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Modelling the Effect of Industrial Effluents on Water Quality: "A Case Study of River Challawa in Nigeria"

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ABSTRACT: *The physicochemical characteristics associated with industrial effluents from the Challawa and Sharada Industrial Estate in Kumbotso Local Government Area of Kano State ad the effect on water quality of a 10.6 km stretch downstream of River Challawa were investigated. The test period covered both wet and dry seasons, with laboratory analysis of field samples and study area. The results obtained indicated that the DO values varied from 0 mg/l to 3.5 mg/l, BOD_5 value ranged from 193 mg/l to 1025 mg/l along the river channel. The reaeration coefficient k_2 of River Challawa varied from 0.013 to 0.140. The 0.013 to 0.140. The coefficient of correlation between k_2 predicted with derived models were 0.229, 0.295, 0.994, 0.842, 0.676, 0.855 and 0.473. An improved technique using the reaeration coefficient values at each section and incorporating the fall velocity gave a profile closer to the measured oxygen deficit values than the conventional approach. The coefficients of correlation for the two approaches are 0.9572 and 0.4558 respectively. The comparison of k_2 observed and predicted k_2 O'Conner and Dobbins, Ugbebor and Agunwamba, Churchill and Buckingham, and Agunwamba indicated standard errors of 1.5156, 2.3376, 04216, 1.3891, 0.0488, 0.3854 and 1.7721 respectively. Test result also gave a purification factor of 0.40, indicating the stream was polluted and has poor assimilatory capacity. There is need for proper monitoring and impact control measures for River Challawa.*

I. INTRODUCTION

The direct discharge of effluents from industries into rivers and the streams in an arbitrary manner without predetermining the impact of such discharges on animal and plant life is a growing third world environmental problem. Most of the wastewaters are extremely hazardous mixtures containing inorganic and organic components (Fu, et al 1994). The industrial operation consists of converting raw hide or skin into leather which can be used in the manufacture of a wide range of products. Consequently, the tanning industry is a potentially pollution-intensive industry.

Chemical impurities mostly comprise of (i). inorganic salt cations such as Fe^{2+}, Zn^{2+}, Cu^{2+}, Ca^{2+}, Na^{+}, anions such as SO_4^{2-}, NO_3^{-}, PO_4^{3-} and (ii) inorganic parameters such as Dissolved Oxygen(DO), Total Dissolved Solids (TDS) (Bosni et al 2000). When industrial waste and domestic sewage are discharged into the receiving water bodies without treatment, it leads to increased water pollution, loss of aquatic life and an uptake of polluted water by plants and animals which eventually affect the human body through consumption resulting in health related problems and a degradation of a sustainable environment.

Effluents generated by the industries are the major sources of pollution and since most of the human and animal population especially in developing countries do not have access to portable water and in most cases use raw river water for drinking purposes, the quality of life is seriously hampered. Studies on heavy metals in industrial effluents (either in free form or adsorbed in suspended solids) have been found to be carcinogenic (Tamburlini et al, 2002) and other chemicals equally present are poisonous depending on the dose and exposure duration (Kupechella and Hyland (1989)). These chemicals are not only poisonous to humans but are found to be toxic to aquatic life (WHO, 2002) and may result in food contamination (Novick 1999).

Study Area

The study was carried out from three different areas: on (i) Challawa River with eight sampling stations, (ii) Waste discharges from effluents in the Sharada Industrial Estate such as the Unique Leather Finishing and others discharging into the Salanta river and flowing through Sabuwar Gandu, Kumbotso and entering the Challawa river at Tamburawa. There were a total number of five sampling points here (iii) The third sampling point was from the industries in the Challawa Industrial Estate, made up of Mario-Jones industrial effluent, God's Little industrial effluent, Maimuda industrial effluent, Clobus industrial effluent and Fata industrial effluent and the confluence of the waste discharges from the Challawa Industrial Estate which finally discharged directly into the Challawa River at Yandanko. There were five sampling points at the Challawa Industrial Estate. There were eighteen (18 No) sampling points in all. Other industries in the areas include the textile industries and bottling company.

