ASSESSMENT OF NUTRIENTS AND DISSOLVED OXYGEN IN A RIVER SYSTEM IN BANGLADESH USING A WATER QUALITY MODEL

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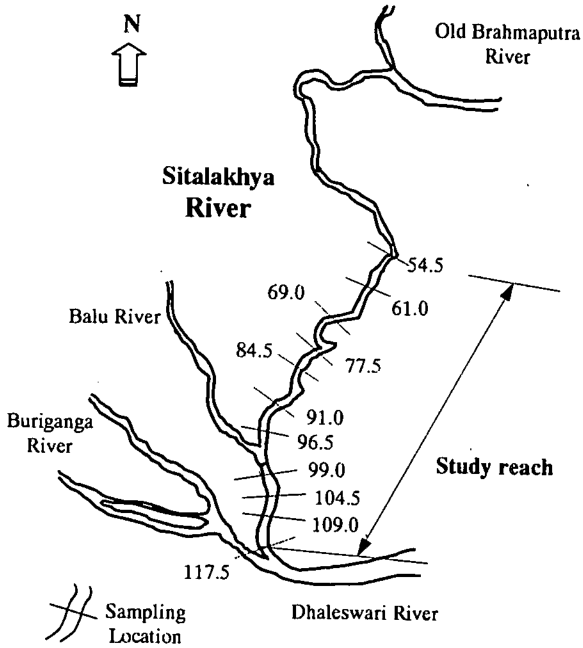
A comprehensive field monitoring and laboratory measurement of water quality of a river in Bangladesh was undertaken from January to April in 1995 and 1996. Subsequently, 1-D water quality model was developed, calibrated and verified with the collected data to quantify the state of pollution and the assimilative capacity of the river during the low flow period. The study indicates that the DO condition of the river water remains above the critical level of 4.0 mg/L, supporting the survival of aquatic life including fish. The river still has significant assimilative capacity and can assimilate the waste load from future new industrial establishment without violating the DO standard.

Key Words: nutrients transport, dissolved oxygen, assimilation capacity, water quality model, model application and projection.

1. INTRODUCTION

Water quality modeling is a reliable and economic method of assessing pollution distribution in surface water and offers an integrated and sound understanding of the cause effect relationships operative in the system. Much of the works and advancements have been done in this field in the past two decades. However, a very few works have been carried out in this regard in Bangladesh. Most of the major industrial and urban establishments in Bangladesh are located along the banks of the rivers. In the recent years, with the increased of population, industrial and agricultural activities, the pollutant loading to the surface waters has increased significantly. At present, there are no effective regulatory rules and legislation in Bangladesh to control wastewater loading from municipalities and industries and most of the industrial and municipal wastewaters are discharging to the nearby river without treatment. In dry season (from December to April), the effect of natural dilution is tremendously reduced due to the decline in river flow. Also the tropical climate is favorable for the rapid stabilization of wastes through biological process. The reaeration characteristics becomes very low due to the stagnant of river water and several pollution symptoms including eutrophication, fish killing and lowering of dissolved oxygen below the critical level (4.0 mg/L) were observed in the low flow (dry) period of the river water.

The Sitalakhya, one of a major river in Bangladesh passing through the industrial and urban zones near Dhaka City (**Fig.1**), is an important source of surface water. The government of Bangladesh is implementing a project called Saidabad Surface Water Treatment Plant to supply 60% of total water demand of Dhaka City from this river water. The capacity of the plant will be 22,00,00,000 Liters/day and is expected to complete by the year 2001. But the water quality of the river is deteriorating day by day. In the recent years, frequent episodes of fish kills and death of other aquatic lives were observed in the lower reach of the river[3),5)]. There are two ammonia fertilizer factories, one paper and pulps industry, dozens of textiles and jute mills, one pharmaceutical industry and several mediums to big urban establishments situated along the reach. The



Wastewater Loading Sources

Chainage (km)	Sources
54.50	Ghorashal and Polash Urea Fertilizer Factories
69.00	Kaligang Town
87.75	Rupganj Industrial Area
96.50	Tarabo Industrial Area
99.00	Balu River
101.75	Bangladesh Paper Mill
106.75	Kanchpur Industrial Area
109.00	Goodnayel Industrial Area
113.25	Narayangang Town

Fig.1 The River Sitalakhya, study reach, sampling and wastewater loading source locations.

effluents from these industries are directly discharged into the river without treatment. A major portion of urban runoff and domestic sewage from the eastern part of Dhaka City are also discharged to this river by its tributary, the Balu river. It was reported that the DO during the dry period has fallen below the critical level, which may cause the death of fishes[4),5),8)]. To prevent the river water from further pollution, the Ministry of Forest and Environment, Bangladesh has decided not to give permission to setup new industry on the bank of certain rivers including the Sitalakhya River (The Daily Ittefaq, March, 1993). But, the site is very convenient and prospective for new industrial establishment, since the location is very close to Dhaka City and has good waterways to carry raw and finished products. This type of proposal may go against our national interest of industrial development, if not based on the proper investigation of the pollution assimilative capacity of the river.

Due to concerns over accelerated pollution of the river water and since the site is very prospective for industrial development, a research program was undertaken, which included: (1) a comprehensive field and laboratory monitoring and measurement program to collect the water quality of the river Sitalakhya during the low flow period from January to April in 1995 and 1996 (two year); (2) to collect information and data of wastewater loading from industries and municipalities to the river and environmental data (solar radiation, wind speed, photo period etc) and (3) to develop a water quality model to give details insight of phytoplankton dynamics and nutrients kinetics and dissolved oxygen into the water column. The water quality model was calibrated and verified with the collected data. The model was used to assess the extent of pollution and the assimilative capacity of the river. Model projection was made to quantify the impact of new industrial setup on the riverbank on water quality of the river especially on dissolved oxygen (DO), which was one of the key issues of this study. This paper presents the results of both measurement and modeling study of the water quality of the river Sitalakhya in Bangladesh.

