Evaluation of the Longitudinal Dispersion Coefficient for Dor-Nwezor-Bodo River using Tracer Experiment and Theoretical Measurement

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ABSTRACT

This paper is focused on determining the longitudinal dispersion coefficient of pollutants in the Dor-Nwezor-Bodo River, located in Ogoni land in the present Rivers State, Nigeria. The measurement of the longitudinal dispersion coefficient for this River will help to ascertain the degree to which the concentrations of pollutants introduced at upstream will dilute at downstream. This parameter will help in the effective control and management of the River Water pollution. Basic hydraulic properties of the River that was measured for this study: flow velocity=0.22 m/s, test travel length (between tracer injection and sampling)=450 m, River depth=10.5 m, channel width=5.2 m, and hydraulic radius=2.7 m. Tracer experiments and theoretical (or empirical) model predictions were the methods adopted for this study. The tracer experiment is an indirect measurement that also adopted the constant distance-variable time method, for which the measured value of the longitudinal dispersion coefficient for the River is 6.572 m^2/s. This value is an indication of a moderate response of injected pollutants to hydraulic mixing and dilution in the River Water within a travel distance of 450 m. The longitudinal dispersion coefficient for the River Water was also predicted using several theoretical models, while their levels of accuracy were assessed with respect to the measured value. Models from Seo and Cheong and that combined with Kashefipour and Falconer showed close approximations to measurement obtained from the Tracer experiment.

INTRODUCTION

Natural water bodies such as creeks, Rivers, lakes, streams, and oceans can be protected from the impact of pollutants often discharged into it, through routine pollution warning and control services [1,2]. Dispersion studies are very significant tools that can support pollution warning and control for natural waters. In actual fact, polluted natural waters can regain its natural status after flowing over a given distance. The process of achieving this is called dispersion (or self-purification). Although it is a complex process, it can be achieved by a combination of physical, chemical and biological mechanisms that can occur simultaneously or stepwise. Typical mechanisms for pollutant dispersion include mixing, dilution, sedimentation, re-aeration, de-oxygenation, absorption, and adsorption. Others are chemical and biological digestion [3,4].

Dispersion of pollutants in a flowing natural water body can be classified: longitudinal, axial and vertical. In longitudinal dispersion, the water mass spreads out in the direction of the flow of the water body in order to cause maximum dilution of pollutants rather than moving it downstream. Axial dispersion will cause the flowing water body to circulate normally to the direction of flow, thereby resulting in mixing with minimum dilution and peak broadening. For vertical dispersion, the non-floatable mass of pollutants can move from the surface to the bottom of the River [2,5].

For most River Water pollution control services, longitudinal dispersion is commonly the focus, and the parameter for determining the extent of the dispersion is called longitudinal dispersion coefficient. Typical methods for measuring longitudinal dispersion coefficient are tracer and empirical. The tracer technique is an experimental procedure that requires spectrometric measurement for which the tracer response curve and its dispersion number in the natural water body are keys. However, this procedure requires several samplings, and it is very costly and time-consuming [6-8].

The empirical method uses both dimensional and non-dimensional theoretical models. The dimensional model is typically the advection-dispersion equation which is a partial differential equation expressed in a form that relates the degree of change of concentration of pollutant in water (C) with respect to its time of travel (t) and directions or travel distances (x, y, z) for which dispersion coefficient (D), velocity (U) and dispersion mechanism (K) are the coefficients. The solution to the equation would require initial and boundary conditions which would help determine the values of the coefficients. A typical expression is shown in equation 1 [1].

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$$\frac{\partial C}{\partial t} = D_i \frac{\partial^2 C}{\partial_{x^2} i} - U_i \frac{\partial C}{\partial x_i} \pm KC \quad (1)$$

On this basis were several non-dimensional models formulated in the literature for the purpose of measuring the dispersion coefficient. In it, the dispersion coefficient was formally expressed as functions of basic hydraulic parameters for River Waters, such as length of River Water (L), width (W), depth (H), flow velocity (U), shear velocity (U*), slope of River (S) and hydraulic radius (R) [7-10].

