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Performance of equations for the longitudinal dispersion coefficient: a case study in the Orashi River

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ABSTRACT

Investigation of the water quality of rivers is a key point in Water Resources Engineering. The longitudinal dispersion coefficient is one of the foremost significant parameters in river water quality monitoring. Several parameters such as hydraulic, morphology, total dissolved solids, and total suspended solids are effective parameters in the determination of the longitudinal dispersion coefficient as revealed by this study. The assessment of the river shows mean hydraulic and geometric properties such as flow, depth, velocity, longitudinal slope, and width to be 354.17 m^3/s, 9.61 m, 0.69 m/s, 0.0079,101.63 m and the range of the longitudinal dispersion coefficient as (72–104.4) m^2/s. Results obtained by employing the established equations revealed standard error indices and RMSE of the developed equation, and Kashefipour and Falconer equation gives correlation coefficient of about 0.819 and 4.182 and 0.421 and 12.186, respectively, as coefficient of determination and RMSE, and they are more accurate among the empirical equations. However, the newly derived equation for the longitudinal dispersion coefficient performed better when compared with others, indicating the fitness of the developed equation to estimate longitudinal dispersion coefficient.

Key words: Longitudinal dispersion coefficient, Rhodamine WT, rivers, root mean square error (RMSE), derived equation

HIGHLIGHTS

- The study provides the choice of equation to be used and to understand the influence of total suspended solids and total dissolved solids on the dispersion coefficient.
- The study guides in estimating the assimilatory capacity of a river, that is, the ability of rivers to absorb the pollutants.
- The study provides the required guide for the monitoring of water quality parameters.

INTRODUCTION

The varied difference between the experimental and the predicted dispersion coefficient points to the fact that some other essential parameters might have been ignored during equation development. To enhance the fit of precision of the estimate of longitudinal dispersion coefficient (*D*), identifying other important features that influence the spread of pollutants in the water environment is important. Such parameters include total dissolved solids and total suspended solids. Some pollutants released into streams have different characteristics from dyes and consequently will exhibit different dispersion characteristics.

River contamination has become a global issue and calls for environmental health monitoring of the water environment. Investigation/monitoring of river water quality is an essential water parameter in Water Resources Engineering (Goel 2006; Li *et al.* 2013; Abbas & Amir 2015; Launay *et al.* 2015; Obi 2015; Samuels *et al.* 2015; Ikebude & Agunwamba 2017; Song 2017). As the longitudinal dispersion coefficient gives a description of the spread of river pollution studies, investigation of the longitudinal dispersion coefficient in rivers is regularly carried out by field examinations. Detailed analyses/studies are regularly carried out by injection of tracer in the river water and discretization of stations marked along the river is considered for sampling the river water (McQuivey & Keefer 1974; Harvey 1997; Michael *et al.* 2004; Baek & Seo 2010; Abbas & Amir 2015; Daila *et al.* 2019). During field investigations, it was considered more important that the used tracer material should interact with water and should have no negative effects on the water environment. Another important thing to consider is related to the place of the sampling station. The location of the first station should be considered after completely mixing the trace material in the cross-section of the river flow (Seo & Cheong 1998; Papadimitrakis 2004; Abbas & Amir 2015).

The evaluation or determination of the longitudinal dispersion coefficient has been studied and gives valuable consideration for a long period of time (Liu 1977; Fischer *et al.* 1979; Seo & Cheong 1998; Kashefipour & Falconer 2002; Yuhong & Wenxin 2014; Ikebude & Agunwamba 2017; Song 2017). Various experimental studies have explored different aspects of longitudinal dispersion (Wang & Huai 2016; Imokhai *et al.* 2016; Song 2017). Furthermore, dimensional analysis and regression methods have been applied over time for the development and estimation of the dispersion coefficients. Results usually have a varied range of variations (Fischer 1968; Seo & Cheong 1998; Kashefipour & Falconer 2002).

The study presented in this paper is an estimate of the performance of longitudinal dispersion coefficient equations for Orashi River using developed equations and existing equations.