Detailed reconnaissance survey of the study area was carried out to ascertain the sampling points. The survey was made by locating the industrial industries in the estates and following the flow through to the points of discharge on Challawa River. Figure 1 shows a schematic view of the study area. A detailed survey of all the points of wastewater discharge into Challawa river were noted and sampling stations designated 1 to 18 were established as explained earlier

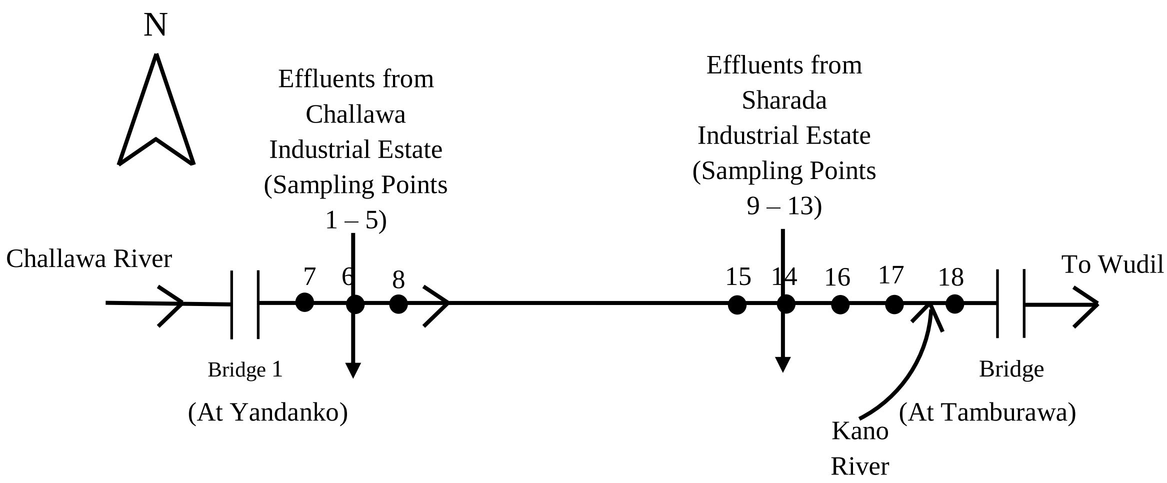

Fig. 1: A schematic outline of Challawa River, effluent discharges, sampling points and confluence with Kano River

