Bioturbation, advection, and diffusion of a conserved tracer in a laboratory flume

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[1] Laboratory experiments indicating the relative influences of advection, diffusion, and bioturbation on transport of NaCl tracer between a stream and streambed are described. Data were collected in a recirculating flume housing a box filled with test sediments. Peclet numbers ranged from 0 to 1.5. Sediment components included a medium sand (d_{50} = 0.31 mm), kaolinite, and topsoil. *Lumbriculus variegatus* were introduced as bioturbators. Conductivity probes were employed to document the flux of the tracer solution out of the bed. Measurements are compared to one-dimensional effective diffusion models assuming one or two horizontal sediment layers. These simple models provide a good indication of tracer half-life in the bed if a suitable effective diffusion coefficient is chosen but underpredict initial flux and overpredict flux at long times. Organism activity was limited to the upper reaches of the sediment test box but eventually exerts a secondary influence on flux from deeper regions. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1832 Hydrology: Groundwater transport; 1831 Hydrology: Groundwater quality; 1894 Hydrology: Instruments and techniques; *KEYWORDS:* bioturbation, advection-diffusion, pore water flux, solute transport, Peclet number

1. Introduction

[2] The exchange of water and solutes between a water body and the underlying sediment bed is relevant to many ecological and environmental problems. Water, chemicals, and biological organisms all may pass through this interface [*Aller*, 1978]. Harmful chemicals, dissolved in the water or absorbed or adsorbed by other particles, are often of interest for pollutant transport descriptions [*Reible et al.*, 1991]. Fluxes of naturally occurring chemicals, particularly dissolved oxygen, are also important [*Sweerts et al.*, 1991; *Steinberger and Hondzo*, 1999]. The direction of the flux may vary seasonally or according to some other timescale, as short as a wind wave period [*Rutgers van der Loeff*, 1981; *Huettel and Gust*, 1992].

[3] The severity and intractibility of the contaminated sediment problem is widely recognized and has resulted in national mitigation efforts [*U.S. Environmental Protection Agency* (*EPA*), 1997]. Remediation efforts are typically quite expensive, with their efficacy questioned. Predictions of outcomes often contain significant uncertainty because of a lack of understanding of the underlying physical, chemical, and biological processes and a lack of data.

[4] A nonsorbing, dissolved, conserved tracer represents the simplest case and is the focus of this study. Emphasis is placed on fluxes through a streambed-stream interface, augmented by tubificid-induced bioturbation. The term bioturbation is taken here to indicate any tracer transport attributable to the presence or activity of biological organisms. This could include direct transport within or through the bodies of the organisms or enhanced transport due to an increased effective porosity due to their movements through the soil matrix.

[5] The measurement technique employed yields a detailed, quantitative description of the spatial and temporal variation of tracer concentration within a streambed and identification of the bioturbated zone. These details are not available from previous studies that involved monitoring only the penetration of a dye front into a streambed or the net mass transfer into or out of the test bed.

2. Previous Related Work

[6] The transport of contaminants between sediment beds and overlying water bodies may be investigated via both laboratory and field observations [e.g., *Bencala*, 1983; *Reible and Savant-Malhiet*, 1993; *Elliott and Brooks*, 1997; *Hutchinson and Webster*, 1998]. Laboratory measurements of effective diffusion coefficients are available for many solvents in many different media [*Mannheim*, 1970; *Li and Gregory*, 1974; *Stoessell and Hanor*, 1975; *McDuff and Ellis*, 1979; *Van Rees et al.*, 1991]. Diffusion coefficients for solutes in pore water are generally reduced from the corresponding free solution values. The magnitude of the reduction is dependent on sediment

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tortuosity, which in turn is dependent on sediment porosity [*Reible and McCutcheon*, 1993].

[7] A mean flow within a sediment bed will translate (advect) a tracer cloud, and velocity gradients within the mean flow will shear the cloud, increasing concentration gradients and the rate of mixing (dispersion). The Peclet number is often used to quantify the relative importance of advection and diffusion

$$Pe = \frac{VL}{D}, \tag{1}$$

where V is a measure of mean flow speed (within the bed, in this case), L is a representative length scale, and D is diffusivity of the tracer in the porous medium [e.g., *Savant et al.*, 1987].

