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DETERMINATION OF DISPERSION PARAMETERS IN OTAMIRI RIVER, OWERRI

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ABSTRACT

The dispersion pattern of Otamiri River was studied by means of a tracer-dye. Measured tracer-response curves produced from the injection of 1kg of soluble Sulphur-Black (BR) dye was used to obtain the data for this study. The dispersion and mixing of the tracer took place in three dimensions of the river. Vertical mixing was rapidly completed within a distance of 50m from the initial point of tracer injection; lateral mixing was completed within a distance of 400m, while longitudinal dispersion continued downstream beyond 450m. The longitudinal dispersion coefficient as a fundamental parameter in hydraulic modeling of river pollution was determined with the statistical moment equation as $38m^2/s$. It was noted that longitudinal dispersion coefficient values are affected by the river flow velocity, hydraulic depth and cross-sectional width of the river.

KEYWORDS: River, tracer-dye, dispersion number, longitudinal dispersion coefficient

1. INTRODUCTION

The behaviour of a soluble pollutant in water is similar to that of a soluble tracer. So the understanding of how tracers mix and disperse in rivers is essential to understanding their application in pollution simulation. For example, Nwaogazie (2008) reported an experimentally determined parameter of dispersion coefficient of Vienne River involving the injection of Rhodamine dye of a given volume; V_o and concentration C_o at specified location x_1 and observing the resulting cross-sectional average concentration at location x_2.

In natural rivers, many processes occur, which lead to a non-uniform velocity field, which allows mixing to occur much faster than molecular diffusion alone. The presence of dead zones also alters or interfers with rapid mixing and dispersion processes. Understanding of mixing of pollutants in rivers is a matter of concern in recent years for effective control of pollution. Mixing length for complete mixing of pollutants over the cross-sectional area of a river must be known for application of longitudinal dispersion model.

Fluorometric Facts (2001) reports that tracer experiments or dye studies are used to comprehend these processes and dispersion for any given reach of a river.

Dye study is one of the most reliable means to estimate dispersion coefficient (Turner Designs, 2001). According to Hubbard and others (1982) dye is introduced into the river site and measurements of the dye concentration are made at several locations (distances) downstream from the point of injection. It can also impact negatively on water especially when present in significant concentration (Environment Canada, 2007). Because dispersion coefficient is dependent on the velocity profile of a river, it is then a function of the river flow rate. Therefore, a dispersion coefficient computed by a tracer-dye study for one flow rate segment of the river will not apply to a situation or another river segment of a different flow rate. In such instance, predictions may be made from the results of one dye study, or a series of dye studies may be performed (Kilpatrick, 1993).

The objective of this is to determine the dispersion system of contaminants in Otamiri River

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for application to modeling of its water quality.

2. STUDY AREA

Present study has been carried out on a small stretch of Otamiri River along the Nekede - Ihiagwa stretch. Otamiri River is the major river in Owerri Metropolis, Imo State and it originates from a spring in Egbu, an outskirt town of Owerri metropolis (Imo Geographic Information Service, 2009). It captured a smaller river (Nworie stream) at the old Nekede, thereby expanding its volumetric flow (Fig. 1). The State Water Co-operation abstracts water for treatment upstream of this stretch and many activities such as fishing and sand mining go on downstream.

3. METHODOLOGY

This study covered field investigation and analysis to determine the extent of dispersion of tracer-dye, hydraulic depth, width, cross-sectional area and flow rate of the river. The sampling was carried out at 10 sampling stations at a distance of 50m interval for a 500m stretch of Otamiri River (Fig. 2). The division was done by the use of surveyors tape and metal poles staked at the marked sampling stations. The velocity of flow at each station was obtained with an Aquaflow Probe - 6900 velocity meter, from which the average velocity (0.36m/s) of the stream was determined.

