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DEVELOPMENT OF OXYGEN SAG CURVE: A CASE STUDY OF OTAMIRI RIVER, IMO STATE

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Abstract

To access the water quality of Otamiri River and develop its oxygen sag curve, water samples were collected from six stations (A,B,C,D,E and F) at a depth of 0.3m, a distance of 100m interval and time of 1 minute. Water samples collected from these stations were taken for laboratory analysis for BOD,COD,DO,TSS, turbidity, temperature and pH. Application of extended version of Streeter-Phelps, Thomas slope and O'Connor re-aeration models respectively, taken into account the BOD exerted on the River by the decomposition charateristics of the waste water. The results of the analysis showed that the critical time t_c i.e. faster rate of DO reducton than reparation time gave 6250 sec (0.072 day). De-oxygenation constant K_d and ultimate BOD L_o gave 0.57 and 13.8 mg/l respctively. The re-aeration constant $K_{r,}$ gave 0.0753. pH which ranged from 4.23 to 5.76 as well as temperature, do not comply with WHO and FMENV standards, with exception of Both COD and TSS having values within the recommended standards. The BOD values ranged from 12.2 to 18.0 mg/l, higher than the set limit of 10mg/l standard limit. The values of DO obtained from laboratory analysis were plotted against time. The DO curve generated showed that the minimum DO level of the River is 2.4mg/l. From the curve, the measured and simulated DO showed that there was no DO in the effluent discharge due to excesses in COD, BOD,TSS and turbidity deposits. Thus DO reduction rate tends to be greater than self-purification rate which might lead to abandonment of the River leading to industrial, agricultural or domestic wastes.

Keywords: Streeter-Phelps model, O'Connor re-aeration model, Effluent, Critical time, Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), and DO deficit

INTRODUCTION

With the advent of increasing population, the range of requirements for water has increased together with greater demands for higher water quality. Overtime, water requirements have emerged for several industrial purposes such as cooling in fossil fuel power plants, hydro-power generation and dispose of water. Each water use, including abstraction of water and discharge of wastewater leads to specific and generally predictable impacts on the quality of aquatic environment. Several industrial activities have contributed to undesirable, if not devastating effects on the aquatic environment. Such industrial activities include the release of chemical substances, discharge of untreated wastewater or release of noxious liquid from solid waste deposit. Dissolved oxygen (DO) is essential and in some cases, the limiting factor for maintaining aquatic life; its depletion in water is probably the most frequent general result of certain forms of water pollution (Abdulaziz and Alabaster, 1980; Kanu and Kinstach, 1992; Mayback and Mull, 1992).

In Nigeria and many other developing countries in Africa at present, most water resources managers are mainly battling with the problem of providing adequate potable water supply to meet the growing demand. At the same time, the available resources are being polluted by the industrial activities particularly in the urban areas. Many rivers and streams in humid tropics and other parts of Nigeria, have suffered from DO deficit which is very critical to aquatic lives and municipal water supply. Giving the rapid increase in shortage of water supply in many cities on one hand and the susceptibility of the raw water supplies to pollution on the other hand, there is need focusing on the water quality trend as it affects purifying efficiency of receiving streams, which is of immense importance particularly for downstream urban fringe and rural communities who may depend on rivers and streams as sources of water for domestic and other uses. Determination of DO concentration is a fundamental part of water quality assessment since oxygen is involved in or influences nearly all chemical and biological process within water bodies (Chapman and Kinstach, 1992). In their work, stated that if receiving water body is one of small volumes, at maximum flow, the discharge into it of a large volume of industrial waste which produces a low rate of dilution will deplete the oxygen (O_2) in the water, and may also cause draw backs, which affects the stream for its ultimate use as a source of portable water for a downstream municipality. The oxygen content of natural water varies with temperature, salinity, turbulence, photosynthetic activity of algae and plants and atmospheric pressure (Marta and Marella, 1990; Foster and Fridrick, 1992; Garg, 2007).

Several industrial activities have contributed to undesirable, if not devastating effects on the aquatic environment. Such industrial activity includes the release of chemical substances, discharge of untreated waste water (WHO 2002; ISEPA 2012), or leaching of noxious liquid from solid waste deposit. Avceivala (1981); Bob-Manuel and Butow (2001), noted that treatment of waste water discharged into stream used for recreational activities is important, so as not to produce offensive odour or deposit floating solids which might interfere with activities such as swimming and even bathing by some indigenes around the river.

Adiete (1994); Hem and Husnain (2002), stated that waste water with high organic content subject to decomposition may cause damage to some structures along the stream course.