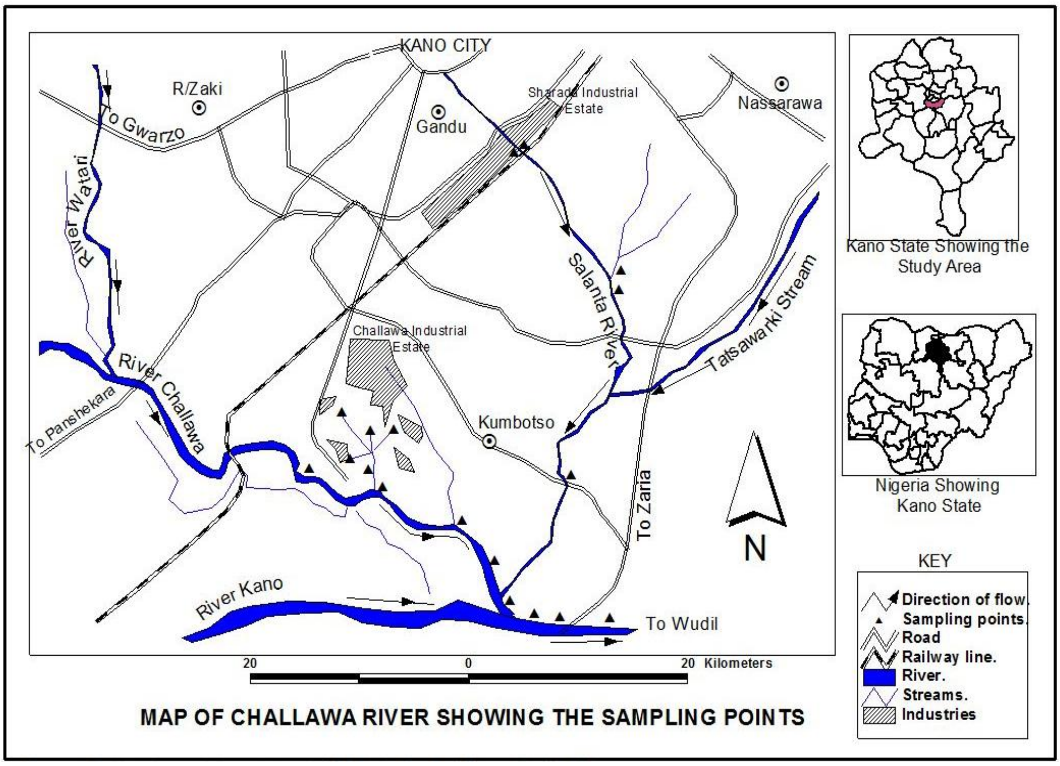

Fig. 2: Map of Challawa River showing the Sampling Points

Scope of Study

The study is composed of three (3) major aspects:

The first aspects is the reconnaissance survey and field work for the gathering of in-situ information on Dissolved Oxygen, the acquisition of raw wastewater effluent sample for BOD, COD, TDS analysis as well as information on other hydrodynamic factors such as stream velocity, depth and width. The sampled reach was limited to 10.644km from the upstream at Yandanko to the downstream at Tamburawa.

The second aspect was the laboratory analysis of the industrial effluents for physical, chemical and bacteriological characteristics.

The final aspect was the development of the k_2 model establishing the relationship between the parameters and developing the Oxygen sag curve for the area investigated based on the data collected. Data recording and handling were carried out with the aid of Microsoft Excel, SPSS and Regression analysis.

Limitations

The research work is limited to the Challawa River and the major sources of pollutants (industrial effluents) into the River. Many researches have been done on the mechanism of reaeration and factors affecting reaeration such as temperature, river geometry and hydrodynamics (Mcbride 1982, Agunwamba, 2001), assessment of assimilatory capacity of streams, and models of reaeration (Dobbins, 1964; Cohen & O'Connell 1976, Campolo et al, 2002). From field observation Nemerow (1987) reviewed series of equations and recommended those of Isaac (1967) and Streeter- Phelps (1925). Generally, it is agreed that Streeter- Phelps equation is not a (true) representative of stream self purification model as it suffers a number of limitations. Apart from questions of stream geometry and flow regime, it ignores a number of mechanisms where BOD and DO concentrations are raised or lowered (Leton, 2007). Some authors have included other parameters in the formulation of their models (Thomas and Mueller 1987, Leton, 2007).

Equations for Determination of Coefficient of Reaeration, k_2

Many attempts have been made to relate empirically the reaeration rate constant to key stream parameters. (Ademoroti, 1998). The most commonly used is O'Connor and Dobbins (1958) which states that

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

where k_2 = reaeration coefficient at 20°C (day^{-1})
V = average stream velocity (m/s)
H = average stream depth (m)

To adjust the temperature to stream temperature, the following equation is applied.

$$k_2 = k_{20}\theta^{T-20} \qquad (2)$$

where θ is the measured temperature. Appropriate value of θ is recommended by early researchers, i.e.
θ = 1.135 for T ranging from 4° – 20°C
θ = 1.056 for T ranging from 20° – 30°C

O' Connor and Dobbins (1958) also produced a model for the determination of reaeration constant of any medium slope to be:

$$k_2 = 46.2679\ \frac{U^{2.696}}{H^{3.902}} \qquad (3)$$

Churchill et al (1962) also produced a model for the determination of reaeration constant of any medium slope to be

$$k_2 = 1.923\frac{U^{1.325}}{H^{2.006}} \qquad (4)$$

Churchill et al (1962) later improved the equation by considering temperature as a factor which influences reaeration constant as follows.

$$k_2 = 5.06(1.024)^{T-20}\ \frac{U^{0.919}}{H^{1.673}} \qquad (5)$$

Gualtieri and Gualtieri (1999) show*ed that

$$k_2 = 3.93\ \frac{U^{0.5}}{H^{1/5}} \qquad (6)$$

Agunwamba et al (2009) analyzed the polluted status of Amadi Creek and its management, considering the effect of hydraulic radius in place of the depth of the river at different location, and obtained.

$$k_2 = 11.635\ \frac{U^{1.0954}}{R^{0.016}} \qquad (7)$$

Ademoroti (1988) confirmed in his work that reaeration rate constants (k_2) depend on the condition of the river. A fast moving shallow stream will have a higher reaeration rate constant than a sluggish stream of stagnant pond or lake.

