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Full Length Research Paper

Self-Purification Potential of Tropical Urban Stream: A Case Study of the New Calabar River in Port Harcourt, Nigeria

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Dissolved oxygen and biochemical oxygen demand (BOD₁₀) as well as hydrological parameters' measurements were carried out on the stream to determine its deoxygenation and reaeration rate coefficients in order to ascertain its natural self – purification potential. Deoxygenation rate of 0.15 and 0.16/day were obtained indicating swift depletion of oxygen in the stream probably due to domestic sewage input whereas values of 0.10/day to 0.33/day were obtained as reaeration coefficients and these values suggest deep and slow moving streams. The measured DO values are quite high and indicate high dissolved oxygen concentration in the stream. FAIR's number-distance plot for these values, and diurnal DO measurement showed respectively that spatially, 69.5% of the stream is under reaeration predominance whereas about 23.3% of the total dissolved oxygen in the stream originates from photosynthetic activity. However, dissolved oxygen profile analysis showed that the stream can re-attain its optimum DO level within flow time of 0.32day in the dry season and 0.21day in the rainy season.

Key Words: Self-Purification Potential, Deoxygenation, Reaeration, Dissolved Oxygen, Biochemical Oxygen Demand, Stream Velocity.

INTRODUCTION

If organic matter such as untreated human or animal waste is placed into a surface water body, dissolved oxygen levels diminish as micro-organisms grow, using the organic matter as an energy source and consuming oxygen in the process (Fetter, 2007). The pollution problem arises when the capacity of stream to assimilate wastes is exceeded under conditions of excessive stream loading with organic wastes (Nwankwor and Okpala, 1993). This limit according to Nwankwor and Okpala (1993) defines the self-purification capacity of a stream and is related to the stream potential to replenish

the dissolved oxygen (DO) that is continually utilized in the oxidation of organic matter.

Clark and others (1977) noted that the replenishment of oxygen in stream water is dependent on the stream flow velocity, water depth and channel geometry. The process and rate of self-purification are influenced by temperature, nature of organic pollutants, size and the hydraulic characteristics including algal content of the receiving stream (Nwankwor and Okpala (1993). According to Reichert and others (2001), the self-purification potential and water quality changes in rivers

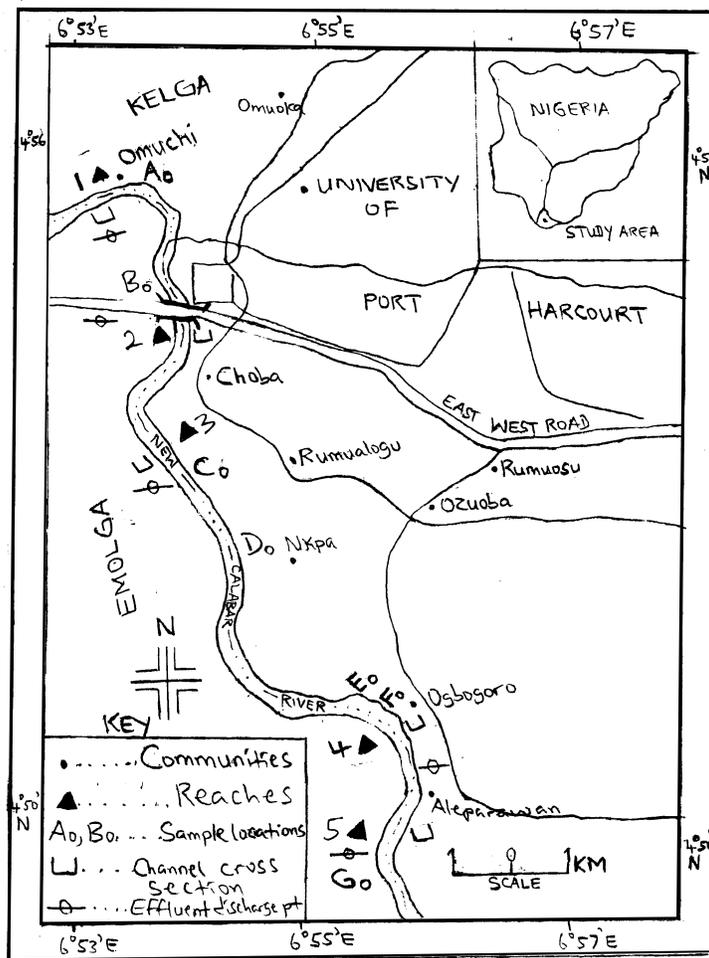


Figure 1. Map of New Calabar River showing sample locations and communities along its course