[8] Advection arises because of pressure gradients. Longitudinal pressure gradients within a streambed will arise or be enhanced by the presence of bed features, such as dunes [*Vaux*, 1968; *Savant et al.*, 1987; *Thibodeaux and Boyle*, 1987; *Reible and Savant-Malhiet*, 1993; *Harvey and Bencala*, 1993; *Rutherford et al.*, 1995] or aquatic organisms or their burrow mounds [*McCall and Tevesz*, 1982; *Huettel and Gust*, 1992; *Hutchinson and Webster*, 1998].

[9] The experiments described here involve open channel flow in a recirculating flume across a sediment bed featuring dunes. Flume studies of diffusive and advective stream-pore water exchange have been performed by several previous investigators, typically using dye as a conserved tracer and measuring net flux either into or out of the sediment bed [*Savant et al.*, 1987; *Elliott and Brooks*, 1997]. Point measurements of conductivity have also been employed [*Nagaoka and Ohgaki*, 1990].

[10] Bioturbation has been addressed in both laboratory and field settings [*Gust and Harrison*, 1981; *Hines et al.*, 1982; *Bosworth and Thibodeaux*, 1990; *Ewald et al.*, 1997]. *Huettel and Gust* [1992] found that organism-induced bed roughness greatly increased pore water flux (by a factor of up to 7) compared to a smooth bed, depending on roughness size, sediment permeability, and flow boundary layer characteristics.

[11] Other studies have addressed fluxes due to direct activity of bioturbators [*McCall and Tevesz*, 1982; *Rippey and Jewson*, 1982; *Robbins*, 1982; *Krantzberg*, 1985; *Muller-Lemans and van Dorp*, 1996; *Ewald et al.*, 1997]. *Reible et al.* [1996] suggest that data describing bioturbation-induced fluxes are lacking. No previous studies quantifying spatial and temporal variations in pore water tracer concentrations due to the combined influences of advection, diffusion, and bioturbation were identified.

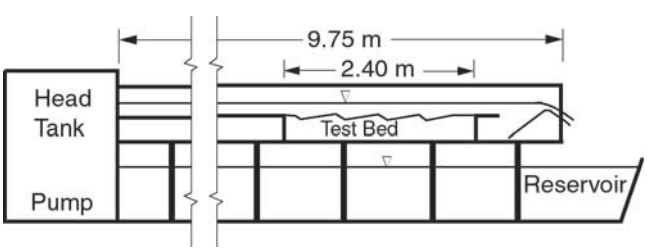

Figure 1. Profile view of recirculating flume. Upstream end of test box is roughly 6 m downstream of head tank.

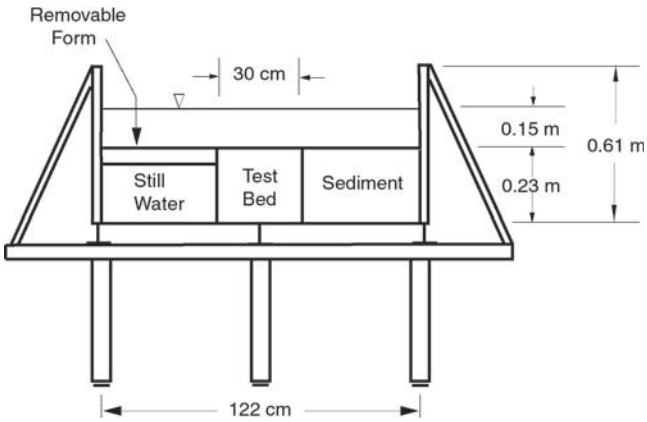

Figure 2. Flume cross section, looking upstream. A plywood sheet divided the test box longitudinally into two 15 cm wide regions to form separate bioturbation and control sections.

