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ORIGINAL RESEARCH ARTICLE

MODELLING SELF PURIFICATION OF RIVER BENUE WITHIN MAKURDI

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ARTICLE INFORMATION

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ABSTRACT

This study considered biochemical oxygen demand (BOD), dissolved oxygen (DO), the re- oxygenation rate, the de-oxygenation rate, the self-purification rate model for River Benue within Makurdi reach. The hydrodynamic data were collected while re-oxygenation rate, de-oxygenation rate and self purification rate were calculated using DO and BOD at 14 different stations along the river stretch. An empirical model for self purification was generated analytically using multiple linear regression equation analysis. The pH varied from 6.8 to 8.08 while DO concentration between 4.0 mg/L and 6.3 mg/L; BOD concentration ranges from 1.0 mg/L to 2.0 mg/L; Mean re-oxygenation rate of 0.179 in the raining season and 0.1 in the dry season; Mean de-oxygenation rate of 0.1186 day-1 in the raining season and 0.1345 day-1in the dry season was calculated; Self purification coefficient had a mean value of 1.3398 in dry season and 0.8354 in rainy season; The model has coefficient of determination (R2) and adjusted R2 of 0.5691 and 0.5469 respectively; a multiple correlation coefficient of 0.7544 and root mean squared error of 0.2433 between the observed field data and the model data. In conclusion, the river has good self purification ability and the model generated is reliable considering the root mean squared error.

1.0 Introduction

Rivers naturally exhibit some level of self-cleansing to reduce or eliminate contaminants completely through one or conglomerate of natural processes (physical, chemical and biological reaction). Bacteria in the water body carry out these processes which biochemically degrades organic matter through a reaction called oxidation. This reduction in oxygen concentration in the rivers is replenished through the surface diffusion of atmospheric oxygen into the river. Therefore, the ratio of this oxygen addition during aeration of the river to the rate of consumption of oxygen during degradation of pollutants is referred to as self purification capacity (Fair, 1939). Self purification is the ability of a river to regenerate itself by degrading pollutants through the use of available aquatic oxygen. The dissolved oxygen (DO) remains the convenient criterion for measuring the surface water quality of a river as far as self purification is concerned because the ecology of a river depends largely on the quantity of dissolved oxygen in its water (Khan and Singh, 2013). This is why oxygen demand (OD) has been traditionally used to assess the pollution degree and self-purification of a water body (Galvis *et al.,* 2014).

Models have been used as a tool to simulate the water quality and self purification of many rivers (Ugbebor *et al* 2012);Khan and Singh,2013;Ogbaji *et al.,*2013;Dikeogu *et al.,* 2014). All these literatures on the study of self purification were encamped on the study of Fair,(1939) and his equation. This equation stated that self purification is the ratio of Re-oxygenation to de-oxygenation. Re-oxygenation is the process of addition of atmospheric oxygen through surface interchange into a water body to replenish the used up dissolved oxygen. The replenishment of oxygen in river water is dependent on the water flow velocity, water depth and river geometry (Dikeogu, *et al.*, 2014). Ugbebor *et al.* (2012) modeled re-oxygenation with these parameters while including hydraulic radius. De-oxygenation is the rate at which this dissolved oxygen is used up which is dependent on temperature and contaminant load present in the river. Yustiani *et al*. (2018) reported that de-oxygenation varies with depth of river since there is reduced presence of microorganism action as the depth of river increases.

River Benue supports many economic activities along its stretch within the Makurdi reach which includes; the Benue breweries effluent disposal at the upstream section of the Makurdi reach, the draw-off of Benue state water board towards the downstream stretch, domestic water use along the river banks and fishing. There is the need for preservation of this water body to limit pollution which may arise due to increasing population. Monitoring is key to effective preservation. Modeling the self-purification potential of this river within the Makurdi reach serves as a way of developing tools which will guide in preservation of this water body within this reach.