Table 1. Dissolved oxygen data measured during the BOD₁₀ test for the river water sample collected from Location 'E₀'

Time (days)	Cumulative DO utilized (mg/l)	DO remaining (mg/l)
0	0.00	100.90
1	19.98	80.92
2	43.17	57.73
3	58.62	42.28
5	70.62	30.28
7	76.81	24.09
10	81.81	19.09

are due to physical transport processes and biological, chemical, biochemical and physical conversion processes.

The New Calabar River represents a typical tropical urban stream and flows through the industrial segments of Port Harcourt. Thus, the river serves as a major drainage unit for Port Harcourt metropolis and by implication, receives wastes from industrial and domestic sources.

This study deals with the biochemical and hydrological properties of the New Calabar River as a basis for ascertaining its optimal waste loading and self-purification potential considering that Biochemical oxygen demand (BOD) and Dissolved oxygen (DO) content are very reliable parameters within the context of surface water sanitation and organic waste pollution management.

Investigation into the natural self-purification potentials of streams has become a very important aspect in the

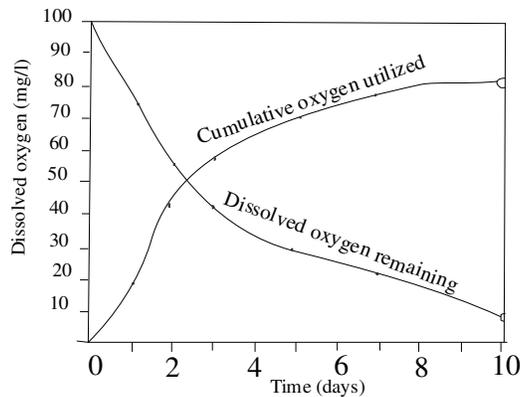


Figure 2. BOD₁₀ exertion curve for oxygen utilized, and oxygen remaining versus time

Table 2. Stream velocity, depth, and calculated k_2 values for the various reaches

Reach	Mean Velocity (m/s)	Mean depth (m)	k_2 values (per day)	
			Equation 2	Equation 3
1	0.59	4.0	0.33	0.30
2	0.45	4.3	0.24	0.20
3	0.22	4.2	0.14	0.10
4	0.52	4.4	0.25	0.23
5	0.32	4.1	0.20	0.16

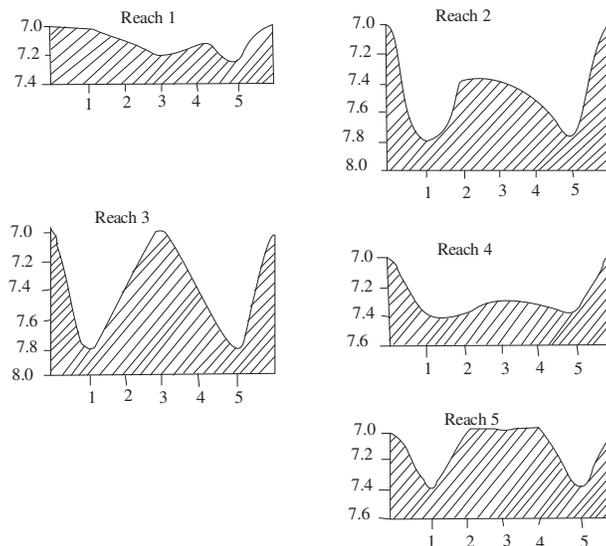


Figure 3. Stream channel cross – sections of the New Calabar River.

quest for a sustainable level of environmental protection through engineering. Thus, its knowledge is required for the design of waste treatment plants by those industries that may desire to use streams and other surface water bodies as disposal channels for their industrial effluents.

