Effects of some functional parameters on DO deficit in a natural stream

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The effects of variation of stream velocity, distance, ultimate biological oxygen demand BOD, on initial dissolved oxygen DO and optimum dissolved oxygen DO deficit, in Amadi creek was studied. Amadi creek, located in Port-Harcourt metropolis is a unique creek that is of high economic importance to the residents of Rumuobiakani, Mini-Ewa, Oginigba, Woji and Okujagu communities as it hosts the activities of the majority of the companies around the Trans-Amadi Industrial area and also provides water for fishing and water transportation. The study was carried out to evaluate the water quality changes resulting from increasing human and industrial activities in and around the creek. A point-source waste water discharge with flow rate \( Q \), biological oxygen demand \( BOD \), and dissolved oxygen demand \( DO \), of 0.000018m\(^3\)/s, 1000 mg/l, and 4.1mg/l formed the first case. The other case contained an additional point source with flow rate \( Q \), biological oxygen demand \( BOD \), and dissolved oxygen demand \( DO \) of 0.000035m\(^3\)/s, 500mg/l, and 4mg/l respectively. The study of the DO resources of the stream was undertaken with the aim of providing concepts which can be of assistance to regulatory agencies responsible for making decisions for water quality management. The DO deficit equations are solved by the methods of simple calculus (classical optimization), which simplifies the mathematical solution of the model equations by avoiding difficult to evaluate integrals. Two scenarios were identified and used to investigate the effect of BOD on the DO level in the...
stream, using mathematical simulation techniques. Simulation results of the two scenarios suggest that the dissolved oxygen DO deficit is depends mainly on the distance between waste discharge points. Hence to ensure minimum impact on water quality waste discharge locations should be placed at the optimal locations of 10015.382m and 6992.282m upstream and downstream waste discharge points respectively, at an optimum DO deficit of 4.135 mg/l for the first scenario, and at 41233.43m, 40995.17m, 33605.69m upstream and downstream waste discharge points respectively for the second scenario at an optimum DO deficit of 4.567mg/l. A characteristic DO curve shows the DO deficit increasing as the BOD in the waste water is being degraded, while the DO deficit decreases as the BOD consumption rate becomes smaller than the reaeration rate, as the waste stream flows downstream. Generally as stream velocity increases, the reaeration coefficient increases, resulting in an increased rate of oxygen transfer between water and the atmosphere, and hence an increase in the DO deficit initially, followed by a gradual decrease further downstream. The ultimate BOD decreases progressively as the waste stream moves downstream. It is recommended that if a new waste input is proposed for a stream both its BOD input and the proposed location with respect to the other functional parameters are important in order to determine the effects on the creeks dissolved oxygen DO level.

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1. Introduction

The dissolved oxygen balance (DO) concentration is a primary measure of a stream's health (Le, 2005, Thomann et al, 1987, Masters, 2007). Many streams and rivers in Port-Harcourt metropolis and other parts of the country have suffered dissolved oxygen (DO) deficit, which is very crucial to survival of aquatic life. Many studies have been made to attempt a prediction of DO uptake characteristics in streams and rivers in relation to stream conditions in order to develop mathematical models describing the DO consumption (Butts et al, 1970, Dune et al, 2012). Stream standards require the maintenance of DO level of 5 mg/l or more at any time. In order to set these standards, it is necessary to understand the factors which affect the state of pollution. The prediction of stream conditions, given a set of parameters and pollutional load is also necessary in setting limits on these loads.

Water quality modeling in a river has developed from the pioneering effort of (Streeter et al, 1925) who proposed a mathematical model demonstrating how DO in the Ohio River decreased with downstream distance due to degradation of soluble organic BOD (Yudianto et al, 2008). According to Yudianto et al, (2008) the simplest manifestation of this equation is usually applied for a river reach characterized by plug flow system with constant hydrology and geometry under steady state condition, as occurred in Amadi creek. For a large river or estuary, considerable longitudinal dispersion influences the phenomenon of DO and BOD distribution and so the governing equations becomes a partial differential equation (Le, 2005) However, the effect of dispersion on DO and BOD in small rivers, like Amadi Creek used in this study, is negligible (Li, 1972, Dobbins, 1964). Water collected for sampling is discharged into Amadi creek without any treatment as point source. Therefore, specifically Amadi creek is modeled with single point source of BOD in this study. Much research has been done on the area of DO depletion in water bodies, providing information on critical deficit, critical distance, and minimum DO concentration, but none of these studies has attempted to optimize the waste discharge locations for minimum impact on water quality. This would have enabled us to establish an optimum DO deficit and parameters affecting it. Such a study has been undertaken in Amadi Creek. Simulation results are presented and discussed.
1.1. Brief Description of Study Area

Amadi creek is located in Port Harcourt metropolis of Rivers State. It flows from Okrika town down to Mini-Ewa, Rumuobiakani through Woji, Oginigba, Okujagu communities and then empties into the Bonny river, en route to the Atlantic ocean. The creek is lined on one side by a mangrove forest while its other side is inhabited. The major economic activities in and around the creek are fishing and water transportation. The location of Amadi creek and its environs is shown in Figure 1.

