PREDICTING PARAMETERS OF TRANSIENT STORAGE ZONE MODEL FOR RIVER MIXING

Tae Sung Cheong[1] and Il Won Seo[2]

Post Doc. Research Assoc., Dept. of Civil & Environmental Engineering,
Univ. of California, Davis, CA 95616, U.S.A.
Prof., Dept. of Civil Engineering, Seoul National Univ., Seoul 152-742, Korea

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Abstract: Previously developed empirical equations used to calculate the parameters of the transient storage model are analyzed in depth in order to evaluate their behavior in representing solute transport in the natural streams with storage zone. A comparative analysis of the existing theoretical and experimental equations used to predict parameters of the transient storage (TS) model is reported. New simplified equations for predicting 4 key parameters of the TS model using hydraulic data sets that are easily obtained in the natural streams are also developed. The weighted one-step Huber method, which is one of the nonlinear multi-regression methods, is applied to derive new parameters equation. These equations are proven to be superior in explaining mixing characteristics of natural streams with the transient storage zone more precisely than the other existing equations.

Keywords: mixing characteristics, transient storage model, parameter estimating, routing method

1. INTRODUCTION

The fate of an accidental spill of a conservative pollutant into a natural stream channel has been described by a combination of the mechanism of advective transport with the mean flow and hydromechanical dispersion due to turbulence and velocity variations from the mean. Researchers have recognized that the classic advection-dispersion model of Taylor (1954) often fails to adequately represent the effects of irregular boundaries, variable depth, pools and riffles, and transient off-channel storage areas that modify natural dispersion processes in real streams with irregular boundaries (Bencala and Walters, 1983; Seo and Maxwell, 1992; and Seo and Cheong, 2001). Natural streams contain quiescent backwater areas, eddies, pool-riffle sequences in the bottom, and interstitial sediment voids that act as transient storage zones where solute particles can be detained for considerable periods of time then released and reentrained into free-flowing transport downstream. It is widely accepted in the literature that storage mechanisms associated with a natural heterogeneous environment can play very important roles in the gross dispersion process, increasing the apparent rate of dispersion. Although the importance of off-channel storage effects for the transport of tracers in the natural streams is well recognized (Chatwin, 1980; and Hart, 1995), it is not yet sufficiently quantified. In recent years, a number of partial differential equation models have been developed for simulation of these processes (Bencala et al., 1990; Castro and Hornberger, 1991; Kim et al., 1992; Seo and Maxwell, 1992; Runkel and Chapra, 1993; D'Angelo et al., 1993; Mulholand et al., 1994; and Fernald et al., 2001).

The transient storage (TS) model presented and discussed here has been developed in an effort to explain more fully the complex mechanism of pollutant transport in natural streams. The TS model is defined by two equations: one for the average solute concentration $C_f(x,t)$ in the free-flowing water zone and the other for the average solute concentration $C_s(x,t)$ in the transient storage zone. For completely-mixed storage zones with conservative solutes and steady uniform flow, the partial differential equations for conservation of mass in the free-flowing water zone and the transient storage zone are as follows:

$$\frac{\partial C_f}{\partial t}+\frac{Q}{A_f}\frac{\partial C_f}{\partial x}=\frac{1}{A_f}\frac{\partial}{\partial x}\left(A_f K_f \frac{\partial C_f}{\partial x}\right)+\varepsilon T^{-1}\left(C_s - C_f\right) \tag{1}$$

$$\frac{\partial C_s}{\partial t}=T^{-1}\left(C_f - C_s\right) \tag{2}$$

in which U_f is the mean velocity in the free-flowing water zone; K_f is the longitudinal dispersion coefficient in the free-flowing water zone, ε is the ratio of the cross-sectional area of the transient storage zone A_s to the cross-sectional area of the channel A, and T is the residence time a conservative tracer in the transient storage zone. The observed mean velocity in the free-flowing water zone, $U_f(Q/A_f)$ used in the TS model is usually larger than the mean velocity observed in the entire cross- section, $U(=Q/A)$ for the simple advection- dispersion model in which Q is the discharge. Observed values of K_f used in the TS model can also be cal-culated by the routing method of Fischer (1968a), however, in this case time- concentration curves measured only in the free-flowing water zone are used. Thus, the bulk dispersion coeffi-cient K for the simple advetion-dispersion model is usually larger than K_f for the TS model because K implicitly accounts for the effects of structural heterogeneity.

For the successful application of the TS model for predicting the river mixing, proper values of the key parameters U_f, K_f, T, and ε, should be incorporated. If the concentration data are observed in natural streams, TS model parameters can be determined by various theoretical and empirical methods (Hays et al., 1966; Okubo, 1973; Pedersen, 1977; Nordin and Troutman, 1980; Wagner and Gorelick, 1986; Hart, 1995; Wagner and Harvey, 1997; Wörman, 2000; Seo and Cheong, 2001; and Fernald et al., 2001). However, for streams where mixing and dispersion characteristics are unknown, the TS model parameters must be estimated by empirical estimation. Based on experimental and field data, Thackston and Schnelle (1970) and Seo and Yu (2000) independently developed empirical equations for estimating the ratio of the cross- sectional area of the transient storage zone to the cross-sectional area of the entire channel. Pedersen (1977) developed empirical equations for estimating both the residence time and the ratio of transient storage zone cross-sectional area to the cross-sectional area of the channel. Cheong and Seo (2000) proposed theoretical equations for estimating the mean velocity in the free-flowing water zone and the dispersion coefficient in the free-flowing water zone by using moment equations derived analytically in solution of both the simple advection dispersion model and the TS model.

In this paper, empirical equations previously used to estimate the model parameters (Hays et al., 1966; Thackston and Schnelle, 1970; Pedersen, 1977; Seo and Yu, 2000; Cheong and Seo, 2000) were analyzed in depth to evaluate their behavior in predicting dispersion characteristics in natural streams. In addition to the analysis of existing empirical equations, new simplified equations for estimating key parameters of the TS model, using hydraulic data sets which are more easily obtained for natural streams, have been developed. Dimensional analysis was carried out, in order to select physically meaningful variables that relate to mechanisms of natural mixing. A weighted one-step Huber method, one of the nonlinear multi-regression methods, was applied to derive regression equations for the TS model parameters using a set of reliable fifty-eight measurements collected from thirty-five natural streams in the United States.

