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SELF-PURIFICATION POTENTIAL OF SMALL TROPICAL URBAN STREAM: A CASE STUDY OF THE RIVER NWAORIE IN IMO STATE, NIGERIA

Using dissolved oxygen and biochemical oxygen demand (BOD_{15}) measurements as well as hydrologic data, deoxygenation and reaeration rate coefficients were determined in order to assess the natural self-purification potential of the River Nwaorie in Owerri (Imo State). The deoxygenation rate coefficient ranged from 0.17/day to 0.19/day indicating that there was organic waste matter input besides the normal domestic waste. The reaeration rate coefficient varied from 0.08/day to 0.91/day. Measurements of dissolved oxygen showed generally its high concentrations. However, the dissolved oxygen concentrations determined analytically on the basis of deoxygenation and reaeration rate coefficients were lower than the concentrations measured at the critical point of dissolved oxygen profile sag. Analysis of the dissolved oxygen profile proved that the stream was able to reestablish its optimum dissolved oxygen content within 0.35 day of flow time during the dry season, and within 0.12 day during the rainy season. These relatively short flow times were probably due to the high reaeration effect and input of oxygen from algal photosynthetic activities.

1. INTRODUCTION

The discharge of organic wastes into surface waters creates a problem of special importance in water pollution control. The pollution problem arises when the capacity of stream to assimilate wastes is exceeded under conditions of excessive stream loading with organic wastes. However, as long as the capacity limit is not exceeded, disposal of organic wastes into streams represents an economical method (CLARK et al. [2]). This limit defines the self-purification capacity of a stream, and is related to the stream potential to replenish the dissolved oxygen (DO) that is

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continually utilized in the oxidation of organic wastes. The process and rate of self-purification are influenced by temperature, nature of the organic pollutants, size and the hydraulic characteristics including algal content of the receiving stream.

The River Nwaorie represents a typical small tropical stream that flows through an urban centre – Owerri, the capital of the Imo State in Nigeria. Over the years, it has been used as a natural sewer line for the urban community, and thereby receives wastes of both industrial and domestic origin. The incidence of pollution of the River Nwaorie has been studied by EGBOKA and UMA [3], NWANKWOR and OKPALA [9], and OSUNDU [11]. These studies allowed them to identify elevated concentrations of inorganic pollutants.

An insight into the organic waste pollution of this river was provided by OSUNDU [11], who carried out a one-time set of measurements of chemical oxygen demand (COD) along the river. The results showed that COD values ranged from 80 mg/dm^3 near the stream source to 172 mg/dm^3 at a point about six kilometers further downstream. The COD profile suggests that there is significant organic waste loading in the stream and hence a consequent lowering of its dissolved oxygen level. In the context of stream sanitation and organic waste pollution control problems, however, biochemical oxygen demand (BOD) and DO content become the more appropriate biochemical parameters. This study deals with these biochemical as well as hydrological properties of Nwaorie stream with a view to assessing its self-purification capacity. It will also form a basis for determining the tolerable level of organic waste loading.

The evaluation of the natural self-purification capacity of a stream is of fundamental engineering value. Its knowledge is important for the design of waste treatment plants by those industries which desire to discharge their wastes into nearby streams, rivers or other surface water bodies.

2. MATERIALS AND METHODS

2.1. CLIMATIC CONDITIONS

The River Nwaorie is a geomorphic first order stream within the Otamiri drainage basin in Owerri. From its source, it flows to the south-east for about six kilometers before joining the River Otamiri (figure 1). The channel is moderately sinuous, rarely braided and exhibits significant width variations over some segments of flow.

The River Nwaorie has a maximum average discharge of 6.9 m^3/s in the rainy season and a minimum of 1.37 m^3/s in the dry season. The drainage basin lies within the rain forest belt of Nigeria. Available rainfall records show that the average rainfall is about 2500 mm, most of which falls between the months of May and

October. This period is characterized by moderate temperatures and high relative humidities. The months of November to April have scanty rains, higher temperatures and low relative humidities.