II. CALIBRATION AND VERIFICATION OF THE RE-AERATION MODEL

Before the calibration was performed, the relationship between k_2 and velocity and water depth were explored. The parameter k_2 was found to increase as the velocity increases but reduces with decrease in water depth. The plot of k_2 versus velocity is shown in the figure below. Hence, a model of the type $k_2 = aV^b/H^C$ was assumed. Calibration of the model showed that it fitted the data well with a= 0.289, b=1.5464 and c= 1.5467. Verification of the model with a separate set of data gave a coefficient of correlation 0.8815.

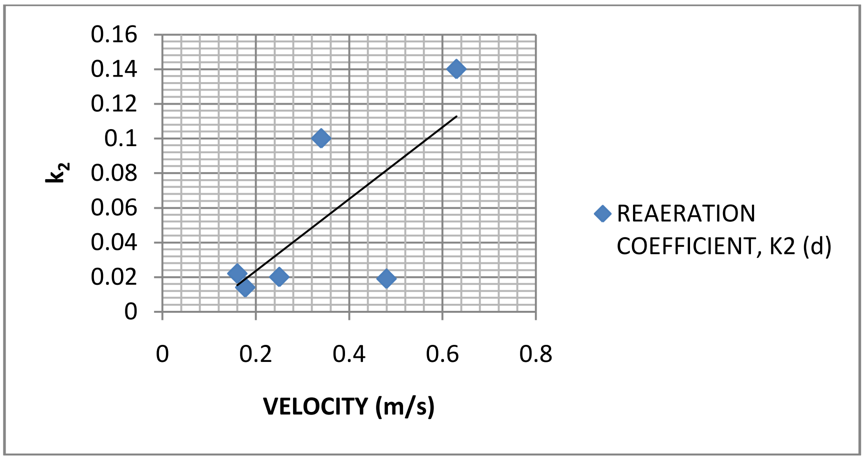

Fig. 3: k_2 versus velocity

Prediction of k_2 using six of the existing models and comparison with the model of this study based on data are shown in Fig 4 with the following corresponding coefficient of correlation: 0.229, 0.295, 0.794, 0.842, 0.0.676, 0.855, and

0.473. The corresponding standard errors of estimate are 1.5156, 2.3376, 0.4216, 1.3891, 0.0488, 0.3854, and 1.7721. Even though this study did not yield the highest coefficient of correlation the standard error of estimate was the least.