Therefore, in modeling self purification of River Benue, Re-oxygenation (Re-aeration) and De-oxygenation were considered in this study in terms of the water quality parameter (temperature, DO and BOD) and hydrodynamic parameters (flow velocity and river depth) which affects the rate of addition or removal of oxygen in river Benue. The empirical model generated here will serve as a tool in predicting the self purification of river Benue at any section within Makurdi reach. This will also serve as a powerful instrument in the river's sustainable management.

2. Methodology

2.1 Study Area and the sampling points

Figure 1. shows the study area with the sampling stations. Sampling was conducted at fourteen (14) stations within the Makurdi reach of river Benue. All field data were acquired over a period of eight months from March, 2018 to October, 2018.

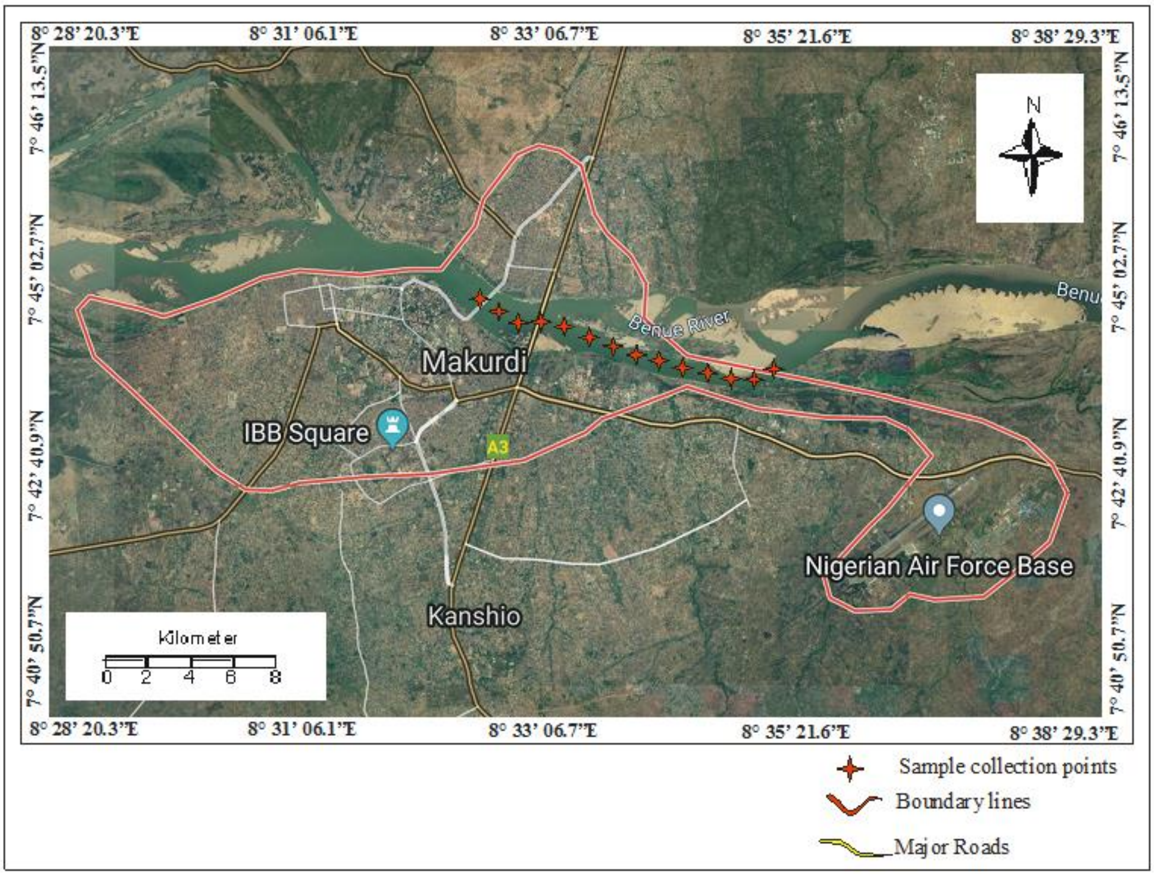

Figure 1. Map of Makurdi showing the sample collection points along River Benue

2.2 Data Collection

2.2.1 Laboratory and Field Measurements

The water samples collected were analyzed for DO and BOD. The hydrodynamic parameters (mean depth of flow and mean flow velocity) at each sample stations were also measured using standard methods. These are the parameters needed to generate a model for self-purification using Fair (1939) equation.

