WATER RESOURCES RESEARCH, VOL. 49, 3642–3650, doi:10.1002/wrcr.20272, 2013

A mean residence time relationship for lateral cavities in gravel-bed rivers and streams: Incorporating streambed roughness and cavity shape

Tracie R. Jackson,[1] Roy Haggerty,[2] Sourabh V. Apte,[3] and Ben L. O'Connor[4]

Received 20 October 2012; revised 27 March 2013; accepted 22 April 2013; published 21 June 2013.

[2] Accurate estimates of mass-exchange parameters in transient storage zones are needed to better understand and quantify solute transport and dispersion in riverine systems. Currently, the predictive mean residence time relies on an empirical entrainment coefficient with a range in variance due to the absence of hydraulic and geomorphic quantities driving mass exchange. Two empirically derived relationships are presented for the mean residence time of lateral cavities—a prevalent and widely recognized type of transient storage—in gravel-bed rivers and streams that incorporates hydraulic and geomorphic parameters. The relationships are applicable for gravel-bed rivers and streams with a range of cavity width to length (W/L) aspect ratios (0.2–0.75), shape, and Reynolds numbers (Re, ranging from 1.0×10^4 to 1.0×10^7). The relationships equate normalized mean residence time to nondimensional quantities: Froude number, Re, W/L, depth ratio (ratio of cavity to shear layer depth), roughness factor (ratio of shear to channel velocity), and shape factor (representing degree of cavity equidimensionality). One relationship excludes bed roughness (equation (13)) and the other includes bed roughness (equation (14)). The empirically derived relationships have been verified for conservative tracers (R^2 of 0.83) within a range of flow and geometry conditions. Topics warranting future research are testing the empirical relationship that includes the roughness factor using parameters measured in the vicinity of the cavity to reduce the variance in the correlation, and further development of the relationship for nonconservative transport.

Citation: Jackson, T. R., R. Haggerty, S. V. Apte, and B. L. O'Connor (2013), A mean residence time relationship for lateral cavities in gravel-bed rivers and streams: Incorporating streambed roughness and cavity shape, *Water Resour. Res.*, *49*, 3642–3650, doi:10.1002/wrcr.20272.

1. Introduction

[3] The fluid dynamics of exchange between a main channel and adjacent lateral cavities has been extensively studied both numerically and experimentally, especially within the last decade, to better understand and quantify solute transport and dispersion phenomena in open channel flows [e.g., *Rockwell and Knisely*, 1980; *Kimura and Hosada*, 1997; *Lin and Rockwell*, 2001; *Patwardhan*, 2001; *Hankin et al.*, 2002; *Yao et al.*, 2004; *Chang et al.*, 2006; *Faure et al.*, 2007; *Tritthart et al.*, 2009]. Studies of open channel flow past adjacent lateral cavities are conducted to provide more accurate estimates of longitudinal dispersion coefficients and mass-exchange parameters at a global scale through the development of hydraulic and geomorphic relationships [*Valentine and Wood*, 1977; *Uijttewaal et al.*, 2001; *Weitbrecht and Jirka*, 2001a; *Kurzke et al.*, 2002; *Weitbrecht et al.*, 2008; *Constantinescu et al.*, 2009]. Developing new or improving previously derived relationships is needed because solute transport parameters are empirical and not transferrable to either different streams or the same stream under different flow conditions [*Harvey et al.*, 2003]. Estimates of effective solute transport parameters in reach-scale studies currently are obtained by empirical relationships [e.g., *Cheong et al.*, 2007] or parameterizing transient storage models, which are numerical models that account for advective and dispersive solute transport in addition to the presence of lateral cavities and other adjacent storage zones, termed transient storage zones [*Hays*, 1966; *Bencala and Walters*, 1983; *Stream Solute Workshop*, 1990; *Runkel*, 1998; *Harvey and Wagner*, 2000].

[4] Lateral cavities and other types of transient storage zones have important functional significance in streams.

Additional supporting information may be found in the online version of this article.

[1]Water Resources Engineering Program, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[2]College of Earth, Ocean, and Atmospheric Sciences, Institute for Water and Watersheds, Oregon State University, Corvallis, Oregon, USA.
[3]Department of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, Corvallis, Oregon, USA.
[4]Environmental Science Division, Argonne National Laboratory, Argonne, Illinois, USA.

Corresponding author: T. R. Jackson, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin. Bldg., Corvallis, OR 97331-5503, USA. (jacksotr@engr.orst.edu)

0043-1397/13/10.1002/wrcr.20272

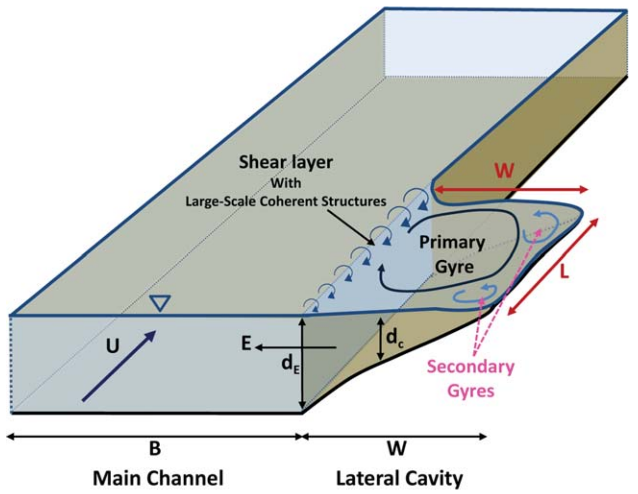

Figure 1. Flow field conceptualization of a lateral cavity in a natural stream and associated hydraulic and geomorphic parameters.

Their lower water velocities and higher local residence times enhance fish and vegetation biodiversity [*Engelhardt et al.*, 2004; *Uijttewaal*, 2005; *Constantinescu et al.*, 2009]. Their recirculating flows also entrain suspended and dissolved particulates, which increases the potential for biogeochemical reactions responsible for removing metals, nutrients, and other contaminants [*Newbold et al.*, 1983; *Bencala et al.*, 1984; *Triska et al.*, 1989; *Cerling et al.*, 1990; *D'Angelo et al.*, 1993; *Valett et al.*, 1994, 1996, 1997; *Benner et al.*, 1995; *Mulholland et al.*, 1997; *Squillace et al.*, 1993; *Gücker and Boëchat*, 2004; *Ensign and Doyle*, 2005; *Argerich et al.*, 2011].

[5] The lateral cavity is a prevalent and widely recognized type of transient storage in open channel flows [*Muto et al.*, 2000, 2002; *Engelhardt et al.*, 2004; *O'Connor et al.*, 2010; *Drost*, 2012; *Jackson et al.*, 2012] and may account for a large fraction of transient storage volume and residence time in the surface stream [*Jackson et al.*, 2012]. Lateral cavities in streams are characterized by a shear layer spanning the entire cavity entrance length and the formation of a recirculation region inside the cavity composed of one or more counter-rotating gyres depending on the cavity aspect ratio—ratio of cavity width (normal to flow) to cavity length (parallel to flow) (W/L) [Figure 1; *Rockwell and Knisely*, 1980; *Lin and Rockwell*, 2001; *Chang et al.*, 2006].