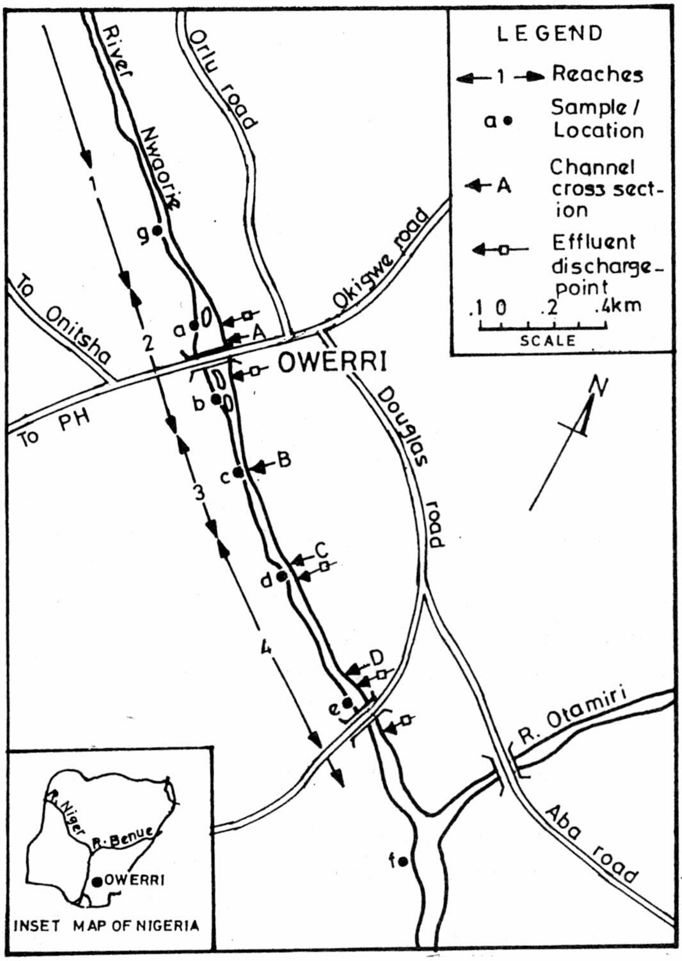

Fig. 1. The map of the River Nwaorie area showing sampling locations (inset: map of Nigeria showing the location of Owerri)

2.2. SAMPLING NETWORK

Water sampling network was based on hydrological factors, distribution of points of waste matter inflow and the seasonality of climatic factors. A rapid reconnaissance survey showed four distinct stream reaches based on stream channel configuration, flow regime and pollutant input source (figure 1). Location, number and intensity of sampling were then concentrated within these four reaches. The wider reaches (2 and 4) were sampled at two different points transversely in the channel, while in the narrower segments (1 and 3), one sampling point located midstream was considered adequate. In each case, water sample was collected at the 0.6 depth position.

A total of seven locations designated 'a' to 'g' were selected and sampled for biochemical and hydrological parameters. The biochemical study involved water sample analysis for dissolved oxygen (DO), biochemical oxygen demand (BOD) and chemical oxygen demand (COD). The hydrological study included determinations of channel cross-sections, depth of flow and stream velocity. The biochemical and hydrologic data were used to determine the coefficients of deoxygenation and reaeration rates, and hence an estimate of the stream self-purification potential.

2.3. DISSOLVED OXYGEN MEASUREMENTS

DO measurements were carried out on March 24, 1991 and June 18, 1991 representing the dry and rainy seasons, respectively. The river water samples were collected in 250 cm^3 amber bottles stoppered under water in order to exclude air bubbles. The samples were immediately pretreated by the addition of 1 cm^3 of manganous sulphate followed by the same amount of sodium iodide. The precipitate which subsequently formed was then dissolved by the addition of 1 cm^3 of concentrated sulphuric acid. The pretreated samples were analysed in the laboratory using the Winkler method of DO determination [5].

