# KINETICS OF BIOCHEMICAL OXYGEN DEMAND ASSIMILATION ALONG KARU RIVER

[1]E. J. EKANEM *PhD, MNSE*; [2]M.H. BICHI *PhD, FNSE*
*Department of Civil Engineering, Bayero University, Kano - Nigeria*
*E-mail: jonniemvon@yahoo.com*

***ABSTRACT***
*The use of mathematical models to assess river pollution and self-purification status is an important tool for effective surface water quality management. The five day BOD test is widely applied to assess organic water pollution, and in defining the BOD ultimate value is adopted. This study is conducted to evaluate the kinetics of BOD assimilation and its assimilative capacity along the Karu River. Thomas slope method is used to evaluate the kinetic rate constant (k1) and the field measurements of hydro-geometric properties for finding the reaeration rate constant (k2) required for assessing the self-purification status of the river. The result established the rate constant, $k_{1,}$ for Karu River as 0.174 per day; with the lowest (0.124 $day^{-1}$) in the dry season and highest (0.223 $day^{-1}$) in the wet season which is within the range of internationally accepted values in practice. The study concludes that the Karu River has a high self-purification potential, and the river is classified as a polluted river. The effluent discharge into the river is below the National Environmental Standards and Regulation Enforcement Agency (NESREA), 2011 recommended limits.*

***KEYWORDS:*** *Karu River, Biochemical Oxygen Demand, Rate Kinetics, Self-Purification.*

## 1.0 INTRODUCTION

Many activities are responsible for the degradation of river water quality. Such activities as agricultural, leachates from solid waste disposal sites, runoff from storm flow, erosion and flood, discharges from the treatment plant sites, and even activities from slaughter houses commonly referred to as abattoirs, often constitute major river pollution sources. Discharge of untreated effluent into surface water body can be detrimental to the river oxygen level, as it helps to deplete the oxygen content and hamper the self-purification potential of such a river. Water purification is a complex process that takes into consideration several kinetic in a river system, to allow the river to undergo its self-recovery naturally. Agunwamba (2007), Chapra (1997), identify such factors as sedimentation, respiration, absorption and adsorption, chemical and biological activities to be responsible for the self-purification of rivers.

A review of literature reveals many theoretical models for modeling constituent interactions in streams. They have been dominated by the classical Streeter and Phelps (1925) model; which has been modified by others (Dobbins 1964; Bhargava, 1986). Various researchers have investigated the values of $k_{1,}$ but there has been no generic and linear nature of these coefficients (Haider et al 2013; Cox 2003). The estimation of rate parameters $k_1$ and $k_2$ involve in their model play important role in the model evaluation.

This paper set to evaluate the Kinetics of BOD assimilation parameters along the Karu River with particular attention to establishing deoxygenation rate constant $k_1$ in Streeter-Phelps model as it affects Karu River which at present is receiving abattoir effluent from Karu abattoir, and to assess the self-purification condition of the river.

## 2.0 MATERIALS AND METHOD

### 2.1 Study Location

Karu is one of the satellite towns in Abuja Municipal Area Council (AMAC) of the Federal Capital Territory, Nigeria. This study area is located about 7 km north - east of the Federal Capital Territory, off the Abuja–Keffi express way and lies between longitudes 7° 33' 17.19"E and 7° 34' 49.61"E and latitudes 8° 59' 38.6"N and 9° 01' 39.6"N. Karu has an area of about 275 square kilometres (Makwe, and Chup, 2013). Map showing the location of the study area is given in Figure 1.

### *2.2 Materials:*

The materials and equipment used in conducting the study are listed below.

i. Respirator meter with Incubators
ii. Turbidity meter
iii. BOD Bottles, Measuring cylinders
iv. Electrical conductivity meter
v. Global Positioning System - Hand Held Model Garmin GPS60
vi. Graduated wading rod
vii. F