Iodometric method was used to determine DO and BOD (APHA *et al*., 2005). Aluminum stake calibrated in metric units with circular iron disc at the base was used in measuring the depth of the river. Temperature was determined using Laboratory thermometer. Velocities were determined using a current meter (model: FP111). Re-aeration and de-oxygenation were calculated using equations 1 and 2 respectively. Equation 3 was applied to get self-purification. The EUTECH instruments' pH meter was used for pH value measurement.

2.2.2 Mathematical determination

The re-aeration coefficient from field values was obtained using Equation 1:

$$K_2 = \frac{\ln\left(^{DO_{initial}}/_{DO_{deficit}}\right)}{\text{time (days)}} \tag{1}$$

where: K_2= re-aeration coefficient (d^{-1});
$DO_{initial}$=initial dissolved oxygen (mg/L);
$DO_{deficit}$= differencebetween saturation dissolved oxygen and observed dissolved oxygen (mg/L).

The de-oxygenation coefficient from field values was obtained using Equation 2:

$$K_1 = \frac{1}{t}\ln\left(\frac{L_A}{L}\right) \tag{2}$$

where: K_1 = de-oxygenation coefficient (d^{-1})
L_A = ultimate BOD (mg /L)
L = BOD at time (t)

The self purification potential from field values was obtained using Fair (1939) equation given by Equation 3 as:

$$F = \frac{K_2}{K_1} \tag{3}$$

where: F = self purification potential/capacity
K_1 = de-oxygenation coefficient (d^{-1})
K_2 = re-aeration rate constant (d^{-1})

2.3 Mathematical Derivation and Analysis of Self Purification Model

Analytical techniques were adopted in this research and were assured by recommended standard techniques and field sampling methods. The results were tabulated, and self purification modelled using Fair (1939) equation as stated in Equation 3 above.

Re-aeration rate constant can be written as;

$$K_2 = f(H, V) \tag{4}$$

where: f = function
K_2 = re-aeration coefficient (d^{-1})
H = depth of river (m)
V = velocity of flow (m/s)

The relationship can be written as;

$$K_2 = \frac{mV^{a_2}}{H^{a_4}} \tag{5}$$

where: the constant (m) and the exponents a_2 and a_4 are dimensionless numbers that follows each quantity.
De-oxygenation rate constant can be written as;

$$K_1 = f(L_A, L, t) \tag{6}$$

where:
f = function
L_A = ultimate BOD(mg /L)
L = BOD at time (t)
t = time of incubation (days)

Therefore, the relationship can be written as;

$$K_1 = \frac{n}{t^{a_1}}\left(\frac{{L_A}^{a_5}}{L^{a_3}}\right) \tag{7}$$

where: the constant (n) and the exponents (a_1, a_3 and a_5) are dimensionless numbers that follows each quantity.
Substituting Equations 5 and 7 into Equation 3, the model equation will take the form as;

$$F = \frac{mnt^{a_1}V^{a_2}L^{a_3}}{H^{a_4}{L_A}^{a_5}} \tag{8}$$

where: a_1, a_2, a_3, $a_4$and a_5 are exponential constants as shown above in Equations 5 and 7.
Since "m" is a constant and "n" is also a constant, a single constant was used to replace the constants. Let "a" be the constant in self purification model taking into consideration "m" and "n" from re-aeration and de-oxygenation respectively. Therefore, m and n are replaced with a in Equation 8 which is rewritten as;

$$F = \frac{at^{a_1}V^{a_2}L^{a_3}}{H^{a_4}{L_A}^{a_5}} \tag{9}$$

where: a, a_1, a_2, a_3, a_4 and a_5 are constants as described above that were obtained using multiple linear regression model analysis.

