

CHARACTERIZATION OF POOL-RIFFLE SEQUENCES IN SOLUTE TRANSPORT MODELING OF STREAMS

Il Won Seo, and Daeyoung Yu

School of Civil, Urban and Geosystem Engineering, Seoul National University, Seoul, Korea

Abstract: A mathematical model to adequately predict complex mixing characteristics of sorptive pollutants in natural streams with pools-and-riffles has been developed. In the model, sorption of pollutants onto the bed sediment as well as mass storage and exchange in the storage zones were incorporated into one-dimensional mass balance equations. The geometric and hydraulic characteristics of the pool-riffle sequences were properly conceptualized. Simulations with parameters of pool-and-riffle streams better fit the measured data in overall shape and peak concentration than simulations with parameters for uniform channels. The analyses on the characteristics of the storage zone model parameters reveal that a linear relationship between the logarithm of the storage zone volume ratio and a function of the friction factor exists. A linear relationship might also be tentatively assumed between the logarithm of the dimensionless mass exchange coefficient and the logarithm of the aspect ratio of the storage zone if some of the high values of the dimensionless mass exchange coefficient collected on the successive bed forms are excluded.

Key Words: water quality modeling, sorption, storage processes, pool-and-riffle sequences

1. INTRODUCTION

The flow and mixing characteristics in real streams are substantially different from those that are observed in uniform channels. Boundary geometry of natural streams is not smooth and regular and each irregularity contributes to mixing of pollutants. Variations in streambed geometry such as pool and riffle structure, which are important features of natural streams (Leopold *et al.*, 1964), play important roles in affecting flow and mixing characteristics of the release of pollutants into the channel. Pools are characterized by deep, slow-moving water, whereas riffles are generally shallow and rap-

idly moving. A typical bed profile of a pool-riffle sequence is concave in the pool and convex in the riffle region. Leopold *et al.* (1964) concluded that an alternating pool-riffle sequence is present in practically all perennial channels in which the bed material is larger than coarse sand. They also found that finer materials are found in the pools, while larger particles are found in riffles. Moreover, within the riffles themselves a sorting of particle sizes take place, with larger materials on top.

Pool-riffle sequences are present in straight and meandering channels. In both instances, deep and shallow areas are spaced more or less regularly with pools occurring at a repeating

distance of approximately 5 to 7 channel widths (Leopold *et al.*, 1964). This generalization is supported by field data collected by Stall and Yang (1972), and Singh and Broeren (1985). The pool-riffle sequences are believed to be closely correlated with the meandering nature of a river (Henderson, 1966). Meanders represent the river's lateral deviation from a straight course, whereas undulating deep and shallow areas of the pool-riffle sequence can be correlated with the vertical deviations. The same mechanism is thought to play a role in both processes (Yang, 1971). Seo and Maxwell (1992) reported that flow through the pool-riffle sequences gives rise to repetition of the contractions and expansions. The flow over the pool-riffle sequences is highly non-uniform and complex, causing the formation of large storage zones with recirculating flow oriented in a horizontal plane in the pools. Therefore, the resulting storage mechanism for the water and tracer changes the dispersion characteristics of a solute in natural streams which contain pools-and-riffles.

In natural streams with pools-and-riffles, slow movements of water and sediment in the pool region enhance sorption onto the relatively immobile bed sediment and thus constitutes a major control on solute transport (Bencala, 1983). Therefore, in natural channels in which pollutants have the opportunity for repeated contact with bed materials and irregularities and unevenness caused by pools and riffles create storage zones, pollutant transport is determined by a combination of physical and chemical processes. Among the physical processes, transient storage and exchange mechanisms are important along with mean flow advection and shear flow dispersion, while, for the case of chemical processes, sorption and desorption

mechanisms constitute major issues. Several investigators including Bencala (1983), Bencala (1984), Bencala *et al.* (1990), Broshears *et al.* (1993), and Chapra and Runkel (1999) investigated the interactions of solute and streambed sediment in small mountain streams. They incorporated transient storage and sorption processes into their solute transport model. However, even though they were successful in explaining the complex solute transport processes occurring in natural streams, most of their model parameters including those representing the storage mechanisms were determined by fitting model simulations to field experimental data. Furthermore, the characteristics of pool-riffle sequences, which have major effects on the transient storage and sorption processes in small natural streams, were not given adequate consideration in their model.

The objective of the present study was to develop a mathematical model to adequately predict the complex mixing characteristics of sorptive pollutants in natural streams that contain pools-and-riffles. In the proposed model, geometric and hydraulic characteristics of the pool-riffle sequences were more adequately conceptualized. Dispersion data from stream experiments were used to test and verify the proposed mathematical model. An equation for the estimation of the important model parameters was proposed.

2. MATHEMATICAL MODEL

2.1 Conceptualization

In this model, a typical cross section is assumed to consist of two distinct zones, a flow zone and a storage zone, as shown in Fig. 1. In the flow zone, the dominant mass transport mechanisms are longitudinal advection and dispersion. The storage zones are assumed to be