3. Laboratory Equipment and Procedures

[12] A large recirculating flume (Figures 1 and 2) was used for many of the experiments described in this paper. Flume dimensions are 9.8 m long by 1.2 m wide by 0.6 m deep, and slope was set at 1:0.0026 (H:V). A planar false bottom and a 2.4 m long by 30 cm wide by 23 cm deep, impermeable acrylic test box were installed in the flume. The test box was located along the flume centerline, at the downstream end of the flume. The relatively wide flume helped reduce sidewall boundary layer importance in the experiments, while the relatively narrow test box made sediment volumes and sampling areas more manageable than if the box had spanned the entire flume width.

[13] A conserved tracer (NaCl, 1 ppt nominal) was introduced into the pore water in the sediment test box, and the concentration of the tracer was monitored at many (80) points within the box, as tracer-free water circulated over and through the bed. The ratio of flume sump volume to test box pore water volume typically exceeded 150:1. Thus tracer concentration within the overlying recirculating water remained negligibly small for the entire experiment.

[14] Sand was glued to the false bottom of the flume, upstream of the test box, to simulate the roughness of a longer (planar) sediment bed. Since the test box was narrower than the flume, a panel was fabricated to fill the gap on one side of the test box. This panel was shaped to match desired dune geometry [*Keown et al.*, 1986] (Figure 3) and roughened with glued sand. The other side of the flume, opposite the test box, was filled with sediment

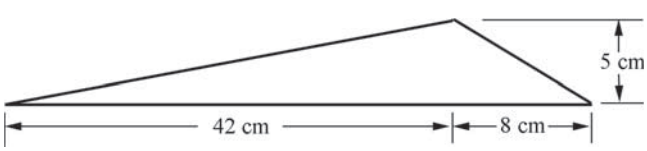

Figure 3. Geometry of dunes for all flume tests (not to scale).

Table 1. Properties of Sediment Mixtures Used in Bioturbation Experiments[a]

Sediment	d_{50}, mm	Porosity	Permeability, cm/s
Medium sand	0.31	0.36	1.48×10^{-2}
Medium sand 90%, topsoil 10%	0.28	0.35	4.93×10^{-3}
Medium sand 60%, kaolinite 30%, topsoil 10%	0.09	0.33	3.20×10^{-5}

[a] Grain sizes were determined by sieve analysis.

(Figure 2). A graded medium sand, kaolinite, and topsoil were included as test sediment components (Table 1).

[15] Sediments were thoroughly mixed in a mortar mixer and introduced to the test box in a dry condition. The mixture was then saturated, and bedforms were contoured by hand. Areas to either side of the test box featured identical bedforms, the goal being horizontally one-dimensional flow. All experiments featured sufficiently low flow speeds that negligible sediment transport resulted. Parameters for each experiment are shown in Table 2.

[16] Changes in pore water salinity were monitored using a set of conductivity probes fabricated for the experiments [*Moore*, 1999]. Each consisted of two 0.5 mm diameter platinum wires encased in epoxy inside a 2.5 mm diameter stainless steel tube. A power supply, Wheatstone bridge circuit, and display panel were added to form a digital conductivity meter. Output voltages from the probes were functions of both pore water salinity and sediment composition, so the probes were calibrated once for each sediment mixture.

[17] Pore water salinity within the test box was monitored at nodes of a sampling grid, with 10 cm resolution in the downstream direction and higher resolution near the top of the box where the greatest concentration gradients were expected. Measurements were made 2.5, 5.0, 7.5, 15.0, and 21.0 cm below a datum which passed through the crests of the dunes. Vertical space steps were halved for experiments B9–B12, and the horizontal length of the sampled region was simultaneously halved longitudinally. Sampling times were selected subjectively on the basis of previous experience and expected relative rates of change of pore water salinity but typically included 1, 3, 6, 12, and 24 hours, with subsequent measurements made every 24 hours. Sampling of the entire bed typically took 30–45 min and was done without stopping the flow.