Climatic Conditions

The New Calabar River is the major surface water

drainage system within the area. The flow is perennial, and toward the South-east direction, emptying into the Bonny River and ultimately into the Atlantic. The channel has meanders and exhibits significant width variations over some segments of flow. It has a maximum average discharge of 15.1m³/s in the rainy season and 3.0m³/s in the dry season. The vegetation in the area is rain-forest vegetation. Available records show that rainfall averages between 1000mm – 2000mm and peaks in the months of July and October. On the other hand, the dry season

Table 3. Calculated f values for the various reaches

Reach	FAIR'S number ($f = k_2 / k_1$)			
	k ₂ of Equation 2		k ₂ of Equation 3	
	k ₁ = 0.15	k ₁ = 0.16	k ₁ = 0.15	k ₂ = 0.16
1	2.20	2.10	2.00	1.86
2	1.60	1.50	1.33	1.25
3	0.93	0.90	0.70	0.63
4	1.70	1.60	1.53	1.44
5	1.33	1.30	1.07	1.00

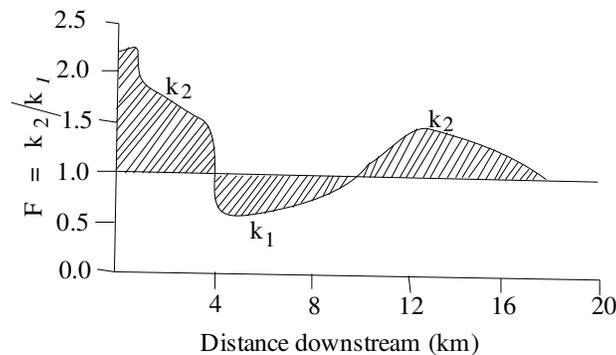


Figure 4. FAIR'S number – distance plot for the New Calabar River.

Table 4. Results of DO measurements along the river profile

LOCATION	March 10, 2010			July 8, 2010		
	DO (mg/l)	Temp.(°C)	Saturation (%)	DO (mg/l)	Temp.(°C)	Saturation (%)
A	94.0	27	116	86.7	25	107
B	72.1	21	90	81.5	23	98
C	74.2	21	90	67.2	19	81
D	67.9	19	81	78.4	22	94
E	61.1	18	77	89.8	26	111
F	60.6	17	73	84.8	24	102
G	89.8	25	107	86.2	25	107

starts around mid-November and ends by March or early April. It is characterized by hazy, dry and dusty winds called the North-East trade winds or Tropical Continental Air Mass emanating from the Arabia-Eurasia high pressure belt.

MATERIALS AND METHODS

Sampling Network

Water sampling network was based on a number of factors. These factors are hydrogeological and climatic factors, and susceptibility to pollution with respect to distribution of points of waste matter inflow. The reconnaissance survey carried out showed five (5) distinct stream reaches based on stream channel geometry, flow system and pollutant source (figure 1).

Location and intensity of sampling were concentrated within these five (5) reaches. Reach 4, a wider reach, was sampled at two (2) different points perpendicularly in the channel whereas in the narrower reaches (1,2,3, and 5), one sampling point midstream was considered even. In each case, water sample was collected at 4.7 depth position.

Water sample was also collected at a distance of 13.7 km away from Reach 3 in the downstream direction. The hydrological parameters of this point were not used because it was not considered a distinct reach based on stream channel configuration and flow system. However, the dissolved oxygen measurements of this point were represented in the dissolved oxygen (DO) profiles.

