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Analysis of pollution status of River Illo, Ota, Nigeria

E. O. Longe · D. O. Omole

Abstract An assessment of the pollution status of River Illo, located within River Owo catchments area in Ota, Ogun State, Nigeria, was carried out. The River's response to deoxygenation due to BOD loading from an abattoir and its dissolved oxygen (DO) level was predicted using the modified Streeter-Phelps model. The average concentrations of measured parameters at the sampling stations include: 2.24 mg/l of DO, 312.85 mg/l of BOD, 782.86 mg/l of chemical oxygen demand, and 620.76 g/l of total solids. The DO model for River Illo showed a positive correlation between measured and calculated DO, while the dissolved oxygen curve gave a double spoon shape of two major segments with distinct zones of degradation, decomposition, and recovery. The self-purification factor (*f*) for both segments ranged between 0.8 and 1.1 depicting River Illo as a slow moving or sluggish river. The above results revealed slow reaeration of the water body while full recovery from pollution was difficult. The treatment of River Illo before usage is very essential to ensure public health safety of users from waterborne diseases.

Keywords Deoxygenation · Reoxygenation · Self-purification · Assimilative capacity · Oxygen sag

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1 Introduction

Pollution of river bodies has become a major and global problem that is becoming critical in developing nations of the world because of inadequacy or non-existence of surface water quality protection measures and sanitation. Lagoons, rivers, and streams are sinks for wastes. Wastes are most often discharged into the receiving water bodies with little or no regard to their assimilative capacities. With over 70% of the planet covered by oceans, it is erroneous to believe that these bodies of water could serve as a limitless dumping ground for wastes, but it is not so. However, discharges of raw sewage, garbage, as well as oil spills are threats to the diluting capabilities of the oceans, lagoons, and rivers in major cities while most coastal waters are grossly polluted (World Bank 1995; UNESCO 2006; Krantz and Kifferstein 2007). The natural purification of polluted waters in itself is never fast, while heavily polluted water may traverse long distances in days before a significant degree of purification is achieved (Chapman 1992; Henry and Heinke 2005; Garg 2006). This in effect makes pollution of river bodies a global issue that has no respect for national or international boundaries. The degrees of pollution and natural purification are measurable physically, biologically, and chemically. The protection of the aquatic life of any potential receiving water body therefore calls for an effective determination of its capacity to assimilate wastes. Hence, constant assessments of the hydraulic and water quality conditions of receiving water bodies are very critical to effective planning and management.

The dissolved oxygen (DO) and the biochemical oxygen demand (BOD) are two useful parameters in tracing pollution profile and natural purification of rivers upon which engineering calculations of permissible pollutional loadings are based (Fair et al. 1971; Garg 2006). The BOD defines in a comprehensive manner the degradable load added to the receiving water body or remaining in it. It is both time and place specific. BOD therefore measures the oxygen absorbing capacity of an effluent. The DO defines the capacity of the body of water to assimilate the imposed load by itself or with the help of reaeration through oxygen absorbed mainly from the atmosphere and also through photosynthesis. The amount of dissolved oxygen that can be held by the water depends mainly on the water temperature (Garg 2006; Agunwamba et al. 2006). The determination of dissolved oxygen concentration relative to its saturation value and the rate of oxygen utilization measured as its BOD become a good measure for identifying the pollutional status of a water body. The knowledge of the progressive utilization of oxygen in a water body has been widely used as a measure of the amount of decomposable or organic matter contained in it at a given time. Also, it has been used to predict aerobic decomposition and the degree of self-purification accomplished in a given interval of time. It therefore follows that the oxygen economy of any receiving water is of paramount aesthetic and economic importance. Determination of the self-purification capacity of water bodies has been the subject of researches by scientists around the world (Villeneuve et al. 1998; Rounds 2001; Radwan et al. 2003; Agunwamba et al. 2006; Alam et al. 2007).

