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Modelling of Dissolved Oxygen Behaviour in Fast Moving Shallow Hilly Streams

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ABSTRACT: Surface water is highly susceptible to contamination with ever growing urbanization and industrialization worldwide. A variety of wastewaters are discharged into streams/rivers leading to depletion of Dissolved Oxygen (DO) of water due to organics stabilization by aerobic activities. DO in river water is a prime consideration for assessing river's health and to support aquatic lives therein. The domain of DO modelling is too extensive to cover each and every aspect, influencing DO behavior in streams. Earlier researchers worked upon modeling of DO using experimental data on a number of slow moving streams or rivers, but devoted less efforts towards fast moving shallow hilly streams. Also, the existing models do not account for some important factors like turbulence, geometry of streams etc., which are essential parameters in case of fast moving shallow hilly streams. The present paper attempts to formulate and modify the existing Bhargava's (1986) model for DO deficit by accounting the parameters like turbulence, width, depth and length of course of streams for the application in fast moving shallow hilly streams. The modified equatins were tested using the data available from literature on river Ganga in India. Experimental observations were also taken on Dikrong river, a shallow fast moving hilly stream in the state capital of Arunachal Pradesh in India, by introducing synthetic soluble glucose waste as pollutant and these observations were used to validate the developed model equations for the fast flowing shallow streams. The results indicate that agreement between the experimental and predicted DO deficits using Bhargava's (1986) model tested on Ganga river was found within ±30%, which reduced to ±23% with modified model. The agreement using simplified model was found even much better (within ±18%) when tested on fast moving shallow Dikrong river. Thus, the present modified model gives certainly a better prediction over the existing model and has a practical utility in assessing river's health, especially in case of fast moving shallow hilly streams.

INTRODUCTION

Dissolved Oxygen in river is one of the most important indices for assessing the river's health and is a prime consideration in streams assimilation capacity. It supports the fish and other aquatic lives in water bodies. With ever-growing urbanization and industrialization municipality waste waters flows into rivers/ streams, mostly being untreated. The discharged wastewater consumes dissolved oxygen from water during the process of stabilization. When an organic effluent is discharged into the river, number of forces and factors affects the self purification of the river. In many cases the oxygen demand initially exceeds the re-aeration rate, resulting into fall of DO concentration which is directly proportional to the oxygen deficit. Thereafter re-aeration predominates and the dissolved oxygen concentration rises to approach saturation DO level. It is not always feasible to measure the DO concentration of the water along the course of the downstream from the point of disposal of the wastes, therefore the variation of the DO and DO deficit along the course or river need to be represented with mathematical model to predict the variations.

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Streeter and Phelps (1925) formulated the mathematical model and tested on the Ohio River which had long uniform stretches between waste discharge and downstream points. Streeter and Phelps described the rate of bio chemical oxidation of the organic matter by a first order kinetics. Bhati and M. Bean (1986) have presented a steady state model for dissolved oxygen in river Speed (Canada). The model accounts for point source loading of organic wastes, natural re-aeration of streams, and artificial re-aeration due to effects of dams and affects of photosynthesis and re-aeration. The model is based on the development of a materials balance, which includes the sources and sinks of pollution, the various reaction phenomena as well as geophysical characteristics of river. The model is reasonably valid over an adequate range of input parameter values. The model is capable of dealing with the steady state situations where reaction rates, sinks and sources do not vary with time which is a major limitation of this model.

Bhargava, (1986) has presented a model for DO accounting bio flocculation and settling of the settleable organic matter during the travel of waste waters and the bio chemical degradation of the non-settleable organic matter. The model computes in sag in DO after sewage outfalls into the streams. Ghosh, N.C. (1996) presented a QUAL2E steady state model for water quality modeling of Kali River in U.P. India. The model was applied to predict the DO, BOD_5, nitrogenous and phosphatic profile of river water. Enhanced stream water quality model QUAL2E permits the simulation of several water quality constraints in a branching stream system, which are well mixed.

