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Estimation of Dissolved Oxygen and Biochemical Oxygen Demand in River Hindon, India Using Dissolved Oxygen Balance Technique

M.K. Sharma[1], Ramakar Jha and V.K. Choubey
National Institute of Hydrology
Roorkee - 247 667, INDIA
E-mail: [1]mks@nih.ernet.in

ABSTRACT: River Hindon, a tributary of river Yamuna, India receives waste-water from municipal and industrial areas of Saharanpur, Muzaffarnagar and Ghaziabad regions without prior treatment. Further, the river also receives non-point sources of pollution from agricultural land as the major landuse in the basin is agriculture. The basin is densely populated due to rapid industrialization and agricultural growth during last few decades and has socio-economic values. Due to the influx of continuous pollution load in River Hindon without prior treatment, the river's environmental matrix has become very complex. It is essential to estimate the self-purification capacity of the river in the form of de-oxygenation rate (K_d) and re-aeration rate (K_r) capacity at different reaches of River Hindon. Keeping this in view, an attempt has been made in the present work to evaluate K_d and K_r values for River Hindon using Texas Water Development Board method, empirical methods based on velocity, depth and slope data and Newton-Raphson technique and estimate Biochemical Oxygen Demand (BOD) and Dissolved Oxygen (DO) values at different reaches of River Hindon using Dissolved Oxygen Balance Technique (DOBT). For the analysis, extensive data (BOD, DO, water temperature, pH and electrical conductivity) on bi-monthly basis for two annual cycles (1997–98 and 1998–99) at thirteen stations were collected and analysed. Error estimation was done using correlation statistics, standard error and mean multiplicative error approaches.

INTRODUCTION

The oxygen consumption by micro-organisms living in water while they decompose biodegradable organic matter is main process affecting the oxygen content of water. In modelling approach, biodegradable organic matter is taken into consideration by the Biochemical Oxygen Demand (BOD) parameter, which is defined as the quantity (mass) of oxygen consumed from a unit volume of water by micro-organisms during a specified period of time (e.g. BOD_5). Reaeration, a physical absorption of oxygen from the atmosphere by water, is another important process by which a water body may recover DO concentration naturally due to turbulent motion of water and to molecular diffusion. Therefore the amount of reaeration should be calculated very carefully. This process reduces the 'oxygen deficit' (D) of water, which is defined as the difference between saturation oxygen content and the actual dissolved oxygen level.

One of the most important water quality parameters is the amount of Dissolved Oxygen (DO) present in natural water. When the DO concentration drops below acceptable values, aquatic ecosystem health could be seriously impaired and desirable uses of water resources could be precluded. That is why water quality standards and criteria for DO are provided by environmental regulating bodies of many countries. The saturated value of dissolved oxygen in water is modest, in the order of 8 to 15 mg/L, depending on temperature and salinity. Dissolved oxygen is the resultant of the interaction between sources and sinks, which affect the DO concentration. Sources are nothing but atmospheric reaeration and photosynthetic production, which tend to increase oxygen levels. Sinks are oxygen demanding wastes i.e. oxidation of carbonaceous and nitrogenous waste material, respiration of aquatic plants, and Sediments Oxygen Demand (SOD).

In order to assess the water quality of rivers at temporal and spatial scale, these processes can be expressed mathematically to quantify their effects. The mathematical expressions, thus obtained, are then incorporated in modelling frameworks, which are applied in water quality and waste load allocation studies. Water quality modelling in a river has progressed from the pioneer work of Streeter and Phelps (1925), who developed the relationship between the decay of an organic waste measured by the BOD and DO resources of the river, producing the classic dissolved oxygen sag model. Subsequent to Streeter and Phelps (1925), several BOD-DO models and several approaches were introduced (Theriault 1927; Fair 1939; Thomas 1948; Li 1962, 1972; Camp

1963; Gundelach and Castillo 1976; Van Genuchten and Alves 1982; Bhargava 1983; Thomann and Muller 1987; Ambrose *et al.,* 1996; Jolankai 1997; Yu *et al.,* 1991; Adrian *et al.,* 1994). Most of these models have gradually increased in terms of the number of parameters affecting the BOD as well as DO concentrations. However, some of the models have very complex functional forms and do not transform to the widely used Streeter and Phelps model. Further, these approaches assumed that the substances present in the water decay according to a first-order reaction, that is the rate of loss of the substance, are proportional to its concentration at any time.

The classical Streeter & Phelps (1925) models for BOD and DO with the inclusion of bio-flocculation and settling of organic matter, were modified by Bhargava (1983) by including the concept of settling in the first order decay concept in large rivers of India having high discharges. Thomann and Muller model (1987) includes the distributed (non-point) sources within the stream causing the variation in BOD and DO concentration. Yu *et al.,* (1991) introduced a superposition method of solution, which described the BOD in a river due to a time series of inputs.

Jolankai (1997) proposed a generalized model for BOD-DO computation, in which longitudinal variation of the mass flux is used, instead of expressing variation of concentration with time, thus allowing inclusion of longitudinally varying river flow in the model; the DO equation is written for dissolved oxygen (termed here Cox), instead of the oxygen deficit D; the non-point input loads are considered in terms of concentrations of BOD and DO in the lateral inflow and finally photosynthesis and respiration of aquatic plants are considered separately.

Cox (2003a) described the methods used to simulate the processes affecting dissolved oxygen in lowland rivers and provided a modeling framework to describe those processes in the context of a mass balance model. The data requirements for modelling DO in lowland rivers were also discussed. Cox (2003b) also reviewed currently available in-stream water-quality models SIMCAT, TOMCAT, QUAL2E, QUASAR, MIKE-11 and ISIS and examined the potential for each model in relation to the issue of simulating Dissolved Oxygen (DO) in lowland rivers and concluded that it is unfair to set one model against another in terms of broad applicability, but that a model of intermediate complexity, such as QUASAR, is generally well suited to simulate DO in river system.