In line with this principle [11,12] proposed the foremost models for dispersion coefficient measurement. These models were simple expressions that showed direct dependence of longitudinal dispersion coefficient on River depth (H) and shear velocity (U^*) **(Table 1)**. Over time, other models that were relatively more complex were also proposed: [12-15] **(Table 1)**. These models showed higher dependence of longitudinal dispersion coefficient on hydraulic parameters for River Waters.

The relative accuracy of the longitudinal dispersion coefficient measured from literature models, in comparison to experimental measurement, has also been evaluated by several reporters. For instance, Duarte et al. evaluated the performance of different 1-D theoretical models (Duflow and ADZ-tool) for estimating pollutant transport and dispersion properties for the Pantanha-Mondego River in Portugal, which receives runoff from Urgeiriça uranium mine. The results revealed a good agreement between the Duflow model and rhodamine-dye tracer measurements. In the same vein [1] found that the more complex models showed the least Root Mean Square Error (RMSE) when compared with simpler ones. It was also observed that the measured longitudinal dispersion coefficients for the River Waters were not constant, but varies between 5.5-43 m^2/s, from point to point along the River Water surface depending on the hydraulic parameters.

Uchenna and Nwaogazie [10] observed that the value of its tracer measurement for the longitudinal dispersion coefficient of the Otamiri River, Nigeria, was 38.1 m^2/s, which was in agreement with the value obtained from the model proposed by Deng [13]. Tenebe [8] reviewed the different approaches (i.e. tracer, empirical and neural network) for measuring longitudinal dispersion coefficient for River or stream waters. Empirical methods were adjudged the most convenient, while the accuracy and constancy of the predicted longitudinal dispersion coefficient along the River Water surface were evidently enhanced by expanding the model dependence on additional hydraulic parameters (e.g. temperature, wind speed, turbidity etc.).

Table 1. Selected theoretical models as proposed for the estimation of River Water longitudinal dispersion coefficient.

Test Model No.	Name of Model	Model Expression
1	Taylor [11]	$D_L = 10.11HU^*$, where, $U^* = \sqrt{gRS}$
2	Elder [20]	$D_L = 5.93HU^*$
3	McQuivey and Keefer [22]	$D_L = 0.058\left[\frac{H}{S}\right]$
4	Fischer et al [23]	$D_L = 0.011\left[\frac{U^2W^2}{HU^*}\right]$
5	Liu [21]	$D_L = 0.18\left[\frac{U^*}{U}\right]^{1.5}\left[\frac{U^2W^2}{HU^*}\right]$
6	Iwasa and Aya [24]	$D_L = 2.0HU^*\left[\frac{W}{H}\right]^{1.5}$
7	Seo and Cheong [12]	$D_L = 5.915HU^*\left[\frac{W}{H}\right]^{0.62}\left[\frac{U}{U^*}\right]^{1.428}$
8	Deng et al [13]	$D_L = \frac{0.15HU^*}{W_{\varepsilon_{ro}}}\left[\frac{W}{H}\right]^{1.67}\left[\frac{U}{U^*}\right]^2$ Where, $\varepsilon_{ro} = 0.145 + \left[\frac{1}{3520}\right]\left[\frac{U}{U^*}\right]\left[\frac{W}{H}\right]^{1.38}$

9	Kashefipour and Falconer [14]	$D_L = 10612HU\left[\frac{U}{U*}\right]$
10	Combined Model: Kashefipour and Falconer [14] plus Seo and Cheong [12]	$D_L = \left\{7.428 + 1.775\left[\frac{W}{H}\right]^{0.62}\left[\frac{U}{U*}\right]^{0.572}\right\}HU\left[\frac{U}{U*}\right]$
11	Sahay and Dutta [15]	$D_L = 2HU*\left[\frac{W}{H}\right]^{0.96}\left[\frac{U}{U*}\right]^{1.25}$

