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Re-aeration Coefficient Modeling: A Case Study of River Atuwara in Nigeria

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Abstract: A study of the self purification capacity of River Atuwara was done with the aim of developing a reaeration coefficient model, k_2, for the river. The k_2 model was evaluated and validated by comparing its performance with the Streeter-Phelps and Agunwamba models. Atuwara model was developed using non-linear regression while its performance was checked by the use of statistical and graphical parameters. The model gave the best dissolved oxygen predictive capacity in comparison with other models when used with the modified Streeter-Phelps equation in spite of the limitations imposed on it by the sinusoidal shape of the dissolved oxygen recovery curve caused by frequent interruptions in the recovery processes of the river system. It is also of note that due to its importance to human and aquatic life sustenance, the natural recovery processes of River Atuwara from frequent pollution loads could only be enhanced through an effective monitoring and regulation of effluent discharges into it by the Ogun State Environmental Protection Agency.

Key words: Dissolved oxygen, model, non-linear regression, Ota, re-aeration coefficient, river system

INTRODUCTION

Re-aeration coefficient modeling is an integral part of water quality modeling which is a scientific tool employed to predict and monitor pollutant loads and nutrient constituents in fresh water bodies for effective resource planning and management (Longe and Omole, 2008). This field of study pioneered by Streeter and Phelps (1925) through their study on the recovery dynamics of River Ohio from pollution, has since become an interesting research area in water quality among scientists world over (Streeter and Phelps, 1925; Streeter *et al.*, 1936; Villeneuve *et al.*, 1998). The principles of Streeter and Phelps had been widely applied to water quality studies across the globe for examples: in England (Owens *et al.*, 1964), Chile (Baecheler and Lazo, 1999) and India (Jha *et al.*, 2001).

Surface water is an important natural resource in Nigeria. The total surface area of inland water bodies in Nigeria, excluding deltas, estuaries and miscellaneous wetlands, is estimated to be 149, 919 km^2 constituting about 15.9% of the total area of the country (Kuruk, 2005). The total surface water resources potential in the country is estimated at 267.3 billion cubic metres. This vast resource serves the purposes of inland navigation, irrigation, hydropower, aquaculture, domestic water supply, recreation and sand quarry among others. Equally, most major surface water bodies in the country serve as sinks for both domestic and industrial effluents discharges (World Bank, 1995; Omole and Longe, 2008; Longe and Omole, 2008; Omole and Isiorho, 2008; Longe and Ogunlana, 2010; Omole, 2011). This situation has resulted in serious surface and groundwater pollution especially in major cities like Lagos, Kaduna, Port-Harcourt and Ota thereby constituting a threat to public health (World Bank, 1995).

The current study investigated the response of River Atuwara to the deoxygenation and reaeration processes occasioned by pollution activities during the two existing climatic seasons (wet and dry) in the country. The study also aimed at the development and validation of re-aeration coefficient (k_2) for Atuwara River

MATERIALS AND METHODS

The study area: The experimental phase of the current study was carried out on River Atuwara which is located in Ota, Ogun State, Nigeria (Fig. 1 and 2). River Atuwara is a perennial water body that runs through the heavily populated Ota town. Ota town hosts major industrial estates in Ogun State whereby the river is constantly subjected to both point and non-point sources of domestic and industrial effluents. The river equally attracts a number of economic activities such as fishing and sand mining. Villages and settlements along the river course rely on it for their domestic water supply. In addition, the