In India, only limited efforts on river water quality modeling have been made during the recent past for BOD and DO simulations (Bhargava 1983; Choudhary *et al.,* 1992; Ghosh and McBean, 1998; Jain, 1996; Sharma *et al.,* 2000; Jain *et al.,* 1998; Jha *et al.,* 2001, 2004, 2005a, b, 2007). Most of these studies are either carried out with limited input data sets and/or with limited parameters. In fact, it is important to undertake a rigorous approach using a large number of physically based parameters and input data for accurate simulation of water quality parameters (BOD and DO) in a highly polluted river system.

Ghosh and McBean (1998) attempted the application of QUAL-2EU to perform water quality modeling in the River Kali in India. Data limitations were found to be the primary constraint associated with use of the model for applications to the River Kali.

Jha *et al.* (2007) tested most commonly used BOD and DO models namely Camp model (1963), Bhargava Model (1983), Thomann and Mullar model (1987) and Jolankai model (1997) for their applicability in the River Kali, a tributary of river Hindon. The model parameters used in the BOD-DO models were optimized using the Newton-Raphson technique and the performance of these models was evaluated using error estimation, namely standard error, normalized mean error and mean multiplicative error and correlation statistics. The results indicate that the BOD-DO models developed after Camp (1963) yielded the best agreement with the observed values as compared with several other approaches.

The river Hindon, an important tributary of Ganges system, carries municipal and industrial effluents of different types of industries surrounding the river system through drains and direct outfalls. In the present study, the self-purification capacity of the river in the form of de-oxygenation rate (K_d) and re-aeration rate (K_r) capacity at different reaches of River Hindon. Keeping this in view, an attempt has been made in the present work to evaluate K_d and K_r values for River Hindon using Texas Water Development Board method, empirical methods based on velocity, depth and slope data and Newton-Raphson technique. Further Biochemical Oxygen Demand (BOD) and Dissolved Oxygen (DO) values at different reaches of River Hindon were estimated using Dissolved Oxygen Balance Technique (DOBT). Error estimation was done using correlation statistics, standard error and mean multiplicative error approaches.

THE STUDY AREA: HINDON RIVER BASIN

The river Hindon is among one of the important rivers in western Uttar Pradesh (India) having a basin area of about 7000 km^2 (Figure 1). The study area is a part of

Indo-gangetic plains, composed of Pleistocene and subrecent alluvium. The catchment area of the river lies between latitude 28° 30′ to 30° 15′ N and longitude 77° 20′ to 77° 50′ E. The river originates from Upper Shivaliks (Lower Himalayas) and flows through four major districts, viz., Saharanpur, Muzaffarnagar, Meerut and Ghaziabad in western Uttar Pradesh and covers a distance of about 200 km before joining the river Yamuna downstream of Delhi. The major landuse in the basin is agriculture and there is no effective forest cover. On the basis of land use map the study area can be demarcated into five categories: agriculture (78.94%), urban area (6.63%), barren land (12.32%), forest cover (2.09%) and water bodies (0.02%). The basin is densely populated because of the rapid industrialization and agricultural growth during last few decades. Several industries related to paper, sugar, distillery and many small scale cottage industries related to electroplating, paper board, food processing, milk products, chemicals and rubber etc., located in the western part of U.P., release their waste effluents into the river through various open drains. Due to the continuous pollution load, the river's environmental matrix has become very complex and need systematic study. The climate of the region is moderate subtropical monsoon type. The average annual rainfall is about 1000 mm, major part of which is received during the monsoon period (June to September). The daily maximum temperature varies from 10 to 43°C and minimum temperature varies from 4.6 to 29.2°C. The daily relative humidity varies from 30 to 100% during the period of sampling (Sharma, 2001).

The main sources of pollution in river Hindon include municipal wastes from Saharanpur, Muzaffarnagar and Ghaziabad urban areas and industrial effluents of sugar, pulp and paper, distilleries and other miscellaneous industries through tributaries as well as direct outfalls. The main effluent discharge in the upper part of the river system is from Star Paper Mill, Saharanpur. The chemical analysis of the waste effluent shows that the effluent is rich in organic substances as reflected by high BOD and COD values (Jain *et al.,* 2002). Beside this, the river has two major drains in its upper portion, viz., Nagdev *nala* and Dhamola *nala*, which join the river Hindon near the villages of Ghogreki and Sadhauli Haria, respectively. The municipal wastewater generated from the Saharanpur city is discharged to the Hindon river through Dhamola *nala.* There is no wastewater collection and treatment system in the city. In addition, the wastes from several small units such as textile factory, sugar factory, cigarette factory, card board factory and laundries etc. also transfer their wastes to the Hindon river through Dhamola *nala*. The industrial effluent from Cooperative distillery and municipal wastewater from Budhana town also join the river in this stretch. The river Kali meets the river Hindon on its left bank near the village of Atali and carries municipal wastewater and effluents of industries located in the Muzaffarnagar city. Another tributary called Krishni meets Hindon on its right bank at village Barnawa in Meerut district and transports the waste water from sugar mill and distillery. In Ghaziabad district, downstream of Karhera village, major part of the river flow is diverted to Hindon cut canal at Mohan Nagar which meets river Yamuna upstream of Okhla barrage. Thereafter the river Hindon receives wastewater through Dhasana drain at village Bisrakh in Ghaziabad district. The Dhasana drain carries the wastewater of municipal as well as industrial establishments in Ghaziabad. River Hindon flows further downstream and joins river Yamuna at village Tilwara.

