Journal of Civil Engineering (IEB), 35 (1) (2007) 59-70

Journal of Civil Engineering IEB

Effect of thermal effluent on water quality of Sitalakhya river

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Received 10 August 2005

Abstract

The Sitalakhya River receives thermal discharges from the Globeleq and Siddhirganj Power Plants and is the designated recipient of the additional thermal discharges from proposed power plants in the area. Thermal discharges produce thermal plumes of elevated temperature and greatly influence the major water quality parameters mainly through alteration of dissolved oxygen level, microbial activity and kinetic coefficients of reactions in the river. This study is aimed at investigating the effects of thermal discharges in the River Sitalakhya from the existing and proposed thermal power plants in the area. Water quality simulation of some major water quality parameters such as BOD, DO, ammonia, nitrate, phosphate was done for existing conditions of the river using the modeling framework of WASP of the USEPA and a fair agreement between simulated and measured values was found. Sensitivity analysis was performed to assess the impact of excess temperature caused by the thermal effluents from the power plants. The results of the analysis showed a small decrease in BOD and ammonia, a small increase in nitrate and a significant decrease in DO (about 0.5 mg/L) due to excess temperature. The model simulated the already deteriorated condition of the river very well and predicted further deterioration of water quality (especially DO) due to the effect of thermal effluents in future.

Keywords: Thermal effluent, water quality, Sitalakhya river

1. Introduction

The Sitalakhya River having a length of 113 km originates from the Old Brahmaputra and falls into the river Meghna. Some of the major industries of Bangladesh are located on the banks of the river and the river assimilates a major portion of domestic and industrial wastes of metropolitan Dhaka. The water quality of this river is of particular importance not only for ecological and commercial reasons but also for concerns regarding safe drinking water supply as the largest surface water treatment plant in

Bangladesh located at Saidabad draws water from it. Previous studies on river water quality by the Department of Environment, Institute of Water Modeling (IWM, formerly SWMC) and Bangladesh University of Engineering and Technology (BUET) suggest that the water quality of this river is gradually deteriorating in certain portions of the reach (IWM and BUET, 2004). Karim (1996) developed a model for the Sitalakhya River using the framework of Water Quality Simulation Program (WASP, documented in Di Toro et al., 1983 and Wool et al.) and applied it to the lower reach of this river. The model results indicated that the river contained an abundance of nutrients and had the potential of algal growth. Although the Dissolved Oxygen (DO) remained above critical levels (4 mg/L), the ammonia and the BOD levels were at critical state. Recent studies showed DO values below 4 mg/L at the lower reach of the river with high ammonia concentrations. Besides various organic and chemical wastes from various point and non-point sources, the river receives thermal effluents from Siddhirganj and CDC Globeleq Power Plants located approximately 6.7 km downstream from the Sitalakhya-Balu confluence. Particularly, since the commencement of operation of the Siddhirganj Thermal Power Plant in January 2005, there has been observable increase in temperature of water. There is a possibility that the already deteriorated conditions can be further aggravated due to the introduction of thermal effluents from the power plants. This study aims at investigating the effect of thermal effluents on different water quality parameters namely DO, BOD, Ammonia, Nitrate and Phosphate for the dry season. The water quality model WASP has been used to simulate various water quality parameters for the Sitalakhya River.

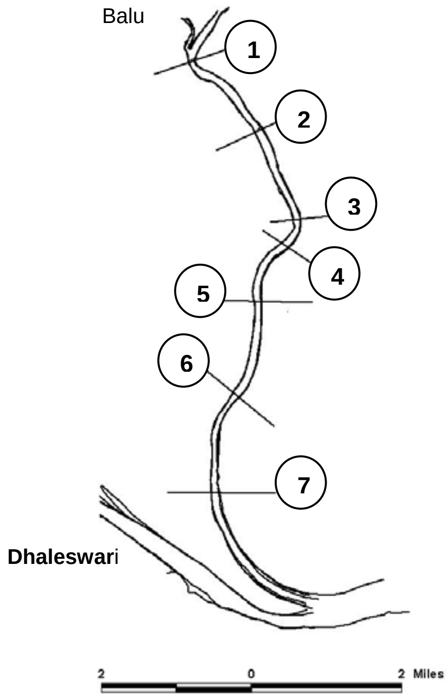
2. Water quality data and environmental parameters

The data available from previous studies are inadequate for spatial analysis of the water quality model. Thus, an extensive field measurement and sampling program followed by laboratory analyses were conducted during the period of February to March, 2005. The planning of the monitoring program was guided by the requirement of the water quality model.