Multiple linear regression analysis is used to predict a continuous dependent variable from several independent variables. Linearity means that there is a straight line relationship between the independent variables and the dependent variable.
Therefore, Equation 9 can be stated in linear form as;

$$\ln F = \ln a + a_1 \ln t + a_2 \ln V + a_3 \ln L - a_4 \ln H - a_5 \ln L_A \tag{10}$$

Then, Equation 10 is rewritten in multiple linear regression equation form as;

$$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 - a_4x_4 - a_5x_5 \tag{11}$$

where:
$Y = \ln F$ with $F = e^Y$
$a_0 = \ln a$ with $a = e^{a_0}$
$x_1 = \ln t$ $x_2 = \ln V$ $x_3 = \ln L$
$x_4 = \ln H$ $x_5 = \ln L_A$

The least-squares normal equations for obtaining the numerical values of the constant (a) and the exponentials (a_1, a_2, a_3, a_4 and a_5) were derived from Equation 11. These least-squares normal equations are then given by;

$$\sum Y = na_0 + a_1 \sum x_1 + a_2 \sum x_2 + a_3 \sum x_3 - a_4 \sum x_4 - a_5 \sum x_5 \quad (12)$$

$$\sum Yx_1 = a_0 \sum x_1 + a_1 \sum x_1{}^2 + a_2 \sum x_1x_2 + a_3 \sum x_1x_3 - a_4 \sum x_1x_4 - a_5 \sum x_1x_5 \quad (13)$$

$$\sum Yx_2 = a_0 \sum x_2 + a_1 \sum x_1x_2 + a_2 \sum x_2{}^2 + a_3 \sum x_2x_3 - a_4 \sum x_2x_4 - a_5 \sum x_2x_5 \quad (14)$$

$$\sum Yx_3 = a_0 \sum x_3 + a_1 \sum x_1x_3 + a_2 \sum x_2x_3 + a_3 \sum x_3{}^2 - a_4 \sum x_3x_4 - a_5 \sum x_3x_5 \quad (15)$$

$$\sum Yx_4 = a_0 \sum x_4 + a_1 \sum x_1x_4 + a_2 \sum x_2x_4 + a_3 \sum x_3x_4 - a_4 \sum x_4{}^2 - a_5 \sum x_4x_5 \quad (16)$$

$$\sum Yx_5 = a_0 \sum x_5 + a_1 \sum x_1x_5 + a_2 \sum x_2x_5 + a_3 \sum x_3x_5 - a_4 \sum x_4x_5 - a_5 \sum x_5{}^2 \quad (17)$$

where: x_1, x_2, x_3, x_4 and x_5 are the predictor variables; and Y is the response variable as stated in Equation 11 above. The values of these variables were derived from the observed field data using 103 samples out of 112 samples observed from the field throughout the study period. Similarly, a_1, a_2, a_3, a_4 and a_5 are as stated in Equations 9 which were calculated by solving Equations 12, 13, 14, 15, 16 and 17 simultaneously using matrix methods of operation. An equation/model for prediction of Self Purification using observed field data was obtained by substituting the values of a, a_1, a_2, a_3,a_4 and a_5 calculated into Equation 9.

The least-squares normal equations for calculating the constants (a_0, a_1, a_2, a_3,a_4 and a_5) in the self purification model using observed field data were derived by substituting data for the statistical equation (multiple linear regression equation) as derived from the observed field data into Equations 12, 13, 14, 15, 16 and 17 to give;

$$103a_0 + 165.72a_1 - 21.35a_2 + 36.97a_3 - 152.27a_4 - 77.93a_5 = -7.04 \quad (18)$$

$$165.72a_0 + 266.80a_1 - 34.37a_2 + 59.50a_3 - 245.07a_4 - 125.42a_5 = -11.33 \quad (19)$$

$$-21.35a_0 - 34.37a_1 - 31.86a_2 - 3.18a_3 + 8.60a_4 + 11.77a_5 = -8.88 \quad (20)$$

$$36.97a_0 + 59.50a_1 - 3.18a_2 - 14.97a_3 - 60.18a_4 - 29.65a_5 = -5.17 \quad (21)$$

$$152.27a_0 + 245.07a_1 - 8.06a_2 + 60.18a_3 - 271.20a_4 - 120.61a_5 = -27.05 \quad (22)$$

$$77.93a_0 + 125.42a_1 - 11.77a_2 + 29.65a_3 - 120.61a_4 - 60.63a_5 = -7.91 \quad (23)$$