The original DO deficit model developed by Streeter Phelps in 1925 was based on BOD assimilation and re-aeration processes only which are affected by several factors. Some of the factors affecting de-oxygenation and re-aeration by two parameters namely deoxygenation constant (k) and re-aeration rate constant (k_R) were accounted in the model. Further improvement of model by Bhargava (1986) divides the organic fractions into settleable and non-settleable parts present in sewage to explain better the DO sag in the river. Although a lot of research works are in progress to improve the existing models to characterize the self purification of stream in much better way, but a number of parameters affecting DO deficit, such as the turbulence, the cross section geometry of river etc. yet to be incorporated especially for fast moving hilly streams. In the present work, it was felt necessary to incorporate these parameters to improve the model features and to examine their inputs on simulation of DO in fast moving shallow streams. The main objectives of the work includes developing of mathematical model for DO deficit for streams with a special emphasis on fast moving streams and testing and validation of the model using the literature data on Ganga river and Dikrong, River in Arunachal Pradesh, India by experimental observations.

MATHEMATICAL MODEL

All the mathematical models for DO sag in streams/ rivers are fundamentally based on the model developed by Streeter and Phelps in 1925, which predicts the change in the DO deficit as a function of BOD exertion and stream re-aeration. However the model does not account for BOD removal due to bio-flocculation followed by settling as well as biochemical degradation of non-settleable BOD. These phenomena do occur after organic wastes are discharged into streams which have been accounted for in the model developed by Bhargava (1986).

Bhargava, D.S. (1986) Model for DO Deficit

In stream purification, the settleable portion of the initial BOD concentration, S_{0-x} stabilizes within a transition time $T = d/v$ (days), where d = depth of river, v = settling velocity of settleable particles (m/day). On the other hand, the non-settleable organic fraction is S_{0-y} sustains and prolongs beyond transition period. Taking this phenomenon into consideration, Bhargava (1986) has proposed the models for DO deficit which are given below by Eqns. 1, 2 and 3.

For $t < T$ (Transition time)

$$D = \left(\frac{m}{k_R}\right) S_{0-x} \left\{1 - e^{-k_R t}\left[1 + \left(\frac{1}{k_R}\right)\left(\frac{v}{d}\right)\right] - \left(\frac{v}{d}\right)\left(t - \frac{1}{k_R}\right)\right\} + \left(\frac{k}{k_R - k}\right) S_{0-y}\left(e^{-kt} - e^{k_R t}\right) + D_0 e^{-k_R t} \quad \ldots (1)$$

For $t = T$ (Transition time)

$$D_T = \left(\frac{m}{k_R}\right) S_{0-x}\left[\left\{1 - e^{\left(-k_R \frac{d}{v}\right)}\right\}\left\{\left(1 + \frac{1}{k_R}\left(\frac{v}{d}\right)\right) - 1\right\}\right] + \left(\frac{k}{k_R - k}\right) S_{0-y}\left\{e^{\left(-k\frac{d}{v}\right)} - e^{\left(-k_R \frac{d}{v}\right)}\right\} + D_0 e^{\left(-k_R \frac{d}{v}\right)} \quad \ldots (2)$$

For $t > T$ (Transition time)

$$D=\left(\frac{k}{k_R-k}\right)S_{0-y}\left[e^{(-kt)}-e^{\left\{(k_R-k)\frac{d}{v}-k_Rt\right\}}\right]+D_Te^{\left\{-k_R\left(t-\frac{d}{v}\right)\right\}} \quad \dots (3)$$

Where, D is DO deficit (mg/L), S_{0-x} and S_{0-y} are BOD of settleable fraction and non-settleable fraction respectively (mg/L), k and k_R are de-oxygenation rate constant and re-aeration rate constant respectively in day^{-1}, d and v are the depth of the river (m) and velocity of flow (m/day), t is the time (day), D_0 *and* D_T are the dissolved oxygen concentration at time, $t = 0$ and at transition time, T (mg/L).