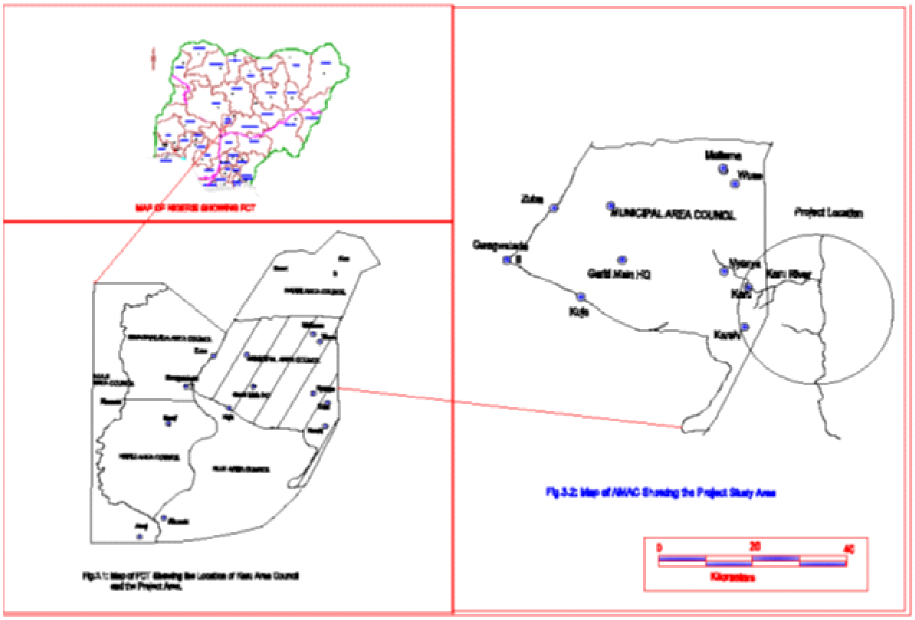

Figure.1: Map of Nigeria Showing FCT and the Study Area in Karu,

viii. Stop Watch
ix. Thermometer (Hand Held, 0-100°C)
x. Swan water plastic bottles 1.5 litres
xi. COD Spectrophotometer Merck cell test equipment Model ISO 15005
xii. Dissolved Oxygen Meter Model OX 4000H Phenomenal
xiii. Thermo reactor Spectroquart- Model TR320
xiv. Photo-spectrometer-Spectroquart-Model Nova 60
xv. Microscope (Nikon)
xvi. 100 Meter long Tape

## 2.3 Location of Sampling Points

For the river, sampling points were located such as to take care of the upstream, point of discharge and downstream from the discharge location. A non-isp-kinetic–sampler method, namely an open-mouth sampler was used. The method allowed the use of 1.5 litre sampling bottle hand-held Eva plastic bottle sampler was used for sampling. During the field work, nine (9) sample points (designated, US, PS, DS-1, DS-2, DS-3, DS-4, DS-5, and DS-6,) were identified along the river and their coordinates were captured with GPS as in Table 1. The spacing of the sampling points was done at an irregular interval due to accessibility problems.

**Table.1: Coordinates and Elevation of Sampling Points (GPS)**
**Date of Sampling: 19-04-2016**

| S/N | Site No. | GPS Coordinates Point | | Elevation | Remarks |
|---|---|---|---|---|---|
| | | Longitude | Latitude | (m) | |
| 1 | US | 90124271 | 75768690 | 406 | Upstream station of the River before discharge point |
| 2 | PS | 90118224 | 75783191 | 405 | Effluent Discharge point location |
| 3 | DS-1 | 90128377 | 75799056 | 404 | Downstream of the river after abattoir effluent discharge point |
| 4 | DS-2 | 90080700 | 75810036 | 400 | Station at Karu- Maraba abattoir road bridge point downstream |
| 5 | DS-3 | 89979478 | 75755872 | 390 | Under PHCN high tension line |
| 6 | DS-4 | 89955370 | 757776361 | 387 | Station downstream at before the confluence of karu river |
| 7a | TS | 89950811 | 75778064 | | Test Station along the tributary stream to the Karu river. |
| 7 | DS-5 | 89945962 | 75785001 | 384 | Station after the confluence of the tributary stream |
| 8 | DS-6 | 89868157 | 75821435 | 380 | Last sampling station downstream of the river |

## 2.4 Sampling Design and Method

Both water quality samples and hydro-geometric properties of the Karu River were collected for a period covering both wet and dry seasons for the experiment. The wet season sampling was carried out to take care of the early rain, mid or peaked rains, and tail rain periods, as such the months of April 2016, August 2016 and September 2016, were selected for this sampling. In the same way, the dry seasons sampling were carried to reflect the start of the dry season, mid dry, and the proper dry periods. So, dry season sampling was done in the months of November 2016, December 2016 and January 2017.