METHODS

The Orashi River flows through the Egi clan, traversing the regions of Igburu and Egi, located at the heart of Orashi in the Ogba/Egbema/Ndoni Local Government Area of Rivers State, Nigeria. The region has a population of about 241,000 and covers an area of about 920 km^2. For the purpose of this study, our area of interest is the Egi clan, which is made up of 17 communities. The GPS coordinates are as follows: an elevation of 20 m, latitude N05° 14.5221 and longitude E06° 40.1571.

The concentration versus time curves (response curves) were generated immediately after injecting Rhodamine WT dye into the Orashi River. The injection point was chosen along the axis of the channel so the mixing length would be reduced (Fischer 1967, 1968). Sampling was made at discretised points, during which concentrations were determined and settleable particles were also evaluated.

Determination of longitudinal dispersion coefficient estimation

Experimenting with the approach of dye tracers in rivers has been investigated by other researchers (Agunwamba 2001). The method of estimation of dispersion number or dispersion coefficient is usually done by conducting a tracer experiment. There are two main approaches to conducting tracer experiments. The constant distance variable time method and the variable distance constant time method. The constant distance variable time method is the conventional method whereby the tracer is introduced or injected at the inlet of a channel. Samples of the tracer are collected at the channel outlet at regular time intervals until all the tracers have flown out.

This method of sampling is tedious and expensive because of the need to sample continuously until the concentration at the outlet reduces to a significant level. This problem is said to be eliminated by using variable distance–time sampling whereby the channel length is divided into equidistant sampling positions (Agunwamba 2001). This means that samples have to be collected at equal distance positions and equal time intervals. This could be done using a hypodermic syringe to minimize disturbances during the collection process, but if the river is already turbulent, alternative techniques must be employed.

A tracer experiment was conducted by using Rhodamine WT dye. 100 g of Rhodamine WT dye was added to 1 l of water to establish an initial concentration of 100 mg/l, and thereafter, it was instantaneously injected into the centre line of the river. The sample collection commenced following adequate dilution of the sample and the concentration of the samples was determined using an instrument called a JENWAY 6305 UV Spectrophotometer. The samples collected were immediately transferred to the laboratory for analysis, allowing for the determination of the tracer concentration in each sample.

Agunwamba's (1997) approach gives better results upon comparison with Levenspiel & Smith (1957) and Ojiako's numerical model (1988). Therefore, we adopted Agunwamba (1997) concepts in the determination of the experimental longitudinal dispersion coefficient as follows:

From Equation (1), t is the time after injection of a tracer (s); c is the tracer response concentration at the exit stream (mg/l); and θ is the average flow time given by Marecos do Monte & Mara (1987).

$$\bar{\theta} = \frac{\sum_{i=1}^{n} c_i t_i}{\sum_{i}^{n} c_i} \tag{1}$$

If the variable distance variable time approach is employed in the tracer experiment, the corresponding equations for δ and σ^2 is derived by Agunwamba (1997).

$$\delta = \frac{1}{29.2}\left\{\sqrt{1+15\sigma^2}-1\right\} \tag{2}$$

Equation (2) is the dispersion number (δ)
where

$$\sigma^2 = \frac{\sum_{i=1}^{n}\left(\frac{\tau}{1-\xi}\right)^2 c}{\sum_{i=1}^{n} c} - \left(\frac{\sum_{i=1}^{n}\left(\frac{\tau}{1-\xi}\right) c}{\sum_{i=1}^{n} c}\right)^2 \tag{3}$$

where the summation is taken over all the uniformly spaced readings. The parameter $\tau = t/\theta$ and $\xi = x/L$; L is the channel length, x is the distance from the outlet and t is the time after tracer injection.

Therefore, the dispersion coefficient (D) is evaluated using the model given as;

$$D = u\delta L \tag{4}$$

where D is the longitudinal dispersion coefficient, u is the velocity, and L is the length of the river (length measured by distance of river).

Equation (4) was used to estimate the longitudinal dispersion of the river.

Longitudinal dispersion was related to properties of flows (u and U_*), properties of the fluid (density ρ and dynamic viscosity μ), river geometry (B, H), total dissolved solids, and total suspended solids (settleable particles) by method of dimension analysis and regression.

