Deoxygenation and Reaeration Coupled hybrid Mixing cells Based Pollutant Transport Model to Assess water Quality Status of a River

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ABSTRACT: Prediction of spatial and temporal variation of water quality is vital for managing pollutants disposal into the rivers. Depletion of dissolved oxygen (DO) takes place due to the consumption of oxygen by microbes to digest bio-degradable pollutants which enter a water course. Reaeration takes place in a specific rate depending on DO deficit. Many investigators have formulated models as an alternative to the Fickian Model for the advection dispersion pollutant transport. Since Streeter-Phelps research on BOD-DO modeling, many researchers have studied fate of pollutant considering first order reaction along with only advection. The Streeter-Phelps dispersion model includes deoxygenation and reaeration along with advection and dispersion and which has been solved by defining an axillary variable relating DO deficit and BOD concentration. Thus this paper considered first order decay and reaeration along with advection and dispersion to simulate spatial and temporal variation of DO concentration using a hybrid mixing cells model. The proposed model has been successfully applied for a hypothetical flow conditions and the River Brahmani, India. River flow requirement and regulation for pollutant disposal with pre-treatment were optimized using the responses of proposed model for this River. This research analyzed the selected river reach using proposed model having a particular flow and channel characteristics and found that release of $1180m^3/s$ from Rengali Dam is required to avoid pollution problem. However, in absence of this flow at least 50% of pretreatment pollutants are required before released into river Tikira.

Key words: Decay, Reaeration, DO Deficit, Water Quality Modelling, River Brahmani

INTRODUCTION

Streams are the major source of water for meeting the domestic, industrial and agricultural requirements. Owing to the rapid urbanization and industrialization, pollutant load to the streams has increased manifold, resulting in the degradation of stream water quality, due to the limited assimilation capacity. Consequently, the associated stream ecosystem is becoming endangered, as it both gains and loses oxygen in the process. Oxygen is gained from the atmosphere and aquatic plants, whereby running water, because of churning, dissolves more oxygen than still water does. On other hand respiration by aquatic lives, pollutant decay and various chemical reactions consume oxygen. According to many authors, non-conservative pollutant decay is governed by a first order reaction kinetics (Streeter and Phelps, 1925; 1944; Rinaldi *et al*. 1979; Thomman and Muller, 1987). Moreover effluents from sewage treatment plants are decomposed by

microorganisms by consuming oxygen from water. Other sources of oxygen-consuming waste include storm water runoff from farmland or urban streets, feedlots, and failing septic systems. Oxygen is measured in its dissolved form as dissolved oxygen (DO). If more oxygen is consumed than is produced, dissolved oxygen levels decline and some sensitive aquatic lives may be forced to migrate, as they would alternatively deteriorate, or even die. DO levels fluctuate both seasonally and during the day. They also vary with water temperature and altitude. Cold water holds more oxygen than warm water and less oxygen can be retained at higher altitudes. Thus, due to thermal discharges, such as cooling water used in a power plant, raise the water temperature and lower its oxygen content. Aquatic lives are most vulnerable to lowered DO levels. Hence, correct assessment and prediction of DO in an aquatic environment is imperative for maintaining the ecosystem integrity and

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regulating the pollutants disposal to the streams. Stream water quality modeling has a long history since development of Streeter and Phelps equation for BOD-DO modeling in 1925. Streeter and Phelps (1944) later gave a generalized equation relating the rate of the biochemical oxidation of pollutants and the dissolved oxygen concentration. This approach accounts advection and decay of pollutant and de-oxygenation and re-aeration processes. After Streeter and Phelps, several concepts were introduced (Bhargava, 1983; Bobba *et al.*, 1983; Barnwell, 1985; Thomman and Muller, 1987; Choudhary *et al.*, 1990; Jolanki, 1997; Guymer, 1998; Sharma *et al.*, 2000) to study pollutant dispersion and decay. All these approaches assumed that the pollutants released into streams decay according to a first order reaction, i.e., the rate of substance loss is always proportional to its concentration.

Young and Beck (1974) proposed continuously stirred tank reactor concept (CSTR) by joining assumptions of hydrology and chemical engineering to account the BOD-DO reactions and the dispersion in the channel. Rinaldi *et al.*, (1979) defined the auxiliary variable that relates the dissolved oxygen deficit and BOD load to obtain the solution for the Streeter-Phelps dispersion model. Cheng et. al., 2000 presented a numerical model to simulate two-dimensional reactive transport in shallow water domains accounting sediment distribution and more conceivable reactions. Tyagi *et al.*, (1999) simulated DO-BOD dispersion accounting varying BOD source using explicit finite difference numerical scheme. As an alternative to advection-dispersion equation model (ADE), Cells-In-Series (CIS) approach (Bear, 1972; Banks, 1974; Vander Molen, 1979; Beltaos, 1980; Stefan and Demetracopoulos, 1981; Yurtsever, 1983; Beven and Young, 1988; Young and Wallis, 1993; Wang and Chen, 1996) has been extensively used in the past for studying solute transport. The advantage of the CIS model is that the governing second order partial differential equation of ADE model is reduced to a first