Modified Model for DO Deficit

In present work, Bhargava's (1986) model has been taken as basis. In order to account for the turbulence and the geometry of river, some new factors such as Reynold's Number (R), width (B), length (L) and depth (d) of stream have been introduced into the model. DO deficit can be expressed as a function of all these parameters as expressed as below,

$$D = f(L, t, C_i, C_s, g, R, d, B) \quad \dots (4)$$

Where, C_i = initial DO of river (mg/L) and g = acceleration due to gravity.

Considering length of the course of stream (L), time (t) and dissolved oxygen concentration at saturation (C_s) as repeating variables in Bukingham Pi theorem, the expression for DO deficit, D can be developed and expressed as,

$$D=C_s^{(1-a)}\left[RC_i,\frac{gt^2}{L^3}Bd\right]^a \quad \dots (5)$$

Where a = constant. This expression for 'D' accounts for the parameters most responsible for DO behaviour in fast moving hilly streams and is used as the modification to Bhargava's (1986) model. Eqn. 5 for D has been substituted in the Bhargava's (1986) models (Eqns. 1, 2 and 3) and the DO deficit model is developed. After the transition time, the settleable organic particles stabiles, therefore separate model equations have been developed for DO deficit for time less than, equal to and greater than transition time (Bhargava, 1986) for DO deficit.

For $t < T$,

$$D = mS_{0-x}t - mS_{0-x}\frac{vt^2}{2d} - S_{0-y}e^{-kt} - k_RC_s^{(1-a)}\left[\frac{RC_iBgd}{L^3}\right]\frac{t^{(2a+1)}}{(2a+1)} + D_0 + S_{0-y} \quad \dots (6)$$

For $t = T$, when $t = d/v$

$$D_T = mS_{0-x}\left(\frac{d}{v}\right) - mS_{0-x}\frac{d}{2v} - S_{0-y}e^{-k\left(\frac{d}{v}\right)} - k_RC_s^{(1-a)}\left[\frac{RC_iBgd}{L^3}\right]^a\frac{\left(\frac{d}{v}\right)^{(2a+1)}}{(2a+1)} + D_0 + S_{0-y} \quad \dots (7)$$

Beyond transition time i.e. when $t > T$, S_{0-x} is assumed as zero. Applying boundary condition such as $t = d/v$ and $D = D_T$, Eqn. 6 can be written as,

$$D = -S_{0-y}e^{-kt} - k_RC_s^{(1-a)}\left(\frac{t^{(2a+1)}}{(2a+1)}\right)\left[\frac{RC_iBgd}{L^3}\right]^a + D_T + S_{0-y}e^{-k\left(\frac{d}{v}\right)} + k_RC_s^{(1-a)}\left[\frac{RC_iBgd}{L^3}\right]^a\left[\frac{\left(\frac{d}{v}\right)^{(2a+1)}}{2a+1}\right] \quad \dots (8)$$

The constant 'a' is determined by equating the model equations 1, 2 and 3 with modified equations 6, 7 and 8 correspondingly and using the literature data on river Ganga. The estimated value of 'a' is 0.2.

At the critical condition deoxygenation and re-aeration are equal; therefore, $kS = k_RD$ (Streeter and Phelps 1925). Based on the main model as given in the Eqn. 6, Critical DO deficit (D_c) and critical time (t_c) were derived. The resulting expressions as follows:

For $t_c \le T$,

$$k_RC_s^{(1-a)}t_c^{2a}\left[\frac{RC_iBgd}{L^3}\right]^a = mS_{0-x}\left(1-\frac{\upsilon}{d}t_c\right) + kS_{0-y}e^{-kt_c} \quad \dots (9)$$

For $t_c > T$,

$$k_RC_s^{(1-a)}t_c^{2a}\left[\frac{RC_iBgd}{L^3}\right]^a = kS_{0-y}e^{-kt_c} \quad \dots (10)$$

The value of t_c can be estimated using Eqns. 9 and 10 by trial and error process. Substituting t_c into Eqns. 6 and 8 respectively one can determine D_c. Moreover, the oxygen sag curve is more accurately assessed by point of inflection, where the net rate of re-aeration is maximum and can be obtained by substituting, $\frac{d^2D}{dt^2} = 0$ and $t = t_i$.