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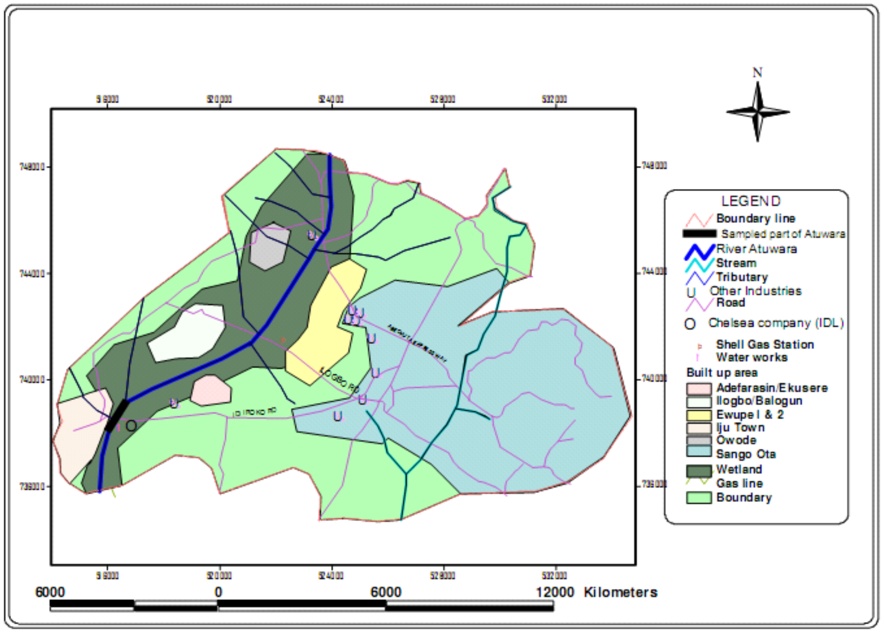

Fig. 1: The map of Ado-Odo Ota LGA showing river Atuwara

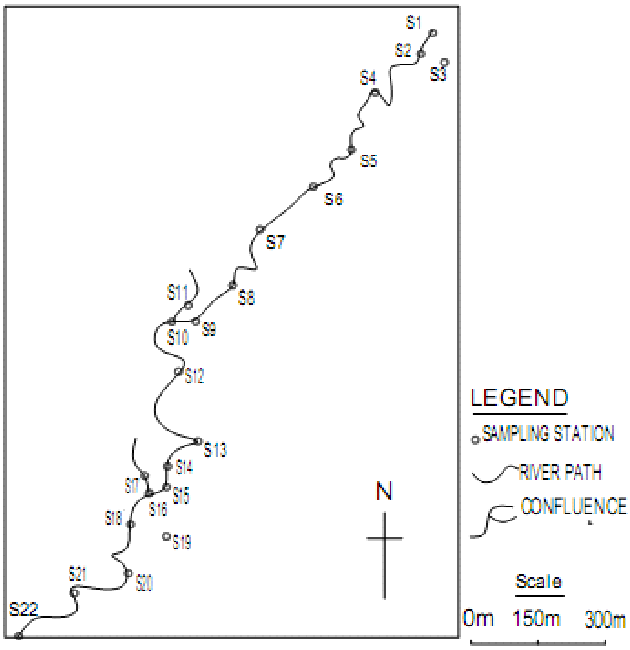

Fig. 2: The sampling stations on river Atuwara

Ogun State Water Corporation also draws raw water from Atuwara River for public water supply to Ota town through an intake station located along its course.

Field sampling and laboratory analysis: Twenty two (22) sampling stations were chosen along the river course based on locations of interest rather than equidistance. The locations are labeled S1 to S22 (Fig. 2). S1 is 30m upstream of a distillery effluent discharge point into the river. S2 is the point of effluent discharge into the river; this point is chosen as 0 m distance while S3 is a pool of raw effluent yet to be mixed with the river. Other locations of interest are S9, which is a point 10 m before the confluence of River Atuwara and River Balogun. S10 is the confluence itself and S11 is a location on River Balogun. Another location (S13) is point of sand dredging activities. A second confluence of River Atuwara and an unidentified stream is further downstream with sampling stations S15 to S17. S19 is raw water intake point by Ogun State Water Corporation, while S22 is point of water withdrawal for domestic purposes by the villagers.