2. MODELING APPROACH

The 1-D governing transport equation describing the conservation of mass and momentum of incompressible fluid for the layer averaged concentration of each state variable subject to first order decay in each segment can be written as[18)]:

$$\frac{\partial C}{\partial t} = -\frac{1}{A}\frac{\partial (QC)}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(E_L A \frac{\partial C}{\partial x}\right) - KC + \sum W_l \quad (1)$$

where, C = the mean concentration of a constituent (M/L^3); E_L = the longitudinal dispersion coefficient (L^2/T); A = the cross sectional area of the channel (L^2); Q = the flow rate (L^3/T); W_l = the external

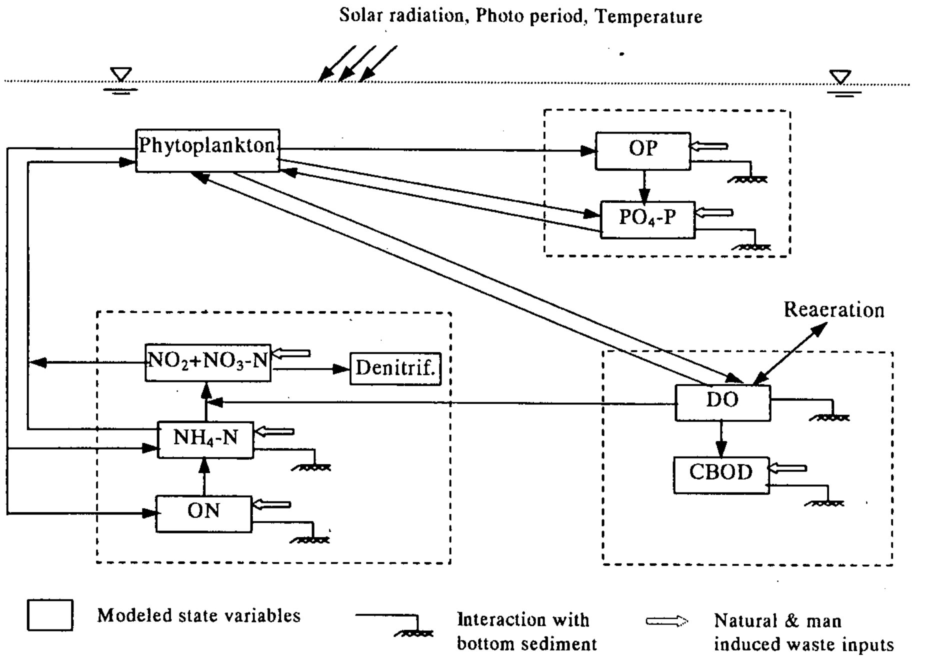


Fig.2 Schematic diagram of the model showing principal kinetic interactions.

loading rates or sinks (M/L^3T); K = the kinetic transformation rate (T^{-1}) and x, t = the spatial and temporal coordinates.

For the development of the water quality model for the river system, a generalized modeling framework WASP (Water Quality Analysis Simulation Program) developed by the USEPA, was used. WASP can simulate the advective-dispersive transport of the water quality parameters using the hydrodynamic and boundary condition of the system, but cannot simulate the kinetic interaction process within a water body. Therefore, a kinetics sub-module was coded in FORTRAN77 within WASP to simulate the kinetic transformation processes of the system variables within the water column. The finite difference or box model approach was used in solving the governing mass transport equations for each state variable. The model incorporates 8 state variables under four interacting systems or cycles such as (i) phytoplankton (ii) phosphorus, (iii) nitrogen and (iv) DO as shown in **Fig.2.** Phytoplankton dynamics and nutrients kinetics are based on well-accepted framework[1),6),7),11),12),18)]. Typical values for the kinetics coefficients and their temperature corrections are adopted from the literature[1),6),7),11)18)].

Algal biomass in the model is represented as chlorophyll-a, since chlorophyll is directly related to biomass and productivity is more closely related to the chlorophyll-a content of algal cell[16)]. Michaelis-Menten relations for algal growth and nutrient uptake are adopted. The principal kinetics involve the growth, death and settling of phytoplankton and grazing by zooplankton. The growth and proliferation of phytoplankton is a result of utilization and conversion of inorganic nutrients into organic plant material through photosynthesis. The growth rate, μ_P depends on three principal components[7),12),18)]: temperature, solar radiation and nutrients and their effect are assumed to be multiplicative, i.e., $\mu_P=g(T).g(I).g(N)$. The decay of phytoplankton is mostly the combination of death and endogenous respiration rate. The temperature limiting function is expressed as[18)]

$$g(T) = \mu_{max}\theta^{T-20} \tag{2}$$

where, μ_{max} = the maximum growth rate of phytoplankton under optimal light and nutrient conditions at 20°C, θ = the temperature correction coefficient and T = water temperature in °C.