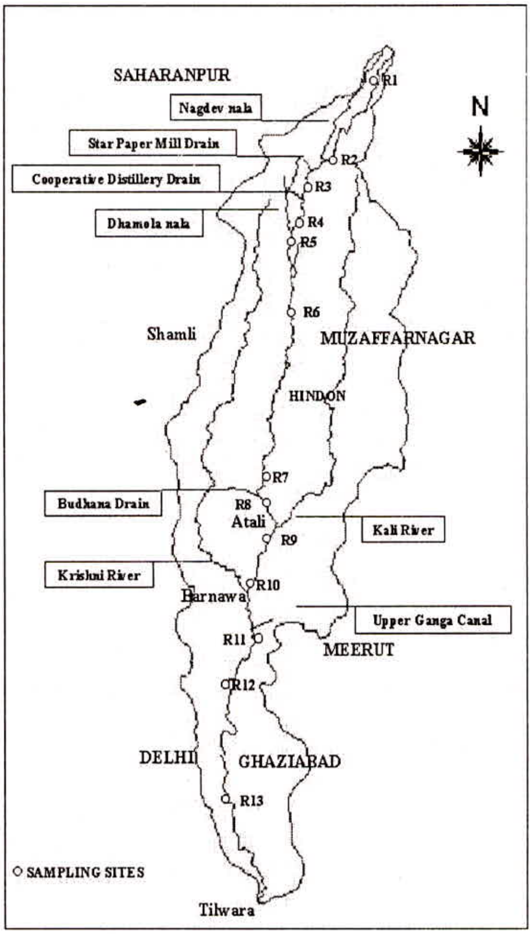

Fig. 1: Hindon river basin showing location of sampling sites

METHODOLOGY

Physico-Chemical Analysis

A general plan of the sampling locations with respect to different outfalls of municipal and industrial effluents in river Hindon is shown in Figure 1. In all, eight stations in the waste effluents, tributaries and canal joining the river and thirteen stations in the river (R1 to R13) were selected for monitoring various water quality constituents. Twelve sets of samples were collected from various locations on alternate months for a period of two years (April 1997 to February 1999) by dip (or grab) sampling method. The water and wastewater samples were collected in polyethylene bottles from 1/3, 1/2 and 2/3 width of the river and mixed together to obtain a composite sample. All the samples were collected at a depth of 15 cm to avoid introduction of floating particles. Some parameters like pH, temperature and conductance were measured in the field at the time of sample collection using portable kits. For other parameters samples were preserved by adding appropriate reagents and brought to the laboratory for chemical analysis. All chemicals used in the study were of analytical reagent grade and procured from Merck/BDH, India. Double distilled water was used through out the study. All glassware and other containers were thoroughly cleaned by socking in detergent and finally rinsed with double distilled water several times prior to use. The physico-chemical analysis was performed following standard methods (APHA, 1992; Jain and Bhatia, 1988). For DO analysis, Winkler method with addition of divalent manganese solution and alkali-iodide-azide reagent was used. The BOD_5 was measured by incubating the un-preserved samples for five days. Discharge at all sampling sites was also determined during each visit using current meter (Seba, Germany) by area-velocity method.

Mathematical Approaches

BOD Model

Mathematically 5 day BOD (BOD_5) can be expressed,

$$BOD_5 = L_0\left(1-e^{-K_d t}\right) \qquad \ldots (1)$$

The deoxygenation rate constant, K_d (1/day), has been estimated from the slopes of the plots taking BOD_5 values on a log scale (*y* axis) and the travel time between stream reaches on a normal scale (*x* axis) (Texas Water Development Board, 1971, Jha *et al.,* 2001).

For calculation of deoxygenation rate constant (K_d) and reaeration cefficient (K_r), the river Hindon reach R6–R7 (Maheshpur-Budhana) is selected. In this reach, there is no point-source contributing to the river. The water quality parameters used for the estimation of K_d and K_r include Dissolved Oxygen (DO) and 5 day Biochemical Oxygen Demand (BOD) of upstream/ downstream site of the reach and contributing point sources; photosynthesis by plants; respiration by plants; and water temperature. The 'light and dark' bottle method was used to determine photosynthesis and respiration rates and overall effect of these processes was observed to be zero in the present study.

DO Model

The rate at which oxygen is replenished is assumed to be proportional to the difference between the actual *DO* in the river at any given location, and the saturated value of dissolved oxygen. This difference is called the oxygen deficit *D* i.e.,

Rate of reaeration = $(K_r)_T D$

Where D = Dissolved oxygen deficit = $DO_s - DO \ldots$ (2)

DO_s = Saturated value of dissolved oxygen
DO = Actual dissolved oxygen at a given location in the river
$(K_r)_T$ = Reaeration coefficient at test temperature T (°C).

The value of $(K_r)_T$ is related to the value $(K_r)_{20}$ as follows,

$$(K_r)_T = (K_r)_{20} \times 1.024^{(T-20)} \qquad \ldots (3)$$

Use of the reaeration coefficient, K_r is essential for dissolved oxygen computation, to model streams and waste load allocation (Jha *et al.,* 2001). For the estimation of K_r, there are three basic approaches, namely, the dissolved oxygen balance technique (Streeter and Phelps, 1925; Churchill *et al.,* 1962), the distributed equilibrium technique (Zogorski and Faust, 1973; Edwards *et al.,* 1961) and tracer technique (Tsivoglou and Wallace, 1972), in practice. Besides these, various empirical relations exist to predict K_r. In the present study, the Dissolved Oxygen Balance Technique (DOBT) has been used. This technique consists of selecting a reach of the stream, measuring all the sources and sinks of Dissolved Oxygen (DO) with the exception of reaeration, and determining by difference the reaeration needed to give the DO concentration observed at the downstream of the reach. Under controlled conditions where all the sources and sinks of DO are monitored, the DO balance technique can be used effectively, as compared with the distributed equilibrium and tracer techniques (Jha *et al.*, 2001). Further, the DOBT used in the present study is a simple, more accurate and cost effective method. The general mass balance equation for DOBT is given by,

$$D = \frac{K_d L_0}{K_r - K_d}(e^{-K_d t} - e^{-K_r t}) + D_0 e^{-K_r t} \qquad \ldots (4)$$

where D is the dissolved oxygen deficit at time t (mg/L), K_d is the deoxygenation rate constant (1/day), t is estimated travel time (days), L_0 is the initial BOD (mg/L), D_0 is the initial DO (mg/L) and K_r is the reaeration coefficient (1/day).