The study reach was a 15 km segment of the Sitalakhya River starting from the Sitalakhya-Balu confluence towards downstream. Seven stations were selected for collection of water samples (Fig. 1a). Laboratory analysis of the water samples was conducted to determine BOD_5 Ammonia, Nitrate, Orthophosphate, and Phytoplankton Chlorophyll-A concentrations. Key environmental parameters associated with the water quality model include total daily solar radiation, fraction of daylight (photoperiod), wind speed, water temperature and air temperature. Water temperature data were collected from field measurements during sampling. The rest of the parameters were collected from Bangladesh Meteorological Department. These environmental parameters were used in the model on a temporal basis. The value of light extinction coefficient in the water column was taken from the previous study on Sitalakhya River by Karim (1996) and it was assumed constant throughout the simulation period. The summary of the average point-source waste loading adopted in the model is based on both Karim (1996) and IWM and BUET (2004). The locations of these wastewater point sources are shown in Fig. 1b.

3. Water quality model segmentation

For water quality modeling, the study reach was divided into 14 longitudinal segments of various lengths. The 14 segment configuration of the study area and major point source discharges are shown in Fig. 1(b). As per the basic concept of the one dimensional finite segment approximation, it is assumed that the water quality parameters are well mixed within a river segment, thus allowing computation of the water quality parameters in the longitudinal directions only. The geometry (volume) of the 14 segments was determined from the channel morphological data of the river.



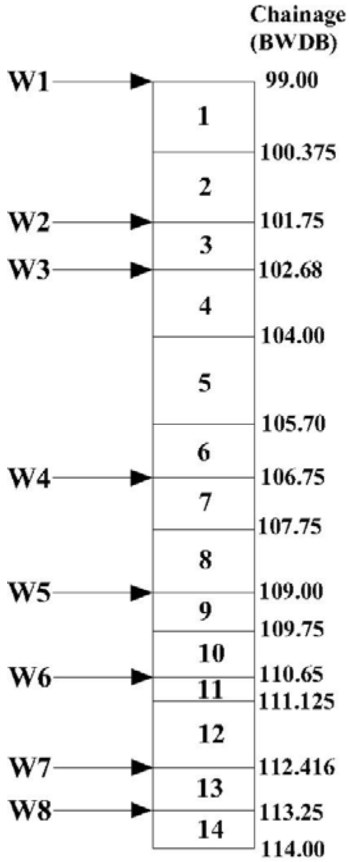


Fig. 1. (a) Sampling locations in the Sitalakhya river; (b) Water quality model segmentation showing locations of the point source waste inputs

4. Setup of model parameters

Six state variables were addressed in the water quality model development. These included organic phosphorous, organic nitrogen, ammonia nitrogen, nitrate nitrogen, BOD_5 and DO. The kinetic processes included organic nitrogen hydrolysis, nitrification, mineralization of organic phosphorous, settling particulate nutrients, sediment release of nutrients, CBOD decay, deoxygenation, reaeration and sediment oxygen demand. In this study, the modeling approach aims to quantify the water quality condition in a seasonal steady state condition. Seasonal steady-state models are used in certain situations, recognizing that hour to hour or day to day variation is not necessary to understand the significance of water quality parameters. All the inputs relevant to some water quality parameters cannot be specified on a fine time scale and the parameters do not significantly vary from hour to hour. Thus steady state calculations are appropriate when seasonal water quality changes are more important than diurnal fluctuations. This approximation is particularly valid for a water system under low, steady flow condition. The 7-day average flow has been used as input river flow for the steady state analysis in this study. The average flow of all the stations from the hydrodynamic simulation was used as input for each of the segment for maintaining the continuity of flow. A time averaged (i.e. constant) effluent loading from the point sources has been assumed because of lack of data. The time varying wind velocity, air temperature and water temperature were used as input within the specific time period. The model was calibrated with the water quality conditions of the river Sitalakhya in February, 2005 and verified with those of the river in March, 2005. The water quality model was run with a time step of 0.02 day to maintain numerical stability.

5. Initial and boundary conditions

The concentrations of different system variables at various stations along the river at the beginning of the simulation were used as initial conditions. However, in most cases, measurements of concentrations are unavailable and reasonable assumptions had to be made in order to initialize the computation. The usual approach is to select initial concentrations arbitrarily because their influence has little effect on the final results of a steady state condition. A steady state is practically reached after a time equal to the time required for a load introduced at the upstream point of the stream to arrive at the downstream end. Therefore, the steady state concentration profiles are independent of the initial concentrations. In this study the simulation was started at February 1, 2005 and all the initial conditions were set to zero at that particular time. Time variable boundary conditions were provided for the time steps February 1, February 20 and March 20 for this simulation. Since the profile measurements and analysis of water quality data were gathered for February 20 and March 20 only, the boundary conditions of February 1 were chosen within a reasonable range. Since the simulation of February 20 and onwards would have been free from the effect of initial conditions, the calibration and verification could be performed reliably from the simulation of those periods.

