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DO-BOD modeling of River Yamuna for national capital territory, India using STREAM II, a 2D water quality model

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Abstract The study illustrates the utility of STREAM II as a modeling package to determine the pollution load due to organic matter in the River Yamuna during its course through the National Capital Territory that is Delhi, India. The study was done for a period from 1995–2005. Model simulates the dissolved oxygen and biochemical oxygen demand parameters in a two-dimensional fashion by performing the numerical solution to a set of differential equations representing aquatic life with the help of Crank–Nicholson finite difference method. The model was simulated and calibrated through the field water-quality primary data and the secondary data which were taken from Central Pollution Control Board. The main reasons for the high river pollution is increasing population of Delhi and other states, leading to generation of huge amounts of domestic sewage into the river Yamuna. The model gave a good agreement between calibrated and observed data, thus, actualizing the validity of the model. However, discrepancies noticed during model calibrations were attributed to the assumptions adopted in the model formulation and to lack of field data.

Keywords STREAM-II · Mathematical modeling · Dissolved oxygen · Biological oxygen demand · Water quality

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Introduction

The River Yamuna is the main source of drinking water for Delhi, the national capital territory (NCT) of India, and other bordering states including Uttar Pradesh, Uttranchal, and Haryana. In the last few decades, there has been a serious concern upon the deterioration in its water quality. An enormous amount of partially treated and untreated wastewater, sewage enters the river during its course between Wazirabad (after water drawing by Wazirabad waterworks) and Okhla. Public interest litigations have also been filed pertaining to pollution and degradation of water quality in the river. The ministry of Environment and Forests Government of India launched the Yamuna Action Plan in 1993 to rejuvenate and revival of the river, with a special attention given to Delhi being the chief contributor to the pollution load. Realizing the implications of water pollution on human and aquatic health the judiciary has also directed central and state authorities to take initiatives to improve the river water quality (Paliwal et al. 2007). Effective and efficient management of this polluted stretch of river is, therefore, of utmost importance. In this context, computer-aided hydrological models have gained wide acceptance as tools to predict water quality. Modeling is not an alternate to observations but, under certain circumstances, can be a powerful tool in understanding observations and in developing and testing theory. Choosing a best-fit function between observed and simulated values that expresses the discrepancy between two values optimizes model parameters. Water-quality models can be used for simulation of various nutrient and biological parameters, which was initially not possible, by hydrological parameters. Limited calibration data results in non-uniqueness of optimized parameters, and often, it is difficult to study river water quality with a sufficient degree of uncertainty. STREAM II model uses Crank Nicholson finite difference numerical scheme to solve the model equations. It allows simulation up to three water quality parameters in the mixing zones of rivers. Specifying boundary conditions does water quality simulations and entering pollution loads during stretch so that adjusting rate constants to produce simulation output reflecting the prevailing river water conditions can perform the model calibrations. It can be used for simulation of following combination of parameters:

- One conservative pollutant alone
- One non-conservative pollutant (exponentially decaying e.g. coliforms)
- Dissolved oxygen (DO) and biochemical oxygen demand (BOD)
- DO, BOD, and a conservative pollutant
- DO, BOD, and a non-conservative pollutant.

This paper describes about using STREAM II as comprehensive tool to study the DO and BOD concentrations in River Yamuna in Delhi in a two-dimensional fashion. DO and BOD are considered as a major factor for determining the pollution load in a river. The major objective of the study is DO-BOD modeling using STREAM II and calibrating model using observed and measured data set for a period of 1995–2005.