Study Area

The Dor-Nwezor section of the Bodo River is the focus area for this study **(Figure 1)**. It is one of the channels of the Bodo River through which it links other neighboring Rivers (e.g. Opobo and Bonny Rivers). Other channels from the Bodo River include Koola-Tobsoi, Koola-Seato and Kpador River **(Figure 2)**. The geology of the Bodo communities is a deltaic basin, whose location is in the Niger-Delta region in Ogoni land, in the present Rivers State, Nigeria. Its geographical coordinates are: Latitude (4° 37l North) and Longitude (7° 16l East). It is surrounded by mangrove vegetation and characterized by an annual rainfall of 2000 mm-3000 mm [16].

The Bodo River strongly supports the livelihood of the inhabitants of the area in fishing, agriculture, transportation and domestic waste disposal. The presence of Bodo West Oilfield and an abandoned fish farm belonging to the Niger Delta Basin Development Authority (NDBDA) in the area are key evidence of Bodo Rivers support for industrial development. The physicochemistry of the water from the Bodo River is reported to be brackish water with moderate salinity and slight alkalinity [17].

Figure 1. Plate of the Dor-Nwezor-Bodo river.

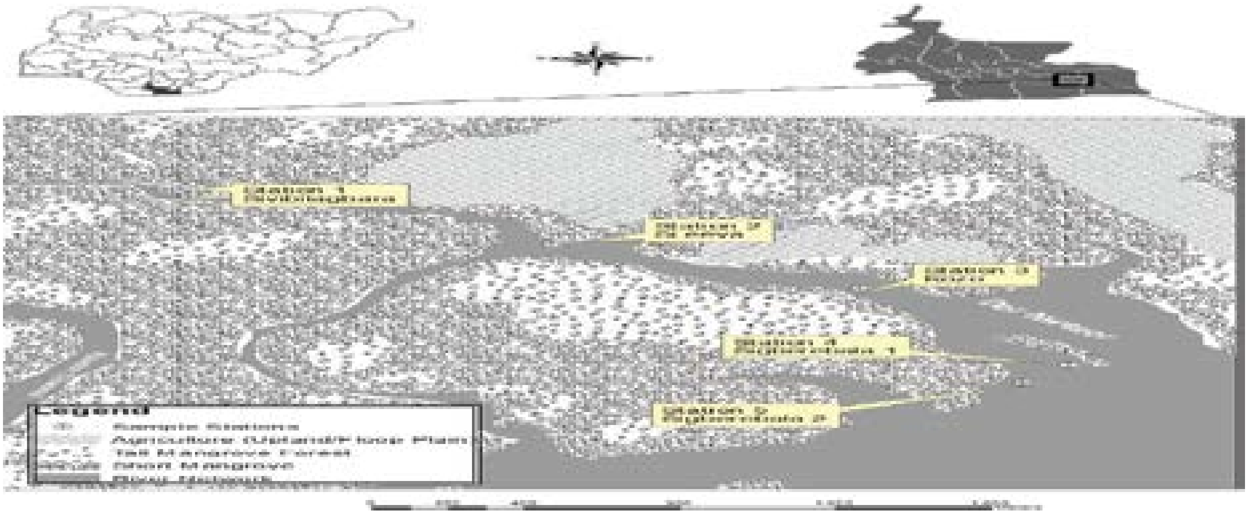

Figure 2. Layout of the Dor-Nwezor-Bodo River (Zabbey and Malaquais) [28].

MATERIALS AND METHODS

Materials

Materials used for this study are as listed: Measuring tape, masking tape, local boat, photographic camera, sample bottles, ice-chest or cooler (for storing tracer and water samples), stopwatch (for measuring travel time of samples), thermometer,

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potassium permanganate (solution in distilled water was used as tracer), an orange fruit (used as floatable object for measuring River flow velocity) and Atomic Absorption Spectrophotometer (AAS).