For the purpose of computation of mixing regions, the river segment was divided into three reaches. Reach 1 consists of sampling stations, S2 - S10. Reach 2 consists of sampling stations comprising S10 to S16 while reach 3 is comprised of sampling stations S16 to S22. For the purpose of the current study 17 sampling stations were considered while sampling stations S3, S11, S17 and S19 that do not fall within the river's path were not taken into consideration. S1 is equally excluded since it did not fall within the polluted region under consideration. A complete set of 22 water samples were obtained at mid-depth from each of the sampling stations in July 2009 and January 2010. Samplings were carried out each month taking into consideration the inter station times of travel. In July (wet season), sampling was carried out within 72 hours of a storm event. The time lapse was required to mobilize the ad-hoc field workers for sampling exercises. A bathymetric survey was carried out in order to describe the river configuration, while hydraulic parameters of river were measured with different portable equipments. The stream velocity was measured with Geopacks stream flow sensor and measurements were carried out in all the sampling stations. Water depth was taken at three points along each river cross section using Speedtech Portable Depth Sounder, the ambient and water temperature data were obtained using a Eurolab Digital Thermometer while water pH was measured using a handheld pH meter. The total distance of the segment and the global position for each sampling station was obtained with the aid of a Garmin Etrex Handheld GPS unit.

All water samples were analyzed for DO and BOD_5 using titrimetric method (Azide Modification). Water samples for BOD_5 analysis were stored in a series cooled Gallenkamp incubator at a controlled temperature of 20°C. All obtained data was analyzed using statistical tools. Non-linear regression analysis was performed using Matlab 7.0 software in order to develop a re-aeration coefficient, k_2 model for the study area. Its suitability for Ota environment was checked by comparing its relative DO predictive capacity two other models:- Agunwamba *et al.* (2007) and Streeter *et al.* (1936). Agunwamba *et al.* (2007) model was developed in the creeks of Port-Harcourt, southern Nigeria. The data for model development was acquired during the rainy season. The choice of Agunwamba *et al.* (2007) model for the purpose of comparison with Atuwara model was based on the similarity in sampling conditions and pollution sources while the choice of Streeter *et al.* (1936) model was based on its wide citation and application.

Theoretical concept: Dissolved Oxygen (DO) levels of surface water bodies normally drop after pollution discharges while their recovery depend on a number of intervening factors such as dilution factor and rate of re-aeration process in the water bodies. Usually, the biodegradable wastes use up the DO content of the surface water in the recovery process. The pollution load in a river body could be measured in terms of Biochemical Oxygen Demand (BOD). The BOD value gives an indication of the level of DO required to breakdown a specific waste load and the higher the load, the higher the BOD value (Weiner, 2003). From pioneering work of Streeter and Phelps (1925), a predictive model for river Ohio was proposed:

$$\frac{dD(t)}{dt} = k_1 L(t) - k_2 D(t) \tag{1}$$

where, D = Dissolved Oxygen deficit, L = Ultimate first stage BOD of mix at the point of discharge in mg/L, BOD, k_1 = deoxygenation coefficient and k_2 = re-aeration coefficient, t = time in days. The deoxygenation coefficient k_1 is dependent on the waste characteristics alone, while the re-aeration coefficient k_2, is dependent on such factors as stream velocity, stream depth and water temperature. Hence, there is need to model for k_2 differently and this could be achieved by data gathering on such parameters as dissolved oxygen, stream velocity, water depth and temperature. From this a k_2 model for a specific environment is calculated from experimental results using Eq. (2) (Agunwamba *et al.,* 2007):

$$k_2 = \frac{(\log_{10} D_u - \log_{10} D_d)}{t} \tag{2}$$

where, D_u = initial DO deficit at the upstream and D_d = DO deficit at any downstream point, t = time of travel between any two points.