[6] Turbulent, incompressible open-channel flow past one or more lateral rectangular cavities has been well studied in hydrology and fluid mechanics, and generalized results regarding mass exchange have been obtained. Previous studies have determined that mass exchange between the main channel and lateral cavities is influenced by the aspect ratio [*Rockwell and Knisely*, 1980; *Uijttewaal et al.*, 2001; *Weitbrecht and Jirka*, 2001a; *Kurzke et al.*, 2002; *Engelhardt et al.*, 2004; *Weitbrecht et al.*, 2008], in-stream (main channel) velocity [*Valentine and Wood*, 1977; *Rockwell and Knisely*, 1980; *Chiang et al.*, 1998; *Yao et al.*, 2004; *Faure et al.*, 2007], upstream boundary layer (i.e., turbulent boundary layer along the wall directly upstream of the cavity entrance) [*Rockwell and Knisely*, 1980], and cavity depth [*Yao et al.*, 2004; *McCoy et al.*, 2006, 2007, 2008; *Faure et al.*, 2007]. Mass exchange is typically quantified using either a mass-exchange coefficient representing the exchange rate between the main channel and lateral cavity [*Hays*, 1966; *Bencala and Walters*, 1983], or a lateral cavity mean residence time. A mean residence time relationship has been postulated that relates mean residence time to the hydraulic and geomorphic parameters listed above (see section 2, equation (1)). The mean residence time relationship (1) includes a dimensionless entrainment coefficient, k, representative of mass exchange [e.g., *Hays*, 1966; *Valentine and Wood*, 1977; *Uijttewaal et al.*, 2001]. However, to date, an accurate and reliable mean residence time relationship quantifying mass exchange in lateral cavities has not been identified because laboratory and field experiments yield values of k ranging between 0.01 and 0.04 with a wider range of variability in k for field studies [*Valentine and Wood*, 1977; *Seo and Maxwell*, 1992; *Wallast et al.*, 1999; *Uijttewaal et al.*, 2001; *Kurzke et al.*, 2002; *Weitbrecht and Jirka*, 2001b; *McCoy et al.*, 2006; *Hinterberger et al.*, 2007; *Chang et al.*, 2007; *Weitbrecht et al.*, 2008; *Constantinescu et al.*, 2009; *Drost*, 2012; *Jackson et al.*, 2012].

[7] Physical factors not accounted for in the current mean residence time relationship need to be considered to reduce, and possibly explain, some of the variance in k. Previous laboratory and numerical studies of flow past lateral cavities have focused on idealized square and rectangular geometries with smooth walls that do not take into account roughness elements, such as streambed roughness and lateral cavity shape. *Muto et al.* [2002] concluded that roughness is one important parameter driving fluid exchange. *Ozalp et al.* [2010] investigated the effect of rectangular, triangular, and semicircular cavity shapes on flow and turbulence fields within and near the cavity. However, neither study considered the effect of bed roughness or cavity shape on mean residence time.

[8] This paper presents two empirically derived relationships for the mean residence time of lateral cavities in natural rivers and streams that incorporate streambed roughness and shape. The mean residence time relationships presented will be tools that hydrologists and water managers can use to predict conservative solute transport in natural fluvial systems with lateral cavities over a range of geometry ($0.2 < W/L < 0.75$), shape, roughness, and flow conditions ($1.0 \times 10^4 < Re < 1.0 \times 10^7$). The empirically derived relationships are developed using dimensional analysis and are verified through comparison to previous laboratory and field studies.

2. Review of Relevant Residence Time, Hydraulic, and Geomorphic Relationships

[9] *Uijttewaal et al.* [2001] derived a predictive mean residence time relationship for a lateral cavity by incorporating the entrainment hypothesis formulated by *Valentine and Wood* [1977] into the mean hydraulic residence time proposed by *Langmuir* [1908], which is a ratio of cavity volume to the volumetric flow rate entering or leaving the cavity through the shear layer. The entrainment hypothesis assumes that $E = kU$, where E is the entrainment velocity (velocity entering or leaving the cavity through the shear

layer interface), [$L\ T^{-1}$]; U is the mean main channel velocity, [$L\ T^{-1}$]; and k is a dimensionless entrainment coefficient. The predictive mean residence time, τ_L, is given by

$$\tau_L = \frac{WLd_c}{kULd_E} = \frac{Wd_c}{Ed_E}, \tag{1}$$

where W is the cavity width (normal to flow), [L]; L is the cavity length (parallel to flow), [L]; d_c is the mean cavity depth, [L]; and d_E is the mean shear layer depth, [L] (Figure 1). The relation in (1) assumes the following: (1) steady flow; (2) a residence time distribution (RTD) that decays exponentially in time; (3) the mechanism of exchange is a linear, first-order process; and (4) k is a constant. It is important to note that the predictive mean residence time is inversely proportional to k and to the mass-exchange coefficient [T^{-1}] [*Bencala and Walters*, 1983; *Runkel*, 1998], as this will become important in the dimensional analysis.

[10] Mean residence time also can be computed from the inverse slope of the exponential RTD, $F(t)$, given by

$$F(t) = \frac{1}{\tau_1}\exp(-t/\tau_1), \tag{2}$$

where t is the current time, [T]; τ_1 is the mean residence time (arithmetic mean of the RTD), [T]; and the RTD is defined as a distribution of fluid particle residence times inside the cavity since their time of entrainment [*Sardin et al.*, 1991]. Notice that we denote the *predictive* mean residence time as τ_L, and denote the mean residence time estimated from concentration breakthrough curves as τ_1. The predictive mean residence time is used for comparison to the empirically derived relationships, which were formulated using τ_1 in the dimensional analysis.

[11] The shear velocity, u_*, is defined by $u_* = \sqrt{\tau_0/\rho}$, where ρ is the fluid density, [$M\ L^{-3}$]; and τ_0 is the shear stress, [$M\ L^{-1}\ T^{-2}$]. For open channel flow, $\tau_0 = \rho g R S_f$, where g is the gravitational acceleration, [$L\ T^{-2}$]; R is the hydraulic radius (ratio of cross-sectional channel area to wetted perimeter), [L]; and S_f is the friction slope, dimensionless. The friction slope is derived from Manning's equation: $S_f = n^2U^2/R^{4/3}$, where n is the Manning roughness coefficient. Thus, by substitution of the shear stress and friction slope, the shear velocity is computed from

$$u_* = \sqrt{gn^2U^2R^{-1/3}}, \tag{3}$$

and n is estimated from either the *Chen and Cotton* [1988] method given by

$$n = \frac{(R/0.3048)^{1/6}}{8.6 + 19.97\log(R/d_{50})}, \tag{4}$$

or the *Henderson* [1966] method given by

$$n = 0.034(3.28d_{50})^{1/6}, \tag{5}$$

where d_{50} is the median diameter of the gravel (m). The *Chen and Cotton* [1988] method provides a good approximation of streambed roughness in gravel-bed streams with very shallow flows. The *Henderson* [1966] method estimates a Manning roughness coefficient for gravel-bed streams at higher flows.

