Self-Purification Capacity of Mmubete Stream in Rivers State, Nigeria

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Abstract:
The continuous discharge of wastes of high organic content into rivers causes water pollution and reduction of dissolved oxygen concentration due to the degradation of the organic matter. The work investigated the self-cleaning abilities of Mmubete stream. Mmubete stream is significant to the people of Rivers State owing to its usefulness in terms of fishing activities and domestic usage. Water samples were collected and tested for dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature and pH. The hydrodynamic data (depth, velocity, surface area, kinematic viscocity and dispersion) of the stream were collected while deoxygenation coefficient, re-aeration coefficient and self-purification rate were generated using empirical models. The DO values in wet and dry season ranges from 3.00mg/l to 5.96mg/l and 4.00mg/l to 10.20mg/l respectively, the de-oxygenation Coefficient of the stream is 2.349d-1, the reaeration rate constant of the stream ranges from 1.983d-1 to 4.182d-1 and the self-purification factors of the stream are 1.084, 1.413 and 1.702 with an average of 1.3997 as deduced from the three empirical models. This value implies that the stream is sluggish and polluted.
Key Word: *Effluent; self-cleaning; capacity; stream; pollution.*

I. Introduction

Streams have been consistently used as the principal pathway for disposing wastewater, be it industrial commercial, agricultural or domestic wastes (Ledogo and Akatah, 2011). This is even likely to continue for a long time especially in developing countries of the world. This is because of the poor attitude or less attention to environmental sustainability and protection.

The continuous discharge of wastes of high organic content into rivers causes water pollution and reduction of dissolved oxygen concentration due to the degradation of the organic matter. Omole & Longe (2012) and Ugbebor (2011), posited that Dissolved Oxygen (DO) concentration plays a vital role in pollution studies in rivers/streams. According to them the determination of DO concentration is a basic part of water quality assessment since dissolved oxygen concentration is useful in the assessment of the pollution strength of a water body, the degradation of organic substances and the level of self-purification of water. Dissolved oxygen depletion in water bodies affects aquatic lives (both fauna and flora). Fishes and other aquatic lives migrate from rivers, sea, streams with low dissolved oxygen concentration and the living organisms (aquatic lives) that cannot migrate will die (Omole, 2011). Even with the numerous demerits of the discharge of wastes and wastewaters into streams, rivers, lakes, etc, they are still being used as pathway for disposing wastes and wastewater. Rivers and streams are principally used for wastewater/waste disposal such as conveying the wastewater away to sea, rapid mixing which dilutes and disperses the wastewater, slow sedimentation and re-suspension which spread the sediment over a large area of the flow path, and often turbulent conditions which cause rapid re-aeration of the water. The discharge of wastewater into surface water bodies causes a chain of events along the stretch of the river or stream, thereby creating different activities zones. The zones include degradation zones, active decomposition zone (Septic Zone), recovery zones and zone of clean water (Agunwamba, 2000).

The self-purification capacity of surface water bodies (rivers, streams, lakes, etc.) allow them to rid themselves of waste through a natural process. Even after the introduction of pollutants, surface water bodies can maintain their initial (pristine) state because to a process known as self-purification (Ledogo and Akatah, 2011; Ugbebor, 2011; Agunwamba, 2006). Self-purification complements artificial methods and processes of maintaining water quality.

Self-purification involves physical, chemical, and biological processes aimed at returning the water bodies to its original state (Leton 2007). Self-purification capacity of a river cannot be effectively handled without proper knowledge of the assimilation capacity of the rivers. Assimilation capacity is the maximum waste in terms of BOD or COD that a stream or river can absorb without being polluted. The assimilation

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capacity of a rivers is directly proportional to the volume of run-off. Therefore, the factors that influence the quantity of run-off also affect the assimilation capacity and self-purification of water bodies (Agunwamba, 2000, Ledogo and Akatah, 2011; Ugbebor et al. 2012). Such factors include temperature, Dissolved Oxygen (DO) concentration from incremental stream/river run-off from the tributaries, photosynthesis by aquatic plants, stored oxygen, aeration of water by atmospheric oxygen, sediments, etc. Consequently, the DO profile of a certain stream or river describes both the characteristics of the stream or river and the degree of pollution existing in the stream or river, even though other criteria may be used to estimate the level of pollution present in the stream or river (Babamiri et al., 2021; Nishimura et al., 2021). The DO profile evaluates the river's capacity to process the wastes that are deposited into it and describes this capacity (Ledogo and Akatah, 2011).