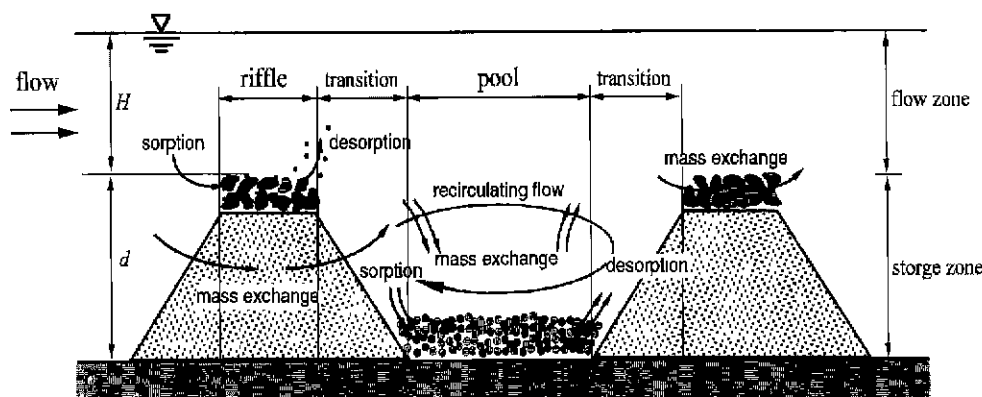


Fig. 1. Schematic Diagram of the Simplified Pool-Riffle Sequences

regions having vortex or recirculating flow and having mass interchange with the main flow across the interface between the flow and the storage zones. In natural streams with pools-and-riffles, in addition to large-scale turbulent eddies generated by major irregularities including pools and riffles, dunes, side pockets, small scale eddies which are located behind flow obstructions such as cobble, small boulders as well as interstices of a streambed, consisting of gravel and sand, also contribute to the creation of the storage zones so that the total volume of storage zones tends to be greater, compared to artificial storage zones used in experiments in laboratory channels (Tsai and Holley, 1979; Seo and Maxwell, 1992). The storage zones serve to retain a portion of the solute as the main cloud passes, and the solute is then slowly released back into the flow zone. Among several conceptually different physical models for the transient storage of mass in the storage zone (Jackman *et al.*, 1984), the exchange model assumes a different uniform concentration in each zone. Mass transfer at the interface between the zones is considered to be proportional to differences in the concentrations of each zone.

In this model, sorption which accounts for

binding of the dissolved pollutant molecules or ions to the bed sediment and desorption which accounts for the release of solute back into the water column of the stream has been considered using a first-order mass transfer model amongst several different kinetic equations (Bencala *et al.*, 1983). Binding forces for sorption are van der Waals' forces in the case of molecules and electrostatic forces in the case of ions. The larger the total solid particle surface area, the greater becomes the sorption effect, i.e., a small particle size enhances the sorption effect. In general, the sediment particles on which sorption of toxic components occurs may be either organic or inorganic, i.e. suspended and bed sediment along with biota or benthos. However, in this study emphasis is on the sorption mechanisms of toxic heavy metals to inorganic bed sediments.

Laboratory experiments and field observations in pool-and-riffle streams (Bencala *et al.*, 1983; Seo and Maxwell, 1992) show that the parameters most likely to spatially vary are the storage zone submodel parameters and sorption submodel parameters, as well as flow depth and velocity. These values could be considerably different in pools vis-a-vis riffle sections. There-

fore, in this model, generalized geometric and hydraulic characteristics of the pool-riffle sequences as shown in Fig. 1 were incorporated. Even though, in reality, the typical structure of the pool-riffle sequence has been reported as a full three-dimensional feature, pool-riffle sequences are simplified so as to be two-dimensional and symmetrical in this model.

2.2 Governing Equations

The equations describing the mathematical model are derived using conservation of mass. The mass balance equation in the flow zone for steady flow is

$$A_f \frac{\partial C}{\partial t} = -U_f A_f \frac{\partial C}{\partial x} + \frac{\partial}{\partial x} \left(A_f K \frac{\partial C}{\partial x} \right) - Pk(C-S) + A_f k_d \rho_f \lambda_f \left(\frac{1}{k_d} C_B - C \right) \quad (1)$$

in which A_f = the cross-sectional area of the flow zone (m^2); C = the concentration of mass in the flow zone (mg/l); U_f = the flow zone velocity which is equal to the discharge divided by the flow zone area (m/s); K = dispersion coefficient (m^2/s); P = the wetted contact length between the flow zone and the storage zone in the transverse or vertical direction (m); k = the mass exchange coefficient (m/s); S = the concentration of mass in the storage zone (mg/l); k_d = the distribution coefficient (ml/g); ρ_f = accessible sediment density in the flow zone which is the mass of the sediment on the streambed which is in effective contact with a given volume of water in the stream (g/m^3); λ_f = first-order rate coefficient for sorption/ desorption in the flow zone ($1/s$); C_B = the sorbate concentration on the streambed sediment of flow zone streambed sediment (g/g); x = the direction of the mean flow (m); and t = time (s). Basically, Eq. (1) has

the same form as the one suggested by Bencala (1984) except terms of lateral inflow and exchange between hyporheic zone are neglected. The role of the hyporheic zone where stream water and shallow groundwater mix and exchange together was well investigated by many researchers including Harvey *et al.* (1996), Wagner and Harvey (1997), Harvey and Fuller (1998), and others.

A mass balance equation describing the concentration of sorbed pollutants on the flow zone streambed sediment is

$$\frac{\partial C_B}{\partial t} = -\lambda_f (C_B - k_d C) \quad (2)$$

A mass balance equation describing concentration of dissolved solutes in the storage zone is

$$A_s \frac{\partial S}{\partial t} = Pk(C-S) + A_s k_d \rho_s \lambda_s \left(\frac{1}{k_d} S_B - S \right) \quad (3)$$

in which A_s = the cross-sectional area of the storage zone perpendicular to the general flow direction (m^2); ρ_s = the accessible sediment density in the storage zone (g/m^3); λ_s = the first-order rate coefficient for sorption/ desorption in the storage zone ($1/s$); and S_B = the sorbate concentration of the sediment associated with the storage zone (g/g). A mass balance equation describing the concentration of sorbed pollutants on the storage zone sediment is

$$\frac{\partial C_B}{\partial t} = -\lambda_s (S_B - k_d S) \quad (4)$$

The sorption model as a chemical submode used in this study is a kinetic first-order mass transfer model. This model relates the rate of change of concentration of the element which is sorbed on the sediment to the difference be-

tween the concentration of that element and its potential equilibrium concentration in the stream. In this submodel, the distribution coefficient k_d , which relates partitioning of the contaminant between the liquid and solid phases at equilibrium, is assumed to be constant. This assumption, the so called linear sorption isotherm, is simple and widely used for the study of sorption kinetic mechanisms (Bencala *et al.*, 1983).