Equations 18, 19, 20, 21, 22 and 24 were solved simultaneously using matrix methods of operation. The matrix form is rewritten to give;

$$\begin{bmatrix} 103 & 165.72 & -21.35 & 36.97 & -157.27 & -77.93 \\ 165.72 & 266.80 & -34.37 & 59.50 & -245.07 & -125.42 \\ -21.35 & -34.37 & -31.86 & -3.18 & 8.60 & 11.77 \\ 36.97 & 59.50 & -3.18 & -14.97 & -60.18 & -29.65 \\ 152.27 & 245.07 & -8.60 & 60.18 & -271.20 & -120.61 \\ 77.93 & -125.42 & -11.77 & 29.65 & -120.61 & -60.63 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} -7.04 \\ -11.33 \\ -8.88 \\ -5.17 \\ -27.05 \\ -7.91 \end{bmatrix}$$

2.3.1 Check for Suitability of the Self Purification Model

This check measures the suitability of the model in predicting the self purification of the river. The model for F is of the form;

$$\widehat{F} = \frac{at^{a_1}V^{a_2}L^{a_3}}{H^{a_4}{L_A}^{a_5}} \tag{24}$$

This model indicates the relationship between the independent variables (velocity (V), depth (H), ultimate BOD (L_A) and BOD_t at time of incubation (t))and the dependent variable (self purification capacity ($\widehat{F}$)) after substituting the constants (a, a_1, a_2, a_3, a_4 and a_5). This model was statistically calibrated and validated using; Coefficient of determination (R^2) and adjusted R^2, multiple correlation coefficient (R), root mean square error (RMSE) and F-test statistic function.

3. Results and Discussion

3.1 Results

The results obtained were presented in graphical form, equation form and by words. Figure 2 shows the results obtained from the field observation, laboratory test and mathematical calculations.