II. Materials and Methods

Study Area

The Mmubete stream is in Aleto, Eleme Local Government Area in Rivers State, Nigeria. The streamis in the Atlantic coast of Southern Nigeria with a coastline of about 450km which terminates at Imo River entrance. It is along the East-West Road and beside the Petrochemical Company. The stream is black freshwater. It is located on the coordinates of between Latitude 5^0 04'06''N and Longitude 6^0 38'56''E and 8^0E. The map of Eleme Local Government Area showing the stream is shown in Figures1.
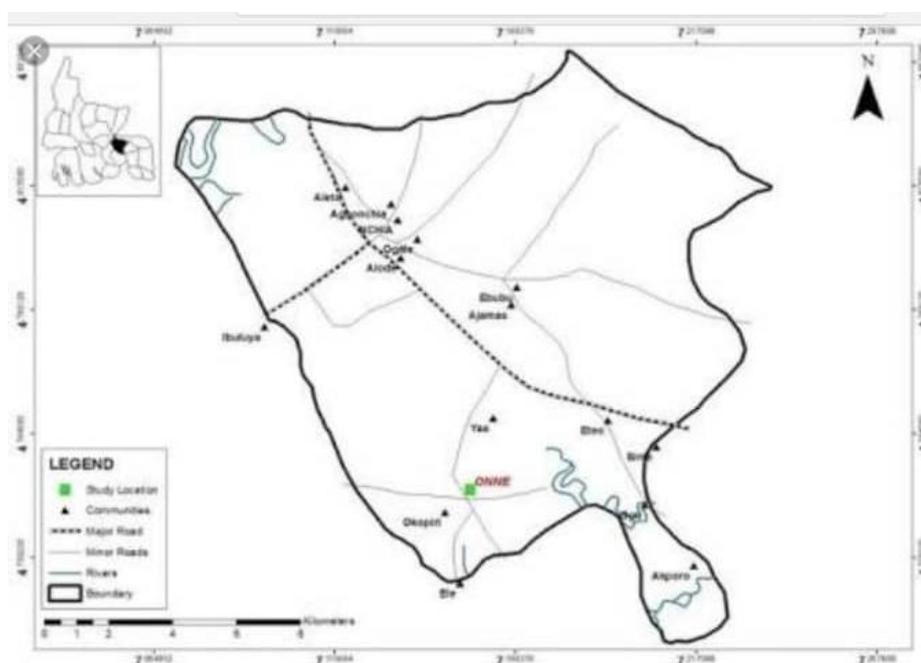
Figure 1: Map of Eleme Local Government Area showing the Study Rivers

Determination of Hydraulic Parameters

Hydraulic parameters namely velocity, depths, surface area and discharge of the rivers at low tide was determined. The velocity of the stream was determined (measured) using Electronic Flowmeter model 2031H Series Real-Time. The depths at different offsets across the breadth of the streams was measured and the Simpson's formula was used to determine the cross-sectional area of the rivers.

Determination of water quality parameters

*Water quality parameters namely temperature, dissolved oxygen and biochemical oxygen demand were determined.*The dissolved oxygen was analysed using Membrane-Electrode Method based on APHA 4500-O G.The biochemical oxygen demand was analysed using 5-Day BOD Test Method based on APHA 5210 B. and the temperature was determined using a digital thermometer.

Determination of Deoxygenation coefficient and Re-aeration Coefficient of the stream

The deoxygenation coefficient of the stream was determined using the Thomas Slope equation as given below.

$$k_1 = 2.61 \frac{B}{A} \tag{1}$$

Where   A= intercept of the best fit line on the ordinate axis; B = slope of the best fit line.
The re-aeration coefficient of the stream was determined using Akatah (2023) models given below.

Model 1

$$K21 = \frac{1.5169\,U^{-0.8760}}{H^{0.1963}} \tag{2}$$

Model 2

$$K_{22} = \frac{15.8833\,U^{0.2746} \cdot A_s^{-0.4493}\,D^{-0.2956}}{H^{-0.5943}\,\mu^{-1.9878}} \tag{3}$$

Model 3

$$K_{23} = \frac{7.62\,U^{0.2017} \cdot D^{0.1255}}{H^{0.0629}\,\mu^{0.6312}} \tag{4}$$

Where; K_2 = re-aeration coefficient (d^{-1}), U = velocity (m/s), H = depth (m), D = dispersion coefficient (m/s^2) and μ = Kinematic viscosity (m/s^2)

Determination of Dispersion Coefficient
The dispersion coefficient of the stream was determined using the constant distance-time method formulated by Leverspiel and Smith as provided in Agunwamba (2001).