2. Evaluation of Prior Research

2.1 Theoretical and Empirical Approaches

Thackston and Schnelle (1970) performed experiments in a recirculating flume with adjustable bed roughness seeking to relate the area ratio, ε (storage zone ratio) to bed roughness and certain hydrodynamic characteristics of the main channel flow. They reported that the area ratio, ε is function of both the relative roughness height and the relative roughness spacing, and proposed an empirical equation for the area ratio as

$$\varepsilon = 0.0152 + 0.89 f^{2.22} \tag{3}$$

in which f is Darcy-Weisbach's friction factor which can be defined as

$$f = 8\left(\frac{U_*}{U}\right)^2 \tag{4}$$

in which U_* is the shear velocity $(=\sqrt{gRS})$, g is the gravitational acceleration, R is the hydraulic radius, and S is the slope of the energy line.

Pedersen (1977) extended the analytical solution of Okubo (1973) for the spatial variance simply by adding a term for the short time behavior of the variance, as obtained from Taylor's classical theory on dispersion by continuous movement, on to an asymptotic solution. He then fitted his solution to some of the experimental data compiled by Nordin and Sabol (1974) and derived a set of prediction formulas or graphs. He presented a following set of the prediction formulas for estimating the key parameters such as the dispersion coefficient in the free-flowing water zone, the residence time, and the area ratio for mixing process in the natural streams:

$$K_f = (0.22 + 35.6 f)\frac{W^2 U_*}{h} \tag{5}$$

$$T = \frac{5 f W^2}{h U_*} \tag{6}$$

$$\varepsilon = 1.78 f - 0.009 \tag{7}$$

in which W is the width of the natural streams.

Cheong and Seo (2000) derived theoretical equations of the mean velocity in the free-flowing water zone using the relations between the average velocity of whole cross section and the average velocity of the free-flowing water zone. They proposed following theoretical equation for the mean velocity of the free-flowing water zone with the assumption in which averaged point velocity in the storage zone is zero.

$$\frac{U_f}{U} = \frac{A_f + A_s}{A_f} = 1 + \varepsilon \qquad (8)$$

The mean velocity in the free-flowing water zone is larger than as the ratio of $1+\varepsilon$ as the mean velocity of the whole cross-section which is the same as the result derived from the moment equations of the simple advection dispersion model and the TS model.

Seo and Yu (2000) derived a dimensionless equation (Equation 9) that relates the area ratio and friction factor. They determined the constants of the equation by the nonlinear least-square regression of the hydraulic data observed by Bencala (1983, 1984).

$$\varepsilon = 0.737\exp\left(-0.956 f^{-1/2}\right) \qquad (9)$$

2.2 Comparisons with the Natural Stream Data

In order to test the behavior of the existing theoretical and experimental equations for the key parameters of the TS model, 58 data sets, measured in 34 natural streams in the United States were collected from published reports of Fischer (1968b), Godfrey and Frederick (1970), Nordin and Sabol (1974), Czernuszenko et al. (1998), and Fernald et al. (2001). These data sets contain temporal distributions of concentration at several measuring sections, and average hydraulic and geometric variables such as channel width, mean depth, mean velocity and channel slope. To calculate the four key parameters for TS model from the temporal distributions of concentration measured in the natural streams, the moment matching method (MMM) developed by Seo and Cheong (2001) and the routing method (RM) developed by Cheong and Seo (2001) were considered. These results of the validation with the experimental data show that, in general, the values of the parameters obtained by the RM the MMM are in good agreement with the observed values. The concentration-time curves given by the RM fit the observed concentration-time curves very well, whereas the concentration-time curves obtained by the MMM is not in good agreement with the observed curves (Cheong and Seo, 2001).

Tests of the transient storage data were performed based on following Damkohler I number (Bahr and Rubin, 1987):

$$Da\mathrm{I} = \frac{(1+\varepsilon)T^{-1}L}{U} \qquad (10)$$

in which L is a reach length. Experimental reach lengths yielding *Da*I values between 0.1 and 100 have been found to provide reliable the TS model parameters estimates (Wagner and Harvey, 1997). Thus, in this study, the measured key parameters were calculated using the RM. The measured key parameters for the TS model calculated using the RM and the results of *Da*I values with the field data sets and are listed in Table 1.

Among the methods for estimating parameters suggested by previous investigators, six simple empirical equations were tested using these fifty-eight field data sets. These included the key parameters proposed by Hays (1966), Thackston & Schnelle (1970), Pedersen (1977), and Seo and Yu (2000). The dispersion coefficient in the free-flowing water zones, the residence time, and the area ratio, which were estimated using the selected equations, were compared with the measured data sets and were shown in Fig. 1. The data in Fig. 1 show that the use of Pedersen's equation significantly overestimates the dispersion coefficient in the

Table 1. Summary of parameters of transient storage model observed at 33 natural streams in USA.

