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WRM Development for Nworie River using Galerkin's Weighted Residual (GWR) Finite Element Model

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ABSTRACT

The increase of oxygen deficit in rivers used for irrigating agricultural land, aquaculture and domestic purposes is of great concern to Nigerian watershed. To determine this effect along the Nworie river, suntex model TS-2 and Hanna HIDR 83200 for physicochemical and biological water quality analysis was conducted at three random locations namely: Amakohia bridge road where biodegradable and non biodegradable wastes are discharged; Assumpta, Holy Ghost college road where municipal waste and sewage are discharged into the river; and Umezurike Hospital road where household and medical wastes are discharged. Development of the Watershed Resources Management (WRM) for the river resulted in application of Galerkin's weighted residual (GWR) finite element model from the lab experimented results to determine the oxygen deficits at discharged nodes (points). The oxygen deficit results at the five discretized nodes were: 2.528, 2.498, 2.395, 2.325 and 2.252mg/l respectively. The result in this research could be applied to watershed resources management for irrigation and public health engineers in predicting the effects of water pollution on downstream users, with minimally associated errors.

1.0 Introduction

It is increasingly being recognized that the issues of wastewater management and water quality have cross-linkages with a range of other water- and non-water issues, not least in respect of the water, energy and food nexus. Organization for Economic Co-operation and Development (OECD, 2012) acknowledged that wastewater management clearly plays a role in achieving future water security in part of the world where water stress had been in the increase. Little wonder when the time frame for the Millennium Development Goals (MDG) nears completion, minds are turning to the post-2015 development agenda. This is accompanied by the realization that the focus on drinking-water and sanitation without due attention being paid to the end products of water and sanitation provision (i.e. wastewater) may have exacerbated some of the water quality problems seen globally. it is therefore crucial that wastewater management and water quality stop being the 'poor relations' and receive attention in their own right. According to the UNEP/UNHABITAT document, waste water is referred to as "Sick Water". Thus, wastewater is defined by Corcoran et al., (2010) as "a combination of one or more of:

a) domestic effluent, consisting of black water (excreta, urine and faecal sludge) and greywater (kitchen and bathing wastewater);

b) water from commercial establishments and institutions, including hospitals;

c) industrial effluent, storm water and other urban run-off;

d) agricultural, horticultural and aquaculture effluent, either dissolved or as suspended matter"

These definitions clearly described the nature of Nworie River in owerri today. The city around Nworie River that is Owerri and its environs has experienced immense population, agricultural and industrial growth since it became the capital of Imo state in 1976. This growing population and industrial activities have caused, and will continue to cause, great stresses on water resources in the area (Ibe and Njemanze, 1998).

Okore, *et al*., (2014) investigated the Impact of disposal of hospital waste into Nworie River in Imo State Nigeria. It was discovered from the research that hospital wastes pose severe effects on the environment and health of the surrounding neighborhood, and to agricultural users who make use of it for irrigation and for aquaculture downstream.

Wastewater discharge from sewage and industries are major component of water pollution, contributing to oxygen demand and nutrient loading of the water bodies, promoting toxic algal blooms and leading to a destabilized aquatic ecosystem (Okereke *et al*., 1998; Morrison *et al*., 2010). However, with these challenges enumerated, there is need to determined the level of BOD and dissolved oxygen in the stream from the point of effluent discharge to the downstream along the River. Thus, the aim of this paper is to determine the physiochemical and biological parameters of the river and using one of these parameters at the point of discharge to determine the effects downstream by applying Galerkin's weighted residual finite element method.

2.0 Materials and Methods

2.1 Area of Study

From geographical area survey of the Nworie River in Figure 2, it is shown to be a first order stream that runs about a 5km course across Owerri metropolis in Imo State, Nigeria, before emptying into Otamiri River (Umunnakwe, *et al*., 2011). Its watershed is subjected to intensive human and industrial activities resulting in the discharge of a wide range of

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pollutants. The River is used for various domestic applications by inhabitants of Owerri (Acholonu, et al., 2008).

Figure 2. Area Survey of Nworie Stream Source: Google Earth

When the public water supply fails, the River further serves as a source of direct drinking water, especially for the poorer segment of the city. Owerri, the capital of Imo State of Nigeria lies between 4^0 55'N and 5^0 35'N, and between 6^0 35'E and $7^0$30'E parallels. It falls within the rainforest zone of 2290mm per annum, relative humidity of 55-85% and temperature of 27^0C.