In the current study, an attempt has been made to assess the pollution status of River Illo, Ogun State, Nigeria. Its response to deoxygenation due to BOD loading as a function of its self-purification capacity was evaluated based on Fick's model of molecular diffusion (Kiely 1998). Finally, an attempt was made to predict its DO level using the modified Streeter-Phelps model (Fair et al. 1971).

2 Materials and methods

2.1 The study area

The study was carried out on River Illo, located within River Owo catchments area in Ota, Ogun State, Nigeria. The river drains 24-km stretch of land along the boundary of Lagos and Ogun States. It is an important source for domestic and agricultural uses. The river receives and transports untreated domestic and industrial wastes from settlements and industries located along the river course. The total organic load received by the stream is currently unknown. At the vicinity of the present study is located an abattoir (Fig. 1). The pollution load of river Illo from the abattoir management has been estimated for different water quality variables (Omole 2006).

The segment of River Illo where the study was carried out is relatively narrow varying from 0.8 m to 4.5 m in width and less than 1 m deep, dry weather flow (DWF) in most places. It is turbid and with presence of algae and other aquatic plants. Actual stream flow is unknown but varies with seasons, high during the wet season (April–September) and low during the dry season months of September through March.

2.2 Field sampling and laboratory analysis

Field sampling of water samples was carried out at the tail end of the dry season in March 2006. Seven water samples designated S_1 to S_7 were collected from designated locations along the river course as shown in Figs. 1 and 2. Sample S_1 was collected at a distance of 10 m upstream of S_2, while S_2 is the abattoir effluent discharge point into the river body and it is designated 0-m distance. Samples S_3 to