[18] Individual measured concentrations contained a random error of up to 25%. The final flume tests were inspected for systematic error to assess the significance of any sensor drift. Horizontally averaged reported concentrations (eight values) were averaged for the bottom of the test box for each of the 17 sampling times during the first 4 days of the 9 day experiment. This included all measurement times for which vertical concentration gradients near the bottom of the bed were negligible, suggesting that tracer transport processes had not yet impacted concentrations in this region. The trend in mean concentration at the bottom of the bed indicates a 12% increase over the 4 day period, attributable either to sensor drift or a measured 4°C rise in water temperature during the same period. Note that many of the results presented here involve integration along at least one space dimension, which will help remove the influence of random errors.

[19] The test box was divided longitudinally to facilitate simultaneous bioturbation and control tests in the flume. A no-flow test was performed in unison with each flume test. The no-flow tests were performed in tubs with identical sediment bed thicknesses and overlying depths.

[20] Numerical integration of all salinity readings within the sampled region yields the total mass of salt within the bed at any time. Experiments were continued until a significant reduction in this total mass had occurred (typically to 50–60% mass remaining) and the rate of change of total mass became qualitatively small.

[21] The aquatic worm *lumbriculus variegatus* was chosen as bioturbator. *L. variegatus* are aquatic worms found primarily in fresh water or transition zones in estuaries, featuring low or zero flows, and sandy or silty soils. They are typically 2–5 cm in length, although occasionally, they are as long as 15 cm [*McCall and Tevesz*, 1982]. They thrive in moderate to warm temperatures (20°–

Table 2. Parameters for Each Experiment[a]

Test	Flow Speed, cm/s	Bed Material	Exchange Mechanism	$Pe = VL/D$
B1	0.0	MS/TS 90/10	D	0
B2	0.0	MS/TS 90/10	B, D	0
B3	6.0	MS/TS 90/10	A, D	1.5
B4	6.0	MS/TS 90/10	A, B, D	1.5
B5	6.0	MS/CL/TS 60/30/10	A, D	1.0
B6	6.0	MS/CL/TS 60/30/10	A, B, D	1.0
B7	0.0	MS/CL/TS 60/30/10	D	0
B8	0.0	MS/CL/TS 60/30/10	B, D	0
B9	6.0	MS/CL/TS 60/30/10	A, D	1.1
B10	6.0	MS/CL/TS 60/30/10	A, B, D	1.1
B11	0.0	MS/CL/TS 60/30/10	D	0
B12	0.0	MS/CL/TS 60/30/10	B, D	0

[a] Bed materials: MS, medium sand; CL, clay (kaolinite); TS, topsoil. Exchange mechanisms: A, advection; B, bioturbation; D, diffusion. All tests with flow include bedforms. *Pe* is estimated Peclet number.

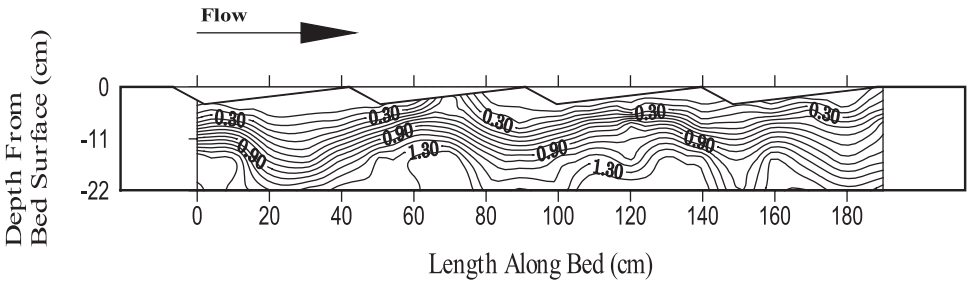

Figure 4. Salinity contour plot for test B6, t = 452 hours (includes bioturbation, flow, and 30% clay), with contour interval of 0.1 ppt.

25°C) and high dissolved oxygen (DO) conditions but can tolerate fluctuations in both DO and temperature. They may burrow as deep as 20 cm from the bed surface but will typically be found in the upper 2–8 cm of the bed [*Goldhaber et al.*, 1977; *McCall and Tevesz*, 1982]. By feeding in this region they are likely to transport contaminants from within the bed to the overlying water column and may increase the hydraulic conductivity of the upper reaches of the bed via their burrowing activities [*Reible et al.*, 1996].