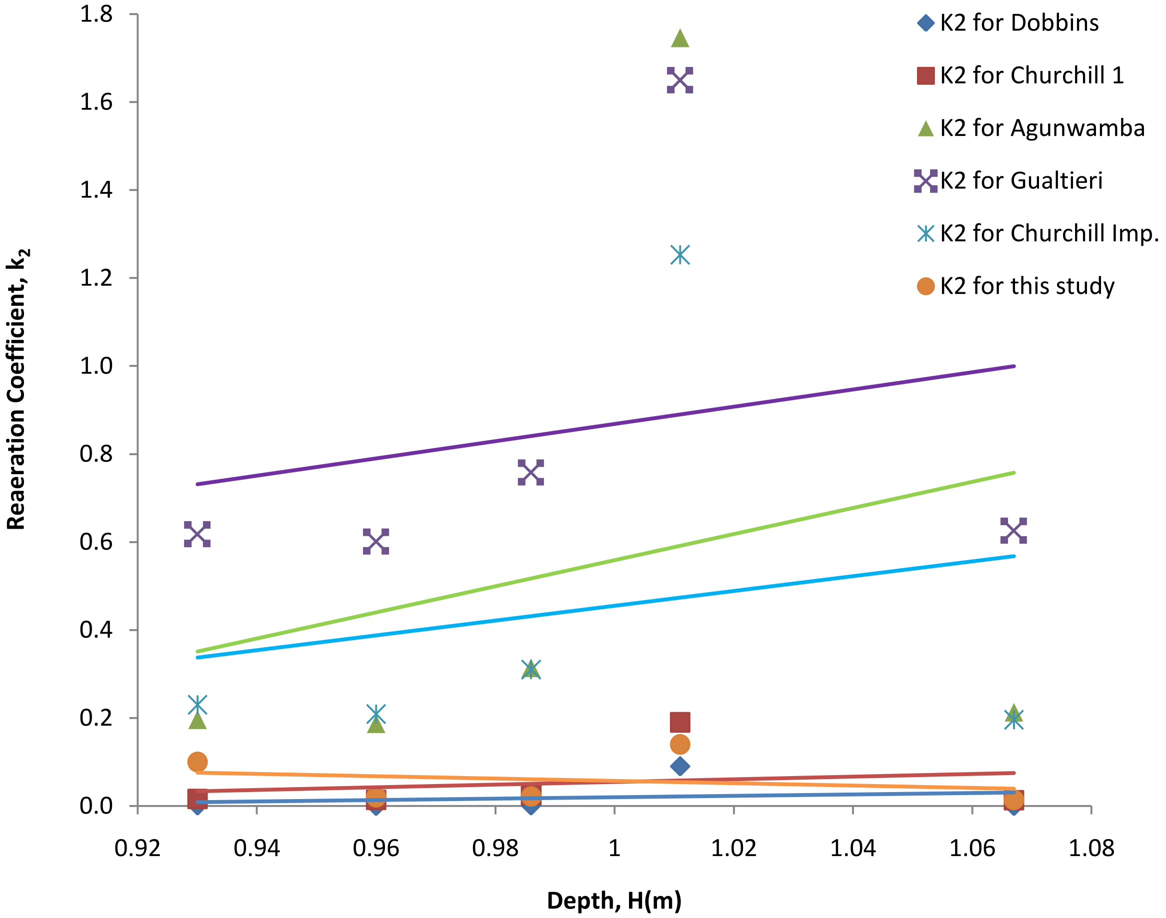

Fig. 4: Model Comparisons for Reaeration Coefficients

III. PREDICTION OF CHALLAWA RIVER OXYGEN SAG

The second modification is based on the fact that the re-aeration coefficient varies along the river reach as has been presented by previous researchers. Hence, computation of the oxygen sag equation based on an average value of k_2 is bound to result in inaccurate prediction.

Solution of the Conventional Oxygen Sag Equation

$$\frac{dD}{dt} = k_1 L - k_2 D \quad (8)$$

$$\frac{dL}{dt} = -kL \quad (9)$$

Where $L(0) = L_0$; $D(0) = D_0$ (10)

Using Laplace Transformation of (ft) defined by $Lf(t) = \int f(t)e^{-st}\,dt$ (Agunwamba, 2007)

Where $\sigma + i\omega = sD(s) - D(0) = \frac{k_1 L_0}{s+k_1} - k_2 D(s)$ (11)

Where $L = L_0 \exp(-kt)$ (12)

Substituting the initial conditions in (8), we obtain

$$(sD(s) - D_0)[s + k_1] + k_2 D(s)[s + k_1] = k_1 L_0 \quad (13)$$

After rearranging, it is shown that:

$$[s^2 + s(k_1 + k_2) + k_1 k_2]D(s) = sD_0 + k_1 D_0 + k_1 L_0 \quad (14)$$

From where:

$$D(s) = \frac{sD_0 + k_1 D_0 + k_1 L_0}{s^2 + s(k_1 + k_2) + k_1 k_2} \quad (15)$$

If equation (15) is resolved into partial fraction, the equation below is obtained:

$$D(s) = \frac{A}{S+k_2} + \frac{B}{S+k_1} \quad (16)$$

With $A = \frac{-D_0 k_2 + k_1 D_0 + k_1 L_0}{k_1 - k_2}$ (17)

$$B = \frac{k_1 L_0}{k_2 - k_1} \quad (18)$$

Integrating (16) around the appropriate Greenwich contour, C using the formula

$$2\pi iF(t) = \int_c e^{st}F(s)ds \quad (19)$$

It is clearly shown that:

$$D(t) = L^{-1}[D(s)] = \frac{k_1 L_0}{(k_2 - k_1)(e^{-k_1 t} - e^{-k_2 t})} + D_0 e^{-k_2 t} \quad (20)$$