Test Reach	Hydraulic Data					Transient Storage Model					1-D		Reference
	L km	W m	h m	U m/s	S	U_f m/s	K_f m^2/s	T sec	ε	k m/s	K m^2/s	Da I	
Green & Duwamish	1.62	21.77	1.58	0.31	0.00022	0.09	0.680	1032.43	0.021	0.001530	6.500	5.17	Fischer (1968b)
	3.08	29.61	1.08	0.36	0.00022	0.20	1.166	386.820	0.038	0.002792	0.500	22.9	
Copper Creek, VA	2.16	15.54	0.45	0.23	0.00144	0.37	6.460	2865.38	0.103	0.000157	16.84	3.62	Godfrey & Frederick (1970)
	3.01	53.64	1.10	0.18	0.00044	0.36	4.570	2761.27	0.091	0.000398	14.76	6.61	
	3.92	18.59	0.41	0.12	0.00290	0.14	4.390	1086.15	0.068	0.000377	20.71	32.1	
Powell River, TN	3.82	37.19	1.09	0.09	0.00029	0.23	4.020	4643.32	0.116	0.000235	15.50	10.2	
Clinch River, VA	4.70	33.53	0.78	0.19	0.00032	0.25	5.870	3264.22	0.076	0.000239	10.70	8.15	
Copper Creek, VA	3.11	19.81	0.82	0.50	0.00130	0.65	23.54	886.210	0.081	0.000925	20.82	7.59	
Clinch River, VA	3.92	62.18	2.21	0.76	0.00040	0.99	16.55	851.482	0.076	0.002595	40.49	6.52	
Coachechella Canal, CA	2.43	24.99	1.54	0.66	0.00009	0.83	7.910	206.850	0.013	0.007445	5.920	17.9	
	3.65	23.77	1.60	0.67	0.00012	0.63	7.200	355.670	0.018	0.004499	5.960	15.4	
Clinch River, VA	2.90	55.78	2.26	0.69	0.00044	0.86	22.45	1842.24	0.063	0.001227	36.93	2.43	
Copper Creek, VA	1.57	13.41	0.69	0.20	0.00116	0.37	6.460	2865.38	0.103	0.000211	24.62	3.02	
Missouri River	121	185.9	3.81	1.25	0.00020	1.38	484.4	3265.31	0.019	0.001330	1468.	30.2	
Antietam Creek, Md	7.00	10.97	0.52	0.21	0.00110	0.14	5.700	8566.31	0.047	0.000061	17.50	4.07	Nordin & Sabol (1974)
	39.7	23.47	0.70	0.52	0.00150	0.36	17.99	3404.43	0.048	0.000206	101.5	23.5	
	18.9	11.89	0.66	0.43	0.00110	0.27	4.830	1841.87	0.060	0.000096	20.90	6.81	
	6.92	24.99	0.45	0.41	0.00150	0.28	6.720	7684.56	0.064	0.000059	25.90	2.34	
Monocacy River, MD	16.5	48.77	0.55	0.26	0.00050	0.18	13.67	8870.40	0.039	0.000062	37.80	7.43	
	20.1	92.96	0.71	0.16	0.00030	0.15	9.260	17524.9	0.037	0.000041	41.40	7.44	
	8.04	49.99	0.95	0.32	0.00060	0.20	7.830	8612.81	0.036	0.000110	29.60	3.02	
	11.5	97.54	1.15	0.05	0.00030	0.24	12.83	5235.69	0.041	0.000220	119.8	45.8	
	11.5	33.53	0.58	0.16	0.00030	0.07	10.11	28129.2	0.086	0.000021	66.50	2.78	
Conococheague Creek, MD	21.6	43.28	0.69	0.22	0.00060	0.35	18.63	5261.21	0.069	0.000131	40.80	19.9	
	8.98	63.70	0.46	0.10	0.00070	0.18	25.18	17150.4	0.048	0.000027	29.30	5.49	
	21.6	59.44	0.76	0.68	0.00070	0.86	10.57	3915.62	0.083	0.000194	53.30	8.77	
Chattahoochee River, GA	41.1	75.59	1.95	0.74	0.00099	0.75	115.7	18067.2	0.036	0.000108	88.90	3.18	
	55.9	99.97	2.50	0.30	0.00045	0.80	88.72	9928.67	0.048	0.000252	166.9	19.7	
Salt Creek, NE	22.1	35.05	0.66	0.18	0.00023	0.23	21.59	7174.80	0.081	0.000092	52.20	18.5	
Difficult Run, VA	1.47	11.58	0.40	0.22	0.00195	0.15	2.070	3650.40	0.054	0.000110	1.900	1.91	
Bear Creek, CO	4.82	13.72	0.85	1.29	0.01080	1.36	2.910	1084.32	0.026	0.000784	2.900	3.54	
Little Pincy Creek, MD	4.56	15.85	0.22	0.39	0.00130	0.16	3.770	4502.11	0.055	0.000049	7.100	2.74	
Bayou Anacoco, LA	11.7	19.81	0.58	0.23	0.00057	0.20	4.010	16241.6	0.067	0.000036	5.800	3.33	
Comite River, LA	53.6	6.10	0.49	0.25	0.00069	0.09	0.810	2726.12	0.048	0.000056	69.00	25.7	
Bayou Bartholomew, LA	22.5	37.49	2.07	0.10	0.00008	0.16	29.50	66790.5	0.045	0.000031	54.70	3.52	
Amite River, LA	137	46.02	0.53	0.41	0.00035	0.32	150.2	34466.4	0.076	0.000015	501.4	10.5	
Tickfau River, LA	43.4	41.45	1.04	0.07	0.00080	0.14	2.110	19898.2	0.064	0.000052	10.30	32.4	
Tangipahoe River, LA	62.7	42.98	1.28	0.26	0.00037	0.39	16.07	7982.50	0.045	0.000160	45.10	31.5	
	73.6	31.70	0.76	0.36	0.00038	0.30	4.820	12660.1	0.047	0.000060	44.00	16.9	
Red River, LA	127	248.1	4.82	0.31	0.00009	0.45	34.48	14923.2	0.038	0.000323	143.8	28.7	
	46.7	161.5	3.96	0.29	0.00009	0.45	50.21	16826.4	0.031	0.000235	130.5	9.86	
	94.9	152.4	3.66	0.45	0.00009	0.59	44.04	18461.8	0.054	0.000198	227.6	12.1	
	127	42.06	2.47	0.33	0.00009	0.45	25.26	9770.81	0.019	0.000253	177.7	40.2	
Sabin River, LA	32.0	90.53	2.16	0.65	0.00017	0.70	30.02	9867.10	0.012	0.000219	131.3	5.05	
	62.6	152.4	2.26	0.98	0.00018	0.76	64.56	5434.40	0.026	0.000416	308.9	12.1	
Sabin River, TX	32.0	21.64	0.61	0.08	0.00030	0.11	2.180	12210.1	0.039	0.000050	12.80	33.7	
	20.1	17.37	1.23	0.04	0.00021	0.08	1.510	8482.26	0.031	0.000145	14.70	61.1	
	72.4	31.39	1.43	0.13	0.00012	0.17	3.770	12754.9	0.033	0.000112	24.20	45.1	
Mississippi River, LA	65.2	731.5	17.7	0.52	0.00001	0.62	156.5	9479.20	0.005	0.001867	237.2	13.3	
Mississippi River, MO	41.8	559.6	5.33	0.99	0.00012	1.08	144.2	3312.90	0.023	0.001609	457.7	12.9	
	249	690.1	7.35	1.43	0.00012	1.49	195.7	15385.6	0.080	0.000478	374.1	12.3	
Wind/Bighorn River, WY	90.8	55.47	1.28	0.75	0.00330	1.05	23.57	9726.43	0.050	0.000132	184.6	13.1	
	21.5	60.35	2.44	1.58	0.00330	1.86	69.26	4677.66	0.055	0.000522	464.6	3.07	
Colorado River	40.6	106.1	6.10	0.79	0.00013	0.82	137.7	12376.4	0.028	0.000493	181.0	4.19	Graf (1995)
	57.7	71.60	8.20	1.20	0.00141	1.13	233.8	9385.88	0.026	0.000874	243.0	5.17	
Botna River	0.40	2.050	0.10	0.22	0.00235	0.24	0.320	98.6400	0.009	0.001014	0.270	18.6	Czernuszenko et al. (1998)
Kogilnik River	0.15	2.300	0.40	0.56	0.00211	0.53	0.740	262.820	0.086	0.001522	1.600	1.11	
Byk River	0.90	2.550	0.14	0.22	0.00084	0.23	0.480	932.211	0.012	0.000150	0.500	4.44	