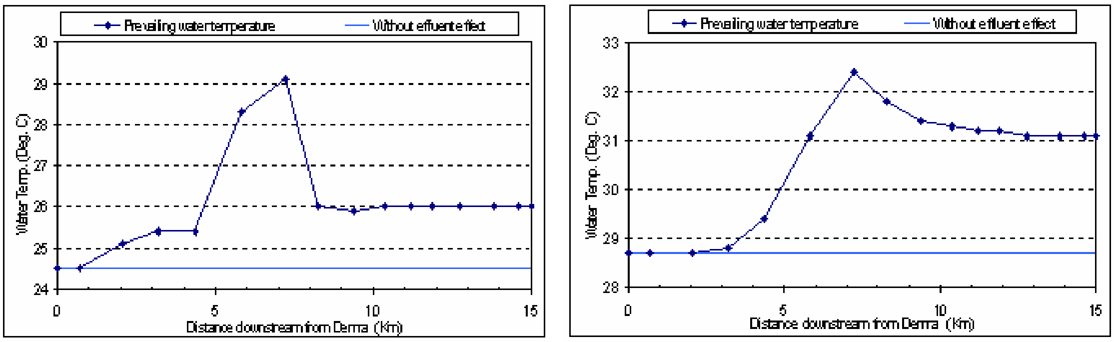
Since the upstream boundary of the study area is at chainage 99.0 km and the downstream boundary is at chainage 114.0 km, the water quality parameters measured at those stations were used as upstream and downstream boundary concentrations, respectively. Table 1 shows the boundary conditions for February 20 and March 20. Based on limited measurements, organic nitrogen and organic phosphorus concentrations are assumed to be 0.56 mg/L and 1.2 mg/L, respectively for February 20. A BOD flux of 2.5 gm/m^2-day was also used to account for the scattered or distributed sources of loading. Besides, a Sediment Oxygen Demand (SOD) of 0.2 gm/m^2-day and a dispersion coefficient of 300m^2/sec was used in the study conducted by Karim (1996).

Table 1
Boundary Concentrations of Water Quality Parameters

Water quality constituents	Upstream boundary		Downstream boundary	
	February 05	March 05	February 05	March 05
Orthophosphate, mg/L	2.03	2.73	1.19	3.18
Ammonia-Nitrogen, mg/L	8.35	7.40	3.75	1.75
Nitrate- Nitrogen, mg/L	0.50	0.50	1.60	2.00
BOD_5, mg/L	7.20	7.20	6.60	3.80
Dissolved oxygen, mg/L	0.28	0.00	0.60	3.42
Organic Phosphorus, mg/L	1.20	1.57	1.20	0.00
Organic Nitrogen, mg/L	0.56	0.69	0.56	0.50

6. Time variable temperature functions

Temperature is a prime factor in the kinetics of the different water quality parameters and there is supposed to be an effect of temperature rise above the ambient on the different parameters due the heated discharge of both the power plants. The segment-specific temperatures were used and to predict the effect of variability with time, additional simulations were performed with different segment temperatures. Simulations were also performed assuming a uniform ambient temperature along the reach to observe the effect of temperature increase on different water quality parameters. Since the data collected for different segments are after the commencement of operation of the Siddhirganj TPS, the simulated effect is the combined effect of both the power plants and individual effects of these power plants on the parameters are indistinguishable. Figure 2 shows the measured temperature profiles along the study reach for February and March which were used as input data in the model as segment temperatures.



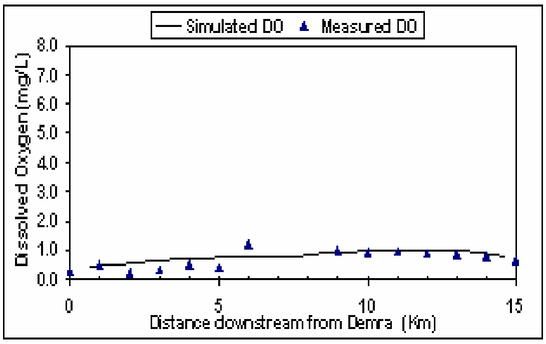
(a) (b)

Fig. 2. Prevailing temperature profiles and ambient temperature (without thermal effect) for February 2005 (a) and March, 2005 (b)

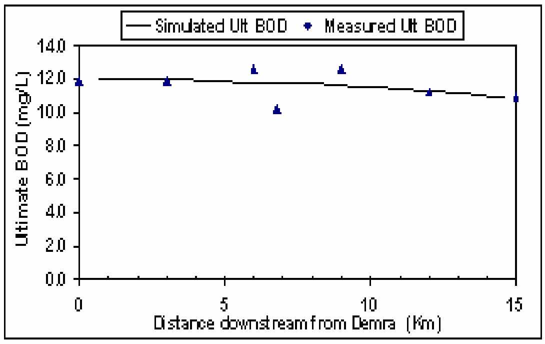
7. Calibration and validation of the water quality model