2.3 Initial and Boundary Conditions

If the pollutant is released with constant concentration for a limited period, the initial conditions for the Dirichlet-type are

$$C(x,0) = 0 \quad (5)$$

$$\begin{aligned} C(0,t) &= C_0 & 0 < t \leq \tau \\ C(0,t) &= 0 & t > \tau \end{aligned} \quad (6)$$

in which C_0 = the initial concentration injected; τ = the period of injection. The Dirichlet-type boundary conditions for an infinite domain are

$$C(\pm\infty,t) = 0 \quad (7)$$

If the pollutant is initially released into only the flow zone so that no concentration in the storage zone exists, the initial condition of Dirichlet-type for the storage zone is

$$S(x,0) = 0 \quad (8)$$

The initial and boundary conditions for the sorbate on the sediment associated with both the flow and storage zones are obtained under the assumption that the pollutant is initially released into only the water column of the flow zone so that there is no concentration in the sorbate on

the sediment associated with both the flow and storage zones. For the sorbate on the sediment of the flow zone, this assumption results in:

$$C_B(x,0) = 0 \quad (9)$$

For the sorbate on the sediment of the storage zone, this assumption results in:

$$S_B(x,0) = 0 \quad (10)$$

2.4 Numerical Modeling

An analytical solution of the given sets of governing equations (Eqs. (1)-(4)) corresponding to the initial and boundary conditions (Eqs. (5)-(10)) was not available because of the non-uniform parameters and the existence of the mass exchange term and sorption term in the equation. Given sets of the working equations consist of four equations, which describe coupled solute transport in the flow zone, sorption onto the flow zone streambed sediment, solute transport and sorption in the storage zone, and sorption onto the storage zone sediment. The equations which describe the mass balance of the solute in two zones are interrelated by the mass exchange term modeling the storage processes. The equations which describe the mass balance of the sorbate on the sediment in each zone are coupled directly to the equations describing mass balance of the solute in each zone. In this study, a combined procedure for the analytical solution of one of the sorbate equations and the iteration method for the numerical solution of the remaining three equations was used to solve complex sets of coupled working equations. In this model, the analytical solution of sorbate concentration at the storage zone was obtained as

$$S_B = \lambda_3 e^{-\lambda_3 t} \int (e^{\lambda_3 t} S) dt \quad (11)$$

A typical detailed procedure is as follows: First, Eq. (11), the analytical solution of S_B was inserted into Eq. (3) to reduce one unknown dependent variable. Second, an estimated value of C was used in numerically solving Eqs. (2)-(3) to obtain C_B and S . Then, S_B is obtained using Eq. (11) in which S is numerically integrated using the simple trapezoidal rule. Eq. (1) was then solved to obtain C with the known values of C_B and S . This process was iterated until the differences between computed and estimated concentrations of C were within the specified tolerance. The general flow chart of this procedure is shown in Fig. 2. For the second stage of solution procedure, among the various types of numerical schemes tested by Seo (1990), the finite difference method developed by Stone and Brian (1963) was selected in order to solve the remaining three equations. This method, based on the Crank-Nicolson implicit approach, was well described by Seo and Maxwell (1992). Runkel and Chapra (1993) also discussed details of the implicit finite difference technique based on the Crank-Nicolson method to solve the transient storage equations for solute transport.

3. MODEL APPLICATIONS

3.1 Stream Data

The numerical model developed in this study was used to simulate the solute transport in a mountain pool-and-riffle stream. Of the several sets of field data for solute transport experiments in small natural streams collected by U.S. Geological Survey, the Uvas Creek data (Avanzino *et al.*, 1984) was selected because this data set contains relatively accurate hydraulic data as well as tracer concentration data. As shown in Fig. 3, Uvas Creek is a small stream

located on the eastern slopes of the Santa Cruz mountains in California, U.S.A. The experiment was conducted in late summer during a period of low flow ($Q = 0.0125 \text{ m}^3/\text{s}$). Strontium tracer, used as a sorptive pollutant, was injected at a constant rate for three hours and reached a maximum concentration of 1.73 mg/l a short distance below the injection point. Background concentration was determined to be 0.13 mg/l. In addition to the intense monitoring of in-stream concentration, some of the sorbed strontium concentrations on bed sediments were measured at $x = 105$ and 281 m .