## 2.5 Laboratory Analysis

Water quality was analysed at the Federal Capital Territory Sewage Treatment Plant

Laboratory, Wupa, Standard laboratory reagents and apparatuses were used to analyse the river water and abattoir effluent samples into physical and chemical parameters, using the method described in Standard Methods of Examination of Water and Effluent (APHA, 1995) edition; which grouped the laboratory analysis into three namely: the Titration, the use of Portable meters and the Spectrophotometer methods. The analysed parameters are Temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), turbidity, conductivity and Total dissolved solids. The ultimate BOD was estimated with the formula (Chin, 2006), expressed as in Equation (1):

$$BOD_u = (BOD5)/ (1- e^{-k_1 t}), \qquad (1)$$

Where: BOD5 is the BOD after 5days incubation, at time t.

### 2.6 Determination of hydro-geometric of the river

The Hydro-geometric properties of the river obtained include flow velocity, channel width, and water depth. The average slope of the channel bed was computed from the established elevation differences. The flow depths were measured using a graduated staff gauge and wading through the river section. A 100m tape was used to measure the top of the river bank and the top width of the water surface.

**Discharge measurement**

The discharge from the river was determined from the area–velocity approach, whose method can be found in most standard hydraulic textbooks, (e.g Leton, 2005). The time of travel, *t*, and the measured distance, d, were used to establish the flow velocity based on the relationship of velocity equals distance (d) divided by time (t).

**Rate Constants for the river**

The rate constants $k_1$ and $k_2$ are for deoxygenation and reaeration constants respectively. The value of $k_1$ was established based on the Thomas' graphical approach, (1950) and compared with values in Table 3, (Chin 2006). $K_2$ values were computed based on Equation 2 (O'Connor and Dobbins, 1958) as in Chin (2006).

$$k_2 = \frac{3.9\, u^{1/2}}{H^{3/2}} \qquad (2)$$

Where, U, is the velocity in m/sec and H, is the depth in meters.

The Thomas graphical approach for finding the value of k1, are stated in the equation below

**Finding the De-oxygenation Coefficient $k_1$ and ultimate BOD, Lo**

The rate constant $k_1$ was found using Thomas slope method by considering the expression

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

Substituting K equal $2.3k_1$, we obtain,

$$\left(\frac{t}{y}\right)^{1/3} = (2.3k_1L_o)^{-1/3} + \left(\frac{k^{2/3}}{3.43L_o^{1/3}}\right) t \qquad (4)$$

Linearize by comparing with the straight line equation z = a + mt, where

$$z = \left(\frac{t}{y}\right)^{\frac{1}{3}}; a = (2.3k_1L_o)^{-1/3}; b = \left(\frac{k^{2/3}}{3.43L_o^{1/3}}\right) \qquad (5)$$

$$k_1 = 2.61\frac{b}{a};\ L_o = \left(\frac{1}{3.43k_1a^3}\right)$$

Temperature correction factor is,

$$k_1 = k_{1(20)}\, 1.047^{(T-20)} \qquad (6)$$

By plotting $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ against time, **t** (days), the slope **(b)** and the intercept **(a)**, of the line of the best fit of the data were used to calculate and $k_1$ and $L_o$.

### 2.7 Dissolved Oxygen Prediction using Streeter-Phelps Equation

Self-purification potential was assessed based on the ratio of reaeration constant, k2, to that of the deoxygenation constant $k_1$ (Agunwamba, 2007; Garg, 1986). The prediction of the

Dissolved Oxygen deficit used the Streeter and Phelps, 1925 oxygen sag model given as.

$$\mathbf{D_t} = \frac{\mathbf{k_1 L_0}}{\mathbf{k_2 - k_1}}\left(\mathbf{e^{-k_1 t} - e^{-k_2 t}}\right) + \mathbf{D_0 e^{-k_2 t}} \quad (7)$$

Where $D_t$ is the dissolved oxygen deficit, $k_1$ and $k_2$ are rate coefficients, t is time, $L_0$ is ultimate BOD, $C_s$ is oxygen at saturation, and $D_o$ is the initial oxygen deficit at mix, and the value of $L_{o,}$ is expressed under mixed condition as:

$$\mathbf{L_0} = \frac{\mathbf{Q_e L_e + Q_r L_r}}{\mathbf{Q_e + Q_r}} \quad (8)$$

Where $Q_e$ and $L_e$ are the discharges and concentration of effluent respectively; and $Q_r$ and $L_r$ are the river flow discharge and river pollution concentration respectively.

