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Effect of Bends on Dispersion in Channels

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ABSTRACT: Bend is fundamental characteristic of rivers and streams which induce flow patterns that distort equilibrium and affect longitudinal dispersion in none consonance with straight channel flows. This research is aimed at finding out how this common feature of rivers affect dispersion of pollutants. This was done by observing the pattern of concentration-time curves from tracer experiments. For this purpose four out-door channels were constructed - two of them straight and two having two and three meanders respectively. Tracer experiments were conducted on all four channels at different velocities. Results showed sharp drops in the concentration peaks and skewed patterns for the plots of the meandering channels against high peaks and Gaussian plots for straight channels. This implies that meanders increase mixing and undermine Gaussianity indicating that equilibrium is disturbed, therefore the one-dimensional advection-dispersion-equation (ADE) is not applicable in modeling dispersion in bends. The factor that affects dispersion in meandering channel is the geometric configuration in bends that induces centrifugal forces that slow down longitudinal velocity on one hand, and enhance transverse mixing on the other. Results also showed that the dispersion coefficient of meandering channels is several times higher than those of straight channels. Therefore plug flow is far more possible in straight channels than it is in meandering flows. It was also observed that dispersion coefficient is not always proportional to velocity because of the effect of dead zones that retard stream-wise transport movement that aid dispersion, consequently reducing average longitudinal velocity. This is believed to be one reason for disparity between the measured and predicted values of dispersion coefficient. Inclusion of the effects of bends in dispersion coefficient models will improve its accuracy for use in design of treatment units, pollution control and surface water management thus leading to better water pollution control and consequent improvement in environmental and health challenges.

KEYWORDS: equilibrium, disparity, gaussianity, meandering, peak concentration, stream-wise, velocity

I. INTRODUCTION

Dispersion is the predominant transport mechanism in the mixing and dilution of pollutants in streams and rivers and remains the major means of defining pollutant transport in these water bodies [1],[2],[3]. Accurate determination of the parameter is thus essential to the engineer [4] for the design of treatment units such as waste stabilization ponds and aerated lagoons, intake works and spill modeling to determine the amount of waste a water course can contain without causing aquatic kill. Its effect is usually measured through tracer studies by which the coefficient of dispersion (D) or its dimensionless equivalent called dispersion number, d , is determined. Dispersion coefficient is a most basic factor of measurement in hydraulic modeling of pollution in rivers and its accuracy is important to measure the characteristic behavior of pollutants in a natural river and to determine water quality [5], [6]. Several models for the determination of dispersion coefficient in both straight and meandering channels have been developed by many researchers all over the world. However, none has resulted in accurate predictions owing to the complexity of the phenomenon [7], [5]) and the cause of the differences in results are scantily known.

II. LITERATURE REVIEW

Flow through Open Channel Bends

Open channel flow around bends is a complex flow pattern that commonly occurs in natural channels [8]. The common characteristics of such a flow include flow separation, transverse flows, losses in energy and variations in water

surface mainly caused by the curvature of the bend [9] Secondary flow is known to enhance velocity which in turn together with the meander effects enhance hydraulic mixing of pollutants.

The presence of centrifugal force is the most influential factor of flow through bends in open channels. This causes two contrasting effects on the flow: transverse acceleration on one hand and longitudinal flow deceleration on the other. Mixing is enhanced at every bend because of flow inversions. Spiral motion induced by bends will continue downstream of the exit of the bend and thereby act as the disturbance at subsequent entry into the next region. Einstein and Harder [10] referred to the spiral motion in bends as imbalance between centrifugal and transverse pressure forces. Experimental results by Ruonan et al [8] show that the flow begins to redistribute before entering the bend and it takes long distance to re-establish to uniform conditions after exiting the bend. These conditions do not permit equilibrium within or near the bend exit.

At the entry of flow into a bend, the centrifugal force emanating from the curvature of the channel produces a slope across the channel in the surface of the water. The interaction between centrifugal force and lateral pressure gradient causes secondary flows in the cross-section and the secondary flows spread further by moving along the bend. Hence, at the bends, these processes lead to longitudinal velocity increase in the outer wall and decrease in the inner wall [11]. Secondary flows around pronounced curvatures are generally responsible for large magnitude of transverse circulation combined with the principal longitudinal flow. Pollutant dispersion by secondary current may therefore not be adequately described by the streamline direction only as there is dispersion effect in the stream-wise direction that is considered much more effective than the transverse turbulent diffusion [12]. Secondary flow is basically flow in the plane perpendicular to the primary flow direction and it tends to decrease longitudinal dispersion.

Dead zones are generally associated with occurrence of secondary currents. What tends to happen is that as the flowing water hits the channel bend at the outer wall, a portion of the water runs tangential to the wall while some form a vortex or even a reverse flow. At the channel wall the liquid adheres to the boundary forming a boundary layer (with negligible velocity) this liquid has very negligible forward momentum that the adverse pressure gradient can stop it or even reverse the flow creating a dead zone of negligible velocity at the bend. Dead zone is thus one of the characteristics of flow around bends.

Trends in Development of Dispersion Models

The earliest known published work on longitudinal dispersion was by Taylor [13]. His concept of classical diffusion equation being appropriate to describe the spreading out of a mass of pollutant measured by an apparent diffusion (or dispersion) equation had wide acceptance even for flows in natural streams for which it was not initially intended. Taylor showed that longitudinal dispersion in a long straight pipe may be described by the one-dimensional diffusion equation, in which the diffusive and convective processes occurring throughout the cross-section interact to produce a longitudinal dispersion coefficient [14]. Taylor's equation was

$$D = 10.1RU_* \quad (1)$$

Where R is pipe radius and U_* is shear velocity.

The shape of tracer cloud is affected mainly by velocity variations across the channel when a pollutant is introduced into it. Taylor [13] suggested that the shear velocity and the transverse mixing are in equilibrium after a certain time scale (convective period) at some point downstream. Beyond this point, Fickian diffusion equation can be used to model the tracer cloud concentration. The one-dimensional dispersion equation as originally formulated by Taylor expresses the concept of a dispersing cloud of tracer following the bulk diffusion equation [14] and given as

$$D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} \quad (2)$$

D = tracer longitudinal or axial dispersion coefficient; U, velocity in the longitudinal(x) direction; C, pollutant concentration and t is time.



If the tracer cloud is introduced in the plane $x = 0$, the solution of equation (2) is

$$C = \frac{M}{\sqrt{4\pi Dt}} \exp(-A) \left[\frac{x-ut}{4Dt} \right]^2 \tag{3}$$

Where M = Total mass of tracer; A = Cross-section area of flow normal to x

Elder [15]) published the first application of Taylor’s work to infinitely wide open channel based on laboratory measurement in which he assumed a logarithmic vertical velocity profile in the vertical direction and obtained a simple expression for dispersion coefficient D, as

$$D = 5.93HU_* \tag{4}$$

Or

$$D = \left[\frac{0.4041}{K^3} + \frac{K}{\sigma} \right] HU_* \tag{5}$$

U_* = average bottom shear velocity along the wetted perimeter on the cross- section.

H = average flow depth; K = Von Karman constant which is approximately 0.41.

For its simplicity and strong theoretical base, Elder’s equation found wide acceptance. However, over time, it has been shown that the model does not accurately predict longitudinal dispersion in natural streams and channels because there were large discrepancies between field measurements and calculated values and consequently its acceptance has waned.

While Elder neglected transverse variations, Fisher neglected vertical variations and obtained the well-known triple integral equation.

$$D = -\frac{1}{A} \int_0^B hu' \int_0^y \frac{1}{\epsilon h} \int_0^y hu' dy dy dy \tag{6}$$

Where D = Dispersion coefficient; B = Width of stream at the free surface; H = Local depth of flow; U' = Partial derivation of the velocity from the cross-sectional; U = Mean flow velocity; ϵ = Transverse or lateral turbulent dispersion coefficient; y = Lateral Cartesian coordinator of the observation point from left bank of the stream.

Following the short falls of equation (6) Fischer et al. [16] developed a simpler expression for D by introducing a reasonable approximation for the triple integral, velocity deviation and transverse turbulent diffusion coefficient [16].

$$D = \frac{0.07U_*^2 L^2}{\epsilon y} \tag{7}$$

Where L is distance from point of maximum velocity to the most distant bank. From laboratory experiment, Fischer found U^2/U_*^2 varied from 0.17 to 0.25 with a mean value of 0.2 and L typically equal to 0.7W. By substituting these two values and setting $\epsilon_y = 0.6HU_*$ they concluded,

$$D = \frac{0.011U^2}{HU_*} \tag{8}$$

Studies have shown that the magnitude of dispersion coefficient is higher in sinuous rivers than in straight courses (Fakouku and Sayre, [17], and that it increases as radius of curvature increases, but decreases with increasing bend length and depth (Guymer, [18]; Tayfur and Singh [19] and Sahay[20] suggested that channel sinuosity (S_i) improved predictive accuracy of models. Sahay (2013) expressed dispersion coefficient as

$$\frac{D}{HU_*} = 2 \left(\frac{B}{H} \right)^{0.75} \left(\frac{U}{U_*} \right)^{1.37} S_i^{1.52} \tag{9}$$

The effect of sinuosity has been investigated by Fakouku and Syre [17] using laboratory flume with various bending conditions. Amir and Milad [7] observed that the dispersion coefficient is larger and the initial convective period is shorter than those of equivalent straight channels. Other investigation with similar results include Bashitialshaaeret al. [21]; Guymer [18]; Boxall et al.[22]; Boxall and Guymer [23].

The major difference between flow in meandering and straight channels is the presence of centrifugal force at the bend. Along the line of meandering in the channel there are dead zones where the water gets isolated from running with the water in the main channel and the more or less still water in these dead zones influences the mixing along the stream. Dead zones not only increase the rate of dispersion but also delay the occurrence of fickian type diffusion (EteinidShahidi et al. [24]) and would generally not sustain Taylor's theory.