2.2 Sample Collection and Procedure

A reconnaissance visit to the river was carried out after which three sample stations were established. The essence of carrying out these three sampling at the different stations along the stretch of the river was for achieving comparative studies. The first Station was taken to be Amakohia bridge road where biodegradable and non-biodegradable wastes are discharged. Station two is the Assumpta, Holy Ghost college road where municipal waste and sewage are discharged into the river. Station three is at Umezurike Hospital road where household and medical wastes are discharged. Samples of water were collected in 4 litre gallon container from these stations during the rainy season in the month of June. These samples were labeled, packed inside an ice cooled container and transported to Federal University of Technology, Owerri (FUTO) and Imo State University (IMSU) laboratories for analysis. Standard analytical methods (UNEP 2000; UNEP 2010; and UNEP 2011) were used for the entire physicochemical and biological test.

3.0 Physicochemical and Biological Test

Insitu measurements of pH, temperature and conductivity for water were taken in the field during sampling and recorded with pH meter (Suntex model TS-2). Laboratory analysis were further carried out with the use of multiparameter bench photometer (Hanna HIDR 83200), approved standard measurement.

3.1 Analysis of Data/Results

3.1.1 Analysis of Data

Statistical tools such as mean, standard deviation and variance were used to analyze the data obtained to ascertain how representative and close, the data obtained were. Two-way analysis of variance used showed the significant difference between the samples and the stations.

The general approach for the development of WRM model using GWR finite element for the determination of oxygen deficit level along the River are given below:

$$\int_0^L \left(\Psi \frac{d^2Q}{dx^2} + \Psi F \right) dx = 0 \qquad (1)$$

This equation can be written or expressed as

$$\int_R (\text{Basic function})^T (\text{Residual})\, dR = 0$$

where, R = region of interest or domain, dR = derivative of R and T = transpose (in matrix sense). For one dimensional model. Likewise

$$\int_R N_k^{e^T} \left(\frac{d^2\phi}{dx^2} + F \right) dx = 0 \qquad (2)$$

where,

$N_k^{e^T}$ = transpose of the weighing function

$\left(\begin{array}{c} \text{same as the transpose of the basis function for} \\ \text{element, e and node, k} \end{array} \right)$

F = constant; ϕ = field variable;

e = element number; and T = transpose

The dissolved-oxygen model of the Nworie stream originally from Streeter and Phelps, predicted changes in the deficit, D, as a function of Biological Oxygen Demand (BOD) exertion and stream reparation. The rate of change in the deficit was given as:

$$\frac{dD}{dt} = K_1 L_t - K_2 D \qquad (3)$$

$$\frac{dD}{dt} + K_2 D - K_1 L_t = 0, \qquad D(0) = D_0 \qquad (4)$$

The application of the Galerkin's weighted residual finite element method in Equation (4) yields:

$$\int_0^L N^T \left(\frac{dD}{dt} + K_2 D - K_1 L_t \right) dt = 0 \qquad (5)$$

$$\int_0^L N^T \left(\frac{dD}{dt} \right) dt + \int_0^L N^T (K_2 D)\, dt - \int_0^L N^T (K_1 L_t)\, dt = 0 \qquad (6)$$

where, the upper limit of the integration, L stands for length of an element and N^T is the transpose of the basis function. Thus, evaluating the individual terms of Equation (6) using linear interpolation (basis) function results as follows:

1st term of Equation (4)

$$\int_0^L N^T \left(\frac{dD}{dt} \right) dt \qquad (7)$$

The linear basis function becomes:

$$D = [N]\{D_i\} = \left[\left(1 - \frac{t}{L}\right) \quad \frac{t}{L} \right] . \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix};$$

and

$$\frac{dD}{dt} = \frac{1}{L} [-1 \quad 1] \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} \qquad (8)$$

where, D is the continuous variable and D_i is the piecewise continuous equivalent.

Substituting the linear basis function as approximate in Equation (8) gives:

$$\int_0^L N^T \left(\frac{dD}{dt} \right) dt \qquad (9)$$

$$= \int_0^L \begin{pmatrix} 1-\frac{t}{L} \\ \frac{t}{L} \end{pmatrix} \frac{1}{L} \begin{bmatrix} -1 & 1 \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} .\, dt \tag{10}$$

$$= \int_0^L \begin{bmatrix} -\left(1-\frac{t}{L}\right) & \left(1-\frac{t}{L}\right) \\ -\frac{t}{L} & \frac{t}{L} \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} .\, dt \tag{11}$$

$$= \frac{1}{2} \begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix}$$

2nd term of Equation (6)