The values of the kinetic constants and coefficients were taken from the literature survey related to water quality modeling works (Zison et al. 1978, EPA 1985 and Karim, 1996). Several runs were made by varying the kinetic constants and coefficients to minimize the difference between the computed and observed profiles. Figures 3 (a)-(e) show the calibration results compared with the actual field data for the February 2005 water quality condition. Longitudinal concentration profiles of DO, Orthophosphate, BOD, Ammonia nitrogen, Nitrate nitrogen from chainage 99 km to 114 km are presented. In general, the model results follow the trend of the observed data reasonably well, reproducing the spatial trend of key water quality parameters. The predictive capability of the calibrated model was tested for the observed data in March 2005 using the same values of the kinetics, constants and coefficients used in calibration. The model verification result together with observed data for March 2005 is presented in Figs. 4 (a)-(f). It is observed that the model simulation reasonably reproduced the spatial trends of the water quality parameters.

The four interactive systems in the water quality modeling are phytoplankton, nitrogen, phosphorus and dissolved oxygen. Some of the samples collected and analyzed for chlorophyll-a (representing phytoplankton) showed negligible to zero concentrations. Thus, this part of the interactive system was excluded from the modeling system assuming that the negligible phytoplankton concentrations have no effect on the other key water quality parameters. The phytoplankton kinetics is closely related to Dissolved Oxygen as well as Nitrogen and Phosphorus. Dissolved oxygen is necessary to support the life functions of higher organisms and for a balanced aquatic environment. The reaeration rate has been calibrated to a range of 1.0 – 2.0 day^{-1} which is an order of 10 to 20 times higher than the natural hydraulic or wind driven reaeration rate computed from established formula (EPA, 1985) for the particular water body type in literature (e.g., Karim, 1996). This is mainly due to the reaeration caused by the frequent movement of watercrafts along the channel as this is a very busy navigation route.



(a)



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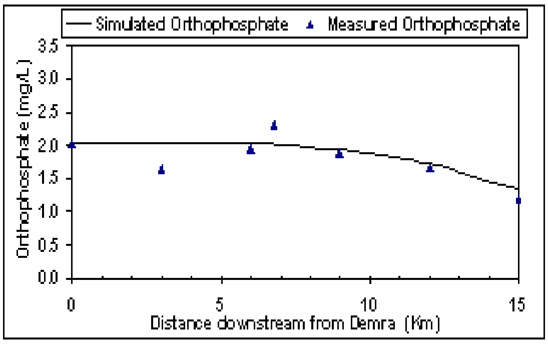

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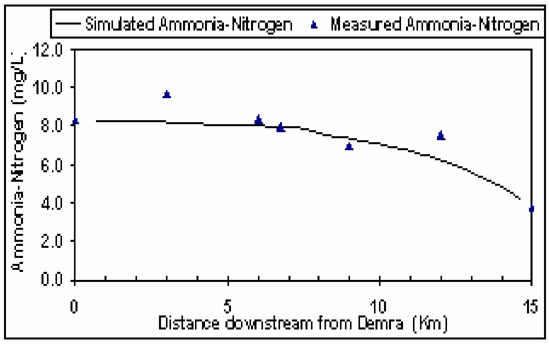

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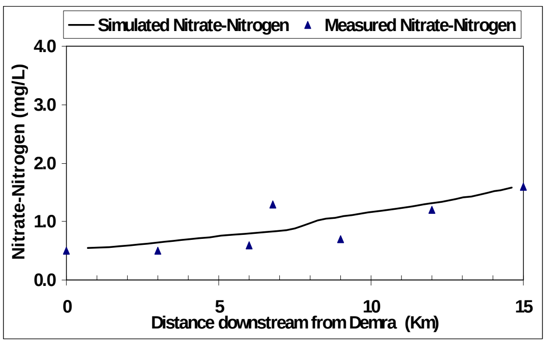


(e)

Fig. 3. Results of Calibration of water quality parameters for February 20, 2005 data (a) Dissolved Oxygen (b) ultimate BOD (c) Orthophosphate (d) Ammonia-Nitrogen (e) Nitrate-Nitrogen.

The concentration profile for orthophosphate does not show any significant variation. But the concentrations varied from 2.03 - 1.19 mg/L in February and 2.66-3.22 mg/L in March. The increase in concentration may be attributed to the relatively low discharge conditions prevailing in March. The concentration of organic phosphorus is lower in the downstream reach than that in the upstream. The values of orthophosphate concentrations are on an average 10-20 times higher than that of the predictions made by Karim (1996), which indicates an increase in concentration in the last 10 years.