Determination of Kinematic Viscosity
The Kinematic Viscosity of the stream was determined using the table of kinematic viscosity of water at different temperature.

Oxygen Sag Prediction
The general Streeter-Phelps equation for predicting dissolved oxygen in a river was used to predict the DO profile of the stream. Haider & Ali, 2020 stated that the DO in stream as a pollutant is introduced into it can be predicted using the mass balance equation written as;

Accumulation = In – Out + Reaction $\tag{5}$

Because the pollutant is the target, there is no flow of water into or out of it. Hence, the oxygen mass balance becomes:

$\frac{vdc}{dt}$ = 0 in - 0 out + V (Rate of oxygen removal by biodegradation) + V (Rate of O_2 addition form the atmosphere)

Considering the two rates, the rate of oxygen removal by biodegradation is:

$$\left(\frac{dc}{dt}\right)_d = (rate\ of\ BOD\ decay) = -K_1 L \tag{6}$$

Where L = ultimate BOD (M_g/l); K_1 = first order deoxygenation rate constant (d^{-1})
The rate of oxygen transfer from the atmosphere by given as:

$$\left(\frac{dc}{dt}\right)r = K_2\,(c_s - c) \tag{7}$$

Where C = dissolved oxygen concentration (m_g/c); C_s = dissolved oxygen concentration at saturation (m_g/c); K_2 = Recreation Constraint (d^{-1})
Substituting the rate expression into the oxygen mass balance equation:

$$V\frac{dc}{dt} = \left(\frac{dc}{dt}\right)_d V + \left(\frac{dc}{dt}\right)_d V \tag{8}$$

$$\frac{dc}{dt} = -K_1L + K_2\,(C_s - C) \tag{9}$$

Using $D = C_S - C$, the equation becomes:

$$\frac{dD}{dt} = \left(0 - \frac{dc}{dt}\right) = k_1 L - K_2\,(C_S - C) \tag{10}$$

But $L = Lo\,e^{-k1t}$ and $(C_s - C) = D$ $\tag{11}$

Therefore, Equation 10 becomes:

$$\frac{dD}{dt} = K_1\,Lo\,e^{-k1t} - K_2 D \tag{12}$$

$$\frac{dD}{dt} + K_2 D = K_1\,L.e^{-k,t} \tag{13}$$

Using the integrating factor, $e^{\int K\,dt} = e^{\int K\,dt}$

$$\frac{dD}{dt}(e^{kt}) + k_2 D\,(e^{k\,t}) = K_1\,Lo(e^{-k_1\,t})(e^{-kt}) \tag{14}$$

$$\frac{dD}{dt}(De^{k_t}) = k_1\,Lo\left(e^{(k_2 - k_2)}\right)t \tag{15}$$

Separating the variables and integrate

$$\int d\,(De^{k_2 t}) = \int (k_1 L_o e^{(k_2 - k_1)t})\,dt \tag{16}$$

$$De^{kt} = \frac{k_1 L_o}{k_2 - k_1}\,e^{(k_2 - k_1)t} + C \tag{17}$$

Applying the boundary condition at t = O, D = D_o

$$D_o e^o = \left(\frac{k_1 L_o}{k_2 - k_1}\right)e^o + C \tag{18}$$

$$C = D_o + \left(\frac{k_1 L_o}{k_2 - k_1}\right) \tag{19}$$

$$De^{k_2 t} = \left(\frac{k_1 L_o}{k_2 - k_1}\right) e^{(k_2 - k_1)t} + D_o - \left(\frac{k_1 L_o}{k_2 - k_1}\right) \tag{20}$$

$$D = \left(\frac{k_1 L_o}{k_2 - k_1}\right) e^{-k_1 t} + D_o e^{-k_2 t} - \left(\frac{k_1 L_o}{k_2 - k_1}\right) e^{-k_2 t} \tag{21}$$

Grouping like terms, integrated equation becomes:

$$D = \left(\frac{k_1 L_o}{k_2 - k_1}\right)(e^{-k_1 t} - e^{-k_2 t}) + Do e^{-k_2 t} \tag{22}$$