2.4. BIOCHEMICAL OXYGEN DEMAND CHARACTERIZATION

In this study, BOD was determined by the DO deficit method in well stoppered bottles that were incubated over a 15-day period (BOD_{15}). Stream water samples were collected at location 'e', very close to a waste effluent and discharge point. The bulk sample was homogenized by vigorous shaking. Replicate samples were made from the bulk sample and distributed into eight amber bottles one of which was immediately analyzed for DO using the method outlined previously. The remaining seven replicates were stored in a laboratory dark chamber, and were analyzed one after the other at predetermined time intervals over a 15-day period. Specifically, the analyses were carried out on the 1st, 2nd, 3rd, 5th, 7th, 10th and 15th day after the storage date. Since the bulk sample was properly homogenized prior to storage and analyses, the initial DO concentration in all the replicate samples was considered to be identical. This provided a basis for determining the cumulative dissolved oxygen progressively utilized for organic matter oxidation during the period of the test. The amount of oxygen so utilized constituted the 15-day BOD value at the measured laboratory temperature of 23 °C. This provided the basis for the determination of deoxygenation reaction rate in the stream water.

2.5. CHEMICAL OXYGEN DEMAND MEASUREMENTS

Water samples for the COD measurements were collected alongside those for DO, and in 10 cm^3 bottles. COD tests were carried out on these samples in the laboratory using a portable spectrophotometer, model/type DREL/5 by HACH Coy, and following the method outlined in [5].

2.6. HYDROLOGIC PARAMETERS

The replenishment of oxygen in stream water is dependent on the stream flow velocity, water depth and channel geometry (CLARK et al. [2]). These parameters were determined at each of the four reaches identified in the reconnaissance survey.

Channel cross-sectional geometries were estimated from measurements of water depth made at several points across the stream at each location within a given reach. The water depth was measured using a graduated pole at five points along each cross-section. Variation in depth across the channel as determined from the pole would be expected to give a reasonable approximation of the channel cross-sectional geometry. Figure 2 shows the cross-sections; the mean flow depths estimated as the

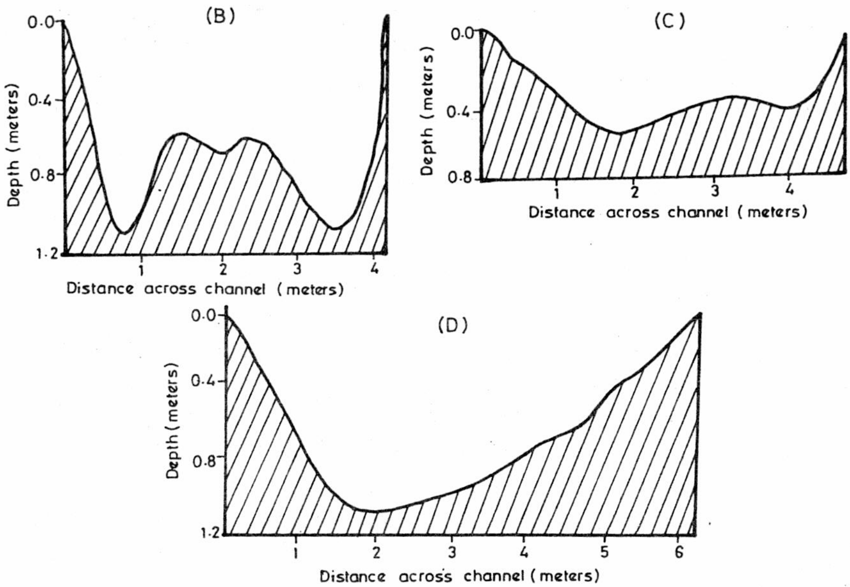

Fig. 2. Nwaorie stream channel across sections at locations B, C, D in reaches 3, 2, 4

depth corresponding to the 60% of maximum water depth along the cross-section are given in table 1.

Stream flow velocity was determined using a float. Time taken for the float to move from a given point to another provided the flow rate of the water surface layer. Mean velocity at the mean flow depth was estimated from the relation (LINSLEY et al. [6])

$$v^1 = v_{\max}(z/h)^{1/7} \tag{1}$$

where $v_{\max}$ is the velocity as measured by the float, v^1 is the mean velocity flow depth, h is the depth corresponding to the 0.6 of maximum depth along the section, and $z = n/30$ where n is the stream-bed roughness coefficient with an average value of 0.023 for natural streams. The computed velocities are shown in table 1.