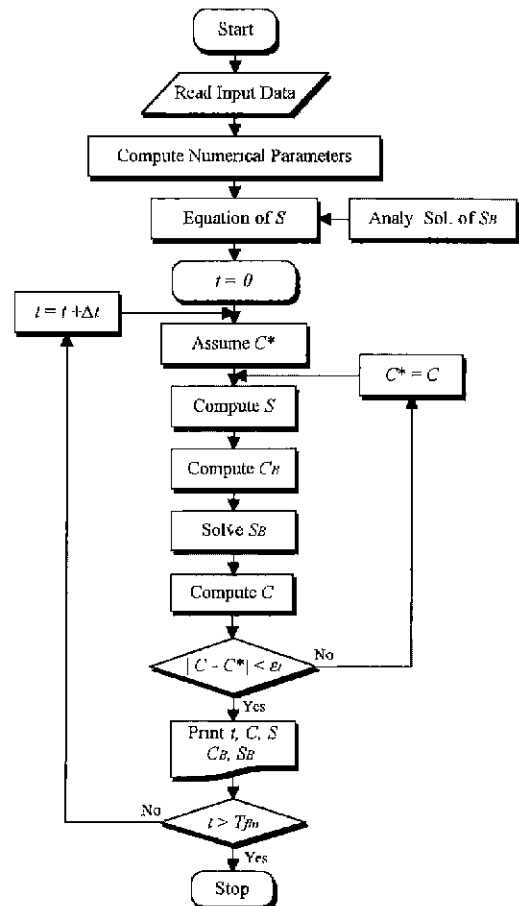


Fig. 2. The General Flow Chart of Computational Procedure

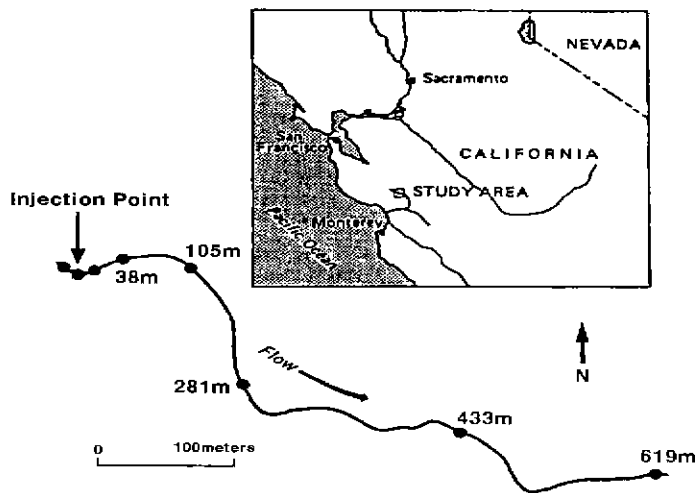


Fig. 3. Experimental Reach of Uvas Creek (After Avanzino *et al.*, 1984)

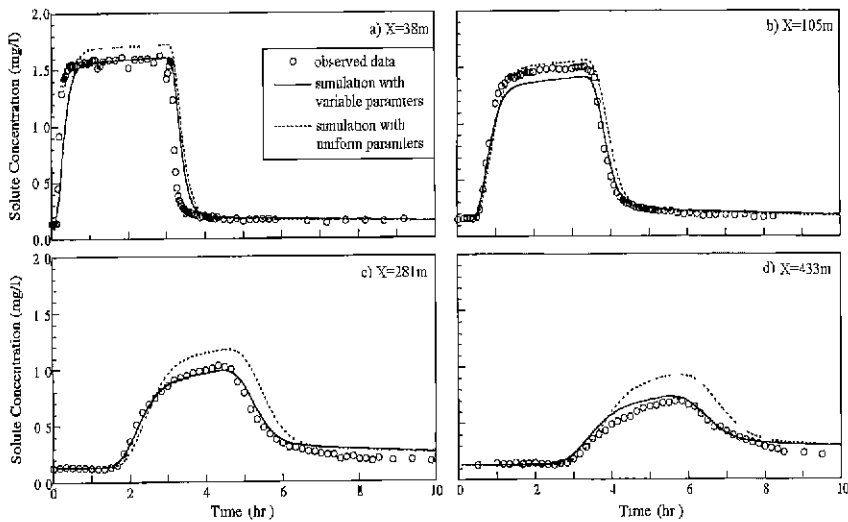
The channel is highly irregular and is composed of alternating pools and riffles. Analyzing the detailed map of the study reach of Uvas Creek (Bencala and Walters, 1983), it is found that the pool frequency ranges mostly 6 to 7 channel widths which falls into the typical range of that of the natural pool-riffle sequences studied by other investigators (Leopold *et al.*, 1964). Thus, in the model simulations of the Uvas Creek, as shown in Fig. 1, the channel reach is assumed to consist of sequences of pools-and-riffles which can be divided into three sections, i.e., pools, riffles, and transition areas in-between. The pool-riffle sequences are assumed to be repeated with pool frequency of 6 channel width throughout the whole reach of the Uvas Creek.

As discussed in the previous section, flow depth, velocity, storage zone submodel parameters and some of the sorption submodel parameters are most likely to be different in pool versus riffle sections. The nonuniform hydraulic parameters, such as the flow depth and the storage zone volume ratio, ε , which is defined as the ratio of storage zone volume to the main flow

volumes, equal to A_s/A when the channel width is uniform, were considered to have single constant values at the pool and riffle, and then to vary in a linear fashion through the transition between the pool and the riffle. The mass exchange coefficient and accessible mass density were also considered to follow the above assumption. Seo (1990), based on his experiments on the mixing characteristics of the pool-riffle sequences, maintained that the storage zone volume ratio and the mass exchange coefficient at the pool are usually higher than those at the riffle. The dispersion coefficient, sorption rate coefficient, and distribution coefficient were assumed to be constant throughout the entire reach regardless of pool or riffle sections. The model parameters used for simulation are presented in Table 1. All the sorption parameters except accessible mass density were selected from independently-decided values by measurements (Bencala *et al.*, 1983). The dispersion coefficient was estimated using the predictive equation proposed by Seo and Cheong (1998), and storage zone parameters were estimated by empirical relationships, which will

Table 1. Summary of the Model Parameters used in the Simulation

	Length (m)	K (m^2/s)	ε	k (m/s)	k_d (ml/g)	ρ_f (g/m^3)	ρ_s (g/m^3)	λ_f (1/s)	λ_s (1/s)
Pool	8		0.49	1.2×10^{-4}		0.14×10^5	0.14×10^5		
Riffle	4		0.35	0.2×10^{-4}		0.14×10^4	0.14×10^4		
Transition	4		linearly varied	linearly varied		linearly varied	linearly varied		
Average		0.21	0.43	0.86×10^{-4}	70.0	0.09×10^5	0.09×10^5	0.3×10^{-1}	0.48×10^{-3}

**Fig. 4. The Solute Concentration-Time Curves of Model Simulations and Experiments Data**

be discussed later.