Site description

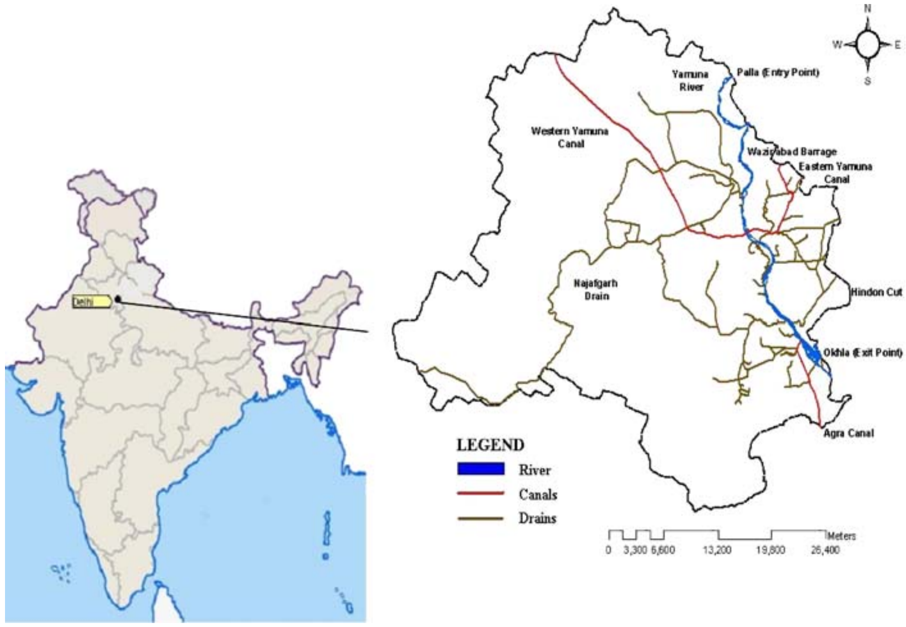
The River Yamuna originates from the Yamunotri Glacier near Banderpunch peaks (38°59′ N, 78°27′ N) at an elevation of 6,320 above mean sea level, and after flowing 200 km, it enters into the plains at Tajewala, where its discharge is fed to the Eastern and Western Yamuna canals (Fig. 1a). In addition to Delhi, it traverses parts of the states of Himachal Pradesh, Haryana, Uttar Pradesh, Uttranchal, Rajasthan, and Madhya Pradesh. The river enters Delhi 1.5 km above village Palla and leaves Delhi at Jaitpur, downstream of the Okhla Bridge after traversing around 22 km (Central Pollution Control Board (CPCB) 1999–2000). The major outfall is Najafgarh drain that contributes nearly 70% of total pollution load to Yamuna in Delhi; other significant drains are the ISBT drain, Civil Mill, Drain Number 14, Power House, Sen Nursing Home, Barapulla, Maharani Bagh, and Shahdara drains (Fig. 1b). According to CPCB, the river water quality standard assigned to the river Yamuna in NCT stretch is class C (Table 1). This classification is done according to the best use designated to the surface water.

STREAM II: model framework

STREAM II model was developed at the Center for Environmental Science and Engineering at Indian Institute of Technology, Bombay in 1988 (Modak et al. 1988). The model was developed under the support of the Ganga Action Plan by the Ministry of Environment and Forests, Government of India. STREAM II was field tested for the stretches on the confluence of rivers Ganga and Yamuna at Allahabad, India. The model can also be downloaded from the website <http://www.emcentre.com>.

Model studies the stretch of river as a series of reaches. Reaches are assumed to represent portions of the river having uniform conditions (geometric, hydraulic and chemical–biological coefficients). Reaches are further subdivided into units called computational elements (Al Rizzo and Al Layla 1987). Each computational element is modeled as a constant volume, completely

Fig. 1 Description of study area



mixed reactor with input, output, and reaction terms.

Input variables

STREAM II requires varying amount of data depending upon the combination of parameters to be simulated. Data requirement can be divided into four classes namely:

- Geometric data: length of reaches (in kilometers); average top width; average depth and measurement at 10–25 points along transect (transverse section at the beginning of the reach) of: distance y from the right bank (looking downstream); depth at y and concentration of pollutant at y.
- Hydraulic data: stream flows at all the starting points in cubic meter per second and wastewater flows at all nodes except the starting point, tail end and confluences in cubic meter per second.
- Water quality parameters: concentration of water quality parameters at all waste water nodes; rate coefficients (subjected to case of simulation before calibration); reaeration coefficient, in per day (K_1) and decay rate coefficient, in per day (K_2)

Table 1 The surface water quality classification given by Central Pollution Control Board (CPCB) (1980–1981), India

Characteristics	Class				
	A	B	C	D	E
DO (mg/l)	>6	>5	>4	>4	<4
BOD (mg/l)	<2	<3	<4	<6	>6

A drinking water sources without conventional treatment but after disinfection, *B* bathing, swimming and recreation, *C* drinking water source after conventional treatment, *D* propagation of wild life, fisheries etc., *E* irrigation, industrial cooling and controlled waste disposal

Assumptions

- Steady-state model i.e., $\partial S/\partial t = 0$
- Within the each reach, all model parameters like K_1, K_2, velocity, depth, etc., remains the same
- SOD is assumed to be zero for the entire course of river. Sedimentation is a mechanism with an important bearing on both BOD and DO levels in a stream (Chapra 1997). CPCB (1982–1983) reported that only 25% of total BOD is settleable for considered stretch. Further, a part of this settled material decomposes anaerobically without affecting DO, also since

river generally has low DO levels. Settling process removes a small part of total BOD without disturbing the DO profile of river (Paliwal et al. 2007). Also, it may be assumed that BOD removed by the settling process is compensated by pollution from nonpoint sources such as bathing, washing, religious offerings, etc. (CPCB 1999–2000).