Simplified Model for DO Sag Applicable to Soluble Wastes in Fast Moving Stream

The river Dikrong, does not receive any effluent either from municipality or from industries. To simulate the condition of soluble wastes (synthetic glucose waste) was discharged as continuous flow basis into the stream. Therefore, the fraction of settleable BOD, i.e. S_{0-x} has been assumed as zero in the simplified model. Also the transition time $T = d/v$ has been ignored as soluble glucose was discharged as pollutant. Therefore, modified model Eqns. 6 and 9 as applicable were further simplified and resulting expression for DO deficit, D, and critical time, t_c are expressed as:

For DO Deficit,

$$D = -S_{0-y}e^{-kt} - k_R C_s^{(1-a)}\left(\frac{t^{(2a+1)}}{(2a+1)}\right)\left[\frac{RC_iBgd}{L^3}\right]^a + D_0 + S_{0-y} \quad \ldots (11)$$

For t_c,

$$kS_{0-y}e^{-kt_c} = k_R C_s^{(1-a)}\left[\frac{RC_iBgd}{L^3}\right]^a \quad \ldots (12)$$

The value of D_c can be determined by estimating t_c from Eqn. 12 by trial and error and then substituting it into Eqn. 11.

PARAMETERS REQUIRED FOR MODELING AND THEIR ESTIMATION

De-oxygenation rate constant (k), re-aeration rate constant (k_R), are two important parameters used in the model equations. The rate at which BOD is satisfied at any time, t i.e. the rate of de-oxygenation is a function of temperature and the amount of organic matter remaining at that follows a first order kinetics (Streeter and Phelps, 1925 and Bhargava, 1986). The constant, k was experimentally determined using following expression,

$$k = \frac{L_0 - L_t}{L_t \times t} \quad \ldots (13)$$

Where, L_t = BOD remaining at any time, t (mg/L), L_0 = BOD at start i.e. ultimate BOD (mg/L).

For determination of k, the synthetic glucose waste (0.333 g/L) was discharged into the river at a flow rate of 1.2 litres/minute and the DO content and the corresponding BOD of the waste was determined at t = 0 min and 60 minutes at a distance 2.5 m downstream of the point of disposal. The constant k_R was also determined similarly using the value of DO at t = 0 min, D_0 and 60 minutes, D_t after discharging the waste into the stream using following equation,

$$k_R = \frac{D_t - D_0}{D_t \times t} \quad \ldots (14)$$

The average value of k and k_R were found as 4.0 day^{-1} and 18.5 day^{-1} respectively. Width of the rivers (B), mean depth of the river (d), length of the course of river (L), velocity of flow (v), mean temperature of river water, initial BOD of waste discharged (S_0), DO of the river water, at various locations and different instant of time (t), initial DO of the river water (C_i), saturated DO of the river water (C_s), DO and BOD of synthetic glucose waste were measured at laboratory by fixing the DO at the river site itself. Reynold's number (R) has been judiciously assumed as 2010 for turbulent flows. BOD of settleable fraction (S_{0-x}) although used in the modified model equations but did not require in the simplified model. BOD of non-settleable particles i.e. of glucose used in this study (S_{0-y}) was determined in the laboratory.

TESTING OF THE MODEL EQUATIONS

In order to verify and compare the accuracy of the model equations, Bhargava's (1986) model, modified model and simplified models given earlier in this paper, have been tested with the literature data and experimental observations on Dikrong river.