Where L_o = ultimate BOD in water at t = 0; D_o = deficit at t = 0

To find the critical conditioning differentiate the DO sag equation and set it equal to zero

$$\frac{dD}{dt} = o = \frac{d}{dt}\left[\left(\frac{k_1 L_o}{k_2 - k_1}\right)\right](e^{-k_1 t} - e^{-k_2 t}) + Do e^{-k_2 t} \tag{23}$$

$$O = \left(\frac{k_1 L_o}{k_2 - k_1}\right)[-k_1 e^{-k_1 t} + k_2 e^{-k_2 t}] - D_o k_2 e^{-k_2 t} \tag{24}$$

Dividing through by $e^{-k_2 t}$ and bring the right-hand term to the other side of the equation, then take the natural log of both sides taking t = tc, the equation becomes;

$$t_c = \left(\frac{1}{k_2 - k_1}\right) in \left[\frac{k_2}{k_1}\left(1 - \frac{D_o(k_2 - k_1)}{k_1 L_o}\right)\right] \tag{25}$$

Solving for critical deficit, D_c, then substitute t_c

$$D_c = \left(\frac{k_1}{k_2}\right) L_o e^{-k_1 t} \tag{26}$$

III. Results and Discussion

Dissolved Oxygen (DO)

Dissolved oxygen (DO) at the different sampling stations during the wet and dry season are below the NDWQS and WHO limit of minimum of 5.00 mg/l in most stations. The DO values in wet and dry season ranges from 3.00mg/l to 5.96mg/l and 4.00mg/l to 10.20mg/l respectively. This is shown in figures 2 to 4. The plot if DO versus distance indicate that DO level from upstream towards the discharge point fluctuates and after the effluent channel at some distance along the stream stretch. This observation DO fluctuation along the stream is an indication that there are several points of pollution into the stream. Figure 4 reveals that the DO is higher in the dry season than in the wet season. This may be attributed to the runoff that entered the stream during the wet season which makes the stream more polluted during the season.
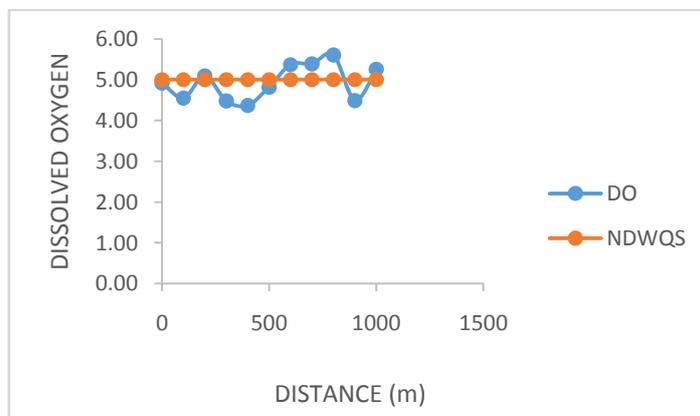
Figure 2: variation of dissolved oxygen along the stream stretch during the wet season
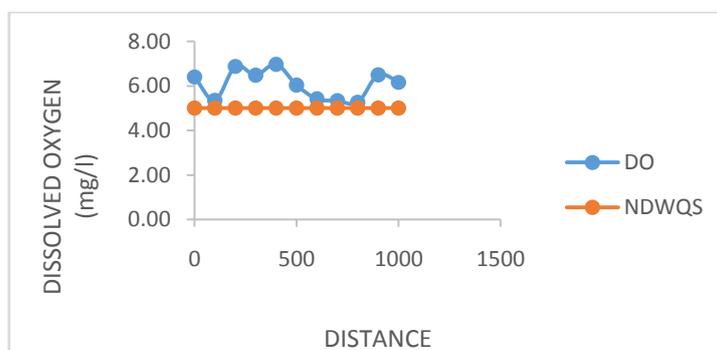
Figure 3: variation of dissolved oxygen along the stream stretch during the dry season
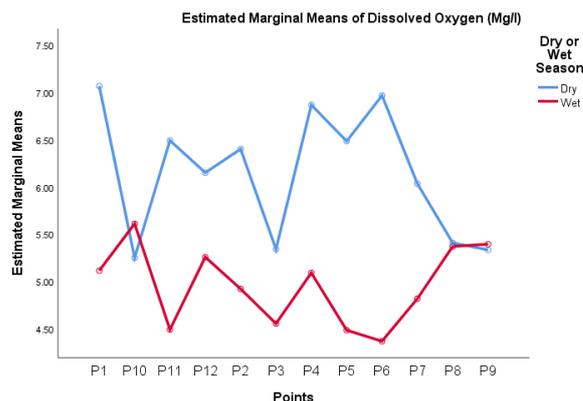
Figure 4: Dissolved oxygen content of water at the different sampling points in wet and dry season