The light limitation function of Steele and Baird[18)] is used in the model. The depth-averaged light limitation function $g(I)$ is expressed as

$$g(I) = \frac{2.718f}{K_e H}\left[\exp(-\alpha_1) - \exp(-\alpha_0)\right] \tag{3}$$

in which, $\alpha_1 = I_a/I_s \exp(-K_eH)$, $\alpha_0 = I_a/I_s$, $I_a = I_T/f$, I_T = the total daily solar radiation, I_s = the saturating light intensity, f = the photo period (fraction of a day when sunlight is available), H = the segment water depth and K_e = the light extinction coefficient. The light extinction coefficient K_e is determined from the observed secchi depth Zs. The nutrient limitation is calculated by Michaelis-Menten type expression given as[18)]

$$g(N) = \min\left\{\frac{DIN}{k_{mN} + DIN}; \frac{DIP}{k_{mP} + DIP}\right\} \quad (4)$$

in which, DIN = the dissolved inorganic (ammonia plus nitrate) nitrogen concentration, DIP = the dissolved inorganic phosphorus (orthophosphate) concentration, k_{mN} and k_{mP} = Michaelis constants for nitrogen and phosphorus uptake by algae, respectively.

Dissolved inorganic phosphorus (PO_4-P) is utilized by phytoplankton for growth. PO_4-P also interacts with particulate inorganic phosphorus via a sorption desorption mechanisms. A fraction of the phosphorus is released in the dissolved inorganic form during phytoplankton respiration and death and is readily available for algal uptake. The remaining fraction (f_{OP}) is released in the organic form. Organic phosphorus is converted to dissolved inorganic form at a time dependent rate through the process of mineralization. Saturating recycle expressions[1)] are employed for the mineralization of organic phosphorus to inorganic phosphorus (k_{23}). PO_4-P is also divided into dissolved and sorbed concentration by a fraction f_{DIP} and its dissolved phase is available for phytoplankton uptake. A partition coefficient K_{PIP} is employed and f_{DIP} is estimated following the Ambrose *et al.*'s[1)] analysis.

Ammonia and nitrate (inorganic) nitrogen are used for the growth of phytoplankton and an ammonia preference factor, p_{NH3} for algal uptake of inorganic nitrogen is employed in the model for physiological reasons[1)], where

$$p_{NH3} = \frac{N_1}{k_{mN} + N_1}.\frac{N_2}{k_{mN} + N_2} + \frac{N_1}{N_1 + N_2}.\frac{k_{mN}}{k_{mN} + N_2} \quad (5)$$

in which, N_1 = NH_4-N concentration, N_2 = NO_2+NO_3-N concentration, and k_{mN} = the half saturation constant in the nitrogen limitation function. During algal respiration and death, a fraction of the cellular nitrogen is returned to the inorganic pool in the form of ammonia nitrogen and the remaining fraction (f_{ON}) is recycled to the organic nitrogen pool. The particulate fraction of organic nitrogen is settled out, leading to source of organic nitrogen in benthic layer. Saturating recycle expressions[1)] are employed for the hydrolysis and bacterial decomposition of organic nitrogen to ammonia (k_{45}). The nitrification (k_{56}) of NH_4-N, the denitrification (k_{60}) of NO_3-N and the deoxygenation rate (k_d) of CBOD are all considered temperature and oxygen dependent as

$$k_{56} = k_{56,20}\,\theta_{56,20}^{T-20}\frac{DO}{K_{NIT} + DO} \quad (6)$$

$$k_{60} = k_{60,20}\,\theta_{60,20}^{T-20}\frac{K_{NO3}}{K_{NO3} + DO} \quad (7)$$

$$k_d = k_{d,20}\,\theta_{BOD}^{T-20}\frac{DO}{K_{BOD} + DO} \quad (8)$$

where, DO = the concentration of DO (mg/L), K_{NIT} and K_{BOD} = the half saturation DO constants for oxygen limitation of nitrification and of organic carbon stabilization (mg O_2/L), K_{NO3} = the half saturation constant for oxygen limitation of denitrification (mg O_2/L) and θ = the temperature coefficient for adjusting the rate at 20^0C.

Five state variables are participants in the DO balance: phytoplankton carbons, ammonia, nitrate, CBOD and DO. In a water body, the sources of DO are reaeration from the atmosphere and the photosynthetic oxygen production. The major sinks of DO are oxidation of both CBOD and NBOD waste input, sediment oxygen demand and use of oxygen for respiration by aquatic plants. Oxygen is transferred from the atmosphere to the water body through the process of reaeration. The reaeration flux is proportional to the oxygen deficit (C_s-C); the reaeration coefficient k_2 is calculated as a function of mean velocity and wind speed using O'Connor-Banks formula[18)] as

$$k_2 = \frac{3.9V^{0.5}}{H^{1.5}} + \frac{0.728W^{0.5} - 0.317W + 0.0372W^2}{H} \quad (9)$$

where, k_2 =the reaeration coefficient at 20^0C, V= the mean velocity (m/s), H= the mean depth (m) and W = the wind speed in m/s at 10m above the water surface. The dissolved oxygen saturation C_s for a particular water temperature is calculated by Elmore and Hayes' formula[6)]. The rate of oxygen production by algal biomass due to photosynthesis[11)] can be expressed as

$$a_{OP}.\mu_P.P = 0.00267(CCHL)\mu_P.P \quad (10)$$

in which $CCHL$ = the carbon to Chl-a ratio, P = the phytoplankton Chl-a in μg/L and the stoichiometric equivalent of oxygen/carbon is 2.67. Like other models which concerned with seasonal average behavior, the saturation light intensity I_s and carbon/Chl-a ratio are assumed to constant in the model and their values considered as 150 ly/day and 100 mg C/mg Chl-a respectively.