The computation of $D_t$ the dissolved oxygen deficit at any other time was by the use of Excel software. In finding the DO deficit of Karu River, the critical time ( $t_c$ ) of the deficit was first calculated using the distance- time of travel relationship in Equation (8) as;

$$tc = x(km)/v(km/day) \quad (9)$$

**2.8 Statistical Evaluation**

Statistical performance between predicted and measured was assessed using: Residual Mean Square Error (RMSE); Relative Root Mean Square Error (RRMSE); Mean Absolute Error (MAE); Coefficient of Correlation ($R^2$)

## 3. RESULTS AND DISCUSSION

Results of the field data collection, hydraulic, laboratory analysis, including statistical evaluation for developed models are presented in this section.

### 3.1 Field Data Collection

**Geometric characteristics of the river channel**

The River Channel Layout and Sampling Points Coordinates and cross sectional surveys data conducted are indicated in Figure 2. The geometric layout of the Karu River indicates distance and station cross section coordinates. The river has a total length of 13.85km, with **a reach of 8.0km distance covered in this** studied.

***Hydro-geometric properties of the river channel – Flow Measurements***

The hydraulic data were collected for six months with three months in wet and three in dry seasons. It includes the computed flow velocities, channel properties, and discharges.

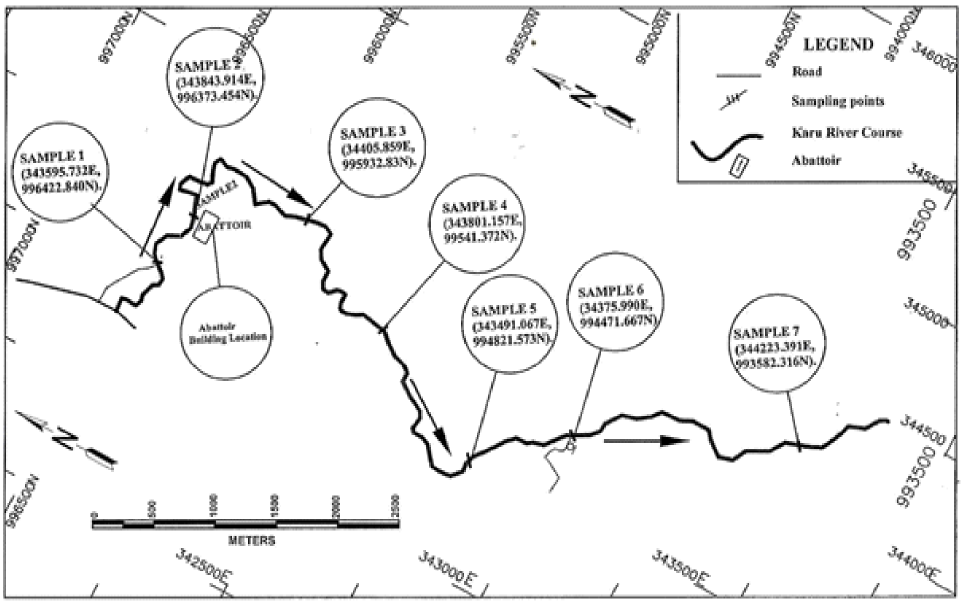


Figure. 2: Geometric Layout of Study Reach of Karu River with Sampling points and Station Coordinates

The mean daily flows for the Karu River assessed are presented in Table 2. The peak average discharge was recorded in the month of August with a value of 7.75$m^3$/s. and the lowest flow of 0.408$m^3$/s recorded in January 2017 representing the dry season period. The average daily measurements of discharges for other months for the river reach are shown in Table 2. The high flows correspond to peak rains and others are for the early rains and tail-dry periods. The flows helped in the dilution of abattoir effluent entering into the river with its ultimate BOD values (Lo) indicated below.

Table 2: Average Daily River Discharge Measurement and Ultimate BOD values

| Month | Ultimate BOD-$L_o$ (mg/l) | Mean Daily Flows ($m^3$/s) |
|---|---|---|
| Apr | 185.87 | 1.388 |
| Aug | 158.62 | 7.750 |
| Sep | 216.15 | 5.125 |
| Nov | 310.58 | 1.228 |
| Dec | 394.42 | 0.775 |
| Jan | 343.00 | 0.408 |

### 3.2 The Self-Purification of the River due to the Assimilation of BOD

**Establishment of Deoxygenation k1 and Reaeration Constants $k_2$**

The typical curve produced with Thomas slope method is presented in Figure 3 from where the constants were obtained.

Table 3 shows the results of the rate constants $k_1$ obtained from the Thomas slope method in MetCalf and Eddy, 1991, and $k_2$, calculated using the O'connor formula. The table also indicates the values of Thomas parameters a, b used in finding $k_1$.