order ordinary differential equation (Ghosh 2001; Ghosh *et al.*, 2008). However, researchers (Banks, 1974; Stefan and Demetracopoulos, 1981; Ghosh 2001; Ghosh *et al.*, 2004; Ghosh *et al.*, 2008) have shown that the CIS model has limitations and which does not adequately simulate the advection component of pollutant transport. Aggregated Dead Zone (ADZ) model (Beer & Young, 1983) and Aggregated Mixing Zone (AMZ) model (Beven & Young, 1988) incorporate advective time delay to the dead zone approach and brought improvement in the simulation of solute transport. However there exist a practical difficulty in identifying and estimating the model coefficients (Rutherford, 1994). The Hybrid Cells In Series (HCIS) Model (Ghosh 2001) over comes the difficulties with ADE and CIS models and thus which has been used to simulate advection-dispersion solute transport (Ghosh 2001; Ghosh *et al.*, 2004; Ghosh *et al.*, 2008). As the HCIS model seems to overcome the limitations of the ADE, the CIS and the ADZ models, it has been further developed to account pollutant sorption process (Muthukrishnavellaisamy K *et al.*, 2011) and decay process (Muthukrishnavellaisamy K *et al.*, 2013) along with advection and dispersion. In this paper, DO concentration has been simulated using the hybrid mixing cells model that incorporates de-oxygenation and re-aeration along with advection and dispersion. The proposed model has also been applied to assess water quality status of river Brahmani, India.

MATERIALS & METHODS

Let us consider a river reach conceptually consists of serious of hybrid units. Each hybrid units are assumed to consist of a plug flow and two well mixed cells with unequal residence time, all connected in series is shown in Fig. 1.

Let the initial concentration of pollutant in each cell be zero, whereby the boundary concentration changes from 0 to C_R. In addition, the initial DO concentration, $C_{DO}(x, 0)$ is set to be equal to S_{DO}, where S_{DO} is saturated DO concentration. In the plug flow
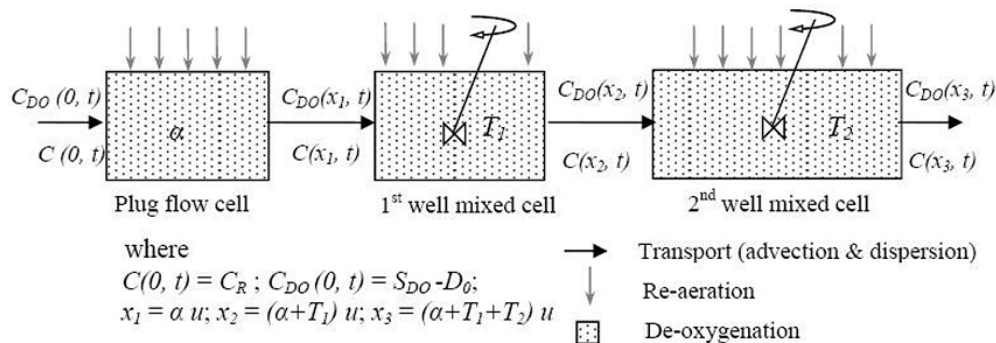

where $C(0, t) = C_R$; $C_{DO}(0, t) = S_{DO} - D_0$;
$x_1 = \alpha u$; $x_2 = (\alpha + T_1) u$; $x_3 = (\alpha + T_1 + T_2) u$

Transport (advection & dispersion)
Re-aeration
De-oxygenation

Fig. 1. Conceptual hybrid unit to represent the transport, decay and re-aeration processes

cell, the fluid is replaced in time α. The pollutant loses some fraction of its concentration due to the decay during downstream transport, as a result of oxygen consumption at a rate, k_1. At the same time, re-aeration takes place, the rate of which depends upon the DO deficit. In the first well mixed cell, whose filling time is T_1, the fluid is thoroughly mixed before entering the second well mixed cell characterized by filling time T_2. De-oxygenation and re-aeration processes take place in all the cells of the hybrid model, and both follow the first order reaction kinetics. The flow rate is Q m^3/unit time and is under steady state condition. Based on these considerations, the aim of this work is to predict the DO concentration at the end of a hybrid unit using Laplace transform and at the end of subsequent units by convolution technique.

Let us consider a plug flow cell of volume, V_0, through which a non-conservative pollutant is transported. Within the plug flow cell, the pollutant concentration in a control volume of size, "x, is denoted as $C(x, t)$. Due to the decay process, some fraction of the pollutant concentration is lost, whereby the remaining pollutant is replaced by the following plug and moved forward in a time interval "t. As the pollutant decays, the dissolved oxygen is consumed from the stream water. At the same time, oxygen levels in the water are replenished from atmosphere at a specific rate. Here we denote the concentration of dissolved oxygen as C_{DO}. Under a steady state flow condition, considering mass balances for the pollutant concentration and dissolved oxygen (DO), the following partial differential equations have been formulated.