Model capabilities

- Side slope of channel which is equal to the depth and bottom width ratio
- Area of channel which was calculated by the *Manning's formula*

$$A = (B_{\mathrm{w}} + z \times y)$$

where:

A	area of channel in m^2
B_w	bottom width that is assumed to be the same as top width
z	Side slope
y	depth of channel

- Flow of channel was calculated as given below:

$$Q = A \times U$$

Where:

Q	flow in m^3/s
A	area in m^2
U	velocity in m/s

- In case of simulation before calibration, K_2, i.e., reaeration constant can be calculated using four different equations Covar Diagram, Owen's equation, O'Connor's equation (1958), Churchill's equation (1962). It is recommended to use O'Connor and Dobbins equation with a standard error of 0.088 for slight slope rivers and Churchill Elmore and Bukhingham equation for medium slope rivers with a standard error of 0.358. Keeping in mind the above recommendations, following equation is proposed for *slight slope rivers*:

$$K_2 = 10,046 \times \mathbf{U}^{\mathbf{2,6969}} / H^{3,902}$$

Likely for *medium slope rivers*, the following equation is recommended:

$$K_2 = 1,923 \times \mathbf{U}^{\mathbf{1,325}} / H^{2,006}$$

K_2	Reaeration constant in per day
U	velocity in m/s
H	medium deepness in meters

Model calibration

Model calibration is actually the process by which one obtains estimates for model parameters through comparison of field observations and model predictions. To identify the coefficient for each reach for the River Yamuna, STREAM was calibrated using four longitudinal sampling locations. The results show reasonable agreement between measured and simulated values of variables (DO, BOD).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2}$$

Where M_i = measured value and S_i = Simulated value.

Model calibrates itself using the observed values for each reach, and user is prompted to input number of iterations (minimum 25). Corresponding to each iteration model assumes a value of model parameter and tries to minimize the RMSE value for whole stretch by changing parameter value, calculates RMSE, and reports the model parameters corresponding to least RMSE. The value of least RMSE is indicative of capability of model to incorporate observed values for simulation. The fluctuations, in time of the reactions, add or remove oxygen; the steady-state models are not very accurate; thus, more general mass balance equations can be introduced. For instance Deb and Bowers (1983) modeled the modeled the diurnal change of DO by the equation:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} = K_2\,(Cs - c) - K_1 L\,(x) - KnN\,(x) + P\,(x,t) - R\,(x) - S\,(x)$$

Where c is the DO concentration, Cs is the Do saturation value, $L(x)$ is carbonaceous BOD, K_1 the BOD reaction rate, K_2 is reaeration coefficient, Kn is coefficient of nitrogenous oxidation, $N(x)$ is nitrogenous BOD, $P(x,t)$ the algal photosynthetic oxygen production rate, $R(x)$ algal respiration rate and $S(x)$ is the bacterial respiration rate. Model uses Crank Nicholson finite difference method in order to solve this partial difference equation. Concentration distance profile of BOD is calculated at each and every node where a drain joins the river by following equations:

$$L = L_0 \times \exp\left(-\left(\frac{K_1 \times x}{U}\right)\right) + \left(\frac{(Q_0 \times L_0) + (Q_e \times L_e)}{Q_0 + Q_e}\right)$$

Where: L: BOD in milligrams per liter at the downstream distance x; L_0: BOD at initial point of a specific reach; K_1: decay constant in per second; x: downstream distance in meters at which load is added; **U**: velocity in meters per second; Q_0: flow of stream at the initial point in cubic meter per second; Q_e: flow of drain joining the stream at distance x and L_e: BOD of drain in milligrams per liter.

Verification and validation

It is testing of the calibrated model against the additional set of field data preferably under different environmental conditions (river flow, waste load) to further examine the range of validity of the calibrated model. Collection of data for validation is such that calibration parameters are fully independent of validation data. The model so verified can be used for forecasting of water quality under a variety of perturbed environmental conditions.

Methodology

The model was run annually for a period of 1995–2005 and was calibrated using the observed datasets from CPCB (1999–2000, 2006).