A total of six (6) locations named 'A' to 'G' were selected and sampled for dissolved oxygen measurement and biochemical oxygen demand (BOD) test, as well as hydrological parameters. The hydrological

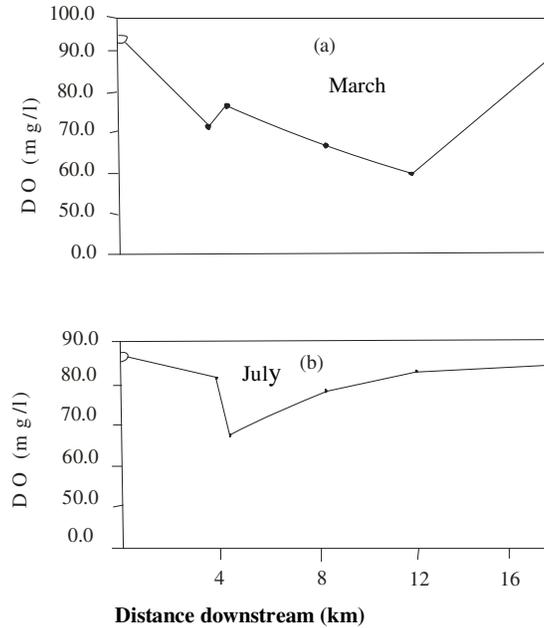


Figure 5. Dissolved oxygen profiles for the New Calabar River

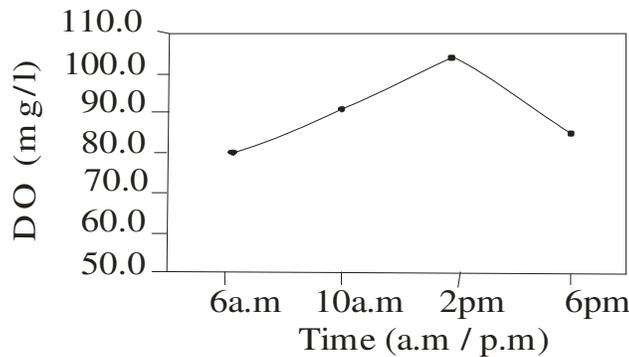


Figure 6. Dissolved oxygen diurnal variation in the New Calabar River

study has as part of it, determination of channel cross section, depth of flow, and stream velocity. The biochemical and hydrological data were used to determine the coefficients of deoxygenation and reaeration rates and hence an estimate of the self-purification potential of the stream.

Hydrological Parameters

The hydrological parameters investigated are water depth, mean flow depth, stream velocity, mean velocity at mean flow depth, and channel cross section geometries. The water depth was measured using a graduated pole at five (5) points along each cross section. There were variations in depth across the channel as determined from the pole and these variations would be expected to

give a reasonable approximation of the channel cross section geometry. The mean flow depths were estimated as the depth corresponding to the 60% of maximum water depth along the cross section.

Stream velocity was determined using a float. The time taken for the float to move from one point to another was recorded. This technique provided the flow rate of the stream. The mean velocity at mean flow depth was estimated from the relation (Linsley and others, 1982);

$$V^1 = V_{max} \times \left(\frac{z}{h}\right)^{1/7} \dots \dots \dots (1)$$

where V_{max} is the velocity as measured by the float, V_1 is the mean velocity at mean flow depth, h is the depth corresponding to 60% of maximum water depth along the cross section, and $z = \frac{n}{30}$ where n is the stream – bed

roughness coefficient with an average of 0.023 for natural streams.

The channel cross section geometries were estimated from measurements of water depth made at several points across the stream at each location within a given reach. Variations in depth across the channel as determined with the use of pole are expected to give reasonable approximations of the channel cross section geometry.

Laboratory Analysis

Dissolved oxygen (DO) measurements were carried out twice in the year, one representing the dry season and the other, representing the rainy season. The measurement representing the dry season was done on March 10, 2010 whereas that of rainy season was done on July 8, 2010. The water samples were collected in one (1) litre plastic containers that were closed tightly so as to shut out air bubbles. The samples were forthwith pretreated by adding 1cm³ of manganoussulphate and sodium iodide. Preceding precipitate was dissolved by the addition of 1cm³ of concentrated sulphuric acid. The pretreated samples were analysed in the laboratory using the method developed by Winkler.