3. Dimensional Analysis: Developing the Relationship

[12] The mean residence time of a lateral cavity is dependent on the hydraulic and geomorphic properties of the main channel and cavity. These properties drive mass and momentum exchange across the shear layer by means of large-scale coherent structures. Therefore, mean residence time can depend on the following parameters:

$$\tau_1 = f(u_*, U, g, \upsilon, W, L, d_E, d_c), \tag{6}$$

where υ is the kinematic viscosity, [$L^2\ T^{-1}$]. Equation (6) includes three parameters not considered in the predictive mean residence time from (1): a shear velocity, the gravitational acceleration, and kinematic viscosity, which account for bed roughness, gravitational forces, and viscous forces, respectively. The median gravel diameter, main channel hydraulic radius, and Manning roughness coefficient are expressed in the shear velocity. Rewriting the above equation of nine parameters composed of two physical dimensions (time and length), Buckingham Pi Theorem predicts that not more than seven nondimensional groups ($9-2=7$) [*Fischer et al.*, 1979] relate to the mean residence time:

$$\frac{\tau_1 U}{L} = f\left(\frac{W}{L}, \frac{d_c}{L}, \frac{UL}{\upsilon}, \frac{U}{\sqrt{gL}}, \frac{u_*}{U}, \frac{d_E}{L}\right). \tag{7}$$

[13] The mean residence time is scaled by L/U, which is the convective timescale—timescale representative of the time for a parcel of fluid to travel the distance of the cavity entrance length. Note that there are four length scales: W, L, d_E, and d_c, and that, for some of the nondimensional groups, d_E is a more appropriate length scale due to the significance of depth-dependent exchange across the shear layer interface. Multiplying nondimensional groups by L/d_E and rearranging terms yields

$$\frac{\tau_1 U}{L} = f\left(\frac{W}{L}, \frac{d_c}{d_E}, \frac{Ud_E}{\upsilon}, \frac{U}{\sqrt{gd_E}}, \frac{u_*}{U}, \frac{\sqrt{Wd_c}}{L}\right), \tag{8}$$

where the last term in (8) is a combination of the first two geometric ratios in (7). Equation (8) can be further reduced to

$$\frac{\tau_1 U}{L} = f\left(\frac{W}{L}, \frac{d_c}{d_E}, \mathrm{Re}, Fr, \frac{u_*}{U}, \frac{\sqrt{Wd_c}}{L}\right), \tag{9}$$

where Re is the Reynolds Number ($Re = Ud_E/\nu$), and Fr is the Froude Number ($Fr = U\sqrt{gd_E}$). The six nondimensional groups can be subdivided into four groups: (1) cavity geometric ratios (W/L, d_c/d_E); (2) hydraulic quantities representative of the flow dynamics (Re, Fr); (3) a bed roughness factor, u_*/U, which is the inverse of Chézy's dimensionless friction factor; and (4) a shape factor, $\sqrt{Wd_c}/L$.

[14] A mean residence time relationship for lateral cavities can be derived with the six nondimensional quantities in (9) using a two-part method. First, the effect of each nondimensional quantity on lateral cavity flow structure and exchange dynamics is summarized. Nondimensional quantities are summarized within their respective subgroups because, as stated earlier, previous studies have concluded that mass and momentum exchange dynamics are dependent on the flow dynamics, cavity geometry, roughness, and shape. Second, qualitative relations between mean residence time and variables in the nondimensional quantities from (9) are discussed to derive a mean residence time relationship.

[15] In the first subgroup, cavity geometric ratios, both the aspect ratio, W/L, and depth ratio, d_c/d_E, influence lateral cavity flow structure and mean residence time. Numerical and experimental studies have shown that the number of gyres that form in a lateral cavity is a function of the cavity aspect ratio [e.g., *Rockwell and Knisely*, 1980; *Koseff and Street*, 1982, 1984a, 1984b, 1984c; *Chiang et al*., 1997, 1998; *Wallast et al*., 1999; *Muto et al*., 2000; *Weitbrecht and Jirka*, 2001a; *Weitbrecht*, 2004; *Cheng and Hung*, 2006]. For example, two gyres form inside rectangular cavities when $W/L < 0.5$. The large primary gyre forms in the downstream region, and a smaller counter-rotating secondary gyre forms in the upstream corner. A large gyre forms inside the cavity when $0.5 < W/L < 1.5$ and, for $W/L >> 1.5$, a large primary gyre forms near the shear layer and a counter-rotating gyre forms adjacent to the primary gyre far from the shear layer [*Weitbrecht and Jirka*, 2001a; *Weitbrecht*, 2004; *McCoy et al*., 2008]. The recirculation patterns formed by the aspect ratio influence the mean residence time inside the cavity. The mean residence time increases with the presence of secondary gyres because of their slower circulation velocities and longer exchange timescales [*Engelhardt et al*., 2004; *McCoy et al*., 2007, 2008; *Jackson et al*., 2012]. The depth ratio influences the large-scale coherent structures within the shear layer. *McCoy et al*. [2007, 2008] show that when the depth ratio is equal to or near 1, the coherent structures in the shear layer are quasi-two-dimensional, and that when the depth ratio is far from 1, the coherent structures in the shear layer are fully three-dimensional. These large-scale coherent structures drive mass and momentum exchange between the main channel and cavity and the circulation of gyres, which influences mean residence time.

[16] In the second subgroup, hydraulic quantities, the *Re* and *Fr* describe the forces driving the flow dynamics of exchange. *Fr* quantifies the relation of inertial to gravitational forces and expresses the influence of the main channel flow (flow conditions) and bed slope on mass and momentum exchange through the shear layer. Thus, the *Fr* accounts for the local flow behavior. The *Re* quantifies the relation of inertial to viscous forces and expresses the influence of mixing by turbulent motion on the dynamics of exchange. Thus, the *Re* accounts for the degree of turbulence in the flow, which is induced and augmented by channel geomorphic complexities (e.g., irregular channel geometry and bedforms), especially for larger rivers.

[17] In the third subgroup, bed roughness, the quantity, u_*/U, influences exchange dynamics and mean residence time. The shear velocity is defined in (3) and the Manning roughness coefficient in (4) and (5) are given for gravel-bed fluvial systems. The roughness factor describes gravel-bed roughness within the main channel, which influences the incoming turbulent boundary layer immediately upstream of the cavity entrance. The strength of the incoming turbulent boundary layer controls the degree of vortical structure coherence within the shear layer, and higher vortical structure coherence increases both mass exchange across the shear layer interface and the circulation of gyres in the cavity, which influences mean residence time [*Rockwell and Knisely*, 1980; *Chiang et al*., 1998].

[18] In the fourth subgroup, shape factors, the quantity, $\sqrt{Wd_c}/L$, influences the cavity flow structure. The cavity shape factor is analogous to the sediment transport shape factor, which is used to compute the degree to which a particle approximates the shape of a sphere (i.e., sediment transport shape factor is equal to 1 for a sphere). In the case of a lateral cavity, the shape factor computes the degree of cavity equidimensionality, which controls the symmetry and three-dimensionality of gyres within the cavity.

[19] Qualitative relations between mean residence time and variables in the nondimensional quantities from (9) are discussed based on their effect on lateral cavity flow structure and mass and momentum exchange. First, an increase in W or L will result in an increase in τ_1, as both will cause the formation of secondary gyres. However, increasing W will cause the formation of larger secondary gyres that form sufficiently far from the shear layer and, thus, will have a greater influence on τ_1. Increasing d_c increases the volume for fluid entrainment and the three-dimensionality of the cavity flow field, resulting in an increase in τ_1. Increasing d_E allows for more exchange through the shear layer, thereby causing a decrease in τ_1. Increasing U causes faster exchange across the shear layer, which causes the mean circulation in the cavity to increase, and a decrease in τ_1. An increase in the shear velocity increases τ_1 as bed roughness slows exchange across the shear layer and the mean circulation in the cavity. From these relations, the normalized mean residence time for a natural lateral cavity is given by

$$\begin{aligned}\frac{\tau_1 U}{L} &= \frac{u_*}{U}\cdot\frac{Ud_E}{\upsilon}\cdot\frac{U}{\sqrt{gd_E}}\cdot\frac{W}{L}\cdot\frac{d_c}{d_E}\cdot\frac{\sqrt{Wd_c}}{L}\\ &= \frac{u_*}{U}\cdot\frac{Ud_E}{\upsilon}\cdot\frac{U}{\sqrt{gd_E}}\cdot\frac{W^{3/2}d_c^{3/2}}{L^2 d_E}.\end{aligned} \quad (10)$$

[20] In (10), there is a codependency and repetition of variables between nondimensional groups, meaning that some variables influence more than one mechanism driving exchange.