RESULTS AND DISCUSSION

Physico-chemical Characteristics

The river Hindon rises in the Saharanpur district from Shivalik hills. In summer months the river is dry from its origin upto Saharanpur town. In effect, the effluents of Nagdev *nala* and Star Paper Mill generate the flow of water in the river. In the course of its flow, it also receives the municipal wastewater from Saharanpur and Muzaffarnagar towns. The first tributary, i.e., Western Kali meets river Hindon on its left bank near the village of Atali, which carries the municipal and industrial wastewater of Muzaffarnagar district. Another tributary, Krishni, meets river Hindon on its right bank near the village of Barnawa in Meerut district and carries the wastewater from sugar industries. In Ghaziabad district, downstream of Karhera village, majority of flow of the river is diverted to Hindon cut canal at Mohan Nagar which outfalls into river Yamuna upstream of Okhla barrage.

The river water is clear and odourless at station R1 (Khajnawar) and R2 (Beherki) while that at station R3 to R6 has foul and pungent organic smell due to the discharge of pulp and paper mill effluent. The odour becomes much more pronounced in summer months. In addition to the floating froth and foam, the river water also becomes brown in colour owing to the discharge of effluent of pulp and paper factory. The water is dark brown at stations R3 and R4, becoming light brown with black tinge at stations R5 and R6. The brown colour of the water reduces the penetration of light and affects the spectrum of the wavelength, which penetrates into the river water.

The pH values at different sampling stations are shown in Figure 2. The determination of pH serves as a valuable index which shows whether the waste is acidic or alkaline in nature. The pH of the river water was always found towards alkaline side except at station R4, where the river water is acidic in nature. The pH at station R1 and R2 ranges between 7.7–8.3 and 7.4–8.3 respectively. At station R4, the pH value gets reduced due to the mixing of distillery effluent and then slightly increased from station R5 to R7 after the discharge of wastewater from Dhamola *nala*. The values of pH show almost the same trend in the downstream section in between the stations R9 to R13. The variation in pH at different sampling station is well within the range of tolerance by the fish.

The electrical conductivity at different sampling stations are shown in Figure 3. The electrical conductivity varies from 328 to 411 µS/cm in the upstream section at village Khajnawar (R1). The same were found to vary from 1022 to 1926 µS/cm and 936 to 2605 µS/cm at station R3 and R4 respectively, mainly due to the mixing of effluent from Star Paper Mill and Cooperative distillery. The excess conductivity, thereby dissolved solids create an

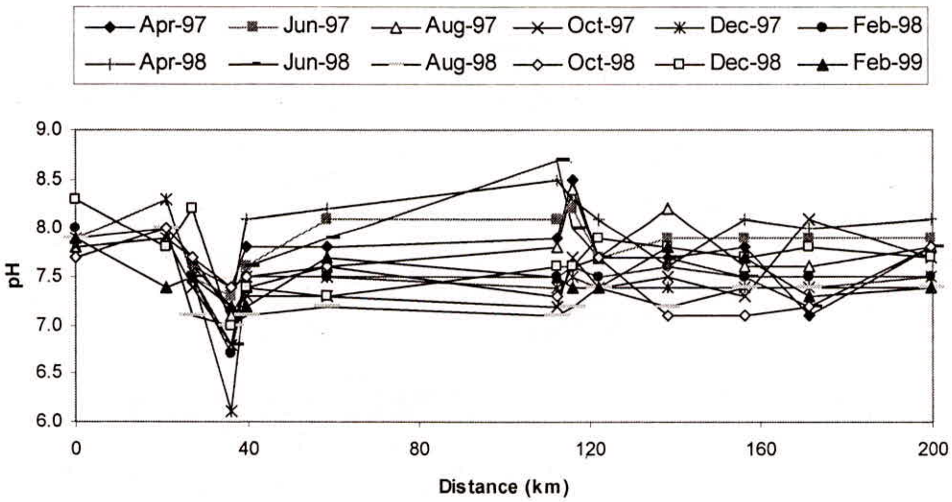

Fig. 2: Monthly variation of pH at different sampling points

imbalance due to increased turbidity and cause suffocation to the fish life even in the presence of high dissolved oxygen. The conductivity decreases considerably at station R-5, R-6 and R-7 due to the dilution effect of the Dhamola *nala*, which has significant flow throughout the year. A slight increase in conductivity was observed at station R-8 (Chandehri) due to the discharge of wastewater from Budhana drain, which then indicated a slight decreasing trend in the downstream section of the river.

The BOD values vary from 0.7 to 1.6 mg/L in the upstream section of the Hindon at the village of Khajnawar and from 0.8 to 1.2 mg/L at the village of Beherki. However, sudden rise in the BOD values was observed at stations R-3 and R-4 due to the discharge of paper mill and distillery effluents, these ranging from from 44 to 172 and 164 to 294 mg/L respectively (Figure 4). The higher values of BOD observed at these stations indicate high degree of organic pollution in this stretch of the river. The effluent of pulp and paper mill and distillery add to the high concentration of organic matter in the river, which is responsible for remarkable decrease in DO alongwith increase in BOD, COD and TDS alongwith other factors. From station R-4 to R-8, the oxygen condition improves significantly with the lowering of BOD values. At upstream of village Atali, the river Hindon has little flow due to significant abstraction for irrigation by the farmers in its course. At village Atali (Station R-9), the river Kali joins the Hindon and the water quality of river Hindon is controlled by the inputs from river Kali. The river Kali also receives significant amount of water from Upper Ganga Canal through Khatauli escape. At village Atali, the values of BOD and COD rises while DO decreases due to the discharge of municipal wastes from Budhana drain and Kali river into the river Hindon. From station R-9 to R-13, the BOD values shows a slight decreasing trend due to reaeration (Figure 4).