$$\frac{\partial C(x,t)}{\partial t} + u\frac{\partial C(x,t)}{\partial x} = -k_1 C(x,t) \tag{1}$$

$$\frac{\partial C_{DO}(x,t)}{\partial t} + u\frac{\partial C_{DO}(x,t)}{\partial x} = \tag{2}$$

$$-k_1 C(x,t) + k_2\left[S_{DO} - C_{DO}(x,t)\right]$$

The initial and boundary conditions for Eq. (1) and Eq. (2) are

$$C(x,0) = 0, \qquad x > 0; \tag{3 a}$$

$$C(0,t) = C_R, \qquad t \geq 0; \tag{3 b}$$

$$C(\alpha u,t) = 0, \qquad 0 < t < \alpha; \tag{3 c}$$

$$C_{DO}(x,0) = S_{DO}, \qquad x > 0; \tag{3 d}$$

$$C_{DO}(0,t) = S_{DO} - D_0, \quad t \geq 0. \tag{3 e}$$

where C_R is the pollutant concentration at the inlet boundary, S_{DO} is the saturated dissolved oxygen concentration and D_0 is the boundary deficit of dis-

solved oxygen concentration due to the entry of waste water with lesser dissolved oxygen.

Considering DO deficit $D = S_{DO} - C_{DO}$ and it's derivatives, Eq. (2) can be solved for DO deficit by incorporating solution of Eq. (1). Then C_{DO} can be obtained by rearranging the DO deficit solution as follows

$$C_{DO}(x,t) = S_{DO} - \left\{ C_R\left(\frac{k_1}{k_2 - k_1}\right) \right.$$

$$\left.\left[e^{-\frac{k_1}{u}x} - e^{-\frac{k_2}{u}x}\right]U\left(t - \frac{x}{u}\right) + D_0 e^{-\frac{k_2}{u}x}U\left(t - \frac{x}{u}\right)\right\} \tag{4}$$

As the residence time of plug flow cell is α, the size of the plug flow cell αu. Hence the DO concentration at the end of plug flow cell can be got from Eq. (4) by replacing x with αu.

The effluent from the plug flow cell is the influent to the first well mixed cell. Decay of the pollutant takes place in the first well mixed cell too. Therefore, dissolved oxygen is consumed in a particular rate for the decay process and simultaneously re-aeration takes place at a specific rate. Considering the mass balance for the pollutant concentration and dissolved oxygen (DO) in the first well mixed cell, the following ordinary differential equations have been formulated.

$$\frac{dC_{M1}}{dt} = \frac{C_R\, U(t-\alpha)e^{-k_1\alpha}}{T_1} - \left(\frac{1 + k_1 T_1}{T_1}\right)C_{M1} \tag{5}$$

$$\frac{dC_{DO}}{dt} = \frac{1}{T_1}\left\{S_{DO} - \left\{C_R\left(\frac{k_1}{k_2 - k_1}\right)\left[e^{-k_1\alpha} - e^{-k_2\alpha}\right]\right. \right.$$

$$\left.U(t-\alpha) + D_0 e^{-k_2\alpha}U(t-\alpha)\right\} \tag{6}$$

$$-\frac{C_{DO}}{T_1} - k_1 C_{M1} + k_2\left(S_{DO} - C_{DO}\right)$$

Considering DO deficit $D = S_{DO} - C_{DO}$ and it's time derivative, Eq. (6) can be solved for DO deficit by incorporating solution of Eq. (5) and rearranging the solution for C_{DO}, one can get

$$C_{DO}\left[(\alpha + T_1)u,t\right] = S_{DO} - \left\{ \begin{array}{l} \xi_1 \beta \chi\left(e^{-k_1\alpha} - e^{-k_2\alpha}\right) \\ -\xi_1 \beta e^{-k_1\alpha}\eta\left[e^{-\varepsilon_1(t-\alpha)}\right.\end{array}\right. \tag{7}$$

$$\left[1 - e^{-\varepsilon_2(t-\alpha)}\right] + \xi_1 e^{-k_1\alpha}\eta T_1 k_1\chi\left[1 - e^{-\varepsilon_2(t-\alpha)}\right]\right]$$

$$\left. - e^{-\varepsilon_2(t-\alpha)}\right] + \xi_2 e^{-k_2\alpha}\chi\left[1 - e^{-\varepsilon_2(t-\alpha)}\right]\right\}$$

where $\xi_1 = C_R U(t-\alpha)$, $\xi_2 = D_0 U(t-\alpha)$, $\beta = k_1/(k_2-k_1)$, $\chi = 1/(1+k_2 T_1)$, $\eta = 1/(1+k_1 T_1)$,

$$\varepsilon_1 = \left(\frac{1+k_1 T_1}{T_1}\right), \ \varepsilon_2 = \left(\frac{1+k_2 T_1}{T_1}\right)$$

Eq. (7) simulates the DO concentration at the end of first well mixed cell, which consists of boundary step pollutant perturbation C_R and boundary step deficit perturbation D_0.