Shear velocity (U_*) estimation

For river flow in the absence of bedforms, the skin friction bed shear stress can be simply related to the bed slope.

The shear velocity is estimated by applying the below equation

$$U_* = \sqrt{gR_hS_o} \tag{5}$$

where g is the acceleration due to gravity (m/s^2), R_h is the hydraulic radius (m), and S_o is the slope.

Based on the fact that experimental data are not available, a rectangular section is assumed and used in the estimation of hydraulic radius.

The flow velocity (U) estimation

Flow velocity was estimated by measuring the distance between sampling sections and the average time of passage tracer cloud on each section.

$$U = \frac{x_2 - x_1}{\bar{t}_2 - \bar{t}_1} \tag{6}$$

Sampling stations are defined as $x_2 - x_1$ and passage average times of tracer as $\bar{t}_2 - \bar{t}_1$.

Let us consider longitudinal dispersion coefficient to be a function of river geometry, hydraulic conditions, fluid properties, total dissolved solids, and total suspended solids (settleable particles).

In this study of longitudinal dispersion coefficient, D_l is said to be dependent of density (ρ), shear velocity (u_*), depth (H), velocity (u), width (W), viscosity (μ), total suspended solid (S_s), and total dissolved solid (D_s). Mathematical correlation is of the form:

$$D_l = f\{\rho,\ u_*, H, u, W,\ \mu,\ S_s,\ D_s\} \tag{7}$$

Applying the dimensional analysis methods of Raliegh and Buckingham's Pi-theorem, which have been used and established as reliable tools, can be used. Equation (9) is derived as follows.

$$f\left(\frac{D_l}{u_*H};\ \frac{u}{u_*};\ \frac{W}{H};\ \frac{\mu}{\rho u_*H},\ \frac{S_s}{\rho}\ \frac{D_s}{\rho}\right)=0 \tag{8}$$

Also,

$$\frac{D_l}{u_*H}=K\left(\frac{u}{u_*}\right)^{a_1}\left(\frac{W}{H}\right)^{a_2}\left(\frac{\mu}{\rho u_*H}\right)^{a_3}\left(\frac{S_s}{\rho}\right)^{a_4}\left(\frac{D_s}{\rho}\right)^{a_5} \tag{9}$$

Linearizing Equation (3), the result is:

$$log\left(\frac{D_l}{u_*H}\right)=logK+a_1\log\left(\frac{u}{u_*}\right)+a_2\log\left(\frac{W}{H}\right)+a_3\log\left(\frac{\mu}{\rho u_*H}\right)+$$

$$a_4\log\left(\frac{S_s}{\rho}\right)+a_5\log\left(\frac{D_s}{\rho}\right) \tag{10}$$

Considering the fact that the flow in natural rivers and channels is said to be fully turbulent and the wall is rough, with Reynolds number effect generally being negligible, the dynamics viscosity in Equation (10) can be ignored (Deng *et al*. 2001; Sinan 2014; Abbas & Amir 2015; Wang & Huai 2016; Song 2017; Daila *et al.* 2019). In order to estimate the impact of the shape factor on the longitudinal dispersion coefficient, a deep investigation or study is required about the bed and wall features of a river. It is important to note that the hydraulic parameters considered in the determination of longitudinal dispersion coefficient, like shear velocity, are established to be related to the shape factor. Kashefipour & Falconer (2002) have shown that the dimensional analysis has revealed several combinations of hydraulic parameters that can establish the same dimension of the longitudinal dispersion coefficient.

Therefore, Equation (10) can be written in the following form

$$Y=a_0+a_1X_1+a_2X_2+a_3X_3+a_4X_4 \tag{11}$$

Substituting the determined hydraulic parameters, total dissolved solids, and total suspended solids into Equation (11), following equation is established:

$$\frac{D_{l,p}}{HU_*}=1.365\left(\left(\frac{U}{U_*}\right)^{0.944}\left(\frac{W}{H}\right)^{-0.012}\left(\frac{S_s}{\rho}\right)^{-0.062}\left(\frac{D_s}{\rho}\right)^{0.044}\right) \tag{12}$$

Equation (12) is obtained for $D_{l,p}$ for the Orashi River and rivers of the same hydraulic characteristics.