Sawyer and McCarty (1978); Peirce (1997) and Garg (2007), in their publications noted that it is obvious that if receiving water body is one of small volume, at maximum flow, the discharge to it of a large volume of industrial waste which produces a low rate of dilution will deplete the oxygen (O_2) in the water. It also cause hedge baulk, which will affect the stream for its ultimate use as a source of potable water for a downstream municipality. Aklilesh and Adewole (2009), in their remarks on the physical characteristic of brewery effluent, talked about the high temperature of the waste water from the coiling operation of the plant. When this waste water is discharged into the stream, it will continuously increase the temperature of the stream thereby depleting oxygen from the stream which results in death of aquatic life in the stream.

Heavy metals present in trace concentrations are also important for the physiological function of living tissues and regulate many biochemical process (Dauda 1993; Nunan 2004; Elaigwu 2007; Yahaya *et al.*, 2009).

The development of classical first order reaction equation of dissolved oxygen (DO) and biochemical oxygen demand (BOD) by the pioneering works of Streeter and Phelps model by developing a balance between dissolved oxygen supply rate from re-aeration and dissolved oxygen consumption rate from stabilization of organic waste, which gave way to significant developments to water quality models. In water quality modeling, most of the processes are expressed in mathematical terminologies in the form of differential equations. Therefore, the aim of this research is to provide detailed explanation focusing on the development of simple dissolved oxygen sag curve for Otamiri River under steady flow condition with the application of extended version of Streeter and Phelps model.

STUDY AREA

Otamiri River, Figure 1, is a fourth order (4°) stream which flows from North to South through Owerri North, Imo State, Eastern Nigeria. The River system lies between 6°20′ N latitudes and 5°31′ E longitudes. The climate of Owerri and its environs, although comparatively stable is not uniform. Typically, the regions have the characteristic features of the humid tropical wet and dry climate governed primarily by the rainfall. There are two distinct seasons, rainy season which is from March to October and the dry season which begins in November and terminates in April.

Figure 1. Otamiri River

MATERIALS AND METHODS

Materials

The materials used for the laboratory analysis included equipment model apparatus and reagents; portable data logging spectrophotometer; dissolved oxygen (DO) analyser; conductivity/TDS meter–DiST3; electronic weighing chemical balance; suntex pH / temperature meter; incubator; conical flask; beaker; measuring cylinder (50ml, 250ml); sample cell bottle (10ml, 25ml).

Methods

Water samples during this project were taken from Otamiri River at different sample points. The first point was the upstream; the second point was the midstream, while the other points were at the downstream. About 100 m spacing was given from each sample point with a time interval of one minute. The water were stirred at a constant depth of 0.3 m before collecting the samples, in 1.5 litre sampling bottles which were labelled for proper identification. The collected samples were refrigerated immediately after collection to avoid further degradation due to microbial activities. Dissolved oxygen demand parameters were carried out within 24 hours for accurate results.

Laboratory Analysis of Water Samples

These samples were taken to the laboratory for analysis of several key parameters which form the basis of the primary data used. These parameters include: temperature, pH, chemical oxygen demand (COD), suspended Solids (SS), biological oxygen demand (BOD), dissolved oxygen (DO) and turbidity. The results obtained from the laboratory investigations of the effluent samples collected along the stretch of the river at intervals of 100 m, were analysed and subsequently used for the development of the oxygen sag curve for the river.

From the experimental results obtained, the COD was calculated from Equation (1).

$$\mathrm{COD} = \frac{\mathrm{Bk} - \mathrm{Ts}}{\mathrm{Vs}}\ (\mathrm{mg/l}) \qquad (1)$$

Where Bk is the blank titre, Ts is the test titre and Vs is the volume of sample oxidized. Similarly, the BOD was then estimated using Equations (2 and 3), using the results obtained from the experimental analysis.

$$\mathrm{BOD} = \frac{\mathrm{Initial\ DO} - \mathrm{Final\ DO}}{\mathrm{P}}\ (\mathrm{mg/l}) \quad (2)$$

where P is obtained from Equation (3), which is expressed thus:

$$\mathrm{P} = \frac{\mathrm{ml\ of\ sample}}{\mathrm{ml\ of\ diluted\ water}} \qquad (3)$$

RESULTS AND DISCUSSIONS

Results

The results of the laboratory analysis of the water samples collected at intervals from different points along the river stretch were presented in Table 1, while Table 2 shows the data obtained from the field during water sample collection. Each of the tested parameters is of economic importance to the water environment and its quality as it directly affects the water use.