4. Verification

[21] The mean residence time relationship was verified using data obtained from laboratory and field experiments of natural lateral cavities with roughness elements (Table 1). See Table S1 in the supporting information for a complete listing of individual parameters. The mean residence time relationship from (10) has linear correlations for both small streams ($R^2 = 0.82$) and larger rivers ($R^2 = 0.97$) (Figure 2) that are statistically significant at the $p < 0.001$ level. Notice that the smaller stream data (1.0 ×

Table 1. Summary of Nondimensional Parameters in Mean Residence Time Relationship

Study	Creek	$\tau_1 U/L$	Re	Fr	W/L	d_c/d_E	u_*/U	$\sqrt{Wd_c}/L$
Seo and Maxwell [1992]	Lab: Pool & Riffle	7.7	3.4×10^4	0.16	0.03	10.5	0.31	0.06
	Lab: Pool & Riffle	6.3	4.4×10^4	0.18	0.03	10.1	0.26	0.06
	Lab: Pool & Riffle	6.6	5.0×10^4	0.20	0.03	9.68	0.24	0.06
O'Connor et al. [2010]	Elder Creek, CA	8.9	3.6×10^4	0.36	0.67	0.50	0.10	0.15
Jackson et al. [2012]	Oak Creek, OR	7.9	4.9×10^4	0.30	0.22	0.83	0.24	0.15
	Oak Creek, OR	8.8	3.9×10^4	0.13	0.32	0.53	0.30	0.18
	Oak Creek, OR	9.5	2.7×10^4	0.37	0.49	0.66	0.23	0.18
	Oak Creek, OR	8.2	3.4×10^4	0.16	0.57	0.60	0.23	0.17
	Oak Creek, OR	5.8	9.9×10^3	0.08	0.34	0.61	0.40	0.13
	Soap Creek, OR	29.1	4.9×10^4	0.55	0.47	1.84	0.20	0.32
	Soap Creek, OR	6.6	6.3×10^4	0.15	0.29	0.45	0.18	0.13
	Soap Creek, OR	7.9	4.6×10^4	0.24	0.29	0.52	0.20	0.11
	Soap Creek, OR	5.4	4.6×10^4	0.10	0.24	0.53	0.14	0.12
	Soap Creek, OR	6.0	3.6×10^4	0.20	0.20	0.42	0.19	0.06
	John Day River, OR	11.2	3.1×10^5	0.36	0.29	0.39	0.23	0.12
	John Day River, OR	16.5	2.5×10^5	0.36	0.49	0.72	0.26	0.18
	John Day River, OR	12.0	2.6×10^5	0.24	0.32	0.74	0.22	0.19
	Lookout Creek, OR	13.0	3.5×10^4	0.10	0.67	0.80	0.29	0.23
	Lookout Creek, OR	20.8	1.4×10^5	0.15	0.60	0.59	0.55	0.25
Engelhardt et al. [2004]	Elbe River, Germany	10.1	2.2×10^6	0.15	0.58	0.71	0.06	0.11
	Elbe River, Germany	6.3	1.2×10^6	0.17	0.55	0.59	0.04	0.07
Kozerski et al. [2006]	Elbe River, Germany	34.4	6.7×10^6	0.43	0.36	1.0	0.09	0.09
	Elbe River, Germany	20.0	3.8×10^6	0.25	0.36	1.0	0.09	0.09
	Elbe River, Germany	17.7	3.6×10^6	0.23	0.36	1.0	0.09	0.09
	Elbe River, Germany	78.2	6.3×10^6	0.50	0.54	1.0	0.10	0.14
	Elbe River, Germany	44.9	4.3×10^6	0.35	0.54	1.0	0.09	0.14
	Elbe River, Germany	27.6	2.8×10^6	0.32	0.54	1.0	0.09	0.13
	Elbe River, Germany	79.3	6.3×10^6	0.50	0.54	1.0	0.10	0.14
	Elbe River, Germany	32.5	2.5×10^6	0.70	0.47	1.0	0.16	0.08
	Elbe River, Germany	62.7	6.7×10^6	0.41	0.58	1.0	0.09	0.13
	Elbe River, Germany	25.3	4.3×10^6	0.13	0.41	1.0	0.09	0.13
Tritthart et al. [2009]	Danube River, Austria	8.1	7.5×10^6	0.08	0.48	0.5	0.06	0.10
	Danube River, Austria	8.8	8.8×10^6	0.09	0.48	0.5	0.06	0.10
	Danube River, Austria	15.4	1.0×10^7	0.10	0.48	0.5	0.06	0.10

$10^4 < Re < 6.0 \times 10^4$) follow a steep linear trend with a slope of 0.011 and that the larger river data ($1.0 \times 10^6 < Re < 1.0 \times 10^7$) follow a shallower linear trend with a slope of 0.003. The John Day River ($Re < 3.0 \times 10^5$), which can be considered a medium-sized stream, has data points that fall in-between the two lines (Figure 2). This suggests that there is a Re discontinuity in the relationship from (10). The two distinct linear trends are attributed to the equal weighting of nondimensional groups in the relationship, which causes the main channel velocity to vary proportionally to the normalized mean residence time in (10). To further illustrate, when (10) is simplified, the mean residence time collapses to the following form:

$$\tau_1 = \frac{u_* W^{3/2} d_c^{3/2}}{\upsilon L\sqrt{g d_E}} = \frac{\sqrt{g n^2 U^2 R^{-1/3}}\, W^{3/2} d_c^{3/2}}{\upsilon L\sqrt{g d_E}} = \frac{U n W^{3/2} d_c^{3/2}}{\upsilon L\sqrt{d_E} R^{1/6}}, \tag{11}$$

and $\tau_1 \propto U$. However, in reality, $\tau_1 \propto U^{-1}$. Thus, the six nondimensional groups are not weighted equally. The unequal weighting of nondimensional groups can be explained, physically, by the shift in influence of predominant mechanisms driving mass and momentum exchange between flow regimes (i.e., between a small stream and large river). The shift in predominant processes from a small stream to a larger river causes: (1) the reduced influence of bed roughness attributed to flow over individual grains, which is attributed to the roughness factor; (2) the inducement of additional turbulence (and roughness) by larger bedforms in larger rivers compared to streams, which is characterized by Re; and (3) a change in the local flow dynamics (balance of inertial to gravitational forces) from smaller high-gradient streams to larger low-land rivers, which is characterized by Fr. Controls driving mass and momentum exchange are embedded within the bed roughness factor, Re, and Fr. To account for the shift in predominant processes influencing mass and momentum exchange, the exponents must be reduced for all nondimensional groups. Equation (10) was expressed as a product of power laws and a log transformation was used to linearize the solution:

$$\log\left[\frac{\tau_1 U}{L}\right] = \log a + b\log\left[\frac{u_*}{U}\right] + c\log \mathrm{Re} + d\log Fr + e\log\left[\frac{W}{L}\right] + f\log\left[\frac{d_c}{d_E}\right] + g\log\left[\frac{\sqrt{W d_c}}{L}\right]. \tag{12}$$