Table 1

Stream velocity, depth data and the calculated k_2 values for the various reaches

Reach	Mean velocity ($m \cdot s^{-1}$)	Mean depth (m)	k_2 values (per day) CHURCHILL et al. method [1]	OWENS et. al. method [10]	NEGULESCU and ROJANSKI method [7]
1	0.09	0.4	0.51	0.08	0.04
2	0.24	0.5	0.53	0.79	0.62
3	0.35	0.3	0.93	0.63	0.91
4	0.26	0.5	0.47	0.72	0.32

3. DATA ANALYSIS AND RESULTS

3.1. DEOXYGENATION REACTION

The data showing the progress of organic matter oxidation during the BOD_{15} test are shown in table 2 in terms of the DO remaining (organic matter to be oxidized) and the DO removed (organic matter stabilized) at any time, t. The corresponding BOD curves are shown in figures 3a and b. The deoxygenation rate constant was then computed from these data using the graphical solution technique of NEMERON [8] and Rhame's two-point method. These methods were chosen because of their suitability for general laboratory procedure and their computational ease. For the deoxygenation rate constant, k_1, values of 0.19/day and 0.17/day were determined from the graphical technique and Rhame's two-point method, respectively.

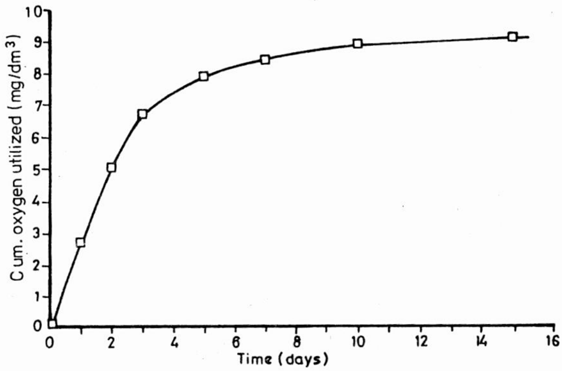

Fig. 3a. BOD_{15} exertion curve. Oxygen utilized versus time

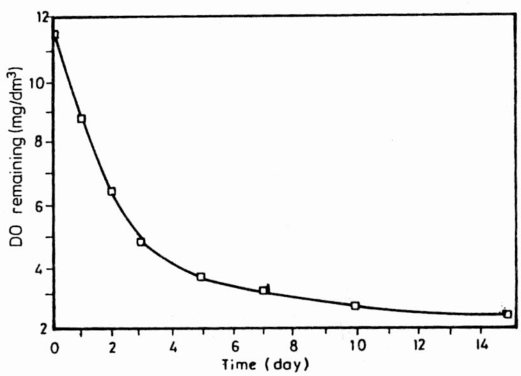

Fig. 3b. BOD_{15} exertion curve. Oxygen remaining versus time

Table 2

Dissolved oxygen data measured during the BOD_{15} test for the river water sample collected at location 'e'

Time (days)	Cumulative DO utilized ($mg \cdot dm^{-3}$)	DO remaining ($mg \cdot dm^{-3}$)	COD ($mg \cdot dm^{-3}$)
0	0.0	11.5	15
1	2.70	8.80	–
2	5.10	6.40	–
3	6.70	4.80	–
5	7.95	3.55	–
7	8.45	3.05	–
10	8.90	2.60	–
15	9.10	2.40	30

3.2. REAERATION COEFFICIENT

Reaeration coefficient, k_2, was determined using the methods developed by CHURCHILL et al. [1], OWENS et al. [10], and NEGULESCU and ROJANSKI [7]. Their formulae are respectively of the forms:

$$k_2 = 5.026 \frac{v^{0.769}}{h^{1.673}}, \tag{2}$$

$$k_2 = 9.4 v^{0.67} h^{1.85}, \tag{3}$$

$$k_2 = 0.0153 De(v/h)^{1.63}, \tag{4}$$

where *De* is the diffusivity of oxygen in water at 20 °C. All these three methods were, for the comparative purposes, applied to stream reaches 2, 3 and 4 for which data were available. The calculated k_2 values are shown in table 1.