The effluent from the first well mixed cell is the influent to the second well mixed cell. Decay of the pollutant takes place in the second well mixed cell. Therefore dissolved oxygen is consumed. Simultaneously re-aeration takes place. Considering the mass balance for the pollutant concentration and dissolved oxygen (DO) in the second well mixed cell, the following ordinary differential equations have been formulated.

$$\frac{dC_{M2}}{dt} = \left\{ \frac{\xi_1 e^{-k_1\alpha}}{T_2\eta}\left[1-e^{-\varepsilon_1(t-\alpha)}\right]\right\} - \left(\frac{1+k_1 T_2}{T_2}\right)C_{M2}$$

$$\frac{dC_{DO}}{dt} = \left\{ \frac{S_{DO}}{T_2} - \frac{1}{T_2}\left\{ \begin{array}{l}\xi_1\beta\chi\left(e^{-k_1\alpha}-e^{-k_2\alpha}\right)\\ -\xi_1\beta e^{-k_1\alpha}\eta\left[e^{-\varepsilon_1(t-\alpha)}\right]\end{array}\right.\right. \quad (8)$$

$$-C_{DO}\Big/T_2 - k_1 C_{M2} + k_2\left(S_{DO}-C_{DO}\right)$$

$$\left.\left.\begin{array}{l}\left[1-e^{-\varepsilon_2(t-\alpha)}\right]+\xi_1 e^{-k_1\alpha}\eta T_1 k_1\chi\left[1-e^{-\varepsilon_2(t-\alpha)}\right]\\ {}-e^{-\varepsilon_2(t-\alpha)}\right]+\xi_2 e^{-k_2\alpha}\chi\left[1-e^{-\varepsilon_2(t-\alpha)}\right]\end{array}\right\}\right\} \quad (9)$$

$$-C_{DO}\Big/T_2 - k_1 C_{M2} + k_2\left(S_{DO}-C_{DO}\right)$$

Considering DO deficit $D = S_{DO} - C_{DO}$ and it's time derivative, Eq. (9) can be solved for DO deficit by incorporating solution of Eq. (8) and one can get the step response for DO deficit at the exit of the hybrid unit comprising the response to boundary step pollutant perturbation C_R (terms with ξ_1) and boundary step deficit perturbation D_0 (terms with ξ_2). The response can be decomposed into two parts based on C_R and D_0. The step response function be represented by K_{D-CR} (t) can be got by assuming $D_0 = 0$ in the solution of Eq. (9). A unit step response function, $K_{D-CR\ U}$ (t) is defined by substituting $C_R = 1$ in K_{D-CR}(t). The impulse response function, k_{D-CR} (t) in respect of deficit owing to an impulse pollutant perturbation can be derived by differentiating K_{D-CR}(t) with respect to t. A unit impulse response function $k_{D-CR\ U}$ (t) is defined by assigning $C_R = 1$ in k_{D-CR} (t). Similarly the step response K_{D-D0} (t) and impulse response k_{D-D0} (t) corresponding to the boundary deficit oxygen perturbation D_0 can be derived by assuming $C_R = 0$ in the solution of Eq. (9). The unit step response $K_{D-D0\ U}$ (t) and unit impulse response $k_{D-D0\ U}$ (t) corresponding to the unit boundary deficit perturbation (i.e $D_0 = 1$)

can be got from K_{D-D0} (t) and k_{D-D0} (t) respectively. The reason for separating these two parts in the solution of Eq. (9) is to handle the equations more easily for second and consequent hybrid units.

The dissolved oxygen deficit, due to the transport of pollutant and boundary deficit of DO, at the end of the nth hybrid unit can be obtained using successive convolution by separately handling both parts. Let the pollutant concentration at the end of $(n-1)^{th}$ hybrid unit be designated as C (n-1, t). Let the time span be discretised into m equal interval. Applying convolution technique, the dissolved oxygen deficit due to the boundary step pollutant perturbation C_R at the end of nth hybrid unit is

$$K_{D-C_R}\left(n,t\right) = \int_0^t C\left(n-1,\tau\right)k_{D-C_R\ U}\left(n-1,t-\tau\right)d\tau :$$
$$(10)$$

$$= \int_0^{m\Delta t} C\left(n-1,\tau\right)k_{D-C_R\ U}\left(n-1,m\Delta t-\tau\right)d\tau$$

where "t is step size and $t = m$ "t. Between an interval $(\gamma-1)$ "t to γ "t, an average rate of perturbation is

$$\bar{C}\left(n-1,\tau\right) = \frac{C\left[n-1,(\gamma-1)\Delta t\right]+C\left[n-1,\gamma\Delta t\right]}{2},$$
$$(11)$$

$$(\gamma-1)\Delta t < \tau < \gamma\Delta t$$

Let $\int_0^{\Delta t} k_{D-C_R\ U}\left(m\Delta t-\tau\right)d\tau$ be designated as discrete kernel $\delta_{D-C_R\ U}\left(m\Delta t\right)$

$$\delta_{D-C_R\ U}\left(m\Delta t\right) = K_{D-C_R\ U}\left(m\Delta t\right)-K_{D-C_R\ U}\left((m-1)\Delta t\right) \quad (12)$$

Selecting a time step size "t, $\delta_{D-C_R\ U}\left(m\Delta t\right)$ can be generated for integer values of m. Then,

$$K_{D-C_R}\left(n,m\Delta t\right) = \sum_{\gamma=1}^m \bar{C}\left(n-1,\gamma\Delta t\right)\delta_{D-C_R\ U}\big($$
$$(13)$$

$$(m-\gamma+1,\Delta t), \qquad n \geq 2$$

Similarly, the oxygen deficit, due to the boundary deficit, at the end of the nth hybrid unit can be obtained using successive convolution as below

$$K_{D-D_0}\left(n,t\right) = \int_0^t D_0\left(n-1,\tau\right)k_{D-D_0\ U}\left(n-1,t-\tau\right)d\tau =$$
$$(14)$$

$$\int_0^{m\Delta t} D_0\left(n-1,\tau\right)k_{D-D_0\ U}\left(n-1,m\Delta t-\tau\right)d\tau$$