Experiment on the interaction between main flow and secondary flows show that the transverse transport of main flow momentum by secondary circulation is the principal cause of velocity redistribution and the deflection of maximum velocity toward the outer wall of the channel occurs at the cross-section where the secondary flow reaches its maximum strength (Bai et al.[25]; Farhadi et al. [26]; Tang and Night, [27]; Abhari et al.[28];Gbolami et al. [29]. A large cross sectional variability of primary velocity component tends to increase longitudinal dispersion by providing a large difference between adjacent fast and slow moving zones of fluid. By contrast, secondary circulation tends to decrease longitudinal mixing by enhancing transverse mixing (Marion and Zaramella[30], (Fakouku and Sayre, [17]) observed that Channel curvature reduces longitudinal mixing. Their equation is

$$\frac{Dr}{hu*} = 1.0 \left(\frac{br^3}{L^2h^2} \right)^{0.86} \text{ and } \frac{Dr}{RuU*} = 0.8 \left(\frac{r^2}{Lh} \right)^{1.4} \quad (10)$$

Where h = water depth; U = shear velocity; r = radius of curvature; R_h = hydraulic radius; and L = bend length.

Noori [31] affirmed that the accuracy of D_L estimation could be improved by accounting for curvature and that aspect ratio showed greater input on D_L than friction factor. Some of the most recent empirical models include those of Li et al [32] and Wang and Huai [33].

$$\text{Li et al (2013)} \quad \frac{D}{HU_*} = 2.82 \& \left(\frac{W}{H} \right)^{3.7613} \left(\frac{U}{U_*} \right)^{1.4713} \quad (11)$$

$$\text{Wang and Huai (2016)} \quad \frac{D}{HU_*} = 17.648 \left\{ \frac{B}{H} \right\}^{0.3619} \left(\frac{U}{U_*} \right)^{1.16} \quad (12)$$

There is nothing fundamentally wrong in the development of all the equations mentioned above. Their major short-coming is the omission of certain parameters believed to affect dispersion, especially for channels with bends or that are sinuous in nature. Such parameters include radius of curvature, sinuosity, hydraulic radius, effects of obstacles to flow etc. Why is there large disparities between measured and predicted values by these models? It will be observed that almost all the models have longitudinal velocity in them proportional to longitudinal dispersion coefficient. This means that all else being constant, dispersion coefficient should increase as velocity increases. However this is not always practically so even for experiments in the same channel of uniform cross section. The effects of friction and centrifugal force generated at bends cause random velocity variations that distort progressive increase of dispersion coefficient with increase in velocity. Thus longitudinal velocity may be small relatively, but results in relatively higher dispersion coefficient. This, in addition to omission of fundamental parameters, is believed to be reason for disparities.

III. MATERIALS AND METHODS

Study Area

The study location is the engineering campus of Kenule Beeson Saro-wiwa Polytechnic, Bori. Bori is a town located in Khana local government area of Rivers State in southern Nigeria at latitude of 4° 40'34.64"N and longitude 7° 21'54.68"E

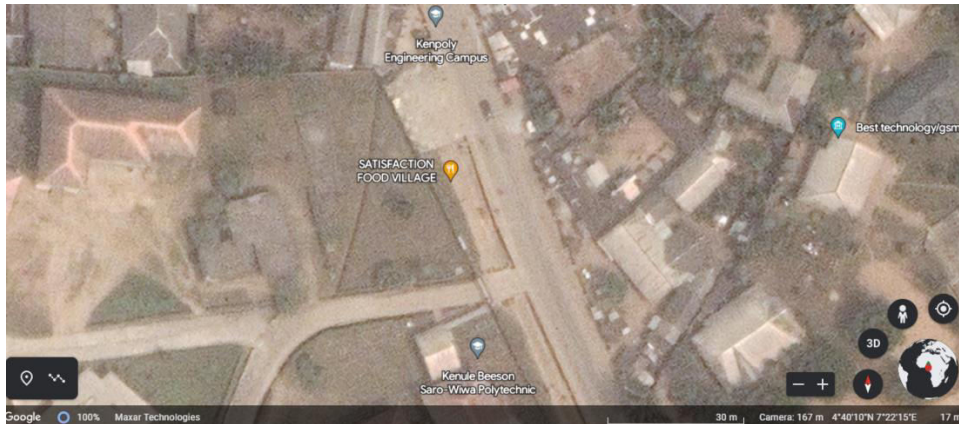


Figure 1. Google Map of Study Area

The materials used in carrying out this research includes out-door channels constructed with sandcrete blocks, sodium chloride as tracer, current meter, steel tape, borehole, and chemistry laboratory. The method used in developing the model is Buckingham π theorem of dimensional analysis.

Experimental Setup

Series of S shaped sinusoidal configurations were made from the overall curvilinear length of the channels was L and straight length was $15.0m$. All channels were constructed in approximately equal slope. Channel shape was basically rectangular at the beginning and end but circular at the various meandering sections. Channel width was $0.2m$ and $0.4m$ while depth variations ranged between $0.2m$ to $0.3m$. The channel was allowed to develop for between 5 and 10 minutes and then uniform flow was maintained before the tracer was introduced and while samples were taken.

All channels were linked to the smaller reservoir which supplied water to them through a $75mm\phi$ pipe fitted with ball valve to control flows. This also regulated velocity of flow once channel was fully developed. Water was supplied to reservoir A from a borehole drilled for that purpose. Reservoir A when half full was made to fill reservoir B from which the channels were developed. This way constant head was maintained in both reservoirs B and the channels. All four supply sources were run concurrently (i.e the borehole-tank A- tank B channel) to maintain a constant head.

Salt solution was made by thoroughly mixing 40grams of sodium chloride (common salt) with 200ml of water. This was used as the tracer material. This solution was introduced at $1.5m$ away from the channel feed point to reduce the effect of turbulence generated by the turbulence generated at the point of supply from tank B. Samples were collected at the channel outlet. Some time in seconds corresponding to twice the detention time was allowed to elapse before the commencement of sample collection. Sampling times were predetermined at regular intervals, constituting constant-distance, variable-time method of sampling. Measurement of velocity was by use of water current meter. Time measurement was by stop-watch. A meter tape was used in measuring water depth. Ten persons were lined up to take samples at the stipulated times.

The channels were constructed of sandcrete walls and floor and sloped. The floor was covered with a layer of river sand. Grass and mold were allowed to grow on the floor and walls before the experiment were performed. These were meant to, as much as possible, mimic natural river conditions. The channels were models of the Kaani river stretch from Yeghe in Gokana local council ($4^{\circ}39'35''N$ $7^{\circ}16'57''E$ to Wiyakare in Khana local council ($4^{\circ}42'N$ $7^{\circ}21'E$) all in the Nigeria's south-south state of Rivers. The river has some bends along the stretch that are difficult to measure. The velocities, and hence water depth, were varied arbitrarily for the purpose of this study. The study area experiences frequent rains between March and late September causing frequent variations in velocity. The sand mining activities upstream also fluctuates velocity. The data obtained in these experiments can therefore compare favorably with those of natural streams of similar features.

Influence of velocity on channel bends

As water flows through meanders, momentum is developed. As it approaches the bend, it has the tendency to proceed in its straight course. However, the walls of the channel force the water to flow through the bend by exerting a reactive force on it in accordance with Newton's first and third laws of motion. Channel walls often not being able to

withstand this excessive forces, cave in, leading to enlarged radius of curvature of the bend thereby increasing bend radius.

Considering a portion of a channel of uniform cross-section (i.e prismatic) as in fig (1) which changes direction only in the horizontal plane (i.e it meanders but no changes in elevation on the centerline) it will be observed that the velocity of flow increases as θ decreases (i.e towards the outside of the bend and the pressure corresponding to the point of measurement of velocity also decreases towards the outside of the bend

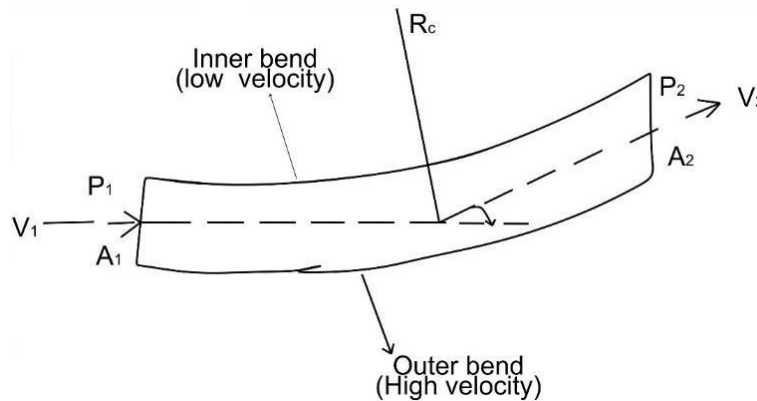


Figure 2. Influence of bends on velocity in channels

Assuming a control volume as shown in figure 1 above, a momentum statement may be written as:

The algebraic sum of external forces $(\sum f)$ acting on the liquid in the control volume in a given direction = Rate of change of momentum in the given direction as a result of the fluid passing through the control volume, $\rho Q(V_2 - V_1)$

Mathematically, the above statement may be written for x and y directions as:

$$\sum F_x = \rho Q(V_2x - V_1x) \tag{17}$$

$$\sum F_y = \rho Q(V_2y - V_1y) \tag{18}$$

Assuming no loss in momentum, equation (11) may be written for the x direction (i.e in the stream-wise direction) as:

$$P_1A_1 - P_2A_2\cos\theta = \rho Q(V_2\cos\theta - V_1) + F_{RX} \tag{19}$$

Assuming there is no deformation of the wall of the channel in which case F_x may be assumed negligible, so that $F_{RX} = 0$, hence

$$P_1A_1 - P_2A_2\cos\theta = \rho Q(V_2\cos\theta - V_1) + F_{RX} \tag{20}$$

Since $A_1 = A_2$ and $V_1 = V_2$

$$A(P_1 - P_2\cos\theta) = \rho QV(\cos\theta - 1) \tag{21}$$

$$\therefore V = \frac{A}{\rho Q} \left[\frac{P_1 - P_2\cos\theta}{\cos\theta - 1} \right] \tag{22}$$

$$P_2 > P_1$$

$$V = \frac{A}{\rho AV} \left[\frac{P_1 - P_2\cos\theta}{\cos\theta - 1} \right]$$



$$V^2 = \frac{1}{\rho} \left[\frac{P_1 - P_2 \cos\theta}{\cos\theta - 1} \right]$$

$$V^2 = \frac{F_c R}{M} = \text{angular velocity}$$

Where F_c = centrifugal force; R = Radius of curvature; M = mass

$$\therefore \frac{F_c}{M} = \frac{1}{\rho R} \left[\frac{P_1 - P_2 \cos\theta}{\cos\theta - 1} \right] \tag{23}$$

In terms of shear stress and at any instant, that is, at t = unity,

$$V = \frac{1}{\rho R} \left[\frac{\tau_1 - \tau_2 \cos\theta}{\cos\theta - 1} \right] \tag{24}$$

IV. EXPERIMENTAL RESULTS

Table 1. Variation in velocity with changes in (θ)

Angle (θ)	0°	30°	45°	60°	90°
$\cos\theta$	1	$\frac{\sqrt{3}}{2}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{2}$	0
Velocity	0	0.8660	0.7071	0.5	0
Velocity	0	0.8660	0.7071	0.5	0

At the exit of the bend, the gradient is positive near the interior wall and negative close to the exterior wall. The free surface slope decreases towards the bend exit until it may gradually become zero at the end of the bend.

