Estimation of Transverse Mixing Coefficient in Rivers and Experimental Flumes

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ABSTRACT: Rivers are the most important resource of drinking water and the chipset drainage for wastewater leaving agricultural lands, industrial regions and urban runoff. In later century, with increasing of civil population, many problems related to the pollution and quality of water resources have appeared. So study of mixing and translocation of materials in the rivers, are the important goals of water resource management programs. In mixing processes, specially, in the large and big rivers, longitudinal Dispersion and the transverse diffusion of pollution are the most parameters respectively. In this paper, in addition to introducing the measuring methods of transverse coefficient in rivers using collection of 19 hydraulic datasets, multiple suitable equations for estimation of this coefficient have been developed and accuracy of these equations compared to Fischer’s equation has been investigated. Furthermore, this coefficient is surveyed and evaluated.

Keywords: transverse mixing coefficient, straight rectangular flume, Fischer’s equation

INTRODUCTION

The distribution of materials has three main parts (Fischer et al. 1979) as follow:

Primary mixing
This process starts from “injection” and continues to the location that concentration depth is uniform. The aim of this study is to determine vertical mixing coefficient and vertical mixing length.

The “Primary mixing” has two subdivisions. In the first region (output region), pollutant is injected to the flow. In fact, required force for distribution is provided by pollutant’s momentum. Secondary region begins at the end of output region and continues to the location in which the vertical mixing is complete.

In many rivers, the ratio of width to depth has a high value. So the occurrence of “Primary mixing” is more rapid than the other processes.

Complete mixing
This process, begins after the “primary mixing” and continues to the location that the detector (pollutant) is distributed in entire cross section. The main point of study in this process is the determination of diffusion coefficient and mixing length. The mentioned length is equal to the distance between injection source and the section whose two different point’s concentration difference is less than 10 %. Therefore, it is clear that in rivers, passed from mixing length, diffusion coefficient has nearly no impact on mixing /

Remote region
This process begins after “complete mixing” region and ends where the detector coefficient is not traceable. In addition to translocations’ particles, the dominant process in this region is longitudinal dispersion which causes an expansion of detector cloth on the longitudinal. Studies of detector for determination of dispersion coefficient are conducted in this step.

The required length for completion of every process depends on cross section geometry, pollutant momentum, detector nature, discharge, depth and width.
According to previous processes, it is calculated that the mixing factor is consisted of three kinds of coefficient (vertical, transverse and longitudinal). From these factors, transverse mixing is the main point for researcher’s efforts. Transverse mixing intensity is defined by a cause known as transverse mixing coefficient. The most researchers are interested in one-dimensional models of water quality (dispersion coefficient) and FEW studies have been conducted on two-dimensional models. So in this essay, there is an investigation for the best optimum equations for estimating diffusion coefficient using available data and information.

Measurement of this coefficient in rivers is very difficult and besides there is few data available. On the other hand, achieving the accurate estimation of river transverse velocity which has an important effect on this coefficient is nearly impossible in many cases and if possible they can only be determined by field measurements. Therefore, the estimations of diffusion coefficient are handled with empirical methods.

The transverse mixing coefficients are defined by each one of two following terms (Fischer et al. 1979).

\[ \varepsilon_x = aHu^* \]  \hspace{1cm} (1)

\[ D_y = \frac{bQ^2}{W} \]  \hspace{1cm} (2)

Where \( \varepsilon_x \) = transverse mixing coefficient; \( D_y \) = lateral dispersion factor; \( H \) = depth of flow; \( a, b \) = localized coefficients; \( u^* \) = shear velocity; \( Q \) = discharge; and \( W \) = width of channel.

\( a \) and \( b \) don’t have constant values because of Various parameters such as river width,... influence mixing process..

Comparing Eq (1) and Eq (2) shows that Eq. (2) has the most application. Meanwhile the relation between \( D_y \) and \( \varepsilon_x \) can be stated by following terms.

\[ D_y = H^2Ux_m\varepsilon_x \]  \hspace{1cm} (3)

Where \( U \) = average velocity; and \( x_m \) = coefficient that is almost equal to unity.