Methods

Experimental Measurement of Longitudinal Dispersion Coefficient of tracer in the River Water Tracer Experiment: The layout of the River under this study was mapped out using a local boat, photographic camera and measuring tape, in order to measure its basic hydraulic geometries (i.e. length, width, and depth). At different points within the River channel, three measurements were taken respectively for length, width and depth, while the averages were taken as substantive. The influent point (upstream) and effluent point (downstream) were respectively determined as points for tracer injection and sample collection.

The cross-sectional area for the River was estimated by multiplying the average width by the average depth. The River flow average velocity was measured by dividing the average travel length of orange fruit by average travel time, while the volumetric flow rate was estimated by multiplying its area by average River flow velocity.

Method of constant distance-variable time was adopted for the tracer study. In it, 200 g of agent grade Potassium permanganate ($KMnO_4$) was dissolved in a 1-liter volume of distilled water to form a purple cloud solution. This was used as a tracer for this study. The basic characteristics of the tracer were good diffusivity, low concentration in natural waters, high detectability, inertness (at River temperature), and low acidity, less sorptive and not toxic. The tracer solution was introduced into the River surface at the designated influent point (upstream). Along the River surface, the tracer channel was monitored for tracer mix and dilution. At a designated effluent point (downstream), water samples were collected at different time intervals, while tracer concentrations in the samples were measured in the laboratory using Atomic Absorption Spectrophotometer (AAS).

Concentration measurement

The atomic absorption spectrophotometer (AAS) (iCE 3000 series) was used for the measurement of the concentration of water samples taken at the designated point on the River surface. APHA 3111B method was adopted. In it, direct aspiration of each test sample into an air/acetylene flame was carried out; this was incident by light rays from a hollow cathode light source emitting at 766 nm spectral line of a characteristic energy. This energy was used to excite free atoms of metals of interest in the test samples (e.g. K and Mn). The concentration of the excited metal atom in the sample was calculated by comparison of its absorbance with standard curves for metals **(Figure 3)**.

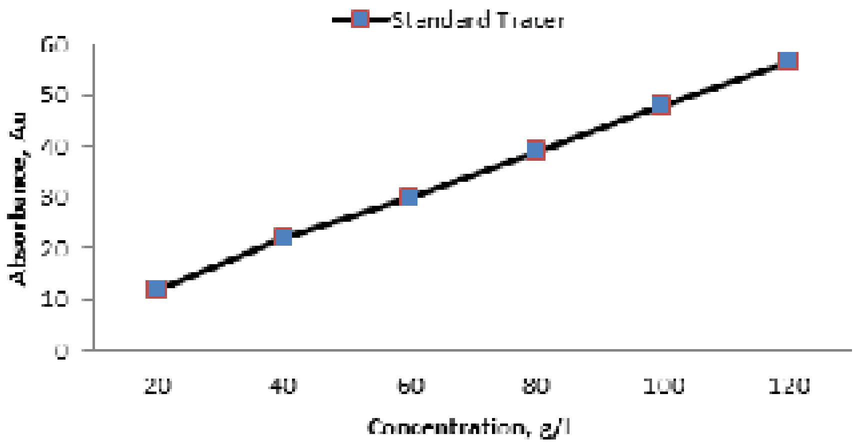

Figure 3. The plot of absorbance against the concentration of a standard solution of potassium permanganate (tracer).

Estimation of longitudinal dispersion coefficient

The longitudinal dispersion coefficient, D_L for the River Water was estimated using equation 1,

$$D_L = \delta U L \quad (1)$$

Where, D=Longitudinal dispersion coefficient, m^2/s; U=River flow velocity; L=Length of River, m and δ=dispersion number.

The dispersion number, δ, was estimated based on the moment equation approach (Leverspiel and Smith [18] as shown in equation 2.

$$\delta = \frac{1}{8}\left[\sqrt{8\sigma^2 + 1} - 1\right] \quad (2)$$

Where, σ^2=Normalized variance, calculated from constant distance-variable time tracer experiment using equation 3.

$$\sigma^2 = \frac{1}{\theta^2}\left[\frac{\sum_{i=1}^{n} C_i t^2{}_i}{\sum_{i=1}^{n} C_i} - \theta^2\right] \quad (3)$$

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For which θ is defined by equation 4 as,

$$\theta = \left[\frac{\sum_{i=1}^{n} C_i t_i}{\sum_{i=1}^{n} C_i} \right] \quad (4)$$

Where, t=travel time of tracer, min; C=concentration of tracer at downstream or sampling point (mg/l); θ=Average River flow time, s, as given by Marecos-do-Monte and Mara [19].

