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Seo, Il Won; Jung, Sung Hyun

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Analysis of Transverse Mixing Using Natural Tracers Continuously Introduced from Tributaries

Il Won Seo, Sung Hyun Jung
Civil & Environmental Engineering, Seoul National University
Seoul, Korea

ABSTRACT

Tracing study using EC (electrical conductivity) was conducted to investigate the transverse mixing characteristics at the confluence of the Nakdong River, Korea. Hydraulic and concentration data was collected simultaneously with the sensors attached to the moving boat.

The measured EC showed uniform distribution transversely at upstream of the confluence. After two tributaries met the main stream, the uniform distribution was changed to skewed distribution, having peak concentration at left bank. Transverse dispersion coefficient was calculated using the moment-based methods and routing methods.

KEY WORDS: Pollutant Mixing; Natural Tracer; Confluence Mixing; Electric Conductivity; Transverse Dispersion Coefficient;

INTRODUCTION

Understanding of pollutant mixing in rivers with complex geometry such as meandering and confluence is important for water resource management and safe water supply. Especially, most of waste water treatment plants release waste water effluent continuously to rivers and these pollutants in water seriously impact on the river ecosystem. These effluents are usually introduced to mainstream when smaller tributaries are converged into the mainstream. Therefore, not only longitudinal but also detailed transverse mixing analysis is indispensable as natural streams generally involve confluence.

Various researches were conducted to study transverse mixing characteristics of pollutant in river. Especially in transverse mixing, most of studies were focused on the estimation of transverse dispersion coefficients which is the most important parameter to analyze transverse mixing in river. Determination of the transverse dispersion coefficients can be briefly classified into two methods (Jeon et al., 2007), one is observing method and the other is predicting methods. The former method is generally used to estimate transverse dispersion coefficients, but it cannot be performed without the fine-quality set of concentration data. Therefore, many field and laboratory tracer tests (Yotsukura et al., 1970, Yotsukura and Cobb, 1972, Beltaos, 1980, Lau and Krishnappan, 1981) were conducted to collect fine-quality dataset.

However, most of tracer tests used fluorescent dye, because of its conservative properties which are important to collect accurate concentration data. Nevertheless, using fluorescent dye such as Rhodamine-WT dye for tracer test need lots of cost and labor, and the appearance of bright color of tracer cloud makes nearby citizens uncomfortable. To avoid these problems, an alternative is to use dissolved substance already present in river, which can measure concentration distribution influenced by the flow conditions. These tracers will be called as natural tracer for convenience. For some particular cases, the natural tracers, such as EC, suspended solid, thermal pollutants can be a good alternative than artificial tracers because previous tracer tests using the artificial tracer like Rhodamine-WT are inadequate in large rivers due to financial problem from amount and cost of injecting tracer materials and environmental problems, i.e. eco-system damages from effect of tracer materials. Besides there are numerous substance dissolved in natural river, most of water quality monitoring system widely use EC and water temperature as standard parameters. Particularly, EC is one of the best representing parameters to measure pollutant's concentration in river due to its indicating characteristic of ion concentration in water (Hem, 1985). Some recent researches show EC can be used as natural tracer in mixing analyisis (Vandenberg, Jerald A., et al, 2005). Moreover, the advancement of measuring device enabled to measure accurate concentration of EC in field easily, which means real-time concentration and hydraulic data measurement is feasible for tracer test. In this study, real-time tracing test using EC as natural tracer was performed at the confluence region, where pollutants are introduced from tributaries from nearby wastewater treatment plant at Nakdong River, Korea. The concentration data was collected using in-situ conductivity meter at 7 sections along 5km reach of the river. The hydraulic data using ADCP and boat tracks from GPS were also collected at the same sections where concentration data was collected.

This paper covers following contents. First, it covers theoretical backgrounds for 2D mixing analysis and method for estimating dispersion coefficients. Subsequently, the process and methodology of conducting field work and data collection is discussed. For result analysis, hydraulic data containing velocity, water depth, and discharge for measured sections and lateral concentration distribution data of EC were analyzed in detail. Observed mixing aspects for steady flow were discussed and transverse dispersion coefficients were estimated and compared with empirical equations. Finally, the paper concludes with a brief summary of all the contents of the research were presented.