Bhargava's (1986) Model

The Bhargava's (1986) model has been tested with the literature data on the Ganga river near Kanpur (Bhargava, 1986). Table 1 presents the comparison of the predicted DO and DO deficit with the observed DO and DO deficit including percentage error band Figure 1 shows that experimental and predicted DO deficit lie within ±30% wide error band. It can also be seen from the figure that all the data points lies within –4% to –30% negative error band indicating that predicted DO deficit from the model equations is always lesser than the experimental observations. The variation of DO deficit versus time is shown in Figure 2 for predicted values (Bhargava, 1986 and modified model) and experimental values on Ganga river. From Figure 2, it can be seen that the Bhargava's (1986) model does not give better prediction and is also not in close resemblance to the experimental DO sag curve.

Table 1: Computation of DO and DO Deficit in Ganga River at Kanpur (summer) Using Bhargava's (1986) Model

Time (days)	*Distance From Sewage Outfall, (m)*	*Predicted DO Deficit, D mg/L*	*Observed DO Deficit, D' mg/L*	*Predicted DO, C mg/L*	*Observed DO, C' mg/L*	*Percentage Error in DO Deficit, mg/L*
0.000	0	3.750	3.750	4.000	4.00	0.00
0.002	94	4.090	–	3.660	–	–
0.005	234	4.415	–	3.335	–	–
0.010	467	4.920	7.000	2.830	0.75	29.71
0.013	607	5.312	–	2.438	–	–
0.020	934	5.418	5.860	2.332	1.89	7.54
0.023	1050	5.453	–	2.297	–	–
0.025	1167	5.445	7.010	2.305	0.74	22.33
0.050	2333	5.170	5.610	2.580	2.14	7.84
0.075	3500	4.800	5.020	2.950	2.73	4.38
0.100	4666	4.590	5.200	3.160	2.55	11.73
0.150	6999	4.014	4.800	3.736	2.95	16.38

Input Parameters: Average Velocity = 0.54 m/secs, Saturation DO (C_s) = 7.75 mg/L, Predicted DO = $C_s - D$, Observed DO = $C_s - D'$, m = 9.0d^{-1}, k = 3.5 d^{-1}, k_R = 9.0d^{-1}, m = 9.0d^{-1}, S_{0-x} = 16 mg/L S_{0-y} = 12 mg/L, D_0 = 3.75 mg/L, T = d/v = 0.025 d^{-1}, C_i = 4.0 mg/L, R = 2010, B = 120 m, d = 5 m, g = 9.81 m/sec^2, a = 0.20.

Modified Model

The modified model has been tested using the literature data on Ganga river (Bhargava, 1986). Predicted DO deficit (D), observed DO deficit (D'), predicted DO and observed DO as well as percentage error in prediction of DO deficit by modified model are presented in Table 2. The variation between the experimental and predicted DO deficits is found within ±23% wide error band as can be seen in Figure 3. Therefore, it can be inferred that the error band (±30%) using Bhargava's (1986) model is reduced to ±23% using modified model. From Figure 2, it can also be seen that the modified model predicts the DO sag better than the Bhargava's (1986) model and is in close agreement to the experimental DO sag curve.

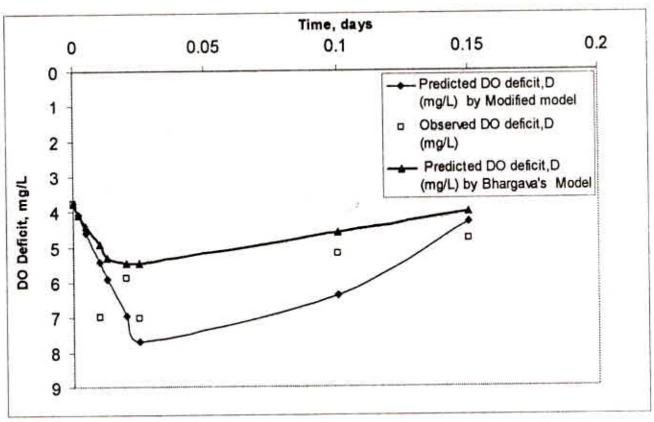

Fig. 2: Variation of observed and predicted DO deficit *vs.* time for Ganga river using Bhargava's (1986) model and modified model