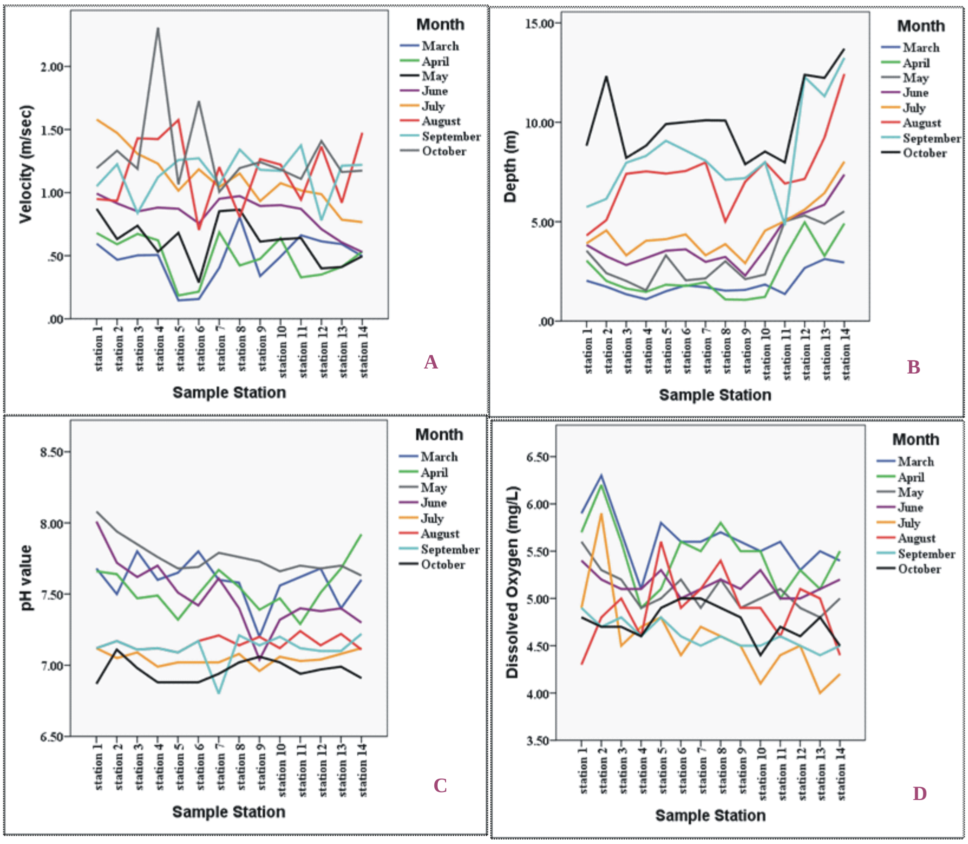

Figure 2. Concentration of Physico-Chemical parameters of River Benue water samples