[22] Linear regression was used to formulate an empirically derived mean residence time. Power-law correlations were plotted for each log-transformed nondimensional group (i.e., $\log[\tau_1 U/L]$ versus log[nondimensional group]) to obtain variable coefficients and determine the predictive ability of each nondimensional group in estimating nondimensional mean residence time (Table 2). The summary of power-law correlations in Table 2 shows that Re

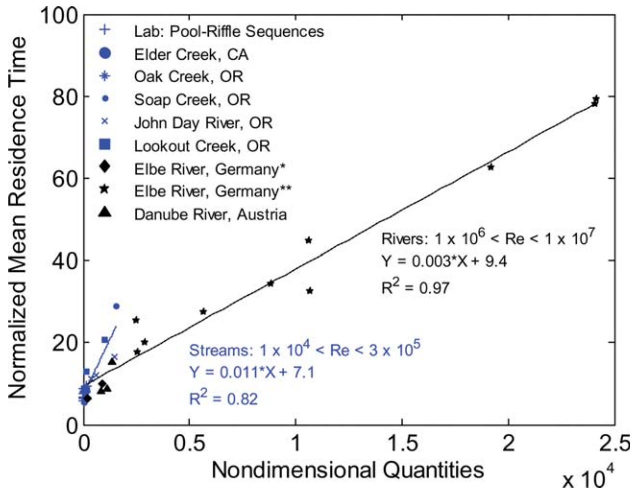

Figure 2. Mean residence time relationship from (10) for lateral cavities in natural fluvial systems using equal weighting to all nondimensional groups. All data were obtained from laboratory and field studies with irregular cavity shapes and bed roughness elements. Data plotted above were obtained from the following references: laboratory experiments of pool-riffle sequences [*Seo and Maxwell*, 1992]; Elder Creek, CA [*O'Connor et al*., 2010]; Oak Creek, Soap Creek, Middle Fork of the John Day River, and Lookout Creek, OR [*Jackson et al*., 2012]; Elbe River, Germany* [*Engelhardt et al*., 2004]; Elbe River, Germany** [*Kozerski et al*., 2006]; and Danube River, Austria [*Tritthart et al*., 2009].

($R^2 = 0.42$) and *Fr* ($R^2 = 0.40$) have the strongest correlations, W/L has a weaker correlation ($R^2 = 0.18$), and the other nondimensional groups are uncorrelated ($R^2 < 0.10$). These correlations suggest that cavity geometry, shape, and roughness do not influence mean residence time, whereas previous studies show that these parameters do influence mean residence time. When cavity geometry and shape factors are combined into a "lumped" geometric factor given by $[W/L]\cdot[d_c/d_E]\cdot\left[\sqrt{Wd_c}/L\right]$, the log transform has a strong correlation ($R^2 = 0.41$) to mean residence time.

[24] Three different cases were formulated from the nondimensional groups (Table 2). Case 1 included the three independent variables with the highest correlations: *Re*, *Fr*, and W/L. Case 2 included the *Re*, *Fr*, and the lumped geometric factor. Case 3 included all independent variables: the *Re*, *Fr*, the lumped geometric factor, and roughness factor. Cases 2 and 3 provided the strongest correlations to nondimensional mean residence time with an $R^2 = 0.83$ and regression coefficient (exponent) of 0.67 for case 2 and an $R^2 = 0.82$ and regression coefficient of 0.60 for case 3. Case 2 yields an empirically derived mean residence time (without roughness) given by

$$\frac{\tau_1 U}{L} = 28\left[\frac{Ud_E}{\upsilon}\right]^{0.15}\cdot\left[\frac{U}{\sqrt{gd_E}}\right]^{0.56}\cdot\left[\frac{W^{3/2}d_c^{3/2}}{L^2 d_E}\right]^{0.44} - 5.0. \quad (13)$$

[25] Case 3 yields an empirically derived mean residence time (with roughness) given by

$$\frac{\tau_1 U}{L} = 21\left[\frac{Ud_E}{\upsilon}\right]^{0.13}\cdot\left[\frac{U}{\sqrt{gd_E}}\right]^{0.49}\cdot\left[\frac{W^{3/2}d_c^{3/2}}{L^2 d_E}\right]^{0.39}\cdot\left[\frac{U}{u_*}\right]^{0.21} - 6.7. \quad (14)$$

[26] Two empirically derived mean residence time relationships are presented: one without a roughness factor (13) and one with a roughness factor (14). The roughness factor was excluded from the analysis in case 2 (13) because roughness was uncorrelated to nondimensional mean residence time. The lack of correlation likely stemmed from estimating u_* with reach-averaged (effective) parameters when the actual bed roughness in the vicinity of the cavity may differ. Estimates of u_* may show a strong correlation to mean residence time if parameters are measured in the vicinity of the cavity; therefore, case 3 (14) is shown as a tentative result. More detailed data of roughness parameters near the cavity are needed to fully test this hypothesis. The empirically derived mean residence time relationships in (13) ($R^2 = 0.83$; Figure 3) and (14) ($R^2 = 0.82$; Figure 4) have strong correlations that are statistically significant at the $p < 0.001$ level (Table 2). The relationship works well for both small streams and larger rivers. The empirically derived mean residence time relationship for (13) reduces to

$$\tau_1 = \frac{28L^{0.27}W^{.66}d_c^{0.66}}{g^{0.28}\upsilon^{0.15}U^{0.29}d_E^{0.16}} - 6.7\times L/U. \quad (15)$$

[27] As a check, the mean residence time relationship in (13) is compared to the predictive mean residence time relationship in (1). Equation (15), when rewritten in the form of (1), yields

$$\begin{aligned}\tau_1 &= \frac{28U^{0.71}d_E^{0.84}L^{0.27}}{g^{0.28}\upsilon^{0.15}W^{0.34}d_c^{0.34}}\left[\frac{Wd_c}{Ud_E}\right] - 6.7\times L/U\\ &= \frac{Wd_c}{kUd_E} - 6.7\times L/U,\end{aligned} \quad (16)$$

where the entrainment coefficient is given by

$$k = \frac{g^{0.28}\upsilon^{0.15}W^{0.34}d_c^{0.34}}{28U^{0.71}d_E^{0.84}L^{0.27}}. \quad (17)$$

5. Implications for Mean Residence Time Relationship and Future Work

[28] The empirically derived mean residence time relationships derived for lateral cavities in natural streams and rivers are useful tools for hydrologists and water managers. The relationships have a wide range of applicability for both gravel-bed streams and rivers with lateral cavities, such as embayments or man-made groyne fields, because the relationships collapse the data into strong linear relations for a wide range of geometries ($0.2 < W/L < 0.75$), complex shapes, and flow conditions ($5.0\times10^3 < Re < 1.0\times10^7$). An additional bonus is that the mean residence time relationships can be obtained from a few field-measurable parameters (i.e., W, L, U, d_E, d_c, n, R, d_{50}) without the need for an empirical entrainment coefficient. The relationships can be used for conservative solute or contaminant