[22] Worms were placed into the test region under a no-flow condition and covered with the last 2 cm of sediment required to complete the desired bed shape. A density of 6000–8000 organisms/m^2 was selected, this being common in nature [*Davis*, 1974; *Mason*, 1994]. Flow was then started, and within 1 hour, many worms were observed to be feeding, with posterior ends extending out of the bed. Few worms migrated out of the test region during the experiment, and worm mortality appeared to be negligible (>95% live at the end of each experiment). Separate tests indicated that the worms could survive at least 1 week in a petri dish with tap water and no food source and that kaolinite and sodium chloride (1 ppt) did not appear to affect survivorship.

[23] Ideally, one would simulate a test section of infinite length to reduce longitudinal flow gradients induced by impermeable end walls. *Elliott and Brooks* [1997] addressed this problem by removing flowing pore water at the downstream end of the test region and reintroducing it at the upstream end. If the pore water is removed at the proper rate, with the proper distribution over the vertical, an infinite test box is simulated, but the correct velocity profile is not known a priori (a similar problem is encountered in laboratory studies of longshore currents within the surf zone [e.g., *Visser*, 1991]). If an excessively large rate is chosen, then this artificially forced exchange could overwhelm the flow that would otherwise occur. An alternative, chosen here, is to use a large sealed test box and recognize that flow rates within the box will be slightly lower than in an infinite length box.

4. Results

[24] The sampling approach described above provided a two-dimensional description of the time-dependent salt concentration within the test box. Plots showing instantaneous concentration as a function of space provide a qualitative picture of the results. Figure 4 provides one result for case B6 (30% clay, flow, worms), which is representative of the trends apparent in most of the flume tests.

[25] Plots shortly after commencement of the experiment reveal relatively uniform concentrations, with flushing due to combined bioturbation, advection, and diffusion just beginning to appear at the dune crests. After 452 hours (Figure 4), significant vertical concentration gradients have developed. Some longitudinal periodicity is evident, controlled by the bed form wavelength. These observations are consistent with the flow fields described by *Savant et al.* [1987] and *Elliott and Brooks* [1997].

[26] Vertical concentration gradients are more evident if all measurements from a given depth are averaged and plotted as a function of depth. Figures 5 and 6 show nondimensional concentration versus nondimensional depth for bioturbation and control tests in the flume. Error bars on each plot indicate ±1 standard deviation in the readings from each depth at the measurement time, reflecting a combination of random error and the longitudinal variability in solute concentration. The error bars near the bottom of the test section for early times reflect primarily random errors since tracer transport processes have not yet propagated to the bottom of the box. Typical values for the standard deviation in the measurements at the bottom of the box, for early times, were ±5–15% of the mean concentration.

[27] In the case including worms (test B10) the relative concentration is seen to be reduced, compared to the matching no-worm case (B9), with this trend being more pronounced in the upper portion of the bed. At 24 hours (Figure 5) the top 25% of the bed has been flushed of >50%

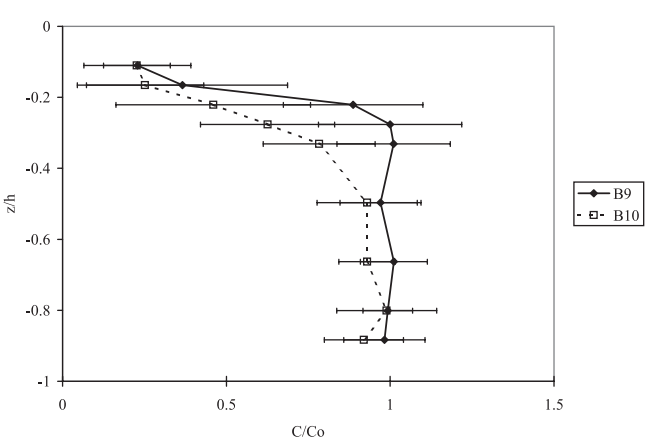

Figure 5. Relative concentration versus nondimensional depth for cases B9 (30% clay, flow, no worms; diffusion and advection) and B10 (30% clay, flow, worms; diffusion, advection, and bioturbation) at t = 24 hours.