Equation (24) shows that:

- (i) As θ increases, shear stress increases and velocity decreases
- (ii) As the radius of curvature increases, velocity decreases. This means that if the walls are unable to stand the pressure forces, there will be deformation leading to increase in radius of curvature with the corresponding decrease in velocity. For a large enough curvature, there will be a point of reverse flow or negligible velocity called dead zone. Intensity of the centrifugal force also increases as θ increases.

As a result of (i) above, it can be seen that velocity will be low towards the inside wall and high towards the outer wall.

Channel flow condition is determined by the Froude number given as

$$Fr = \frac{u}{\sqrt{gH}}$$

Where u is flow velocity, g is gravity and H is water depth of channel. The flows in the experiments are subcritical. The longitudinal dispersion coefficient (D) representing the actual or measured dispersion ability of the channel was determined by the Levenspiel and Smith method [37]. The procedure for computation of D by this method is as follows:

Determine the dispersion number (d) by

$$d = \frac{1}{8} \left[\sqrt{8\sigma^2 + 1} - 1 \right]$$

Where $\sigma^2 = \frac{1}{T^2} \left[\frac{\sum C_i t_i}{\sum C_i} \right] - \left[\frac{\sum C_i t}{\sum C} \right]^2$

t is time taken after injection of tracer, C is tracer concentration at exit of channel (mg/l), T is average flow time (Marcos de Monte and Mara, 1987) given as actual detention time and is given as

$$T = \frac{\sum C_i t_i}{\sum C_i}$$

Dispersion coefficient D was determined by $D = uL$
L = length of channel.

Distance downstream from point source beyond the convective period is equivalent to (Fischer, 1968), $Lt \geq \frac{1.8L_0^2}{RU}$

Where L is distance from point source beyond the convective period (that is to the point where Taylor's one dimensional dispersion equation begins to apply), L_0^2 is characteristic width of channel, R is hydraulic radius (Area/wetted perimeter) and U is mean flow velocity

Figures 3 -6 are plots of experiments 1- 10 for each of channels of 2 and 3 meanders and experiments 1 – 7 for each of the straight channels 1 and 2 respectively. The concentration-time data for these plots are shown in appendices A- D. The curves of the meandering channels show large drops in concentration peak compared to the drops in concentration peaks of the straight channels. This implies that mixing is effected much more in the meandering channels indicating that meanders improve mixing. It is observed that the concentration peaks in straight channels are tens of times higher than those in the meandering channels, indicating plug flow in straight channels as against mixed flow in meandering channels. This is supported by their dispersion numbers shown in table 5. Meanders constantly create regions of higher concentration (at the outside of the bend) and regions of lower concentration (at the inside of the bend) and would therefore continually disturb equilibrium of concentration in contrast to the assumption in the ADE. This implies that skew cannot be eliminated as seen in the figures. Meanders undermine gaussianity because they do not create spatial profile influences in which the one dimensional Advection-Dispersion-Equation may apply. Consequently, ADE is not applicable to channels with bends. Equations that have their development based on the ADE will therefore have not yield good result of dispersion coefficient for channels with bends. This may be one reason for large disparity between measured and predicted values of D in many dispersion coefficient models. Therefore dispersion in meandering channels cannot be determined by any equation that is based on the ADE. Plug flow conditions show perfect hydraulic conditions that imply high efficiency in the mixing and treatment required in ponds for effective performance. Treatment plants are better straight and of uniform cross section.

Experiments of channels of 2 meanders

These set of experiments were performed in channel of 2 meanders. All the experiments in this channel showed common characteristics that included (1) Poor Gaussianity as indicated by the skew that is common to all. (2) Relatively small concentration values in between sampling times observed in all figures show that the channels could cause sharp and sudden drops in concentration values. These sharp drops indicate good mixing, a characteristic associated with mixed flow regimes. The implication of this result is that meanders aid mixing and can create mixed flow conditions. This is in agreement with the observation of Pein, et al, [38]. Some of the experiments showed non-proportionate increase in dispersion coefficient as mean flow velocity increased, a result that disagrees with the direct proportionality of velocity to dispersion coefficient as seen in many models of dispersion. The dispersion coefficient of experiment 1 was estimated at 0.2287m²/s at a velocity of 0.23m/s and that of experiment 2 was 0.149m²/s at a velocity of 0.252m/s. It is observed that the dispersion coefficient dropped from the value obtained in experiment 1 even though the velocity in later experiment was higher. This situation is also seen between experiments 5 and 6; and in S1 experiments, between 2 and 3; 5 and 6; 6 and 7. In S2 experiments, the condition is seen in experiments 3 and 4; and 4 and 5. This can be explained by the interplay between transvers shear and longitudinal velocity. At high shear velocity usually created at bends and bottom friction, longitudinal dispersion diminishes, and mixing increases. This is evident in the reduction in the sum of concentration values between the pair of experiments and may be completely incidental. It shows two things

1. That the effect of transverse velocity can be more in some flows in the same channel, usually because of obstructions that cause change in velocity, turbulence and unpredictable increase in centrifugal force.
2. That longitudinal dispersion coefficient cannot be said to be proportional to longitudinal velocity when velocities of experiments 1 and 2; 5 and 6 etc are compared. This situation may be caused by effect of reverse flow as the water hits the walls of the channel at the bend and by secondary currents developed at the bends, or by the effect of dead zones and the factors mentioned in 1 above. This reduction in velocity is considered to be one of the causes of disparity between measured and predicted results of dispersion coefficient as velocity is always included in the equations as directly proportional to D.