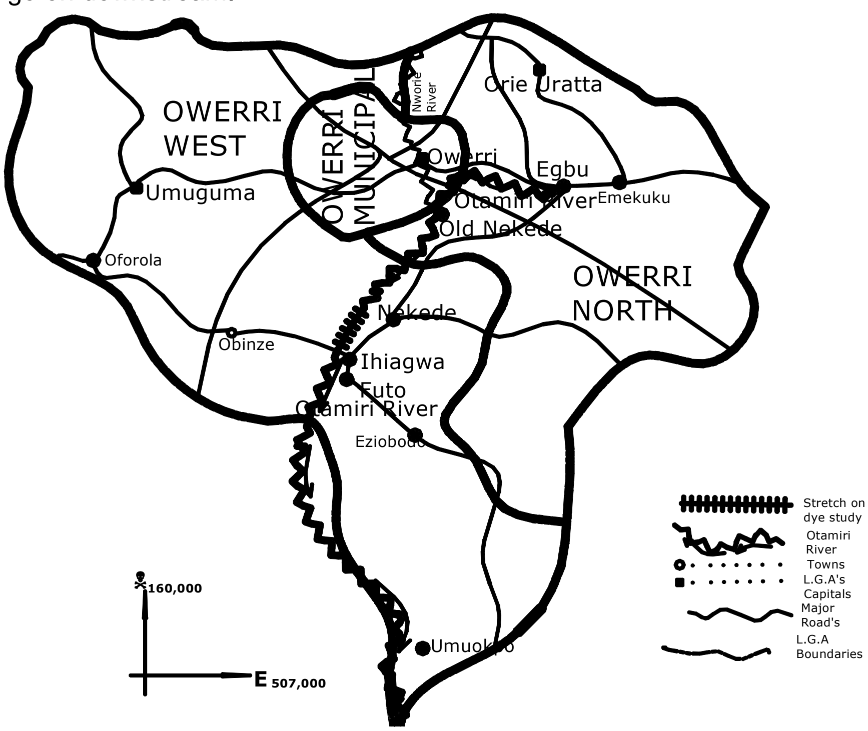

Fig. 1: Map Showing the Study Area
Source: Ministry of Lands, Survey, Urban Development and Planning

The sample collections were facilitated with the aid of two paddled boats. One boat aided the collection of samples at the center line of the river while the other boat was used to collect samples near the right bank of the river. The paddled boats were used so as to minimize disturbances of the river flow pattern. The samples were collected at a time interval of 3 minutes for each sampling stations. The timing was regulated by the use of a stop watch by one of the field assistants.

The concentration of tracer, C was obtained from the sampling stations; average velocity, u; cross sectional area, A_x; and distance of travel of tracer, x, were obtained from field measurements at the various sampling stations. A litre of water was added to 1kg of tracer to produce an initial tracer concentration of 1kg/l before it was instantaneously injected into the center line of the river as was suggested by Smart and Laidlaw (1977). After a thorough dilution of the tracer by the river water, a first sample was collected to