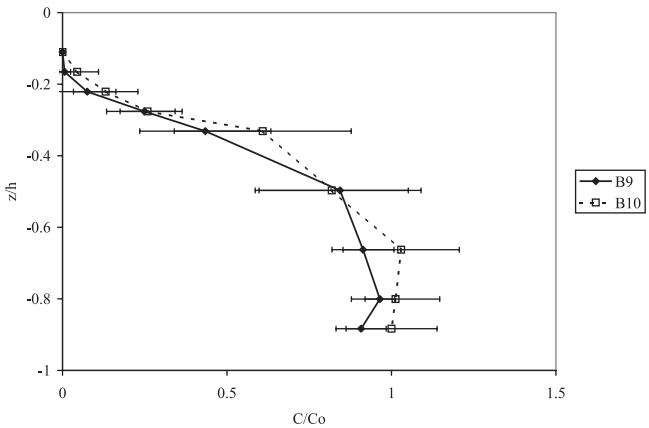

Figure 6. Relative concentration versus nondimensional depth for cases B9 (30% clay, flow, no worms; diffusion and advection) and B10 (30% clay, flow, worms; diffusion, advection and bioturbation) at t = 166 hours.

of its initial solute, and the case including worms has significantly less solute remaining than the case without worms (note that error bars, though large, barely overlap for some depths). After 166 hours, the two curves are similar, with the top 25% of the bed being flushed nearly completely of solute (Figure 6).

[28] The diffusion-only tests would be expected to agree well with analytical solutions for one-dimensional diffusion. Tests including advection and/or bioturbation feature a greater flushing rate in the top 25–30% of the bed. The importance of advective effects decreases with depth into the bed owing to lower pore water velocities. A similar trend would be found for bioturbators that exhibit a preference for the top of the sediment bed. In either case, a one-dimensional diffusion solution that allows for two different sediment diffusivities might provide a better fit to the data than a simple one-layer solution. Both one- and two-layer solutions will be considered here.

[29] The simplest description of the tracer exchange is based on the percentage of initial mass remaining within the bed, obtained by integrating concentration over the entire test box. Analytical solutions to the one-dimensional diffusion equation are readily available for this case, for simple initial and boundary conditions [e.g., *Dixon*, 1978]. Transport is assumed to be vertical, with constant initial concentration within the bed and zero flux through the bottom boundary. For flume experiments, zero concentration in the overlying water was assumed for all time. For the no-flow experiments, where concentration in the overlying fluid is time-dependent, a different solution governs. One diffusion coefficient controls each solution.

[30] Some terminology must be established to distinguish among the different diffusion coefficients since the tracer transport mechanisms differ from case to case. The term molecular diffusion coefficient will be used to describe the diffusion coefficient for a solute in still pore water, where molecular diffusion is the sole transport process. The term effective diffusion coefficient will be used to reflect the coefficient lumping together all active mechanisms. Biogenic diffusion coefficient will be taken to reflect the effective diffusion coefficient for the portion of the bed subject to bioturbation. Including the word "diffusion" in each term is not intended to suggest that diffusion is the dominant transport process but rather reflects that the analytical solution for which the coefficient represents a best fit describes a diffusive process.

[31] The one-layer, analytical solutions for concentration $C(z, t)$ and fraction of mass remaining $P(t)$ for the flume case (zero concentration in overlying flow for all time) are [*Dixon*, 1978]

$$C(z,t) = \frac{4C_o}{\pi}\sum_{n=1}^{\infty}\frac{1}{2n-1}\sin\left[\frac{-(2n-1)\pi}{2}\frac{z}{h}\right] \cdot \exp\left[\frac{-(2n-1)^2\pi^2 Dt}{4h^2}\right] \tag{2}$$

$$P(t) = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[\frac{-(2n-1)^2\pi^2 Dt}{4h^2}\right], \tag{3}$$

where h is bed thickness, z is zero at the bed surface and increases vertically upward, and t is time since the start of the experiment. D is the applicable diffusion coefficient.