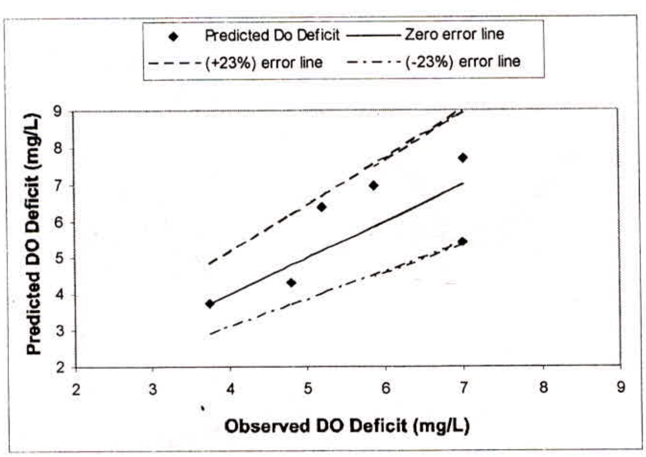

Fig. 1: Comparison of predicted and observed DO deficits using Bhargava's (1986) model

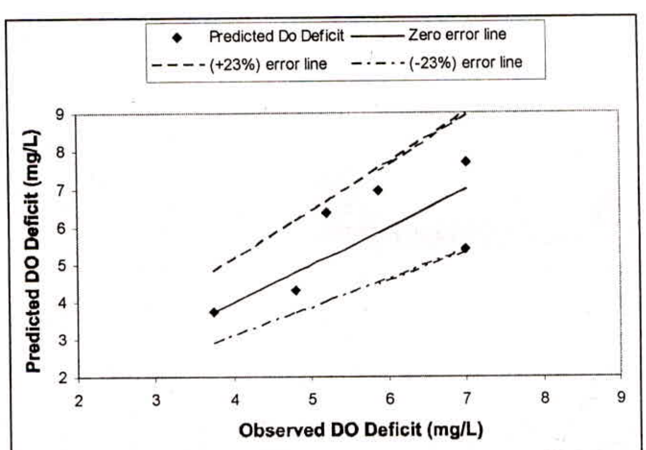

Fig. 3: Comparison of predicted and observed DO deficits using modified model

Table 2: Computation of DO Sag of Ganga River at Kanpur (Summer) Obtained from Modified Model

Time (days)	*Distance From Sewage Outfall, (m)*	*Predicted DO Deficit, D mg/L*	*Observed DO Deficit, D' mg/L*	*Predicted DO, C mg/L*	*Observed DO, C' mg/L*	*Percentage Error in DO Deficit, mg/L*
0.000	0	3.75	3.75	4.00	4.00	0.00
0.002	94	4.10	–	3.65	–	0.00
0.005	234	4.61	–	3.14	–	0.00
0.013	607	5.89	–	1.86	–	0.00
0.020	934	6.96	5.86	0.99	1.89	–18.77
0.025	1167	7.70	7.01	0.05	0.74	–9.84
0.100	4666	6.39	5.20	1.36	2.55	–22.88
0.150	6999	4.31	4.80	3.44	2.95	10.21

Input Parameters: average velocity = 0.54 m/secs, Saturation DO (C_s) = 7.75 mg/L, Predicted DO = $C_s - D$, Observed DO = $C_s - D'$, m = 9.0d^{-1}, k = 3.5 d^{-1}, k_R = 9.0d^{-1}, m = 9.0d^{-1}, S_{0-x} = 16 mg/L S_{0-y} = 12 mg/L, D_0 = 3.75 mg/L, T = d/v = 0.025 d^{-1}, C_i = 4.0 mg/L, R = 2010, B = 120 m, d = 5m, g = 9.81 m/sec^2, a = 0.20.

Simplified Model Applicable to Soluble Waste for Fast Moving Streams

The Reynold's number (R) is one of the main controlling factor of DO sag in turbulent streams because, the eddies caused due to turbulence leads faster re-aeration. The modified model was then simplified accounting above factor and given by equations (11 and 12), which are applicable to soluble wastes, hence the validity of the simplified model was tested using data on Dikrong river.