The values of the calculated ultimate BOD for each month are shown also with values varying from 161 mg/l in the wet season to 439.77mg/l in the dry season.

Table 4 summarises the computed critical time for DO deficit occurrence for both wet and dry seasons. Dissolved Oxygen was predicted by applying the calculated $k_1$, $k_2$ in Oxygen sag model. The computed Dt and measured DO (mg/l) are plotted against computed time of travel (Figures 4 and 5). Typical data used in the Thomas slope method for April is shown in Table 3, and the curve in Figure 3 used in finding the constants and the slope.

Table3: Computed $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ using BOD values (April)

| Time,t (d) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Y | 189.6 | 167 | 154.2 | 149.6 | 125 | 119.4 |
| **$(t/y)^{1/3}$** | 0.177 | 0.232 | 0.273 | 0.303 | 0.346 | 0.373 |

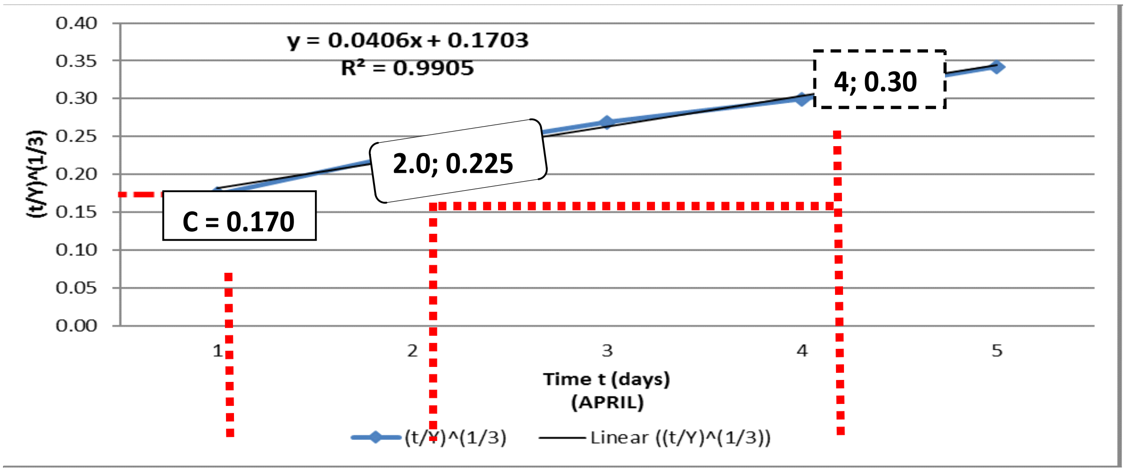


**Figure 3: A plot $\left(\frac{t}{y}\right)^{\frac{1}{3}}$ against ( t)**

Table 4: Showing the assessment of Deoxygenation and Reaeration Constants

| Table:- Computation of $k_1$, $k_2$ and $BOD_{ult}$ ($L_o$) | | | | | | |
|---|---|---|---|---|---|---|
| Time | Wet Season | | | Dry Season | | |
| Variables | Apr | Aug | Sep | Nov | Dec | Jan |
| a | 0.199 | 0.244 | 0.225 | 0.221 | 0.195 | 0.21 |
| b | 0.02 | 0.017 | 0.02 | 0.011 | 0.01 | 0.009 |
| $K_1$ ($d^{-1}$) | 0.259 | 0.185 | 0.226 | 0.129 | 0.133 | 0.111 |
| $L_o$ (mg/l) | 213 | 161 | 169 | 311 | 439.77 | 421.3 |
| $K_2$ | 1.08 | 3.51 | 2.9 | 0.57 | 0.70 | 0.111 |
| f | 4.17 | 18.91 | 12.83 | 4.43 | 5.26 | 1.0 |
| Ave Wet | $k_1$ | 0.223 | | Av Dry k1 | 0.124 | |
| $K_1$ for Karu River | | 0.174/d | | | $k_2$ | varies |

**Note: a, b = Thomas constants; Lo = ultimate BOD; k1, k2 = rate constants**

**Table 5: Computation of Critical Time $t_c$ at various stations**

| Points | Distance $x$ (m) | Velocity $u$(m/s) | | Critical time $t_c$ (day) | |
|---|---|---|---|---|---|
| | | Mean wet | Mean Dry | Wet | Dry |
| PS | 150 | 0.925 | 0.528 | 0.002 | 0.003 |
| DS-1 | 300 | 0.96 | 0.496 | 0.030 | 0.006 |
| DS-2 | 950 | 1.253 | 0.654 | 0.088 | 0.017 |
| DS-3 | 3200 | 0.977 | 0.553 | 0.379 | 0.067 |
| DS-4 | 1500 | 1.018 | 0.532 | 0.171 | 0.033 |
| DS-5 | 1100 | 1.104 | 0.742 | 0.115 | 0.017 |
| DS-6 | 1445 | 0.965 | 0.662 | 0.173 | 0.025 |