Table 1: Summary results of average value of measured parameters from laboratory

analysis

Parameter	Control Upstream	Effluent	Point of Discharge (A)	Point B	Point C	Point D	Point E	Point F
BOD (mg/l)	9.2	140	18.00	14.40	14.20	12.50	12.18	12.35
COD (mg/l)	28.4	2301.60	30.00	30.50	30.80	28.03	28.01	28.00
DO (mg/l)	8	Nil	2.40	2.43	3.10	4.40	5.45	6.51
pH (dimensionless)	4.23	4.52	4.93	5.21	5.34	5.46	5.76	5.50
Temperature (℃)	27.1	27.90	27.90	26.90	27.60	27.40	26.50	27.60
Turbidity (NTU)	0.04	12.00	0.04	0.04	0.04	0.04	0.04	0.04
TSS (mg/l)	20.04	500.00	20.00	20.80	18.72	18.02	18.00	18.00

Table 2: Data obtained from field work

Station	Distance	Depth, d (m)	Width, w (m)	Velocity, V (m/s)	Area $A = w \times d$ (m^2)	Flow Rate $Q = AV$ (m^3/s)
1	0	0.85	9.1	0.018	7.735	0.139
2	100	1.95	18.1	0.016	35.295	0.565
3	200	1.66	22.1	0.017	36.686	0.624
4	300	2.25	36.0	0.016	81.000	1.296
5	400	4.70	72.0	0.015	338.400	5.076
6	500	8.65	135.0	0.014	1167.750	16.349
7	600	4.45	153.0	0.015	680.850	10.213
Average		**3.501**	-	**0.016**	-	-

Comparison of the Results from Laboratory Analysis with Standards of FEPA and WHO

In order to ascertain the extent of pollution at its drastic effects on the dissolved oxygen level as its affects the environment and aquatic life present, the results of the laboratory analysis of the water samples where compared with the WHO (Garg, 2000) and FEPA (1991) standards in Table 3.

Table 3: Results of laboratory analysis as compared with WHO and FEPA standards

Sample Point/Parameter	BOD (mg/l)	COD (mg/l)	DO (mg/l)	pH (dimensionless)	Temperature (℃)	Turbidity (NTU)	TSS (mg/l)
WHO	**10**	**80**	**6.5-8.5**	**6.5-8.5**	**20-30**	**5**	**50**
FEPA	**10**	**80**	**-**	**6.0-9.0**	**$<$ 40**	**5**	**30**
Point A	18.00	30.00	2.40	4.93	27.90	0.04	20.00
Point B	14.40	30.50	2.43	5.21	26.90	0.04	20.80
Point C	14.20	30.80	3.10	5.34	27.60	0.04	18.72
Point D	12.50	28.03	4.40	5.46	27.40	0.04	18.02
Point E	12.18	28.01	5.45	5.76	27.40	0.04	18.00
Point F	12.35	28.00	6.51	5.50	27.60	0.04	18.00
Range	12.18-18.0	28.0 – 30.80	2.40 – 6.51	4.93 – 5.76	26.90-28.0	-	18.0 – 20.80
Variance	0	0	<0.65 - 1.49	0	0	0	0

Dissolved Oxygen Sag Curve and Model Development

In the development and prediction of the DO sag curve for solving Otamiri River quality problems, the following necessary procedures were observed: (1) Representing the picture of the present situation; (2) Identifying every condition given in the problems; (3) Estimating the dissolved oxygen and biochemical oxygen demand after the effluent mix with the river; (4) Estimating time of travel for the river; (5) Estimating rate constant necessary; (6) Applying appropriate equations to calculate the oxygen deficit at the desired locations; (7) Calculating the dissolved oxygen at the location. (8) Calculating the critical time; and (9) Calculating the deficit critical.

Oxygen Sag Curve for Otamiri River

Figure 2 shows the oxygen sag curve developed for Otamiri River on a plot for dissolved oxygen concentration DO against distance, x in the direction of flow.