Improved Oxygen Sag Equation

The conventional oxygen sag equation expressed in equations (1) and (2) are modified by incorporating the settling of the industrial waste which occurs along the River reaches. Equation (1) and (20), following the above analysis, may be expanded to include the rate of removal of BOD by benthal decomposition. The resulting relations are:

$$\frac{dD}{dt} = k_1 L_0 e^{-(k_2 + V_s)t} - k_2 D \quad (21)$$

and

$$D = \frac{k_1 L_0}{[k_2 - (k_1 + V_s)]} + D_0 e^{(-k_2 t)} = e^{-(k_1 + V_s)t} - e^{(-k_2 t)} + D_0 e^{(-k_2 t)} \quad (22)$$

Again, equations (1) and (2) are expressed as:

$$\frac{dD}{dt} = k_1 L - k_2(t) D \quad (23)$$

$$\frac{dL}{dt} = -KL \quad (24)$$

Since $L = L_o \exp(-k_1 t)$

$$\frac{dD}{dt} = k_1 L - k_2(t) D$$

$$\frac{dD}{dt} = k_1 L_o \exp(-k_1 t) - k_2(t) D \quad (25)$$

Obtaining explicit solution of equation (25), subject to the usual initial conditions, is possible only if the exact function $k_2(t)$ is determined. But $k_2(t)$ is a random variable since it is a function of the depth, flow and wind velocity at each section as well as temperature. In fact, the presence of k_2 makes equation (25) a stochastic equation. Hence, for simplicity, we resort to numerical solution.

The finite difference template of equation (21) can be expressed as

$$\frac{D_{i+1} - D_i}{\Delta t} = k_1 L_o \exp[(-k_2 + V_s)t] - \frac{(k_{2i+1} + k_{2i})}{2} \cdot \frac{(D_{i+1} - D_i)}{2} \quad (26)$$

Re-arranging, we have:

$$D_{i+1}\left[1 + \frac{\Delta t}{4}(k_{2i+1} + k_{2i})\right] = D_i + \Delta t \cdot k_1 L_o \exp[(-k_2 + V_s)t] + \frac{\Delta t}{4} \cdot D_i (k_{2i+1} + k_{2i})$$

$$\therefore D_{i+1} = \frac{D_i + \Delta t \cdot k_1 L_o \exp[(-k_2 + V_s)t] + \frac{\Delta t}{4} \cdot D_i (k_{2i+1} + k_{2i})}{\left[1 + \frac{\Delta t}{4}(k_{2i+1} + k_{2i})\right]} \quad (27)$$

For unit consistency, Δt values attached to k_1 have to be expressed in minutes

Table 1: Data requirement for computation of oxygen sag

Section	Part	k_2	C_s	Temperature (T°C)	Dissolved Oxygen (C)	$D_u = C_s - C$
Yandanko	Upstream	0.022	7.4	30.8	2.30	5.10
	Point Source	0.140	7.4	31.0	0	7.40
	Downstream	0.020	7.5	30.3	1.53	5.47
	Further Downstream	0.100	7.5	30.0	2.00	5.50
Tamburawa	Upstream	0.014	7.7	29.4	2.36	5.34
	Intermediate point	0.025	7.7	29.8	3.10	4.60
	Point source	0.013	7.7	29.8	1.07	6.63
	Downstream	0.019	7.7	29.4	1.85	5.80
	Further Downstream (G)	0.018	7.7	29.4	2.40	5.30

By substituting the values of Δt, Di, K_{2i}, K_{2i+1} and other parameters in equation (B7), D_{i+1} was obtained.

e.g. if t = 0, then $\Delta t = 0$, the value of deficit dissolved oxygen recorded against row 1, column 5 was obtained (Table 4.19).

$$D_{i+1} = \frac{7.4 + 0 - 0}{1} = 7.4\ mg/l$$

$K_1 = 0.251\ d^{-1}$; $V_s = 0.157$cm/min →

Deposition coefficient, V_s / h

Table 2: Oxygen Sag Calculation with Variable k_2

Section	Part	Δt (day)	Δt (min)	k_{2i}	k_{2i+1}	$\frac{(k_{2i+1}+k_{2i})\Delta t}{4}$	$e^{(-(k_1+V_s))}$	D_i	D_{i+1}
Yandanko	Upstream	0	26.52	0.140	0.020	0.259	0.974	7.40	7.40
	Point Source	0.018	25.92	0.020	0.020	0.259	0.965	7.40	6.32
	Downstream	0.037	27.36	0.018	0.018	0.2599	0.929	6.32	5.30
Tamburawa	Upstream	0.27	14.4	0.014	0.014	0.115	0.947	5.30	5.14
	Point Source	0.147	28.8	0.013	0.013	0.194	0.745	5.14	5.93
	Downstream	0.157	14.4	0.013	0.013	0.187	0.730	4.94	6.07