Theoretical measurement of longitudinal dispersion coefficient for river water

In this section, the estimation of longitudinal dispersion coefficient (D_L) for River Water was carried out using empirical models in non-dimensional format, which relied on mean values of basic hydraulic parameters of the River Water as input parameters: River depth (H), River channel width (W, m), flow velocity (U, m/s) and volume flow rate of the River Water (Q, m^3/s). Others are hydraulic radius (R, m), the slope of River (S) and shear velocity (U^*, m/s). The shear velocity is estimated based on equation 5.

$$U^* = \sqrt{(g * R * S)} \quad (5)$$

Assessment criteria for comparing the accuracy of tested models

The discrepancy ratio (λ), absolute error (AE) and relative error (RE) were used as principal criteria for assessing the accuracy of the predicted longitudinal dispersion coefficient (D_L) of the River Water by theoretical models. This was done by comparing the measured value (by tracer technique) with predicted values. The criteria are presented as follows:

- Discrepancy ratio (λ): assesses the degree of accuracy of the prediction made by model. The tolerance limit for the assessment is ± 0.5. The equation describing the discrepancy ratio is presented in equation 6

$$\lambda = Log\left(\frac{D_{LP}}{D_{LM}}\right) = Log\left(D_{LP} - D_{LM}\right) \quad (6)$$

Where, λ=discrepancy ratio; D_{LP}=predicted longitudinal dispersion coefficient, m^2/s and $D_{LM=}$measured longitudinal dispersion coefficient, m^2/s.

The following are the conditions of assessment:

a. If λ=0, $D_{LP}=D_{LM}$ (predicted value equals measured value)

b. If λ>0, $D_{LP}>D_{LM}$ (over-prediction by model)

c. If λ<0, $D_{LP}<D_{LM}$ (under-prediction by model) [9]

- **Absolute Error (AE):** measures the margin of error that is associated with the model predictions. In another word, it measures the difference between the actual value and the predicted value from the model. The equation for AE measurement is presented in equation 7

$$AE = \left| D_{LM} - D_{LP} \right| \quad (7)$$

- **Relative Error (RE):** measures the margin of error relative to the actual value. In another word, it is the ratio of the absolute error to the actual value of the measurement. The RE is measured using equation 8

$$RE = \left| \frac{\left(D_{LM} - D_{LP}\right)}{D_{LM}} \right| \quad (8)$$

RESULTS AND DISCUSSION

The results obtained from this work are presented in tables and figures, while the discussions are made under the following subheadings: (1). Hydraulic Parameters for the Dor-Nwezor-Bodo River, (2). Longitudinal Dispersion Coefficient for the River Water, (3). Assessment of the Accuracy of Model Predictions

Hydraulic Parameters for the Dor-Nwezor-Bodo River

The Dor-Nwezor-Bodo River is made of networks of several River channels surrounded by mangrove forest, and with moderate River slope and flowing at relatively moderate velocity **(Figures 1 and 2)**. The hydraulic parameter measurements were considered as baseline parameters for both the tracer experiment and theoretical measurements for the longitudinal dispersion coefficient. A narrow section of the river having a travel length (L) of 450 m was chosen as test distance. This distance is between points of injection of tracer and response sampling. Other hydraulic parameters measured for the River are shown in **Table 2**.

Table 2. Hydraulic parameters for the river water.