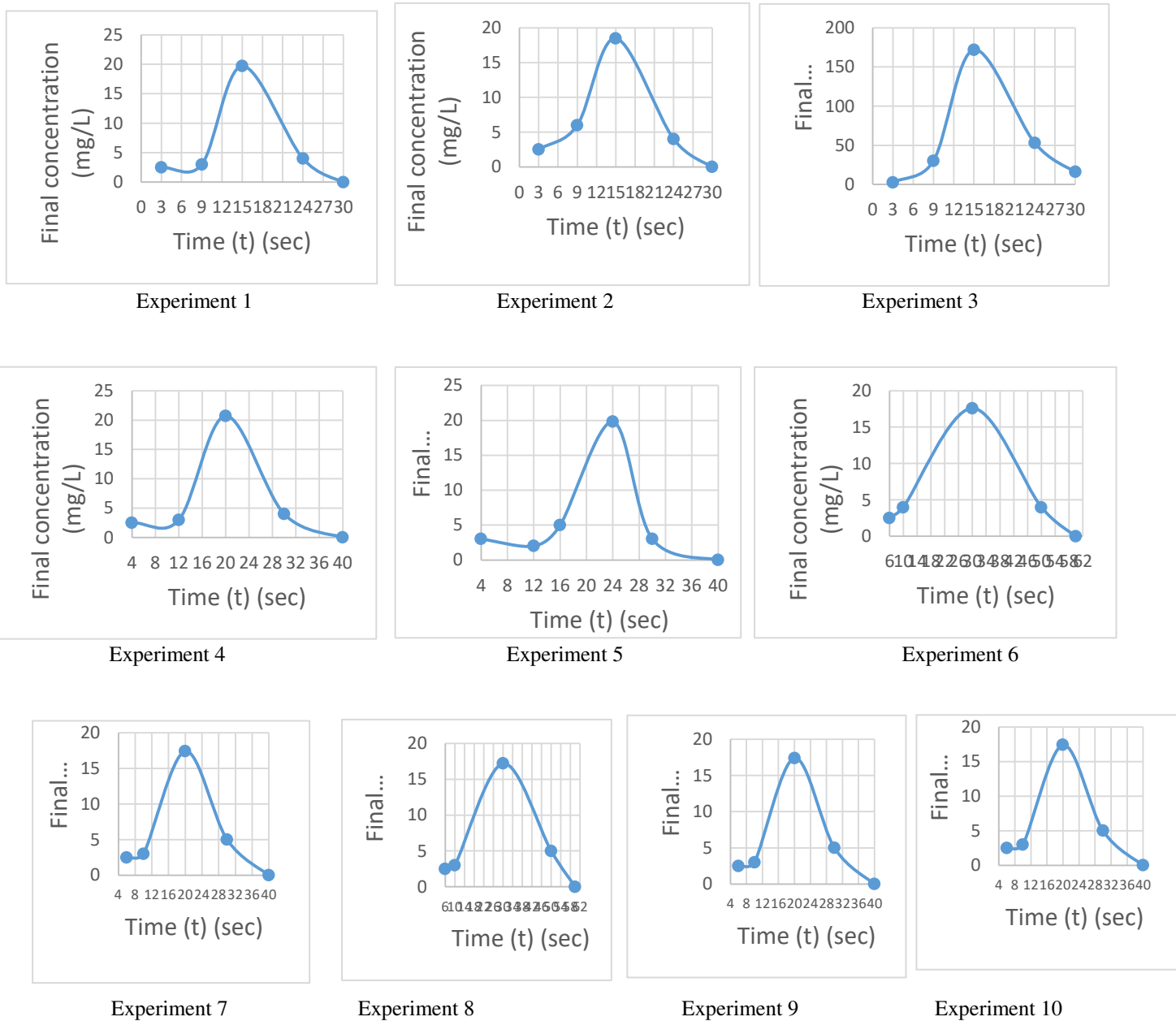


Figure 3. Concentration-time Plots for Channel of 2 Meanders

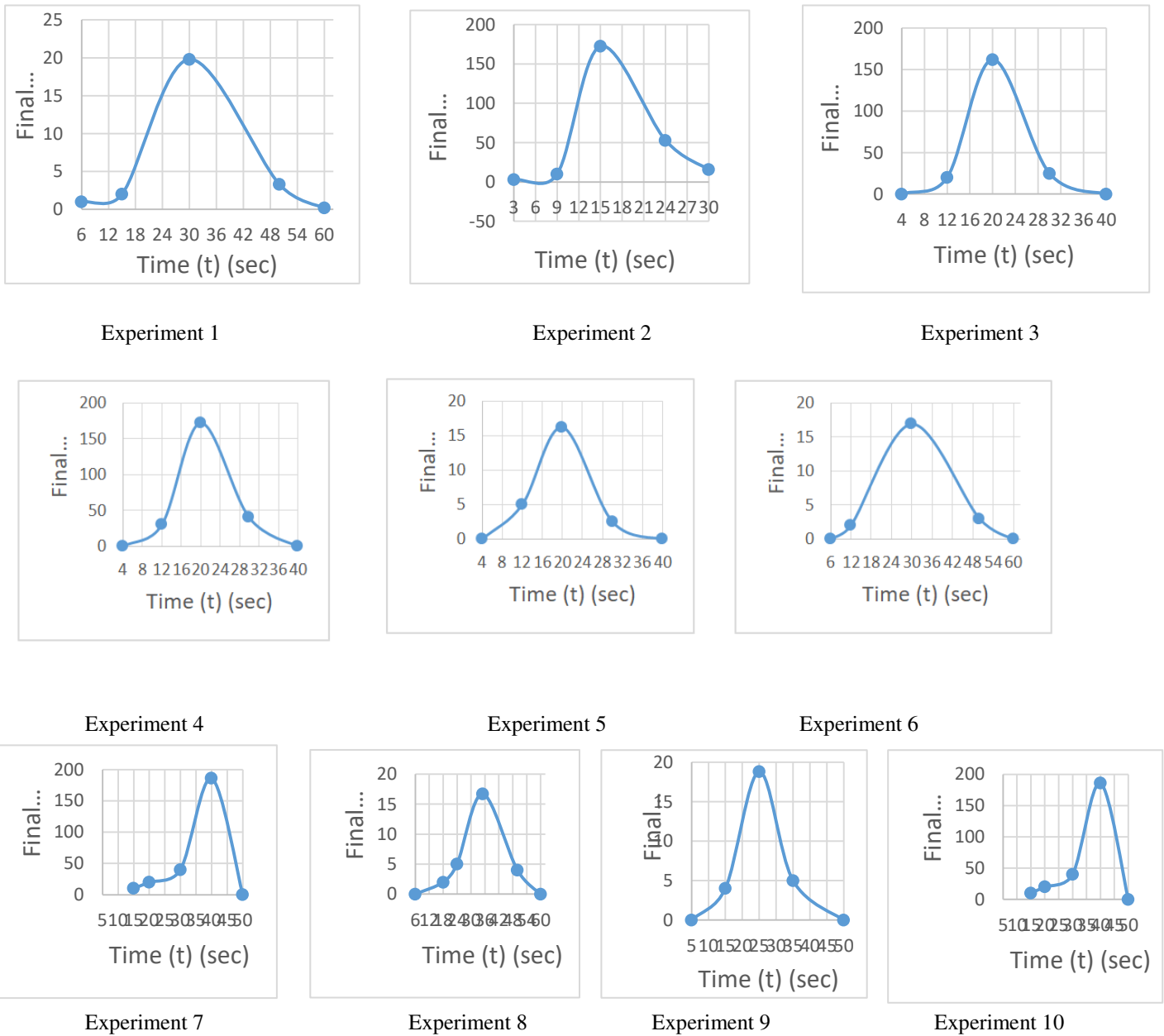


Figure 4. Concentration-time Plots for Channel of 3 Meanders

Experiments on Straight Channels

The general results showed a marked contrast to the results of the experiments with meandering channels. It is observed that concentration peaks were very high and the dispersion coefficient (and hence, dispersion numbers) were much lower than for meandering channels even for comparatively lower velocities. The coefficients of dispersion for meandering channels are several orders of magnitudes higher than those of the straight channels, while the peak concentration values of the straight channels are several tens of times higher than those of meandering channels. This confirms the observations of Deng et al. [39] and Fakuoka and Sayre [17]. The high values of peak concentration show poor ability of the straight channels in mixing and dispersion.

Many of the channel flow conditions indicated approach to plug flow which itself is indication of poor mixing. This is to be expected as the fundamental mechanism to mixing involved in straight channels are bed friction and turbulence which are also present in meandering channels. Thus the absence of centrifugal force effect in straight channels is a major difference. This view is also held by Engman [40]. Secondary currents are short-lived but its continuous generation by centrifugal forces at the bends sustains its effect through the meandering channel and for a good distance from the bend.

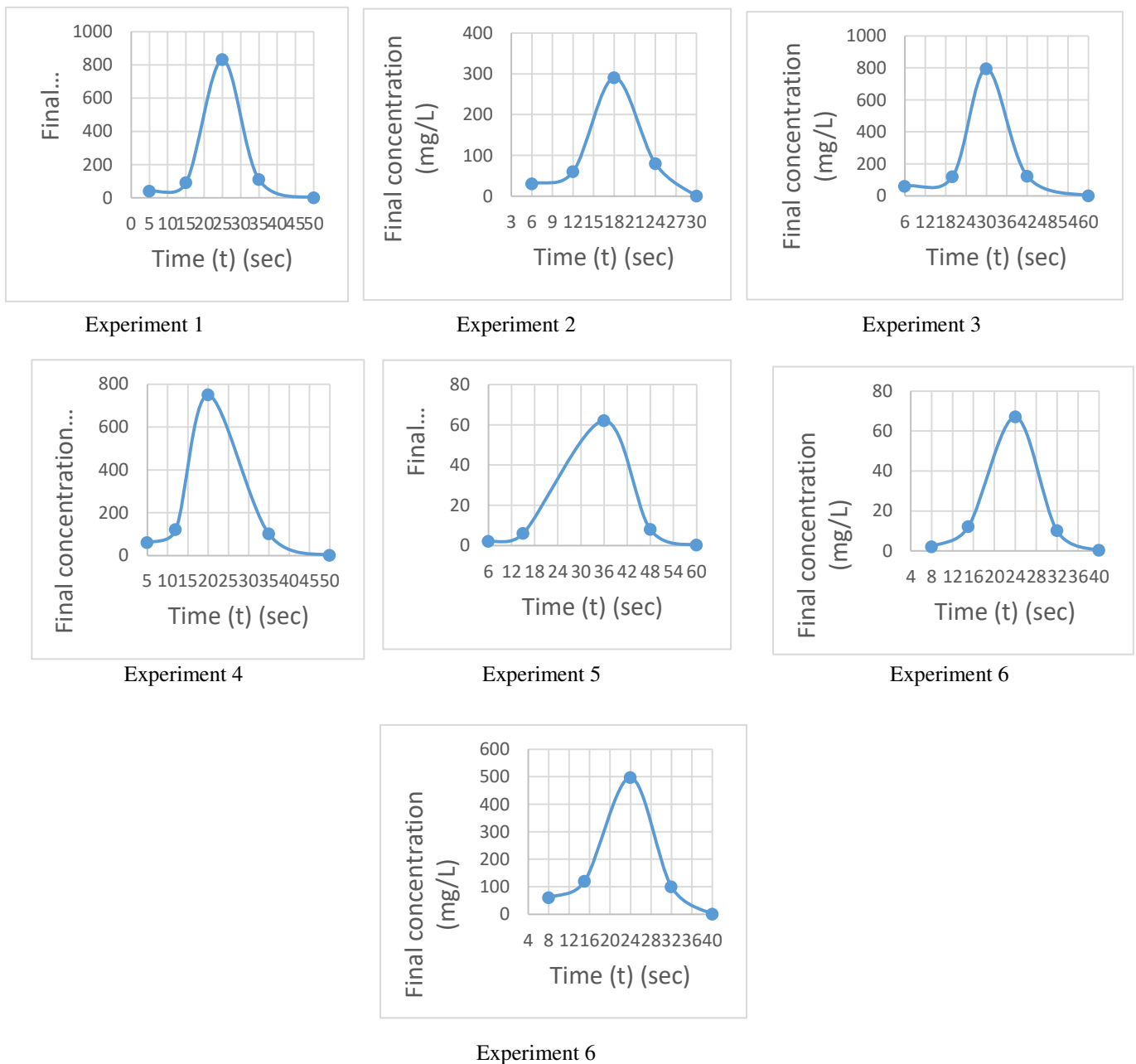
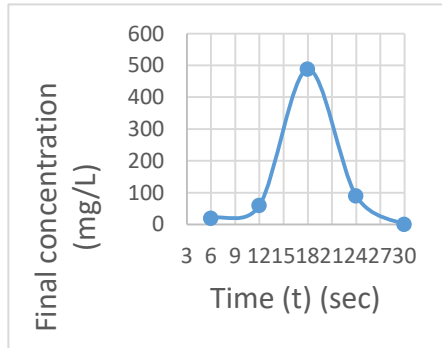
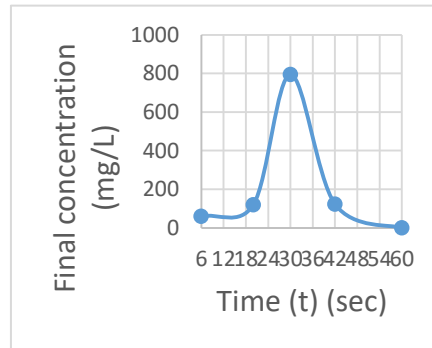