For biochemical oxygen demand (BOD) test, stream water samples were collected in one (1) litre plastic containers and the bulk samples was made homogeneous by shaking it strongly. Identical samples were made from the bulk sample and apportioned into seven (7) brownish bottles. One of the bottles was immediately analysed for DO using the DO deficit method whereas the remaining six (6) identical samples were stored in the laboratory dark chamber and were analysed one after the other specifically on the 1st, 2nd, 3rd, 5th, 7th, and 10th day after the storage date. The initial DO concentration in all the identical samples was considered to be the same because of the intense shaking to which the bulk sample was subjected. This provided the basis for determining the cumulative dissolved oxygen continually utilized for the oxidation of organic matter during the period of test and the amount of oxygen so consumed formed the 10-day BOD value at a laboratory temperature of 20 °C. Based on this, the deoxygenation rate coefficient in the stream was determined.

Diurnal Variation of Dissolved Oxygen

Dissolved oxygen concentrations were measured in-situ, and within the river environment at various time of the day, precisely at about 6:30 am, 10:00 am, 2:00 pm and 6:00 pm on March 13, 2010. This measurement was done to ascertain the level of dissolved oxygen variations in the river with time, during the day-light period.

Self-Purification Parameters

The deoxygenation rate coefficient k_1 , reaeration rate coefficient k_2 , and FAIR’s number ($f = k_2/k_1$) were the self –purification parameters used in the study. By definition of k_1 and k_2 , the value of f expresses the degree of predominance of reaeration over deoxygenation (Nwankwor and Okpala, 1993). The k_2 values were computed for all the stream reaches using two (2) different methods developed by Churchill and others (1962). Their formulae are of the forms:

$$K_2 = \frac{5.026V^{0.769}}{h^{1.673}} \dots \dots \dots (2)$$

and

$$K_2 = \frac{5.23u}{H^{1.67}} \dots \dots \dots (3)$$

where h and H respectively are mean flow depth (m) and v is mean stream velocity (m/s).

The k_1 was determined using Thomas (1950) curve fitting technique, and the relation developed by Tebbut (1998). The relation is of the form:

$$K_T = K_{20}(\theta)^{(T-20)} \dots \dots \dots (4)$$

where θ is the temperature coefficient with value of 1.047. The f values were computed using two (2) different values of k_2 as determined with respect to equations (2) and (3) and k_1 values as determined with respect to equation (4).

DATA ANALYSIS AND DISCUSSION

Deoxygenation Reaction

The deoxygenation rate constant was computed from BOD test data and the corresponding curves, using Thomas (1950) curve fitting technique and Tebbut (1998) temperature equation. Values of 0.15 / day and 0.16/day were obtained respectively. Table 1 shows the organic matter oxidized and stabilized at time, t and figure 2 shows the corresponding BOD curves.

The Deoxygenation reaction coefficient, k_1 of 0.15/day and 0.16/day obtained using Thomas curve fitting technique and Tebbut temperature equation respectively, suggest domestic origin for the waste. Tebbut (1998) gave the value of 0.17/day at a temperature of 20° C, as the deoxygenation rate coefficient for domestic sewage. The measured laboratory temperature for the BOD test was 20° C, and the higher value is very close to 0.17/day characteristic of domestic sewage as given by Tebbut

(1998). The k_1 values depict swift depletion of oxygen in the river.

Reaeration Reaction

The reaeration coefficient, k_2 , determined using two (2) different methods developed by Churchil et al (1962) are shown in table 2. The formulae for the two (2) methods are as given in equation (2) and (3).

Reaeration coefficient, k_2 , varies from one stream reach to another, and also with the method used in its calculation. In view of the fact that stream velocity and depth are the two (2) major factors that control the degree of reaeration, it is expected that its coefficient varies from one stream reach to another. This is because these factors vary from one stream channel to another.

The k_2 values range from 0.10/day in the reaches where the flow is inactive to 0.33/day in the sections where the flow is faster. Apparently from the table, all the k_2 values are below 0.35/day, and indicates deep and slow moving streams. This is in line with the observed stream velocity and depth as measured with a graduated pole.

Hydrologic Parameters

The replenishment of oxygen in stream water is dependent on the stream flow velocity, water depth and channel geometry (Clark et al, 1977). Mean velocity and mean flow depth for the various reaches are shown in table 2. The mean flow depth is estimated as the depth corresponding to the 60% of maximum water depth along the cross – section.