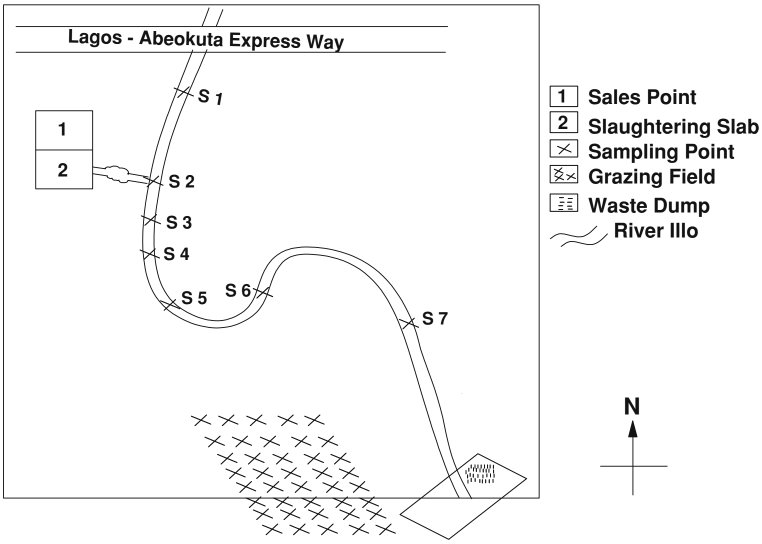

Fig. 1 A sketch of studied area with sampling points

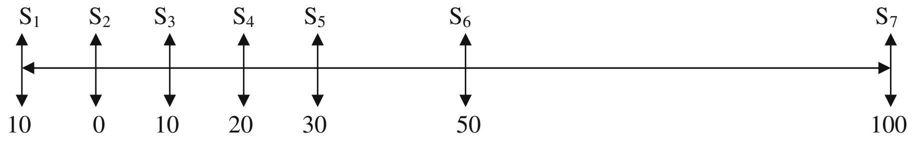

Fig. 2 Longitudinal sampling profile along River Illo in metres

S_7 were taken downstream of S_2 and at distances of 10 m, 20 m, 30 m, 50 m, and 100 m, respectively (Fig. 2). Table 1 gives the full description of the sampling locations. At each sampling location, water samples were collected in polyethylene bottles for the determination of dissolved oxygen (DO), total dissolved solids (TDS), total solids (TS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). These are important parameters in evaluating the degree of pollution and indices of self-purification of a river body (Chapman 1992; USEPA 1995; Garg 2006). All bottles were previously washed with non-ionic detergent and finally rinsed with deionized water prior to usage. Before the final water samplings were done, the bottles were rinsed three times with the river water at the points of collection. The sample bottles were labeled according to sampling location. All samples were preserved at 4°C and transported to the laboratory. The physico-chemical analyses of the selected water quality parameters were conducted following standard analytical methods (APHA 1992). Results of laboratory analysis were subjected to data evaluation by standard statistical methods (Chapman 1992; Nwadinigwe 2002). The modified Streeter-Phelps was used to predict the DO at critical point, the critical time, the DO at inflection, and the time at inflection. The predicted DO trend was also established using the modified Streeter-Phelps models (Waite and Freeman 1977; Fair et al. 1971). Fick's model for longitudinal dispersion was used to predict kinetics of aerobic decomposition of BOD/COD along the river course. A bathymetric survey was carried out to describe both the river depth and morphology, while hydraulic parameters, such as velocity, depth, and cross-sectional area, were either measured or evaluated.

3 Theoretical concept

3.1 The BOD-DO model

The BOD-DO model of a river is essential to predict the pollution status or longitudinal variation of constituents' concentrations along the river course.

Applications of water quality models in water management include: assessment of pollutant transport, quantification of source and sink processes, determination of assimilative capacities as well as in the design of regulatory compliance requirements (USEPA 1995; Conrads 1998; Rounds 2001; Adrian et al. 2004; Agunwamba et al. 2006). For instance, the dynamic water quality model is based on mass balance approach, with factors to allow for the non-conservative nature of water quality variables. Hence, dissolved oxygen in a river body is a balance between the various sources of oxygen (e.g. reaeration) and sinks of oxygen (e.g. oxygen loss by biochemical decay processes). In this regard two major processes come into play, first is the exertion of the BOD which normally results into deoxygenation process of receiving waters, and second the response of the water body through oxygen input from the atmosphere and by a combination of photosynthetic activity resulting in reoxygenation or reaeration. This interplay between deoxygenation and reoxygenation in streams produces a dissolved oxygen profile, the oxygen sag (Fair et al. 1971; Tchobanoglous and Burton 1991; Radwan et al. 2003; Garg 2006). The rate at which the oxygen is supplied to the polluted water body or river depends on a number of factors as water depth, stream velocity, oxygen deficit, and water temperature among others. Depending on these factors, the general mathematical properties of the sag curve, that

Table 1 Measured hydraulic properties

Sampling location	Distance (m)	Width (m)	Mean depth (m)	Cross-sectional area (m^2)	Velocity (m/s)	Discharge (10^{-3} m^3/s)
1	10	4.150	0.225	0.559	0.400	22.40
2	0	1.500	0.100	0.095	0.200	1.90
3	10	1.800	0.325	0.316	0.125	4.00
4	20	1.740	0.195	0.205	0.333	6.80
5	30	1.080	0.238	0.159	0.250	4.00
6	50	2.100	0.325	0.335	0.046	1.5
7	100	2.400	0.465	0.512	0.333	17.5

underlies engineering calculations of the permissible pollutional loading of receiving waters, have been formulated in the classical studies of Streeter and Phelps (Fair et al. 1971; Garg 2006).

$$\frac{\mathrm{d}D(t)}{\mathrm{d}t} = k_1 L(t) - k_2 D(t) \tag{1}$$

where $k_1 =$ Deoxygenation constant; $k_2 =$ Reaeration constant; $D =$ Oxygen deficit; $L =$ Ultimate first stage BOD of mix at the point of discharge in mg/l.