![Port-Harcourt road network map showing Amadi Creek](image)

Fig. 1. Port-Harcourt road network map showing Amadi Creek.

2. Methodology

Water samples were collected between September 2009 and April 2010 from aboard a boat along the creek from various point-sources. Two samples of the creek water were obtained from each sample station for the determination of DO and BOD in the laboratory. Other parameters determined include, creek depth, width, water temperature, and flow velocity. In addition, several visits were made to the communities and settlements along the creek to determine the BOD of sewage contributions to the creek. The BOD and DO were determined following the procedures given in the Standard Methods (Apha, 1998). The BOD contributed per person per day in most developing countries is taken as 0.045kg, according as cited in Dune et al, (2012). The depth of the creek was measured by dropping a loaded tape to the bottom of the creek. The width of the creek was measured by stretching a tape across the creek. Temperature readings were taken with a thermometer at every station simultaneously with the other readings. Time was measured with a stop watch while flow velocity was determined with a current meter.

2.1. Formulation of equations for multiple discharge of waste water into rivers

Case 1 – One Source of Waste Water Discharge

\[
A \quad X \quad B
\]

\[
L_o, D_o \quad L_1, D_1 \quad L_2, D_2 \quad L_3, D_3 \quad L_4, D_4
\]

\[
Q_2 \quad h_o
\]
Fig. 2. Two reach model of a stream with a single point-source.

The dissolved oxygen deficit along the reaches are:

\[ D_{AB} = D_1 = \frac{K_{11}L_o}{K_{21} - K_{11}} \left( e^{-k_{11}t_1} - e^{-k_{11}t_1} \right) + D_3 e^{-k_{21}t_1} \]

where, \( L_o \) is ultimate BOD concentration upstream effluent discharge, \( D_0 \) initial \( D_0 \) concentration upstream effluent discharge

\[ D_{BC} = D_4 = \frac{K_{12}L_3}{K_{22} - K_{12}} \left( e^{-k_{12}t_2} - e^{-k_{12}t_2} \right) + D_3 e^{-k_{22}t_2} \]

The concentrations just downstream are computed by a mass balance as;

\[ L_3 = L_1 \frac{Q_1 + L_2 \frac{Q_2}{Q_1}}{Q_1 + Q_2} \]

\[ D_3 = \frac{D_1 \frac{Q_1}{Q_1} + D_2 \frac{Q_2}{Q_2}}{Q_1 + Q_2} \]

where, \( Q_1, Q_2 \) are the stream and effluent discharges respectively. \( L_1, L_2, L_3 \) are BOD of stream upstream and downstream respectively, \( L_2 \) is BOD of Effluent discharge, \( D_1, D_3, D_2 \) are the DO concentrations upstream and downstream respectively, \( D_2 \), is the DO concentration of Effluent discharge. In the Streeter and Phelps derivation the differential for \( L \) is assumed as

\[ \frac{dL}{dt} \]

which integrates to;

\[ L_1 = L_o e^{-k_{11}t_1} \]

Substituting equations (3) and (4) into eq (2), gives

\[ D_4 = \alpha_1 \left[ \frac{L_o e^{-k_{11}t_1} Q_1 + L_2 Q_2}{Q_1 + Q_2} \left( e^{-k_{12}t_2} - e^{-k_{12}t_2} \right) \right] \]

\[ + \frac{e^{-k_{12}t_2} Q_1}{Q_1 + Q_2} \left[ \frac{K_{12} L_3}{K_{22} - K_{12}} \left( e^{-k_{12}t_1} - e^{-k_{12}t_1} \right) + D_3 e^{-k_{22}t_2} \right] \]

\[ + \frac{D_2 Q_2}{Q_1 + Q_2} e^{-k_{22}t_2} \]

\[ \alpha_1 = \frac{K_{12}}{K_{22} - K_{12}} \]

where

Case 2 – Two Sources of Waste Water Discharge
The dissolved oxygen deficit along the reach CD, gives;

\[ D_{CD} = \frac{k_{13} L_6}{k_{23} - k_{13}} \left( e^{-k_{13}t_1} - e^{-k_{23}t_1} \right) + D_6 e^{-k_{23}t_1} \] ............................................................................(6)

\[ L_6 = \frac{L_4 Q_4 + L_5 Q_5}{Q_4 + Q_5} \] ..................................................................................(7)

\[ D_6 = \frac{D_4 Q_4 + D_5 Q_5}{Q_4 + Q_5} \] ..................................................................................(8)

\[ L_4 = L_3 e^{-k_{13}t_1} \] ........................................................................................................(9)

where, \( Q_4, Q_5 \) are the stream and Effluent discharge respectively, \( L_4, L_6 \) are BOD upstream and downstream respectively, \( L_3 \) is BOD of Effluent discharge, \( D_4, D_5 \) are the DO concentrations of stream and Effluent respectively.