The allowable pollution load into a river is determined by the parameters $\mathbf{k}_1$, **f**, $\mathbf{D}_c$, and $\mathbf{D}_o$. Typical values of $\mathbf{k}_1$ and *f* are given in Table 6 and Table 7 respectively.

**Table 6: Typical Deoxygenation Constants**

| Type of Water | $K_1$ (at 20$^0$C day $^{-1}$) | | |
|---|---|---|---|
| Untreated Waste water | 0.35 | - | 0.70 |
| Treated Waste water | 0.10 | - | 0.35 |
| *Polluted River* | *0.10* | - | *0.25* |
| Unpolluted River | less than - | | 0.05 |

*Source: Chin (2006)*

**Table 7: Ratio $K_2/K_1$ For Different Hydraulic Conditions of Streams**

| Description of the water body | Range of $K_2/K_1$ |
|---|---|
| Small reservoir or lake | 0.5 - 1.0 |
| Slow sluggish stream, large lake | 1.0 – 2.0 |
| Large slow river | 1.5 - 2.0 |
| Large river of medium flow velocity | 2.0 – 3.0 |
| Fast flowing stream | 3.0 – 5.0 |
| Rapids and water falls | 5.0 – and above |

*Source: Fair and Okun (1985)*

The deoxygenation rate constant $k_1$ assessed for the river is 0.174 per day. Compared with the range of values in Table 6, the river can be classified as a polluted river. The computed ratio of $k_2/k_1$ ie *f*, (self-purification factor), when compared with values in Table 7, are relatively higher, with values ranging from 5.1 – 18.0 for the wet season and 24.3 – 134.7 for the dry seasons (Table 4). The high values are attributed to shallow river depth and high local flow velocities measured. The values were compared with Akpen and Ekanem (2016) on Wupa River within the same hydrological zone. Karu River thus has a good assimilative capacity.

### 3.2.3 DO Evaluation of Predicted and Measured using S-P Equations

From the typical curves for April shown in (Fig 4), and December (Fig 5), a comparison was made between the oxygen predicted using sag curve and the measured oxygen values. The curves show good correlation between measured and predicted except for the month of January.