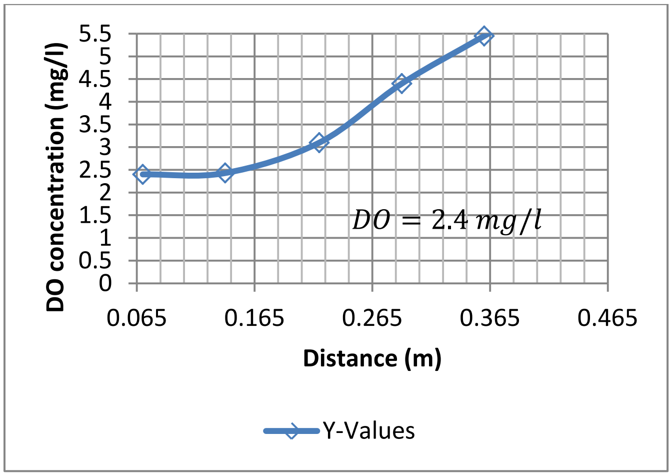


Figure 2. Plot of DO measured against distance x

As pollution enters the river of point A, i.e. $x = 0$ and $t = 0$, decomposition process withdraws oxygen at a faster rate than reparation occuring to replace the oxygen. This causes the DO to drop sharply reducing it to minimum at some point C and time downstream. This is the critical point t_c. At this point, re-aeration gradually exceeds de-oxygenation and the stream recovers its natural forms steadily, as a result of self-purification.

Critical time t_c was determined from Equation (4) as:

$$t_c = \frac{\text{Distance along the stream, x}}{\text{Average velocity of stream, U}} \quad (4)$$

where $x = 100\ \text{m}$, and $U = 0.016\ \text{m/s}$

$$= \frac{100}{0.016} = 6250\ s$$

$$= \frac{6250}{60 \times 60 \times 24} = 0.072\ day$$

Determination of the de-oxygenation constant K_d and ultimate (BOD) L_o, using Thomas Slope method

Considering the linear form of Equation (5),

$$\left(\frac{t}{y}\right)^{\frac{1}{3}} = (KL_o)^{-\frac{1}{2}} + \frac{\left(K^{\frac{2}{3}}\right)}{6L_o^{\frac{1}{3}}} t \qquad (5)$$

Modifying Equation (5) by putting $K = 2.3K_d$ yields:

$$\left(\frac{t}{y}\right)^{\frac{1}{3}} = (2.3K_dL_o)^{\frac{1}{3}} + \left(\frac{K_d^{\frac{2}{3}}}{2.43L_o^{\frac{1}{3}}}\right) t \qquad (6)$$

Comparing Equation (6) with the straight line formula $Z = bt + a$, gave the following relationships:

$$Z = \left(\frac{t}{y}\right)^{\frac{1}{3}} \qquad (7)$$

$$a = (2.3K_dL_o)^{\frac{1}{3}} \qquad (8)$$

$$b = \frac{K_d^{\frac{2}{3}}}{2.43L_o^{\frac{1}{3}}} \qquad (9)$$

Plotting $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ as a function of t, the slope b and the intercept a of the line of best fit can be used to estimate the values of K_d and L_o as follows:

$$K_d = 2.61^{\frac{b}{a}} \qquad (10)$$

$$L_o = \frac{1}{2.3K_da^3} \qquad (11)$$

where y = exerted BOD, K_d= re-aeration rate constant, L_o = ultimate BOD, a, and b = constant.

Table 4 shows the values for the computation of $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ with the application of BOD values obtained from experimental analysis in Tables 1 and 3 respectively. The values of $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ as presented in Table 4 were computed with an Excel template.

Table 4: Computation of $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ using BOD values

Time (day)	*Y*	$\left(\frac{t}{y}\right)^{\frac{1}{3}}$
1	18.0	0.3817
2	14.40	0.5179
3	14.20	0.5956
4	12.50	0.6840
5	12.18	0.7432
6	12.35	0.7861

Using the values from the table, the graph of $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ against t is plotted in order to determine the values of L_o and K_d in Figure 3.