A non-linear regression analysis could be used to find the relationship between the calculated values of k_2, the stream velocity and stream depth by obtaining the constants of the relationship which are also known as the coefficients of regression, β_1 , β_2, β_3 using Eq. (3):

$$k_2 = \beta_1 \frac{V^{\beta_2}}{R^{\beta_3}} \tag{3}$$

where, V = stream flow velocity and R = Hydraulic Radius. Stream flow velocity and depth are the regressors, k_2 is the dependent variable. These coefficients of regression are the factors that change and define the different systems in different geographical environments.

Following the calibration of the k_2 model, a linear regression analysis of the measured k_2 and the modeled k_2 is performed. This is obtained by plotting the scatter plot of k_2 (measured) and k_2 (computed), a relationship that is defined by Eq. (4):

$$y = \beta_o + \beta_1 x + e \tag{4}$$

From Eq. (4), y is the modeled k_2 and also the dependent variable, while the regressor or predictor, x is the measured k_2 and e is the error term (Montgomery and Runger, 2003). β_o and β_1 in this linear regression process is the intercept and slope respectively and are also known as the unknown regression coefficients (Chatterjee and Hadi, 2006). The linear regression of the measured and computed k_2 values help to obtain and compare the performance of different developed k_2 models in quantitative terms such as regression sum of squares (SSE), standard deviation, root mean squared error (RMSE) and coefficient of determination, R^2.

The re-aeration coefficient proposed by Streeter *et al.* (1936) is defined thus:

$$k_2 = 5.026 \frac{U^{0.969}}{H^{1.673}} \tag{5}$$

Equation (5) is also known as the USGS (United States Geological Survey) equation (USEPA, 1995). In Nigeria, Agunwamba *et al.* (2007), working on the Amadi Creek, proposed a k_2 defined by Eq. (6):

$$k_2 = \frac{11.6325 U^{1.0954}}{R^{0.0016}} \tag{6}$$

The importance of k_2 models is their use within the modified Streeter-Phelps equation which is defined by Eq. (7) (Fair *et al.*, 1971; Longe and Omole, 2008; Omole, 2011), which could be used to predict the DO deficit along a stream:

$$D = \frac{L_a}{f-1} 10^{-k_2 t} \left\{ 1 - 10^{[-(f-1)k_2 t]} \left[1 - (f-1)\frac{D_a}{L_a} \right] \right\} \tag{7}$$

From Eq. (7), D = predicted DO deficit along the curve of recovery, L_a = Ultimate first stage BOD of mix at the point of discharge in mg/L; D_a = Initial dissolved oxygen deficit of the mix at the mixing point in mg/L; k_1 = Deoxygenation coefficient for the effluent which can be considered as equal to the BOD rate constant which is determined in the laboratory; k_2 = Reoxygenation coefficient for the stream; t = Time; f = Self-purification factor, The self-purification factor is further defined by Eq. (8):

$$f = \frac{k_2}{k_1} \tag{8}$$

RESULTS AND DISCUSSION

Atuwara model: Atuwara model Eq. (9) was developped using the data obtained through the process described in section 2.0 and the non-linear regression analysis of data using the statistics toolbox in Matlab 7.0 environment:

$$k_2 = 46.2679 \frac{U^{1.5463}}{H^{0.0128}} \tag{9}$$

Following the non-linear regression analysis, the model output passed with the following statistics: error sum of squares, SSE = 9.343; Coefficient of determination, R^2 = 0.9524; Adjusted Coefficient of determination, R^2 = 0.9048 and a root mean square error (standard error of regression), RMSE = 1.528.

The model was subsequently verified by comparing its performance with the model proposed by Agunwamba *et al.* (2007). The performance check was done by carrying out a linear regression between the modelled and computed k_2 values for each model using independent data.

The statistical parameters used in the performance check include variance (standard error), σ^2; sum of squares of regression, SSR; coefficient of determination, R^2; Adjusted coefficient of determination, Adj. R^2 and root mean square error, RMSE. The results are presented in Table 1.