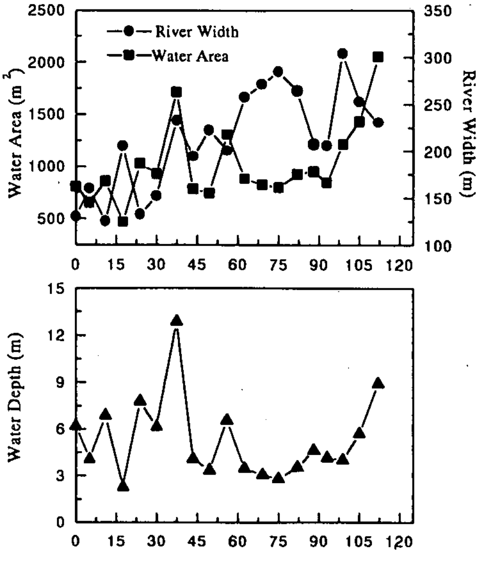


Fig.3 Channel morphometry of the river Sitalakhya.

3. HYDRAULIC CHARACTERISTICS OF THE RIVER

The model was applied to the lower reach of the river Sitalakhya (**Fig.1**) during the period of low flow condition. For streams and rivers, the principal morphometric factors of importance include depth, width and cross sectional area each as a function of distance and for a specific period of time. Variation of such parameters with river distance forms an important part of the water quality analysis. Hydraulic geometry parameters such as width, depth and cross-sectional area are measured every two years interval by BWDB (Bangladesh Water Development Board) at 19 locations along the river. These data was collected from BWDB and the average hydraulic geometric conditions during the modeling period are shown in **Fig.3**.

Discharge parameter of the river at a reference section at a specific time is needed to compute the concentrations of the water quality parameters at that time. Review of literature showed that water discharge pattern is characterized by a large variation of flow rate between the wet period (>1000 m^3/sec) and the dry period (0-150 m^3/sec). The low flow period usually starts in the month of December and extends to the end of April in Bangladesh. BWDB measures the daily river flow during the period of monsoon, but they do no take continuous measurements during the dry period and measure the river flow twice in a month. Analysis of the available data of the river flow indicated that there exists a small net downstream flow[3),4)] during the dry period. SWMC (Surface Water Modeling Center) has been using a hydrodynamic model MIKE11 to calculate and verify the hydrodynamics (flow, stage, etc.) of each river network every year (both dry and wet period) in Bangladesh[17)]. This model was used in this study to the Sitalakhya river network to simulate river flow and stage data during the dry period in 1995 and 1996 due to want of continuous river flow data. The result of the hydrodynamic model was also verified using measured discharge and stage data of the river of BWDB. The results of the hydrodynamic model (flow and stage) in each segment were stored in a file for subsequent use in the water quality model.

Table 1 Mean (Jan. to Apr.) concentrations (mg/L) of measured water quality parameters.

Water quality parameters	1995	1996
Chlorophyll a	0.0027	0.0039
NH_4-N	1.16	1.82
NO_2+NO_3-N	7.87	7.98
PO_4-P	0.125	0.089
DO	4.97	6.20
BOD_5	2.04	2.10
SS	23.85	19.50

4. WATER QUALITY MONITORING PROGRAM

Review of the existing water quality data[4),5),8),9),10)] revealed that the existing data were extremely inadequate for model development. No previous study was carried out to investigate the algal biomass in the river. Since the present study was carried out to give detail insight of the phytoplankton dynamics and dissolved oxygen, thus we conducted extensive field measurements, sampling and laboratory analyses during the period from January to April of the year 1995 and 1996. Eleven sampling locations (**Fig.1**) were routinely monitored once in every month for the seasonal water quality parameters.

In-situ measurements of dissolved oxygen (DO), temperature and secchi depths were conducted at each location spreaded over the cross sections. Field temperature and DO were measured at a depth of about 30 cm using a HACH portable dissolved oxygen meter. A 20-cm diameter secchi disc, painted with alternate black and white quadrants, was used to measure the secchi depth. The disc was lowered into the water until it just disappeared by naked eye and the depth was recorded to estimate the light extinction coefficient.

Table 2 Average wastewater loading rates (kg/day) from different sources into the river Sitalakhya.

Location	Types of wastewater	OP	PO_4-P	ON	NH_4-N	NO_3-N	BOD_5
Ghorashal	Industrial; Domestic	-	-	205	428	29	454
Kaliganj	Domestic	-	-	-	-	-	821
Rupganj	Industrial	-	-	94	94	-	1290
Tarabo	Industrial	-	-	-	13	-	1475
Balu river	Industrial; Domestic	45	97	363	726	788	6910
Paper & Pulp Mill	Industrial	-	136	-	-	-	4254
Kanchpur	Industrial	91	119	136	635	816	4264
Goodnayl	Industrial; Domestic	45	39	38	58	-	844
Narayanganj	Industrial; Domestic	70	67	134	654	907	2097

Samples for the laboratory analyses were collected from the main stream at three points (quarters and mid width) at a depth of about 30 cm below the water surface at each sampling location. Samples taken from the river were analyzed for Chlorophyll-a, suspended solids (SS), 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), organic nitrogen, ammonium (NH_4-N), nitrite plus nitrate nitrogen (NO_2+NO_3-N), organic phosphorus, and orthophosphate (PO_4-P) according to Standard Method[2]. The mean concentrations of the measured water quality parameters are given in **Table 1**. From the monthly monitoring data, no significant seasonal variation of the water quality parameters in the longitudinal direction was observed and a relatively steady state condition exists during the survey period (January to April).