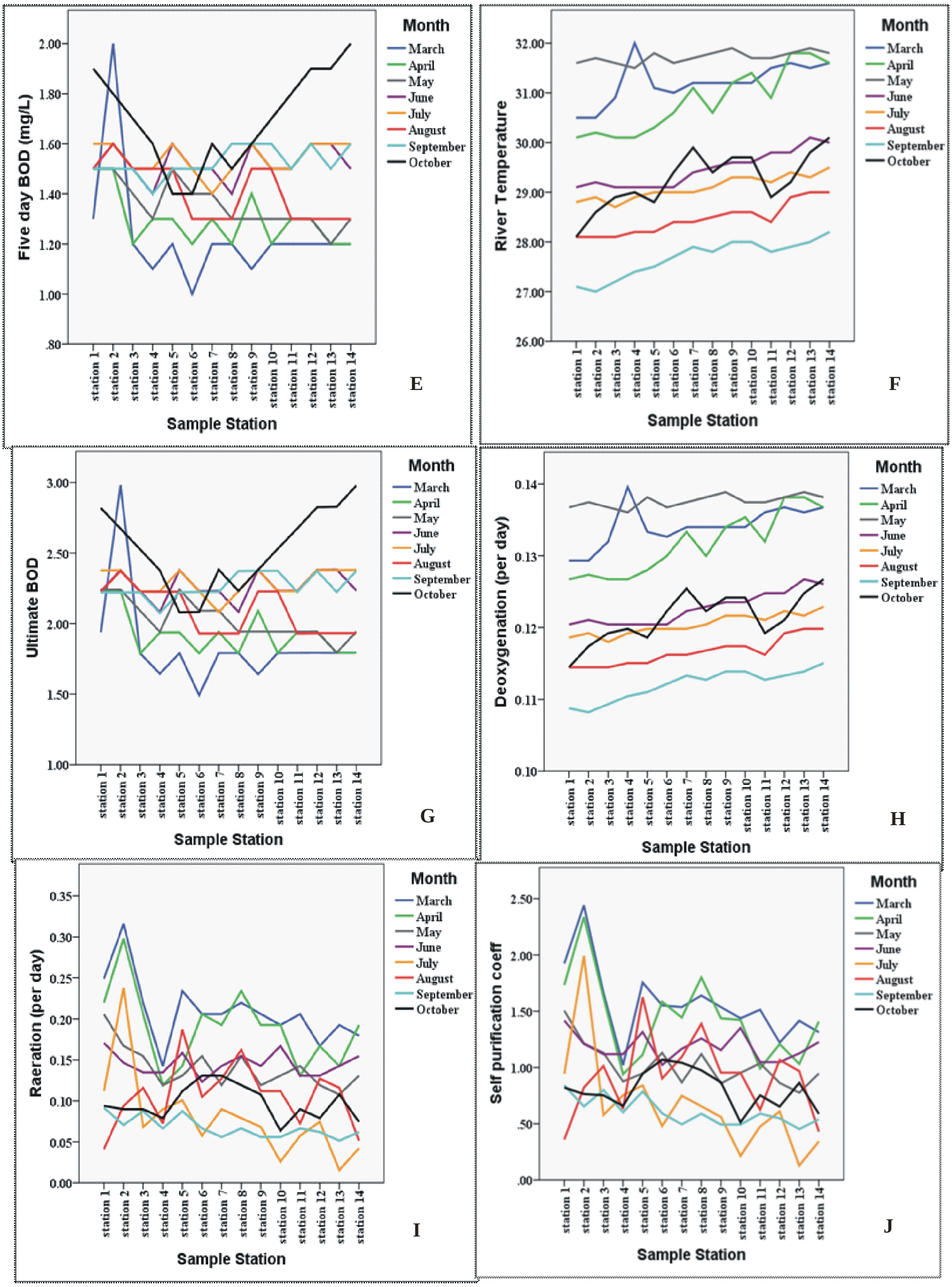

Figure 2 (continued). Concentration of Physico-Chemical parameters of River Benue water samples

3.1.1 Self Purification Model /Equation for the River

The following results were obtained from the matrix methods of operation; a_0 = 0.4472, a_1 = 0.2593, a_2 = 0.0197 and a_3 = 0.0009, a_4 = 0.2949 and a_5 = 0.651. Then a = 1.56393 (where; a= e^{a_0}).

Substituting the values of a, a_1, a_2, a_3, a_4 and a_5 in equation 9, we obtain

$$F = \frac{1.56393t^{0.2593}V^{0.0197}L^{0.0009}}{H^{0.2949}L_A{}^{0.651}} \tag{25}$$

Since the time of incubation for BOD testing was constant throughout the study, substituting t = 5 days in Equation 25 gives;

$$F = \frac{2.37389V^{0.0197}L^{0.0009}}{H^{0.2949}L_A{}^{0.651}} \tag{26}$$

3.2 Discussion

The range of DO in the dry season was between 4.7 mg/L and 6.3 mg/L with mean value of 5.36 mg/L while in the rainy season, it was between 4.0 mg/L and 5.9 mg/L with mean value of 4.8 mg/L. This is due to increased waste discharge introduced into the river by runoff. These ranges are NER (2011) compliant with a minimum of 4.0 mg/L as the lowest permissible concentration for surface waters. On the contrary, some of the values of DO in some months especially during the rainy season lies below the WHO standard of DO concentration of 5.0 mg/L. Sharma et al. (2008) reported a DO value range of 6.5–15 mg/L which is WHO compliant. Similar report by Yisa and Jimoh (2010), in the DO values ranging from 3.10 mg/L to 5.20 mg/L for River Landzu in Bida, Niger State, Nigeria. The implication is that they are all flowing rivers with oxygen recharge through surface interchange.

During dry season, minimum BOD concentration of 1.0 mg/L and maximum of 2.0 mg/L with a mean value of approximately 1.3 mg/L were recorded while during rainy season, minimum BOD was 1.3 mg/L maximum of 2.0 mg/L and mean value of 1.54 mg/L. These values are less than 3.0 mg/L which was the maximum permissible concentration stipulated by NER (2011). Gupta *et al*. (2017) reported the Effect of physicochemical and biological parameters on the quality of river water of Narmada, Madhya Pradesh, India where the minimum and maximum BOD were observed to be 0.35 mg/L and 2.18 mg/L respectively, a very close result to the present study arising from the fact that some areas of the river bank were used for waste discharge. Consequently, the BOD concentration of River Benue is NER (2011) compliant (surface waters BOD of 0 mg/L to 3.0 mg/L). Generally, the mean BOD concentration of the dry season reduces downstream while those of the rainy season increases downstream due to effluents being washed into the river by runoff especially during rainfall. This actually supported the view of Sawyer *et al*. (1994) that the effluents disposed by households and industries into the surface and ground water contaminate the quality of the water which can be assessed by BOD determination.

The flow velocity of the river increases progressively from March (peak dry season) to October (peak rainy season). This is due to increasing rainfall, increased recharge from the subsurface sources, reduced recharge to the ground water and reduced evaporation due to reduction in average daily temperature and high humidity. It was observed that the mean flow velocity in dry season is reduced compared to that of rainy season. This could be likened to the increased discharge of the tributaries and rainfall.