area ratio values.

The value of some parameters evaluated by Pedersen (1977) appeared to be physically unreasonable for most rivers. However, for large rivers having channel width larger than 200 m, both the dispersion coefficient in the free- flowing water zone and the residence time give high estimates as shown in Fig. 1. The most probable reason for overestimation is the fact that both equations include a term for the square of the channel width. Thackston and Schnelle's equation generally overestimates the area ratio values, whereas Thackston and Schnelle's equation gives values with more accuracy compared to Seo and Yu's equation.

To evaluate the difference between the measured and the predicted values of the key parameters more quantitatively, the discrepancy ratio as defined by White et al. (1973) was used as an error measure.

$$R_D = \log\left[\frac{P_p}{P_o}\right] \qquad (11)$$

in which R_D is the discrepancy ratio, P_p is the predicted key parameter of the TS model, and P_o

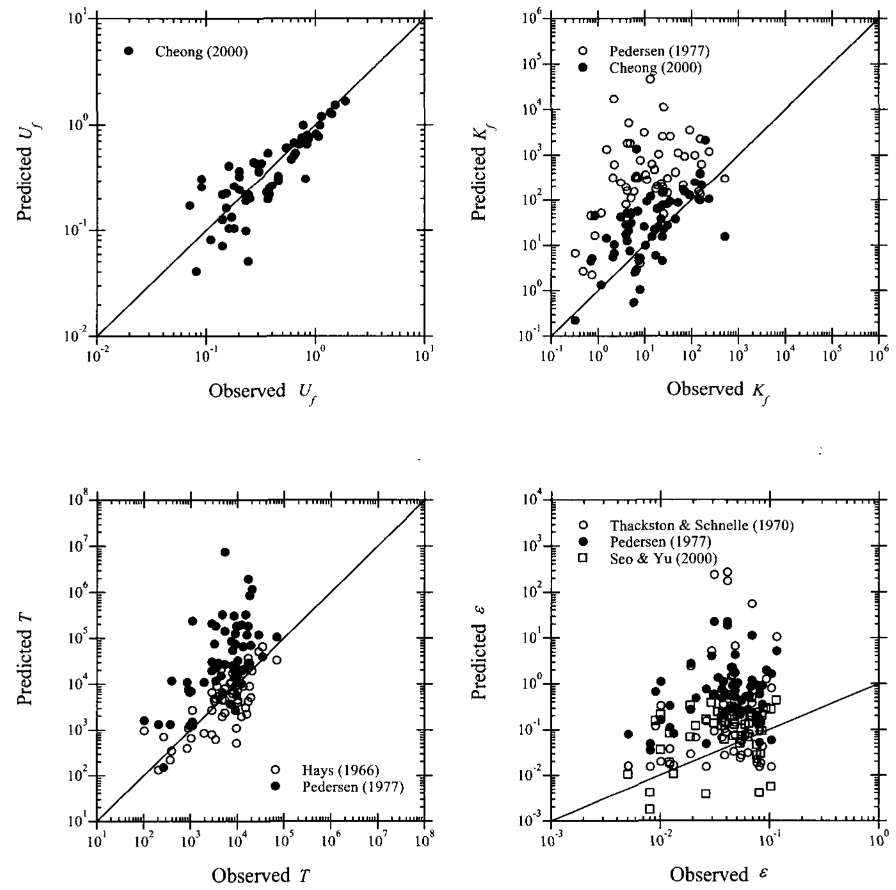

Fig. 1 Comparisons of calculated key parameters of the TS model with observed values