3.3. DISSOLVED OXYGEN SAG

Figures 4a and b are the DO profiles (DO sag) for the River Nwaorie based on the sampled locations and for the indicated dates. The equation for the DO sag is (CLARK et al. [2]):

$$\frac{dD}{dt} = k_1 L - k_2 D, \tag{5}$$

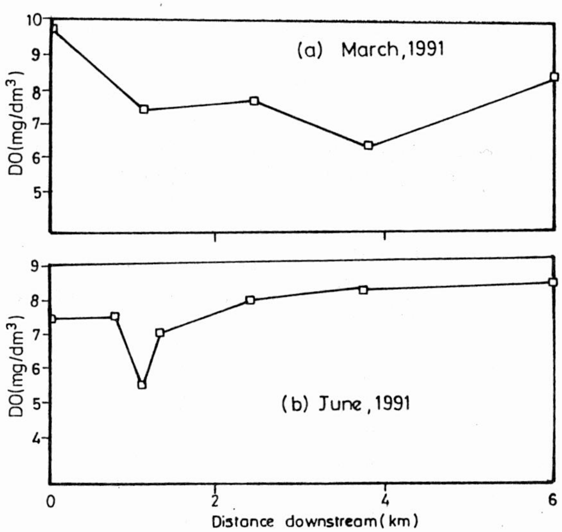

Fig. 4. Dissolved oxygen profiles for the River Nwaorie

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. Thus, integration and simplification of equation (5) for that particular point yield:

$$Dc = \frac{k_1 L}{k_2}, \tag{6}$$

where Dc is the DO deficit at the point of maximum sag. It is evident from equation (6) that Dc is primarily controlled by k_1 and k_2. These are the coefficients relating to deoxygenation and reaeration reaction rates, and hence the self-purification potential.

3.4. SELF-PURIFICATION PARAMETERS

A more appropriate form of the ratio (k_1/k_2) has been introduced by FAIR [4] as $f = k_2/k_1$. By the definitions of k_1 and k_2 the f value expresses the degree of predominance of reaeration over deoxygenation. The f values were computed for stream reaches 2, 3 and 4 using various combinations of k_2 values of table 1 and the estimated k value of 0.19/day. The f values range from 0.2 (for reach 2) to 4.5 (in reach 3). Based on FAIR's [4] table of f values for various waters, the lower values obtained in reach 2 are characteristic of sluggish streams of poor to moderate reaeration potential. The higher values of f in reaches 3 and 4 are indicative of swift streams possessing high reaeration potential.

4. DISCUSSION

4.1. REACTION COEFFICIENT CHARACTERISTICS

The reaction coefficients include k_1 (for deoxygenation reaction) and k_2 (for reaeration process). The deoxygenation rate coefficients of 0.19/day and 0.17/day determined using Rhame's and graphical methods are in good agreement. They are almost twice as high as the value of 0.1/day characteristic of normal domestic sewage as given by CLARK et al. [2]. The higher value suggests that the source of waste is probably of industrial origin. The direct consequence of the k_1 value is a more rapid depletion of oxygen in the stream.

The reareation coefficient k_2 varies from one stream reach to another, and also with the method used in its calculation. The variation between the stream reaches is not unexpected considering the parameters that control its magnitude. Generally, the values range from 0.08/day in the reaches where flow is sluggish to 0.93/day in the faster flowing segments. It is apparent from table 1 that over 90% of the k_2 values are above 0.4/day. Such values indicate moderately shallow and slow moving streams, which is consistent with the observed hydrologic regimen.

The simultaneous action of deoxygenation (as determined by k_1) and atmospheric reaeration (as indicated by k_2) gives the DO profile shown in figures 4a and b. The measured DO values show high dissolved oxygen saturation, with over-saturation effects observed in some locations (table 3). The high DO saturation suggests either a proportionately high atmospheric reaeration process or other sources of input of

Table 3

Results of DO and COD measurements along the river profile

Location	Date						
	24 April, 1991				10 June, 1991		
	DO ($mg \cdot dm^{-3}$)	Temperature (°C)	Saturation (%)	COD ($mg \cdot dm^{-3}$)	DO ($mg \cdot dm^{-3}$)	Temperature (°C)	Saturation (%)
'a'	9.70	29.9	128	110	7.50	27.0	94
'b'	–	–	–	–	7.52	27.0	94
'c'	7.40	29.3	96	355	5.52	27.0	69
'c'	–	–	–	–	7.04	27/–	88
'd'	7.70	30.5	102	195	8.0	28.0	102
'e'	6.40	31.0	86	150	8.26	28.5	105
'f'	8.40	31.0	113	16	7.10	29.0	92
'g'	9.20	30.6	120	28	8.10	28.4	104

oxygen other than from ordinary atmospheric exchange. Elevated concentrations of dissolved oxygen in streams have been ascribed to the processes of organic sedimentation, scouring and photosynthesis (NEMEROW [8]). Figure 5a shows the dissolved oxygen concentrations measured at various times of the day. The DO increased from