$$\int_0^L N^T (K_2 D)\, dt = K_2 \int_0^L N^T D .\, dt \tag{12}$$

$$= K_2 \int_0^L \begin{Bmatrix} 1-\frac{t}{L} \\ \frac{t}{L} \end{Bmatrix} \begin{bmatrix} \left(1-\frac{t}{L}\right) & \frac{t}{L} \end{bmatrix} . \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} .\, dt \tag{13}$$

$$= K_2 \int_0^L \begin{bmatrix} \left(1-\frac{2t}{L}+\frac{t^2}{L^2}\right) & \left(\frac{t}{L}-\frac{t^2}{L^2}\right) \\ \left(\frac{t}{L}-\frac{t^2}{L^2}\right) & \frac{t^2}{L^2} \end{bmatrix} . \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} .\, dt \tag{14}$$

$$= \frac{LK_2}{6} \int_0^L \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} . \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} .$$

3rd term of Equation (6)

$$\int_0^L N^T (K_1 L_t)\, dt = K_1 L_t \int_0^L N^T\, dt \tag{15}$$

$$K_1 L_t \int_0^L N^T\, dt = K_1 L_t \int_0^L \begin{bmatrix} 1-\frac{t}{L} \\ \frac{t}{L} \end{bmatrix} dt \tag{16}$$

$$= \frac{L_t K_1 L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}$$

Combining the 1st, 2nd and 3rd terms of Equation (6) gives the element equation:

$$\frac{1}{2} \begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} + \frac{LK_2}{6} \int_0^L \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} . \begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} = \frac{L_t K_1 L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \tag{17}$$

Assemblage of Equation (17) as carried out with selected distance discretized along the stretch of the river from the point of discharge is shown in Figure 1and Equation (18) respectively.

t =	0	____	1/4	____	1/2	____	3/4	____	1.0
Node =	1		2		3		4		5

Figure 1. Discretized nodal river discharge

$$\frac{1}{2} \begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \end{Bmatrix} + \frac{LK_2}{6} \begin{bmatrix} 2 & 1 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 \\ 0 & 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 1 & 2 \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \end{Bmatrix}$$

$$-\frac{K_1 L}{2} \begin{Bmatrix} L_t \\ L_t + L_{2t} \\ L_{it} + L_{(i+1)t} \\ L_{(i+1)t} + L_{(i+2)t} \\ L_{(n-1)t} \end{Bmatrix} = 0 \tag{18}$$

where,

L= length of an element, t = time and $L_t = L_0 e^{-k_1 t}$

$L_{(i+1)t} = L_0 e^{-k_1 (i+1)t}$

Expanding Equation (18) to arrive at first two, interior, and the last two nodes respectively, using Gaussian elimination technique without matrix reduction yielded these nodal equations:

1st two nodal Equations

$$\left(-\frac{1}{2}+\frac{LK_2}{3}\right) D_1 + \left(\frac{1}{2}+\frac{LK_2}{6}\right) D_2 = \frac{K_1 L}{2} . L_t \tag{19}$$

Interior nodal Equation

$$\left(-\frac{1}{2}+\frac{LK_2}{6}\right) D_i + \left(\frac{2LK_2}{3}\right) D_{i+1} + \left(\frac{1}{2}+\frac{LK_2}{6}\right) D_{i+2}$$

$$= \frac{K_1 L}{2} . (L_{it} + L_{(i+1)t} \tag{20}$$

where, i assumes the values of 1, 2, 3, etc for the 1st, 2nd and 3rd rows of the interior nodes.

Last two nodal Equations

$$\left(-\frac{1}{2}+\frac{LK_2}{6}\right) D_{n-1} + \left(\frac{1}{2}+\frac{LK_2}{3}\right) D_n = \frac{K_1 L}{2} . L_{(n-1)t} \tag{21}$$

Oxygen deficit (D) = (DO saturation – DO actual). However, the DO saturation value for fresh water depends upon the temperature and total dissolved salts present. The value varies from 14.62 mg/l at 0^o C to 7.63 mg/l at 30^o C, and lower DO at higher temperatures. The relationship between DO saturation (DOS) and temperature of the stream is given as:

$$\frac{0-30}{T-30} = \frac{14.62-7.63}{DOS-7.63} \tag{22}$$

Therefore, using the data from Table 1 of the physicochemical and biological analysis of the Nworie River, recorded temperature at the point of discharge of the waste water as 24^oC; BOD 3.30mg/l; actual DO 6.5 mg/l; deoxygenation constant 0.26; and reaeration constant K_2 0.42. Considering DOS and oxygen deficit (D) gave:

$$\therefore \frac{0-30}{24-30} = \frac{14.62-7.63}{DOS-7.63},$$

$$\therefore S.DO = 9.028 mg/l$$

Thus, oxygen deficit 'D' at that point = (DO Saturation – Actual DO)