The above equation is thus modified (Waite and Freeman 1977):

$$D = \frac{L_a}{f-1} e^{-k_2 t}\left\{1 - e^{[-(f-1)k_2 t]}\left[1 - (f-1)\frac{D_a}{L_a}\right]\right\} \tag{2}$$

where $D =$ the DO deficit in mg/l after time t; $L_\mathrm{a} =$ Ultimate first stage BOD of mix at the point of discharge in mg/l; $D_\mathrm{o} =$ Initial dissolved oxygen deficit of the mix at the mixing point in mg/l; $K_1 =$ Deoxygenation coefficient for the effluent which can be considered as equal to the BOD rate constant determined in the laboratory; $K_2 =$ Reoxygenation coefficient for the stream; $t =$ Time; $f =$ Self-purification factor.

On the predicted DO curve, the critical point or the maximum oxygen deficit is located at $\frac{\mathrm{d}D}{\mathrm{d}t} = 0$ (critical) and $\frac{\mathrm{d}^2 D}{\mathrm{d}t^2} < 0$ (inflection).

Therefore at critical point, Eq. 2 reduces to:

$$D_\mathrm{c} = \frac{L_\mathrm{a}}{f\left\{f\left[1 - (f-1)\frac{D_\mathrm{a}}{L_\mathrm{a}}\right]\right\}^{\frac{1}{(f-1)}}} \tag{3}$$

$$t_\mathrm{c} = \frac{2.3}{k(f-1)} \log\left\{f\left[1 - (f-1)\frac{D_\mathrm{a}}{L_\mathrm{a}}\right]\right\} \tag{4}$$

$$D_\mathrm{i} = \frac{(f+1)L_\mathrm{a}}{f^2\left\{f^2\left[1 - (f-1)\frac{D_\mathrm{a}}{L_\mathrm{a}}\right]\right\}^{\frac{1}{(f-1)}}} \tag{5}$$

$$t_\mathrm{i} = \frac{2.3}{k(f-1)} \log\left\{f^2\left[1 - (f-1)\frac{D_\mathrm{a}}{L_\mathrm{a}}\right]\right\} \tag{6}$$

D_c is the critical point or maximum oxygen deficit, while the critical time (t_c) is when the minimum dissolved oxygen occurs. Similarly, (D_i) is the DO value at point of inflection while (t_i) is the time it occurs.

3.2 Dispersion

The longitudinal dispersion of the molecules of pollutants given by D_L is derived from Fick's law of molecular diffusion which states that, 'the rate of mass transport of a material 'A' (in this case, the BOD or COD), through a unit cross-sectional area of fluid by molecular diffusion is proportional to the concentration gradient of the material in the fluid' (Kiely 1998):

$$q = -D_\mathrm{L}\frac{(C_1 - C_2)}{(X_1 - X_2)} = -D_\mathrm{L}\frac{\mathrm{d}C_\mathrm{A}}{\mathrm{d}x} \tag{7}$$

q, could also be obtained as follows:

$$q = C_\mathrm{A} U_\mathrm{A}, \tag{8}$$

where $U_\mathrm{A} =$ Advective velocity; $q =$ The flux of material injected into the water body at origin in kg/m^2; $C =$ The BOD or COD concentration; $X =$ The distance traveled by pollutant.

For the model analysis, the velocity of the dispersed pollutants (molecular velocity, U_m) was assumed to be equal to the advective velocity (velocity of the water body, U_a), in reality, $U_\mathrm{a} > U_\mathrm{m}$. Equally the measured values of velocities used were taken constant in between the measured intervals. In reality also the velocity along the cross-section of a streambed changes with its morphology.

4 Results and discussion

The hydraulic and physico-chemical characteristics of River Illo are presented (Tables 1–3). The use of laboratory results as presented in (Tables 2 and 3) and its application to actual or real situation demands consideration of a number of factors. Such prevailing factors include the nature of the stream channel, flow and flow variations, finally, the transfer of potential load to the stream bottom, and its benthal decomposition.