**Determination methods of transverse mixing coefficient**

There are several methods for estimation of mixing coefficient.

**MOMENTUM METHOD**

In this method, coefficients of longitude and transverse mixing are obtained from following equations.

\[ \varepsilon_x = \frac{\sigma^2_x}{2t} \]  \hspace{1cm} (4)

\[ \varepsilon_y = \frac{\sigma^2_y}{2t} \]  \hspace{1cm} (5)

Where \( \sigma^2_x, \sigma^2_y \) are the variances of detector concentration curve in the longitudinal and transverse direction. The parameters \( \varepsilon_x \) and \( \varepsilon_y \) are the coefficient of longitudinal and transversal mixing, respectively.

From disadvantages of momentum method is that it doesn’t include transverse velocity and concentration effects on the river bank. Holly and Abraham (1973) (momentum method) attained better method according to momentum method. In this new method, the effect of transverse velocity and river bank are considered.

They determined the change of transverse velocity as the change of adjacent sections in the transverse distribution of cumulative discharge. Nevertheless, estimating transverse velocity precisely is very difficult, especially in bends. Therefore, every mistake in estimation causes a great error in calculation of transverse mixing coefficient.
Determining pollution area versus concentration

In this method, linear slope obtained from sketching the pollutant mass area versus the logarithmic concentration is considered to be \(2\pi\sigma_x\sigma_y\). So with having \(\sigma_x\) and \(\sigma_y\) you can get the longitude and transverse mixing coefficients (Fischer et al. 1979).

Mixing determination using the detector quantity

In third method, for estimating mixing coefficient, you need the detector value. Considering pollutant bulk have an elliptical shape, we can obtain the ratio of concentration variance in length to width direction, if the shape of pollutant bulk is ellipsoid.

\[
\frac{\sigma_y^2}{\sigma_x^2} = \frac{D^2}{d^2}
\]

Where \(D\) and \(d\) are the long and small diameters of ellipse, respectively. So from the following equation, you can get the mixing coefficients (Fischer et al. 1979).

\[
e_x e_y = \left( \frac{W_D}{C_{\text{max}}} \right)^2 \frac{1}{2t}
\]

STREAM TUBE METHOD

The using of this method was first proposed by Yotsukura and Cobb (1972). And later it was developed by Yotsukura and Sayre (1976).

In stream tube method, the transverse distance is replaced by the gathering discharge; that this distance is determined by following equation.

\[
q(y) = \int_0^y \bar{u}(y) h(y) dy
\]

In this equation, \(\bar{u}(y)\) and \(h(y)\) are the average velocity and average depth in transverse distance of river bank \(y\), respectively.

Measurement or estimation of discharge distribution in all sections is the main problem in application of gathering discharge method. Nevertheless, this method is the most common method for estimation of transverse mixing coefficient.

In stream tube method, the one-dimensional mixing equation is changed to following relationship.

\[
\frac{\partial \bar{c}}{\partial x} = D \frac{\partial^2 \bar{c}}{\partial y^2}
\]

Wherein \(\bar{c}\) is the average concentration depth.

RUTHERFORD’S METHOD

Rutherford used the fashionable momentum method in Eq. (8) and offered the Eq. (10).

\[
\frac{d}{dx} \left[ \int_{q=0}^{Q} \frac{\bar{c}(q-\bar{q})^2 dq}{\int_{q=0}^{Q} cdq} \right] = -2D \left[ \int_{q=0}^{Q} \varphi(q) \left( \frac{\partial \bar{c}}{\partial q} \right) dq \right]
\]

In which \(Q = \) total of river discharge and \(\bar{q} = \) center of detector distribution related to gathering discharge. Also \(\varphi\) is a function that is applied for description of transverse diffusion coefficient changes. In a way that:

\[
\int_0^Q \varphi(q) dq = 1
\]
The research history

Fischer et al. (1979) used the experimental investigations in straight canals (without bend and curvature) with uniform longitudinal conditions, and proposed the empirical Eq. (12) for calculation of transverse diffusion coefficient.

$$\varepsilon_y = 0.15 H u^*$$  \hspace{1cm} (12)