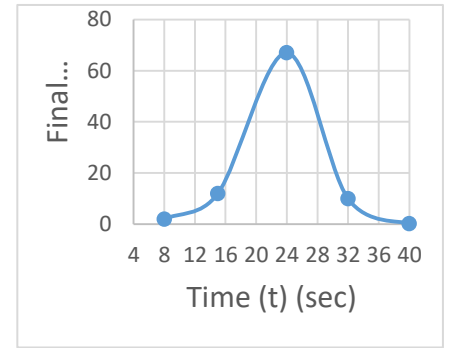
Figure 5. Concentration-Time plots for straight channel 1



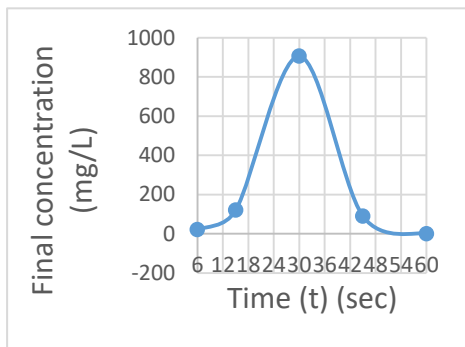
Experiment 1



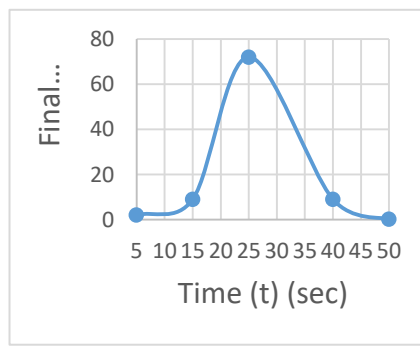
Experiment 2



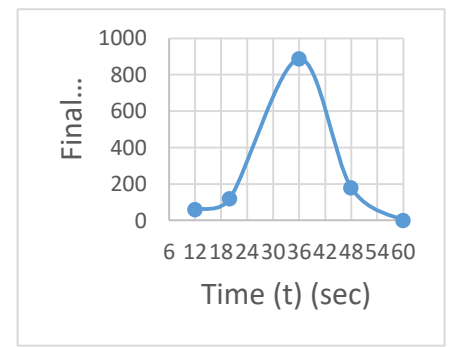
Experiment 3



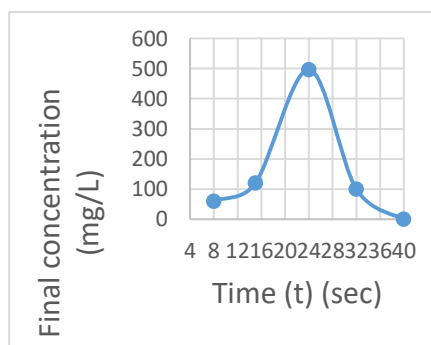
Experiment 4



Experiment 5



Experiment 6



Experiment 7

Figure 6. Concentration-Time plots for straight channel 2

Table 3 shows experimental results for channels of 2 and 3 meanders. Ten experiments were conducted in each channel paying attention to the longitudinal dispersion coefficient (D_L), shear velocity(U_x), mean velocity(U), radius of curvature(R_c), width of channel(B), depth of channel(H), hydraulic radius(R_H), number of meanders(N), and sinuosity(S_i) and their various result as presented. The tables show that there is a linear relationship amongst longitudinal dispersion coefficient and longitudinal velocity, shear velocity, depth of flow, radius of curvature and hydraulic radius. It indicates that as velocity increases dispersion coefficient increases. This is in agreement with dispersion coefficient models in literature. The result of experiment 2 in channel of 2 meanders where there is a deviation from the order in the relationship between D_L and U may be due to the effects of dead zones and centrifugal force being overwhelming in this particular instance.



Table 2: Experimental results for Channel of 2 meanders

Expt.	D (m/s ²)	U(m/s)	U* (m/s)	B(m)	H(m)	Rc	R _H	N	S _i
1	0.22867	0.231	0.043	0.2	0.028	2.25	0.0219	2	1.53
2	0.14925	0.252	0.041	0.2	0.036	2.25	0.0265	2	1.53
3	0.45732	0.311	0.043	0.2	0.042	2.25	0.0396	2	1.53
4	0.51615	0.401	0.044	0.2	0.055	2.25	0.0324	2	1.53
5	0.44446	0.365	0.041	0.2	0.048	2.25	0.0355	2	1.53
6	0.64146	0.482	0.045	0.2	0.068	2.25	0.041	2	1.53
7	0.60265	0.563	0.047	0.2	0.078	2.25	0.044	2	1.53
8	0.54451	0.44	0.045	0.2	0.061	2.25	0.038	2	1.53
9	0.78204	0.63	0.049	0.2	0.082	2.25	0.0451	2	1.53
10	0.90693	0.71	0.051	0.2	0.089	2.25	0.0471	2	1.53

Table 3: Experimental results for Channel of 3 meanders

Expt.	D (m/s ²)	U(m/s)	U* (m/s)	B(m)	H(m)	Rc	R _H	N	S _i
1	0.12597	0.212	0.047	0.2	0.022	1.85	0.016	3	1.65
2	0.25158	0.261	0.042	0.2	0.034	1.85	0.025	3	1.65
3	0.38032	0.388	0.046	0.2	0.045	1.85	0.031	3	1.65
4	0.45961	0.452	0.046	0.2	0.06	1.85	0.038	3	1.65
5	0.38553	0.413	0.037	0.2	0.052	1.85	0.052	3	1.65
6	0.82692	0.686	0.052	0.2	0.078	1.85	0.044	3	1.65
7	0.63678	0.639	0.05	0.2	0.084	1.85	0.046	3	1.65
8	0.40172	0.466	0.047	0.2	0.05	1.85	0.037	3	1.65
9	0.53074	0.587	0.051	0.2	0.069	1.85	0.039	3	1.65
10	0.65603	0.791	0.056	0.2	0.088	1.85	0.044	3	1.65

Table 4: Experimental Result for Straight Channel S1

EXP	D	U	U*	B	H	R _H	$\frac{U}{U^*}$	B/H
1	0.070213	0.385	0.0570	0.2	0.036	0.0206	6.790	5.5556
2	0.151518	0.504	0.0497	0.2	0.063	0.035	10.121	3.1746
3	0.074186	0.622	0.050	0.2	0.084	0.043	12.465	2.3810
4	0.145955	0.714	0.0517	0.2	0.092	0.046	13.810	2.1739
5	0.173227	0.803	0.0530	0.2	0.1101	0.050	15.266	1.8182
6	0.151559	0.878	0.055	0.2	0.118	0.054	16.597	1.6949
7	0.082511	0.901	0.053	0.2	0.127	0.056	17.129	1.5748



Table 5: Experimental Result for Straight ChannelS2

EXP	D	U	U_*	B	H	R_H	$\frac{U}{U_*}$	B/H
1	0.026049	0.240	0.0409	0.40	0.028	0.25	5.864	14.2857
2	0.041163	0.328	0.0416	0.40	0.039	0.033	7.810	10.2564
3	0.365126	0.403	0.0393	0.40	0.058	0.045	10.255	6.8966
4	0.106353	0.550	0.0423	0.40	0.072	0.053	13.002	5.5556
5	0.054664	0.581	0.0415	0.40	0.081	0.058	14.000	4.9383
6	0.167162	0.662	0.0407	0.40	0.102	0.068	16.146	3.9216
7	0.074102	0.748	0.0401	0.40	0.132	0.080	18.653	3.0303

V. SUMMARY

This work explored the effect of bends on dispersion of rivers. To achieve this, four artificial channels were constructed, 2 of them with two and three meanders respectively and the other two kept straight. Tracer experiments with sodium chloride were performed on each channel and titrations done to determine chloride concentrations.

The concentration-time plots showed marked difference between straight and meandering channels. There were sharp drops in concentration peak values in the meandering channels indicating good dispersion and mixing against the poor performance of the straight channels in those regards. The dispersion number and coefficients of dispersion of the meandering channels were several orders of magnitude greater than those of the straight channels. The reason for the sharp difference between the two types of channels is that meanders increase mixing through the helical motion caused by centrifugal forces generated at the bends as the solute flows through them.

Although secondary current exists in both types of channels and increases mixing in them, but the secondary current created by the helical motion in meandering channels is much higher as a result of the effect of the bends, hence the better mixing. The concentration of high velocities on the outer (convex) side of the bend results in increased dispersion, hence the higher dispersion values in meandering channels.

Centrifugal forces in bends continuously create back flows and dead zone effects that retard stream-wise transport movement that aids dispersion, hence dispersion is reduced for average longitudinal velocity. The dead zone effect may also occur in straight channel flows because of obstacles and bottom friction of the channel. When this condition prevails in a flow, dispersive ability of the channel is not proportional to the longitudinal velocity. This condition is believed to be one of the reasons for the disparity between measured and predicted dispersion coefficients because velocity is involved as being proportional to dispersion coefficient in the equations.

The Concentration-Time plots for meandering channels indicate that there is neither gaussianity nor equilibrium zone in meandering channels in which the concentration of tracers is uniform over the cross-section. The implication of this is that the one-dimensional Advection-Dispersion Equation (ADE) cannot apply in meandering channels because of the constant redistribution of concentration gradients created by velocity shear and effect of dead zones from back flows coupled with the effect of the centrifugal force developed at bends. Also, channels with bends do not meet the prismatic condition required for the application of the ADE. Therefore, dispersion coefficient models developed from the ADE cannot yield good results and may not be used for meandering rivers, instead empirical models should.

VI. CONCLUSION

The impact of the irregular variation of width, elevation and bends as may be observed in meandering channels course large disparities between the longitudinal dispersion coefficient of straight and meandering channels. One reason for this is that there is concentration of high velocities on the outer side of the channel bend which results in increased dispersion. In contrast, river bends create secondary currents which increase transverse (Lateral) mixing resulting in a more uniformly distributed concentration of pollutant in the cross-section of the channel and hence a reduction in the longitudinal dispersion. Any of these two conditions may prevail in effect in a flow and whichever does determines the

value of dispersion coefficient with respect to longitudinal velocity. Hence dispersion coefficient is not always proportional to longitudinal velocity.