THEORY

Transverse Mixing Process in River

When pollutant were introduced to the river, concentration of pollutant decrease slowly by mixing process. This mixing process of pollutants can be caused by several factors, advection process by currents and diffusion terms by molecular process and turbulent flow (Rutherford, 1994). However, most of rivers are composed with relatively much larger lateral width than water depth (i.e. large aspect ratio) which means vertical mixing finish in short time. The distance required to complete vertical mixing is known as 50 to 100 times the flow depth (Yotsukura and Sayre, 1976). Therefore two-dimensional model is used in common.

The two-dimensional advection-dispersion equation can be derived from depth-averaging three-dimensional equation. Due to most of mixing characteristics analysis in natural river follow streamwise direction, most of equations are derived to curvilinear coordinate system (Seo et al., 2008 and Lee and Seo, 2013). 2D advection-dispersion equation can be written as (Eq. 1)

$$\frac{\partial \bar{c}}{\partial t}+\bar{u}_s\frac{\partial \bar{c}}{\partial s}+\bar{u}_n\frac{\partial \bar{c}}{\partial n}=\frac{\partial}{\partial s}\left(D_L\frac{\partial \bar{c}}{\partial s}\right)+\frac{\partial}{\partial n}\left(D_T\frac{\partial \bar{c}}{\partial n}\right) \tag{1}$$

Where s denotes streamwise distance, n is lateral distance, $\bar{c}$ is depth-averaged concentration, $\bar{u}_s$ and $\bar{u}_n$ is local s and n direction depth averaged velocity, D_L is longitudinal dispersion coefficient; D_T is transverse dispersion coefficient and t is time.
If the river flow in constant discharge and concentration of contaminants is in steady state, above equation can be rewritten as (Eq.2)

$$\bar{u}_s\frac{\partial \bar{c}}{\partial s}+\bar{u}_n\frac{\partial \bar{c}}{\partial n}=\frac{\partial}{\partial n}\left(D_T\frac{\partial \bar{c}}{\partial n}\right) \tag{2}$$

The lateral direction velocity $\bar{u}_n$ in natural river is negligibly small compare to streamwise direction. The final form of equation can be written as (Eq.3)

$$\bar{u}_s\frac{\partial \bar{c}}{\partial s}=\frac{\partial}{\partial n}\left(D_T\frac{\partial \bar{c}}{\partial n}\right) \tag{3}$$

For this constant-coefficient model, the transverse dispersion coefficient D_T is most important parameter for using the model and should be provided to the users, but for most cases these coefficients are simply estimated just using the range of $D_T/HU^* = 0.15 \sim 1.0$ proposed by Rutherford (1994). Nevertheless, verification of range of transverse coefficients is still not sufficient enough and needs more verification for accurate analysis.

Method of Estimating Transverse Mixing Coefficients

Moment Method

Beltaos (1980) developed the streamtube moment method model to overcome disadvantages of simple moment method, which is hard to apply the method in complex geometry such as meandering and confluence. Following equations is governing equation for streamtube model

$$\frac{dC}{dx}=E_T\frac{d^2C}{dq^2} \tag{4}$$

Where q denotes cumulative discharge from left bank and E_y denotes diffusion factor which is defined as $E_T=\psi D_T U H^2$.
ψ is shape factor, U and H is reach averaged values.
Detail information for streamtube moment method is well explained in Beltaos (1980).

Routing Method

After Fishcer (1968) first applied the routing process in mixing analysis for estimating longitudinal dispersion coefficient in the 1D mixing model, routing method have been known as a reliable dispersion coefficient estimation method for the mixing analysis of soluble contaminants (Baek and Seo, 2010).

To apply these routing procedure in steady-state 2D flow, analytical solution for line source mixing of streamtube model by Yotsukura and Cobb (1972) was used. Following equation shows the solution of line source considering wall reflection.