Table 3. Best Fit Effective Diffusion Coefficients for Each Experimental Case[a]

Test	Mechanisms	D, cm^2/s	D_e, cm^2/s	D_b, cm^2/s	ε_1, % mass	ε_2, % mass
B1	D	2.4×10^{-5}			3.9	NA
B2	D, B		5.4×10^{5}	3.4×10^{-4}	7.2	5.8
B3	D, A		9.6×10^{-5}		1.1	NA
B4	D, A, B		3.2×10^{-5}	4.2×10^{-5}	1.9	1.6
B5	D, A		5.8×10^{-5}		4.3	NA
B6	D, A, B		6.7×10^{-5}	2.1×10^{-4}	4.6	3.9
B7	D	3.2×10^{-5}			2.7	NA
B8	D, B		4.7×10^{-5}	1.0×10^{-4}	3.9	3.5
B9	D, A		1.3×10^{-4}		5.9	NA
B10	D, A, B		1.9×10^{-4}	3.5×10^{-4}	5.2	5.0
B11	D	1.6×10^{-5}			7.3	NA
B12	D, B		3.4×10^{-5}	5.5×10^{-5}	7.1	6.9

[a] The effective diffusion coefficient represents a best fit of the one-layer, one-dimensional diffusion solution to the data. The biogenic diffusion coefficient represents the best fit value for the top layer in the two-layer solution.

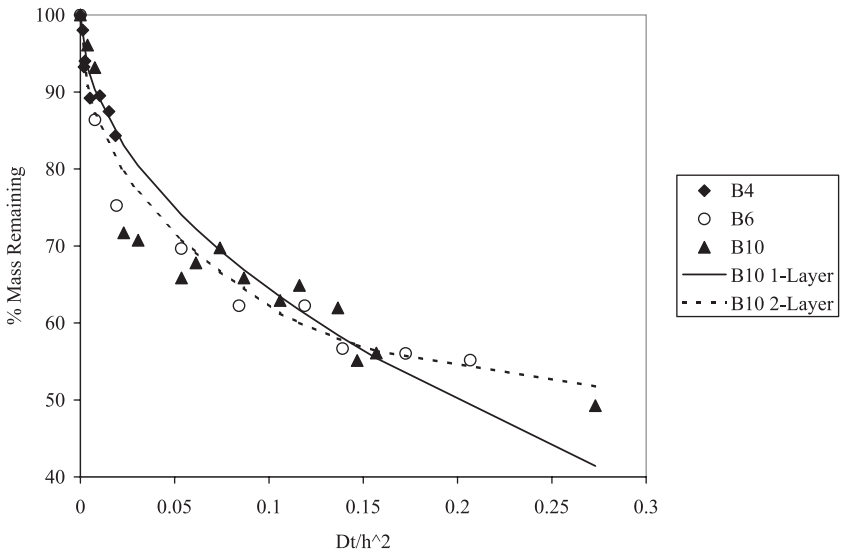

Figure 7. Percent mass remaining versus nondimensional time for cases B4, B6, and B10 (all include flow and worms) and best fit one- and two-layer analytical diffusion solutions for case B10. Best fit molecular diffusion coefficient from one-layer solution and bed thickness used to nondimensionalize time for this and similar plots.

[32] For the no-flow case, where concentration of solute in the overlying water increases over time, the solution for concentration in the overlying water is [*Stoessell and Hanor*, 1975; *Van Rees et al.*, 1991]

$$\frac{C(t)}{C_o} = \left\{1 - \left[\exp\left(\frac{DtV_p^2}{h^2V_r^2}\right)\operatorname{erfc}\left(\frac{(Dt)^{1/2}V_p}{hV_r}\right)\right]\right\}. \quad (4)$$

where V_p is pore water volume and V_r is volume of the overlying water.