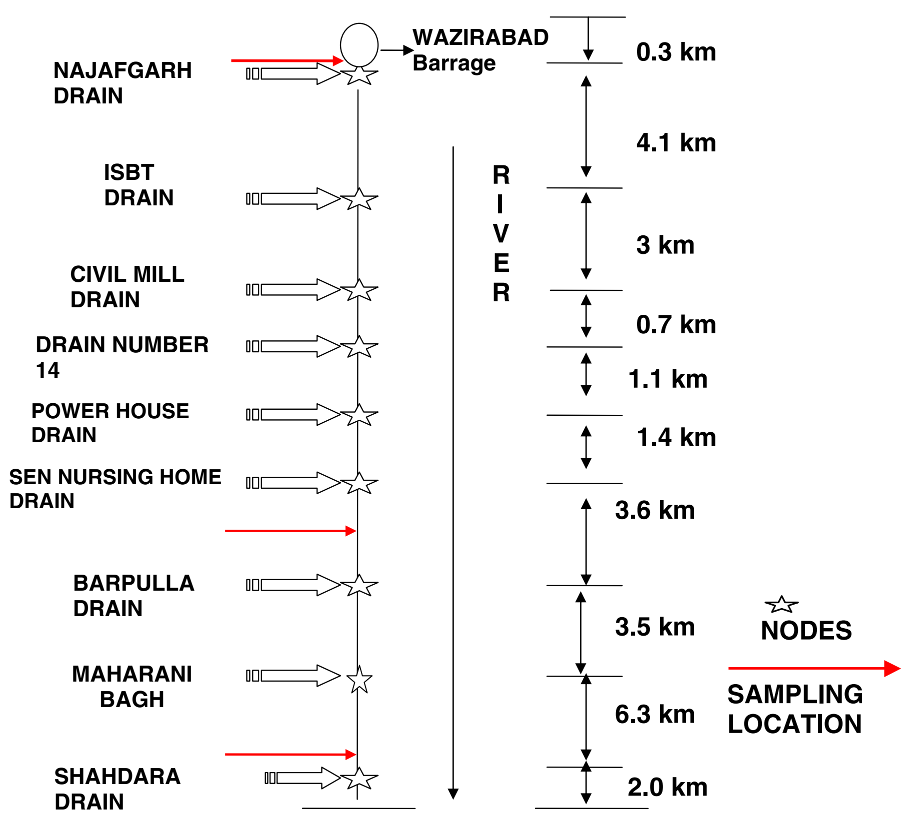


Fig. 2 Simplified diagram showing pollution loads (drains) as nodes and sampling locations across the study area

Table 2 Various pollution loads characteristics outfalling in Yamuna

Node name	Node no.	Discharge (m^3/s)	DO conc. (mg/l)	BOD conc. (mg/l)
Wazirabad	1	3.9	8.38	1.92
Najafgarh drain	2	20.43	0	47
ISBT	3	.39	0	120
Civil mill house drain	4	.43	0	271
Drain number 14	5	.14	0	16
Power house drain	6	.50	0	252
Sen nursing home drain	7	1.3	0	176
Barapulla drain	8	.96	0	69
Maharani bagh	9	.73	0	256
Shahdara drain	10	7.44	0	111
Okhla	11	4.3	1.64	18.13

Source: CPCB 2006

The model was run for ten reaches with nine drains (Fig. 2, Table 2), and the observed datasets were for the location U/S Wazirabad Barrage and Nizamuddin (mid-stream; 36 km D/S Palla). For this study, STREAM was calibrated annual observed datasets from CPCB for a period of 1995–2005.

Results and discussion

The river in this area has low flow especially in months from October to March leading to high concentration of pollutants. Enormous organic loads in river water are unsuitable for any use to humans, animals, industries, etc. Observed and simulated BOD for river Yamuna (D/S Wazirabad barrage) using STREAM II is illustrated in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13. As expected, the BOD concentration decreases gradually downstream due to natural self-purification phenomenon. There is a sharp increase in BOD as soon as drains join the river throughout the stretch. It was observed that for all the years (1995–2005), the levels of BOD were far above the standard levels.