Chang (1971) found that the relationship between transverse diffusion coefficient and curvature is the cycling changes form. Iao and Krishnappan (1977) founded the constant values of transverse diffusion coefficient in meander cycle. Fisher (1969) proposed the Eq. (13) to describe effects of rivers’ curvature on transverse diffusion coefficient.

$$\frac{\varepsilon_y}{H u^*} \propto \left( \frac{U}{u^*} \right)^2 \left( \frac{H}{R_c} \right)^2$$  \hspace{1cm} (13)

Wherein $R_c =$ curvature radius; Also the symmetry constant is equal to 25. Fisher pointed that this Eq. is accurate for experimental conditions; but it has less accuracy in the field ones.

Yotsukura and Sayre (1976) used the apparent ratio in Fischer’s Eq. and proposed the new Eq. (14) for meanders.

$$\frac{\varepsilon_y}{H u^*} \propto \left( \frac{U}{u^*} \right)^2 \left( \frac{W}{R_c} \right)^2$$  \hspace{1cm} (14)

It is seemed that the mixing coefficient increases with growth of apparent ratio ($W/H$); because the apparent ratio relates to transverse turbulent scale in canal. Nevertheless, determination of transverse diffusion coefficient by mentioned methods is very difficult. Because:

Measurement of geometry parameters such as curvature radius ($R_c$) and sinuosity ($S$) is more difficult than those of the hydraulic elements ($H, U, W, u^*$). Also, in this case there is less information available.

Curve characteristics change along the channels especially in curvature radius.

Sinuosity is a more suitable criterion for estimating transverse diffusion coefficient; because, determining of this coefficient is applied in the reach form.

Fischer et al. (1979) presented the following Eq. for rivers. This Eq. is the most common method for estimation of transverse diffusion coefficient in rivers, regardless of the curvature radius.

$$\varepsilon_y = 0.6 H u^*$$  \hspace{1cm} (15)

Rutherford (1994) with usage of collection of field data, comprehended that the $(\varepsilon_y/H u^*)$ is variable between 0.1 to 0.26.

Deng et al. (2001) surveyed the Rutherford’s dimensionless data collection. They eliminated the outlying number (0.847) of them and obtained Eq. (16) for calculation of diffusion coefficient in direct channels.

$$\frac{\varepsilon_y}{H u^*} = 0.145$$  \hspace{1cm} (16)

it could be Observed from Eq. (16) that this ratio is compatible to obtained amount of Fischer’s Eq. (12). Also Deng et al. (2001) developed the other Eq. for estimating transverse mixing coefficient.

$$\frac{\varepsilon_y}{W u^*} = \frac{0.145}{W/H}$$  \hspace{1cm} (17)

Dimensionless analysis and effective parameters

Various parameters are effective on the mixing coefficient which can be clustered in three general groups.
Flow characteristics

This group includes the averaged velocity (U), shear velocity (u*), hydraulic radius (R), depth of flow (H), turbulent intensity and acceleration due to gravity (g).

Canal’s geometry characteristics

The width of channel (W), curvature radius (R_0), sinuosity (S), angle of curvature (θ), length of meander (M_μ), width of meander (M_μ), straight partition length between two continuous curves (T), length of the reach or length of the arc (L), hydraulic kind of river-bed (smooth or rough), height of roughness (K_s) and rough' distance from each other (L_i) are pointed from this group.

Fluid characteristics

This group includes the dynamic viscosity (μ) and fluid’s density (ρ).

Those mentioned parameters can be summarized as Eq. (18).

\[ e_y = f_i(\rho, \mu, g, H, U, u^*, W, R_s, S, \theta, M_L, M_b, T, K_s, L_i, L) \] (18)

The Eq. (19) is obtained by using the Buckingham dimensionless analysis and compounding the dimensionless groups.

\[ \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = f_2\left(\frac{W}{H}, \frac{U}{u^*}, \frac{M_L}{M_b}, \frac{L_i}{L}, \frac{R_s}{W}, \frac{Re}{H}, \frac{K_s}{S}, \theta\right) \] (19)

Wherein \( M_L/M_b \) = meander ratio; \( L_i/L \) = roughness accumulation; \( K_s/H \) = rough' averaged depth and \( Re= \) Reynolds number. Also \( \{e_y/Hu^*\}, \{e_y/Wu^*\}, \{e_y/Wu\} \) and \( \{e_y/Hu^*\} \) are the dimensionless coefficients of transverse mixing.