These values of the model parameters were chosen in such way to give better fit the measure data.

3.2 Simulation Results

Comparisons of the concentration-time curves of the model simulations with those obtained in the stream experiments are depicted in Fig. 4. In general, in overall shape, the concentration-time curves given by the numerical model give an excellent fit to the measured concentration-time curves. The tails of the concentration-time curves of the model simulations are

quite close to those measured for the concentration-time curves. The model also predicts the elapsed times to peak concentration very accurately. In Fig. 4, concentrations are compared for simulations with variable parameters for pool and riffle sections and parameters of uniform channel which are the average values of parameters of the pool-and-riffle sequences. In overall shape and peak concentration, simulations with variable parameters of pool-and-riffle streams provide a better fit for the measured data than simulations with parameters of uniform channel. These data demonstrate the differences between solute transport in pool-and-

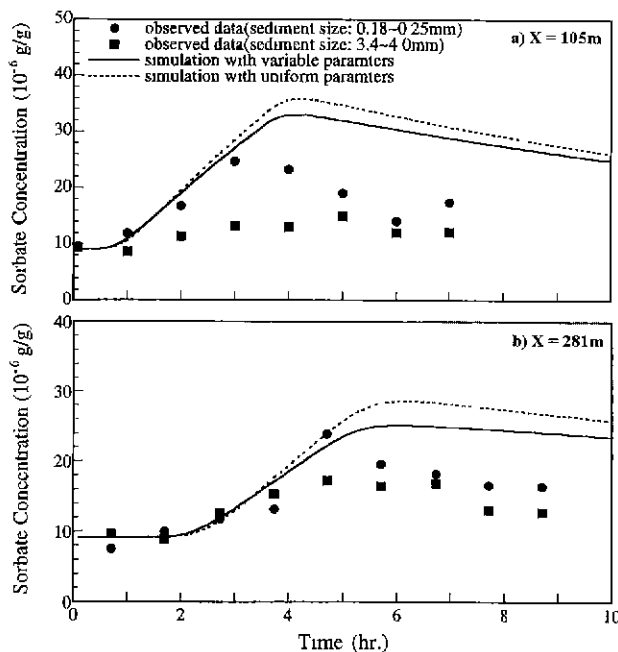


Fig. 5. The Sorbate Concentration-Time Curves of Model Simulations and Experiments Data

riffle streams versus in uniform channels.

In addition to comparisons of dissolved solute concentration, the concentrations of sorbate in the sediment were also compared for simulations with variable parameters and uniform parameters. These comparisons are depicted in Fig. 5. Both simulation results show moderate agreement with the measured sorbate concentrations for sediments of two different sizes in time to peak and in the persistence of the tails.

Simulations with variable parameters of pool-and-riffle streams show a better fit to the measured data.

4. ESTIMATION OF MODEL PARAMETERS

4.1 Calculation of Model Parameters

Among the model parameters, storage zone submodel parameters, i.e., storage zone volume ratio and mass exchange coefficient are the most important factors affecting solute transport proc-

esses in small natural streams with pools-and-riffles. Values of storage zone submodel parameters estimated in this study are compared with parameters obtained in the previous studies in Table 2. Model parameters shown in this table were determined using various methods, obtained by different researchers. In this table, k^* represents the dimensionless mass exchange coefficient, $k^* = k/U_f$.

As shown in Table 2, the value of the storage zone volume ratio of the natural streams shows wide variation, ranging from 0.01 to 3.0. This might be due to the widely varying characteristics of the natural streams from the standpoint of storage capacity of solute, and also due to uncertainties arising from the different methods of parameter calculation. The dimensionless mass exchange coefficient, k^* measured in a laboratory flume ranges between 0.01 ~ 0.12 whereas k^* values obtained in the natural streams ranges between 0.0003 ~ 0.006.

Table 2. Summary of the Storage Zone Submodel Parameters

	Channel Type	Method	ε	k^*
Hays <i>et al.</i> (1967)	laboratory flume	AS ¹⁾	N/A	0.013-0.116
Thackston and Schnelle (1970)	natural stream	AS	0.009-0.063	N/A
Day (1975)	natural stream	AS	0.068-0.18	N/A
Westrich (1976)	laboratory flume	AS	N/A	0.013-0.020
Valentine and Wood (1979)	laboratory flume	AS	N/A	0.014-0.026
Petersen (1977)	natural stream	MM ²⁾	0.008-0.255	N/A
Nordin and Troutman (1980)	natural stream	MM	0.025-0.056	N/A
Czermuszenko <i>et al.</i> (1998)	natural stream	MM	0.007-0.100	N/A
Tsai and Holley (1979)	laboratory flume	EM ³⁾	N/A	0.016-0.096
Seo and Maxwell (1992)	laboratory flume	EM	0.43-0.63	0.023-0.076
Bencala (1983)	natural stream	NS ⁴⁾	0.33-3.0	0.00089
Bencala (1984)	natural stream	NS	0.33-2.5	0.00567
Bencala <i>et al.</i> (1990)	natural stream	NS	0.036-0.79	0.00048
Broshears <i>et al.</i> (1993)	natural stream	NS	0.42-1.8	0.00030
This study	natural stream	NS	0.35-0.49	0.00375