5. LOADING RATES

The main pollution sources entering the river reach consist of one tributary, the Balu river carrying domestic sewage from the eastern part of Dhaka city, and from two fertilizer factories at Ghorashal, one paper and pulp industry, one pharmaceutical, dozens of textiles mills and from the several urban establishments. Data on non-point sources are not available. In the dry period, there is no significant runoff; therefore non-point pollution loading is not considered in the model. BKH and others[5] has conducted a survey to quantify pollution loading from these industries and their data was used in this study. Moreover, we also conducted survey during 1995 and 1996 to quantify wastewater loading from urban establishment along the riverbanks and through the Balu river. **Table 2** lists the average loading rates from different sources to the study reach.

The study area of 65 km was divided into 26 longitudinal segments and the segment geometry was determined using the channel morphometric (**Fig.3**) and the recorded water level data. Velocity of water in each segment was calculated using the simulated flow and flow area and was incorporated into the model to calculate advection transport and stream reaeration coefficient in each reach.

6. MODEL APPLICATION

Phytoplankton growth is a seasonal event and approximation of the phytoplankton-nutrient interactions on a seasonal steady-state basis are quite appropriate[13),14)] for rivers and streams under summer low flow condition. This approximation is particularly valid for the study area, since a relatively steady state condition is existed during the study period. In this study, the modeling approach aims to quantify the river water quality in a seasonal steady-state condition. In addition, steady state approximations have a modest data requirement and provide a significant amount of insight into eutrophication in the system to support decision making[14)]. The model was run time variably with seasonal model inputs (loading, solar radiation, photo-period, wind speed and water temperature) to quantify the water quality on a seasonal steady-state condition. Data of solar radiation, photo period and wind speed were collected from a nearby observation station from the Department of Meteorology, Dhaka for a period of five years and monthly averaged values were inputted into the model (**Fig.4**).

Data collected from the survey in 1995 (Jan. to Apr.) was used for model calibration. The values of the kinetic constants and coefficients were taken from the literature. **Table 3** shows the kinetic constants and coefficients that were adjusted to fit the simulation results with the observed data and their values that were finally adopted in the calibration. **Table 3** also shows the reported values of these coefficients in the literature. Results of the model calibration as compared with the observed data of phytoplankton Chl-a, BOD_5, DO, PO_4-P,

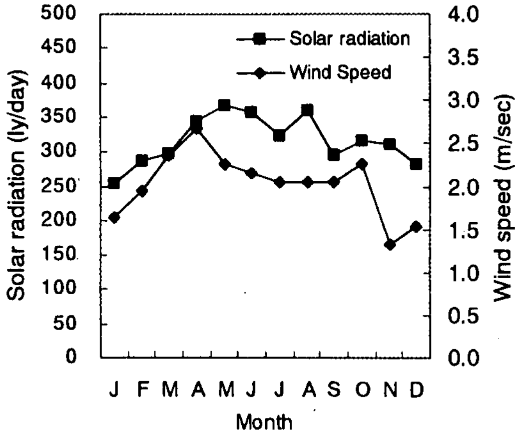


Fig. 4 Monthly averaged solar radiation and wind speed.

NH_4-N, NO_2+NO_3-N from 54.5 to 117.5 km is presented in **Fig.5.**

The predictive capability of the model was further tested for the observed data in 1996 (Jan. to Apr.), using the same values of the kinetic constants and coefficients as shown in **Table 3**. **Fig.6** shows the longitudinal concentration profiles of model verification. The model reasonably well simulated the system behavior of the water quality parameters and followed the trend of the field data.

The key parameters associated with the growth of phytoplankton are temperature, solar radiation and nutrients (N, P). In a tropical country like Bangladesh, temperature and solar radiation are always favorable enough to stimulate the growth of algae. The concentration of major nutrients (inorganic nitrogen and phosphorus) limits primary production in many aquatic environments. The concentration profiles for NH_4-N, NO_2+NO_3-N and PO_4-P (**Figs.5 and 6**) show no significant spatial variations. The lowest levels of NH_4-N and PO_4-P concentrations were about 1.25 mg/L and 0.085 mg/L, respectively. These concentrations are much higher than the Michaelis-Menten constants (0.005 mg/L for N and 0.001 mg/L for P) limiting the algal growth in the model. Therefore, nutrients are not the limiting factor controlling the algal growth in the reach. The algal growth in the river is not high, although the river water contains a significant amount of nutrients and the temperature and solar radiation was sufficient enough for the algal growth. High turbidity and lower light penetration (maximum secchi depth of 1.25m only) were observed in the river water. Phytoplankton growth in the river is highly suppressed due to the lower level of light penetration caused by high turbidity in the water column.

Most concentration profiles do not show much spatial variations in the longitudinal direction. River flows dominate the kinetics in the water column and becoming also a controlling factor for significant

Table 3 Kinetic constants and parameters used in the model.