The experimental data were obtained by discharging synthetic glucose as pollutant into middle of stream. Thus, the settleable portion of total BOD was nil. The data acquired during the experiments were: average velocity = 0.53 m/secs, S_{0-y} = 14 mg/L, C_i = 8.7 mg/L, B = 58.3 m and d = 0.63 m. Table 3 presents the comparison between the predicted and observed DO and DO deficits at two locations (50m and 100m) down stream of point of waste disposal. The DO sag curve at these two locations predicted by the simplified model and obtained from observed data are presented in the Figure 4. It is inferred from the Figures 5 and 6 that the prediction of the DO deficit by this model lies within ±18% wide error band at both the locations, indicating better estimation of the DO deficits at shallow fast moving stream. The values of t_c, D_c, are obtained as 0.025 days, 0.425 mg/L respectively for 50 m distance and 0.056 days, 0.927 mg/L for 100 m distance respectively.

Table 3: Computation of Simple DO Sag of Dikrong River at a Distance of 50 m and 100 m Downstream from the Point of Discharge Using Simplified Model

Time (days)	*Distance From Sewage Outfall, (m)*	*Predicted DO Deficit, D mg/L*	*Observed DO Deficit, D' mg/L*	*Predicted DO, C mg/L*	*Observed DO, C' mg/L*	*Percentage Error in DO Deficit, mg/L*
0.000	50	0.030	0.03	8.70	8.70	0.00
0.003	50	0.160	0.14	8.57	8.59	–14.29
0.007	50	0.310	0.33	8.42	8.40	6.06
0.021	50	0.670	0.61	8.06	8.12	–9.84
0.004	50	0.900	0.76	7.83	7.97	–18.42
0.080	50	0.715	0.61	8.015	8.12	–17.21
0.125	50	0.000	.00	8.73	8.73	0.00
0.000	100	0.030	0.030	8.7	8.7	0.00
0.003	100	0.014	0.017	8.59	8.56	17.65
0.007	100	0.260	0.310	8.47	8.42	16.13
0.021	100	0.424	0.430	8.31	8.30	1.40
0.004	100	0.290	0.370	8.54	8.52	21.62
0.080	100	0.000	0.000	8.73	8.73	0.00
0.125	100	0.000	0.000	8.73	8.73	0.00

Input Parameters: Average Velocity = 0.53 m/sec, Saturation DO (C_s) = 7.75 mg/L, Predicted DO = $C_s - D$, Observed DO = $C_s - D'$, k = 4.0 d^{-1}, k_R = 18.5d^{-1}, S_{0-y} = 14 mg/L, D_0 = 0.03 mg/L, C_s = 8.73 mg/L, C_i = 8.7 mg/L, R = 2010, B = 58.3 m, d = 0.63m, g = 9.81 m/sec^2, a = 0.20.

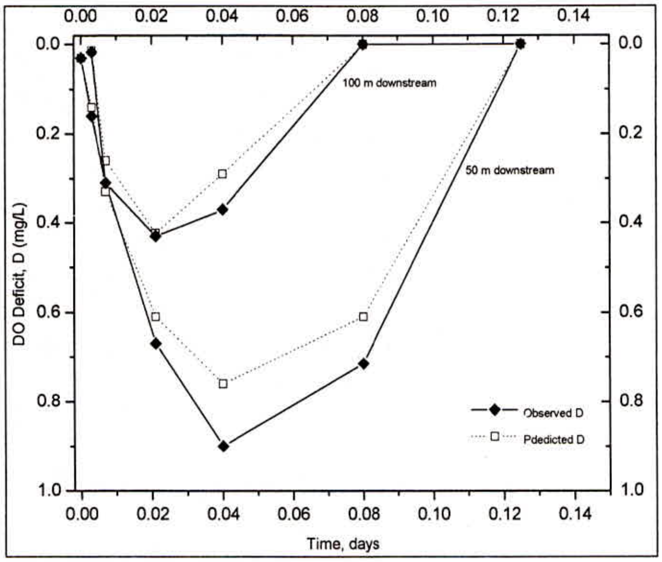

Fig. 4: Variation of Experimental and Predicted DO deficit vs. time using simplified modified model at a distance of 50 m and 100 m downstream from point of discharge for Dikrong River