- 1) Parameters are determined by comparing the concentration curve of analytical solutions to the measured concentration curve
- 2) Parameters are determined by comparing moment values computed by Aris' (1956) moment equation with the moments calculated directly from the measured concentration curve
- 3) Parameters are determined independently using the experimental data
- 4) Parameters are determined by comparing the concentration curve of numerical solutions to the measured concentration curve

4.2 Storage Zone Volume Ratio

For fully rough flow conditions, Henderson (1966) maintained that, since the flow resistance is entirely due to form drag on projections, the resistance is dependent only on the ratio of surface roughness to flow depth. As explained previously, since the storage zone could be thought of as an aggregation of various irregularities and roughness of the stream, it can be related to the coefficient of the surface roughness, such as Darcy-Weisbach friction factor, f . Thackston and Schnelle (1970), by best-fitting a power-form equation to field data collected in the natural streams, suggested a predictive equation for ε as a function of f as

$$\varepsilon = 0.0152 + 0.89f^{2.22} \quad (12)$$

in which f = Darcy-Weisbach friction factor that is defined as

$$f = 8 \left(\frac{U_*}{U} \right)^2 \quad (13)$$

in which U_* = shear velocity (m/s); U = cross-sectional average velocity (m/s). Fig. 6 shows the relation between the storage zone volume ratio ε and the function of friction factor f . This figure is a revision of a figure which appeared in the report of Bencala and Walters (1983) and includes additional data points. As shown in this figure, a clear linear relationship between the logarithm of the storage zone volume ratio and a function of the friction factor exists. However, the equation suggested by Thackston and Schnelle (1970), Eq. (12), does not explain the general tendency of the measured data. Therefore, in this study, new predictive equation for the storage zone volume ratio is proposed by best-fitting to the data as

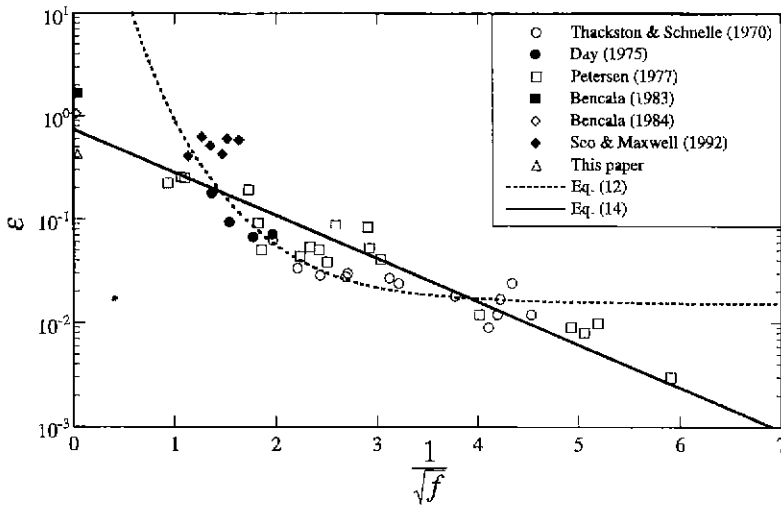


Fig. 6. The Relation between the Storage Zone Volume Ratio and the Function of Friction Factor

$$\varepsilon = 0.737 \exp\left(-\frac{0.956}{\sqrt{f}}\right) \quad (14)$$

$$k^* = \frac{k}{U_f} = f_1\left(\frac{U_f}{\sqrt{gH}}, \frac{U_f H}{\nu}, \frac{W}{H}, \frac{H}{d}, \frac{L}{d}, S_f\right) \quad (15)$$

Based upon the relation shown in Fig. 6 and Eq. (14), it might be concluded that in small mountain streams, such as Uvas Creek, examined in this study and by Bencala (1983), and Little Lost Man Creek studied by Bencala (1984), the total flow resistance attributed to small scale flow obstructions as well as large-scale channel irregularities, such as pool-riffle sequences, which usually generate the large storage zones with recirculating flow oriented in a horizontal plane in the pools, are quite large compared to those of medium-to-large rivers.

4.3 Mass Exchange Coefficient

In general, the mass exchange coefficient depends on the flow and fluid characteristics and geometric characteristics of storage zones. Using dimensional analysis, a functional relationship between dimensionless terms can be derived as

in which U_f/\sqrt{gH} = the Froude number; $U_f H/\nu$ = the Reynolds number; ν = kinematic fluid viscosity (m^2/s); W/H = width-to-depth ratio of the channel; W = the channel width (m); H/d = flow-zone depth-to-storage-zone depth ratio; d = storage-zone depth (m); L/d = length-to-depth ratio of the storage zone; and L = storage-zone length (m); and S_f = the shape factor accounting for other geometric characteristics for the storage zones.

For fully turbulent flow in rough open channels, such as natural streams, the effect of the Reynolds number is negligible. If the Froude number is sufficiently small it can also be neglected. If it is further assumed that the channel aspect ratio, H/W is not a significant parameter, Eq. (15) can be reduced to

$$k^* = f_2\left(\frac{H}{d}, \frac{L}{d}, S_f\right) \quad (16)$$

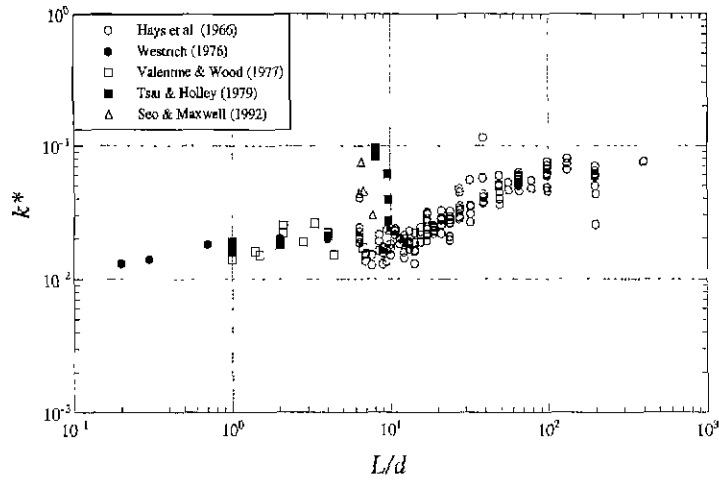


Fig. 7. The Relation between the Dimensionless Mass Exchange Coefficient and the Aspect Ratio of the Storage Zone

The complete identification of the effects of each dimensionless parameter in Eq. (16) on the k^* values would require a significant amount of experimental data for various types of storage zones. However, only limited data are available for some of the parameters in Eq. (16).