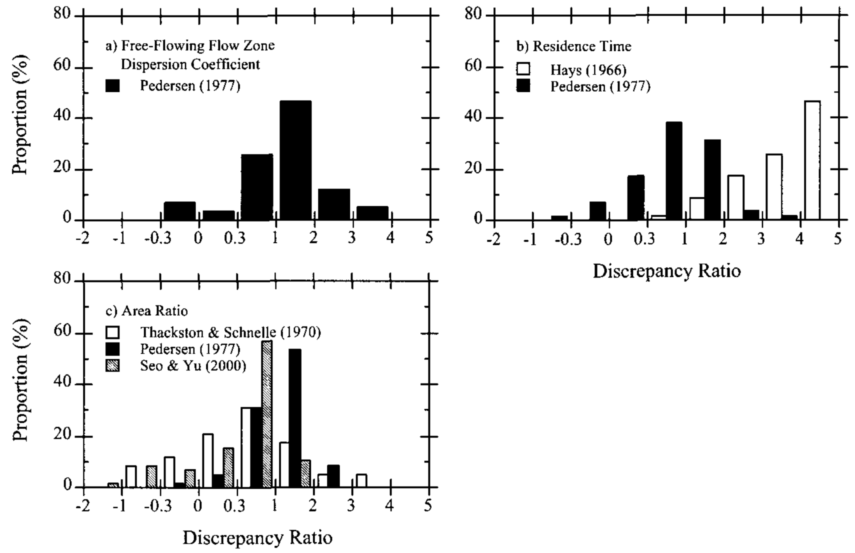

Fig. 2 Comparison of discrepancy ratio of selected equations

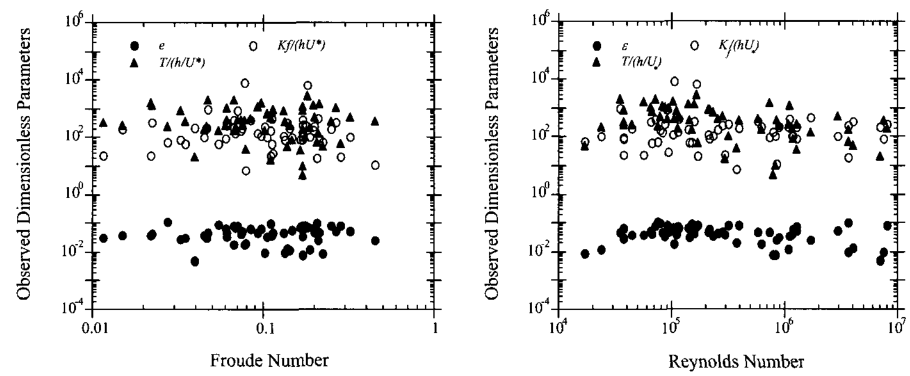

Fig. 3 Plots of observed dimensionless parameters versus dimensionless Froude number and dimensionless Reynolds number

is the observed key parameter of the TS model. If the discrepancy ratio is 0, the predicted value is identical to the observed parameters. If the discrepancy ratio is larger than 0, the predicted value of the parameters overestimates, and if discrepancy ratio is smaller than 0, it underestimates. Accuracy is defined as the proportion of numbers for which the discrepancy ratio is between - 0.3 and 0.3 to the total number of data.

The Histogram of discrepancy ratios of each existing equations for the fifty-eight field data sets are shown in Fig. 2. The discrepancy ratio distributions of three Pedersen's equations present a maximum number of values between 0.3 and 2. The discrepancy ratio distribution of the Hays' residence time equation presents a maximum number of values between 4 and 7. The discrepancy ratio distributions of both equations of the Thackston & Schnelle (1970) and the Seo & Yu (2000) are flatter than Pedersen's equation showing a maximum number of values of both equations in the range between 0 and 1. Accuracy of the Pedersen's equation for the dispersion coefficient in the free-flowing water zone is 10.4 %. Accuracy of the Hays' equation and the Pedersen's equation for the residence time are 0 % and 10.3 % respectively. Accuracy of the Thackston and Schnelle's equation, the Pedersen's equation, and the Seo and Yu's equation for the area ratio are 32.7 %, 6.9 %, and 22.4 % respectively. Of the equations, examined, the Thackston and Schnelle's equation for the area ratio shows the highest accuracy and the Seo and Yu's equation for the area ratio ranks the second.

3. Development of the New Equations for the TS Model Parameters

In this study, a nonlinear multi-variable weighted one-step Huber regression (Seo and Cheong. 1998) was used to estimate the key dimensionless parameters selected from dimensionless analysis as functions of the friction factor and width-to-depth ratio. The regressions used 58 data sets measured in 34 natural streams in the United States. These data sets contain temporal distributions of concentration at several measuring sections, and average hydraulic and geometric variables such as channel width, mean depth, mean velocity and channel slope.

3.1 Selection of Meaningful Variables

The major factors which influence mixing characteristics of solutes in the natural streams can be categorized into three groups: fluid properties, hydraulic characteristics of the stream channel, and geometric characteristics of the stream channel. The fluid properties include fluid density, viscosity, and so on. The cross-sectional mean velocity, shear velocity, channel width, and depth of flow can be included in the category of hydraulic characteristics. The bed forms, and sinuosity can be regarded as the geometric characteristics. The key parameters for the TS model P=$\{K_f, T, \varepsilon\}$ can be related to these variables as

$$\mathrm{P} = f_1(\rho, \mu, g, U, U_*, h, W, S_b, S_i) \tag{12}$$

in which ρ is the fluid density; ρ is the fluid viscosity; g is the acceleration of gravity; S_b is the bed shape factor which dimensionless factor represents vertical irregularities in the natural streams; and S_i is the sinuosity which dimensionless factor represents transverse irregularities in the natural stream. Using Buckingham Pi dimensional analysis, a new functional relationship between dimensionless terms was derived as

$$\left(\frac{K_f}{hU_*}, \frac{T}{(h/U_*)}, \varepsilon\right) = f_2\left(\frac{U}{\sqrt{gh}}, \rho\frac{Uh}{\mu}, \frac{U}{U_*}, \frac{W}{h}, S_b, S_i\right) \tag{13}$$

in which K_f / hU_* is the dimensionless dispersion coefficient in the free-flowing water zone, $T/(h/U_*)$ is the dimensionless residence time, $U/\sqrt{gh}$ is the Froude number, $\rho hU/\mu$ is the Reynolds number, W/h is the width-to-depth ratio, and U/U_* is the friction term. The vertical and transverse irregularities cause secondary currents and shear flows that affect the hydraulic mixing processes in the natural streams. In this study, however, these two variables were dropped because they represent parameters not easily collected for natural streams, and, furthermore, the influences of these two parameters are included in the friction term. For fully turbulent flow in rough open channels, such as natural streams, the effects of both the Reynolds number and the Froude number are negligible. Thus equation (13) reduces to

$$\left(\frac{K_f}{hU_*}, \frac{T}{(h/U_*)}, \varepsilon\right) = f_2\left(\frac{U}{U_*}, \frac{W}{h}\right) \tag{14}$$

The dimensionless functional relationship given in equation (14) relies entirely on hydraulic variables readily obtained in the natural streams. These variables are the channel width, the mean depth of the flow, the mean velocity, and the shear velocity. To test the correlation between the dimensionless key parameters for the TS model and the dimensionless variables included in equation (13), plots of the observed key parameters versus the measured hydraulic variables were constructed using a log-log scale. The plot of the dimensionless key parameters versus the Reynolds number and the Froude number are shown in Figure 2 using the data from Table 1. This figure shows that, for the data collected in natural streams, the Reynolds number and the Froude number have an insignificant effect on the dimensionless key parameters for the TS model. This confirms the assumption that, for turbulent flow in the rough natural stream, the effect of the Reynolds number is probably negligible. The plots of the key dimensionless parameters for the TS model versus both the friction term and the width-to-depth ratio are shown in Figure 3. This figure demonstrates that the dimensionless dispersion coefficient in the free-flowing water zone and the dimensionless residence time have some dependency on these two dimensionless variables, even though the data are somewhat scattered.