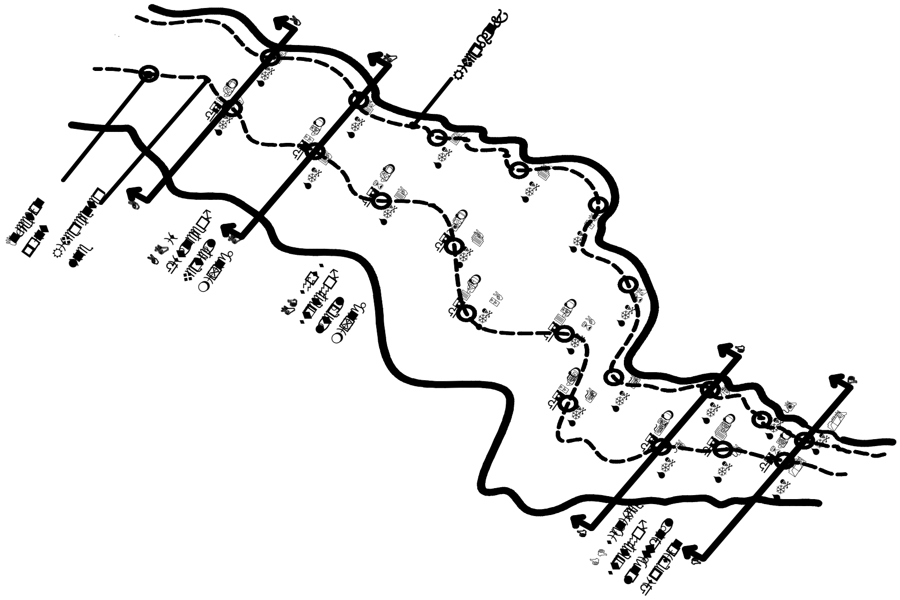

Fig. 2: A segment of Otamiri River showing the centerline and river bank sampling stations (stn)

establish the initial concentration (17,000mg/l) of tracer before dispersion commenced. The samples were collected with sterilized plastic containers labeled 1 - 10. These samples were transferred immediately to a low-temperature chamber and taken to the laboratory for analysis with a JENWAY 6305 UV Spectrophotometer where the tracer concentrations in the samples at the various sampling stations were obtained.

4. RESULT AND DISCUSSION

The dispersion data of Otamiri River are presented in Table 1, and the plot of tracer concentrations against sampling stations for river centre point and river bank are as shown in Fig. 3.

Variance Dispersion Relationships

The relationship between variance and dispersion is derived analytically by using statistical moment method based on (Leverspiel and Smith, 1957):

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

Where σ^2 is the normalized variance which is computed from constant length variable time tracer experiment and it is given by:

Table 1: Otamiri River Dispersion Data

Station, stn	Distance, *x* (m)	Tracer Conc., mg/l		Time of release of tracer (sec)	Ave x-sectional			
		@ RCP*	@RRB**		Area, A_x (m^2)	Width,w (m)	Depth, h (m)	Veloc, u (m/s)
	0	17,000$^{\pm}$ mg/l	-	-	-	-	-	-
1	50	240.8	428.6	180	38.3	7.50	5.1	0.39
2	100	337.1	462.3	360	57.8	10.50	5.5	0.36
3	150	339.2	320.5	540	310.9	50.96	6.1	0.30
4	200	346.7	300.5	720	302.4	33.60	9.0	0.31
5	250	144.5	100.2	900	22.8	6.00	3.8	0.42
6	300	91.5	65.30	1080	23.8	6.80	3.5	0.40
7	350	4.8	3.10	1260	85.5	15.00	5.7	0.35
8	400	3.4	2.75	1440	153.5	20.20	7.6	0.34
9	450	1.7	1.68	1620	38.4	9.14	4.2	0.37
10	500	0.4	0.40	1800	151.2	24.00	6.3	0.33
Average	-	-	-	-	$\bar{A}_x$ = 118.48	$\hat{W}$ = 18.4	đ = 0.57	$\bar{U}$ = 0.36

* RCP = River Centre Point **RRB = River right bank, 17,000mg/l$^{\pm}$ = resulting cross-sectional concentration coefficient of dye C