The Concentration-Time plots for meandering channels indicate that there is neither gaussianity nor equilibrium zone in meandering channels because at no point is the concentration of tracer uniform over the cross-section. The implication of this is that the one-dimensional Advection-Dispersion Equation (ADE) does not apply in meandering channels because of the constant redistribution of concentration gradients created by velocity shear and effect of dead zones from back flows coupled with the effect of the centrifugal force developed at bends. Also, channels with bends do not meet the prismatic condition used in the development of the ADE. Therefore, dispersion coefficient models developed from the ADE should not be expected to yield good results and may not be used for meandering rivers. Again this is believed to be one of the reasons for large discrepancy between measured and predicted values of the phenomenon.

VII. RECOMMENDATION

It is recommended that federal ministry of Water Resources and Environment should sponsor and encourage the use of newly developed models likes this as it will help encourage creative innovations and technological development

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IX. DECLARATION AND FUNDING

Data Availability Statement

All relevant data used for this research are included in the paper

Declaration of Competing Interest

There are no conflicts of interest between the authors and his institutions that could appear to have influenced the work presented in this publication.

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APPENDIXES

APPENDIX A: Concentration-Time Data for channel of 2 meanders

Table A1: M2 Experiment 1

	Test number	θ	C	θC	$\theta^2 C$
$R_H = 0.0219$	Blank	0.00	0.00	0.00	0.00
$S_i = 1.48$	1	3	6.2	18.6	55.8
	2	6	9.0	54	324
$H = 0.028m$	3	9	14.0	126	1134
$W = 0.20m$	4	12	15.00	192	304
$U = 0.231m/s$	5	15	19.7	295.5	4432.5
$T = 3 sec$	6	18	18.80	228.4	6091.2
$U_* = 0.00377$	7	21	16.90	354.9	7452.9
$\theta^2 = \left[\frac{1537.5}{107.3} \right]^2 =$	8	24	4.90	117.6	2822.4
	9	27	10.5	40.5	1093.5
$d = 0.065995m^2/s$	10	30	0.00	0.0	0.00
$D = 0.228672m^2/s$		165	107.3	1537.5	25710.3

Table A2: M2 Experiment 2

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00
2	10	10.7	107.0	1070.0
3	15	14.2	213.0	3195.0
4	20	13.4	268	536
5	25	18.5	462.5	1156



$R_H = 0.0265$
 $S_i = 1.48$
 $H = 0.036m$
 $W = 0.20m$
 $U = 0.252m/s$
 $T = 5 \text{ sec}$
 $U_* = 0.00358$

6	30	15.5	465	13950
7	3	14.5	507.5	15225
8	40	3.40	136	5440
9	45	0.00	0.00	0.00
10	50	0.00	0.00	0.00
		275	90.20	2159
				56402.5

$$\theta^2 = \left[\frac{2159}{90.2} \right]^2 = 572.918$$

$$d = 0.03948m^2/s$$

$$D = 0.14925m^2/s$$

Table A3: M2 Experiment 3

$R_H = 0.0296$
 $S_i = 1.48$
 $H = 0.042m$
 $W = 0.20m$
 $U = 0.311m/s$
 $T = 3 \text{ sec}$
 $U_* = 0.00376$

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	3	12.5	37.5	112.5
2	6	13.40	80.4	723.6
3	9	13.10	117.9	1061.1
4	12	14.5	174	2088
5	15	14.8	222	3330
6	18	13.70	246.6	4438.8
7	21	14.00	294	6174
8	24	5	134.4	32256
9	27	2.2	59.4	1603.8
10	30	0.00	0.00	0.00
		165	103.8	1366.2
				22757.4

$$\theta^2 = \left[\frac{1366.2}{103.8} \right]^2 = 173.234$$

$$d = 0.09803m^2/s$$

$$D = 0.45732m^2/s$$



Table A4: M2 Experiment 4

$R_H = 0.0355$

$S_i = 1.48$

$H = 0.055m$

$W = 0.20m$

$U = 0.401m/s$

$T = 5 sec$

$U_* = 0.0039$

Test number	θ	C	θC	$\theta^2 C$	
Blank	0.00	0.00	0.00	0.00	
1	5	12.10	60.5	302.5	
2	10	13.60	136	1360	
3	15	17.10	256.	3847.5	
4	20	14.70	294	5880	
5	25	20.70	517.5	12937.5	
6	30	13.50	405	12150	
7	35	14.40	5 4	17640	
8	40	5.50	220	8800	
9	45	1.20	54	2430	
10	50	0.00	0.00	0.00	
		275	112.8	2447.5	65347.5

$$\theta^2 = \left[\frac{2447.5}{112.8} \right]^2 = 470.790$$

$$d = 0.08581m^2/s$$

$$D = 0.5162m^2/s$$

Table A5: M2 Experiment 5

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	4	10.00	40	40
2	8	15.5	992	124
3	12	18.8	2707.2	225.6
4	16	16.20	4147.2	259.2
5	20	17.8	7120	356
6	24	19.80	11404.8	475.2
7	28	11 4	8937.6	319.2
8	32	4.2	4300.8	134.4



9	36	1.2	1555.2	43.2
10	40	0.00	.00	0.00
		220	114.9	41324.8
				1976.8

$R_H = 0.0324$

$S_i = 1.48$

$H = 0.048m$

$W = 0.20m$

$U = 0.365m/s$

$T = 4 sec$

$U_* = 0.00390$

$$\theta^2 = \left[\frac{1976.8}{114.9} \right]^2 = 295.996$$

$d = 0.081179m^2/s$

$D = 0.444446m^2/s$

Table A6: M2 Experiment 6

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	12.3	73.8	442.8
2	12	17.5	210	2520
3	18	15.00	270	4860
4	24	13.60	326.4	78336
5	30	17.60	528	15840
6	36	15.90	572.4	20606.4
7	42	8.40	352.8	4817.6
8	48	2.20	105.6	5068.80
9	54	0.00	0.00	0.00
10	60	0.00	0.00	0.00
		330	102.5	2439
				719889.2

$WS_i = 1.48 = 0.20m$

$U = 0.44m/s$

$T = 4 sec$

$U_* = 0.00395$

$$\theta^2 = \left[\frac{1924.4}{104.6} \right]^2 = 338.512$$



$$d = 0.082502m^2/s$$

$$D = 0.54452m^2/s$$

$$R_H = 0.0379$$

Table A7 M2 Experiment 7

Test number	θ	C	θC	$\theta^2 C$	
Blan	0.00	0.00	0.00	0.00	
1	6	6.30	37.8	226.8	
2	12	11.40	136.8	1641.6	
3	18	10.40	205.2	3693.6	
4	24	15.30	367.2	8812.8	
5	30	18.60	558	16740	
6	36	9.00	324	11664	
7	42	13.50	567	23814	
8	48	5 20	249.6	11980.80	
9	54	1.40	75.6	4082.4	
10	60	0.00	0.00	0.00	
		330	91.1	2521.2	82656

$R_H = 0.044$
 $S_i = 1.48$
 $H = 0.078m$
 $W = 0.20m$
 $U = 0.56m/sT = 6 sec$
 $U_* = 0.00414$

$$\theta^2 = \left[\frac{2521.2}{91.1} \right]^2 = 765.91$$

$$d = 0.071729m^2/s$$

$$D = 0.602652m^2/s$$

Table A8 M2 Experiment 8

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	4	9.70	3 8	155.2
2	8	13.20	05.6	844.8
3	12	11.60	139.2	1670.4
4	16	13.70	219.2	3507.2
5	20	17.40	348	6960



$R_H = 0.0379$	6	24	15.50	372	8928
$S_i = 1.48$	7	28	14.90	417.2	11681.6
$H = 0.061m$	8	32	6.30	2 1.6	6451.2
$W = 0.20m$	9	36	2.30	82.8	2980.8
$U = 0.44m/s$	10	40	0.00	0.00	0.00
$T = 4 sec$			220	104.6	1924.4
$U_* = 0.00395$					43179.2
$\theta^2 = \left[\frac{1924.4}{104.6} \right]^2 = 338.512$					2

$d = 0.082502m^2/s$

$D = 0.54452m^2/s$

Table A9: M2 Experiment 9

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	8.2	49.2	295.2
2	12	12.4	148.8	178 .6
3	18	10.8	194.4	3499.2
4	24	10.7	256.8	6163.2
5	30	15.10	453	13590
6	36	17.20	619.2	22291.2
7	42	15.4	646.8	27165.6
8	48	8.20	393.6	8892.8
9	54	2.20	118.8	6415 2
1	60	1.20	72	4320
	330	101.4	2943.6	104418

$\theta^2 = \left[\frac{2943.6}{101.4} \right]^2 = 843.862$

$d = 0.082755m^2/s$

$D = 0.782038m^2/s$



Table A10: M2 Experiment 10

	Test number	θ	C	θC	$\theta^2 C$
	Blank	0.00	0.00	0.00	0.00
$R_H = 0.0471$	1	5	8.50	42.5	312.5
$S_i = 1.48$	2	10	12.10	121	1210
$H = 0.089m$	3	15	14.4	216	3240
$W = 0.20m$	4	20	14.50	290	5800
$U = 0.71m/s$	5	25	12.70	317.5	7937.5
$T = 5 sec$	6	30	16.20	486	14580
$U_* = 0.00451$	7	35	14.30	500.5	17517.5
$\theta^2 = \left[\frac{2904.5}{114.5} \right]^2 = 643.475$	8	40	12.30	492	19680
$d = \frac{0.085185m^2}{s}$	9	45	7.20	324	14580
$D = 0.90722m^2/s$	10	50	2.30	5	5750
		275	275	2904.5	90507.5