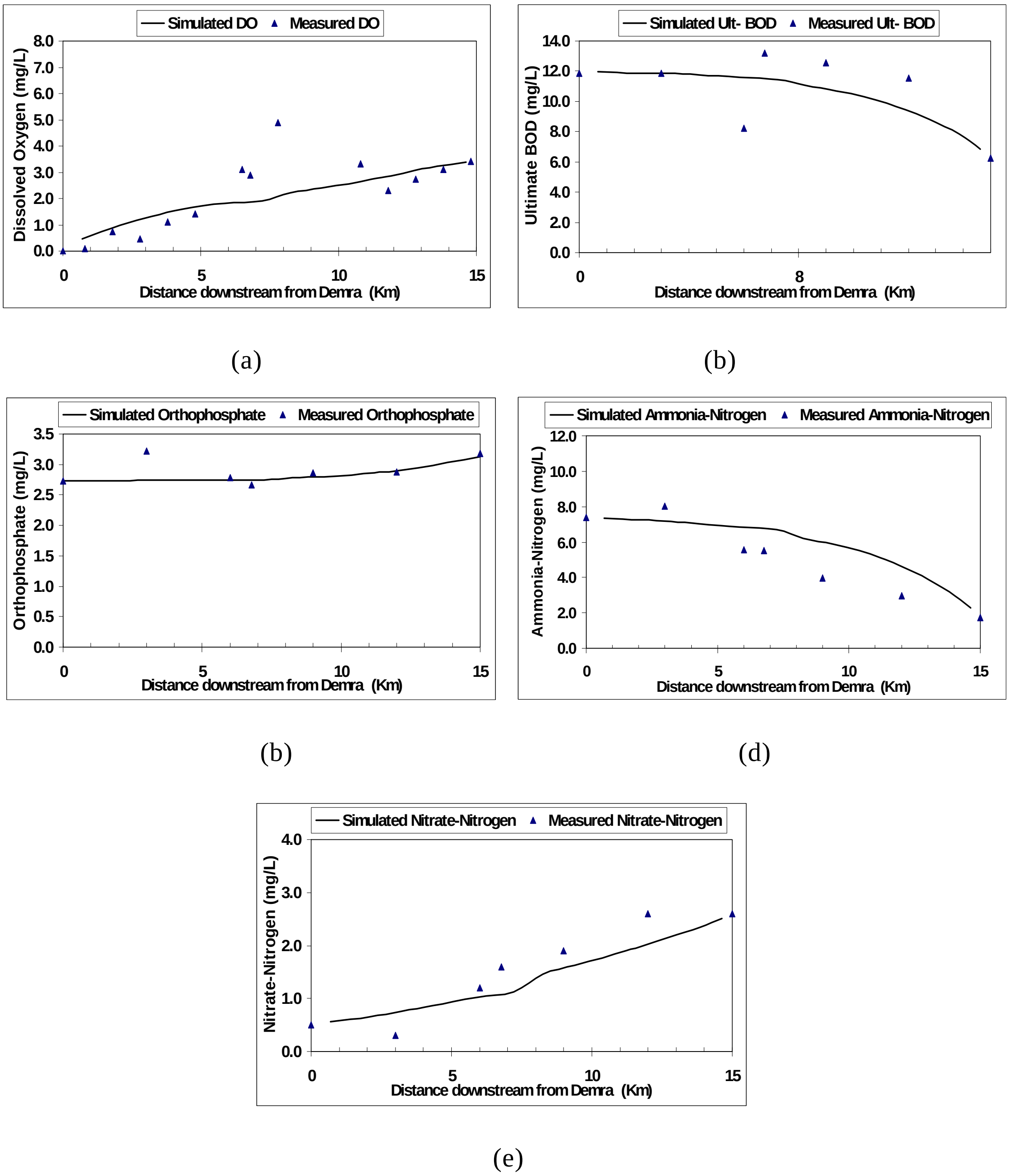


Fig. 4: Results of verification of water quality parameters for March 20, 2005 data (a) Dissolved Oxygen (b) ultimate BOD (c) Orthophosphate (d) Ammonia-Nitrogen (e) Nitrate-Nitrogen.

From the profiles of NH_3-N and NO_3-N, it can be observed that the NH_3-N concentrations decrease from 7.4 mg/L at the upstream to 1.73 mg/L in the downstream boundary whereas the concentrations of NO_3-N slightly increase in the same locations as NH_3-N is oxidized to NO_3-N over the stretch of the river. The NH_3-N concentrations are reported to be alarmingly high in this river in the dry season which is further verified by the observed and simulated values. The situation is relatively better in downstream locations where the river channel broadens and deepens and greater dispersion and dilution occurs in spite of the pollution load in that region. Besides, the concentration of NH_3-N also depends on the nitrification rate which depends on temperature and also the availability of dissolved oxygen. The dissolved oxygen half saturation limit is set to 2 mg O_2/L. Since in the upstream locations the dissolved oxygen frequently fall below this saturation limit, it reduces the nitrification rate to half of its value resulting in the higher concentrations of ammonia and lower concentrations of nitrate. The dissolved oxygen availability is more restricted in February than in March which also affects the rate of nitrification. The corresponding concentrations of nitrate are also lower in February than in March because of the same reasons.