Channel cross – section geometries as estimated from measurements of water depth made at several points across the stream at each location within a given reach are shown in figure 3.

FAIR’S Number

Based on the definitions of k_1 and k_2 , and FAIR’S number ($f = k_2 / k_1$), f values less than 1.0 depict predominance of deoxygenation over reaeration whereas values greater than 1.0 depict predominance of reaeration over deoxygenation. Hence, it is expected that at f value of 1.0, the rate of reaeration equals that of deoxygenation. Table 3 shows the f value for the various reaches. It is apparent from the table that except in Reach 3, reaeration predominates in all the reaches.

Region of predominance of the reaction coefficients can be represented with a plot. Figure 4 shows FAIR’S number – distance plot for the New Calabar River. It is apparent from the plot that reaeration reaction decreases downstream from Reach 1 and equals deoxygenation

reaction at a distance of 3.6 kilometers.

Deoxygenation reaction begins to increase from this point and peaks at a distance of 4.6 kilometres where it rapidly decreases and equals reaeration at a distance of about 9.6 kilometres. From this point also downstream, reaeration increases and peaks at a distance of approximately 12.2 kilometers. It decreases from this point and equals deoxygenation at 17.6 kilometres downstream.

In the downstream direction, the stream begins to recover from pollution problem at a distance of about 12.2 kilometres and this is where FAIR’S number equals 1.0 after the peak of deoxygenation at a distance of 4.6 kilometres.

The f values range from 0.6 (for Reach 3) to 2.2 (for Reach 1). Based on FAIR’S table of values for $f = k_2 / k_1$, the lower value of 0.6 corresponds to the value for sluggish streams of poor reaeration potential whereas the higher value of 2.2 in Reach 1 shows large streams of normal velocity possessing moderate reaeration potential.

Dissolved Oxygen Profile

The results of the DO measurements along the river profile based on the sampled locations, and for the dates indicated are shown in table 4. The equation for the DO sag is

$$\frac{dD}{dt} = k_1L - k_2D \dots \dots \dots (5)$$

where D is the dissolved oxygen deficit, and L is the amount of BOD remaining at time, t . At the point of maximum sag, the reaeration rate equals the deoxygenation rate. At this point, equation (5) can be integrated to yield;

$$Dc = \frac{k_1L}{k_2} \dots \dots \dots (6)$$

where Dc is the DO deficit at the point of maximum sag.

Figures 5 (a) and (b) are the DO sag (profile) for the New Calabar River based on the sample locations and for the dates indicated.

The simultaneous action of deoxygenation and reaeration in the stream gave the DO profiles shown in figures 5(a) and (b). The measured DO values are quite high and indicate high dissolved oxygen concentration in the stream. Table 4 shows that some locations are over-saturated and this indicates high atmospheric reaeration

or some other source of dissolved oxygen input in the stream. The over-saturation as observed in some locations suggests predominance of reaeration over deoxygenation in those locations because over-saturation could not have been possible if deoxygenation process equals or out-weighs that of reaeration.

Diurnal Variation In Dissolved Oxygen

Nemerow (1985) attributed elevated concentrations of dissolved oxygen in streams to the processes of organic sedimentation, scouring and photosynthesis. Thoman et al (1987) noted that the presence of aquatic plants in a water body can have profound effect on the DO resources and the variability of the DO through-out a day or from day to day. Figure 6 shows the dissolved oxygen concentrations measured at various time of the day.

The DO increased from 80.8 mg/l in the morning hours to 105.3 mg/l in the afternoon hours and sinked to 80.6 mg/l at about 6p.m on the 13th day of March, 2010. The result of this experiment confirms that the stream has other source(s) of dissolved oxygen input and that algal photosynthesis is a major factor responsible for the elevated DO concentration in the stream and hence, its diurnal variation. Tchobanoglous and Edward (1985) ascribed diurnal variation in dissolved oxygen concentration of streams to the presence of large algal populations.