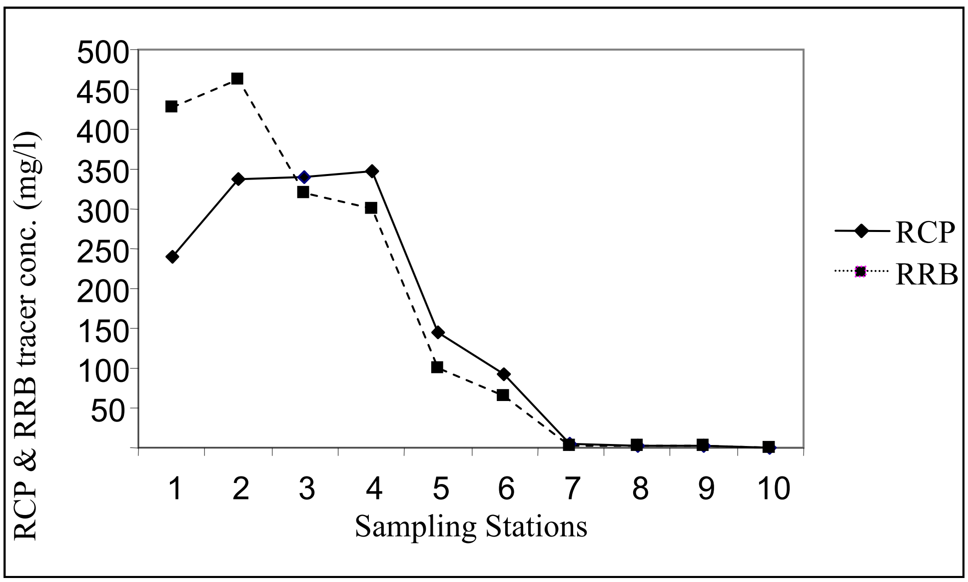

Fig. 3: RCP and RRB Tracer Concentrations against sampling stations

$$\sigma^2 = (1/\theta)^2 \left[\sum_{i=1}^{n} C_i t_i^{\,2} / \sum_{i=1}^{n} C_i - \theta^2 \right] \quad \text{------------------} \quad (2)$$

In which t, is the time after injection of tracer (seconds), C = tracer response concentrations at the exit stream (mg/l); and θ is the average flow time given as:

$$\theta = \sum_{i=1}^{n} C_i t_i \; / \sum_{i=1}^{n} C_i \quad \text{----------------------------} \quad (3)$$

If variable distance – variable time approach is employed in the tracer experiment, the corresponding equations for ∂ and σ^2 have been derived by Agunwamba (1997):

$$\partial = \frac{1}{29.2}\left(\sqrt{1+15\sigma^2}-1\right) \quad \text{-----------------} \quad (4)$$

Where:

$$\sigma^2 = \sum_{i=1}^{n} k^2 C_i / \sum_{i=1}^{n} C_i - \left[\sum_{i=1}^{n} kC_i / \sum_{i=1}^{n} C_i\right]^2 \quad \text{---------------} \quad (5)$$

Where $k = \tau/(1-\xi)$; the summation is taken over all the spaced readings. The parameter $\tau = t/\theta$, $\xi = x/L$, L is the river stretch (500m), x is the distance from injection point to any station and t is the time after tracer injection.

The dispersion coefficient, D_L is usually computed by:

$D_L = u\,\partial^2 L$ -------------------------------------- (6)

Where u = average river velocity, 0.357 and ∂^2 dispersion number.

Application of Agunwamba (2001) model

The computation of dispersion number for the Otamiri River using Agunwamba's (2001) model (see Equation (4)) is accomplished using the field data of Table 1. The evaluation of Equation (5) over ten stations of 50 – 500m span is as presented in Table 2. The normalized variance σ^2 is obtained by direct substitution of values from Table 2 as follows:

$\sigma^2 = (32{,}465.596/1{,}510.1) - (6{,}434.73/1{,}510.1)^2 =$ 3.37

The dispersion number as given by Equation (4) is thus evaluated:

$\partial = \frac{1}{29.2}\left[\sqrt{1+15(3.37)}-1\right]$ = 0.2117

Therefore, the dispersion coefficient, D_L is obtained as follows:

D_L = (0.36m/s)(500m)(0.2117)=38.1m^2/s.