$$\begin{aligned} c'(\alpha,q') &= \frac{1}{2(q'_{s2}-q'_{s1})}\Bigg[\sum_{n=0}^{\infty}\Bigg\{erf\,\frac{Q(q'_{s2}+2n-q')}{2\sqrt{Dx}}-erf\,\frac{Q(q'_{s1}+2n-q')}{2\sqrt{Dx}} \\ &\qquad +erf\,\frac{Q(q'_{s2}+2n+q')}{2\sqrt{Dx}}-erf\,\frac{Q(q'_{s1}+2n+q')}{2\sqrt{Dx}}\Bigg\} \\ &\quad +\sum_{n=1}^{\infty}\Bigg\{erf\,\frac{Q(q'_{s2}-2n-q')}{2\sqrt{Dx}}-erf\,\frac{Q(q'_{s1}-2n-q')}{2\sqrt{Dx}} \\ &\qquad +erf\,\frac{Q(q'_{s2}-2n+q')}{2\sqrt{Dx}}-erf\,\frac{Q(q'_{s1}-2n+q')}{2\sqrt{Dx}}\Bigg\}\Bigg] \end{aligned} \tag{5}$$

erf is the error function defined as

$$erf\ q=\frac{2}{\sqrt{\pi}}\int_0^q e^{-p^2}\,dp \tag{6}$$

(Eq. 5) was applied in this study by assumption of the upstream EC distribution consisted of a series of line sources. Predicted EC distribution was compared with the measured distribution by computing the RMS and variance of EC difference to estimate best-fit diffusion factor D.

FIELD TRACING TESTS

The field test using EC was conducted to investigate the transverse mixing characteristics at the confluence of the Nakdong River, Korea. Pollutants are continuously introduced from two tributaries, the Keumho River and Jincheon Creek merging to the main stream, the Nakdong River from the left bank (Fig. 1), including various contaminants from several waste water treatment plants located along urban areas and industrial complexes.

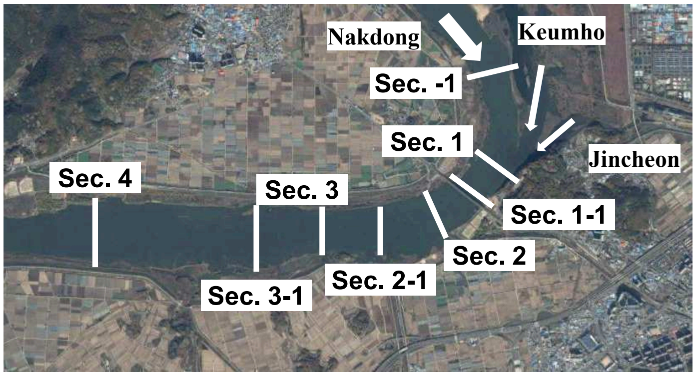

Fig. 1 Field study area and measurement sections (adapted from Google Earth). Copyright 2016 Google.

In this study, EC was used as a tracer of the contaminants in the river. EC has been generally used to monitor water quality in natural rivers due to its characteristic representing amounts of soluble ions in water. In study area, concentration of EC in the tributaries was relatively high enough, compared to that in the main stream, which shows EC is well tracing pollutants from tributaries.

Even though there will be various source of pollutant to the river, both two tributaries in study area discharge effluents from large scale waste water treatment plants. Therefore major factors of pollutant from the tributaries can be assumed as effluents from the plants. For most cases, pollutant from the plants could be assumed as a steady source, which means tracers continuously injected into the flow at a steady rate.

Field tests were conducted at 18 Sep. 2015 and 8 Oct. 2015, during late summer and autumn months of 2015. All data was collected in real-time using moving boat which measuring sensors are installed. Total 7 cross sections downstream from confluence were measured.

Conductivity meter used in this study was YSI-6600 OMS. This senor can basically measure water temperature, conductivity and water depth. This conductivity meter can measure conductivity from $0 \sim 100000 \mu S/cm$ with 1 $\mu S/cm$ sensitivity. Conductivity were measured with sampling frequency 1Hz. The data were collected near water surface (30cm down from water surface).

Hydraulic data were also collected using RDI Workhorse Sentinel ADCP (Acoustic Doppler Current Profilers). Using ADCP, water velocity and water depth were measured in 1Hz sampling frequency, installing ADCP at the bottom of boat. All the tracks of moving boat in field test were recorded using portable GPS: Magellan eXplorist 610. GPS's accuracy is up to 3 ~ 5 meters.

ANALYSIS OF FIELD DATA

Hydraulic Data

The measured velocity and water depth data were used to calculate the river discharge, and to elucidate the transverse distribution of water depth and velocity. Table.1 shows summarized average data from hydraulic measurement. Overall discharge shows low flow condition due to drought effect in Korea 2015. The results showed that, due to the effect of meandering and confluence of the tributaries from left side of the river, the water depth is deeper at the left side which means discharge of early sections after the confluence showed left skewed discharge distribution.