S/No.	Parameter	Value
1	Travel length, L (m)	450

2	River Depth, H (m)	10.5
3	River Flow Velocity, U (m/s)	0.22
4	River Channel Width, W (m)	5.2
5	River Shear Velocity, U* (m/s)	0.367
6	The slope of River, S	0.005
7	River Hydraulic Radius, R (m)	2.7

Longitudinal Dispersion Coefficient for the River Water

The value of the longitudinal dispersion coefficient (D_{LM}) for the Dor-Nwezor-Bodo River as measured by the tracer experiment is given as 6.572 m^2/s. This value appeared to be low, thus indicating a lesser degree of pollutant dispersion in River Water. However, it is somehow in agreement with Naved [1] whose measured values of longitudinal dispersion coefficient for a River Water ranged as 5.5-43 m^2/s, while it varied widely from Uchenna and Nwaogazie [10] which had its measured longitudinal dispersion coefficient for Otamiri River as 38.1 m^2/s. Reasons for the variations in River Water longitudinal dispersion coefficient measurement are largely adduced to the nature of its hydraulic parameters and to the level of residual impurities in the River.

For this study, the trend of the tracer response concentration-time curve **(Figure 4)** displayed a normal distribution, wherein the tracer concentration in the water sample grew from 0 g/L to peak concentration of 36 g/L at a sampling time of 1000s and thereafter drops to near zero concentration after 3000 s. The normalized variance was also estimated from the tracer response concentration-time data **(Tables 3 and 4)**, and its value was actually dependent on the mean tracer time of travel, and not on the uniformity in time spacing.

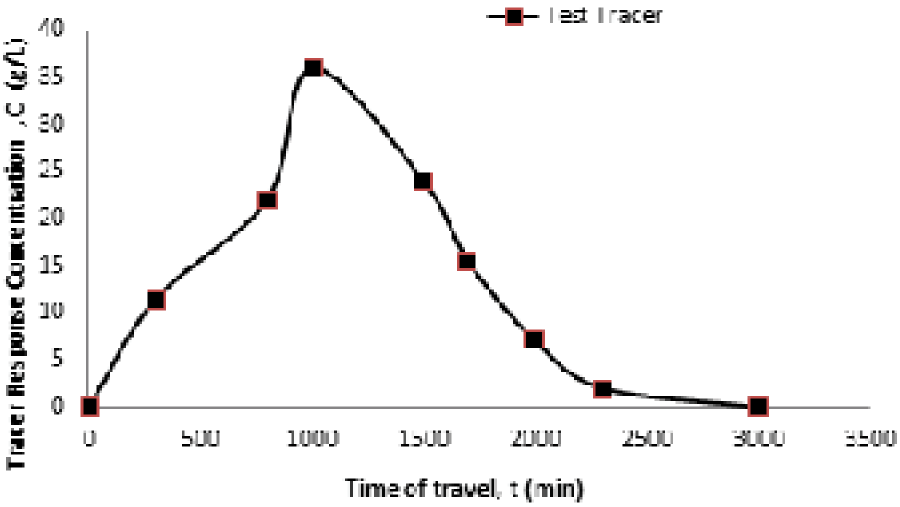

Figure 4. The plot of tracer response concentration in river water against its time of travel.

Table 3. Concentration of sample of tracer taken from river water and its time of travel.

Sample No.	1	2	3	4	5	6	7	8	9
Tracer response concentration, C (g/L)	0	11.5	22	36	24	15.4	7	2	0
Time of travel, t (s)	0	300	800	1000	1500	1700	2000	2300	3000

Table 4. Application of Leverspiel and Smith Model for DLM measurement using experimental data from tracer technique.

Sample No.	Tracer time of travel, t (s)	Tracer response conc., C (g/L)	$t^2(s^2)$	Ct (gs/L)	$Ct^2(gs^2/L)$
1	0	0	0	0	0
2	300	11.5	90000	3450	1035000
3	800	22	640000	17600	1.4E+07
4	1000	36	1000000	36000	3.6E+07
5	1500	24	2250000	36000	5.4E+07
6	1700	15.4	2890000	26180	4.5E+07
7	2000	7	4000000	14000	2.8E+07
8	2300	2	5290000	4600	1.1E+07
9	3000	0	9000000	0	0
SUM	12600	117.9	2.5E+07	137830	1.9E+08

Where, θ=1169.04 s, σ^2=0.168, δ=0.0664, L=450 m, U=0.22 m/s and Measured longitudinal dispersion coefficient, D_{LM}=6.572 m^2/s.