Table 2: Tabular evaluation of Equation 5 for Dispersion Number using Agunwamba (2001) model

Station	Distance (m)	Time, t sec.	RCP Conc., C mg/l	Ct	T = t/θ	1-ξ = B	ξ = x/L	T/B	(T/B)^2	C(T/B)	C(T^2/B)
1	50	180	240.8	43344	0.350	0	1.0	0.325	0.106	78.26	25..53
2	100	360	337.1	121356	0.647	0.1	0.9	6.470	41.86	2187.037	14111.006
3	150	540	339.2	183168	0.971	0.2	0.8	4.855	23.57	1646.816	7994.44
4	200	720	346.7	249624	1.294	0.3	0.7	4.313	18.60	1495.317	6448.62
5	250	900	144.5	130050	1.618	0.4	0.6	4.045	16.36	584.503	2364.00
6	300	1080	91.5	98820	1.941	0.5	0.5	3.822	15.07	355.203	1378.905
7	350	1260	4.8	6048	2.265	0.6	0.4	3.775	14.25	68.40	68.40
8	400	1440	3.4	4284	2.588	0.7	0.3	3.697	13.67	12.57	46.478
9	450	1620	1.7	2754	2.912	0.8	0.2	3.640	13.25	6.188	22.525
10	500	1800	0.4	720	3.235	0.9	0.1	3.594	12.92	1.438	5.168
-	-	Σ 9,900	Σ 1,510.1	Σ 840,168	Σ 17.82	Σ 4.5	Σ 5.5	Σ 38.536	Σ 169.656	Σ 6,435.73	Σ 32,465.596

Application of Leverspiel and Smith (1957) model

Applying the Leverspiel and Smith (1957) model to the field data of Table 1, results in a tabular evaluation of normalized variance (see Equation (2)) as presented in Table 3. Thus, the resulting value of the normalized variance σ^2 is given as:

$\sigma^2 = (1/556.4)^2(574{,}328{,}880)/(1510.1) - (556.37)^2$ = 0.2285

And the dispersion number ∂ (see Equation (1)) is evaluated as:

$$\partial = \frac{1}{8}\left[\sqrt{8(0.2285)+1}-1\right] = 0.085$$

The corresponding dispersion coefficient, D_L = 0.36x0.085 x 500 = 15.3 m^2/s.

Application of Deng and Others (2001) model:

The dispersion coefficient of Otamiri River can be equally determined based on geomorphological parameters of the river as presented by Deng and others (2001):

$$D_L = \frac{0.15}{8\xi}\left[\frac{w}{h}\right]^{0.17}\left[\frac{u}{u_*}\right]^2 \text{ ---------------- (7)}$$

Where:

$$\xi = 0.145 + \left[\frac{1}{3520}\right]\left[\frac{u}{u_*}\right]\left[\frac{w}{h}\right]^{1.38} \text{ ----- (8)}$$

Table 3: Tabular evaluation of Equation (2) for Dispersion Coefficient using Leverspiel and Smith (1957) model

Station	Distance (m)	Time, t (Sec)	RCP Conc., (c) mg/l	Ct	t^2	Ct^2
1	50	180	240.8	43344	32400	7801920
2	100	360	337.1	121356	129600	43688160
3	150	540	339.2	183168	291600	98910720
4	200	720	346.7	249624	518400	179729280
5	250	900	144.5	130050	810000	117045000
6	300	1080	91.5	98820	1166400	106725600
7	350	1260	4.8	6048	1587600	7620480
8	400	1440	3.4	4284	2073600	7050240
9	450	1620	1.7	2754	2624400	4461480
10	500	1800	0.4	720	3240000	1296000
-	-	9,900	1,501.1	840,168	12,474,000	574,328,880

Given that u = 0.36 m/s, w = 18.4m (see Table 1);

But u^* = shear velocity = $\sqrt{gds}$ -------------- (9)

Where: g = acceleration due to gravity (9.8 m^2/s) d = river depth (5.7m) (see Table 1), and s = slope of river which was obtained as 0.00005 from topographic map of the study area.