Table 1 Summary of average hydraulic measurement

Case	Date	Q(m^3/s)	H(m)	U(m/s)	W/H	U/U^*
ND-EC21	18 Sep. 2015	38.8	4.40	0.055	108.2	11.6
ND-EC22	08 Oct. 2015	58.6	4.36	0.059	100.6	11.4

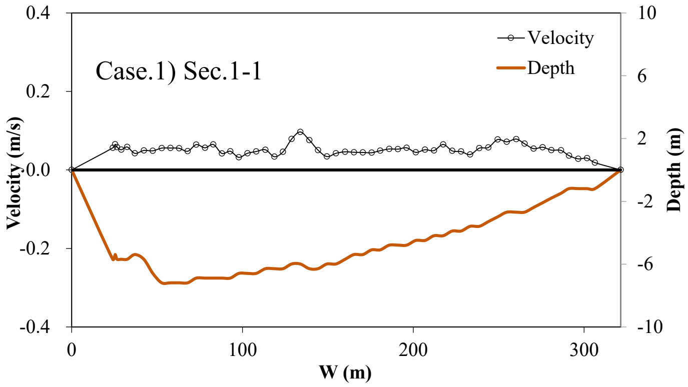

Fig. 2 Velocity-depth distribution in transverse direction for Sec.1-1 in Case.1

EC Data

The transverse EC data was plotted for Sec.-1 ~ Sec.2.1 of Case.2, where x-axis is normalized transverse distance(y/W). The results of the EC data showed that, at the upstream section of the Nakdong River before the confluence of the Keumho River (Sec.-1), the EC concentration is low, showing uniform distribution in the transverse direction compared to the high concentration level in the Keumho River and Jincheon Creek. However, effluents from the plants were introduced from two tributaries at the left bank side of the river, thus most of the transverse concentration distribution showed peak concentration at the left side. At the first downstream section of the Nakdong River, after two tributaries merged at the left bank (Sec.1) showed the steep concentration gradient at the left side of the river. At right half of the river cross section, EC concentration is almost the same as the background concentration before the confluence. This steep gradient of the EC concentration was slowly smoothed due to transverse mixing at further downstream sections.

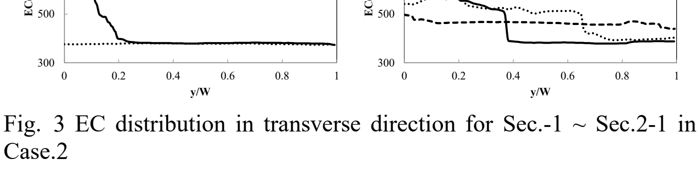

Fig. 3 EC distribution in transverse direction for Sec.-1 ~ Sec.2-1 in Case.2

TRANSVERSE DISPERSION COEFFICIENT

Transverse dispersion coefficient was calculated using the stream-tube moment method suggested by Beltaos (1980) and routing method as mentioned above. Before estimating the coefficients, mass check was conducted using (Eq.7) and to consider some inevitable reasons in field test, recovery ratio suggested by Nordin and Sabol (1974) was applied to concentration data.

$$m = \int_0^Q C dq = Q\int_0^1 C dq' \tag{7}$$

Applying routing method, number of the dispersion coefficients came out for one case because of diversity of selecting sections in study area, for example, Sec.1 to Sec.2, Sec.1 to Sec.3, Sec.2 to Sec.3, etc. From these different dispersion coefficients, values in early stage of mixing was selected as the representative value for each case.

The calculated values of the dimensionless transverse dispersion coefficient were 1.003 ~ 3.050, which were in the range of the values suggested by Rutherford (1994) for sharply curved channels. Both effects of confluence and meander caused these high dispersion coefficients. It is hard to define the reasons of difference between 2 methods with only 2 cases and high uncertainty from difference between the model and natural rivers. The estimated values were compared with the empirical equation (Eq.8) for transverse dispersion coefficient suggested by Deng et al. (2001) and Jeon et al. (2007). The non-dimensional transverse dispersion coefficients by Deng et al. (2001) overestimated than calculated values, while Jeon et al. (2007) underestimated the coefficient.