The statistical results (Table 1) reveal that in the dry season, Agunwamba model had optimum statistical output, Streeter model had minimum statistical output and Atuwara model performed averagely. In the wet season, Streeter model performed optimally, Atuwara model performed minimally and Agunwamba *et al.* (2007) model had the average performance.

Furthermore, the predictive capacity of the three different k_2 models, namely Atuwara, Agunwamba and

Table 1: Statistical goodness of fit

Statistical parameter	January data Atuwara	Agunwamba *et al.* (2007)	Streeter *et al.* (1936)	July data Atuwara	Agunwamba *et al.* (2007)	Streeter *et al.* (1936)
$\hat{\sigma}^2$	8.619	1.105	50.620	322.929	16.638	0.750
SSR =	22.282	2.118	70.900	4.050	0.376	0.090
R^2 =	0.147	0.113	0.090	0.001	0.002	0.010
RMSE =	2.936	1.051	7.120	17.970	4.079	0.870
Adj. R^2 =	0.090	0.054	0.020	-0.066	-0.065	-0.060

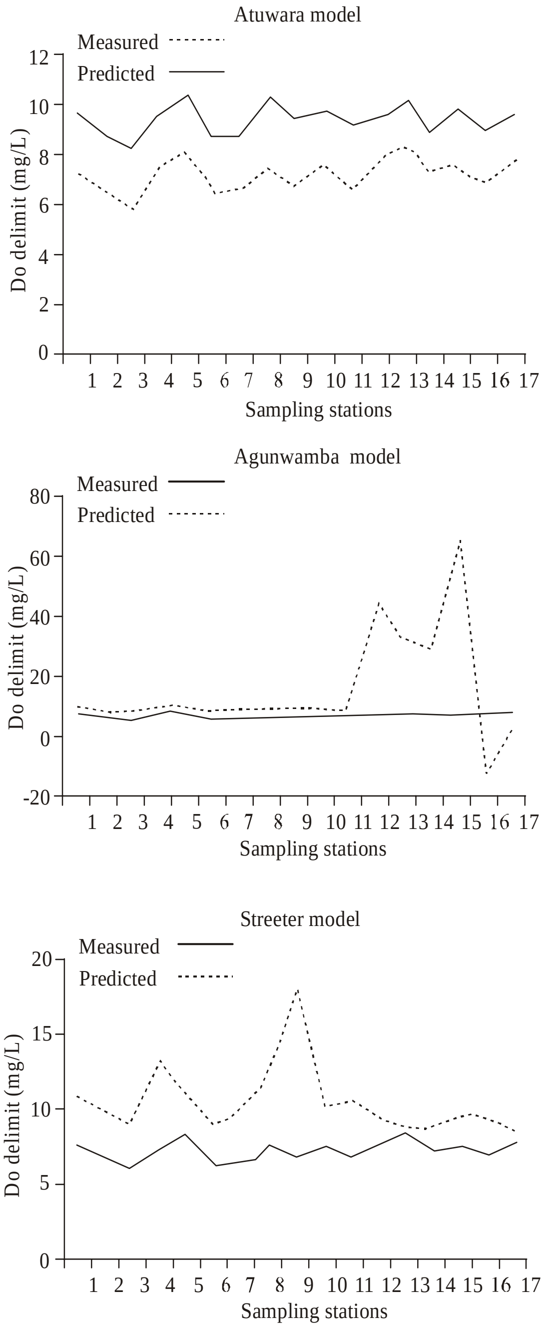

Fig. 3: DO deficit plot against sampling stations using the modified Streeter-Phelps equation (January data)