It is necessary to mention that the viscosity influence is ignored in many open channels. Therefore the Reynolds number can be ignored. Also there is little information related to river bed form; and more investigations have been conducted in experimental flumes. So the experimentally-obtained values are different to actual ones; because of the complicated three-dimensional conditions and other various causes. Therefore the roughness accumulation \( (L_i/L) \) and relative height of roughness \( (K_s/H) \) can be ignored and their influence can be placed in some factors such as \( (U/u^*) \) that it is a criteria for river roughness coefficient.

Also the river morphology is a function of various factors. These parameters cause the river plan not to have a regular geometry shape. In other words the curves characteristics show the important changes along the river. In case the river sinuosity has a constant value in an especial reach. The detector experiments are applied in long distances; therefore it is offered that sinuosity is considered for presentation of curves influence on mixing coefficients.

According to mentioned explanations the Eq. (20) can be applied.

\[ \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = f_3\left(\frac{W}{H}, \frac{U}{u^*}, S\right) \] (20)

Nevertheless in the most of the proposed equations, dimensionless transverse mixing coefficients are only and only functions of the \( (U/u^*) \) and \( (W/H) \). In other words:

\[ \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = \frac{e_y}{Hu^*} = f_4\left(\frac{W}{H}, \frac{U}{u^*}\right) \] (21)
PRESENTATION AND ANALYSIS OF CONCLUSIONS

Authors started performing transverse diffusion coefficient approximation and evaluation based on available data.

The experimental of straight rectangular flumes

The 136 collected data-sets (appendix A) were used to obtain an equation for mixing coefficient estimation in these kinds of flumes. According to table (1) is seen that in these flumes the ratio \( W/H \) correlates only to \( (\varepsilon_y/W_u) \) and \( (\varepsilon_y/H_u) \) form; and dimensionless groups of \( (\varepsilon_y/H_u) \) and \( (\varepsilon_y/W_u) \) are almost independent from this ratio.

Also \( (U/u^*) \) correlates to \( (\varepsilon_y/W_u) \) and \( (\varepsilon_y/H_u) \) relatively well and \( (\varepsilon_y/W_u) \) or \( (\varepsilon_y/H_u) \) is independent of \( (U/u^*) \). According to mentioned explanations \( (\varepsilon_y/H_u) \) is the only group that independent of \( W/H \) and \( (U/u^*) \). So according to the general Eq. (21) the ratio \( (\varepsilon_y/H_u) \) is almost equal to a constant value.

Also in table (2) \( \varepsilon_y/H_u \), \( \varepsilon_y/W_u \) and \( \varepsilon_y/H_u \) have been analyzed statistically. It can be calculated that the dimensionless diffusion coefficient ratio in straight rectangular flume doesn’t have a constant value; but, since the 95% of \( \varepsilon_y/H_u \) data have a range with the little variation (0.1414-0.1502), therefore it can be calculated that Eq. (12) with correlation coefficient equal to 0.963 is a good relationship for estimation of transverse diffusion coefficient.

Figure (1) is comparing the calculated diffusion coefficients of mentioned equation to measurement values.

Table 1. The Correlation Matrix of Effective Parameters in Estimation of Transverse Mixing Coefficient in Straight Rectangular Shape Flumes

<table>
<thead>
<tr>
<th>Dimensionless Group</th>
<th>( W/H )</th>
<th>( U/u^* )</th>
<th>( \varepsilon_y/(H_u) )</th>
<th>( \varepsilon_y/(W_u) )</th>
<th>( \varepsilon_y/(H_u) )</th>
<th>( \varepsilon_y/(W_u) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W/H )</td>
<td>1</td>
<td>0.07092</td>
<td>0.2238</td>
<td>0.7485</td>
<td>0.0381</td>
<td>0.5295</td>
</tr>
<tr>
<td>( U/u^* )</td>
<td>1</td>
<td>0.0132</td>
<td>0.0909</td>
<td>0.8336</td>
<td>0.4303</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The Statistical criterion of Transverse Mixing Coefficients in Straight Rectangular Flumes