Between an interval $(\gamma-1)$ "t to γ "t, an average rate of perturbation is

$$\bar{D}_0\left(n-1,\tau\right) = \frac{D_0\left[n-1,(\gamma-1)\Delta t\right] + D_0\left[n-1,\gamma\Delta t\right]}{2},$$

$$(15)$$

$$(\gamma-1)\Delta t < \tau < \gamma\Delta t$$

Let $\int_0^{\Delta t} k_{D-D_0 U}\left(m\Delta t - \tau\right) d\tau$ be designated as $\delta_{D-D_0 U}\left(m\Delta t\right)$

$$\delta_{D-D_0 U}\left(m\Delta t\right) = K_{D-D_0 U}\left[m\Delta t\right] - K_{D-D_0 U}\left[(m-1)\Delta t\right] \quad (16)$$

Then,

$$K_{D-D_0}\left(n,m\Delta t\right) = \sum_{\gamma=1}^{m} \bar{D}_0\left(n-1,\gamma\Delta t\right)\delta_{D-D_0 U}$$

$$(17)$$

$$\left((m-\gamma+1)\Delta t\right), \qquad n \geq 2$$

The total deficit, $K_D(n, m \text{ "}t)$, at the end of the nth hybrid unit is obtained by adding Eq. (13) and (17). Then the dissolved oxygen concentration is obtained by:

$$C_{DO}(n, m \text{ "}t) = S_{DO} - K_D(n, m \text{ "}t) =$$
$$S_{DO} - \{K_{D-CR}(n, m \text{ "}t) + K_{D-D0}(n, m \text{ "}t)\} \quad (18)$$

RESULTS & DISCUSSION

Spatial and temporal variations of DO have been simulated using the proposed model for a hypothetical data set. The temporal variations of dissolved oxygen concentrations (C_{DO}) at the end of 1ˢᵗ hybrid unit of size, $\Delta x = 200$ m are presented in Fig. 2 for $D_0 = 0$, $\alpha = 1.7$ min, $T_1 = 2.3$ min, $T_2 = 6.0$ min, $k_1 = 0.3$ per min and $k_2 = 0.1$ per min for impulse inputs of non-conservative pollutant (BOD = 50, 100, 170 mg/L), which consume the dissolved oxygen. The dissolved oxygen
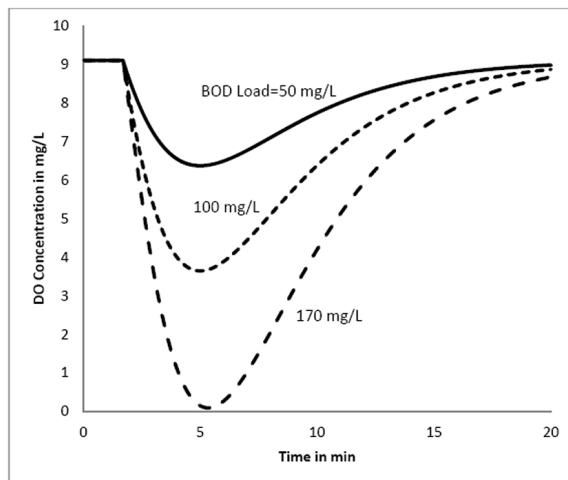
concentration at saturated level, S_{DO} is taken as 9.1 mg/L. From the figure, it is seen that C_{DO} attains minimum value between 5 to 6 min and regains the saturation level after 20 min. For a higher BOD of 170 mg/L, the minimum C_{DO} becomes nearly zero after 4 min and starts regain oxygen level after 6 min. Oxygen level reaches about 8 mg/L (allowable limit for the most of the purposes) in 20 min. BOD load more than 170 mg/L would result in septic condition.

Step response functions (Cumulative DO curve) at the end of first hybrid unit is computed from the solution of Eq. (9) and presented in Fig. 3 for the following set of data: $D_0 = 0$; $\alpha = 1.70$ *min*; $T_1 = 2.3$ *min*; $T_2 = 6.0$ *min*; $\Delta x = 200$ m; $k_1 = 0.1$ per min; $k_2 = 0.3$ per min; $C_R = 50$ mg/L; The Dissolved oxygen concentration is equal to saturated level until time $t = \alpha$, and decreases with time and reaches 2 mg/L at 18 min. Fig. 3 also shows the impulse response function (Oxygen sag curve) and DO deficits. It can be noted that the critical low dissolved oxygen, about 8.1 mg/L, is shown at 5 min in DO sag curve; however this is within the allowable limit.