The Figs. 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24 show the predicted and observed DO levels along with the expected standard. The DO levels did not match the standard levels throughout the stretch almost for all the years except for the 1997. The reason is the high rainfall in the NCT and less sewage discharge into the River Yamuna via drains. However, the discrepancies between the simulated and observed values of BOD and

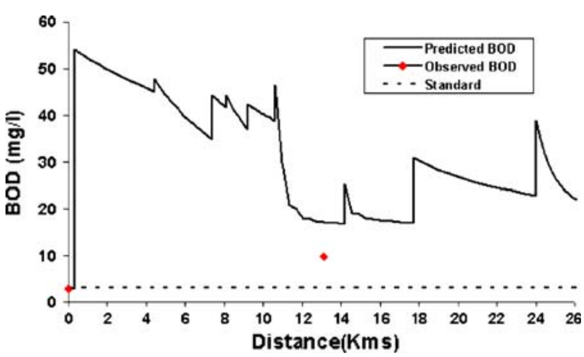


Fig. 3 Predicted and observed BOD for 1995

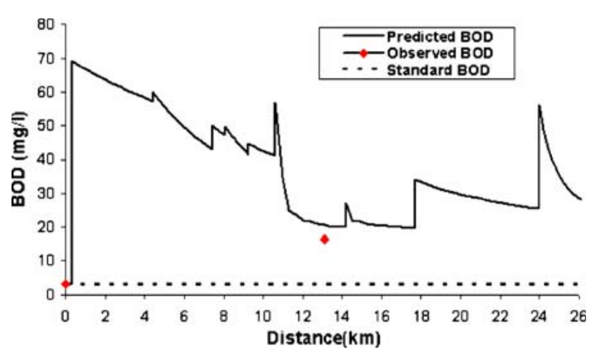


Fig. 4 Predicted and observed BOD for 1996

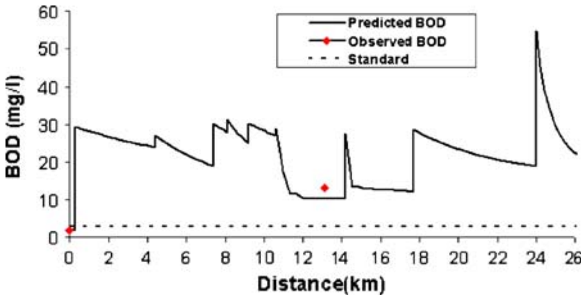


Fig. 5 Predicted and observed BOD for 1997

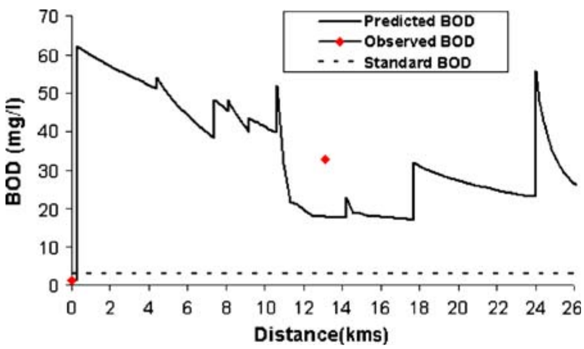


Fig. 6 Predicted and observed BOD for 1998

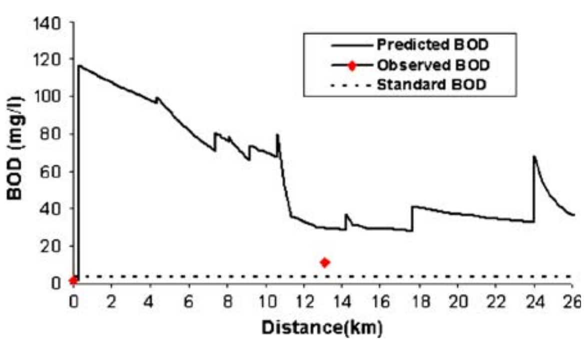


Fig. 7 Predicted and observed BOD for 1999

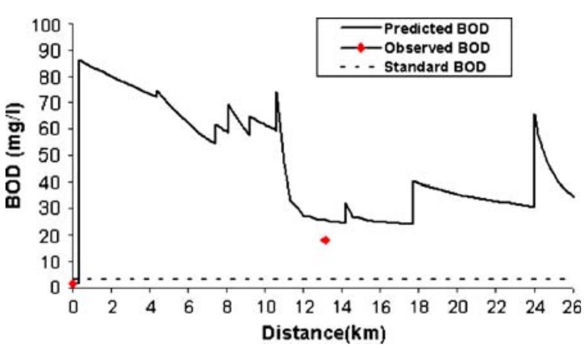


Fig. 8 Predicted and observed BOD for 2000

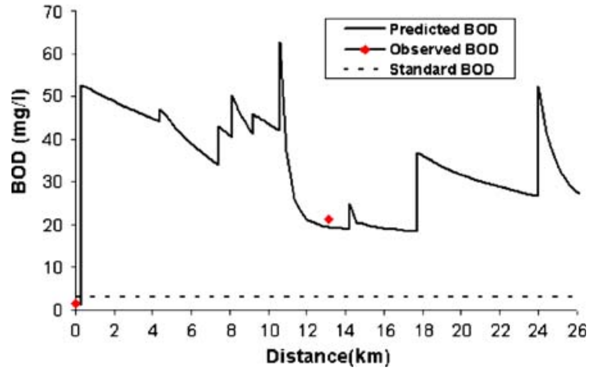


Fig. 9 Predicted and observed BOD for 2001

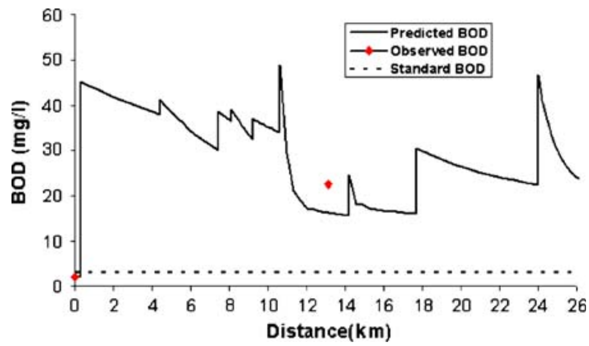


Fig. 10 Predicted and observed BOD for 2002

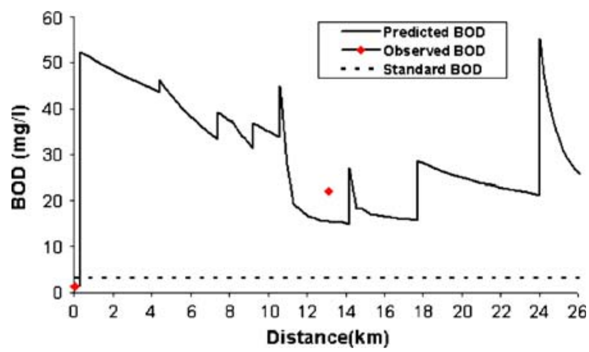


Fig. 11 Predicted and observed BOD for 2003

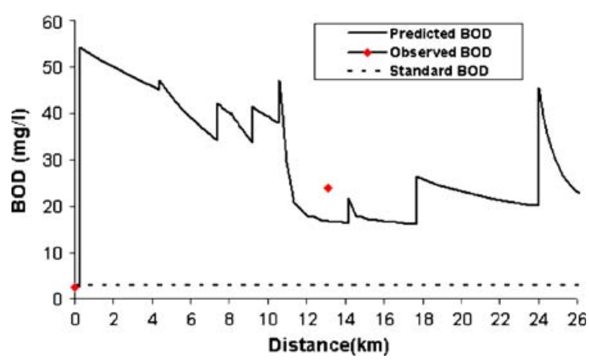


Fig. 12 Predicted and observed BOD for 2004

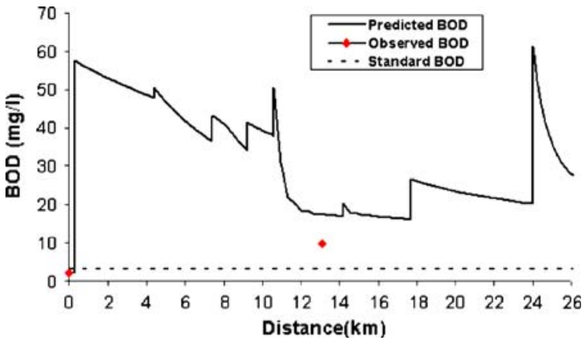


Fig. 13 Predicted and observed BOD for 2005

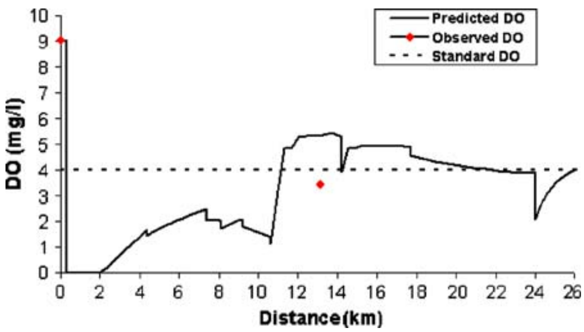


Fig. 14 Predicted and observed DO for 1995