Average values of total suspended solids and total dissolved solids determined in the study were taken and substituted in Equation (12), therefore, Equation (13) is transformed as follows

$$D_l=\ 21.158HU_*\left(\frac{U}{U_*}\right)^{0.944}\left(\frac{W}{H}\right)^{-0.012} \tag{13}$$

Equation (13) is the modified equation for the longitudinal dispersion coefficient developed.

The derivation of Equation (13) resulted in an R^2 value of 0.974, adjusted R^2 of 0.970 with a standard error of regression as 0.032 and RMSE of 0.028. The fitted model is valid for estimating the assimilatory capacity of the longitudinal dispersion coefficient of the Orashi River, and rivers of similar hydraulic characteristics. The developed equation is in a form similar to that reported by Seo & Cheong (1998), Devens *et al.* (2006), Vanessa Vaz de *et al.* (2017), Ikebude & Agunwamba (2017), Kashefipour & Falconer (2002) and Liu (1977) (Table 1).

Table 1 | Derived equations

Derived equations	Author	Symbols	Row
$D_l = 5.93Hu_*$	Elder (1959)	ED	1
$\frac{D_l}{u_*H} = 5.915\left(\frac{B}{H}\right)^{0.620}\left(\frac{U}{u_*}\right)^{1.428}$	Seo & Cheong (1998)	SC	2
$D_l = 10.612\,HU\left(\frac{U}{u_*}\right)$	Kashefipour & Falconer (2002)	KF	3
$D_l = \frac{3.1938B^{0.9229}V^{1.1275}}{u_x^{0.3516}\ H^{0.01470}}\left(\frac{T_a}{T_R}\right)^{0.6567}$	Ikebude & Agunwamba (2017)	IA	4
$D_l = 3.55\ 10^{-4}\frac{U^{-0.793}B^{0.739}}{H^{1.610}\ S^{0.026}}$	Devens *et al.* (2006)	D	5
$D = 11.0071HU\left(\frac{u}{u_*}\right)$	Obi (2015)	O	6
$D_l = 0.058\frac{HU}{S}$	McQuivey & Keefer (1974)	MK	7
$D_l = \beta R_h U$	Sinan (2014)	S	8
$D_l = 0.\ 011\left(\frac{W^2}{H}\right)\left(\frac{U^2}{U_*}\right)$	Liu (1977)	L	9
$D_l = 0.744\frac{H^{0.036}U^{1.59}}{u_*^{2.22}\ B^{0.66}}$	Vanessa Vaz de *et al.* (2017)	V	10
$D_l =\ 21.158HU_*\left(\frac{U}{U_*}\right)^{0.944}\left(\frac{W}{H}\right)^{-0.012}$	Derived equation	UA	11

RESULTS AND DISCUSSION

The precision of the selected equations is shown in Figures 1–5, where values for longitudinal dispersion coefficients, both predicted and measured, are depicted. These values were generated from data gathered during field studies such as hydraulic properties, total dissolved solids, and total suspended solid. Figure 1 shows the results of the derived equations versus the measured data, and studies revealed the standard error indices such as coefficient determination (R^2) and root mean square of error (RMSE). The analysis revealed a derived equation. Seo & Cheong (1998) and Kashefipour & Falconer (2002) give R^2 and RMSE as 0.819, 0.407, and 0.421 and 4.182, 20.991, and 12.186, respectively, as shown in Figures 1–5, and results of existing equations are confirmed as reported by Abbas & Amir (2015) except the newly derived equation. Overall, assessing the performance of the derived equations for the longitudinal dispersion coefficient shows that these equations have an unacceptable level of accuracy. Thus, they are not suitable to be used in managing and monitoring river assimilatory capacities