Parameter	Description and range in literature	Value (and θ)
μ_{max}	Maximum algal growth rate (1-2.7 day-1) [1),6),7),18)]	2.4 (1.066)
k_{mN}	Michaelis constant for nitrogen uptake by algae (5-20 μg N/L) [6),7),18)]	5.0
k_{mP}	Michaelis constant for phosphorus uptake by algae (5-20 μg N/L) [6),7),18)]	1.0
k_{mPC}	Half saturation of phytoplankton limitation for phosphorus cycle (mg C/L) [1),6)]	1.0
K_{NIT}	Half saturation constant for oxygen limitation of nitrification (mg O_2/L) [1),6),18)]	2.0
K_{NO3}	Half saturation constant for oxygen limitation of denitrification (mg O_2/L) [1),6),18)]	0.10
K_{BOD}	Half saturation constant for CBOD oxygenation (mg O_2/L) [6),18)]	0.50
r_A	Endogenous respiration rate of algae (0.05-0.25 day^{-1}) [6),18)]	0.075
M_A	Non predatory phytoplankton death rate (0.003-0.17 day^{-1}) [6),18)]	0.020
C_g	Zooplankton grazing rate (0-1.0 L/ mg Zoopl C/day) [6),18)]	0.0
k_{23}	Mineralization of OP to PO_4-P (0.001-0.05 day^{-1}) [6),18)]	0.003 (1.045)
k_{45}	Mineralization of ON to NH_4-N (0.001-0.20 day^{-1}) [6),18)]	0.075 (1.045)
k_{56}	Nitrification rate of NH_4-N to NO_3 via NO_2-N (0.025-0.50 day^{-1}) [6),18)]	0.03 (1.085)
k_{60}	Denitrification rate (0.002-0.10 day^{-1}) [6),18)]	0.05 (1.058)
K_d	Deoxygenation rate of CBOD (0.10-0.50 day^{-1}) [6),18)]	0.13 (1.047)
BOD_{U5}	Ratio of ultimate to 5-day CBOD (1.46-1.85) [1),6),18)]	1.65
f_{Op}	Fraction of dead and respired phytoplankton recycled to OP	0.80
f_{ON}	Fraction of dead and respired phytoplankton recycled to ON	0.50
CCHL	Carbon to Chl-a ratio (50-100) [7),18)]	100
a_{PC}	Stoichiometric ratio of phosphorus to algal carbon (0.01-0.47 mg P/ mg C) [7),18)]	0.015
a_{NC}	Stoichiometric ratio of nitrogen to algal carbon (0.05-0.25 mg P/ mg C) [7),18)]	0.167
a_{OC}	Oxygen to carbon ratio (mg O_2 / mg C) [7),12),18)]	2.67
SOD	Sediment oxygen demand (gm/m^2-day)	0.10 - 0.30
SPO_4	Flux of inorganic phosphorus from bottom sediment (gm/m^2-day)	0.01-0.05
SDIN	Flux of inorganic nitrogen from bottom sediment (gm/m^2-day)	0.30-0.50

algal growth in the water column. The Sitalakhya River is a wide flowing river and because of its large width, the water becomes well mixed that caused the water quality parameters to be uniformly distributed in the longitudinal direction.

The important parameter that affecting the health and the capacity of water body to support a balanced aquatic habitat is DO. The assimilative capacity of a

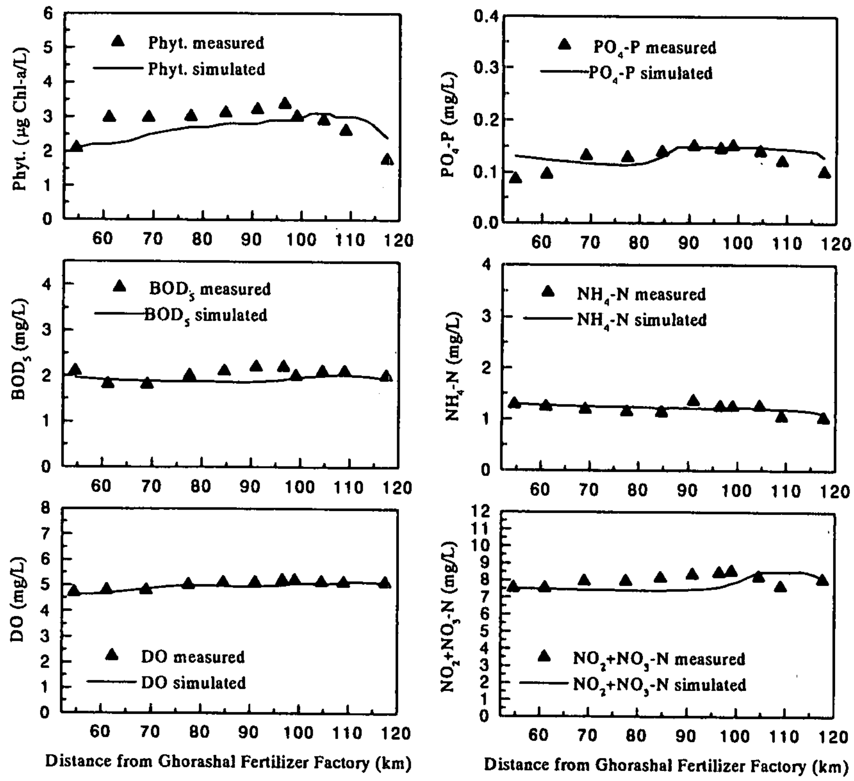


Fig.5 Calibration result of water quality parameter at steady state (January – April, 1995).

river, representing the amount of $CBOD_5$ that can be assimilated without excessively taxing ambient DO levels, is also of major concern. It was observed from the model results that average $CBOD_5$ concentration is about 2.0 mg/L throughout the reach and is almost uniformly distributed. The dissolved oxygen (DO) concentration would remain above the critical level of 4.0 mg/L, which is generally accepted as the threshold level for the survival of aquatic life including fishes. The most significant observation from field observation and modeling analysis is that, the DO concentrations are consistently above 4.0 mg/L. The DO concentration gradually increases in the downstream direction. In general, a significant assimilative capacity of the river exists during the dry period and the DO concentration is still good for the survival of fishes and other aquatic plants. However, under the present condition, NH_4-N concentration is very high (1.25 mg/L) and exceeds the fishing water standard of 0.025 mg/L[8] and the total nitrogen concentration exceeds 8.0 mg/L. Ammonia nitrogen exists in two states in natural waters: ammonium ion (NH_4^+) and un-ionized ammonia (NH_3). At sufficient high levels (0.01 to 0.10 mg/L), unionized form is toxic to fish and aquatic organisms and the fraction unionized is a function of water temperature and pH[7]. The observed pH level of the river water would remain within 7.5 for the maximum period of the year, but sometimes rises to a great extent above 8.5 in the low flow period[5),8),9]. At a water temperature of 25^0C, the fraction of unionized ammonia is about 1% at a pH of 7.5, but it is about 10% at pH of 8.5, which means that the concentration of unionized NH_3-N (about 125 μg/L) exceeds the threshold level of 100 μg NH_3-N/L[15]. It is, therefore, hypothesized that ammonia toxicity (presence of unionized free ammonia) is associated with the frequent kill of fishes in the river reach during the dry period. However, detailed field studies are needed to verify this hypothesis. Moreover, DO could be fall below the critical level for a certain period of a day due to its fluctuation and fish kill may be associated with this phenomena. Extensive hourly field DO data are needed to verify this phenomenon.