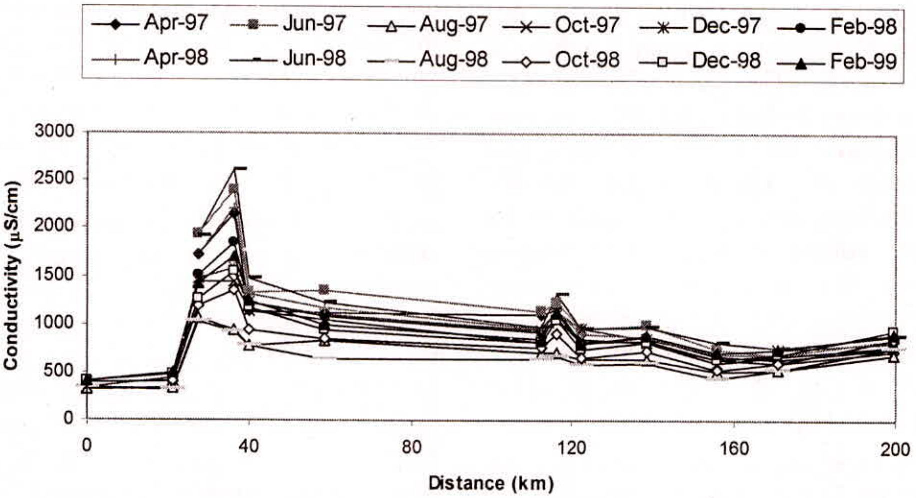

Fig. 3: Monthly variation of conductivity at different sampling points

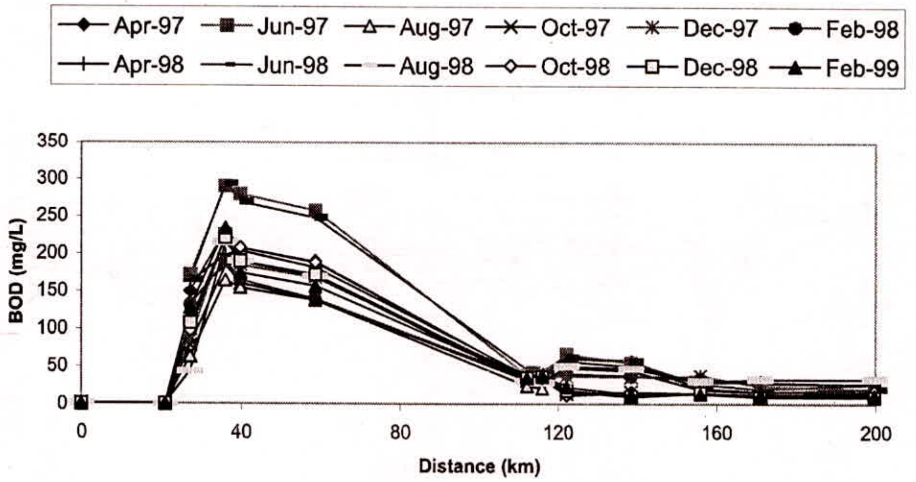

Fig. 4: Monthly variation of BOD at different sampling points

The dissolved oxygen content in the upstream section at Khajnawar was quite satisfactory (6.7 to 9.0 mg/L), but a critical situation was observed at station R-3 and R-4. The sudden fall in dissolved oxygen at stations R-3 and R-4 is attributed to the discharge of untreated municipal and industrial wastes from Nagdev *nala*, Star Paper Mill and Cooperative distillery. However, the distribution of dissolved oxygen at all the stations is not the same (Figure 5).

The dissolved oxygen content gets reduced to zero at station R-3 and R-4 during summer months so that complete anaerobic condition is developed. This indicates that the river flow is mainly composed of the wastewater generated from the industries. The DO values gradually improve from station R-5 to R-8 due to reaeration and photosynthesis. The river Kali is another polluted stream carrying wastewater of municipal and industrial establishments of Muzaffarnagar district and meets the river Hindon at village Atali (Station R-9) thus augmenting the flow of the river Hindon. It was observed that quite a substantial amount of water is discharged in river Kali from the Upper Ganga Canal at Khatauli. The level of dissolved oxygen in river Hindon after confluence with river Kali deteriorates further and observed to be nil during summer months. At village Barnawa, the another tributary Krishni joins river Hindon, which flows only during the winter season and remains stagnant for the rest of the year. In this stretch (Station R-9 to R-13), the dissolved oxygen shows a large variation depending on the flow in the river. During summer months, the dissolved oxygen even gets reduced to nil at station R-9 and R-10. The quality of the river water in this stretch is controlled by the discharge of water from the Upper Ganga Canal through Khatauli and Jani escapes.

River water temperature variation in different months for selected reaches is shown in Figure 6. In the reach R9–R10, the temperature varies from 17.2 to 31.4°C and 19.0 to 32.0°C at site R9 and R10 respectively. In the reach R11–R12, the temperature varies from 23.4 to 30.4°C and 24.4 to 30.4°C at site R11 and R12 respectively. Finally, in the reach R12–R13, the temperature varies from 26.0 to 31.0°C at site R13. The largest variation in the temperature was observed in the reach R9–R10.

Mathematical Approach

The deoxygenation rate constant (K_d), L_0, D_0 and D for the unpolluted reach R6–R7 were computed. Putting the values of these variables in equation (3) and using the Newton-Raphson alogorithm, the values of reaeration coefficient K_r for each data set, have been computed. The computed value of K_d and K_r of reach R6–R7 were summarized in Table 1 and were used for estimating the values of BOD and DO for the reach R9–R10, R11–R12 and R12–R13.

Table 1: The Computed Value of K_d and K_r for the Reach R6–R7 of River Hindon

Month	*Deoxygenation Rate Constant (K_d)*	*Reaeration Rate Constant (K_r)*
April 1997	0.5639	0.8102
June 1997	0.6317	1.0420
August 1997	0.7059	1.2030
October 1997	0.5775	1.3990
December 1997	0.6017	0.8012
February 1998	0.5523	0.8996
April 1998	0.4698	0.7992
June 1998	0.4413	0.8022
August 1998	0.6350	0.7008
October 1998	0.6034	0.7506
December 1998	0.5910	0.3496
February 1999	0.6692	0.3598