<table>
<thead>
<tr>
<th>Dimensionless Group</th>
<th>Data No.</th>
<th>Averaged</th>
<th>The 95% of Sure Distance</th>
<th>Middle</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_y/(W_u) )</td>
<td>136</td>
<td>0.012</td>
<td>0.0102</td>
<td>0.0131</td>
<td>0.0088</td>
<td>7.22*10^{-5}</td>
<td>0.0369</td>
</tr>
<tr>
<td>( \varepsilon_y/(H_u) )</td>
<td>136</td>
<td>0.146</td>
<td>0.1414</td>
<td>0.1502</td>
<td>0.1381</td>
<td>6.76*10^{-4}</td>
<td>0.1783</td>
</tr>
<tr>
<td>( \varepsilon_y/(H_u) )</td>
<td>136</td>
<td>0.014</td>
<td>0.013</td>
<td>0.0151</td>
<td>0.0127</td>
<td>3.9*10^{-5}</td>
<td>0.0326</td>
</tr>
<tr>
<td>( \varepsilon_y/(W_u) )</td>
<td>136</td>
<td>0.001</td>
<td>0.001</td>
<td>0.0014</td>
<td>0.0007</td>
<td>1.82*10^{-6}</td>
<td>0.0077</td>
</tr>
</tbody>
</table>

Figure 1. The comparison of the obtained \( \varepsilon_y \) of Eq. (12) to measurement values.

Transverse mixing coefficient in natural streams

Table (3) has been drawn according to 19 series of collected hydraulic data-sets from various references.
It can be concluded that in rivers, the dimensionless ratio of \((\varepsilon_y / H u^*)\) doesn’t have a constant value in comparison to the common equations. In a way that 95% of data range has a large relatively range. Therefore \((\varepsilon_y / H u^*) = 0.6\) can’t be applied for estimating river transverse mixing coefficient in various conditions. It is guessed that the other hydraulic factors are (can be) effective on this coefficient.

**Presentation of new equations for rivers**

For estimation of river transverse mixing coefficient, many equations are proposed by application of nonlinear regression methods; in extension the important ones are pointed.

<table>
<thead>
<tr>
<th>Number</th>
<th>Equation</th>
<th>The Usage Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>(\varepsilon_y = 0.05295 \left( \frac{W}{H} \right)^{0.13996} \left( \frac{U}{u^<em>} \right)^{0.72878} H u^</em>)</td>
<td>(\varepsilon_y \frac{W}{H u^<em>} \left( \frac{U}{u^</em>} \right))</td>
</tr>
<tr>
<td>23</td>
<td>(\varepsilon_y = 0.07639 \left( \frac{W}{H} \right)^{0.13992} \left( \frac{U}{u^*} \right)^{-0.40768} HU)</td>
<td>(\varepsilon_y \frac{W}{H} \left( \frac{U}{u^*} \right))</td>
</tr>
<tr>
<td>24</td>
<td>(\varepsilon_y = \left( \frac{0.05694 - 0.00398 \left( \frac{U}{u^*} \right)}{0.28973} \right) HU)</td>
<td>(\varepsilon_y \frac{U}{H u^*})</td>
</tr>
<tr>
<td>25</td>
<td>(\varepsilon_y = -0.04373 + 0.04288 \left( \frac{W}{H} \right)^{0.12406} \left( \frac{U}{u^*} \right)^{0.08295} H U)</td>
<td>(\varepsilon_y \frac{W}{H} \left( \frac{U}{u^*} \right))</td>
</tr>
<tr>
<td>26</td>
<td>(\varepsilon_y = \left( \frac{0.00717 - 0.00294 \left( \frac{W}{H} \right)^{0.1780} \left( \frac{U}{u^*} \right)^{0.08295} WU)</td>
<td>(\varepsilon_y \frac{W}{W H} \left( \frac{U}{u^*} \right))</td>
</tr>
<tr>
<td>27</td>
<td>(\varepsilon_y = \left( \frac{-0.06471 - 0.08816 \left( \frac{W}{H} \right)^{-4.7808} U}{u^<em>} \right)^{1.84846} H u^</em>)</td>
<td>(\varepsilon_y \frac{U}{H u^<em>} \left( \frac{U}{u^</em>} \right))</td>
</tr>
</tbody>
</table>