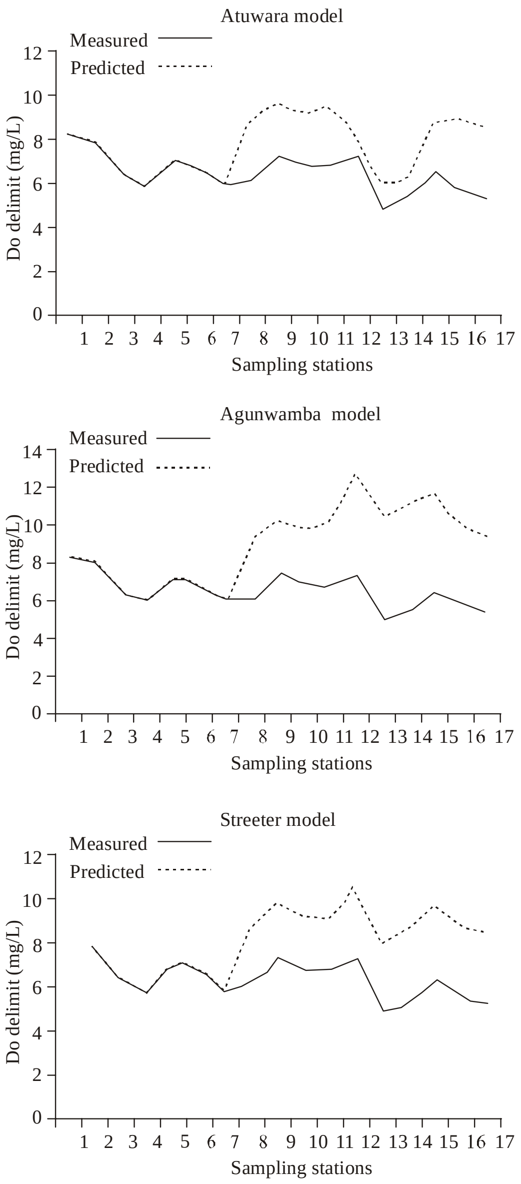

Fig. 4: DO deficit plot against sampling stations using the modified Streeter-Phelps equation (July data)

Streeter were tested by inserting them into Eq. (7). The resulting measured DO plots reveal sinusoidal shapes rather than the expected exponential curve shape. This trend is attributed to frequent interruptions in the river recovery system from pollution discharges and this makes prediction a difficult task. The stacked line plots of the measured and predicted DO along the stream path are as shown in Fig. 3 and 4. The choice of stacked line plot over the trend line plot is born from the fact that a trend line chart distributes category data evenly along the horizontal category axis (Simon, 2000). In reality however, distance (which is represented in the horizontal category axis) is not evenly distributed.

The plots demonstrate that in the dry season, Atuwara model performed optimally, Agunwamba model performed minimally and Streeter model performed averagely when in use with the modified Streeter-Phelps equation Eq. (7) for the prediction of DO deficit (Fig. 3). In the wet season, however, the three models displayed a marked similarity between the measured DO deficit and the predicted DO deficit.

CONCLUSION

The development and validation of Atuwara model has been carried out. Its relative predictive capacity was also established by comparing it with Agunwamba and Streeter models. The results reveal a slight disparity between the statistical performance of the models and their predictive capacity. However, the aim of model development is predictability and Atuwara model performed better in this regard. Atuwara model is therefore recommended for application in future re-aeration studies on River Atuwara and environ.

River Atuwara, like other surface water bodies in Nigeria, is very important for multi usage activities ranging from domestic water supply, agricultural services, fishing to waste disposal. As a sink, the river is subjected to potential contamination from domestic and industrial pollutions. There is a need to preserve the resource by introducing regulations informed through research findings such as the current study. The observed fluctuations in the measured DO deficit as against the expected spoon-shaped graph of a normal DO deficit recovery graph (Fig. 3 and 4) point to the disturbance in the recovery process of the river system. This is best explained by the existence of pollution point sources at intervals along the river path which thus slow down the process of natural recovery system of the river. Despite the size of the river, this observed situation also impinges on the natural purification capacity of the river body. The observed frequent fluctuations in DO deficit make the predictive capacity of k_2 model very difficult since the modified Streeter-Phelps equation was designed for exponential DO recovery shapes and not for sinusoidal curves.

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