De-oxygenation Constant of the Stream

The Thomas slope method is a useful tool for the estimation of deoxygenation constant K_1 for Munubete stream. This method aids the calculation of the intercept and slope. The result of the deoxygenation constant K_1 is presented in Table 4.9.
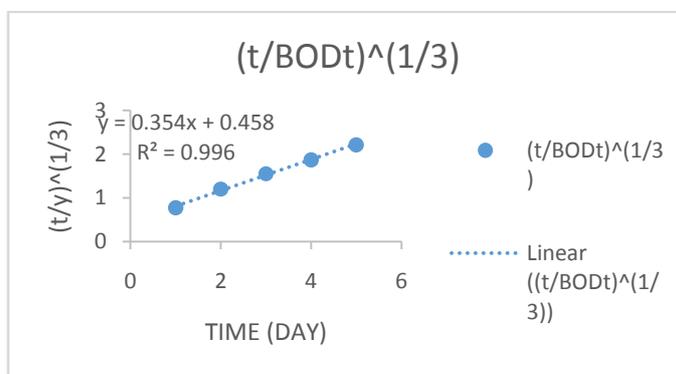
Figure 5: Thomas slope plot for wet season

Figure 5 is the Thomas Slope plot for BOD analysis for the determination of the Deoxygenation coefficient of the stream. From the figure, the intercept is 0.45 and the slope is 0.405. Using the Thomas method equation, the deoxygenation coefficient of the stream during the wet season is 2.349d^{-1}
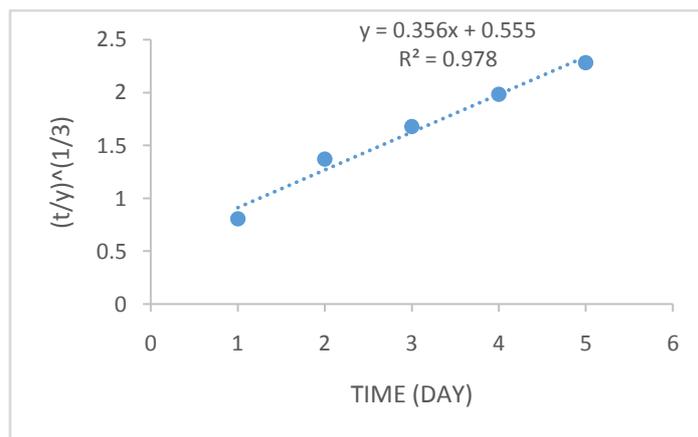
Figure 6. Thomas slope plot for dry season

Figure 6 is the Thomas Slope plot for BOD analysis for the determination of the Deoxygenation coefficient of the stream. From the figure, the intercept is 0.5 and the slope is 0.45. Using the Thomas method equation, the deoxygenation coefficient of the stream during the dry season is 2.346d^{-1}.

Reaeration Coefficient of Mmubete Stream
The reaeration coefficient of the stream as determined by the Akatah (2023) model I is presented in table 1. The reaeration coefficient of the stream as determined by the Akatah (2023) model 2 is presented in table 2. The reaeration coefficient of the stream as determined by the Akatah (2023) model 3 is presented in table 3.

Table no 1: Reaeration constant of Mmubete stream at the different sampling stations using Akatah (2023) model 1

VELOCITY	DEPTH	K2
0.6	0.7	2.545261
0.739	0.81	2.060713
0.681	1.42	1.982689
0.634	1.83	2.008335
0.51	1.77	2.446115
0.45	1.96	2.675479
0.44	2.69	2.564252
0.42	2.51	2.707467
0.38	2.58	2.93964
0.35	2.9	3.087545

Table no 2: Reaeration constant of Mmubete stream at the different sampling stations using Akatah (2023) model 2

Surface Area (m2)	Velocity (m/s)	Depth (m)	Dispersion coefficient (m/s^2)	Kinematic Viscosity (m/s^2)	K_2
235.000	0.600	0.700	0.005	0.836	3.320455
396.000	0.739	0.810	0.006	0.854	2.978175
610.000	0.681	1.420	0.005	0.854	3.429917
815.000	0.634	1.830	0.005	0.854	3.506479
1050.000	0.510	1.770	0.004	0.854	3.081873
1395.000	0.450	1.960	0.003	0.873	3.018804
1585.000	0.440	2.690	0.003	0.854	3.29488
2065.000	0.420	2.510	0.003	0.836	2.6913
2125.000	0.380	2.580	0.003	0.854	2.826124
2495.000	0.350	2.900	0.003	0.854	2.823562