Table 2. Summary of Regression Analysis

Independent Variable	Regression Coefficients	Correlations		Nondimensional Products[a]		
		R^2	p Values	Case 1	Case 2	Case 3
log *Re*	0.22	0.42	1.4×10^{-3}	X	X	X
log *Fr*	0.83	0.40	3.4×10^{-5}	X	X	X
$\log(W/L)$	0.41	0.18	2.3×10^{-2}	X	—	—
$\log(d_c/d_E)$	0.02	0.0007	4.1×10^{-1}	—	—	—
$\log(\sqrt{Wd_c}/L)$	0.52	0.08	4.6×10^{-1}	—	—	—
$\log(u_*/U)$	−0.34	0.08	8.7×10^{-2}	—	—	X
$\log(W/L \cdot d_c/d_E \cdot \sqrt{Wd_c}/L)$	0.66	0.41	3.4×10^{-2}	—	X	X
Case 1	0.69	0.70	2.1×10^{-12}			
Case 2	0.67	0.84	3.6×10^{-15}			
Case 3	0.60	0.79	1.8×10^{-17}			

[a]Nondimensional products indicate the nondimensional groups used in the formulation of a nondimensional mean residence time (denoted by "X") for each case and unused terms for each case are denoted by a dash.

transport studies to predict the residence time of solutes in lateral embayments within natural streams and rivers. The relationships also can be used to compute the mean residence time of in-stream structures emplaced along streams for stream restoration projects used to enhance stream biodiversity.

[29] Three key elements need to be considered when using the empirically derived relationships. First, the mean residence time relationships were derived for gravel-bed fluvial systems because data were readily available to test this relationship. The relationships may or may not hold for fluvial systems with substrates other than gravel, such as mud or sand, or for heavily vegetated fluvial systems. Second, lateral and vertical channel roughness could have a more significant contribution to mean residence time than that was observed in the dimensional analysis if parameters used to compute the shear velocity are measured in the vicinity of the cavity. More detailed data of roughness parameters near the cavity shear layer are needed to fully test this hypothesis. If bed roughness is found to be highly correlated with mean residence time, this could possibly explain and reduce some of the variance in the empirically derived relationship (14). In the case where bed roughness does significantly contribute to mean residence time, the user should refer to the literature for the appropriate Manning roughness coefficient [e.g., *Carter et al.*, 1963;

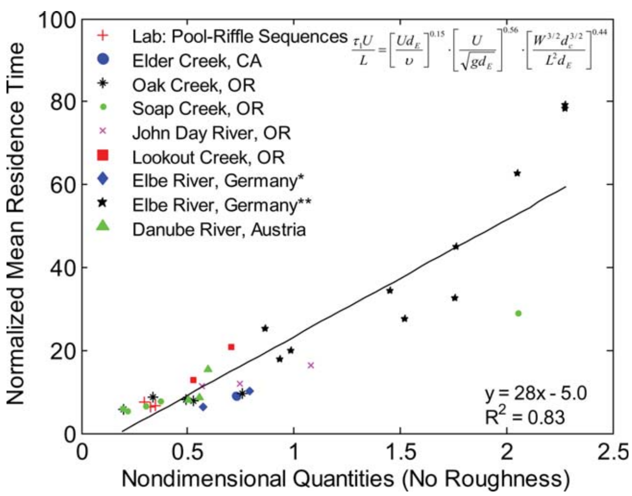

Figure 3. Empirically derived mean residence time relationship excluding roughness (13) for lateral cavities in natural fluvial systems. All data were obtained from laboratory and field studies with irregular cavity shapes and bed roughness elements. Data plotted above were obtained from the following references: laboratory experiments of pool-riffle sequences [*Seo and Maxwell*, 1992]; Elder Creek, CA [*O'Connor et al.*, 2010]; Oak Creek, Soap Creek, Middle Fork of the John Day River, and Lookout Creek, OR [*Jackson et al.*, 2012]; Elbe River, Germany* [*Engelhardt et al.*, 2004]; Elbe River, Germany** [*Kozerski et al.*, 2006]; and Danube River, Austria [*Tritthart et al.*, 2009].

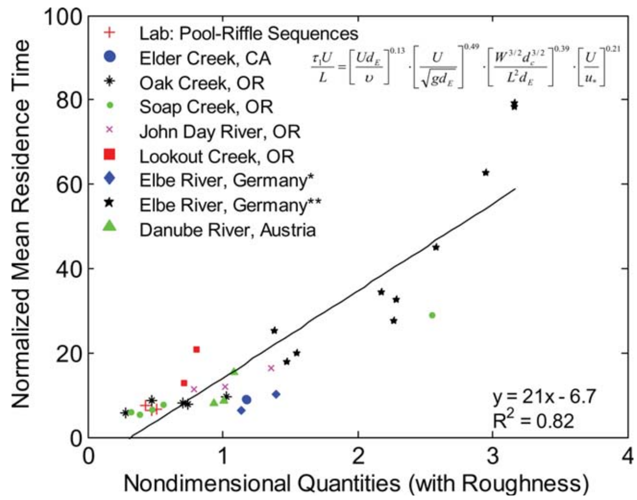

Figure 4. Empirically derived mean residence time relationship with roughness (14) for lateral cavities in natural fluvial systems. All data were obtained from laboratory and field studies with irregular cavity shapes and bed roughness elements. Data plotted above were obtained from the following references: laboratory experiments of pool-riffle sequences [*Seo and Maxwell*, 1992]; Elder Creek, CA [*O'Connor et al.*, 2010]; Oak Creek, Soap Creek, Middle Fork of the John Day River, and Lookout Creek, OR [*Jackson et al.*, 2012]; Elbe River, Germany* [*Engelhardt et al.*, 2004]; Elbe River, Germany** [*Kozerski et al.*, 2006]; and Danube River, Austria [*Tritthart et al.*, 2009].

Barnes, 1967; *Chen and Cotton*, 1988; *Chaudhry*, 2008]. Third, the relationship was derived and tested for conservative solutes. For a nonconservative solute, one or more additional terms need to be added to the relationship, such as a retention factor, to account for biogeochemical processes driving solute retention in the cavity. Testing the relationship using roughness parameters measured in the cavity vicinity and further development of the empirically derived relationship for nonconservative transport are topics that warrant future research.

6. Conclusions

[30] Mean residence time relationships for lateral cavities in natural gravel-bed streams and rivers can be computed from six nondimensional groups: *Fr*, *Re*, cavity aspect ratio, cavity depth ratio, a shape factor, and a roughness factor. The *Fr* is representative of local channel hydraulics driving mass and momentum exchange. The *Re* is representative of the turbulence and mixing mechanisms driving exchange. The cavity aspect ratio—ratio of cavity width (normal to flow) to length (parallel to flow)—and the cavity depth ratio—ratio of cavity depth to exchange interface depth—are representative of cavity geometry. The shape factor is a measure of the degree of cavity equidimensionality. The roughness factor is a ratio of the shear velocity to the main channel velocity, and the shear velocity is a function of channel hydraulic radius and Manning roughness coefficient. We formulated two empirical mean residence time relationships: one without a roughness factor (13) and one with a roughness factor (14). Both empirically derived relations had strong linear correlations to normalized mean residence time. The relationships have been validated for conservative tracers within a range of geometry ($0.2 < W/L < 0.75$) and flow conditions ($1.0 \times 10^4 < Re < 1.0 \times 10^7$). However, further testing of the relationship using roughness parameters measured in the vicinity of the cavity and further development of the relationship for nonconservative transport are topics worthy of future research.