The mean monthly re-aeration rate of River Benue in Dry season is 0.1792 day^{-1} while that of the rainy season is 0.0995 day^{-1}. The variation is as a result of increased depth of the river and greater volume of the river water not exposed to atmospheric oxygen. This is in line with Von-Sperling (2014) observation that shallower waters have higher coefficient of re-aeration due to the ease of mixing across the depth profile, greater surface turbulence and oxygen exchange. There is also increased quantity of floating water plants covering the river surface in rainy season which reduces the surface area in contact with the atmospheric oxygen. Additionally, surface turbulence is also reduced and the ease of oxygen exchange.

The mean monthly de-oxygenation rate of River Benue in Dry season was 0.1345 day^{-1}, and 0.1186 day^{-1} in rainy season and over the study period recorded 0.1246 day^{-1}. It will be noticed that there was a reduced rate of River Benue's organic waste degradation during the rainy season than in the dry season. This could be as a result of decreased temperature, increased organic waste load being washed into the river through runoff and increased non-point discharge from various tributaries along the riverbank during the rainy season. More so, the mean monthly de-oxygenation rate decreases with increase in the mean monthly depth of River Benue which is in agreement with Yustiani *et al.* (2018) who reported the de-oxygenation rate of water of Cimanuk river in Indonesia.

The mean self purification coefficient of the river in the dry season is 1.3398 which reduced to 0.8354 in the rainy season indicating less pollution in the dry season than in the rainy season. The mean self purification coefficient of the river in the dry season is greater than 1.0 at all the stations studied. This implies that re-aeration is greater than de-oxygenation as was reported in the work of Patrick (2016) on River Kaduna in Kaduna State, Nigeria. Conversely, the mean self purification coefficient is less than 1.0 in most of the stations in the rainy season where the de-oxygenation is greater than the re-aeration as reported by Omole and Longe (2008) and Patrick (2016). Consequently, River Benue can grossly purify itself over a distance downstream as supported by Demars and Manson (2013) who stated that rivers has the capacity to purify itself. This is due to the large surface area and moderate velocity attributed to the river.

Equations 25 and 26 were able to predict the self-purification capacity of the river with coefficient of determination (R^2) value of 0.5691 and adjusted value (considering the degree of freedom due to the number of variables and dataset)of 0.5469. These values of both R^2 and adjusted R^2 were greater than 0.5 indicating that the model generated have a better fit in predicting the self-purification capacity of River Benue. The multiple correlation coefficient (R) gave the values of 0.7544 using R^2 and 0.7495 using adjusted R^2. These values were greater than 0.5 and closer to 1.0 indicating a strong positive linear relationship between the predictor variables (velocity (V), depth (H), ultimate BOD (L_A), BOD_t (L) and time of incubation (t)) and the response variable (self purification coefficient (F)).The Root Mean Squared Error was 0.2433 which is close to zero showing that the error in using the model in predicting the self purification of the river is minimal.

F-test statistic function to test the significance of the regression model was done to remove redundant variable from the model. The null hypothesis considered that any or one of the exponential constant in the model is equal to zero. It was discovered that the F-value calculated as 21.7312 was greater than the F-critical value from the F-test table (F_{crit} = 4.48, with a probability function of 0.001). Therefore, the null hypothesis was rejected. This portrays that all the predictor variables are relevant in estimating the response variable.

Consequently, the empirical model generated for predicting the self purification of the river is with high degree of accuracy.The observed concordance between the model and the experimental data is due to the fact that the kinetic coefficients of de-oxygenation (K1) and re-aeration (K2) were obtained from the observed field data and used as calibration parameters.

4. Conclusion

It is noteworthy that an increased velocity and depth affects the re-aeration of River Benue resulting in reducing the self purification potential of the river. The mean self-purification potential of River Benue was found to be greater than 1.0 indicating the re-aeration was more than de-oxygenation rate. An empirical model has been generated for self purification of River Benue which was statistically validated.

It is recommended that the model from this study should form bases and guide for further future models of River Benue.

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