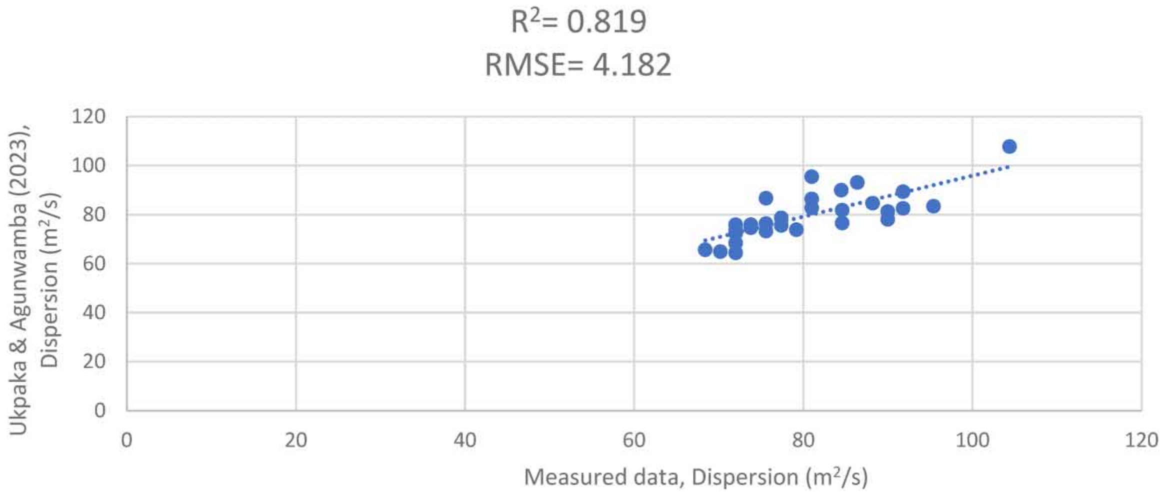

Figure 1 | Data from derived equation versus measured data dispersion.

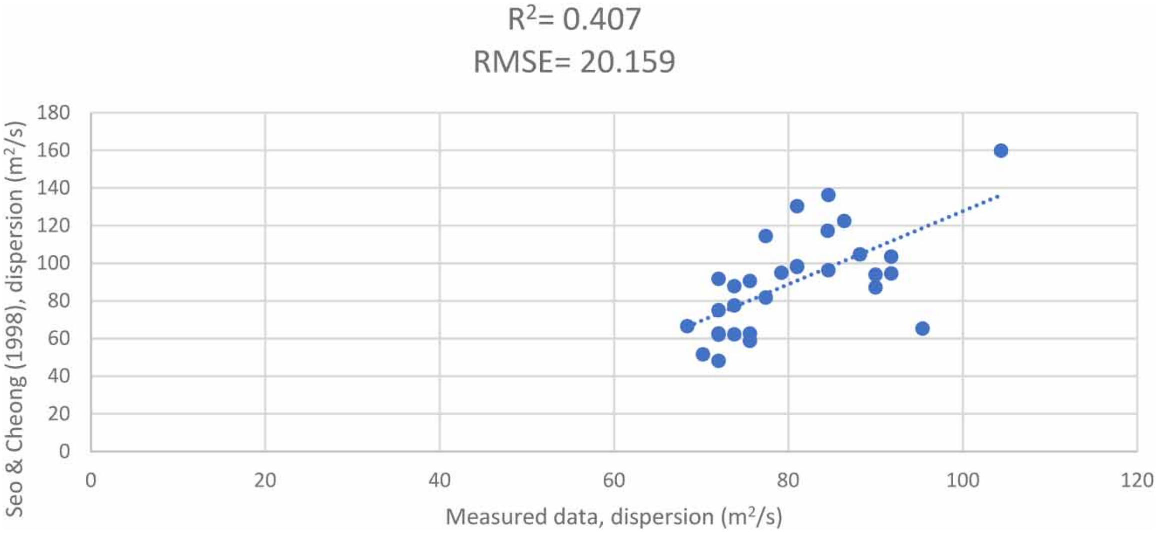

Figure 2 | Data from Seo & Cheong (1998) versus measured data dispersion.