$$= (9.028 - 6.5) mg/l = 2.528 mg/l$$

Table 1. Physicochemical and biological results of Nworie water analysis

Parameter	WHO Standard	Mean	Range	Amakohia bridge road	Assumpta, Holy Ghost college road	Umezurike Hospital road	Standard Deviation
pH	6.5-8.5	7.133	7.1-7.3	7.1	7.0	7.3	0.0694
Alkalinity (mg/l)	200	10	5-15	15.0	10.0	5.0	5.0
Temperature	ambient	24.67	24-25	24.0	25.0	25.0	0.577
Colour of Water in PCU	500	568.67	431-640	431	640	635	119.249
Conductivity (μs/cm)	100	111.3	60.5-141	60.5	141.0	132.50	44.23
TSD(mg/l)	250	53.667	40-73	40	48	73	17.21434
turbidity NTU	50	114.833	5-65	63.50	146.30	134.70	44.83273
BOD(mg/l	40	3.233	2.9-3.5	3.30	3.50	2.90	0.305505
DO(mg/l)	4.0	5.9	5.4-6.5	6.50	5.80	5.40	0.556776
TSS (mg/l)	50	262.667	85-368	85	368	335	154.746
Nitrate(mg/l)	40	348.418	259.15-520.30	265.8	520.30	259.155	148.891
Nitrite (mg/l)	1.0	5.269	3.04-6.384	6.384	6.384	3.04	1.931
Sulphate (mg/l)	250	5.6	1.8-10	1.8	10	5	4.133
Hardness (mg/l)	150	53.667	39.5-64.2	39.50	57.30	64.20	12.74454
Iron(Fe)(mg/l)	0.3	0.1967	0.12-0.25	0.22	0.12	0.25	0.0681
Manganese mg/l	0.5	0.5	0.2-0.8	0.2	0.5	0.8	0.3
Calcium mg/l	70	90	80-100	100	90	80	10
Zinc mg/l	5	0.5533		0.55	0.43	0.68	0.12503
Copper mg/l	1.0	0.3333	0.2-0.5	0.2	0.3	0.5	0.152753
Chlorine (mg/l)	200	11.23333	9-11.5	9	13.2	11.5	2.11266

From the linear element at the first node $D_1 = D = 2.528$mg/l, while L_t at node 2, time (t) at the respective nodes gave:

$$L_t = L_0 e^{-k_1 t} = 3.30e^{-0.26(0.25)} = 3.09232$$

Evaluating Equation (19) gave D_2:

$$\left(-\frac{1}{2}+\frac{LK_2}{3}\right)D_1 + \left(\frac{1}{2}+\frac{LK_2}{6}\right)D_2 = \frac{K_1 L}{2}.L_t$$

$$\text{where } L = \frac{1}{4} = 0.25$$

$$\left(-\frac{1}{2}+\frac{0.25\,(0.42)}{3}\right)2.528 + \left(\frac{1}{2}+\frac{0.25\,(0.42)}{6}\right)D_2 = \frac{0.25\,(0.26)}{2}.3.09232$$

$$D_2 = \frac{1.2760}{0.51083} = 2.49789$$

For the 1st interior nodes (1, 2 and 3), Equation (20) was evaluated as:

$$\left(-\frac{1}{2}+\frac{LK_2}{6}\right)D_i + \left(\frac{2LK_2}{3}\right)D_{i+1} + \left(\frac{1}{2}+\frac{LK_2}{6}\right)D_{i+2} = \frac{K_1 L}{2}.(L_{it} + L_{(i+1)t}$$

Where i = 1 and the term $(L_{it} + L_{(i+1)t}$ on the right hand side equals:

$$(L_t + L_{2t} = L_0\left(e^{-k_1 t} + e^{-k_1 2t}\right) \quad (23)$$

$$= 3.3(e^{-0.26(0.25)} + e^{-0.26(0.5)}) = 5.990061$$

Substituting the values of D_1 and D_2 into Equation (20) gives:

$$\left(-\frac{1}{2}+\frac{0.25\,(0.42)}{6}\right)*2.528 + \left(\frac{2(0.25)(0.42)}{3}\right)2.49789 + \left(\frac{1}{2}+\frac{(0.25)(0.42)}{6}\right)*D_3 = \frac{0.25\,(0.26)}{2}*5.99$$

$$= -0.4825(2.528) + 0.07(2.498) + (0.5175)D_3 = 0.19468$$

$$\therefore D_3 = \frac{1.23959}{0.5175} = 2.3953$$

For the last two nodes in Equation (21) is evaluated where i = 4, 5 and the term $L_{(n-1)t}$ for n = 4