The impulse response functions at distances 200, 400 and 600 m from the point of injection of BOD load (150 mg/L) have been computed using Eq. (18) and are presented in Fig. 4 for the following set of parameters: $D_0 = 0$; $\alpha = 1.70$ min; $T_1 = 2.3$ min; $T_2 = 6.0$ min; $\Delta x = 200$ m; $k_1 = 0.3$ per min and $k_2 = 0.1$ per min. It shows the DO concentration at 400 m is within allowable limit for bathing, recreational purposes and it shows slight risk for drinking purpose, whereas the critical low DO at 600 m is about 8 mg/L. Having $k_1 = 0.15$ per min and $k_2 = 0.1$ per min and keeping other parameters same as mentioned above, the impulse response functions have
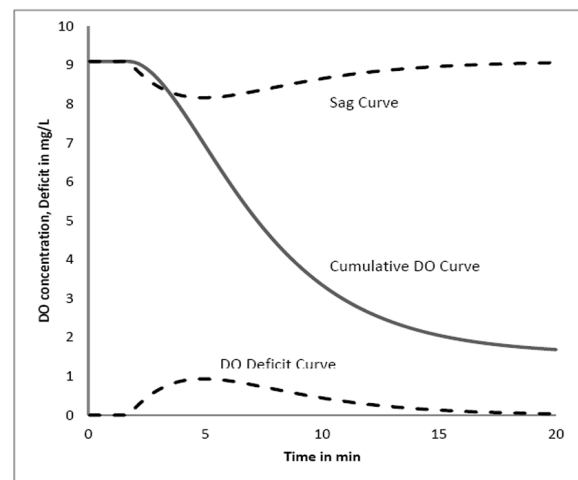
Fig. 2. DO concentration - time profile for different BOD load (C_R) with $k_1 = 0.3$ per min and $k_2 = 0.1$ per min ($\alpha = 1.7$ min, $T_1 = 2.3$ min and $T_2 = 6.0$ min) at $x = 200$ m

Fig. 3. Step and Impulse response functions for DO concentration and impulse response for DO Deficit

Table 1. Channel geometry &flow details of River Brahmani during non-monsoon period

Location	Q (m³/s)	U (m/s)	A (m²)	H (m)	W (m)	D_L m²/s
Rengali Dam	196.55	0.898	218.65	3.22	68.01	431.54
Before Tikira joins	195.98	0.897	218.12	3.21	67.91	430.74
After Tikira joins	239.72	0.928	257.99	3.43	75.10	490.05
Talcher	238.62	0.927	257.01	3.43	74.93	488.61

Table 2. Water quality data

Locations	Q (m³/s)	BOD mg/L	DO mg/L
Rengali Dam	196.55	16	7.7
Location A	-	12	7.8
Location B	-	8.0	8.0
Tikira	13.3	229.5	0.9
Nalco AP u/s	195.98	12.6	9.0
Nalco AP d/s	239.72	23.9	4.5
Talcher	238.62	16.8	6.1

been computed and presented in Fig. 4. It shows at 200 m, minimum DO concentration about 3.2 mg/L and DO concentration at 400 m is within allowable limit for drinking purpose.

The variations of dissolved oxygen concentration, C_{DO}, and deficit, D, with time for different values of boundary deficit (D_0 = 1, 2 and 5 mg/L) in the first hybrid unit have been presented in Fig. 5 for the following set of parameters: α = 3.6 min; T_1 = 4.5 min; T_2 = 6.9 min; Δx = 300 m; k_2 = 0.3 per min, BOD input, C_R = 0. From the plots, it can be noted that the variation of C_{DO} and D occurs linearly with respect to values of D_0. Even though the BOD input, C_R = 0, the DO concentration still reduces with initial DO deficit (D_0). This dictates that considering D_0 is important in order for correct prediction of DO.

Dissolved oxygen concentration for river Brahmani has also been simulated using the proposed model in this study. The river Brahmani is one of the major rivers in India. Many reaches of river run in Orissa state where a numerous industries located near the river are discharging their effluents to the river as on today. The consequence is that, many reaches of the river are under the grim of pollution exceeding the limiting level of waste load. In this study, the river reach (57 km) from Rengali dam to Talcher has been chosen. Talcher is affected seriously by the wastewater discharged by river Tikira, main tributary of river Brahmani. The river reach between two locations Rengali Dam and Talcher having lat-long, 85°02' E - 21°17' N and 85°13' E - 20°57' N respectively, is presented in Fig 6. In the past, the river was a source of drinking water; a natural bathing place for the rural
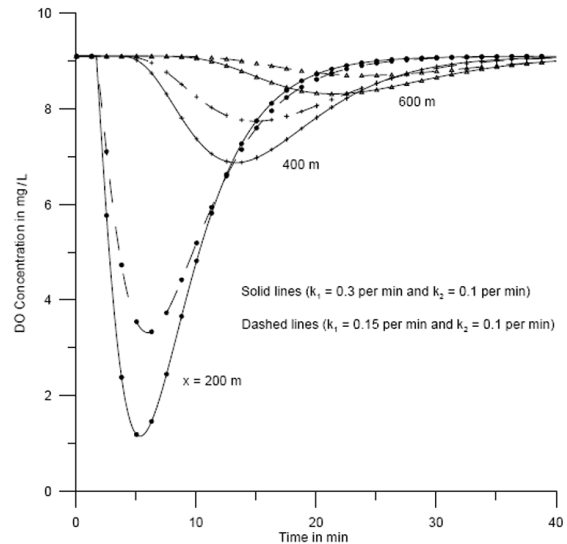

Fig. 4. DO concentration at different locations (x = 200, 400 and 600 m) downstream of point of injection and BOD load, C_R = 150 mg / L; DO at Saturation = 9.1 mg / L; α = 1.7 min, T_1 = 2.3 min and T_2 = 6.0 min

people and supported associated ecosystem. Presently, the river ecosystem is in danger due to pollutant discharge.