Highest values of hydraulic parameters (velocity, discharge, and cross-sectional area) are obtained at S_1 and S_7, 10 m upstream of the point of discharge (S_2) and 100 m downstream of S_2, respectively. High velocity running streams enhances high reaeration rates, while high discharge

Table 2 Selected pollution parameters and characteristics of River Illo

Sample	Distance (m)	pH	TDS (mg/l)	TS (mg/l)	DO (mg/l)	BOD (mg/l)	COD (mg/l)
S1	10	6.7	87.5	447.5	4.6	170	425
S2	0	6.8	45.5	1071.5	0.01	670	1,675
S3	10	6.6	87.7	507.7	0.39	270	675
S4	20	6.5	77.9	601.9	2.7	270	680
S5	30	6.9	73.7	473.7	3.7	140	350
S6	50	6.8	79.9	771.9	0.39	380	950
S7	100	6.2	87.3	471.3	3.9	290	725

Table 3 Descriptive statistics of selected pollution parameters of River Illo

Parameter (mg/l)	Min	Max	Mean	Standard Deviation	Variance	Range	Standard Error
pH	6.20	6.90	6.64	0.24	0.06	0.70	0.09
TS	447.50	1071.50	620.79	228.45	52188.68	624.00	86.35
DO	0.01	4.60	2.24	1.94	3.75	4.59	0.73
BOD	140.00	670.00	312.86	176.33	31090.48	530.00	66.65
COD	350.00	1675.00	782.86	440.61	194140.48	1325.00	166.54

favors accelerated dilution and dispersion of concentrated pollutants in water bodies (Fair et al. 1971; Garg 2006).

The above assertion is corroborated by the high coefficient of correlation of 0.73 obtained between stream velocity and the DO (Fig. 3), and the coefficient of correlation of 0.63 obtained between hydraulic radius and coefficient of reaeration (Fig. 4). These factors could be said, apart from their distant proximity to S_2, to be responsible for the relatively less polluted status at S_1 and S_7 with respect to the physicochemical parameters tested for. The lowest stream velocity of 0.046 m/s was measured at S_6 with a corresponding discharge value of 1.5×10^{-3} m^3/s. Measured DO level at S_6 stands at 0.39 mg/l. The above observations are further described by the pattern of pollution profile along River Illo (Figs. 5 and 6).

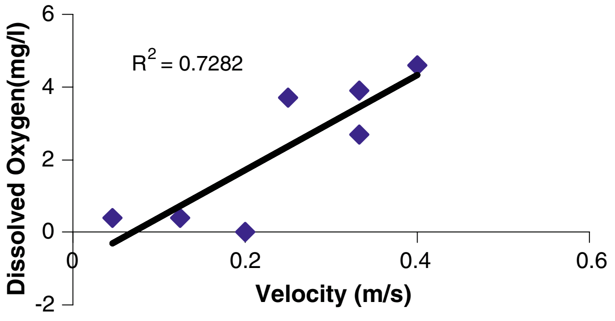

Fig. 3 Variation of Velocity with DO along River Illo

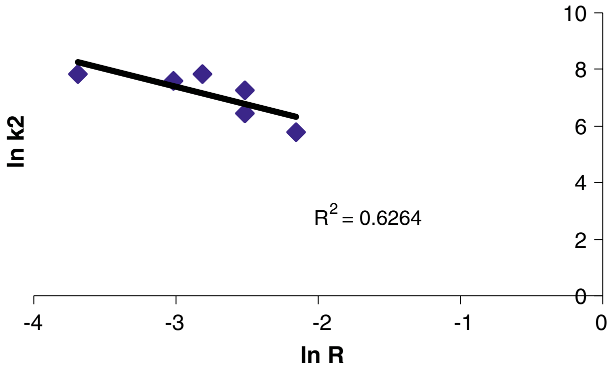

Fig. 4 Variation of Hydraulic Radius with Coefficient of Reaeration

4.1 Pollution profile

Pattern of change in pollution abatement in a river course is always modified by changes in season and hydrography. As it could be observed, as water moves steadily away from the outfalls (S_2), the successive changes in pollution establish profiles of pollution and purification as depicted in Figs. 5 and 6. Downstream of the discharge point (S_2), BOD exertion results in DO deficit. At 10 m away from the discharge point, the input from reaeration becomes feasible but low with the DO level rising from 0.01 mg/l to 0.39 m/