In Fig. 7, the dimensionless mass exchange coefficient is plotted against the aspect ratio of the storage zone, L/d . In this figure, Hays *et al.* (1967), Westrich (1976) and Valentine and Wood (1979) conducted their experiments in a laboratory flume with a rectangular pockets, whereas Tsai and Holley (1979) collected their data on a laboratory flume with various types of storage zones, recessed cubical boxes, strips across flume bed, and two-dimensional dunes. Data by Seo and Maxwell (1992) was collected using a simplified model of pool-and-riffle sequences in a laboratory flume. From Fig. 7, if the high values of k^* collected by Tsai and Holley (1979) and Seo and Maxwell (1992) on the successive bed forms are excluded, a linear relationship might be assumed between the logarithms of k^* and L/d .

In Fig. 7, the higher k^* values collected by Tsai and Holley (1979) and Seo and Maxwell (1992) where sequences of dunes or pools and riffles exist could be due to higher turbulence resulting from flow over a series of large-scale channel irregularities. The deviations from the linear relationship between the logarithms of k^* and L/d might also be explained as the result of influences of other parameters, such as shape factor and the flow-zone depth-to-storage-zone depth ratio, which are included in Eq. (16). Since the k^* value determined for Uvas Creek in this study is significantly low, based on the linear relation as shown in Fig. 7, it could be concluded that the value of L/d of the most of storage zones existed in the Uvas creek might be very low. This suggests that in small mountain streams with cobbles and gravel on the stream bed, such as Uvas creek, small scale recirculating zones located behind flow obstructions such as cobbles, small boulders and/or interstices of the streambed are major contributing factors to the transient storage of solute compared with the large-scale recirculating zones generated by

major channel irregularities, such as pool-riffle sequences, of medium-to-large rivers.

5. CONCLUSIONS

In this study, a mathematical model to adequately predict complex mixing characteristics of sorptive pollutants in natural streams with pools-and-riffles has been developed. In this model, geometric and hydraulic characteristics of the pool-riffle sequences were properly conceptualized. A comparison between measured and predicted concentration curves by the numerical model shows that a good level of agreement exists in the general shape, peak concentration and time to peak. Simulations with variable parameters of pool-and-riffle streams better fit the measured data in overall shape and peak concentration than simulations with parameters of uniform channels. Simulation results also show moderate agreement with measured sorbate data of sediment of two different sizes in time to peak and in the persistence of the tails.

The relation between the ratio of storage zone volume to the main flow volume and the function of friction factor was examined using available data. It is suggested that a linear relationship between the logarithm of the storage zone volume ratio and a function of the Darcy-Weisbach friction factor f exists. A linear relationship might also be tentatively assumed between the logarithm of the dimensionless mass exchange coefficient and the logarithm of the aspect ratio of the storage zone.

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University, Seoul, Korea.

REFERENCES

- Aris, R. (1956). "On the Dispersion of a Solute in Fluid Flowing through Tube." *Proceedings of the Royal Society*, London, England, Series A, 235, Vol. 200, pp. 67-77.
- Avanzino, R. J., Zellweger, G. W., Kennedy, G. W., Zand, S. M., and Bencala, K. E. (1984). *Results of a Solute Transport Experiment at Uvas Creek, September 1972*. Open-File Report 84-236, U.S. Geol. Surv., Menlo Park, Calif.
- Bencala, K. E. (1983). "Simulation of Solute Transport in a Mountain Pool-and-Riffle Stream With a Kinetic Mass Transfer Model for Sorption." *Water Resources Research*, Vol. 19, No. 3, pp. 732-738.
- Bencala, K. E. (1984). "Interactions of Solutes and Streambed Sediment 2. A Dynamic Analysis of Coupled Hydrologic and Chemical Processes That Determine Solute Transport." *Water Resources Research*, Vol. 20, No. 12, pp. 1804-1814.
- Bencala, K. E., and Walters, R. A. (1983). "Simulation of Solute Transport in a Mountain Pool-and-Riffle Stream: A Transient Storage Model." *Water Resources Research*, Vol. 19, No. 3, pp. 718-724.
- Bencala, K. E., Jackman, A. P., Kennedy, V. C., Avanzino, R. J., and Zellweger, G. W. (1983). "Kinetic Analysis of Strontium and Potassium Sorption Onto Sands and Gravels in a Natural Channel." *Water Resources Research*, Vol. 19, No. 3, pp. 725-731.
- Bencala, K. E., Jackman, A. P., McKnight, D. M., and Zellweger, G. W. (1990). "Characterization of Transport in an Acidic and Metal-Rich Mountain Stream Based on a Lithium Tracer Injection and Simulations