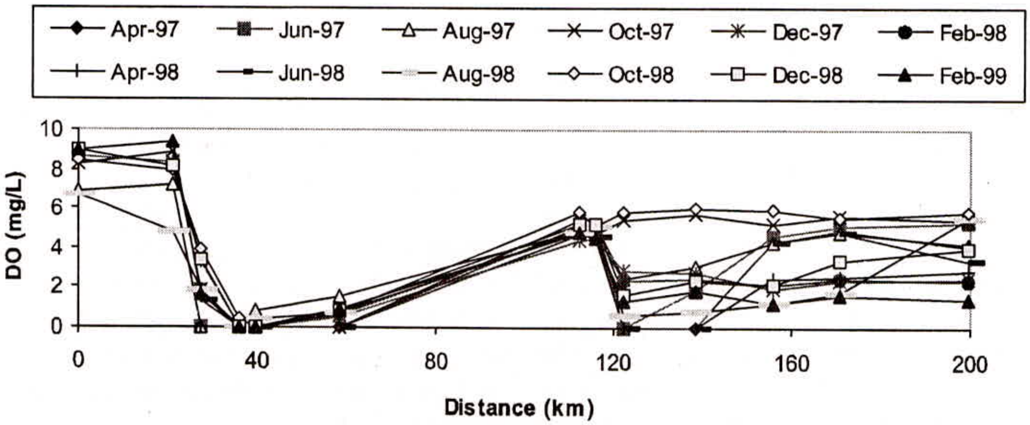

Fig. 5: Monthly variation of DO at different sampling points

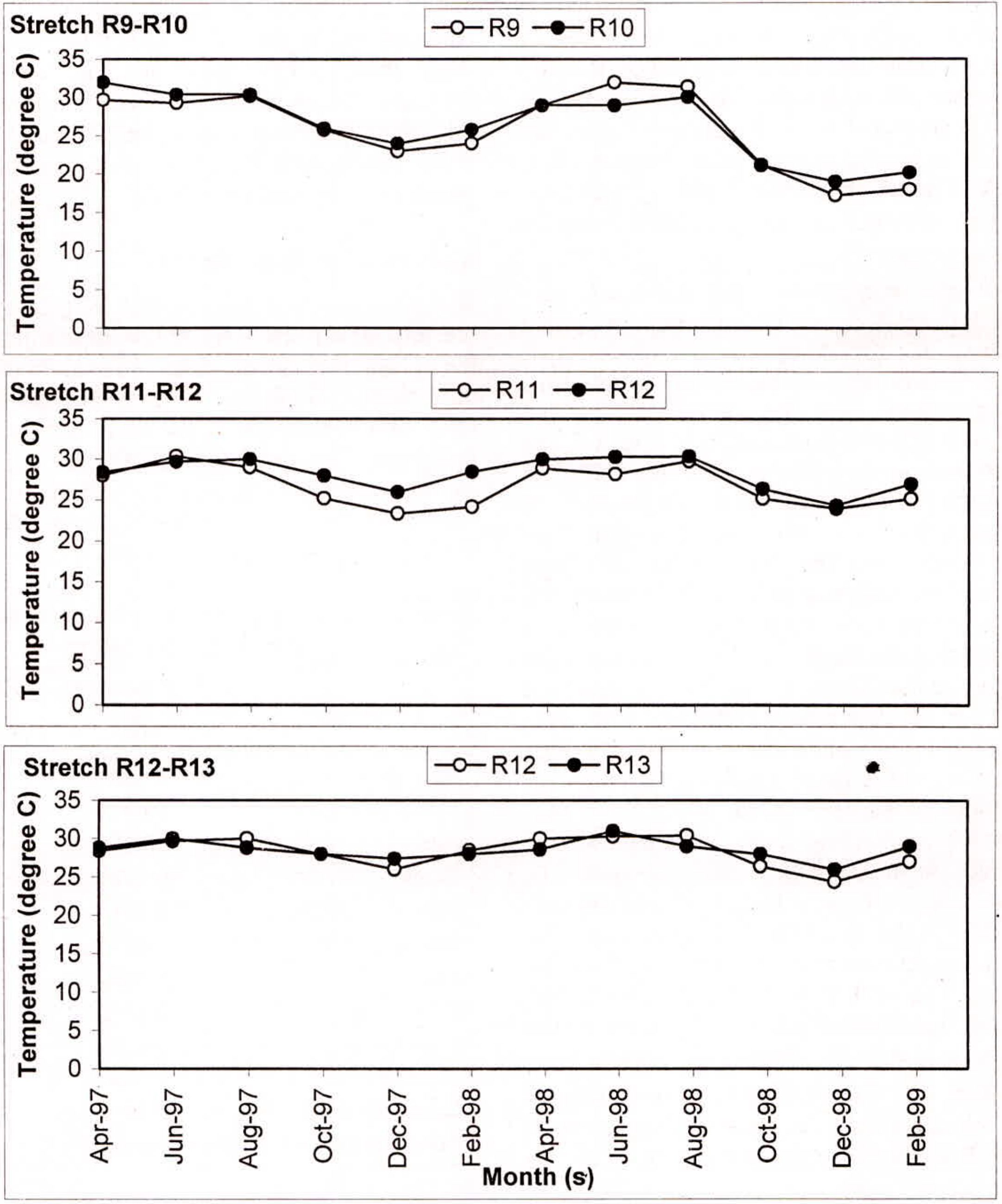

Fig. 6: Temperature variation in different strteches of the river

BOD Model

The BOD values for reaches R9–R10, R11–R12 and R12–R13 are calculated using BOD model defined by equation (1). The value of deoxygenation rate constant (K_d) used for calculation of BOD varies from 0.4413 to 0.7059 in different months. The computed values of BOD for these reaches with observed values in the field are summarized in Table 2 and plots between observed and computed values are illustrated in Figured 7 to 9.

DO Model

The DO values for reaches R9–R10, R11–R12 and R12–R13 are calculated using DO model defined by equations (2) and (4). The value of reaeration coefficient (K_r) used for calculation of DO varies from 0.3496 to 1.3990 in different months. The computed values of DO for these reaches with observed values in the field are summarized in Table 3 and plots between observed and computed values are illustrated in Figures 7 to 9.