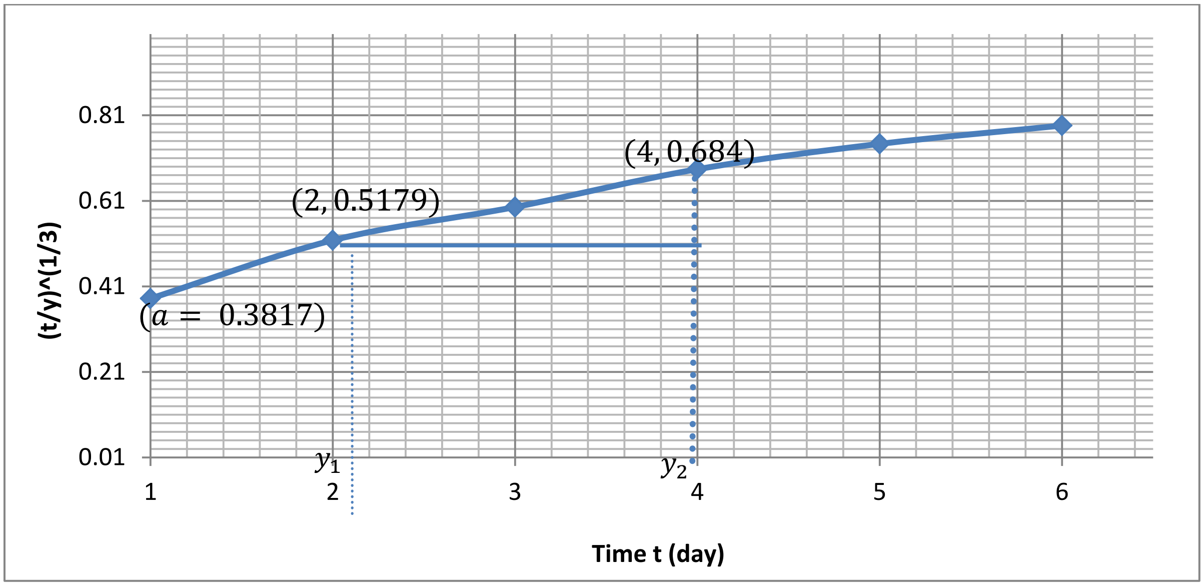


Figure 3: Plot of $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ against *t*

$$\therefore \text{Slope } b = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0.684 - 0.5179}{4 - 2} = \frac{0.1661}{2} = 0.0831$$

From Equation (10) $K_d = 2.61^{\frac{b}{a}}$, where $a = 0.3817$ and $b = 0.0831$

$$\therefore \quad K_d = 2.6 \times \frac{0.0831}{0.3817} = \frac{0.0831 \times 2.6}{0.3817}$$

$$= \frac{0.21606}{0.3817} = 0.566$$

$$\therefore \quad K_d = 0.566$$

Estimating the ultimate BOD from Equation (11) yields:

$$L_o = \frac{1}{2.3K_d a^3} = \frac{1}{2.3 \times 0.566 \times 0.3817^3}$$

$$= \frac{1}{0.0724} = 13.8\, mg/l$$

Determination of re-aeration constant using O' Connor Model

The re-aeration constant, k_r is determined by tracer study using O' Connor from Equation (7).

$$k_r = \frac{3.9V^{0.5}\sqrt{(1.037)^{(T-20)}}}{H^{\frac{3}{2}}} \qquad (12)$$

where V = mean stream velocity = (0.016 m/s Table 2); H = average depth of river = (3.501 m Table 2); and T = temperature (at 20℃). Since the value of T is 20℃, Equation (12) can also be written as:

$$k_r = \frac{3.9V^{0.5}}{H^{\frac{3}{2}}} \qquad (13)$$

$$= \frac{3.9 \times (0.016)^{0.5}}{(3.501)^{\frac{3}{2}}} = \frac{0.4933}{6.5507}$$

$$= 0.075$$

Determination of dissolved Oxygen using Streeter - Phelps model

The Streeter-Phelps model Equation (14) was used to estimate the dissolved oxygen of Otamiri River viz:

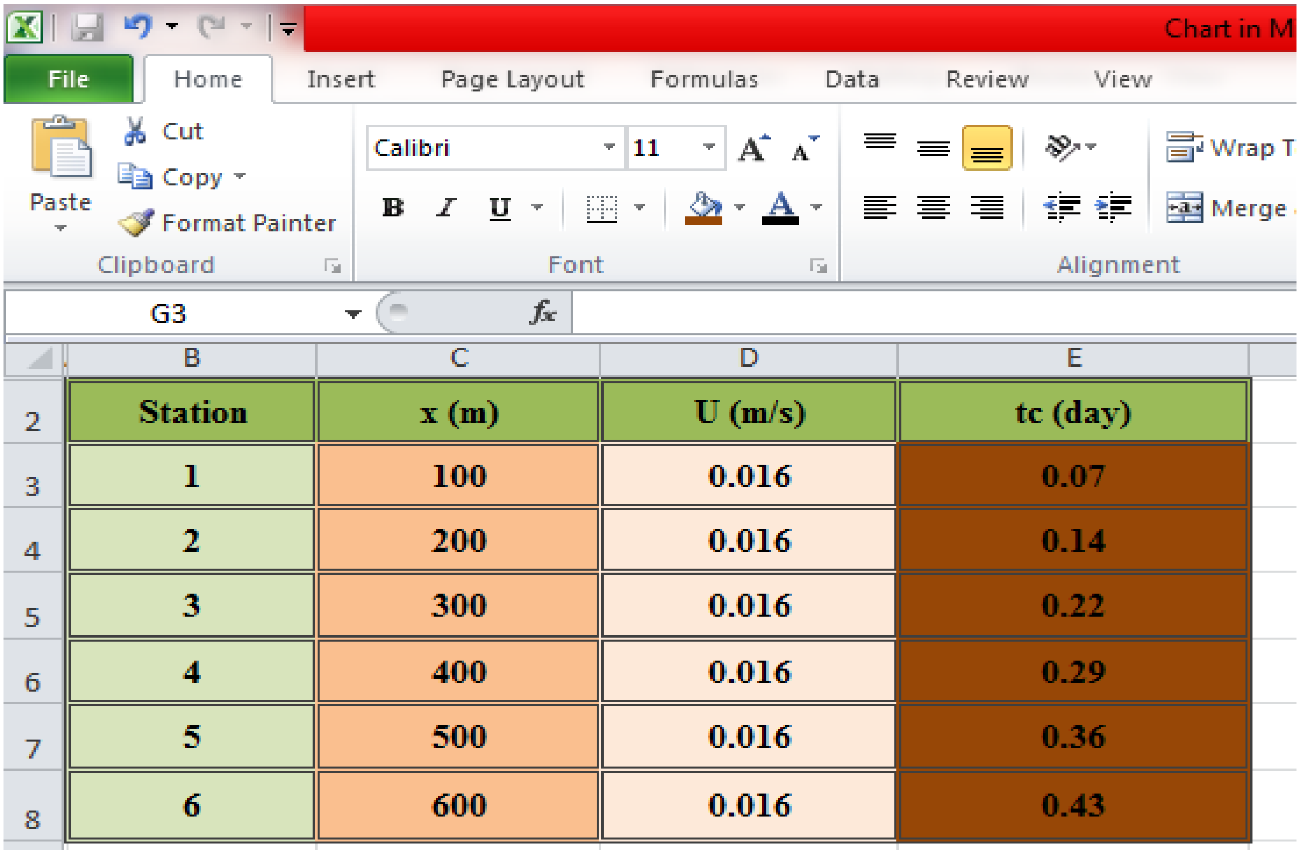
$$D_t = \frac{k_d L_o}{k_r - k_d}\left(e^{-k_d t} - e^{-k_r t}\right) + D_o\left(e^{-k_r t}\right) \qquad (14)$$

where t_c = critical time; D_t = oxygen deficit in the river at time t; L_o = initial ultimate BOD at mix, D_o = initial oxygen deficit at mix; k_r= re-aeration rate constant; k_d = de-oxygenation rate constant.

In estimating the dissolved oxygen deficit of Otamiri River, the critical time of the deficit was first estimated from Equation (15).

