major processes within the model such as transport of substances. Due to the shallowness of the lake, the impact of wind forcing is important on the lake water quality processes and it is recommended to develop a wind model that will simulates the wind speed and direction over the lake to provide the water quality model spatially varying wind forcing inputs.

In-depth water quality data analysis must be carried out to fully resolve the uncertainties in the model regarding trends and correlation of water quality parameters. As most of the monitoring stations on the lake are located off-shore, more stations should be added along the highly industrialized and congested shore of Laguna de Bay and as well as increase the frequency of sampling until the relationship of near-shore activities and lake pollution is established.

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