The primary production of phytoplankton is not high and the seasonal and spatial distribution of nitrogen, phosphorus and carbon in this river is not dominated by primary production. Rather, the seasonal and spatial distribution of these parameters is dominated by external loadings from industries and municipalities and released from bottom sediment. The major land use in the river watershed is agriculture and enormous amount of N and P rich

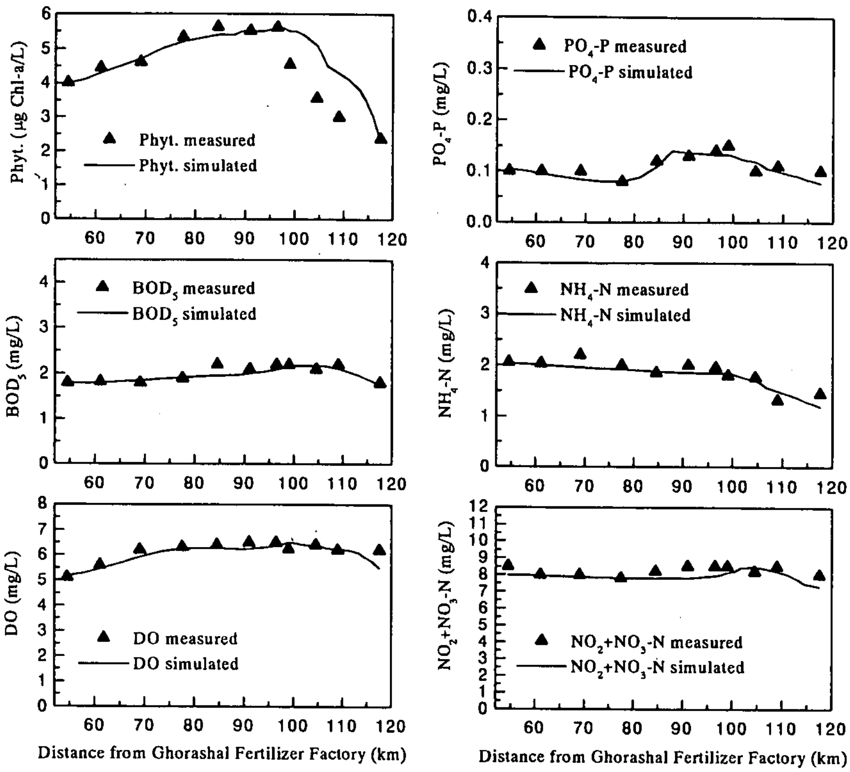


Fig.6 Verification result of water quality parameter at steady state (January – April, 1996).

fertilizers are applied to the land for agriculture. A huge quantity of applied N and P are washed out and reached to the river during monsoon. A significant part of the N and P inputted by surface runoff are retained into the bottom sediment and subsequently released during the summer dry flow period, which caused higher N and P as compared to BOD. This study shows that the mean released rate of SOD, DIP and DIN from the bottom sediment are 0.20, 0.03 and 0.40 (gm/m^2/day), respectively. These are equivalent to a loading rate of SOD of 2756 kg/day, DIP of 413.4 kg/day and DIN of 5512 kg/day for the 65 km long study reach with a mean bottom width of 212 m.

7. SENSITIVITY ANALYSIS

In the model, literature values for the kinetic constants and coefficients have been used due to limited site-specific data. An analysis was performed to identify the key parameters and coefficients that have greatest impact on model prediction of DO concentration. These were algal endogenous respiration and settling velocity, deoxygenation rate (k_d) of CBOD and SOD. Since the river water contains sufficient amount of nutrients and do not limit the algal growth and temperature and solar radiation were favorable enough for the algal growth, we assumed that the algal growth rate was remained at the maximum level of 2.4 day^{-1} during the study period. As a result, we did not performed sensitivity analysis of algal growth rate on DO.

One difficult problem associated with algal dynamic model is the evaluation of effective settling velocity of algal biomass from the water column to bottom sediment. No site-specific data was available and there exist uncertainty about settling velocity due to seasonal variation of river flow. Sensitivity analyses were conducted by varying the settling velocity from 1.5 cm/day to 30.48 cm/day and the endogenous respiration rate from 0.075 day^{-1} to 0.15 day^{-1}. The phytoplankton concentration declined from 3.1 µg/L to 2.4 µg/L and no significant influence on DO concentration profile was observed. The organic matter can exert a high oxygen demand and considerable spatial and temporal variation in SOD would occur. The effluent discharged from downstream industries especially from paper and pulp mill containing particulate organic matter can result in a wide variation in SOD. The model was calibrated and verified to have 0.10-0.20 gm/m^2-day of SOD. Sensitivity analysis was conducted to increase SOD two to five times of the model values and the results showed that DO concentration would remain above the critical level of 4.0 mg/L, even if the SOD increased five times of the model value. A substantial variation in the rate of deoxygenation coefficient (k_d) is observed in river due to variation in water temperature, river-flow and water depth. Concentration profile of DO is directly related to k_d and variation of DO profile was tested by varying value of k_d from 0.13 day^{-1} to 0.23 day^{-1}. The DO concentration profile remained above the critical level required for the survival of aquatic live in water. One conclusion can be drawn again from these observations is that; the river DO conditions are good enough to support the survival of fish and other aquatic life.