3.2 New Key Parameters Equation of the TS Model

Among 58 data sets, 34 measured data sets superscripted "a" in Table 1, were selected to derive the dimensionless key parameters, and the other 24 measured data sets were used to verify the new empirical equations for the TS model parameters. Separation of total data sets into two groups was done so that where more than two data sets were obtained from the same stream, these sets were divided between the two groups in order that the groups have similar statistical characteristics. The characteristics of the dimensionless TS model parameters, and hydraulic and geometric variables for both the derivation and the verification data sets are summarized in Table 2.

The new regression equation derived by using the weighted one-step Huber method is given as

$$\mathrm{P} = \alpha\left(\frac{W}{h}\right)^{\beta}\left(\frac{U}{U_*}\right)^{\gamma} \tag{15}$$

Values of α, β, and γ and the correlation coefficients are summarized in Table 3. An equation for the dimensionless mean velocity in the free-flowing water zone was also derived by substituting the area ratio from equation (15) into the equation (8). The dimensionless mean velocity in the free-flowing water zone is given as

$$\frac{U_f}{U} = 1 + 0.850\left(\frac{W}{h}\right)^{0.008}\left(\frac{U}{U_*}\right)^{-0.401} \tag{16}$$

The correlation coefficient for U_f/U from equation (16) is 0.94. In this study, regression coefficients were also computed using the least-squares method, and those values were used as an initial condition for the solution of

Table 2. Range of dimensionless variables

Dimensionless Data	Range Derivation Data	 Verification Data
U_f / U	0.29 - 4.80	0.36 – 6.90
K_f / hU_*	7.37 – 6646.75	22.37 – 7926.6
$T / (h / U_*)$	4.95 – 2772.71	9.64 – 1726.65
ε	0.005 – 0.103	0.008 – 0.116
$U / \sqrt{gh}$	0.02 – 0.45	0.01 – 0.32
$\rho hU / \mu \ (\times 10^6)$	0.17 – 8.05	0.37– 4.04
U / U_*	0.86 – 17.91	0.78 – 15.45
W / h	5.75 – 138.5	12.45 – 130.9

Table 3. Range of dimensionless variables

Dimensionless Data	Parameters α	 β	 γ	Correlation Coefficient
K_f / hU_*	0.583	1.287	0.562	0.89
$T / (h / U_*)$	56.68	0.767	-0.884	0.71
ε	0.850	0.008	-0.401	0.78

thee weighted one-step Huber method.

4. VERIFICATION

Twenty-four measured data sets that were not used in the derivation of the regression equation were used to verify the proposed equations for estimating key parameters of the TS model. For the verification of the proposed equations, the key parameters estimated by the proposed equations and the existing equations were compared with measured key parameters of the TS model. For the dispersion coefficient in the free-flowing water zone, the Pedersen's equation was selected. The Pedersen's equation was selected for verification of the residence time. Two existing area ratio equations, equations proposed by Thackston and Schnelle (1970), and Seo and Yu (2000), which were proven to be relatively accurate compared with the Pedersen's equation in predicting the area ratio in the natural streams were selected.

The comparisons of estimated key parameters of the TS model with measured data sets are shown in Fig. 5. This figure shows that the other proposed equations predict quite well whereas the Pedersen's equations overestimate in the dispersion coefficient in the free-flowing water zone, the residence time, and the area ratio values. Seo and Yu's equation overestimates in the area ratio values. The comparison between predictions by the new equations developed in this study and field parameters measured by RM method indicates good agreement, according to different error measures and statistical analysis.

Fig. 6 is the histogram of discrepancy ratios for proposed and selected existing equations included in the analysis of the twenty-four field data sets. The discrepancy ratio distributions of all proposed equations excepting residence time equation present a maximum number of values between –0.3 and 0.3. The discrepancy ratio distributions of the Pedersen's two equations are flatter, showing a maximum number of values in the range between 0.3 and 3. The discrepancy ratio distribution of the Hays' residence time equation presents a maximum number of values between 3 and 5. The discrepancy ratio distributions of both equations of the Thackston & Schnelle (1970) and the Seo & Yu (2000) are flatter than proposed equation, showing a maximum number of values of both equations in the range between 0 and 1. Accuracy of the proposed equation for the mean velocity in the free-flowing water zone is 66.7 %. Accuracy of the Pedersen's equation for the dispersion coefficient in the free-flowing water zone is 12.5 % and the result of proposed equation is 50 %. Accuracy of the Hays' equation and the Pedersen's equation for the residence time are 0 % and 16.7 % respectively, and the result of proposed equation is 41.7 %. Accuracy of the Thackston and Schnelle's equation and the Seo and Yu's equation for the area ratio are 41.7 % and 33.3 % respectively, and the result of proposed equation is 62.5 %. The accuracy of proposed equation ranges from 41.7 to 66.7 %, which is the highest of all. These results demonstrate that the new equations developed in this study are superior to the other existing equations in predicting key parameters of the TS model more precisely in natural streams.

In Fig. 7, the dimensionless dispersion coefficient of the TS model was plotted against both the W/h and the U/U_*, in which the K_f/hU_* for both the Pedersen's equation and this study increased as the W/h increased however, the Pedersen's result increased more rapidly than that of this study. In the while K_f/hU_* of this study increased with the U/U_*, the Pedersen's result decreased as the U/U_* increased. In Fig. 8, the dimensionless residence time of the TS model was plotted against both W/h and U/U_*, in which $T/(h/U_*)$ for both Pedersen's equation and this study increased as the W/h increased however, the $T/(h/U_*)$ for both the Pedersen's equation and this study decreased as the U/U_* increased. The Pedersen's results increased more rapidly than that of this study with the W/h and the Pedersen's results decreased more rapidly than that of this study with the U/U_*. In Fig. 9 the area ratio results of the Thackston & Schnelle (1970), Pedersen (1977), Seo & Yu (2000), and this study were plotted against the U/U_*, in which all equation decreased as the U/U_* increased.

5. CONCLUSIONS

The results of this study show that, among the existing equations for estimating parameters of the TS model, the Pedersen's equation is not amenable because it overestimates all key parameters significantly except the mean velocity in the free-flowing water zone. Cheong and Seo's equations predict parameters relatively well, whereas the Seo and Yu's equation overestimates in most cases. However, for large rivers with channel widths larger than 200m, the Pedersen's two equations overestimate significantly.