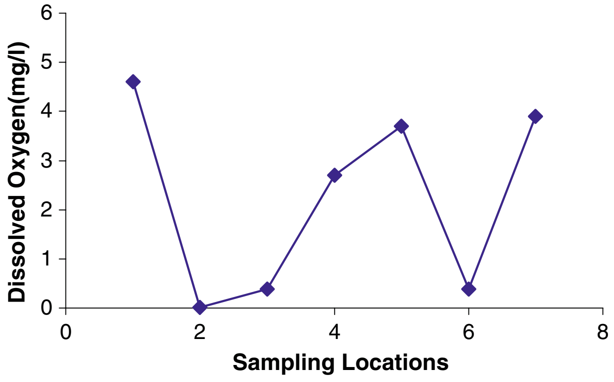

Fig. 5 Trend in DO Concentrations along River Illo

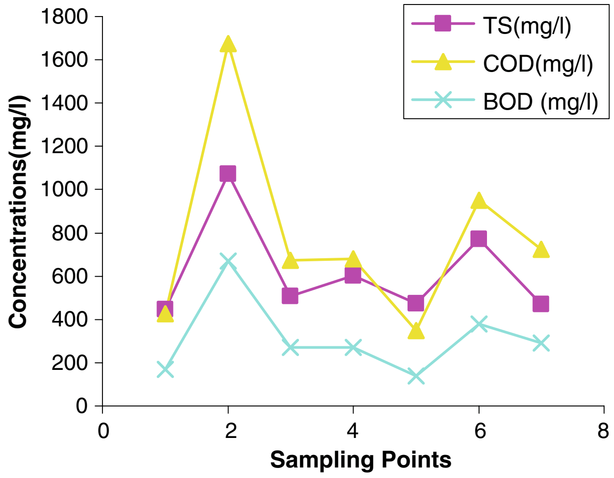

Fig. 6 Trends in TS, COD and BOD concentrations along River Illo

l. At S_2, the BOD consumption and DO deficit appeared to have reached the maximum.

The impact of low DO concentration due to BOD exertion is often reflected in the disruption of ecological process. Such disruptions can be demonstrated by development of septic or anaerobic condition as observed in this case. However, downstream of S_3, at S_4 and $S_{5,}$ 20 and 30 m away, respectively, oxygen input could be said to have exceeded consumption, hence deficit decreases while reaeration sets in. At S_6, DO level of 0.39 obtained compares with the value at S_3 at 10 m downstream of outfalls. The ambient DO level is likely to have been affected by factors other than waste input from outfalls even though the rate of BOD is normally expected to drop along the course of the stream below the point of maximum pollution (Garg 2006). As observed on the field, this section of the river has a reduced velocity, aside, the presence of aquatic plants at this point indicates possible source of photosynthetic and respiration activities and thus account for the observed DO deficit. S_6 is equally characterized with high suspended solids with a concentration level of 692 mg/l. Suspended solids affect water column turbidity which ultimately settles to the bottom. This phenomenon favors possible benthic enrichment, toxicity, and ultimately sediment oxygen demand. This observation thus suggests other possible sources of pollution aside from the abattoir effluents; this may however need further verification. Nutrients enrichment in river body normally leads to eutrophication and DO depletion (Henry and Heinke 2005).

4.2 The DO model

The plot of measured and predicted DO is presented in Fig. 7. The DO curve for River Illo gave a double spoon shape. At 10 m upstream of point of discharge, the DO value of 4.6 mg/l obtained is about 40% less than the theoretical DO value of 8.4 mg/l at saturation in river system (Alam et al. 2007). This condition will normally favor increased CO_2 level, hence reaeration occurs but at slower rate than the deoxygenation rate. This result indicates a non-pristine environment and hence River Illo is not totally devoid of pollution before S_2, the discharge point of abattoir wastes. The DO curve is marked with distinctive zones of degradation, decomposition, and recovery along the river course (Fig. 7).