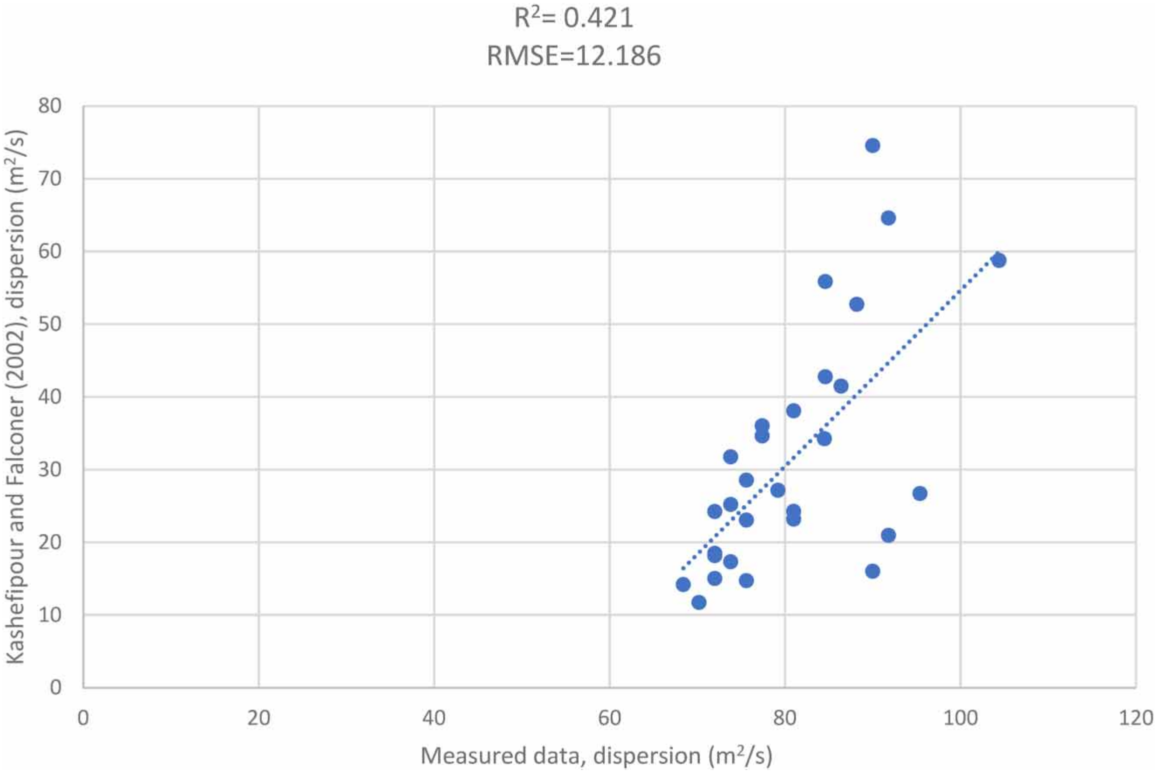

Figure 3 | Data from Kashefipour & Falconer (2002) versus measured data dispersion.

and addressing pollution transport iisues within the Orashi River. This underscores the fact that applications of empirical equations should be wisely applied in rivers of the same hydraulics characteristics (Table 2).

Performance of the derived equations to calculate the D_l

Table 3 presents the commonly used empirical equations and newly developed equation for the longitudinal dispersion coefficient for the Orashi River and rivers of the same hydraulics characteristics.