The lowest levels of NH_3-N and orthophosphate concentrations were about 1.75 mg/L and 1.19 mg/L, respectively which are much higher than the Michaelis-Menton constants (0.005 mg/L for N and 0.001mg/L for P). So the nutrients are not the limiting factors controlling the algal growth. Measurements made on the algal concentrations did not justify the occurrence of algal growth under the prevailing circumstances. Light extinction is also a limiting factor which controls the growth of algae in the reach. Also the river flow control the algal growth in the system to some extent. Karim (1996) measured an average concentration of algae of 3µg/L in the Sitalakhya River and showed that the concentration gradually decreases downstream towards the Dhaleswari confluence. Karim (1996) argued that the water turbidity and river flow inhibited the growth of algae in Sitalakhya river and the average concentration of chlorophyll_a is 3µg/L which is much lower than that of any relatively stagnant water body under the same environmental conditions. Since no stagnant water is present within the reach, it is unlikely to have significant algal growth. Therefore it justifies that, the model is a simulation without considering the algal kinetics which is presumed to have an insignificant effect on other water quality parameters.

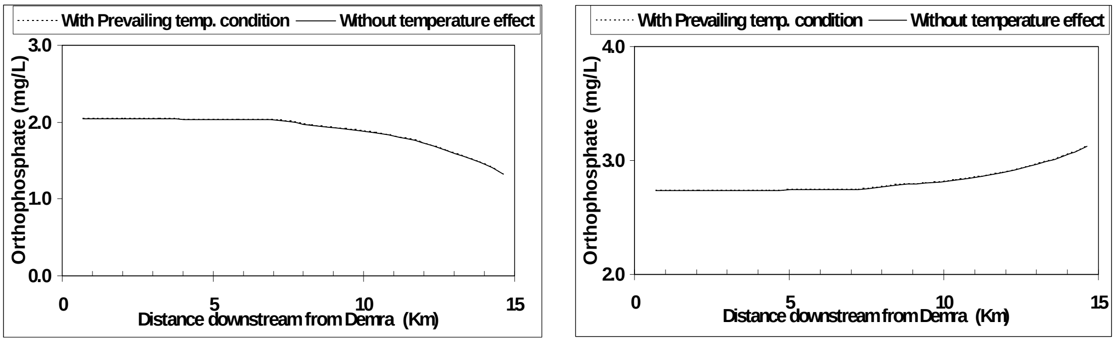
The BOD values are higher in the upstream of the river, which progressively decreases downstream where the water quality is improved with increased DO specially in March. The high BOD in the upstream boundaries (7 mg/L) is mainly due to the pollutant load from Balu River. The concentrations further decrease downstream depending on the BOD exertion capacity and oxygen availability. The half saturation limit for BOD decay rate is set to 0.5 mg O_2/L which indicates that the BOD decay rate is half of its calibrated value when the available DO is below 0.5 mg/L. This fact is verified by observing the profiles of DO and BOD for both February and March. In February, the oxygen was a limiting factor ($<$0.5 mg/L) throughout the entire reach and the BOD exertion rate is reduced. But in March the water quality (with respect to DO concentrations) are somewhat improved ($>$0.5 mg/L) which made sufficient DO available for BOD exertion. Since in most of the segments during this period, DO is not a limiting factor, the decay rate is also higher than that during February.

However, spatial trend observed in the model for orthophosphate, NH_3-N and NO_3-N matches with the trend reported by Karim (1996) with an exception of some higher values for some water quality parameters. The spatial trend of BOD and DO from the model also followed the trend of measured values. In spite of the slight difference noted between the measured and the simulated values, the model followed the trend of the field data. The overall behavior of the system can be reasonably represented by the model.

In general, the concentration profiles calculated by the model as well as the field data, show a smooth trend without any sharp peak or dip. It may seem unlikely to have no peak or dip with so many point sources of waste load located along the reach of the river where the effluents from the main point sources enter the river along one side. The primary reason is that the Sitalakhya is a wide river and the pollutants become dispersed, diluted and mixed to a large extent. Thus the model results represent the well-mixed condition rather than any jumps in concentrations at the input locations. The river has high assimilative capacity and uniform mixing which caused the water quality parameters to be uniformly distributed along the reach.

8. Sensitivity to thermal effluents

The simulations of different water quality parameters for the month of February and March are compared with simulations considering a uniform ambient temperature at all the segments to assess the effect of thermal effluents on water quality. Since the data used for calibration and validation were collected after the commencement of operation of the Siddhirganj TPS, they will represent a condition which is affected by high temperatures in water. The comparisons of the simulations are presented in Figs. 5 to 9.