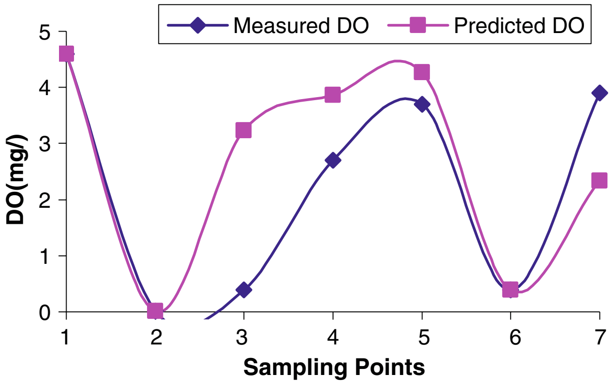

Fig. 7 Predicted and measured dissolved oxygen curves

Three zones could be clearly identified: the first is located between S_1 and S_2. The zone is marked by heavy pollution (S_2); the observed DO concentration of 0.01 mg/l indicates the prevalence of an anaerobic condition marked with active degradation and decomposition. The zone is equally characterized with high concentration of suspended solids, BOD, and turbidity. The second is a zone of recovery depicted by S_4 and S_7, respectively. In this segment of the river, recovery of the river body from its degraded condition gradually begins. Full recovery was however never achieved at the distance of 100 m downstream of outfalls. However, the water becomes clearer, the BOD level reduced with a corresponding increase in the levels of DO. This observation could be attributed to the dual sources of major pollution namely the outfalls of abattoir effluent discharge and the area with threatened eutrophication. The segment with threatened eutrophication, though not having any direct effluent discharge into the river, heightened BOD concentration due to lack of free flow of water. The observed reduced flow in this segment of the river accounts for the accumulation of all the pollution already remediated naturally upstream. This informed the breaking of the DO curve into two segments before subjecting them to individual analysis. Pollution is at its peak at points S_2 (0 m for segment 1) and S_6 (50 m for segment 2). Self-purification factor (*f*), obtained for segments 1 and 2 are 1.1 and 0.8, respectively, depicting River Illo as a sluggish river (Garg 2006).

The critical DO occurred at 2.5 m and 50 m for segments 1 and 2, respectively, while the calculated critical times of 0.00018 d and 0.003 d were obtained for both segments, respectively. The predicted DO levels at critical distance (X_c), are 0.02 mg/l for segment 1 and 0.03 mg/l for segment 2. Both occurring at critical time (t_c) of 0.0004 d and 0.0035 d, respectively while X_c was at 5.5 m and 50 m, respectively. The calculated DO value at the point of inflection (D_i), are 0.03 mg/l and 0.04 mg/l for segments 1 and 2, respectively. They both occurred at inflection distances (X_i) of 11 m and 88 m, respectively, with calculated inflection time (t_i) of occurrence of 0.0008 d and 0.0069 d, respectively. The measured and predicted oxygen sag curves apparently follow the same patterns while the observed difference as shown (Fig. 7), is mainly due to intervening natural factors which could affect the oxygen sag from the governing equations. BOD dispersion rate (D_L) of 7.5 m^2/s and 44.4 m^2/s were obtained for segments 1 and 2, respectively.

5 Conclusions

Reaeration of the river body was slow while full recovery from pollution was never attained even at 100 m downstream of outfalls. The narrowing of River Illo, as well as reduction in flow velocity downstream are major identified inhibiting factors, a phenomenon that favored nutrients' enrichment and eutrophication process. The resulting photosynthetic and respiration activities are other identified intervening factors which accounted for DO deficit downstream of outfalls.

River Illo is a significant sink for wastes but findings show that it has limited assimilative capacity. There is an urgent need for implementation of a sanitation program that will initiate remediation and ensure adequate protective measures for the river body. This becomes imperative so as to improve on its quality as an important source of water supply for various usages. Moreover, the waterways should be kept clear of obstacles for ease of stream flow. This simple measure would drastically improve the rate of reaeration and pollutant dispersion.

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