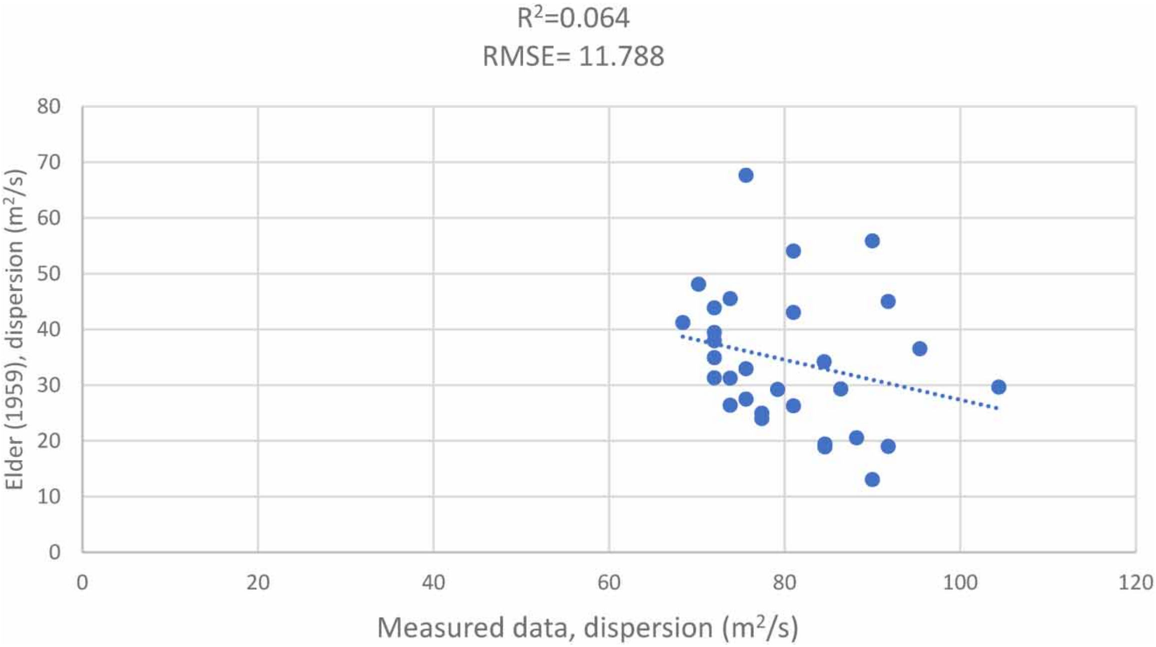

Figure 4 | Data from Elder (1959) versus measured data dispersion.

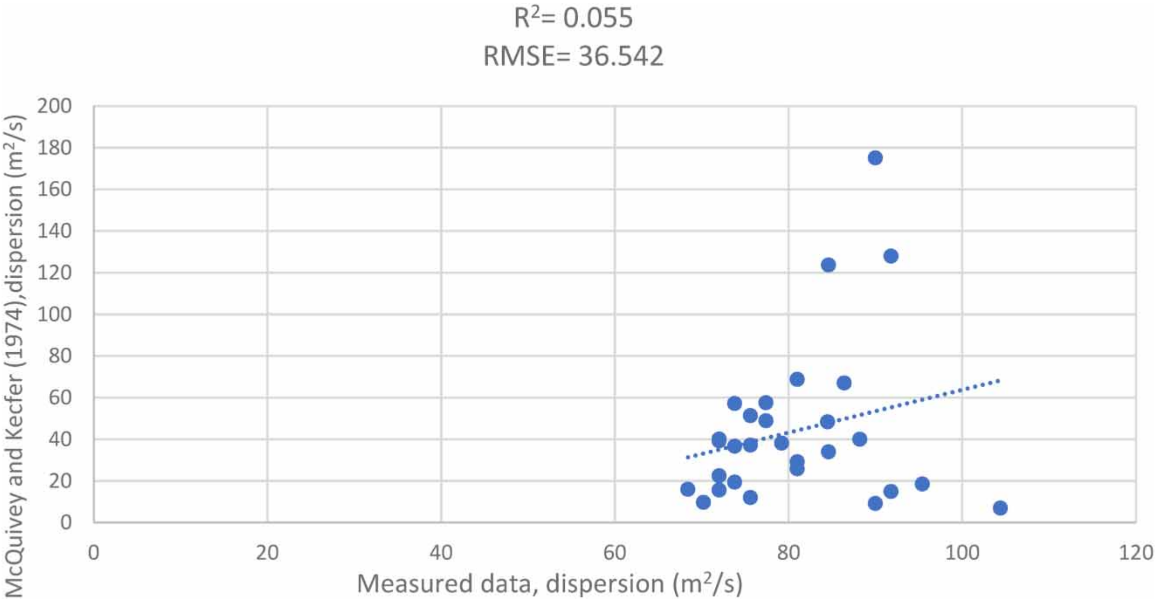

Figure 5 | Data from McQuivey & Keefer (1974) versus measured data dispersion.