Table no 3: Reaeration constant of Mmubete stream at the different sampling stations using Akatah (2023) model 3

U (m/s)	H (m)	D(m/s^2)	μ(m/s^2)	K_2(d^{-1})
0.600	0.700	0.005	0.836	3.996657943
0.739	0.810	0.006	0.854	4.181651209
0.681	1.420	0.005	0.854	3.930047967
0.634	1.830	0.005	0.854	3.778387402
0.510	1.770	0.004	0.854	3.526066479
0.450	1.960	0.003	0.873	3.316550383
0.440	2.690	0.003	0.854	3.272482632
0.420	2.510	0.003	0.836	3.281937065
0.380	2.580	0.003	0.854	3.12741393
0.350	2.900	0.003	0.854	3.022075312

Tables 1 to 3 show the K_2 values of the stream as predicted by Akatah (2023) models. Model 1 as presented in Table 1 predicted that K_2 ranges from 1.983d^{-1} to 3.088d^{-1}. Model 2 as presented in Table 2 predicted that K_2 ranges from 2.691d^{-1} to 3.506d^{-1}. Model 3 as presented in Table 3 predicted that K_2 ranges from 3.127d^{-1} to 4.182d^{-1}.

Oxygen Sag Prediction

Figures 7 shows the oxygen sag curve for the wet (rainy) season using model 1for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is -5.4mg/L, critical time is 0.3 day and the critical distance is 13478.4m (13.48km) from the point of entry of the effluent. The DO at the point of inflection is 7.8mg/L, the time of inflection is 2.9days.
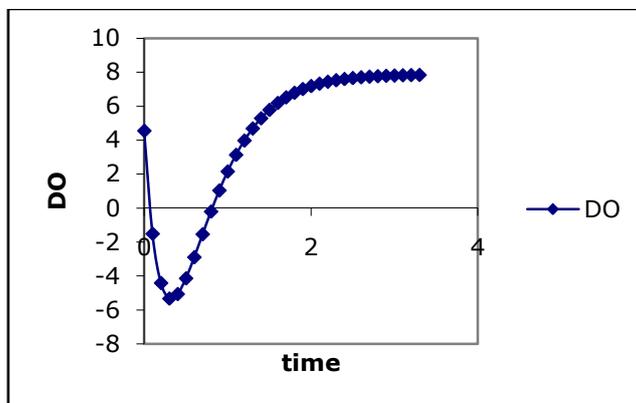
Figure 7: Oxygen sag curve for wet season using model 1 and Thomas slope method for the calculation of K1

Figures 8 shows the oxygen sag curve for the dry season using model 1for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is 2.3mg/L, critical time is 0.3 day and the critical distance is 10368m (10.368km) from the point of entry of the effluent. The DO at the point of inflection is 7.55mg/L, the time of inflection is 3days.
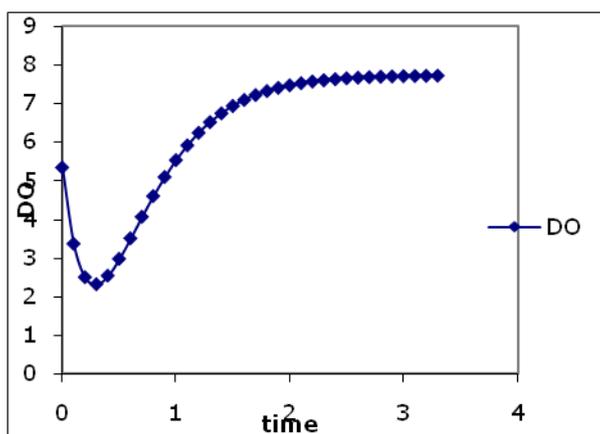
Figure 8: Oxygen sag curve for dry season using model 1 and Thomas slope method for the calculation of K1