[31] **Acknowledgments.** This work was supported by the National Science Foundation, EAR 09–43570. B. O'Connor's contribution to this study was supported by the U.S. Department of Energy under contract DE-AC02–06CH1711357. The authors thank all the reviewers for their exceptional reviews and suggestions, which have improved the outcome of this manuscript. They personally thank Daniele Tonina for providing helpful suggestions in the implementation of the dimensional analysis.

References

Argerich, A., E. Martí, F. Sabater, R. Haggerty, and M. Ribot (2011), Influence of transient storage on stream nutrient uptake based on substrata manipulation, *Aquat. Sci.*, *73*, 365–376, doi:10.0007/s00027-011-0184-9.

Barnes, H. H. (1967), *Roughness characteristics of natural channels, U.S. Geol. Surv. Water-Supply Pap.* 1849, U.S. Government Printing Office. Washington, DC.

Bencala, K. E., and R. A. Walters (1983), Simulation of solute transport in a mountain pool-and-riffle stream: A transient storage model, *Water Resour. Res.*, *19*, 718–724.

Bencala, K. E., V. C. Kennedy, G. W. Zellweger, A. P. Jackman, and R. J. Avanzino (1984), Interactions of solutes and streambed sediments: 1. An experiment analysis of cation and anion transport in a mountain stream, *Water Resour. Res.*, *20*, 1797–1803.

Benner, S. G., E. W. Smart, and J. N. Moore (1995), Metal behavior during surface-groundwater interaction, Silver Bow Creek, Montana, *Environ. Sci. Technol.*, *29*, 1789–1795.

Carter, R. W., H. A. Einstein, J. Hinds, R. W. Powell, and E. Silberman (1963), Friction factors in open channels, Progress report of the task force on friction factors in open channels of the Committee on Hydromechanics of the Hydraulics Division, in *Proc. Am. Soc. Civ. Eng., J. Hydraul. Div.*, *89*(HY2), 97–143.

Cerling, T. E., S. J. Morrison, and R. W. Sobocinski (1990), Sediment-water interaction in a small stream: Adsorption of 137Cs by bed load sediments, *Water Resour. Res.*, *26*, 1165–1176.

Chang, K., G. Constantinescu, and S. O. Park (2006), Analysis of the flow and mass transfer processes for the incompressible flow past an open cavity with a laminar and a fully turbulent incoming boundary layer, *J. Fluid Mech.*, *561*, 113–145.

Chang, K., G. Constantinescu, and S. O. Park (2007), Purging of a neutrally buoyant or a dense miscible contaminant from a rectangular cavity. II: Case of an incoming fully turbulent overflow, *J. Hydraul. Eng.*, *133*(4), 373–385, doi:10.1061/(ASCE)0733–9429(2007)133:4(373).

Chaudhry, M. H. (2008), *Open Channel Flow*, Springer Science and Business Media, LLC, New York.

Chen, Y. H., and G. K. Cotton (1988), Design of roadside channels with flexible linings, Hydraul. Eng. Circular 15, Publ. FHWA-IP-87-7, U.S. Dep. of Transportation, Federal Highway Administration, McLean, Va.

Cheng, M., and K. C. Hung (2006), Vortex structure of steady flow in a rectangular cavity, *Comput Fluids*, *35*, 1046–1062.

Cheong, T. S., B. A. Younis, and I. W. Seo (2007), Estimation of key parameters in model for solute transport in rivers and streams, *Water Resour. Manage.*, *21*, 1165–1186.

Chiang, T. P., R. R. Hwang, and W. H. Sheu (1997), On end-wall corner vortices in a lid-driven cavity, *Trans. ASME: J. Fluids Eng.*, *119*, 201–204.

Chiang, T. P., W. H. Sheu, and R. R. Hwang (1998), Effect of Reynolds number on the eddy structure in a lid-driven cavity, *Int. J. Numer. Methods Fluids*, *26*, 557–579.

Constantinescu, G., A. Sukhodolov, and A. McCoy (2009), Mass exchange in a shallow channel flow with a series of groynes: LES study and comparison with laboratory and field experiments, *Environ. Fluid Mech.*, *9*, 587–615, doi:10.1007/s10652-009-9155-2.

D'Angelo, D. J., J. R. Webster, S. V. Gregory, and J. L. Meyer (1993), Transient storage in Appalachian and Cascade mountain streams as related to hydraulic characteristics, *J. N. Am. Benthol. Soc.*, *12*(3), 223–235.

Drost, K. (2012), *RANS and LES predictions of turbulent scalar transport in dead zones of natural streams*, MS thesis, Oreg. State Univ., Corvallis, Oreg.

Engelhardt, C., A. Krüger, A. Sukhodolov, and A. Nicklisch (2004), A study of phytoplankton spatial distributions, flow structure and characteristics of mixing in a river reach with groynes: *J. Plankton Res.*, *26*(11), 1351–1366.

Ensign, S. H., and M. W. Doyle (2005), In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations, *Limnol. Oceanogr.*, *50*(6), 1740–1751.

Faure, T. M., P. Adrianos, F. Lusseyran, and L. Pastur (2007), Visualizations of the flow inside an open cavity at medium range Reynolds numbers, *Exp. Fluids*, *42*, 169–184.

Fischer, H. B., E. G. List, R. C. Y. Koh, J. Imberger, and N. H. Brooks (1979), *Mixing in Inland and Coastal Waters*, Academic, New York.

Gücker, B., and I. G. Boëchat (2004), Stream morphology controls ammonium retention in tropical headwaters, *Ecology*, *5*(10), 2818–2827.

Hankin, B. G., M. J. Holland, K. J. Beven, and P. Carling (2002), Computational fluid dynamics modeling of flow and energy fluxes for a natural fluvial dead zone, *J. Hydraul. Res.*, *40*(4), 389–401.

Harvey, J. W., and B. J. Wagner (2000), Quantifying hydrologic interactions between streams and their subsurface hyporheic zones, in *Streams and Ground Waters*, edited by J. B. Jones, and P. J. Mulholland, p. 425, Academic, San Diego, Calif.

Harvey, J. W., M. H. Conklin, and R. S. Koelsch (2003), Predicting changes in hydrologic retention in an evolving semi-arid alluvial stream, *Adv. Water Resour.*, *26*, 939–950.

Hays, J. R. (1966), *Mass transport mechanisms in open channel flow*, PhD dissertation, Vanderbilt Univ., Nashville, Tenn.

Henderson, F. M. (1966), *Open Channel Flow*, MacMillan, New York.

Hinterberger, C., J. Fröhlich, and W. Rodi (2007), Three-dimensional and depth-averaged large-eddy simulations of some shallow water flows, *J. Hydraul. Eng.*, *133*(8), 857–872.

Jackson, T. R., R. Haggerty, S. V. Apte, A. Coleman, and K. J. Drost (2012), Defining and measuring the mean residence time of lateral surface transient storage zones in small streams, *Water Resour. Res.*, *48*, W10501, doi: 10.1029/2012WR012096.

Kimura, I., and T. Hosada (1997), Fundamental properties of flows in open channels with dead zone, *J. Hydraul. Eng.*, *123*(2), 98–107.

Koseff, J. R., and R. L. Street (1982), Visualization studies of a shear driven three-dimensional recirculating flow, paper presented at AIAA/ASME Thermophysics and Heat Transfer Conference, St Louis, Mo.

Koseff, J. R., and R. L. Street (1984a), Visualization studies of a shear driven three-dimensional recirculating flow. Trans. ASME: *J. Fluids Eng.*, *106*, 21–29.