$$t_c = \frac{x\ (\text{km})}{U\ (\text{km/day})} \qquad (15)$$

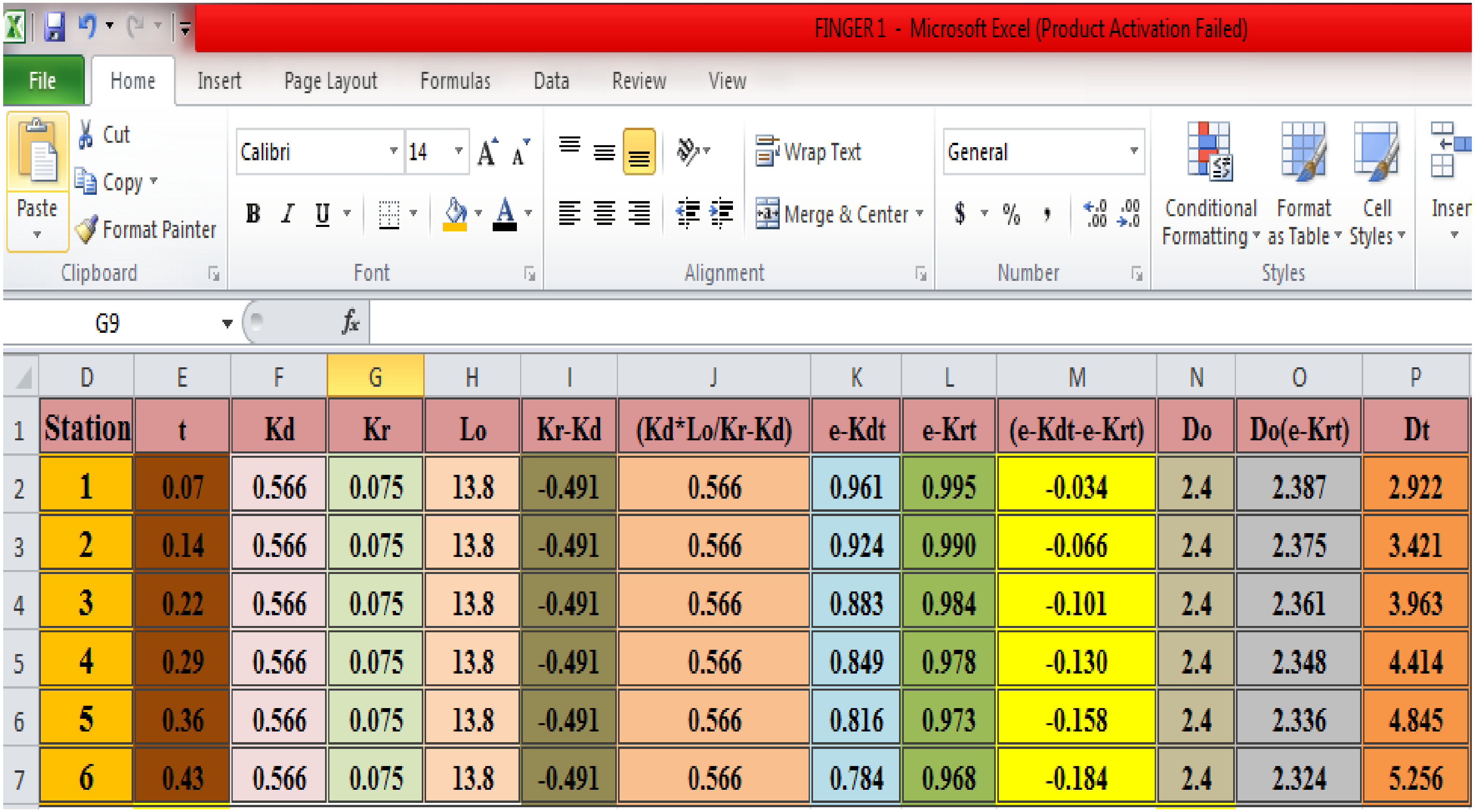
For the different days of sample collections as presented in Table 2, the critical time was calculated from a developed Excel template in Figure 4.



Station	x (m)	U (m/s)	tc (day)
1	100	0.016	0.07
2	200	0.016	0.14
3	300	0.016	0.22
4	400	0.016	0.29
5	500	0.016	0.36
6	600	0.016	0.43

Figure 4. Critical time for DO deficit occurrence

Since the critical time has been estimated in Figure 4, the dissolved oxygen at the different points was also estimated using a developed Excel template in Figure 5.



	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Station	t	Kd	Kr	Lo	Kr-Kd	(Kd*Lo/Kr-Kd)	e-Kdt	e-Krt	(e-Kdt-e-Krt)	Do	Do(e-Krt)	Dt
2	1	0.07	0.566	0.075	13.8	-0.491	0.566	0.961	0.995	-0.034	2.4	2.387	2.922
3	2	0.14	0.566	0.075	13.8	-0.491	0.566	0.924	0.990	-0.066	2.4	2.375	3.421
4	3	0.22	0.566	0.075	13.8	-0.491	0.566	0.883	0.984	-0.101	2.4	2.361	3.963
5	4	0.29	0.566	0.075	13.8	-0.491	0.566	0.849	0.978	-0.130	2.4	2.348	4.414
6	5	0.36	0.566	0.075	13.8	-0.491	0.566	0.816	0.973	-0.158	2.4	2.336	4.845
7	6	0.43	0.566	0.075	13.8	-0.491	0.566	0.784	0.968	-0.184	2.4	2.324	5.256

Figure 5. Dissolved Oxygen (DO) deficit estimation

Combining the results from the last column Figure 6 with the measured value of dissolved oxygen Tables 1 and 3 respectively, a dissolved oxygen sag curve was plotted and compared with the curve generated by Streeter-Phelp simulated model and measured DO values. Table 5 shows the different values of DO simulated and measured with respect to time.