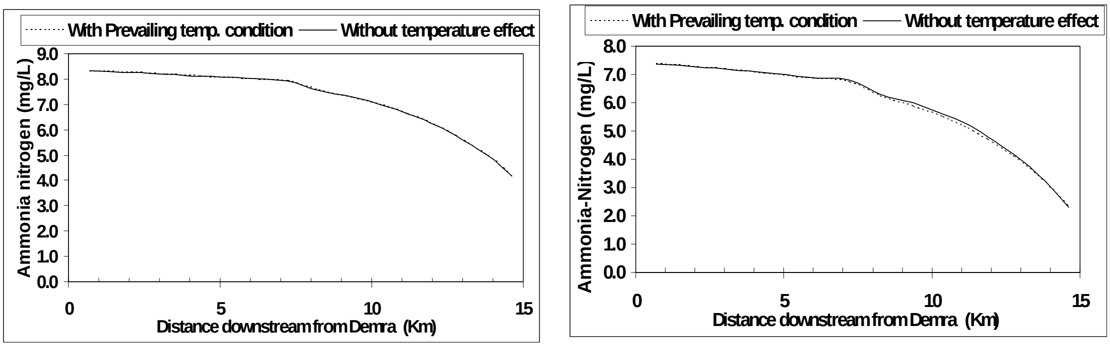
(a) (b)

Fig. 5. Sensitivity of orthophosphate to temperature for the simulation of (a) February, 2005 and (b) March, 2005

The orthophosphate concentration profile observed is apparently not affected by the increase in temperature in the study reach (Fig. 5). This may be due to the low organic phosphorus mineralization rate and the increase in temperature seems to have insignificant effect on this temperature-dependent rate. Besides the organic phosphorus availability is gradually decreasing downstream and since the algal kinetics is insignificant, the release of dissolved organic phosphorus is zero due to algal death and there is no source of additional organic phosphorus for mineralization. Besides the mineralization process is also dependent on a limiting value of algal population which further inhibits the reaction rate.

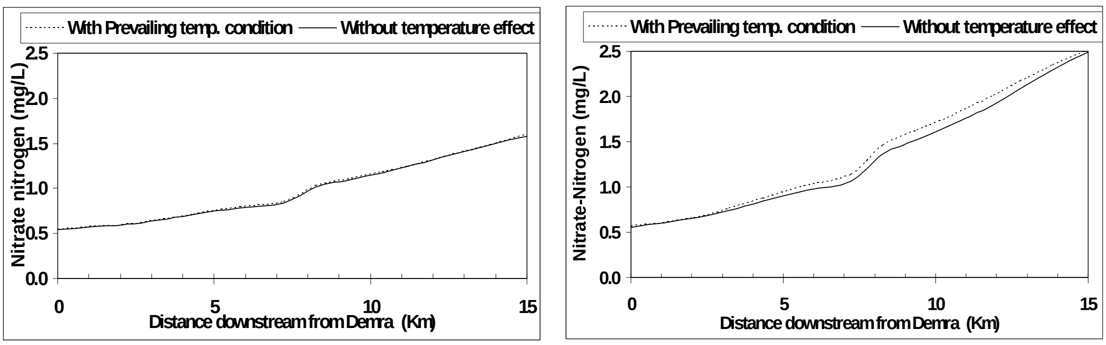
There is a slight decrease in ammonia concentration profile (a maximum of 0.1 mg/L) in the vicinity of the thermal effluent discharge and extending slightly upstream and downstream for the profiles of March, 2005 (Fig. 6). The NO_3-N profile for the same period also shows a maximum increase in concentration of 0.1 mg/L (Fig. 7). But no significant change is visible with the increase in temperature in the simulation results for February 2005. Again the reason is not the increase in temperature rather the increase in the nitrification rate under oxygen-limited conditions. The increase of the nitrification rate is likely to occur due to rise in temperature which is reflected in the simulation for March 2005 where the oxygen level was close to the half saturation constant for nitrification limit. On the other hand, the nitrification process itself is inhibited by the unavailability of oxygen. Therefore, although there was an increase in temperature, the reaction rate did not increase due to oxygen limiting conditions. The BOD profiles for both the periods show very small decrease in concentration due to the rise of temperature (Fig.8). This is mainly due to the fact that the BOD decay rate is expedited due to the increase in temperature and higher BOD is exerted in locations of high temperatures with sufficient oxygen availability. A maximum BOD_5 reduction of 0.064 mg/L is observed due to temperature effect for the simulation of March, 2005.