Figure9 shows the oxygen sag curve for the wet (rainy) season using model 2 for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is -3.78mg/L, critical time is 0.3 days and the critical distance is 13,478.4m (13.48km) from the point of entry of the effluent. The DO at the point of inflection is 7.76mg/L, the time of inflection is 2.4days.
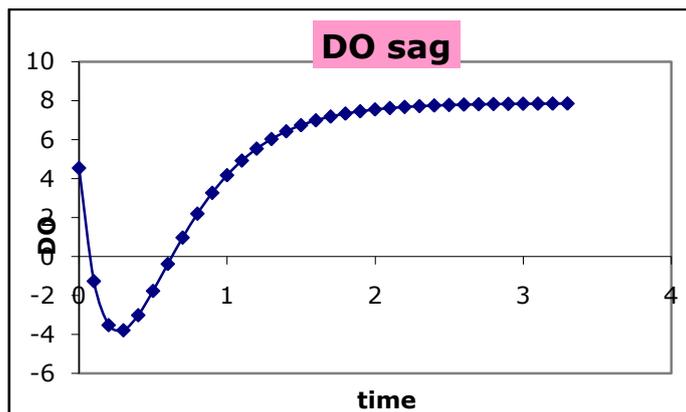
Figure 9: Oxygen sag curve for wet season using model 2 and Thomas slope method for the calculation of K1

Figures 10 shows the oxygen sag curve for the dry season using model 2 for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is 2.95 mg/L, critical time is 0.2 day and the critical distance is 8,985.6m (8.99km) from the point of entry of the effluent. The DO at the point of inflection is 7.62mg/L, the time of inflection is 2days.
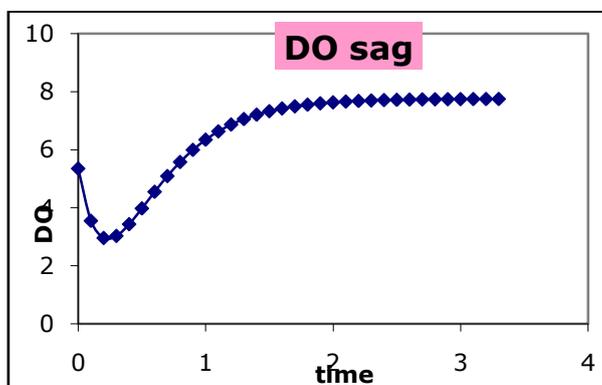
Figure 10: Oxygen sag curve for dry season using model 2 and Thomas slope method for the calculation of K1

Figures 11 shows the oxygen sag curve for the wet season using model 3 for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is -2.76mg/L, critical time is 0.2 day and the critical distance is 8,985.6m (8.99km) from the point of entry of the effluent. The DO at the point of inflection is 7.53mg/L and the time of inflection is 3.3days.
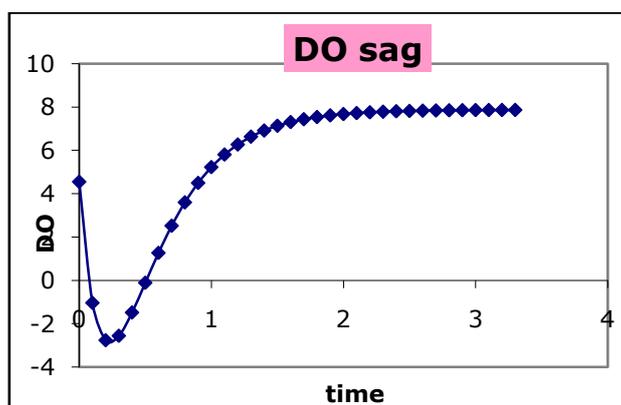
Figure 11: Oxygen sag curve for wet season using model 3 and Thomas slope method for the calculation of K_1

Figures 12 shows the oxygen sag curve for the dry season using model 3 for predicting K_2 and Thomas slope method for predicting K_1. From the figure, the critical DO (DO_c) is 3.33mg/L, critical time is 0.2 day and the critical distance is 8,985.6m (8.99km) from the point of entry of the effluent. The DO at the point of inflection is 7.46mg/L and the time of inflection is 1.5days.
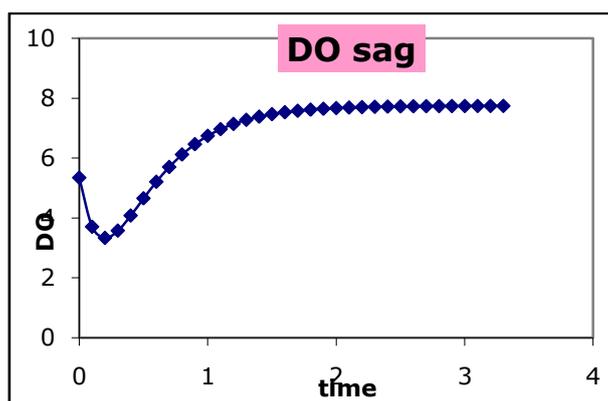
Figure 12: Oxygen sag curve for dry season using model 3 and Thomas slope method for the calculation of K_1