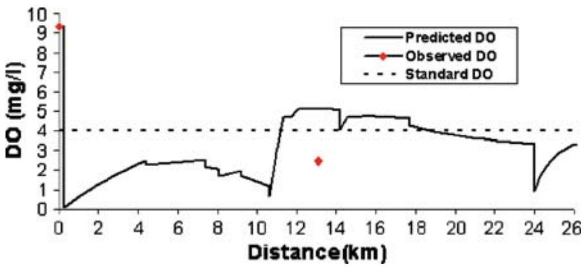


Fig. 15 Predicted and observed DO for 1996

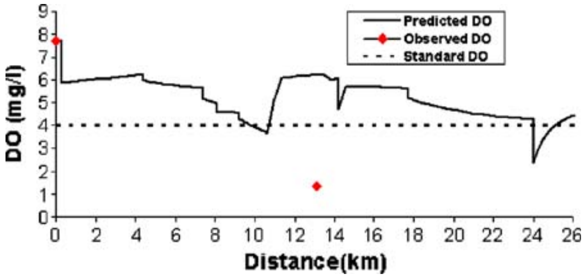


Fig. 16 Predicted and observed DO for 1997

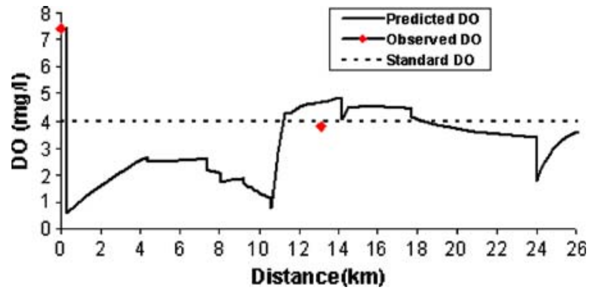


Fig. 17 Predicted and observed DO for 1998

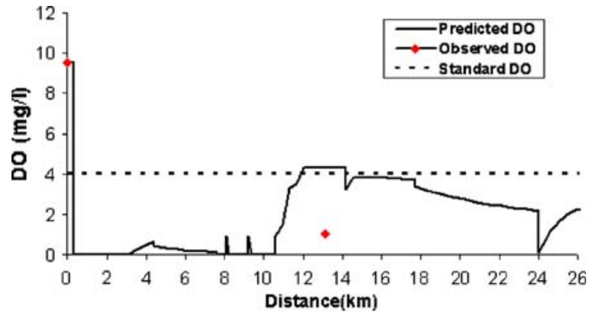


Fig. 18 Predicted and observed DO for 1999

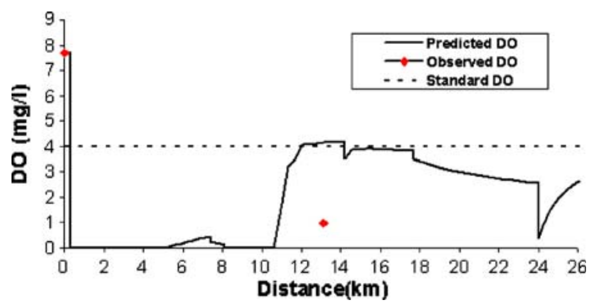


Fig. 19 Predicted and observed DO for 2000

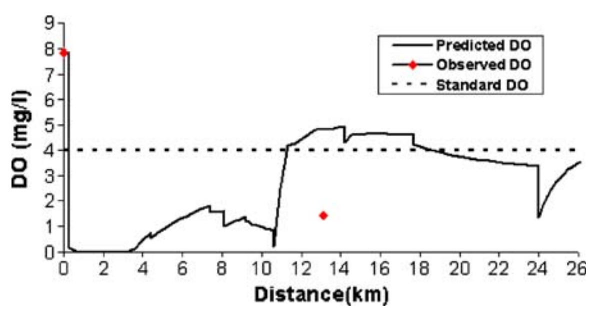


Fig. 20 Predicted and observed DO for 2001

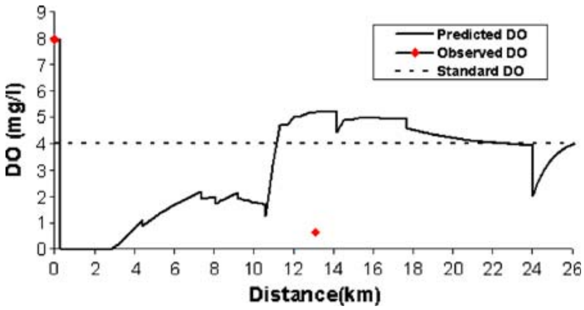


Fig. 21 Predicted and observed DO for 2002

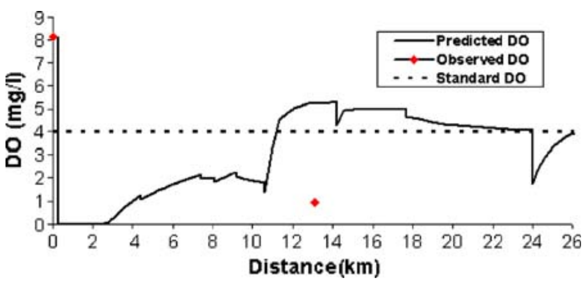


Fig. 22 Predicted and observed DO for 2003

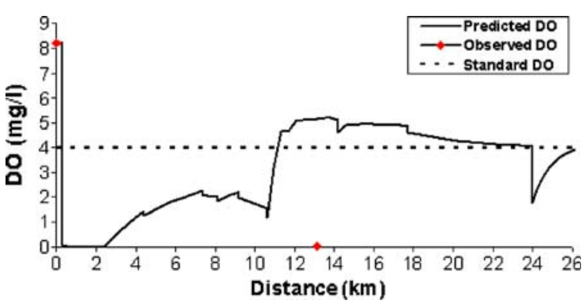


Fig. 23 Predicted and observed DO for 2004

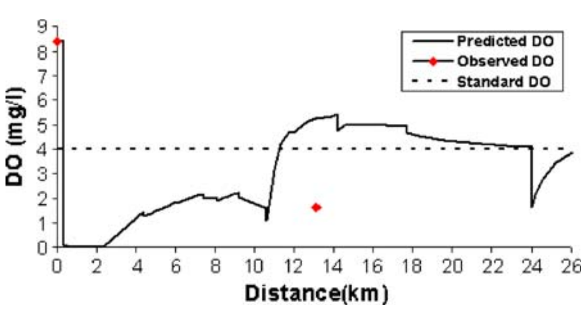


Fig. 24 Predicted and observed DO for 2005

DO can be explained by the other processes occurring in the natural surface water system like photosynthetic activity of aquatic plants, notably the green and blue algae (O'Connor and Dobbins 1958), sediment activity, stream temperature, and other assumptions adopted in formulation. It is inevitable that Najafgarh Drain has disastrous effect on the water quality of river, shooting up the BOD from as low as to 0.27 mg/l to as high as 57 mg/l in 2005 and dipping DO concentration to zero from a satisfactory level. Other major drains contributing to high organic sewage in the river