Table 5: Comparison between measured and simulated DO with respect to time

Station	t (day)	D_o Measured	D_t Simulated
1	0.07	2.40	2.922
2	0.14	2.43	3.421
3	0.22	3.10	3.963
4	0.29	4.40	4.414
5	0.36	5.45	4.845
6	0.43	6.51	5.256

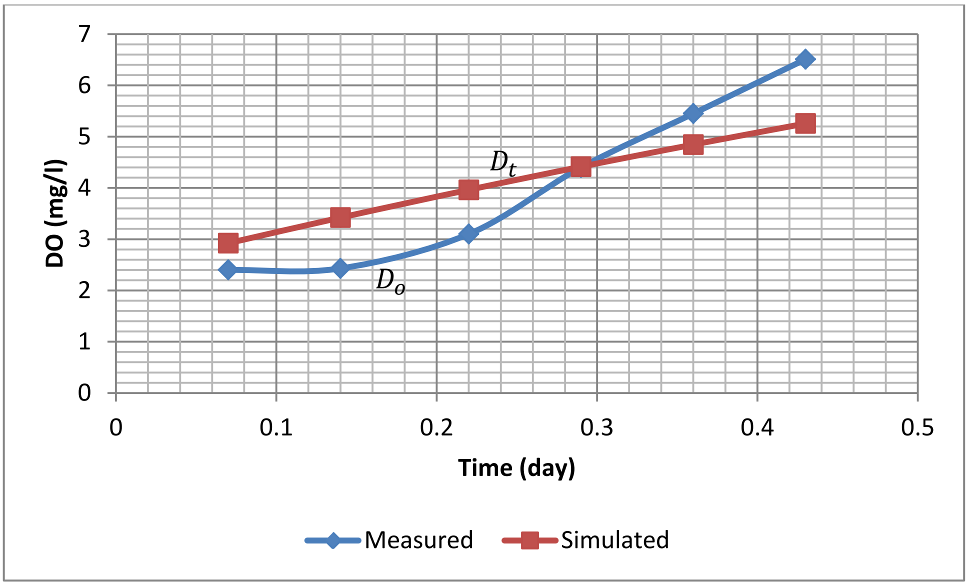


Figure 6. Predicted and measured DO sag curve of Otamiri River

Discussion of Results

From the laboratory results in Tables 3, the pH the water samples ranged from 4.23 to 5.76 which is higher than the standard limits of WHO and FMENV. This directly implies that the water samples are acidic in nature and is below FEPA limit. The temperature of all the samples collected ranged between 26.90℃ to 28.0℃, which is higher than the minimum limit of WHO but lower than maximum limit. The TSS values ranged between 18.0 mg/l to 20.8 mg/l and are within WHO and FMENV limits Table 3.

From Table 3, the TSS value for sample B, is higher than that of sample A (point source) by 0.08 mg/l. This is possible as some suspended solids discharged into the river must have flowed from point A to point B. The turbidity of the samples was within limits of WHO and FMENV with value of 0.04 each for the 6 station as compared with the standard limit of 5 NTU of WHO and FMENV respectively. This is possible as the TSS which directly affects water turbidity was within the set limits. The COD values ranged from 28 mg/l to 30.8 mg/l and are within the standard limits of WHO and FMENNV. Though they are within limits, their presence in a river consumes DO present in the river. The BOD values for the six stations range from 12.18 mg/l to 18 mg/l and are higher than the set limits of WHO and FMENV (i.e. 10 mg/l) respectively. This high value is due to waste discharge in the river.

From the values of DO in Table 3, the value of DO is 2.4 mg/l (Figure 2) which implies a low level of oxygen. However, the values kept increase along the stretch of the river as a result of self-purification of the river (Table 3) which is the ability of the river to maintain an adequate DO concentration. From Figure 6, the plot of DO measured and DO simulated showed that the DO measured decreased to some point D_o after which its value begins to increase as a result of self-purification of the river. The curve of the simulated DO showed a straight increase in the DO level following a rapid self-purification of the river.

Conclusion and Recommendations

Form the study, there was no DO in the effluent discharged from the point source due to excesses in COD, BOD, TSS and Turbidity. The unavailability of DO as earlier explained could lead to “Fish Kill” and anaerobic actions, thus releasing odorous gases like hydrogen sulphide and methane gas which are toxic to most organisms. Also high rate of self-purification experienced by the river showed the recovery of dissolved oxygen necessary for aquatic life within the River. While the effects of high BOD of the point source leads to depletion of DO, no significant direct effect was observed for temperature and pH. Therefore, the general low acidity of the river may be explained by factors other than the discharged from the out fall.

There is no doubt that the water quality of Otamiri River has deteriorated seriously and would continue if urgent measures are not put in place to control the fast continuous rate of waste discharge into the river without breaking down some of these wastes. Existing enabling laws to restrict contaminants levels of effluent discharge to water bodies should be enforced as there is possibility that the rate of DO reduction might be greater than the rate of self-purification, which in this case may result in the death of aquatic lives as well as the abandonment of the River

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