$V_s = 0.157$cm/min

$= \frac{0.157 \times 60 \times 24}{1.22} d^{-1}$

$= 1.853 d^{-1}$

$K_1 + V_S = 2.104\ d^{-1}$

Table 3: Measured versus Predicted Oxygen Sag

Section	Part along Challawa River	Distance (km)	Measured oxygen deficit (Cs – C)	Computed oxygen Deficit (mg/l) Conventional	With v_s and variable k_2
Yandanko	Upstream	0	7.4	5.60	7.4
	Point Source	1	5.47	1.21	6.32
	Downstream	2	5.50	0.75	5.30
Tamburawa	Upstream	8.015	5.34	4.92	5.14
	Point Source	8.565	4.60	5.76	5.93
	Downstream	9.610	6.63	1.38	6.07
	Further Downstream	10.644	5.30	11.68	5.45

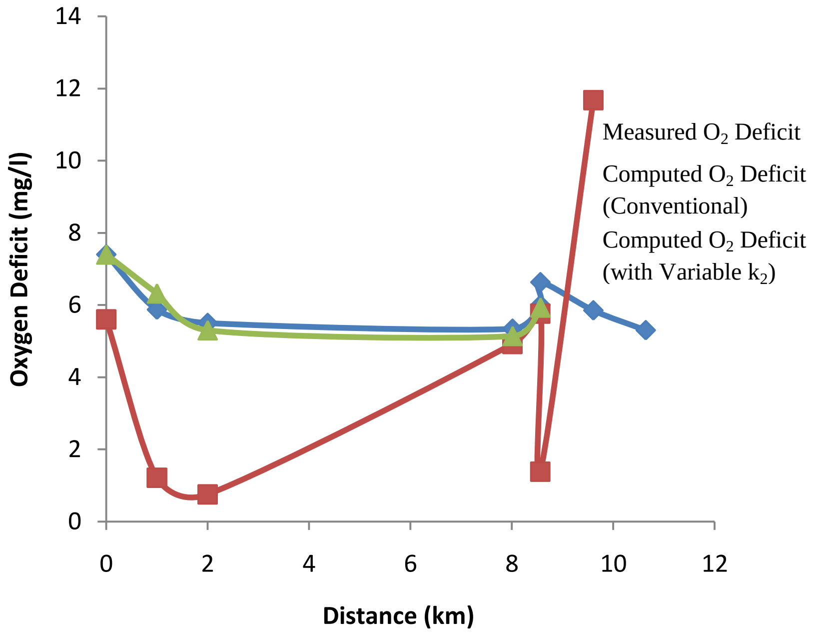

Fig. 5: Oxygen Deficit against Distance (combined graphs)

IV. CONCLUSION

Based on this study, the following conclusions were made

1. The concentrations of pollutants in industrial wastewaters in Challawa River are very high.
2. The industries should leverage on the ameliorating dilution effect in the wet season for discharging the wastewater into the rivers and storage pits in the dry season. However, considering the large concentration of pollutants, effective reduction of BOD is required to comply with Federal Ministry of Environment (FMEnv) standard.
3. The new re-aeration equation for River Challawa has been determined. This equation was found better than the existing six other equations.
4. An improved numerical approach for determination of the oxygen sag predicted the oxygen sag better than the conventional approach.

V. RECOMMENDATIONS

The recommendations arising from this work are as follows:

1. The industrial industries should treat their waste to avoid further pollution of River Challawa with its negative effects on public and environmental health
2. The BOD in River Challawa can be predicted using the relationship obtained from the study to reduce cost and time, especially for monitoring purposes.
3. The model proposed can be preferred to the existing models so far developed for use in the semi-arid areas.
4. Determination of the oxygen sag equation should be based on the spatial values rather than one time average value of the re-aeration coefficient.

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