Average channel geometry, flow details and longitudinal dispersion co-efficient at various locations along the river reach during non-monsoon period has been tabulated in Table 1. The longitudinal dispersion co-efficient has been estimated using the empirical equation proposed by Seo & Cheong (1998) having measured data tabulated in Table 1. The average flow rate in the river reach between Tikira confluence point and Talchar town is taken as 239.17 m³/s. Water quality data at different locations in river Brahmani and its tributary Tikira, are collected. In this river reach, a point pollution load is discharged by river Tikira into the river Brahmani at 30 km downstream of Rengali dam. Water samples were collected from various locations, as shown in Fig. 6 along the river Brahmani and Tikira. Laboratory tests were conducted in National Institute Hydrology, Roorkee, India and have been presented in Table 2.

The response of hybrid mixing cells model matches with the advection dispersion equation model, if the
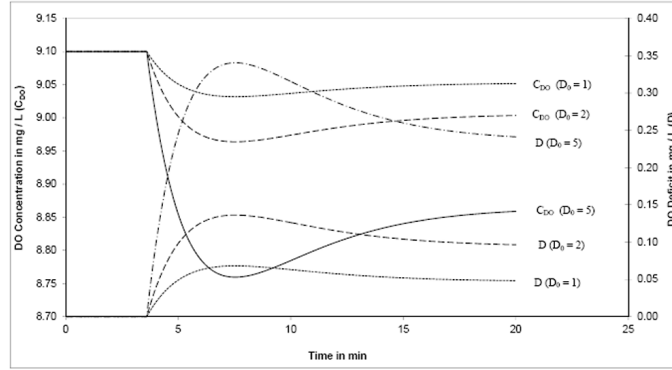
Fig. 5. Variation of C$_{DO}$ and D with time in the first hybrid unit for different values of boundary deficit (D$_0$ = 1, 2 and 5 mg / L) and BOD input, C$_R$ = 0.
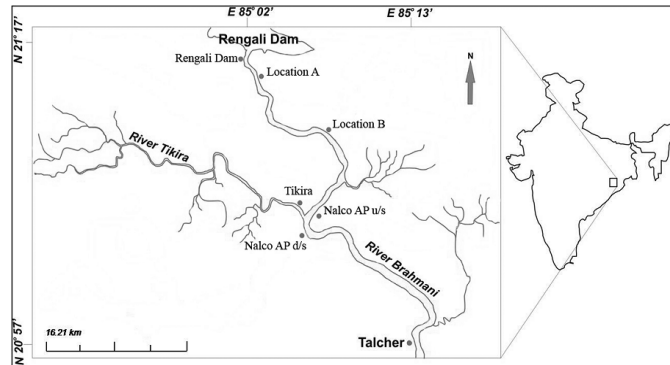

Fig. 6. Study area map showing river system and sampling locations

Table 3. Model parameters and pollution loading scenario considering pretreatments

Model Parameters									
Q in m^3/s	H in m	U in m/s	D_L in m^2/s	$?x$ in m	α in min	T_1 in min	T_2 in min	k_1 in /min	k_2 in /min
239.17	3.432	0.92	489	3375	15.518	19.398	25.727	0.001901	0.00041

Pollutant Loads			
Actual Load	**25 % treated**	**50 % treated**	**75 % treated**
24.03 mg/L	21.003 mg/L	17.98 mg/L	14.96 mg/L

Peclet number ($P_e = \Delta x\, u\, / D_L$) is greater than or equal to 4 (Ghosh et. al 2004, Ghosh et. al 2008). The parameters of the hybrid model (α, T_1 and T_2) are estimated using

$$\alpha = \left(0.04\Delta x^2\right)\big/D_L\, ; T_1 = \left(0.05\Delta x^2\right)\big/D_L\, ; T_2 = \frac{\Delta x}{u} - \left(0.04\Delta x^2\right)\big/_l$$

D_L. Validity of these relations has been verified (Ghosh, 2001; Ghosh et. al 2004; 2008) using the simulation by the HCIS model with that of Ogata and Banks (1961). The other parameters like decay rate and re-aeration rate co-efficient have been estimated using the collected water quality and flow data. The estimated parameters are tabulated in Table 3. The reach length of 27 km (from Tikira confluence to Talcher) is covered with 8

hybrid units of size 3375 m. For analyzing the effect of treatment of discharged pollutant on pollutant transport and fate of pollutants' concentration, 25, 50 and 75% of treatments for the pollutant discharge by Tikira tributary have been considered and corresponding input BOD loads have been found from dilution equation and tabulated in Table 3.