Table 2: The Observed and Computed Value of BOD for Different Reaches of River Hindon

Month	*Reaches*					
	R9–R10		*R11–R12*		*R12–R13*	
	BOD_{obs}	BOD_{comp}	BOD_{obs}	BOD_{comp}	BOD_{obs}	BOD_{omp}
Apr. 1997	57.00	57.36	21.00	25.39	27.00	19.75
Jun. 1997	55.00	64.15	18.00	20.11	16.00	17.24
Aug. 1997	45.00	47.56	17.00	19.41	21.00	16.50
Oct. 1997	17.00	14.16	13.00	14.16	15.00	12.28
Dec. 1997	37.00	36.12	25.00	36.12	21.00	23.76
Feb. 1998	38.00	38.41	28.00	31.85	27.00	26.23
Apr. 1998	51.00	51.56	30.00	27.14	27.00	27.14
Jun. 1998	58.00	56.06	17.00	19.58	21.00	15.13
Aug. 1998	48.00	48.87	34.00	29.70	34.00	32.58
Oct. 1998	17.00	11.41	11.00	14.27	18.00	10.46
Dec. 1998	11.00	18.01	10.00	15.17	10.00	9.48
Feb. 1999	14.00	22.18	13.00	13.51	12.00	12.54

Table 3: The Observed and Computed Value of DO for Different Reaches of River Hindon

Month	*Reaches*					
	R9–R10		*R11–R12*		*R12–R13*	
	DO_{obs}	DO_{comp}	DO_{obs}	DO_{comp}	DO_{obs}	DO_{comp}
Apr. 1997	0.00	0.96	4.90	3.57	4.10	3.73
Jun. 1997	1.80	2.32	5.10	4.07	5.30	4.12
Aug. 1997	3.10	3.53	4.80	4.29	4.20	4.61
Oct. 1997	5.70	5.73	5.60	5.03	5.40	5.08
Dec. 1997	2.80	4.00	2.30	3.43	2.50	3.94
Feb. 1998	2.50	3.60	2.40	3.44	2.30	3.81
Apr. 1998	0.00	0.94	2.60	2.67	2.90	2.98
Jun. 1998	0.00	0.41	4.80	3.14	3.40	3.38
Aug. 1998	0.80	1.12	1.70	2.50	1.80	2.53
Oct. 1998	6.00	7.14	5.50	4.74	5.80	4.57
Dec. 1998	2.30	3.45	3.40	2.67	4.00	3.53
Feb. 1999	1.80	2.31	1.60	2.81	1.40	2.54