$$\text{Deng et al. (2001)}: \frac{D_T}{HU^*} = 0.145 + \frac{1}{3520}\left(\frac{U}{U^*}\right)\left(\frac{W}{H}\right)^{1.38} \tag{8.a}$$

$$\text{Jeon et al. (2007)}: \frac{D_T}{HU^*} = 0.03\left(\frac{U}{U^*}\right)^{0.46}\left(\frac{W}{H}\right)^{0.3} S_n^{0.73} \tag{8.b}$$

Table 2 Summary of estimated transverse dispersion coefficients

	Moment Method		Routing Method	
Case	DT(m^2/s)	DT/HU*	DT(m^2/s)	DT/HU*
1	0.0213	1.003	0.0645	3.050
2	0.0363	1.752	0.0262	1.278

	Deng et al.		Jeon et al.	
Case	DT(m^2/s)	DT/HU*	DT(m^2/s)	DT/HU*
1	0.0478	2.259	0.0095	0.450
2	0.0413	2.024	0.0089	0.436

CONCLUSIONS

The EC tracing study was conducted in the Nakdong River at the downstream reach of confluence of the Keumho River and Jincheon Creek. The results of EC measurements showed that, at the first downstream section after two tributaries merged at the left side, the peak concentration was found at the left side leading to the steep concentration gradient to the right side of the river. At further downstream sections, the gradient of the EC concentration was gradually reduced due to transverse mixing. The transverse dispersion coefficient was calculated using the stream-tube moment method and routing method. The dimensionless transverse dispersion coefficient had a range of 1.003 ~ 3.050, which were close to the values suggested by Rutherford (1994) for sharply curved channels. From the results of this study, tracer test using EC as a natural tracer can be suggested as a viable solution for collecting data in natural stream to analyze the characteristics of transverse mixing of soluble pollutants.

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REFERENCES

Baek, K. O. and Seo, I. W. (2010). Routing procedures for observed dispersion coefficients in two-dimensional river mixing. Advances in Water Resources, 33(12), 1551-1559.

Beltaos, S. (1980). Transverse mixing tests in natural streams. Journal of the Hydraulics Division, 106(10), 1607-1625.

Deng, Z. Q, Singh, V. P., and Bengtsson, L. (2001). "Longitudinal dispersion coefficient in straight rivers." J. Hydral. Eng., Am. Soc. Civ. Eng., 127(11), 919-927.

Fischer, H. B., List, E. J., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). Mixing in inland and coastal waters, Academic, New York.

Hem, J. D. (1985). Study and interpretation of the chemical characteristics of natural water (Vol. 2254). Department of the Interior, USGS.

Jeon, T. M., Baek, K. O., and Seo, I. W. (2007). Development of an empirical equation for the transverse dispersion coefficient in natural streams. Environmental Fluid Mechanics, 7(4), 317-329.

Lau, Y. L. and Krishnappan, B. G. (1981). Modeling transverse mixing in natural streams. Journal of the Hydraulics Division, 107(2), 209-226.

Lee, M. E. and Seo, I. W. (2012). Spatially variable dispersion coefficients in meandering channels. Journal of Hydraulic Engineering, 139(2), 141-153.

Nordin, C. F. and Sabol, G. V. (1974). Empirical data on longitudinal dispersion in rivers (No. 74-20), USGS.

Rutherford, J. C. (1994). *River mixing*. John Wiley & Son Ltd.

Seo, I. W., Lee, M. E., and Baek, K. O. (2008). 2D modeling of heterogeneous dispersion in meandering channels. Journal of Hydraulic Engineering, 134(2), 196-204.

Vandenberg, J. A., Ryan, M. C., Nuell, D. D., and Chu, A. (2005). Field evaluation of mixing length and attenuation of nutrients and fecal coliform in a wastewater effluent plume. Environmental Monitoring and Assessment, 107(1-3), 45-57.

Yotsukura, N., Fischer, H. B. and Sayre, W. W. (1970). Measurement of mixing characteristics of the Missouri River between Sioux City, Iowa, and Plattsmouth, Nebraska (No. 1899-G), USGS.

Yotsukura, N. and Cobb, E. D. (1972). Transverse diffusion of solutes in natural streams (No. 582-C), USGS.

Yotsukura, N. and Sayre, W. W. (1976). Transverse mixing in natural channels. Water Resources Research, 12(4), 695-704.