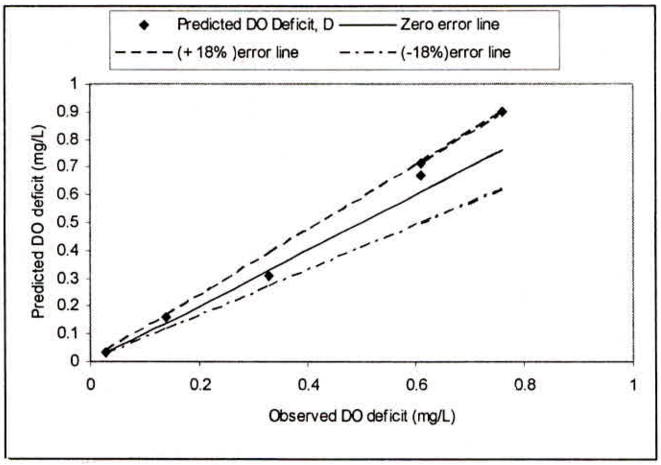

Fig. 5: Comparison of predicted and observed DO deficits using simplified model at 50 m downstream of the point of disposal of the wastes

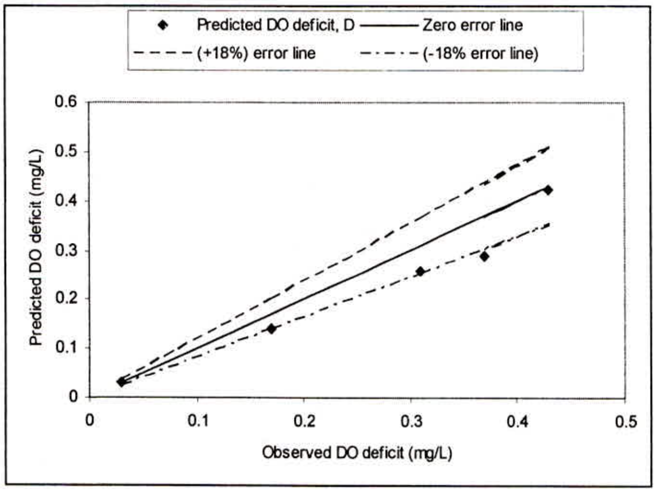

Fig. 6: Comparison of predicted and observed DO deficits using simplified model at 100 m downstream of the point of disposal of the wastes

CONCLUSIONS

The models developed in the present work are extremely useful for the fast flowing shallow river especially in the hilly areas. The main emphasis in this project was given to check the accuracy of the Bhargava's (1986) model in prediction of the DO and DO deficit especially in the hilly stream where turbulence is a prime concern. The detail testing and validation of the Bhargava's (1986) model and modified model indicated that the Bhargava' (1986) model gives good prediction in case of non turbulent rivers but has limitation in case of hilly streams where the river bed is non uniform with higher velocity of flow. On verification of the Bhargava's (1986) model it was found that the predicted DO deficits are within ±30% error range when tested on Ganga river during non monsoon season. The prediction of the DO deficit by the modified model is found still better (±23% error band) than the Bhargava's (1986) model. The simplified model is found much better in prediction of DO deficit for Dikrong river and soluble waste where the error band was within ±18% and the velocity of the flow was 0.53 m/sec.

The applicability of the modified and simplified models become more versatile as it incorporated the turbulence and geometry of the river cross section. Therefore it can be concluded that the developed models in the study could provide a excellent solution in characterization of the DO Sag in the fast moving hilly stream.

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