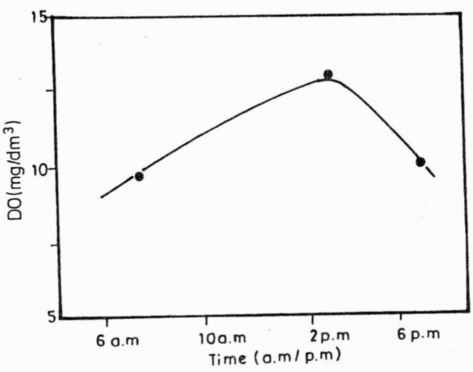

Fig. 5a. Dissolved oxygen variations in the River Nwaorie with time of a day

9.5 mg·dm^{-3} in the morning hours to almost 14.0 mg·dm^{-3} in the afternoon, and then declined to 10.2 mg·dm^{-3} at about 6.30 p.m. on the 26th day of April 1991. The same day stream water samples were collected and isolated in the laboratory, and the DO measurements were carried out over a period of several days. The results show an initial increase in DO from about 13.4 mg·dm^{-3} to 14 mg·dm^{-3}, and then DO declined rapidly (figure 5b). The results of these two experiments clearly suggest that algal photosynthesis is a major factor accounting for the observed elevated DO concentrations in the stream.

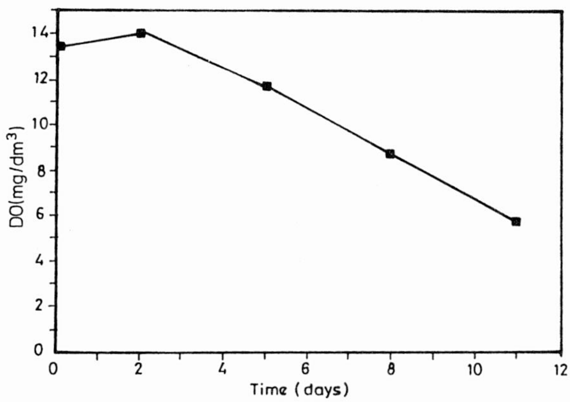

Fig. 5b. Dissolved oxygen variation in the river water sample under closed system in the laboratory

4.2. SELF-PURIFICATION POTENTIAL

Taking account of stream sanitation and stream self-purification, the DO must be maintained above some critical concentrations, depending on the intended use of the stream water. For example, a DO concentration of 5.8 mg·dm^{-3} or 72.5% saturation is required for preservation of most aquatic life (NEMEROW [8]). A consideration of the DO profiles shows that the minimum dissolved oxygen concentrations (i.e. DO at maximum sag point) are 6.4 mg·dm^{-3} and 5.7 mg·dm^{-3} (figures 4a, b). Compared to the value of 7.70 mg·dm^{-3}, the standard saturation value at the observed river temperature of about 29 °C gives deficit values of 1.3 mg·dm^{-3} and 2.0 mg·dm^{-3}.

Ideally, the observed *Dc* should be consistent with the value that one would obtain on the basis of the deoxygenation/reaeration rates coefficients. This consistency was determined by calculating *Dc* using the relation given by NEMEROW [8]:

$$\log\ Dc = \log \frac{L_0}{f} - k_1 t_c, \tag{7}$$

where t_c is the time of the flow from the point of maximum DO concentration to the critical point of sag, and L_0 is the ultimate BOD (i.e. the value of L at $t = 0$). This t_c was determined by successively computing the time of flow over the various reaches and taking the variations in velocity into consideration. A t_c value of 0.25 day was determined. On the basis of the f values of 0.5 and 5.0 that had earlier been determined, a mean value of 2.7 was estimated. Substituting these values into equation (7) provides a Dc of 2.80 $mg \cdot dm^{-3}$ which is more than twice the measured DO deficit value of 1.3 $mg \cdot dm^{-3}$.