Appendix B: Concentration-Time data for channel of 3 meanders

Table B1: M3 Experiment 1

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	3	8.30	0.00	0.00
2	6	10.50	498.00	2,988.00
3	9	10.50	0945.00	8505.00
4	12	17.2	1260.00	15120.00
5	15	14.8	2580.00	38700.00
6	18	14.4	2664.00	47952.00
7	21	15.6	3024.00	63,504.00
8	24	5.3	3744.00	89856.00
9	27	0.00	1431.00	38,637.00



$$U_* = 0.00413;$$

10	30	1.60	480.00	14400
----	----	------	--------	-------

$$d = \frac{1}{8}(\sqrt{8 \times 0.114759936 + 1} - 1) = 0.04080$$

$$R_h = 0.0167 ;$$

$$D = UdL = 0.212 \times 0.04080 \times 15 = 0.1259744$$

$$S_i = 1.46$$

$$R_c = 1.706$$

$$H = 0.0201$$

$$W = 0.20m$$

$$U = 0.212m/s$$

$$T = 3$$

$$R_h = 0 \frac{BVH}{W + 2H} = 0.0187$$

$$U_* = \left(\frac{1.5UV}{R_h}\right)^{0.5}$$

$$V = 8.9 \times 10^{-7}m^2/s$$

$$U_* = 0.00413$$

$$\theta = \frac{16626}{982} = 16.908sec$$

Table B2: M3 Experiment 2

$$R_c = 1.706$$

$$U_* = 0.003318$$

$$R_h = 0.0254$$

$$S_i = 1.46$$

$$H = 0.03m$$

$$W = 0.20m$$

$$U = 0.261$$

$$\theta = \frac{37614}{1198} = 31.397329$$

$$\theta^2 = 985.7922609$$

$$\theta = \frac{37614}{1180} = 31.87627$$

$$d = \frac{1}{3.39733} \left(\frac{1371780}{1198} - \left(\frac{37614}{1198} \right)^2 \right)$$

$$= 0.1615616$$

$$d = \frac{1}{8}(\sqrt{8 \times 0.16156 + 1} - 1)$$

$$= 0.064262253$$

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	0.00	0.00	0.00
2	12	12.4	1488	17856
3	18	16.3	2934	52812
4	24	12.8	3072	73728
5	30	19.8	5940	178200
6	36	18.5	6660	239760
7	42	17.2	7224	303408
8	48	17.6	8448	405504
9	54	3.2	1728	93312
10	60	2	120	7200
		1198	37614	1,371,780



$$D = UdL = 0.261 \times 0.0642623 \times 15 = 0.25158672$$

Table B3: M3 Experiment 3

	Test number	θ	C	θC	$\theta^2 C$
$R_h = 0.031$	Blank	0.00	0.00	0.00	0.00
$S_i = 0.46$	1	4	0.00	0.00	0.00
$H = 0.045m$	2	8	10.9	872	6976
$W = 0.20m$	3	12	14.9	1788	21456
$U = 0.388m/s$	4	16	15.2	2432	38912
$T = 4$	5	20	15.2	3040	60800
$R_H = 0.03104$	6	24	14.3	3432	82368
$U_* = \sqrt{gR_H S_o}$	7	28	13.0	3640	101920
$U_* = \left(\frac{1.5Uv}{R_h}\right)^{0.5}$	8	32	13.5	4320	138240
$U_* = 0.004107$	9	36	5.5	1980	71280
$\theta = \frac{22504}{1050} = 21.43238$	10	40	2.5	1000	40,000
$\sigma^2 = \frac{1}{21.4^2} \left[\frac{561952}{1050} - \left(\frac{22504}{1050}\right)^2 \right]$					
$= 0.16511559$					
$d = \frac{1}{8} (\sqrt{8 \times 0.16511559} - 1)$		184	1050	22504	561,952
$= 0.0654322$					

$$D = UdL = 0.388 \times 0.0654328 \times 15 = 0.380815$$

Table B4 M3 Experiment 4

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00
2	10	8.9	890	8900
3	15	1 .3	2745	41175
4	20	14.4	2880	57600
5	25	15.5	3875	96874
6	30	15.7	4710	141300



$R_H = 0.0375$	7	35	14.0	4900	171500
$S_i =$	8	40	13.8	5520	228800
$H = 0.106m$	9	45	8.3	3690	166050
$W = 0.20m$	10	50	5.2	2704	135200
$U = 0.452$				1140	31914
$T = 5 \text{ sec}$					1047399

$$\theta = \frac{31914}{1140} = 27.9947$$

$$\theta =$$

$$U_* = 0.00403$$

$$d = 0.677897$$

$$D = 0.45961$$

Table B5: M3 Experiment 5

	Test number	θ	C	θC	$\theta^2 C$
$R_h = 0.052$	Blank	0.00	0.00	0.00	0.00
$S_i =$	1	4	0.00	0.00	0.00
$H = 0.052$	2	8	13.0	1040	8320
$W = 0.20$	3	12	15.1	1812	21744
$U = 0.85m/s$	4	16	14.4	2304	36864
$T = 4 \text{ sec}$	5	20	16.2	3240	6480
$\theta = \frac{19432}{985} = 19.72792$	6	24	15.2	3648	87552
$\theta^2 = 389.1907795$	7	28	14.6	4088	11464
$U_* = 0.003269$	8	32	7.5	2400	76800
$d = 0.06223216$	9	36	2.5	900	32400
$D = 0.79092$	10	40	0.00	00	00
			985	19432	442944



Table B6: M3 Experiment 6

	Test number	θ	C	θC	$\theta^2 C$
$R_h = 0.044$	Blank	0.00	0.00	0.00	0.00
$S_i =$	1	5	11.8	590	2950
$H = 0.078m$	2	10	9.6	960	9600
$W = 0.20$	3	15	13.7	202	30825
$U = 0.686$	4	20	14.6	2920	58500
$T = 5 sec$	5	25	14.8	3700	92500
$\theta = \frac{39135}{1377} = 28.421$	6	30	15.4	4620	138600
$\theta^2 = 807.724$	7	35	16.6	5810	203350
$U_* = 0.00458$	8	40	8.6	7740	297600
$d = 0.080361829$	9	45	10.6	4770	214650
$D = 0.82692322$	10	50	12.00	6000	300,000
			1377	39,135	1,348,475

Table B7: M3 Experiment 7

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	10.0	630	3780
2	12	10.50	1260	15120
3	18	10.50	1890	34020
4	24	15.30	3672	8128
5	30	16.90	5070	152100
6	36	16.30	5868	176040
7	42	13.50	5670	238140
8	48	12.50	6000	288000



$H = 0.0457$
 $S_i =$
 $H = 0.084m$
 $W = 0.20m$
 $U = 0.639m/s$
 $T = 6 \text{ sec}$
 $U_* = 0.043$
 $\vartheta = \frac{32610}{1102} = 29.5917$
 $d = 0.06643551$

9	54	4.5	2430	131220
10	60	0.2	120	720
		1102	32610	1,127,268

$D = 0.636777m^2/s$

Table B8: M3 Experiment 8

$R = 0.037$
 $S_i =$
 $H = 0.059m$
 $W = 0.20m$
 $U = 0.466m/s$
 $T = 3 \text{ sec}$
 $\theta = \frac{16321}{1022} = 15.9697$
 $U_* = 0.00412$
 $d = 0.057470$
 $D = 0.41775076$

Test number	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00
2	6	10.90	654	3924
3	9	10.50	945	8505
4	12	15.60	1872	22464
5	15	16.20	2430	36450
6	18	17.00	3060	5 080
7	21	15.30	3213	67473
8	24	12.20	2923	70272
9	2	4.20	1134	30618
10	30	0.30	90	2700
		1022	16321	297,486



Table B9: M3 Experiment9

	Test number	θ	C	θC	$\theta^2 C$
$R = 0.039$	Blank	0.00	0.00	0.00	0.00
$S_i =$	1	6	0.20	12	72
$H = 0.0647m$	2	12	12.20	1224	14688
$W = 0.20m$	3	18	12.70	2286	41148
$U = 0.587m/s$	4	24	10.00	2400	57600
$T = 6 sec$	5	30	16.40	4920	147600
$U_* = 0.0045$	6	36	14.90	5364	193104
$\theta = \frac{30708}{955} = 32.1508$	7	42	10.70	4494	188748
$\theta^2 = 1033.9423$	8	48	17.00	8160	391680
$d = 0.060276836$	9	54	3.20	1728	93312
$D = 0.5307372$	10	60	0.20	120	7200
			955	30708	1,135,152

Table B10: M3 Experiment 10

	Test number	θ	C	θC	$\theta^2 C$
$R = 0.039$	Blank	0.00	0.00	0.00	0.00
$S_i =$	1	5	0.00	0.00	0.00
$H = 0.0647m$	2	10	10.50	1050	10500
$W = 0.20m$	3	15	16.80	2520	37800
$U = 0.587m/s$	4	20	15.70	3140	62800
$T = 6 sec$	5	25	18.80	4700	117500
$U_* = 0.0045$	6	30	17.60	5280	158400
$\theta = \frac{30708}{955} = 32.1508$	7	35	14.80	5180	181300
$\theta^2 = 1033.9423$	8	40	12.30	4920	196800
$d = 0.060276836$	9	45	12.70	5715	257175
$D = 0.5307372$	10	50	12.60	6300	315000
			1318	38805	1337275



Appendix C : Concentration-Time Data For Straight Channel 1

Table C1: S1 Experiment 1

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	5	0.20	1.00	5.00
2	10	8.5	85	850
3	15	23.5	352.5	5287.5
4	20	92.5	1850	37000
5	25	830.5	20762.5	519062.5
6	30	105.0	3150	94500
7	35	65.5	2292.5	80237.5
8	40	10.2	408	16320
9	45	2.6	112.5	5062.5
10	50	0.00	00	00
		11384	29014	758325

$H = 0.026$

$W = 0.20m$

$U = 0.385m/s$

$T = 5 sec$

$R_h = 0.0206$

$\theta = \frac{29014}{1138.4} = 25.487$

$\theta^2 = 649.5692$

$U_* = \left(\frac{1.5Uv}{R_h}\right)^{0.5}$

$= \left(\frac{1.3455E - 7U}{R_h}\right)$

$= 0.00432$

$d = 0.012158003m^2/s$

$D = 0.07021247m^2/s$

Table C2: S1 Experiment 2

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00
2	6	5.5	33	198
3	9	32.0	288	2592
4	12	71.50	858	10296
5	15	160.5	2407.5	36112.5
6	18	290.5	5229	94122
7	21	59.50	1249.5	26239.5
8	24	17.50	420	10080
9	27	5.00	135	3645