$$L_{(n-1)t} = L_{(4-1)t} = L_{3t} = L_0(e^{-k_1 3t} = 3.3e^{-0.26(0.75)}) = 3.3(0.82283)$$

$$= 2.7153$$

Substituting it into the Equation (21) gives:

$$\left(-\frac{1}{2}+\frac{0.25\,(0.42)}{6}\right)D_3 + \left(\frac{1}{2}+\frac{0.25\,(0.42)}{3}\right)D_4 = \frac{0.25\,(0.26)}{2}.2.7153$$

$$= -0.4825(2.3953) + 0.5350\,D_4 = 0.08825$$

$$\therefore D_4 = \frac{1.24398}{0.5350} = 2.3252 \text{ mg/l}$$

For n = 5,

$$L_{(n-1)t} = L_{(5-1)t} = L_{4t} = L_0(e^{-k_1 4t} = 3.3e^{-0.26(0.75)}) = 3.3(0.77105) = 2.5444$$

Substituting it into Equation (21) gives

$$\left(-\frac{1}{2}+\frac{0.25\,(0.42)}{6}\right)D_4 + \left(\frac{1}{2}+\frac{0.25\,(0.42)}{3}\right)D_5 = \frac{0.25\,(0.26)}{2}.2.5444$$

$$= -0.4825(2.3252) + 0.5350D_4 = \mathbf{0.082693}$$

$$\therefore D_5 = \frac{1.2046028}{0.5350} = 2.2516 \text{ mg/l}$$

4.0 Discussion

Table, 1 showed the concentration of the physicochemical and biological variables from surface water samples along Nworie River. For the surface water, the mean of the measured parameters were within the standard limits with the exception of turbidity, color of water, TSS, dissolved oxygen, nitrate, nitrite and calcium concentrations. These were observed to exceed the WHO limits for water samples. The exceeded mean concentrations respectively recorded 114.83 mg/l turbidity, 262.67 NTU; DO 5.9mg/l, 348.40 mg/l nitrate, 5.27 mg/l nitrite and 90 mg/l calcium. From these exceeded values, it was observed that the second sample location (Assumpta-Holy Ghost college road) had highest concentration in turbidity 146.3 NTU, colour of water 640 PCU, conductivity 141 µs/cm, TSS 368 mg/l and Nitrate 520.3mg/l respectively. This was an indication of heavy pollution with associated reduced dissolved oxygen thus endangered aquatic species with high demand for oxygen content. Beside the pollution load, there was presence of murky or clouded ferns thus reduced light penetration.

Table 2: Generated results of oxygen deficit along Nworie River

Node No / Parameter	1	2	3	4	5
Oxygen Deficit (mg/l))	2.528	2.49789	2.3953	2.3252	2.2516
Dissolved Oxygen	6.500	6.53011	6.6327	6.7028	6.7764

From the forgoing it has been shown from Table 2, that GWR finite element remained an accessible tool for determining the effect of wastewater discharge on the oxygen content downstream along the river. The result of the oxygen deficit at the first node which is the point of effluent discharge gave 2.528 mg/l. As pollutants move a distance of one fourth of the distance under consideration as linear global domain element, reoxygenation occurred, and reduced oxygen deficit along the downstream of the river with the following results at the five nodes: 2.528, 2.498 2.395, and 2.325 and 2.252 mg/l at the end node respectively. The dissolved oxygen along the river was calculated by subtracting the value of each oxygen deficit from the dissolved oxygen saturation (DOS) of 9.028 mg/l. The dissolved oxygen results 6.500, 6.530, 6.633, 6.703 and 6.776 mg/l were observed to be increasing as the oxygen deficit reduces. However, this is quite different from the DO of the three samples analyzed in the laboratory. This observation was, due to other sources of effluent into the river thereby reduced the dissolved oxygen at one point and increased it at another.

5.0 Conclusion

WRM model approximation using Galerkin's weighted residual finite element method was used in predicting the effect of effluent discharge downstream of Nworie River. The river was discretized into five nodes and four elements as a linear element of a global domain with the aid of a well chosen interpolation function. Elemental equations were derived by integral form of Galerkin's finite element equation, assembled from the first two nodes, interior nodes and the last nodal function. These evaluated equations resulted to oxygen deficit at each node respectively, thus determining the possible effect when there is waste water discharge into the river. This work is recommended for predicting the effect of sewage discharge downstream of any river and for effective irrigation, aquaculture, domestic and aesthetic purposes.

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