There is therefore a greater amount of dissolved oxygen in the stream than it can be predicted basing on the deoxygenation and reaeration processes. This condition has earlier been attributed to algal photosynthetic activity.

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. It is apparent from figure 4a (the DO profile measured during the dry season) that such a re-attainment of the DO level occurred just beyond location f, about six kilometers downstream from the point of organic matter input. Taking the velocity variations along the stream reaches into consideration, the distance amounts to 0.35 day of flow time. During the rainy season, as represented by the DO profile in figure 4b, a shorter flow time of 0.12 day is required. The shorter flow time is probably due to changes in hydrologic region. These flow times are apparently relatively short, and suggest a high self-purification potential.

5. CONCLUSIONS

The resultant dissolved oxygen profile produced by the simultaneous action of deoxygenation and reaeration shows high oxygen saturation values, suggesting a predominance of reaeration over deoxygenation. Sources of oxygen appear to include the direct atmospheric component and that from algal photosynthetic activity. The stream is capable of re-establishing its optimum dissolved oxygen level within a relatively short time ranging from 0.35 day in the dry season to 0.12 day in the rainy season. The above conditions indicate a high self-purification potential.

ACKNOWLEDGEMENTS

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SAMOOCZYSZCZANIE SIĘ MAŁEGO STRUMIENIA TROPIKALNEGO, PRZEPŁYWAJĄCEGO PRZEZ MIASTO, NA PRZYKŁADZIE RZEKI NWAORIE W STANIE IMO W NIGERII

Określono współczynnik szybkości zużywania tlenu i napowietrzania na podstawie zarówno pomiarów rozpuszczonego tlenu (DO) i biologicznego zapotrzebowania tlenu (BZT), jak i danych hydrologicznych. Współczynniki te są niezbędne do oszacowania naturalnego samooczyszczania się rzeki Nwaorie w Owerri (stan Imo). Współczynnik szybkości zużywania tlenu wahał się od 0,17 do 0,19/dzień, co świadczyło, że oprócz zwykłych ścieków bytowych w wodzie są również ścieki organiczne. Współczynnik szybkości napowietrzania wynosił od 0,08 do 0,91/dzień. Pomiary stężenia rozpuszczonego tlenu wskazywały na jego duże stężenie. Jednak stężenia tlenu oznaczone analitycznie na podstawie współczynników szybkości zużywania tlenu i napowietrzania były niższe od stężeń zmierzonych w krytycznym punkcie profilu rozpuszczonego tlenu. Analiza tego profilu świadczy, że w strumieniu zachodził proces ponownego ustalenia się optimum zawartości rozpuszczonego tlenu w ciągu 0,35 dnia (pora sucha) i w ciągu 0,12 dnia (pora deszczowa). Czas ten był stosunkowo krótki z powodu silnego napowietrzenia wody tlenem wyprodukowanym podczas fotosyntezy.

САМООЧИСТКА МАЛОГО ТРОПИЧЕСКОГО РУЧЬЯ, ПРОТЕКАЮЩЕГО ЧЕРЕЗ ГОРОД, НА ПРИМЕРЕ РЕКИ НВАОРИ В ШТАТЕ ИМО В НИГЕРИИ

Определен коэффициент скорости потребления кислорода и аэрации на основе как измерений растворенного кислорода (DO) и биологической потребности в кислороде (БПК), так и гидрологических данных. Эти коэффициенты необходимы для оценки природной самоочистки реки Нваори в Оверри (штат Имо). Коэффициент скорости потребления кислорода колебался от 0,17 до 0,19/день, что свидетельствовало о том, что кроме обычных бытовых сточных вод в воде находятся также органические сточные воды. Коэффициент скорости аэрации составлял от 0,08 до 0,91/день. Измерения концентрации растворенного кислорода указывали на его большую концентрацию. Однако концентрации кислорода, обозначенные аналитически на основе коэффициентов скорости потребления кислорода и аэрации были ниже концентраций, измеренных в критической точке профиля растворенного кислорода. Анализ этого профиля свидетельсвует о том, что в ручье имел место процесс вторичного установления оптимума содержания раствореного кислорода в течение 0,35 дня (сухое время) и в течение 0,12 дня (дождливое время). Это время было относительно коротким из-за сильной аэрации воды кислородом, возникающим во время фотосинтеза.