$H = 0.053$

$W = 0.20m$

$U = 0.504m/s$

$T = 3 \text{ sec}$

$\theta = \frac{10620}{642} = 16.54206$

$\theta^2 = 273.63962$

10	30	0.00	00	00
		642	10620	183283

$R_h = 0.035$

$U_* = 0.00440$

$d = 0.020042031m^2/s$

$D = 0.151517754m^2/s$

Table C3: S1 Experiment 3

$H = 0.074$

$W = 0.20m$

$U = 0.714m/s$

$T = 6 \text{ sec}$

$R_h = 0.046$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	0.00	0.00	0.00
2	12	0.00	0.00	0.00
3	18	12.00	216	3888
4	24	82.50	1968	47232
5	30	794.20	23826	774780
6	36	91.00	3276	117936
7	42	25.00	1050	44100
8	48	09.50	456	21888
9	54	0.00	00	00
10	60	0.50	30	1800
		1014.7	30822	951624

$\theta = \frac{44196.6}{1347.2} = 32.806265$

$\theta^2 = 1076.251013$

$U_* = 0.004577$

$d = 0.013627999m^2/s$

$D = 0.145955879Sm^2/s$



Table C: S1 Experiment 4

$H = 0.088$

$W = 0.20m$

$U = 0.504m/s$

$T = 3 \text{ sec}$

$R_h = 0.035$

$\theta = \frac{10620}{642} = 16.54206$

$\theta^2 = 273.63962$

$U_* = 0.00440$

$d = 0.020042031m^2/s$

$D = 0.151517754m^2/s$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	0.00	0.00	0.00
2	12	10.5	126	1512
3	18	64.50	1161	20898
4	24	112.00	2688	64512
5	30	258.00	7740	232200
6	36	888.00	31668	1150848
7	42	12.00	504	21168
8	48	2.20	9.6	460.8
9	54	0.00	00	00
10	60	0.00	00	00
			1347.2	44196.6
				149158.8

Table C5: S1 Experiment 5

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00
2	10	5.00	50	500
3	15	31.00	465	6975
4	20	749.00	14980	299600
5	25	197.00	4925	123125
6	30	82.00	2460	73800
7	35	15.00	525	18375
8	40	2.20	88	3520
9	45	0.20	9	409



10	50	0.00	0.00	0.00
		1081.4	23502	586304

$H = 0.101$

$W = 0.20m$

$U = 0.803m/s$

$T = 5 \text{ sec}$

$R_h = 0.050$

$\theta = \frac{23502}{1081.4} = 21.73293878$

$\theta^2 = 472.3206281$

$U_* = 0.00465$

$d = 0.014381622m^2/s$

$D = 0.173226647m^2/s$

Table C6: S1 Experiment 6

$H = 0.118$

$W = 0.20m$

$U = 0.878m/s$

$T = 4 \text{ sec}$

$R_h = 0.0541$

$\theta = \frac{18494.4}{793} = 23.3220681$

$\theta^2 = 543.9188603$

$U_* = 0.00467m/s^2$

$d = 0.011507922m^2/s$

$D = 0.151559335m^2/s$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	4	0.00	0.00	0.00
2	8	24.00	19.2	153.6
3	12	5.10	61.2	734.4
4	16	73.00	1168	18688
5	20	102.00	2040	40800
6	24	497.00	11928	286272
7	28	91.00	2548	71344
8	32	20.00	640	20480
9	36	2.50	90	3240
10	40	0.00	00	00
		793	18494.4	4417712



Table C7: S1 Experiment 7

$$H = 0.127$$

$$W = 0.20m$$

$$U = 0.901m/s$$

$$T = 4 \text{ sec}$$

$$R_h = 0.0560m$$

$$\theta = \frac{17922}{742} = 24.15363881$$

$$\theta^2 = 583.398268$$

$$U_* = 0.00465$$

$$d = 0.012508007m^2/s$$

$$D = 0.006104923326m^2/s$$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	4	0.00	0.00	0.00
2	8	26.50	20	160
3	12	2.50	30	360
4	16	10.50	168	2688
5	20	58.0	1160	23200
6	24	67.00	13608	386592
7	28	80.50	2254	63112
8	32	18.50	592	18944
9	36	2.50	90	3240
10	40	0.00	00	00
		742	17922	438296

Appendix D: Concentration-Time Data For Straight Channel 2

Table D1: S2 Experiment 1

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	5	0.00	0.00	0.00
2	10	0.00	0.00	00
3	15	10.00	150	2250
4	20	50.5	1010	202.00
5	25	112.00	2800	70000
6	30	798.00	23940	718200
7	35	81.00	2835	99225
8	40	15.00	600	24000
9	45	2.00	90	4050
10	50	0.00	00	00



10685	31425	937925
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$H = 0.028$

$W = 0.4m$

$U = 0.241m/s$

$T = 5 \text{ sec}$

$R_h = 0.0246$

$\theta = \frac{31425}{1068.5} = 29.41038839$

$\theta^2 = 864.9709455$

$U_* = 0.00363$

$d = 0.007205863381m^2/s$

$D = 0.026049196m^2/s$

Table D2:S2 Experiment 2

$H = 0.039W = 0.4m$

$U = 0.328m/s$

$T = 3 \text{ sec}$

$R_h = 0.0326$

$\theta = \frac{13860}{770.6} = 17.98599$

$\theta^2 = 323.4956545$

$U_* = 0.0037$

$d = 0.008366412565m^2/s$

$D = 0.041162749m^2/s$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	3	0.00	0.00	0.00
2	6	0.30	1.8	10.8
3	9	0.80	7.2	64.8
4	12	25.00	300	36.00
5	15	121.00	1815	27725
6	18	488.00	8784	158112
7	21	102.00	2142	44982
8	24	31.50	756	18144
9	27	2.00	54	1458
10	30	0.00	00	00
		7706	13860	253596.6



Table D3: S2 Experiment 3

$H = 0.058$
 $W = 0.4m$
 $U = 0.403m/s$
 $T = 6 \text{ sec}$
 $R_h = 0.045$
 $\theta = \frac{32245}{1110} = 29.0495$
 $\theta^2 = 843.876329$
 $U_* = 0.00347$
 $d = 0.060401315m^2/s$
 $D = 0.36512595m^2/s$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	2.00	12	24
2	12	5.00	60	720
3	18	12.50	225	4050
4	24	30.00	720	17280
5	30	905.00	27150	814500
6	36	92.00	3312	119232
7	42	53.00	2226	93492
8	48	5.00	240	11520
9	54	5.00	270	14580
10	60	0.50	30	1800
		1110	32245	10771198

Table D4: S2 Experiment 4

$H = 0.072$
 $W = 0.4m$
 $U = 0.55m/s$
 $T = 6 \text{ sec}$
 $R_h = 0.053$
 $\theta = \frac{33774}{1097} = 30.78760$
 $\theta^2 = 947.8764709$
 $U_* = 0.00374$
 $d = 0.12891217m^2/s$
 $D = 0.16352541m^2/s$

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
1	6	0.00	0.00	0.00
2	12	2.00	24	288
3	18	18.00	324	5832
4	24	28.00	672	16128
5	30	8800.00	26400	792000
6	36	62.00	2232	80352
7	42	97.00	4074	171108
8	48	10.00	48	2304
9	54	00.00	00	00
10	60	0.00	00	00
		1097	33774	1068012



Table D5: S2 Experiment 5

	Test	θ	C	θC	$\theta^2 C$
$H = 0.081$	Blank	0.00	0.00	0.00	0.00
$W = 0.40m$	1	5	0.00	0.00	0.00
$U = 0.581m/s$	2	10	5.5	55	550
$T = 5 sec$	3	15	9.5	142.5	2137.5
$R_h = 0.058$	4	20	10.5	210	4200
$\theta = \frac{26662.5}{897.5} = 29.70752$	5	25	72.00	1800	45000
$\theta^2 = 882.5367975$	6	30	723	21690	650700
$U_* = 0.00368$	7	35	65.00	2275	79625
$d = 0.006272386826m^2/s$	8	40	10.00	400	16000
$D = 0.05466351m^2/s$	9	45	2.00	90	4050
	10	50	0.00	00	00
			897.5	26662.5	802262.5

Table D6: S2 Experiment 6

	Test	θ	C	θC	$\theta^2 C$
$H = 0.102$	Blank	0.00	0.00	0.00	0.00
$W = 0.4m0$	1	4	0.2	0.8	3.2
$U = 0.662m/s$	2	8	7.2	57.6	460.8
$T = 4 sec$	3	12	24.00	288	3456
$R_h = 0.068$	4	16	28.00	448	7168
	5	20	386.00	7720	154400
	6	24	41.00	984	23616
	7	28	16.00	448	12544
	8	32	8.00	256	8192
	9	36	2.50	90	3200
	10	40	2.50	00	4000
			515.4	10392.4	217080



$$\theta = \frac{10392.4}{515.4} = 20.16375631$$

$$\theta^2 = 406.5770684$$

$$U_* = 0.00362$$

$$d = 0.016833982m^2/s$$

$$D = 0.167161448m^2/s$$

Table D7: S2 Experiment 7

Test	θ	C	θC	$\theta^2 C$
Blank	0.00	0.00	0.00	0.00
$H = 0.132$	1	5	0.00	0.00
$W = 0.4m$	2	10	5.20	5200
$U = 0.748m/s$	3	15	31.00	6975
$T = 5 sec$	4	20	70.00	28000
$R_h = 0.080$	5	25	898.00	561250
$\theta = \frac{26539.5}{1074.2} = 24.7062931$	6	30	58.00	52200
$\theta^2 = 61040092$	7	35	9.50	11637.5
$U_* = 0.00355$	8	40	2.50	4000
$d = 0.006604488072m^2/s$	9	45	00.00	00.00
$D = 0.074102356m^2/s$	10	50	00.00	00.00
		1074.2	26539.5	664582.5



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