The DO concentrations at 3.375 km and 27 km have been simulated using Eq. 18 by having the data given in tables 3 and presented in Fig 7. For controlling and regulating the pollutants disposal to the river, the water quality status of river along the river reach
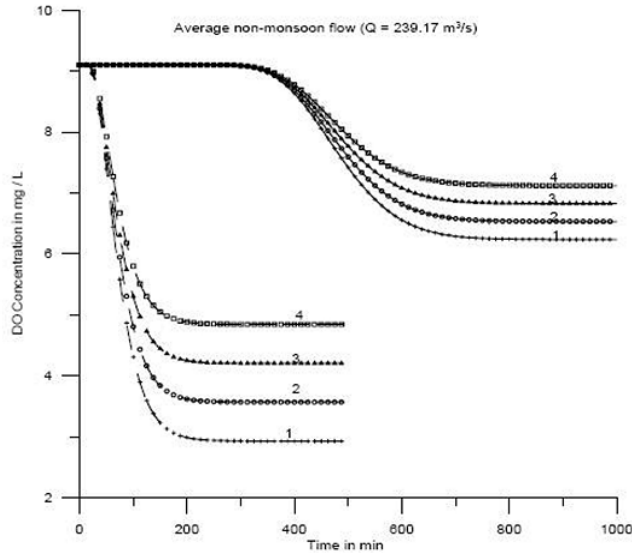
Fig. 7. Variation of DO concentration with time at 3.375 km (Dashed lines) and at Talcher, 27 km (Solid lines) for actual BOD & COD inputs [1], 25 % treated [2], 50 % treated [3] and 75 % treated [4] loads discharged at Tikira confluence for $k_1 = 0.001901$ per min, and $k_2 = 0.00041$ per min, Q = 239.17 m³/s
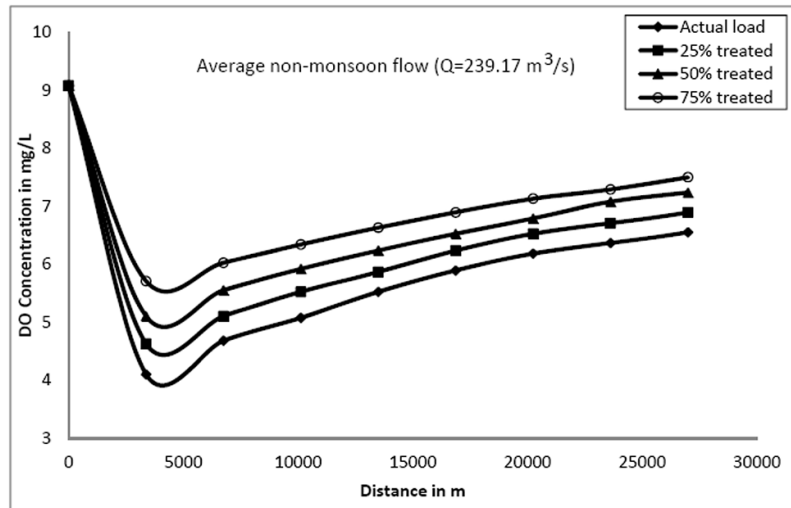

Fig. 8. Variation of DO concentration with distance for input with varying degree of treatment before disposal during non-monsoon flow.

should be simulated. In order to analyze the state of pollutant load and DO concentration, variation of DO concentration along the river up to Talcher with various input loads for non-monsoon flow has been simulated and plotted in Fig. 8. It can be noted from the Fig. 8 that the DO concentrations at different locations up to Talcher are in safer limit for various purposes and to maintain the ecosystem during high flow condition. However, the locations near to Tikira confluence are under pollution threat where DO level is below 4mg/L.

For avoiding pollution threat in those areas due to pollutants from Tikira, pretreatment of pollutant load is required. As seen from Fig 8, a treatment level of 75% ensures the water quality has been improved even after confluence where DO level is between 5.5 & 6 mg/L. However, this level is not safer for drinking purpose. Fig. 8 also shows that the DO level is adequate for most purposes nearer to Talcher (27 km from source), if a pretreatment of 50% is adopted for Tikira discharge (at source).

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CONCLUSIONS

A hybrid model is developed adopting first order reaction kinetic along with advection and dispersion of pollutant and first order re-aeration to predict the DO concentration whereas the classical Streeter and Phelps (1944) model incorporates advection of pollutant, first order de-oxygenation and re-aeration only. For the Peclet number greater than 4, the dissolved oxygen deficit and DO sag curves have been plotted for different BOD load at the entry. To predict the concentration of DO for the given BOD load, the decay rate co-efficient (k_1) for the pollutant load can be determined from the Laboratory experiments and re-aeration rate co-efficient (k_2) can be estimated from any suitable empirical equations. Flexibility of the hybrid mixing cells model for adopting reaction kinetics and first order re-aeration along with basic transport processes has been demonstrated with responses of the proposed model having hypothetical data and collected data from River Brahmani.

If a flow of 1180 m^3/s of flow is released from the Rengali reservoir during non-monsoon period, with same flow and pollutant concentration in Tikira tributary, the boundary pollutant perturbation would be 15mg/L. Then there may not be any danger to the aquatic life with the present pollutant load. To take into account of non-availability of this required flow, 50% pretreatment of discharged pollutant is required to maintain the ecosystem. Downstream of Talcher, industrial effluents are also dumped into Brahmani through streams Nandhira and Bangura. Transport of these pollutant loads need to be ascertained and overall status of water quality beyond Talcher town needs to be investigated.

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