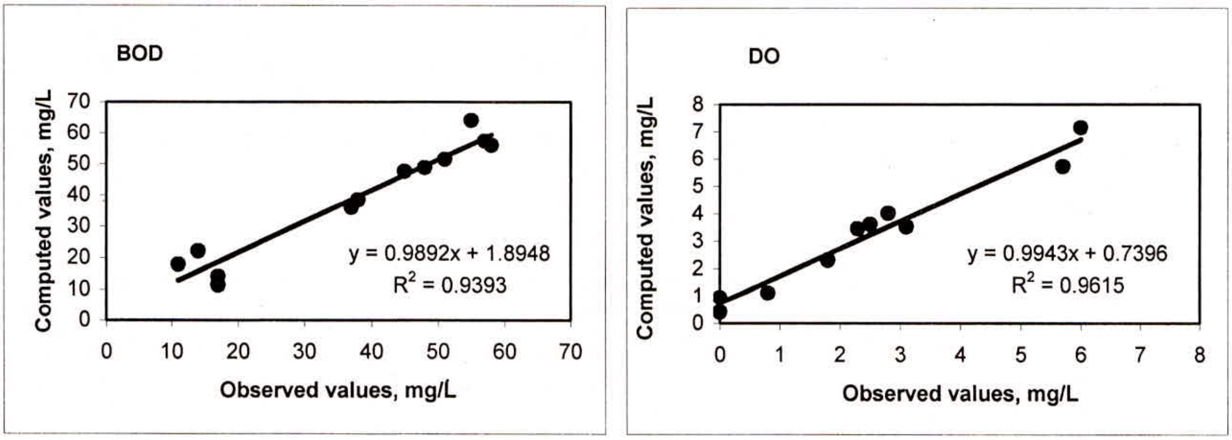

Fig. 7: Observed and computed BOD and DO for the strectch R9–R10

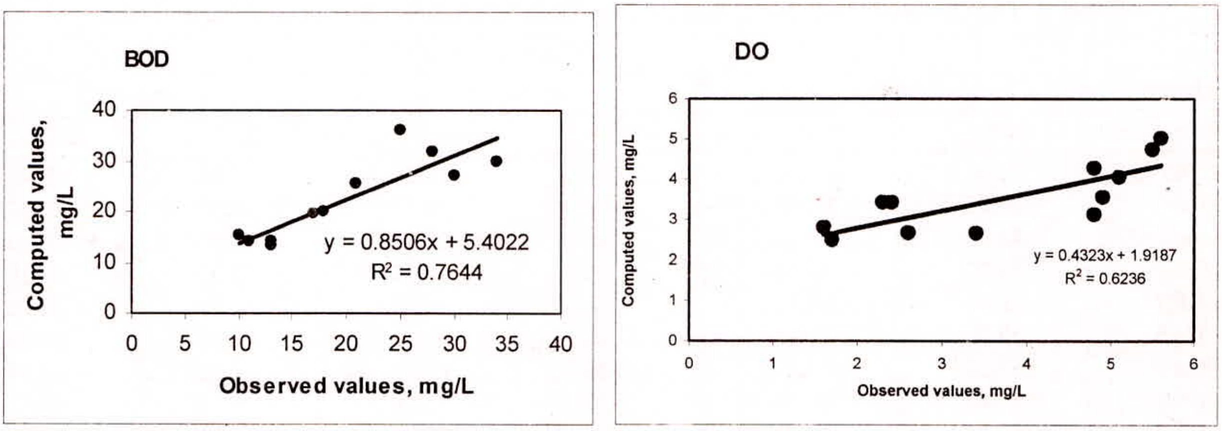

Fig. 8: Observed and computed BOD and DO for the strectch R11–R12

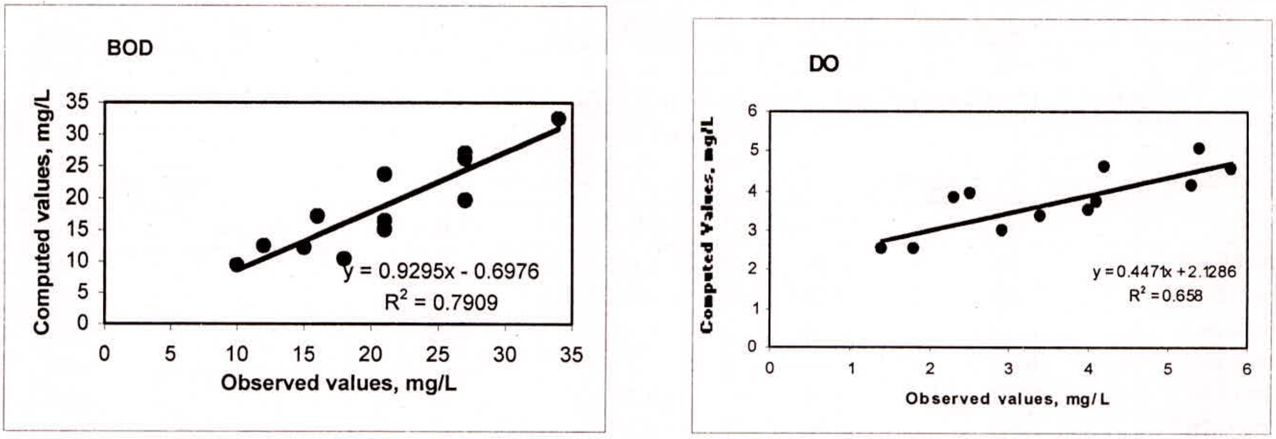

Fig. 9: Observed and computed BOD and DO for the strectch R12–R13

EVALUATION OF ERROR

The error estimation was carried out using statistics based on differential errors (SE), Mean Multiplicative Errors (MME) and a correlation coefficient. The standard error has been determined using the following equation,

$$SE = \left[\sum_{i=1}^{N} \frac{\left(K_P - K_M\right)^2}{N} \right]^{1/2} \qquad \ldots (5)$$

where N is the number of measurements and K_p and K_M are the predicted and measured values. The Mean Multiplicative Error (MME), K_p/K_M, which is considered to provide a better basis for assessing the impact of inaccuracies in predicting the variable (Moog and Jirka, 1998) is defined as,

$$MME = \exp\left[\frac{\sum_{i=1}^{N} \left| \ln\left(K_P/K_M\right)_i \right|}{N} \right] \qquad \ldots (6)$$

The correlation analysis can be used to measure the strength and statistical significance of the association between two or more random water quality variables. Presently, the values of this coefficient, r, have been computed by Pearson's product moment correlation equation.

Using equations (5) to (6), SE and MME for DO and BOD model for the selected reaches are estimated and plots of these errors are illustrated in Figure 10. It can be inferred from the plot that the SE and MME values are almost same for these reaches in both case of DO and BOD model (Moog and Jirka, 1998). The MME value, which is considered to be the most accurate criteria for error estimation, is observed to be uniform and very low. The maximum value of MME is observed for the reach of R11–R12 for both DO and BOD model, which may be attributed to the difference in the width and depth of this reach with that of R6–R7. From this discussion, it may be inferred that suggested DO and BOD models based on the dissolved oxygen balance technique (DOBT) may be successfully used for prediction of DO and BOD values for these above said reaches of the river Hindon.

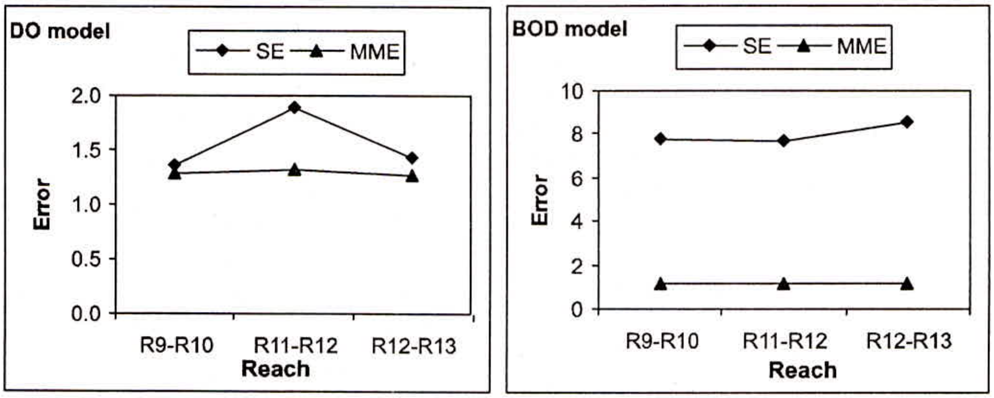

Fig. 10: Mean Multiplicative error for DO model and BOD model for different reaches

It was observed that estimated values of BOD and DO for the reach R9–R10 are in excellent agreement with the observed values having a correlation coefficient (r^2) 0.94 and 0.96 respectively (Figure 7). A fairly good agreement was observed for the reach R11–R12 with correlation coefficient (r^2) 0.76 and 0.62 respectively (Figure 8) and a good agreement was observed for the reach R12–R13 with correlation coefficient (r^2) 0.79 and 0.66 respectively (Figure 9). Lower values of correlation coefficient for reaches R11–R12 and R12–R13 may be attributed to the difference in the hydraulic characteristics of these reaches with that of R6–R7.

CONCLUSIONS

From the above discussion it may concluded that even for very complex riverine system like river Hindon, the Dissolved Oxygen Balance Technique (DOBT) can be successfully used for the computation of reaeration coefficient K_r, and thereby estimation of dissolved oxygen and biochemical oxygen demand for other reaches, which has no point sources contribution. Error estimation further indicated that DO and BOD models based on the Dissolved Oxygen Balance Technique (DOBT) may be successfully used for prediction of DO and BOD values. An excellent agreement was observed between observed and computed values of BOD and DO (r^2>0.9) for the reach R9–R10, while a good agreement (r^2≥0.7) was observed for reach R11–R12 and R12–R13.

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