Koseff, J. R., and R. L. Street (1984b), On end wall effects in a lid-driven cavity flow, *Trans. ASME: J. Fluids Eng.*, *106*, 385–389.

Koseff, J. R., and R. L. Street (1984c), The lid-driven cavity flow: A synthesis of qualitative and quantitative observations, *Trans. ASME: J. Fluids Eng.*, *106*, 390–398.

Kozerski, H. P., R. Schwartz, and T. Hintze (2006), Tracer measurements in groyne fields for the quantification of mean hydraulic residence times and of the exchange with the stream, *Acta Hydroch. Hydrob.*, *34*, 188–200.

Kurzke, M., V. Weitbrecht, and G. H. Jirka (2002), Laboratory concentration measurements for determination of mass exchange between groin fields and main stream, paper presented at IAHR Conference, 'River Flow', Louvain de la Neuve, Belgium.

Langmuir, I. (1908), The velocity of reactions in gases moving through heated vessels and the effect of convection and diffusion, *J. Am. Chem. Soc.*, *30*, 1742–1754.

Lin, J. C., and D. Rockwell (2001), Organized oscillations of initially turbulent flow past a cavity, *AIAA J.*, *39*(6), 1139–1151.

McCoy, A., G. Constantinescu, and L. Weber (2006), Exchange processes in a channel with two vertical emerged obstructions, *Flow Turbul. Combust.*, *77*, 97–126, doi:10.1007/s10494-006-9039-1.

McCoy, A., G. Constantinescu, and L. Weber (2007), A numerical investigation of coherent structures and mass exchange processes in channel flow with two lateral submerged groynes, *Water Resour. Res.*, *43*, W05445, doi:10.1029/2006WR005267.

McCoy, A., G. Constantinescu, and L. Weber (2008), Numerical investigation of flow hydrodynamics in a channel with a series of groynes, *J. Hydraul. Eng.*, *134*(2), 157–172.

Mulholland, P. J., E. R. Marzolfl, J. R. Webster, D. R. Hart, and S. P. Hendricks (1997), Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams, *Limnol. Oceanogr.*, *42*(3), 443–451.

Muto, Y., H. Imamoto, and T. Ishigaki (2000), Turbulence characteristics of a shear flow in an embayment attached to a straight open channel, paper presented at the 4th International Conference on HydroScience and Engineering, IAHR, Seoul, Korea.

Muto, Y., Y. Baba, and I. Fujita (2002), Velocity measurements in rectangular embayments attached to a straight open channel: River Flow 2002, paper presented at International Conference on Fluvial Hydraulics, IAHR, Louvain-la-Neuve, Belgium.

Newbold, J. D., J. W. Elwood, R. V. O'Neill, and A. L. Sheldon (1983), Phosphorus dynamics in a woodland stream ecosystem: A study of nutrient spiraling, *Ecology*, *64*, 1249–1265.

O'Connor, B. L., M. Hondzo, and J. W. Harvey (2010), Predictive modeling of transient storage and nutrient uptake: Implications for stream restoration, *J. Hydraul. Eng.*, *136*(12), 1018–1032.

Ozalp, C., A. Pinarbasi, and B. Sahin (2010), Experimental measurement of flow past cavities of different shapes, *Exp. Therm. Fluid Sci.*, *34*, 505–515.

Patwardhan, A. W. (2001), Prediction of residence time distribution of stirred reactors, *Ind. Eng. Chem. Res.*, *40*, 5686–5695.

Rockwell, D., and C. Knisely (1980), Observation of the three-dimensional nature of unstable flow past a cavity, *Phys. Fluids*, *23*, 425–431.

Runkel, R. L. (1998), One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers, *U.S. Geol. Surv. Water Resour. Inv. Rep.* 98–4018.

Sardin, M., D. Schweich, F. J. Keij, and M. T. van Genuchten (1991), Modeling the nonequilibrium transport of linearly interacting solutes in porous media: A review, *Water Resour. Res.*, *27*(9), 2287–2307.

Seo, I. W., and W. H. C. Maxwell (1992), Modeling low-flow mixing through pools and riffles: *J. Hydraul. Eng.*, *118*(10), 1406–1423.

Squillace, P. J., E. M. Thurman, and E. T. Furlong (1993), Groundwater as a nonpoint source of atrazine and deethylatrazine in a river during base flow conditions, *Water Resour. Res.*, *29*(6), 1719–1729.

Stream Solute Workshop (1990), Concepts and methods for assessing solute dynamics in stream ecosystems, *J. N. Am. Benthol. Soc.*, *9*(2), 95–119.

Triska, F. J., V. C. Kennedy, R. J. Avanzino, G. W. Zellweger, and K. E. Bencala (1989), Retention and transport of nutrients in a third-order stream in Northwestern California: Hyporheic processes, *Ecology*, *70*, 1893–1905.

Tritthart, M., M. Liedermann, and H. Habersack (2009), Modeling spatiotemporal flow characteristics in groyne fields, *River Res. Appl.*, *25*, 62–81.

Uijttewaal, W. S. J. (2005), Effects of groyne layout on the flow in groyne fields: Laboratory experiments, *J. Hydraul. Eng.*, *131*(9), 782–791.

Uijttewaal, W. S. J., D. Lehmann, and A. V. Mazijk (2001), Exchange processes between a river and its groyne fields: Model experiments, *J. Hydraul. Eng.*, *127*(11), 928–936.

Valentine, E. M., and I. R. Wood (1977), Longitudinal dispersion with dead zones, *J. Hydraul. Eng.*, *103*(9), 975–990.

Valett, H. M., S. G. Fisher, N. B. Grimm, and P. Camill (1994), Vertical hydrologic exchange and ecological stability of a desert stream ecosystem, *Ecology*, *75*(2), 548–560.

Valett, H. M., J. A. Morrice, C. N. Dahm, and M. E. Campana (1996), Parent lithology, surface-groundwater exchange, and nitrate retention in headwater streams, *Limnol. Oceanogr.*, *41*, 333–345.

Valett, H. M., C. N. Dahm, M. E. Campana, J. A. Morrice, M. A. Baker, and C. S. Fellows (1997), Hydrologic influences on groundwater-surface water ecotones: Heterogeneity in nutrient composition and retention, *J. N. Am. Benthol. Soc.*, *16*, 239–247.

Wallast, I., W. Uijttewaal, and A. van Mazijk (1999), Exchange processes between groyne field and main stream, paper presented at 28th International Association for Hydro-Environment Engineering and Research (IAHR) Congress, Graz, Austria.

Weitbrecht, V. (2004), *Influence of dead-water zones on the dispersive mass transport in rivers*, PhD dissertation, Univ. of Karlsruhe, Karlsruhe, Germany.

Weitbrecht, V., and G. H. Jirka (2001a), Flow patterns and exchange processes in dead zones of rivers, paper presented at IAHR 29th Congress, Beijing, China.

Weitbrecht, V., and G. H. Jirka (2001b), Flow patterns in dead zones of rivers and their effect on exchange processes, paper presented at IAHR 3rd International Symposium Environmental Hydralics, Tempe, Ariz.

Weitbrecht, V., S. A. Socolofsky, and G. H. Jirka (2008), Experiments on mass exchange between groin fields and main stream in rivers, *J. Hydraul. Eng.*, *134*(2), 173–183.

Yao, H., R. K. Coopssser, and S. Raghunathan (2004), Numerical simulation of incompressible laminar flow over three-dimensional rectangular cavities, *J. Fluids Eng.*, *126*, 919–927.