Several non-dimensional theoretical models **(Table 4)** were applied for the prediction of the longitudinal dispersion coefficient, D_{LP} for the Dor-Nwezor-Bodo River using hydraulic parameters **(Table 2)**. The results obtained from the models also varied from the experimentally measured value ($D_{LM=}$6.572 m²/s). However, the closest model prediction to the experimental measurement is that of Seo and Cheong [12] which had a D_{LP}=7.096 m²/s. Other model predictions: 39.0 m²/s, 22.89 m²/s, and 26.8 m²/s, which are respectively from Taylor [11], Elder [20] and McQuivey and Keefer varied widely from the measured value of longitudinal dispersion coefficient **(Table 5).** Reasons for the variations are traceable to, first on the models' constitution which did not depend reasonably well enough on the hydraulic parameters of the River Water. Another reason is the very low value for the slope of the River [21,22].

Table 5. Predicted longitudinal dispersion coefficient for river water and its test of accuracy.

Test model	Predicted longitudinal dispersion coefficient, d_{lp} (m²/s)	Discrepancy ratio, λ	Absolute error, ae	Relative error, re
Taylor [11]	39.004	0.773	-32.43	-4.93
Elder [20]	22.878	0.542	-16.31	-2.48
McQuivey and Keefer [22]	26.796	0.610	-20.22	-3.08
Fischer et al [23]	0.004	-3.216	6.57	1.00
Liu [21]	0.132	-1.697	6.44	0.98
Iwasa and Aya [25]	2.689	-0.388	3.88	0.59
Seo and Cheong [12]	7.096	0.033	-0.52	-0.08
Deng et al [13]	0.085	-1.888	6.49	0.99
Kashefipour and Falconer [14]	14.678	0.349	-8.11	-1.23
Combined Model	9.558	0.163	-2.99	-0.45
Sahay and Dutta [15]	2.07	-0.502	4.50	0.69
Measured Longitudinal Dispersion Coefficient, D_{LM}=6.572 m²/s				

Assessment of the Accuracy of Model Predictions

Discrepancy ratio, absolute and relative errors were the criteria used for assessing the level of accuracy of the tested models for predicting longitudinal dispersion coefficient for the River Water [22-25]. Discrepancy ratios for Taylor [11], Elder [20], McQuiver and Keefer [22] models were observed to be greater than zero (λ>0), hence indicating overestimations of longitudinal dispersion coefficient for the River Water, while models from Fischer et al. [23], Liu [21] and Deng et al. [13] showed underestimations for the longitudinal dispersion coefficient for the River Water due to observed discrepancy ratios of less than zero (λ<0) **(Table 5).** Thus, an observed discrepancy ratio, λ=0.033 for Seo and Cheong [12] model indicates a close approximation to the experimentally measured longitudinal dispersion coefficient for the River Water [26-28]. This was followed by the combined model. Similar inferences can be drawn from the absolute and relative error criteria as shown in **Table 5.**

CONCLUSION

The Dor-Nwezor-Bodo River is a channel from the main Bodo River that is surrounded by mangrove forest. This River had been impacted negatively by contact with impurities from human activities: domestic, agriculture, transportation, oil and gas operations. Hydraulic parameters measured for the River Water were obtained as average values from three separate measurements. This is because the River Water showed variable hydraulic geometry, for which a moderate value of River Water velocity was evident.

A longitudinal dispersion coefficient (D_{LM}) of 6.572 m²/s was measured for the River Water using tracer method. This indicates a moderate pollutant dispersion capacity. Theoretical models from Seo and Cheong and that of a combined model respectively showed 7.096 m²/s, and 9.558 m²/s as the closest approximations to the experimentally measured value of longitudinal dispersion coefficient of the River Water.

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