Government of Bangladesh in recent year has decided that no new industry will be permitted to setup along the bank of river Sitalakhya to prevent further pollution of this river water. Model projection was carried out to asses the effect of new industrial and urban establishment using the input load twice that of the present condition, and **Fig.7** shows the model result under the projected condition. The additional load will reduce the dissolved oxygen concentration in the river, but will not depress the DO level to below 4.0 mg/L anywhere in the river. This was due to the enormity of water volume and depth and the subsequent flushing caused by river flow. Although the available nutrient had increased, the change in phytoplankton concentration was insignificant. Thus, it is apparent that the high turbidity associated with lower light penetration controls the growth of algae in the system. The model results with respect to DO concentration indicate that the river can assimilate the waste loads from new industrial establishment, if the present flow conditions exist in the future. However, some water quality parameters like total nitrogen and SS would remain very high and cause a potential threat to the aquatic life. Therefore, some management and control of projected waste loadings and ensuring current river flow must be formulated to permit new industrial establishment and to support balance aquatic life and best uses of the river assimilative capacity.

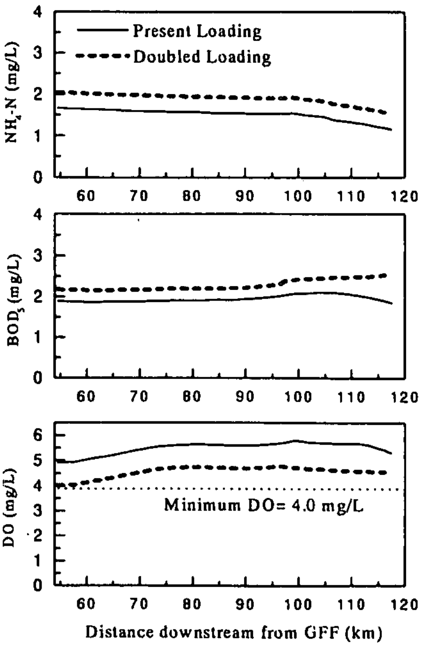


Fig.7 Model projection under two times of wastewater loading than that of the present condition.

8. CONCLUSIONS

A comprehensive field and laboratory monitoring and measurement and a water quality modeling study was conducted to quantify the state of pollution and the assimilative capacity of a river near Dhaka city in Bangladesh. The model was calibrated and verified for the observed water quality data during the period of low flow in 1995 and 1996 (January to April). The model performs satisfactorily for the simulation of the depth averaged water quality parameters being considered. Sensitivity of the model was analyzed to determine the effects of different key kinetic parameters on the spatial distribution of the water quality parameters especially on dissolve oxygen.

This study demonstrated that the algal growth is not high though the river water contains an abundance of nutrients and temperature and solar radiation is sufficient enough for algal growth. Lower light penetration resulting from high level of turbidity, limits the algal growth during low flow conditions. Most concentration profiles do not show significant spatial variations in the longitudinal direction. River flows dominate the kinetics in the water column and also becoming a controlling factor of algal growth. The dissolved oxygen concentration remains above the critical level of 4.0 mg/L during the dry period, thus the river DO condition would support the survival of aquatic life including fish. The river still has significant assimilative capacity and can assimilate the wastewater loads from new industrial establishment without violating the DO standard under present flow condition. However, the river water contains ammonia nitrogen much higher than fishing water standard and causes a potential threat to aquatic biota including fish. Thus, some management and control of waste loadings, especially reduction of ammonia loading from the fertilizer factories to the river must be undertaken to support balance aquatic life.

A steady-state condition is prevailed in the river during the dry low flow period and the model was calibrated and verified under steady-state condition. The present model cannot calculate the daily fluctuation of DO, although the DO fluctuation is important and DO may be fall below the critical level in some location of the river in some period of a day due to daily fluctuation. At present, we have no data of the daily fluctuation of DO during the dry period and further hourly field monitoring is needed to quantify the daily variation of DO and its possible impact on aquatic plants including fish.

In the present model, the sediment-water interaction process was not incorporated. Instead, we used site-specific flux of SOD and nutrients and adjusted during the process of model calibration. Coupling sediment-water interaction processes will increase its capability to better address the effects of nutrient and waste load control strategies and we are extending the model into 3-dimensional, coupling both digenetic sediment-water interaction process and hydrodynamic model. This present model is easy to apply and can be used in planning decisions as further industrial growth in the area is considered alongside water quality concerns.

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水質モデルを用いたバングラデシュの河川における栄養塩および溶存酸素の評価

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1995 年と 1996 年の 1 月から 4 月にかけて，バングラデシュの一河川を対象として水質に関する広範な野外モニタリングおよび室内分析を行った．さらに，一次元水質モデルを開発し，得られたデータを用いて校正と検証を行い，低水時における河川の汚染状況と環境容量を定量化した．その結果，河川水の DO は危険レベルである 4mg/L を上回り，魚類を含む水生生物の生存には問題のないことが明らかになった．また，河川は十分な環境容量を持ち，将来の産業立地による汚染物質の負荷に対しても DO の基準を維持できることが示された．