are Civil mill, Sen nursing home, Barapulla, and Shahdara drain. Only 335 MGD out of estimated domestic sewage of 719 MGD is being treated before discharge into the river; thus, a huge amount of waste approximately 380 MGD is discharged far exceeding the assimilative capacity of the river estimated to be about 9 tons/day (NEERI 1996), thereby affecting the river oxygen levels directly.

Conclusion

STREAM II, a surface (river) water quality model can be successfully used for the calibration and validation approaches to determine fate of pollutants in river and determine effects of fluctuations in pollution loads, respectively. It can satisfactorily identify behavior of conservative and non-conservative pollutants in river in a two-dimensional pattern. The river is highly polluted to a capacity that it does not revive in the complete stretch of 26 km. There is no effect of self-purification and reaeration capacity of the river. Due to almost zero DO concentration, during whole stretch, no aquatic life is expected to exist in the river, which is a very crucial factor as far as self-purifying capacity of river is concerned. The ways to restore river quality is either by a considerable decrease in pollution load from incoming drains or maintaining a substantial flow of water in the river. Artificial aeration and flow augmentation must be incorporated to achieve the standards. The statistical variation of calculated DO and BOD are also due to variation of hydrological and meteorological parameters. If these variations had been taken into account, the results would have been considerably changed. Model fit is not good in the most adverse situations. There has been observed quite a few zero levels of DO concentrations while the calculated values were all above 1.0 mg/l. The performance of model could have been significantly enhanced if more ground observations were available. Model calibration gave a satisfactory agreement between the simulated and measured concentrations of conservative constituents (DO and BOD). However, the discrepancies arising between the measured and simulated concentrations may be attributed to the lack of field data, complexity of the model formulation and assumptions adopted in the model construction.

Model is very user-friendly, and data input can be done in a very systematic and lucid manner. Less number of hydrological parameters and topographical conditions are required to carry out simulations in STREAM II, contrary to other models which require exhaustive field observations. The effects of measurement errors can be minimized by optimizing data-collection procedures like collecting data in most sensitive locations and by collecting optimum number of replicates.

Acknowledgements We sincerely acknowledge the Central Pollution Control Board, India for providing the data regarding the water quality of river Yamuna.

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