CONCLUSION

In this investigation, some established equations in Table 1 were selected for the purpose of estimating the longitudinal dispersion coefficient (D_l) for the Orashi River and rivers of the same properties. For this reason, experimental data for the Orashi River were generated. Results obtained by employing the established equations revealed standard error indices and RMSE of the developed equation, and Kashefipour & Falconer (2002) give correlation coefficients of about 0.819 and 4.182 and 0.421 and 12.186, respectively, and they are more accurate

Table 2 | Summary of hydraulic properties, experimental longitudinal dispersion coefficients due to Rhodamine WT experiment

		Hydraulic measurements and $D_{l,e}$ data				
Stations	**Distance (m)**	***W* (m)**	***H* (m)**	***U* (m/s)**	**U_*(m/s)**	**$D_{l,e}$(m/s^2)**
P0	0	76.0	8.77	0.43	0.48	77.4
P1	100	120.0	9.15	0.48	0.54	86.4
P2	200	130.0	9.07	0.45	0.80	81
P3	300	115.0	7.99	0.38	0.87	68.4
P4	400	115.50	8.91	0.40	0.83	72
P5	500	135.0	9.91	0.45	0.92	81
P6	600	128.0	7.54	0.50	1.25	90
P7	700	114.4	8.08	0.44	0.61	79.2
P8	800	117.00	8.64	0.41	0.61	73.8
P9	900	1,318	9.15	0.47	0.63	84.5
P10	1,000	129.0	8.65	0.40	0.61	72
P11	1,100	124.0	9.09	0.58	0.53	104.4
P12	1,200	120.0	7.59	0.51	1.00	91.8
P13	1,300	122.0	8.65	0.41	0.89	73.8
P14	1,400	95.0	7.53	0.40	0.85	72
P15	1,500	95.4	9.43	0.42	1.21	75.6
P16	1,600	86.0	7.65	0.39	1.06	70.2
P17	1,700	86.0	8.53	0.40	0.78	72
P18	1,800	56.5	8.90	0.41	0.50	73.8
P19	1,900	56.5	8.43	0.42	0.55	75.6
P20	2,000	56.5	7.96	0.40	0.74	72
P21	2,100	118.5	8.54	0.42	0.65	75.6
P22	2,200	145.5	8.86	0.45	0.50	81
P23	2,300	134.0	8.43	0.43	0.48	77.4
P24	2,400	120.2	8.62	0.47	0.37	84.6
P25	2,500	76.9	7.98	0.47	0.41	84.6
P26	2,600	50.44	7.85	0.50	0.28	90
P27	2,700	76.84	8.45	0.49	0.41	88.2
P28	2,800	64.00	8.65	0.51	0.37	91.8
P29	2,900	53.00	7.42	0.53	0.83	95.4

Table 3 | Performance of empirical equations to estimate D_l

Derived equations	**Author**	**R^2**	**RMSE**
$D_l = 21.158HU_*\left(\frac{U}{U_*}\right)^{0.944}\left(\frac{W}{H}\right)^{-0.012}$	Derived equation	0.82	4.18
$\frac{D_l}{u_*H} = 5.915\left(\frac{B}{H}\right)^{0.620}\left(\frac{U}{u_*}\right)^{1.428}$	Seo & Cheong (1998)	0.41	20.17
$D_l = 10.612HU\left(\frac{U}{u_*}\right)$	Kashefipour & Falconer (2002)	0.42	12.19
$D_l = 5.93Hu_*$	Elder (1959)	0.06	11.79
$D_l = 0.058HU/S$	McQuivey & Keefer (1974)	0.05	36.54

among the empirical equations. However, a newly derived equation for the longitudinal dispersion coefficient, Equation (8), performed better when compared with others. The variation between experimental results and empirical equations results for the longitudinal dispersion coefficient can also be attributed to the uniqueness of rivers.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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