New equations for predicting key parameters of the TS model by using hydraulic data sets which are easily obtained from the natural streams have been developed. Dimensional analysis was implemented to select the physically meaningful variables that are required for the new equations in order to predict mixing in

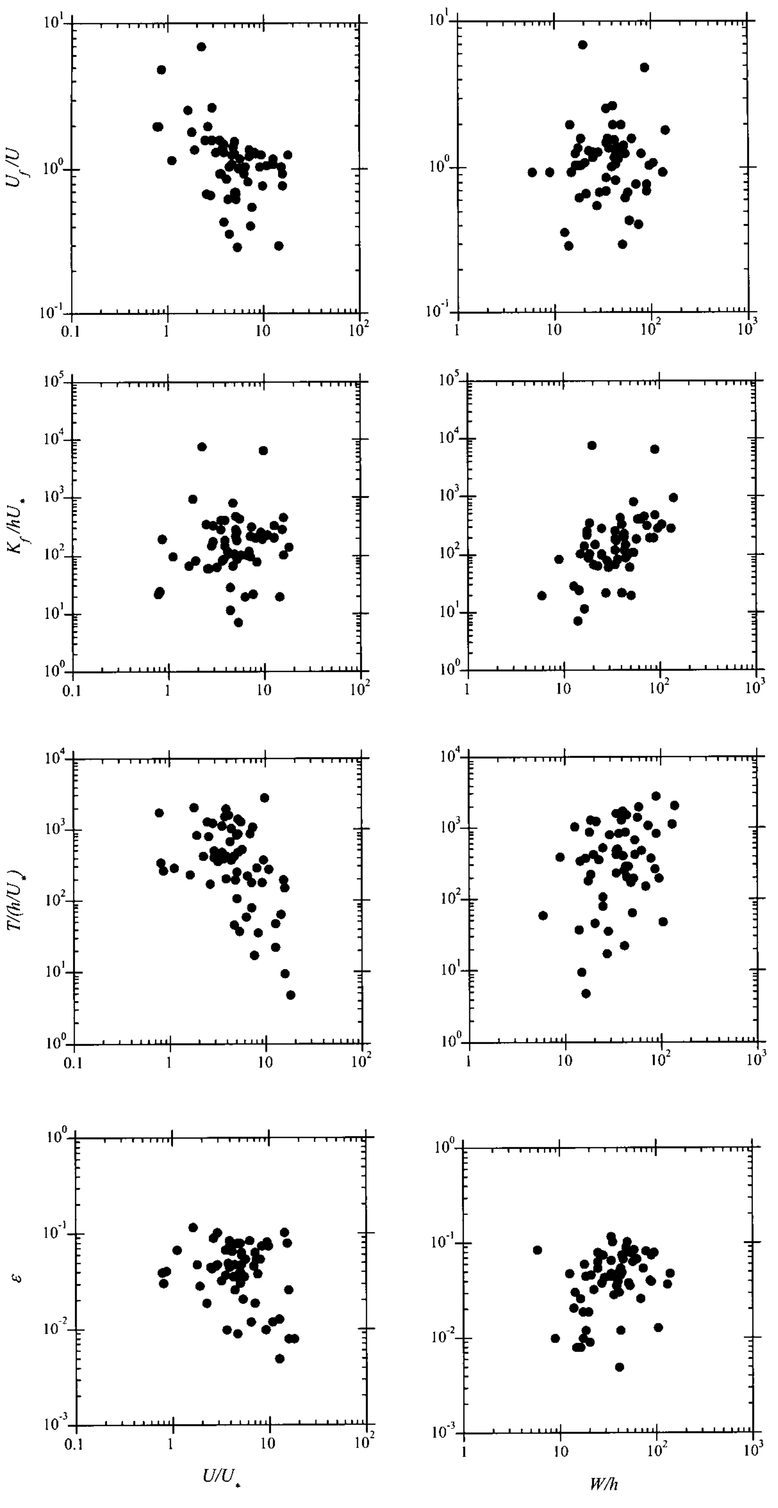

Fig. 4 Plots of observed dimensionless parameters versus friction term and width-to-depth ratio

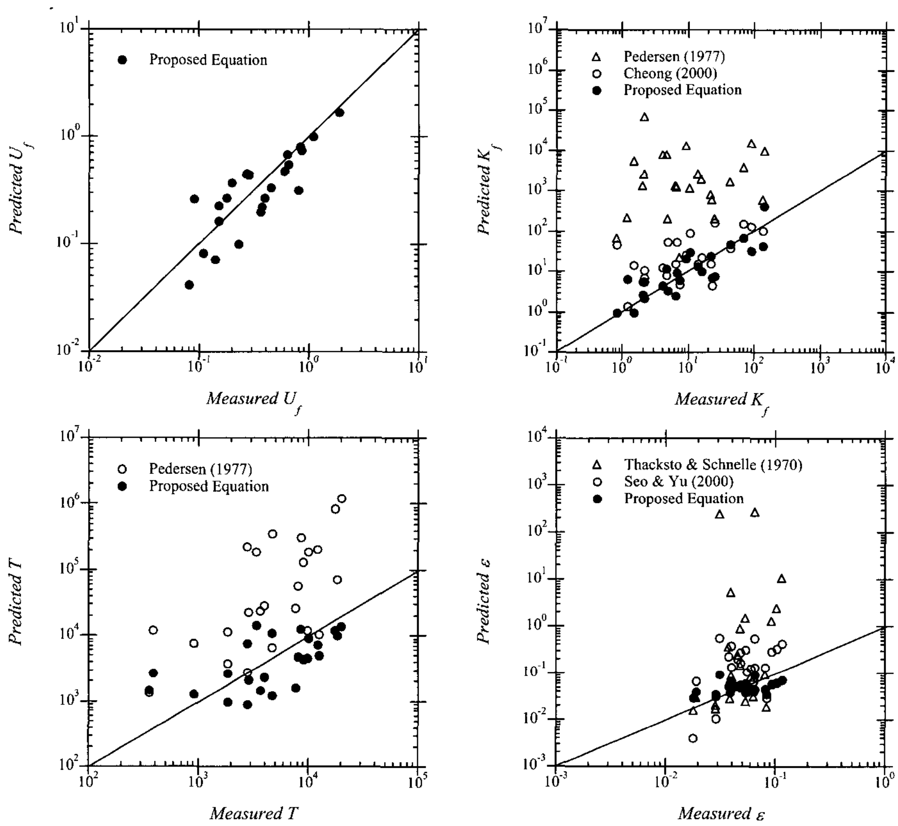

Fig. 5 Comparison of determined parameters with observed data used in verification