Eqs. (22 to 27) and also Fischer’s Eq. (15) are analyzed and surveyed using the various statistical methods, according to the table (5).

<table>
<thead>
<tr>
<th>Eq. Number</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE</td>
<td>0.0948</td>
<td>0.0957</td>
<td>0.1004</td>
<td>0.095</td>
<td>0.1079</td>
<td>0.1011</td>
<td>0.1071</td>
</tr>
<tr>
<td>MAD</td>
<td>0.1362</td>
<td>0.1383</td>
<td>0.1337</td>
<td>0.13</td>
<td>0.1079</td>
<td>0.1027</td>
<td>0.1452</td>
</tr>
<tr>
<td>R²</td>
<td>0.439</td>
<td>0.4128</td>
<td>0.5154</td>
<td>0.5001</td>
<td>0.6075</td>
<td>0.6245</td>
<td>0.3196</td>
</tr>
<tr>
<td>MSE</td>
<td>0.052</td>
<td>0.0542</td>
<td>0.0484</td>
<td>0.047</td>
<td>0.0322</td>
<td>0.0309</td>
<td>0.0625</td>
</tr>
<tr>
<td>STD</td>
<td>0.2344</td>
<td>0.2337</td>
<td>0.231</td>
<td>0.2372</td>
<td>0.2583</td>
<td>0.2652</td>
<td>0.2286</td>
</tr>
<tr>
<td>SSE</td>
<td>0.9878</td>
<td>1.0293</td>
<td>0.9202</td>
<td>0.8939</td>
<td>0.6118</td>
<td>0.5867</td>
<td>1.188</td>
</tr>
<tr>
<td>Max (e)</td>
<td>0.8007</td>
<td>0.8261</td>
<td>0.7467</td>
<td>0.7355</td>
<td>0.4734</td>
<td>0.5113</td>
<td>0.9081</td>
</tr>
<tr>
<td>Min (e)</td>
<td>-0.0915</td>
<td>-0.0747</td>
<td>-0.1232</td>
<td>-0.1387</td>
<td>-0.3925</td>
<td>-0.4301</td>
<td>-0.0528</td>
</tr>
</tbody>
</table>
Figure 2. The comparison of the obtained \( \varepsilon_y \) of Eqs. (22 to 27) and also (15) in rivers by using the DR

As observed from table (5), it can be seen that the Eq. (27) have the best correlation coefficient \( R^2 = 0.62 \). But the correlation coefficient isn’t a high value; so this parameter or other similar statistical ones can’t alone indicate that the equation or equations are pleasing, here, the other statistical parameter known as DR must be used. This criterion is defining by following form.

\[
DR = \log_{10} \left( \frac{\varepsilon_{yp}}{\varepsilon_{ym}} \right)
\]

Fig. (2) is evaluating the mentioned equations by using this statistical parameter. According to this figure it can be distinguished that Eq. (22) is the best relationship for estimation of river transverse mixing coefficient.

CONCLUSION

In this paper, in addition to definition of transverse diffusion coefficient and its common determining methods, the various equations were obtained for estimation of this coefficient. For experimental straight rectangular flumes it is be calculated that although the dimensionless ratio of transverse diffusion isn’t a constant value but the 95% of data have a limit with little variance, therefore by using data analysis it can be told that the Eq. (12) is a good relationship for calculation of this coefficient.

But in rivers the Eq. (15) isn’t a suitable relationship. So in this case 6 equations are proposed for estimation of this coefficient. Also these equations are surveyed by several statistical criteria.

Finally Eq. (22) was chosen as the best relationship for calculation of river transverse mixing coefficient.

REFERENCES