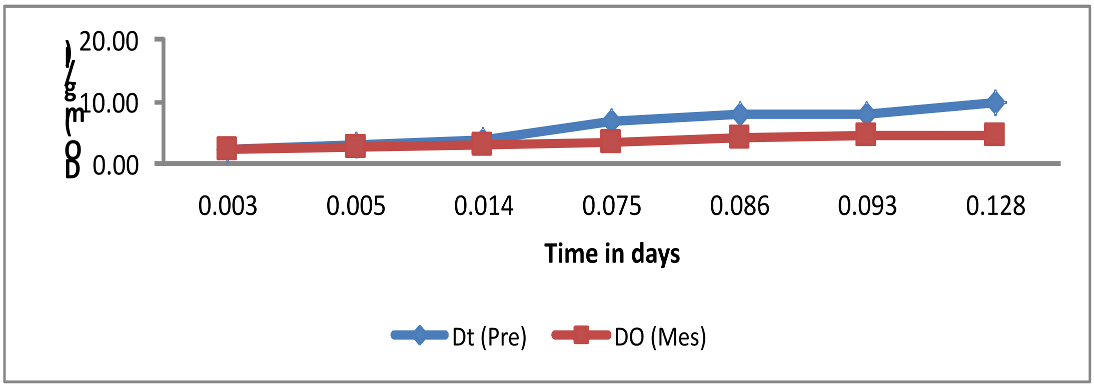


Fig 4 : Comparison of Predicted Dt and measured DO SAG for April

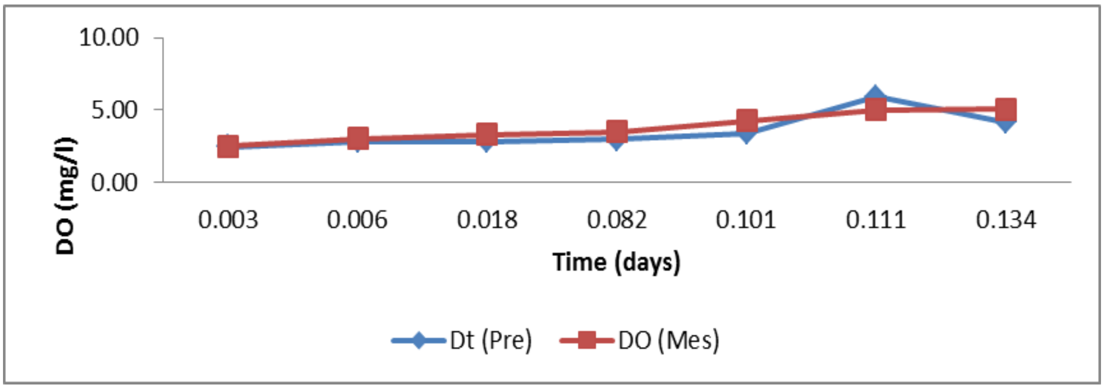


Figure 5: Comparison of Predicted Dt and measured DO Sag for December

### 3.2.4 Evaluation of DO Sag Model Performance

Shown in Table 8 is the value of the computed model performance parameters for MAE, RMSE, and $R^2$ compared with the measured and predicted DO concentration statistically, based on Oxygen sag model.

Table 8: Statistical model performance assessment parameters

| PARA | APR | AUG | SEPT | NOV | DEC | JAN |
|---|---|---|---|---|---|---|
| MAE | 2.3146 | 0.1383 | -0.0266 | 0.0042 | -0.3090 | -0.2364 |
| RMSE | 0.8748 | 0.0545 | 0.0710 | 0.0511 | 0.2142 | 0.6254 |
| $R^2$ | 0.9615 | 0.9615 | 0.9739 | 0.9869 | 0.8564 | -0.2525 |

To find the relative merits associated with the use of the model, the performance evaluation was done based on differential errors and other statistical criteria. The MAE has a calculated mean value for the 6-months ranging from -0.309 to 2.314 and overall absolute mean of 0.536 which is low and considered to be better. The RMSE is the measure of scatter of the residual with mean value of 0.311 which is close to zero, indicating the model performance is good. The coefficient of determination $R^2$ has a value of 0.935 indicate a moderate correlation when compared to standard value of 1.0**.** It means the relationship between the data sets is good, except for January condition which gives negative values. This could be as a result of too low flow in some reach along the river.

### 3.2.5 DISCUSSIONS

***Data Collection and Flow Measurements***

Field data collection was carried out for both the rainy and dry seasons. The dry season data indicated high concentration of BOD load than in the wet season, conversely the wet season had more dissolved oxygen than the BOD load due to the dilution effect from the rainfall.

The average flows of the river were higher during the rainy period while low flows characterized the dry season measurements. The mean flows varied from 1.388 to 7.75$m^3$/s in august for the wet period, and 1.227$m^3$/s to as low as 0.408m3/s for the dry period.

The hydraulic parameters such as flow velocities, channel characteristics were noted to have varied with the season due to fluctuations in discharge.

From the field measurements, the width of the Karu river channel varies from 5 to 22 meters during peak flow and 2 to 12 m during normal flow. According to WHO (1996), classification based on discharge, drainage area and width, Karu River can be classified as a small river with an average width of 8-15 meters, a depth of 0.3-2.0 meters and a velocity of 0.3-2.2 m/s.

**Deoxygenation k1 and Reaeration Constants $k_2$ for the Karu River**

From the results in Table 4, the average computed rate constants $k_1$ for the wet and dry seasons are 0.223 $d^{-1}$ and 0.124 $d^{-1}$ respectively. The values of the Thomas parameters a, b used in finding $k_1$ are also indicated. The high $k_1$ value in the wet season could be due to increased organic concentration from overland flows into the river, noting that $k_1$ is affected by temperature. The $k_1$ values for the Karu River were similar to values available in literature (Chin, 2006, Agunwamba, 2007; Thomas and Mueller, 1987; Chapra, 1997). Based on the work of Fair and Okun (1991), the values fall within the class of polluted rivers with a range between 0.10 – 0.25 (Table 7).

The $k_2$ values were found to range between 1.1 and 3.51 for the six months. The $f$ values ranges from 1.0 to 18.91 for the six months, which exceeds the minimum reaeration value of 2 required for the river. The mean value of $f$ for the river is 11.54, showing the quick recovery of depleted Oxygen in the river. The established value of $k_1$ for Karu River is 0.174 per day (Table 4).