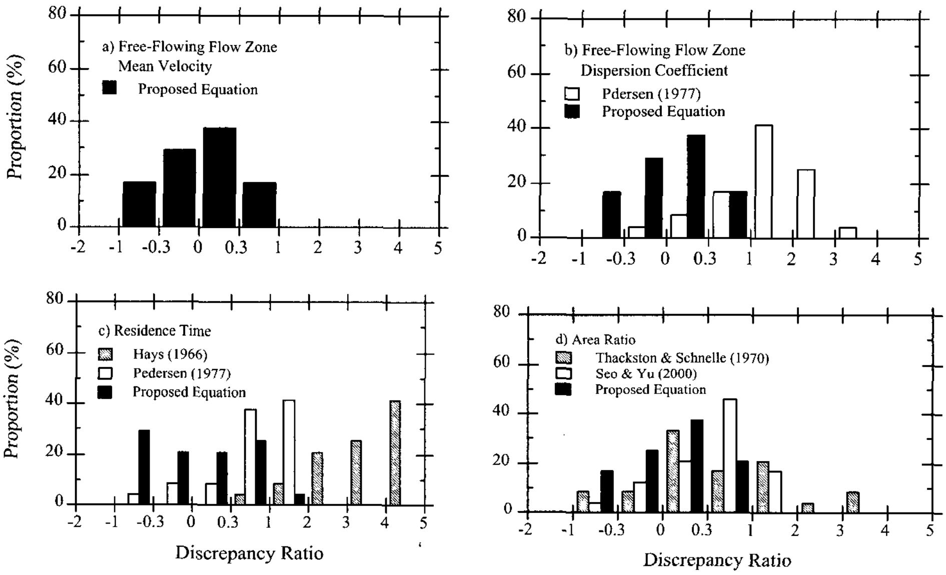

Fig. 6 Comparison of discrepancy ratios of existing and new equations for observed data used in verification

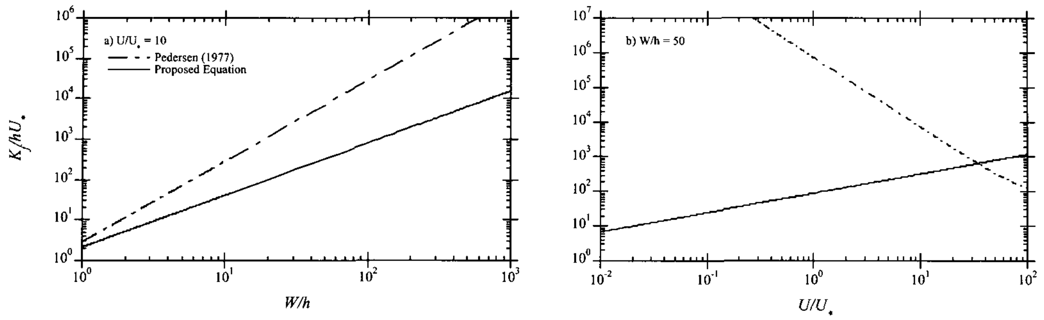

Fig. 7 Comparison of determined dimensionless free flowing water zone dispersion coefficient versus friction term and width-to-depth ratio

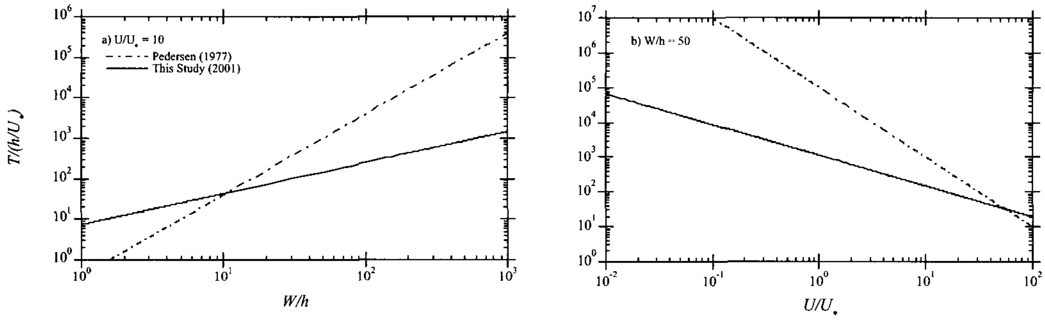

Fig. 8 Comparison of determined dimensionless residency time versus friction term and width-to-depth ratio

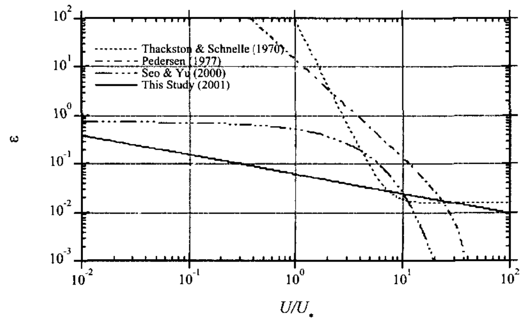

Fig. 9 Comparison of determined dimensionless area ratio versus friction term and width-to-depth ratio

natural streams. The weight One-step Huber method was applied to calculate coefficients of the new key parameters equation for the TS model. The proposed equations allow superior prediction as compared to the other existing equations and the discrepancy ratio of the new parameters equation ranges from -1 to 2. The accuracy of proposed equations ranges from 73 to 100%. The key parameters of the TS model estimated by the proposed equations can be used when the transient storage model is applied to the natural streams where mixing and dispersion data has not been collected, and thus the measured key parameters are not available.

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Post Doc. Research Assoc., Dept. of Civil & Environmental Engineering, Univ. of California, Davis, CA 95616, U.S.A.
(E-mail: tcheong@ucdavis.edu)

Prof., Dept. of Civil Engineering, Seoul National Univ., Seoul 152-742, Korea.
(E-mail: seoilwon@snu.ac.kr)