Self-Purification of Mmubete stream

Table no 4: Self-purification factor of Mmubete stream based on the three newly developed models

Model	$K_1(d^{-1})$	$K_2(d^{-1})$	$F = K_2/K_1$
I	2.349	2.545	1.083
II	2.349	3.320	1.413
III	2.349	3.997	1.702
Field (wet)	2.349	3.316	1.411
Field (dry)	2.349	2.403	1.023

Table 4. shows the re-aeration constant, de-oxygenation constant and the self-purification factor of Mmubete stream. The re-aeration constant, ranges from 2.5452 to 3.997. de-oxygenation constant is 2.349 and self-purification factor ranges from 1.084 to 1.702. The average self-purification factor is 1.3997.

IV. Conclusion

The study carried out on the Mmubete stream centered on self-purification of the stream. From the work, the de-oxygenation Coefficient of the stream is $2.349d^{-1}$. This value implies that the stream requires 2.349 oxygen for the degradation of organic matters and nitrification. The reaeration rate constant of the stream ranges from $1.983d^{-1}$ to $4.182d^{-1}$. This range implies that 1.983 to 4.182 of oxygen is dissolved by the stream per day.The self-purification factors of the stream are 1.084, 1.413 and 1.702 with an average of 1.3997 as deduced from the three newly developed models (see table 4.39). This value implies that the stream is sluggish and polluted. The pollution is because of closeness of the values deoxygenation and reaeration.

References

[1]. Agunwamba, J. C. (2000). Water engineering systems. *Enugu: Immaculate Publications Limited*, 33–139.
[2]. Agunwamba, J. C., Maduka, C. N., &Ofosaren, A. M. (2006). Analysis of pollution status of Amadi Creek and its management. *Journal of Water Supply: Research and Technology - AQUA*, *55*(6). https://doi.org/10.2166/aqua.2006.036
[3]. Akatah, B.M.(2023). *Evaluation and modelling of pollution level and self-purification capacity of Mmubete stream, Rivers State, Nigeria* [Unpublished doctoral dissertation]. University of Benin.
[4]. Babamiri, O., Vanaei, A., Guo, X., Wu, P., Richter, A., & Ng, K. T. W. (2021). Numerical simulation of water quality and self-purification in a mountainous river using QUAL2KW. *Journal of Environmental Informatics*, *37*(1). https://doi.org/10.3808/jei.202000435
[5]. Haider, H., & Ali, W. (2010). Development of Dissolved Oxygen Model for a Highly Variable Flow River: A Case Study of Ravi River in Pakistan. *Environmental Modeling and Assessment*, *15*(6). https://doi.org/10.1007/s10666-010-9240-4
[6]. Ledogo, A.B. and Akatah, B.M, (2011). Assimilative capacity of Khana rivers in Present day Niger Delta, Nigeria. Intl Journal of Empirical Research and Sustainable Devt. 2(2), 210-217.
[7]. Leton, T. G. (2007). Water and waste water engineering. *Port Harcourt: Celwill Publication Ltd.,* 9–15.
[8]. Nishimura, F., Koike, Y., & Masuda, M. (2021). Influence of light on a microbial river water ecosystem and its self-purification potential. *International Journal of GEOMATE*, *20*(81). https://doi.org/10.21660/2021.81.GX315
[9]. Omole, D. O. (2010). *Water Quality Modelling: Case study of the Impact of Abattoir Effluent on River Illo, Ota, Nigeria*. LAP Lambert Academic Publishing GmbH & Co. KG.
[10]. Omole, D. O. (2011). *Evaluation of Water Quality Modelling Parameters: towards the Evolvement of Re-aeration Coefficient for Rivers in the Nigerian Environment.*
[11]. Omole, D. O., & Longe, E. O. (2012). Re-aeration coefficient modeling: A case study of river Atuwara in Nigeria. *Research Journal of Applied Sciences, Engineering and Technology*, *4*(10).
[12]. Ugbebor, J.N., Agunwamba, J.C. & Amah, V.E. (2012). Determination of reaeration coefficient K2 of Polluted streamas a function of depth, hydraulic radius, temperature and Velocity. Nigeria Journal of Technology, 31(2), 174 – 180.
[13]. Ugbebor, j.N. (2011). Modelling the variability of water qualityof the Oshika Lake. PhD Thesis, University of Nigeria, Nsukka.