Although both BOD and Ammonia concentrations decrease slightly with an increase in temperature, it is observed to have very significant effect on the dissolved oxygen profile (Fig. 9). Higher temperature results in a decrease of the saturation value of oxygen as oxygen becomes less soluble (Elmore et al., 1960). Besides, the dissolved oxygen is used up both for the nitrification and BOD exertion and both of these processes are expedited with the increase in temperature. So, there is an observable decrease of the dissolved oxygen profile both upstream and downstream. This magnitude of decrease is 0.58 mg/L on some locations along the reach corresponding to increase in temperature caused by thermal effluent discharge. This decrease in dissolved oxygen concentration along the profile of 15 km is of significant concern due to the already deteriorated water environment.



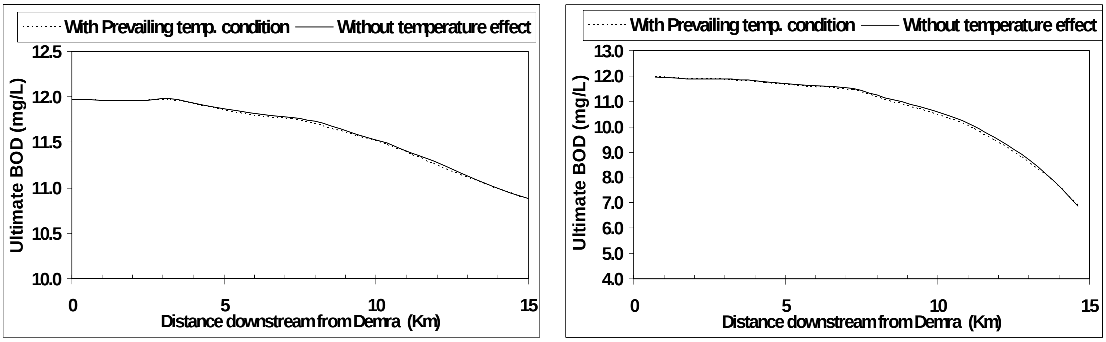
(a) (b)

Fig. 6. Sensitivity of Ammonia-Nitrogen to temperature for the simulation of (a) February, 2005 and (b) March, 2005



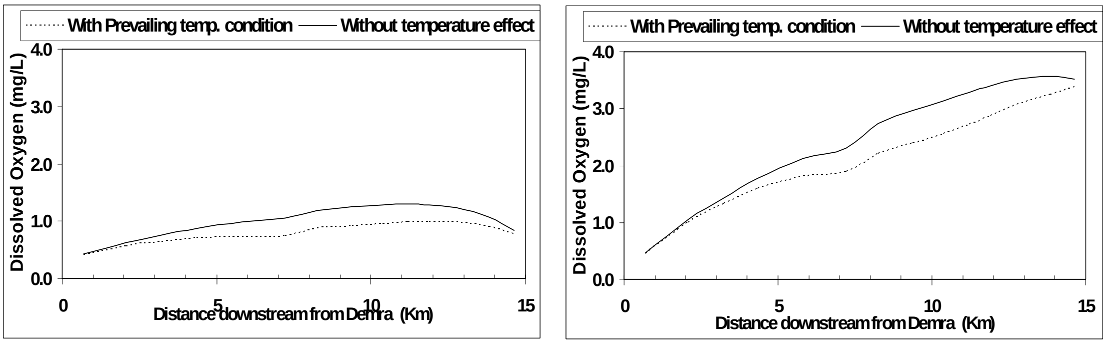
(a) (b)

Fig. 7. Sensitivity of Nitrate-Nitrogen to temperature for the simulation of (a) February, 2005 and (b) March, 2005



(a) (b)

Fig. 8. Sensitivity of ultimate BOD to temperature for the simulation of
(a) February, 2005 and (b) March, 2005



(a) (b)

Fig. 9. Sensitivity of dissolved oxygen to temperature for the simulation of
(a) February, 2005 and (b) March, 2005.

9. Conclusions

It can be concluded that the WASP model fairly simulates the actual conditions of the Sitalakhya River and hence can be used as a useful tool for sensitivity analysis for thermal effluents. The thermal effluents have significant effect especially on the dissolved oxygen concentration of the river and minor effect on other water quality parameters. The current national effluent discharge standard allows a thermal discharge having a temperature of 45°C in Summer and 40°C in Winter from power plants. This particular guideline neither mentions these temperatures with respect to some ambient water temperature nor does it have any criteria regarding a mixing zone. It is obvious from the analysis that a power plant which discharges effluent with a temperature of 4-5°C above the ambient temperature has the effect of significantly reducing the dissolved oxygen. Besides, it has been seen that discharge configurations for releasing thermal effluents also have significant effect on the thermal regime of the receiving waters. Hence, the guidelines should be more specific regarding the discharge of thermal effluents and should be based on case studies, observation of local conditions and analysis of discharge configurations. Appropriate management measures regarding waste load abatement/ reduction are also needed to restore the water quality of the river particularly in the dry season.

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