Diurnal variation in dissolved oxygen concentration of streams can be used to estimate the percentage of dissolved oxygen which a stream acquires through photosynthesis if the DO levels in the morning and afternoon hours are measured. Thus, let the minimum dissolved oxygen value in the morning hours be DOV_1 and the maximum dissolved oxygen value in the afternoon hours, DOV_2 . Therefore, the percentage of dissolved oxygen can be estimated using the relation:

$$DOV_2 - DOV_1 / DOV_2 \times 100 \% \dots\dots\dots (7)$$

This relation was used to estimate the percentage of dissolved oxygen which the New Calabar River acquires through photosynthesis and a value of 23.3% was obtained. Thus, about 23.3% of the dissolved oxygen in the stream originates from algal photosynthesis.

Self-Purification Potential

The DO profiles show that at maximum point of sag, the dissolved oxygen concentrations are 60.6 mg/l and 67.2 mg/l (figures 5a and b). These values compared respectively to optimum DO values of 94.0 mg/l for the month of March and 86.7 mg/l for the month of July give deficit values of 33.4 mg/l and 26.8 mg/l. Using equation

(6) to calculate the DO deficit where $L = 10$ days gives deficit values of 15.3 mg/l and 21.8mg/l for the months of March and July respectively. Ideally, the observed Dc should be consistent with the value that one would obtain on the basis of deoxygenation/reaeration rates coefficients (Nwankwor and Okpala, 1993). The measured DO values are not consistent with the calculated values such that the calculated values are lesser than the measured values as deduced from the DO profiles. This suggests that there is more dissolved oxygen in the stream than can be determined through deoxygenation/reaeration rates coefficients especially when the f value for the location/reach corresponding to the maximum point of sag is greater than 1.0. This is the case with reach 5 which corresponds to the maximum point of sag for the month of March, in which the f value ranges from 1.0 to 1.3. Based on the results of the experiment to investigate diurnal variation in dissolved oxygen, the extra amount of dissolved oxygen has earlier been attributed to algal photosynthesis.

Self-purification potential can also be expressed in terms of the time of flow required for the stream to re-attain its optimum DO level (Nwankwor and Okpala, 1993). Based on the DO profile for the dry season (figure 5a), re-attainment of the DO level occurred at reach 5. Taking into consideration variations in velocity along the stream reaches, the distance amounts to 0.32 day of flow time. During the rainy season as represented by the corresponding DO profile (figure 5b), a shorter flow time of 0.21 day is required. Thus, the river is capable of re-attaining its optimum dissolved oxygen level within a time interval ranging from 0.32 day in the dry season to 0.21 day in the rainy season. The difference in flow time for the two seasons is probably due to seasonal factors. Relatively, the flow time for the rainy season is short. The shorter flow time suggests a high self-purification potential during the rainy season whereas the longer flow time suggests moderate self-purification potential for the dry season.

Besides expression in terms of flow time, self-purification potential can also be expressed in terms of spatial predominance of the reaction coefficients. It is apparent from figure 4 (FAIR'S number-distance plot for the New calabar River) that about 69.5% of the stream is under reaeration predominance. This condition is indicative of moderate to high self-purification potential.

SUMMARY AND CONCLUSION

Dissolved oxygen profiles for both the dry and rainy seasons suggest predominance of reaeration over deoxygenation. Spatially as could be deduced from FAIR'S number-distance plot, about 69.5% of the stream is under reaeration predominance. Sources of oxygen include atmospheric reaeration and algal photosynthesis

with the latter accounting for about 23.3% of the total dissolved oxygen in the stream. The stream is capable of re-attaining its optimum dissolved oxygen level within a time interval ranging from 0.32 day in the dry season to 0.21 day in the rainy season. These flow times suggest moderate and high self-purification potential for the dry and rainy seasons respectively.

RECOMMENDATIONS

Even though the New Calabar River has the potential to be purified by itself within relatively a short time interval, discharge of wastes into the stream should be discouraged and the government should provide a central sewage disposal system. Also government should ensure that companies do not dispose into surface waters, effluent that will unsafely alter the water chemistry.

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