- of Transient Storage". *Water Resources Research*, Vol. 26, No. 5, pp. 989-1000.
- Broshears, R. E., Bencala, K. E., Kimball, B. A., and McKnight, D. M. (1993). *Tracer-Dilution Experiments and Solute Transport Simulations for a Mountain Stream, Saint Kevin Gulch, Colorado*. Water Resources Investigations Report 92-4081, U.S. Geol. Surv., Denver, Colorado.
- Chapra, S. C. and Runkel, R. L. (1999). "Modeling Impact of Storage Zones on Stream Dissolved Oxygen". *Journal of Environmental Engineering*. ASCE, Vol. 125, No. 5, pp. 415-419.
- Czernuszenko, W., Rowinski, P., and Sukhodolov, A. (1998). "Experimental and Numerical Validation of the Dead-Zone Model for Longitudinal Dispersion in Rivers". *Journal of Hydraulic Research*, Vol. 36, No. 2, pp. 269-280.
- Day, T. J. (1975). "Longitudinal Dispersion in Natural Channels". *Water Resources Research*, Vol. 11, No. 6, pp. 909-918.
- Harvey, J. W., and Fuller, C. C. (1998). "Effect of Enhanced Manganese Oxidation in the Hyporheic Zone on Basin-Scale Geochemical Mass Balance". *Water Resources Research*, Vol. 34, No. 4, pp. 623-636.
- Harvey, J. W., Wagner, B. J., and Bencala, K. E. (1996). "Evaluating the Reliability of the Stream Tracer Approach to Characterize Stream-Subsurface Water Exchange". *Water Resources Research*, Vol. 32, No. 8, pp. 2441-2451.
- Hays, J. R., Krenkel, P. A., and Schnelle, K. B. (1967). *Mass Transport Mechanisms in Open-Channel Flow*. Technical Report, No. 8, Vanderbilt University, Nashville, Tennessee.
- Henderson, F. M. (1966). *Open Channel Flow*, Macmillan, New York, N.Y.
- Jackman, A. P., Walters, R. A., and Kennedy, V. C. (1984). "Transport and Concentration Controls for Chloride, Strontium, Potassium and Lead in Uvas Creek, A Small Cobble-Bed Stream in Santa Clara County, California, U.S.A". *Journal of Hydrology*, Vol. 75, pp. 111-141.
- Leopold, L. B., Wolman, M. G., and Miller, J. P. (1964). *Fluvial Processes in Geomorphology*. W. H. Freeman, San Francisco, Calif.
- Nordin, C. F. and Troutman, B. M. (1980). "Longitudinal Dispersion in Rivers: the Persistence of Skewness in Observed Data". *Water Resources Research*, Vol. 16, No. 1, pp. 123-128.
- Petersen, F. B. (1977). *Prediction of Longitudinal Dispersion in Natural Streams*. Series Paper 14, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark, Copenhagen.
- Runkel, R. L., and Chapra, S. C. (1993). "An Efficient Numerical Solution of the Transient Storage Equations for Solute Transport in Small Streams". *Water Resources Research*, Vol. 29, No. 1, pp. 211-215.
- Seo, I. W. (1990). *Low Flow Mixing in Open Channels*. Ph.D. Dissertation, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.
- Seo, I. W., and Chcong, T. S. (1998). "Predicting Longitudinal Dispersion Coefficient in Natural Streams". *Journal of Hydraulic Engineering*, ASCE. Vol. 124, No. 1, pp. 25-32.
- Seo, I. W., and Maxwell, W. H. C. (1992). "Modeling Low Flow Mixing through Pools and Riffles". *Journal of Hydraulic Engineering*, ASCE, Vol. 118, No. 10, pp. 1406-1423.
- Singh, K. P., and Broeren, S. M. (1985). *Basin-*

- wide Instream Flow Assessment Model to Evaluate Instream Flow Needs. Water Resources Center Research Reports, No. 197, University of Illinois, Urbana, Illinois.
- Stall, J. B., and Yang, C. T. (1972). *Hydraulic Geometry and Low Streamflow Regimen*. Water Resources Center Research Reports, No. 54, University of Illinois, Urbana, Illinois.
- Stone, H. L., and Brian, P. T. (1963). "Numerical Solution of Convective Transport Problems". *AIChE J.*, Vol. 9, No. 5, pp. 681-688.
- Thackston, E. L., and Schnelle, Jr. K. B. (1970). "Predicting Effects of Dead Zones on Stream Mixing". *Journal of Sanitary Engineering*, ASCE, Vol. 96, No. 2, pp. 319-331.
- Tsai, Y. H., and Holley, E. R. (1979). *Temporal and Spatial Moments for Longitudinal Mixing in Prismatic Channels with Storage in Separation Zones*. Hydraulic Engineering Series, No. 35, University of Illinois, Urbana, Illinois.
- Valentine, E. M., and Wood, I. R. (1979). "Dispersion in Rough Rectangular Channels". *Journal of Hydraulics Division*, ASCE, Vol. 105, No. 12, pp. 1537-1553.
- Wagner, B. J., and Harvey, J. W. (1997). "Experimental Design for Estimating Parameters of Rate-Limited Mass Transfer: Analysis of Stream Tracer Studies". *Water Resources Research*, Vol. 33, No. 7, pp. 1731-1741.
- Westrich, B. (1976). "Simulation of Mass Exchange in Dead Zones for Steady and Unsteady Flow Conditions". *International Symposium on Unsteady Flow in Open Channels*, Newcastle-upon-tyne, England.
- Yang, C. T. (1971). "Formation of Pools and Riffles". *Water Resources Research*, Vol. 7, No. 6, pp. 1567-1574.
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- Il Won Seo and Daeyoung Yu, School of Civil, Urban and Geosystem Engineering, Seoul National University, Kwanak-Gu, Seoul, 151-742, Korea.
(E-mail: seoilwon@plaza.snu.ac.kr)
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