The Self-purification of the Karu River was based on Streeter-Phelps model and indicated a good fit for the two seasons. Low DO noted for the dry season and high for wet. The $BOD_{5,20}$ exceeded the NESREA (2011) limit of 5.0mg/l attributed to input from residents along the river banks.

The values of the calculated ultimate BOD ($L_o$) for each month are shown in Table 4 with values varying from 161 mg/l in the wet season to 439.77mg/l in the dry season. The high dry season values are attributed to non-dilution effect in the river when compared with the wet season values.

## 4 CONCLUSION

The study has established the kinetic parameter of k1 for Karu River to be 0.174 per day; with the lowest in the dry season and highest in the wet season which is within the range of internationally accepted values in practice. The DO sag model of Streeter- Phelps fit into the data collected from the river. The data set, correlated at 0.95 considered good. The study shows that the Karu River has a high self-purification potential despite effluent contribution from the abattoir and the overland inflow.

## *REFERENCE*


Agunwamba, J. C. (2007). Engineering Mathematical Analysis. De Adroit Innovation, Enugu, Nigeria

APHA, (1995). Standard Methods for the Examination of Water and Wastewater, 19th Edn. Washington, DC: American Public Health Association.

Akpen, G.D; Ekanem, E.J.; and Agunwamba, J.C (2016). Impact of Sewage effluent discharges on water Quality of Wupa River in Abuja, Nigeria.

Bhargava, D.S, (1986). DO Sag Model for Extremely Fast River Purification. J.Environmental Engineering ASCE Vol. 112, No.3

Chapra, S. C.(1997). Surface water quality modeling. New York: McGraw-Hill, 1997. 844 p.

Cox, B.(2003). A. A review of dissolved oxygen modelling techniques for lowland rivers. Science of Total Environment, v. 314, p.303-334,2003.http://dx.doi.org/10.1016/S0048-9697(03)00062-7»http://dx.doi.org/10.1016/S0048-9697(03)00062-7

Chin, D. A. (2006). Water Quality Engineering in Natural Systems. John Wiley & Sons Inc., New York, USA.

Dobbins, W.E (1964). BOD and Oxygen Relationship in Streams, J. Sanitary Engineering Division ASCE 90 (SA3), pp53-78

Garg, S. (1986). Waste Water Engineering. Khanna Publishers, New Delhi, India.

**Fair, G.M., and D.A. Okun (1985).** *Elements of water supply and wastewater disposal.* 3rd edition, John Wiley & Sons. N.Y.

Haider, H.; Ali, W.; Haydar, S. Evaluation of various relationships of reaeration rate coefficient for modeling dissolved oxygen in a river with extreme flow variations in Pakistan. Hydrological Processes, v. 27, p. 3949-3963, 2013. http://dx.doi.org/10.1002/hyp.9528» http://dx.doi.org/10.1002/hyp.9528

Leton, T. G . (2005). Element of Civil Engineering Hydraulics. Lagos. Nigeria Reynolds Grits Publishing Co.

Makwe, E. and Chup, C. D. (2013).Seasonal Variation in Physico-Chemical Properties of Groundwater around Karu Abattoir. Ethiopian Journal of Environmental Studies and Management, 6(5): 489-497.

MetCalf and Eddy (1991) 3rd Ed Waste Water Engineering, Treatment, Disposal and Reuse. McGrawHill International Editions. Civil Engineering Series. New York

National Environmental Standards Regulation and Enforcement Agency-NESREA(2011) Surface and Ground Water Quality Control Regulation, Vol. 98, No.136.

O'Connor, D. J. and Dobbins, W. E. (1958). "Mechanism of Re-aeration in Natural Streams." Transactions of the American Society of Civil Engineers, 123:641-684.

Streeter, H. W.; Phelps, E. B. (1925). A study of the natural purification of the Ohio River. Washington: U. S. Public Health Service, 1925. 75 p. (Public Health Bulletin, v. 146)

Thomann, R. V.; Muëller, J. A. (1987). Principles of surface water quality modelling and control. New York: Harper & Row, 1987. 644p.

Thomas, H. A.(1950). Graphical determination of BOD rate constants. Water Sewage Works, v. 97, p. 123-124, 1950.

WHO (1996). Water quality assessments: A guide to the use of biota, sediments and water in environmental monitoring 2nd. Ed. UNESCO, World Health Organization, United Nations Environment Programme, London. prepared by Chapman, D.,