Substituting equations (7) and equation (8) into equation (6), gives:

\[ D_{CD} = \varphi_1 Q_4 \left[ \frac{L_4 e^{-k_{13}t_1} e^{-k_{23}t_2} + L_5 Q_5}{Q_4 + Q_5} \right] \left[ e^{-k_{13}t_1} - e^{-k_{23}t_1} \right] \]

\[ + e^{-k_{23}t_1} Q_4 \left[ \frac{k_{12}}{k_{23} - k_{12}} \left( \frac{L_5 e^{-k_{13}t_1} Q_4 + L_5 Q_2}{Q_4 + Q_2} \right) \left[ e^{-k_{13}t_1} - e^{-k_{23}t_1} \right] \right] \]

\[ + \frac{Q_4 K_{11} L_o e^{-k_{23}t_1}}{(Q_4 + Q_2) (Q_4 + Q_3) (k_{23} - k_{11})} \left[ e^{-k_{13}t_1} - e^{-k_{23}t_1} \right] + D_6 e^{-k_{23}t_1} \] ............................................................................(10)

where \( \varphi_1 = \frac{k_{13}}{k_{23} - k_{13}} \)

3. Results and Discussions

The results of the simulations are presented graphically in Figure 4 through Figure 9.

3.1. Effect of velocity on the optimal DO deficit

The average stream velocity is an important factor that influences the position of the DO deficit through the instrumentality of the re-aeration coefficient and time of travel along the creek. Generally, as velocity increases,
the re aeration coefficient increases, resulting in an increased rate of oxygen transfer between water and the atmosphere, and hence an increase in the DO deficit initially, followed by a gradual decrease further downstream (Figure 4). The velocity also affects the spatial distribution of the DO deficit, because an increased velocity results in a decreased travel time. Thus the combined effect of these two relationships should result in a lower overall DO deficit due to the increased re aeration coefficient, with a more widespread effect of the DO deficit, due to decreased travel time. It is also seen from Figure 4 that for low velocities, after the BOD is degraded, enough oxygen is produced to maintain the stream in supersaturated conditions. This may have been due to the release of oxygen produced by phytoplankton species. This is contrary to a report by Brown (2005) who submits that as velocities increase, the re aeration coefficient increases, and the oxygen produced by the phytoplankton specie is released to the atmosphere, resulting in lower DO concentrations.

![Graph showing the variation of dissolved oxygen (DO) deficit with velocity (V).](image)

**Fig. 4.** Variation of dissolved oxygen (DO) deficit with velocity (V).

### 3.2. Effect of ultimate bod (Io) on optimum do deficit

Figure 5 shows the effect of Lo on the DO deficit. The magnitude of the of DO deficit is most affected by the Lo value (Peavy et al, 1985). Not only do heavier loads result in greater deficit, but they extend the influence of the waste further downstream. Heavy loads of organics may result in the development of anaerobic conditions. Under these conditions, oxygen is transferred in at a higher rate, but is used up by facultative organisms that may also be utilizing the organic material produced by anaerobic metabolism (Agunwamba, 2001). In a deep stream, true anaerobic organisms may flourish near the bottom. Only after the strength of the waste has been sufficiently reduced will aerobic conditions be restored. Since anaerobic conditions is a slow process, recovery of an overloaded stream will be slow and the dissolved oxygen deficit curve will extend far downstream.
3.3. Variation of optimum DO deficit with distance

The results shown in Figure 6 agree with our expectations. Here we see the characteristic DO deficit curve where the DO deficit is increasing as the BOD is being degraded, and then the DO deficit begins to decrease as the BOD consumption rate becomes smaller than the reaeration rate, as waste stream flows downstream.

3.4. Effect of ultimate BOD (L0) on optimal locations

The results shown in Figure 7 indicate a progressive decrease in the ultimate BOD as we move downstream. This is probably due to the fact that over time the concentration of organic matter is gradually reduced due to increased microbial activities. Hence the ultimate BOD decreases as distance increases.
Effect of Initial DO deficit on Optimal Locations

3.5. Effect of initial dissolved oxygen deficit (Do) with optimal location (X1).

The waste water contains some dissolved oxygen at the point of discharge. However as the waste stream moves down stream this initial concentration of DO is gradually being used up as the waste water is being degraded. This is shown in Figure 8, which indicates a progressive decrease in the initial DO deficit, as the distance increases.
3.6. Effect of velocity on optimal locations

The effect of velocity on the optimal locations is shown in Figure 9. It is seen that as we move downstream the velocity increases with increasing distance. This is to be expected, since an increase in travel time means an increase in velocity, resulting in the optimal location extending far downstream.

Fig. 9. Variation of velocity (V) with upstream location (X1).

4. Conclusions and recommendations

If a new waste input (e.g. a new sewage treatment plant) is proposed for a stream or river, both its BOD input and the proposed location (distance) with respect to the other functional parameters, such as stream velocity, initial dissolved oxygen deficit are important in order to determine the effects of pollution on the stream DO level. It is recommended that industrial establishments planning to site their treatment facilities along rivers or streams should be compelled to discharge their waste stream in compliance with the optimal locations (distance) with respect to any existing plant, so as to avoid undue dissolved oxygen (DO) depletion.

References