$\therefore u^* = \sqrt{9.8 \times 5.7 \times 0.00005}$ = 0.0528m/s

Evaluating

$$\xi \text{ gives } \xi = 0.145 + \left[\frac{1}{3,520}\right]\left[\frac{0.36}{0.053}\right]\left[\frac{18.4}{5.7}\right]^{1.38} = 0.1547$$

$$\therefore D_L = \frac{0.15}{8(0.1547)}\left[\frac{18.4}{5.7}\right]^{1.67}\left[\frac{0.36}{0.053}\right]^2 = 9.418 m^2/s$$

The model developed by Agunwamba (2001), gave a value of 38.1 m^2/s for Otamiri River dispersion profile. It conforms to the method applied in collecting the data – variable distance of 50m increment at each sampling station with a variable time of 3 minutes interval. The model developed by Leverspiel and Smith (1957) which was based on constant distance – variable time method gave a very low dispersion coefficient value of 15.3m^2/s for Otamiri River. This suggests that this model does not fit the Otamiri River dispersion profile.

The dispersion coefficient 39.4m^2/s obtained using Deng and others (2002) model conforms to the model developed by Agunwamba (2001). Fischer and others (1979) developed a model for estimating the dispersion coefficient of a river. But this model was based only on two sampling stations which may not be adequate to represent dispersion and therefore cannot be applied to this study. This study considered a total of 10 sampling stations and represented dispersion to a great extent.

Tracer Response Curve

According to Harvey (1997), the conventional way to display the response of a stream to a slug injection of tracer is to plot the variation of concentration with time. As illustrated in Fig. 3 the tracer – response curve was defined by the analysis of water samples taken at selected time interval of 180 seconds. Replacing sampling stations (1 through 10) with cumulative time since sampling started yields the required curved (RCP curve). According to Alberta Environment (1991) the characteristics and magnitude of the tracer-response curve are affected by (1) the volume/quantity of tracer injected; (2) the nature of tracer that is its conservative nature; (3) the stream discharge rate and; (4) the dispersion coefficient.

It could be seen from the tracer response curve (Fig. 3, RCP curve) that the leading edge of the contaminant of the tracer arrived first before the peak concentration of the tracer at station 4 after 720 seconds. Doubling the amount of tracer injected doubles the observed concentrations. The shape of the tracer-response curve will remain; and will not be altered. Tracers are equally lost in transit due to a lot of factors like: absorption on sediments (silt and clay), adhesion on sediments, photochemical/ decay and reaction (Fluorometric Facts, 2001) Concentration distribution is essentially one dimensional: it is well mixed in the y and z directions and Gaussian. The experiment and dispersion models reviewed indicate that the dispersion coefficient is affected by cross-sectional width, depth of flow, river velocity of flow, shear velocity, presence of dead zones, stagnation, rapids, and others.

5. CONCLUSION

Based on the results of this study, the following conclusions can be drawn:

1. The result of this study with respect to dispersion number and coefficient were evaluated as 0.2117 and 38.1m^2/s by Agunwamba (2001) model; 0.085 and 15.3 m^2/s by Leverspiel and Smith (1957) model and 39.418m^2/s by Deng and Others (2001) model.
2. Contaminant discharged in Otamiri River would be dispersed and well mixed within 200m downstream from the outfall. The contaminants will be dispersed longitudinally as it travels downstream. Such dispersion is induced by turbulence initiated from the shearing effects of Otamiri River channel boundaries and its flow velocity.
3. The threat of a contaminant finding its way in a river upstream of a water supply is still present with us. Whether intentional or accidental, this method of immediately estimating dispersion in rivers is needed by water - resource managers or controllers to arrest or contain any eventual pollution occurrence.
4. Dispersion data could be applied to enhance water quality monitoring and pollution prevention measures. Relying on mathematical models alone cannot immediately be predictive because data from the river must be generated and later used in the model calibration.
5. Without dispersion studies, accurate parameters (dispersion number and coefficients) cannot be obtained. As per this study, longitudinal dispersion coefficient is influenced by hydraulic characteristics of the river. It is therefore necessary to further the study to some distance downstream in order to increase our knowledge of Otamiri River.

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