[33] A best fit, one-layer, diffusion coefficient was calculated for each experiment to minimize the RMS difference between the observations of fraction mass remaining within the test box and that predicted by the analytical solutions. This involved selecting D such that RMS difference ε was minimized

$$\varepsilon = \frac{1}{P'(0)}\sqrt{\frac{\sum_{n=1}^{N}\left[P'(t_n) - P(t_n)\right]^2}{N}}, \quad (5)$$

where N is the number of measurement times t_n for a given experiment. P denotes a theoretical value for fraction of mass remaining, and P' indicates a value derived from laboratory observations. The best fit diffusion coefficients for the one-layer analytical solution are given in column 3 of Table 3 for the diffusion-only experiments, and in column 4 for all other experiments. RMS differences for each case are given in column 6. The mean value of the RMS difference is 4.6% mass remaining.

[34] Figure 7 shows results for cases B4, B6, and B10, all of which include advection, diffusion, and bioturbation. The best fit, one-layer, analytical solution for test B10 is also shown. In general, the one-layer, analytical solution (equation (3)) underpredicted the initial flux from the test box and overpredicted flux later [*Moore*, 1999]. The order of magnitude of the best fit diffusion coefficient is well defined, but smaller changes in the value of the effective diffusion coefficient (less than an order of magnitude) affect the goodness of fit only slightly.

[35] Introduction of clay to the sediment did not significantly alter the calculated molecular diffusion coefficient (compare cases B1 and B7 in Table 3). The added clay drastically reduced permeability but only weakly influenced porosity (Table 1), on which molecular diffusivity is more strongly dependent [*Reible and McCutcheon*, 1993].

[36] Molecular diffusion coefficients reported in Table 3 are slightly higher than what is expected for chloride in water, when lower values would be expected because of the sediment tortuosity (*Li and Gregory* [1974] report $D = 1.6 \times 10^{-5}$ cm^2/s for sodium chloride in water). This is likely due to the difficulty of preserving the initial condition in the no-flow tests. Introduction of the overlying water likely caused some mixing. This problem was much less severe in

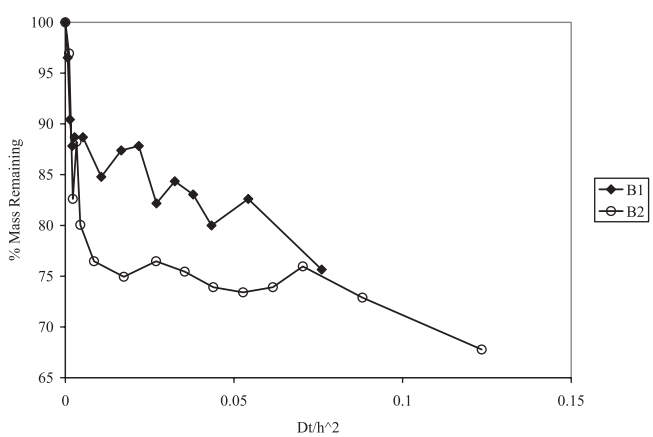

Figure 8. Percent mass remaining versus nondimensional time for cases B1 (no clay, no flow, no worms; diffusion only) and B2 (no clay, no flow, worms; diffusion and bioturbation).

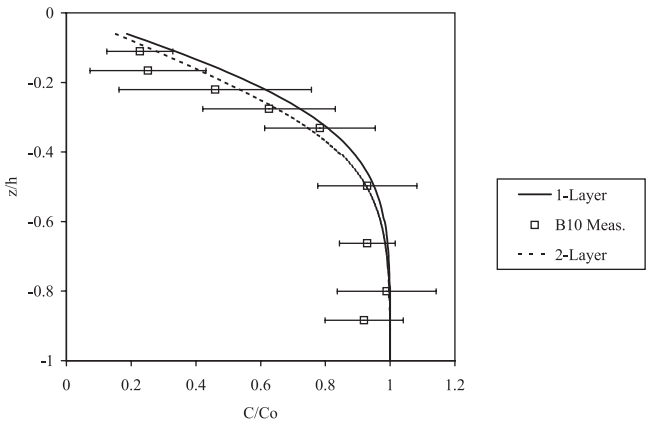

Figure 9. Relative concentration versus nondimensional depth measurements for case B10 (30% clay, flow, worms; diffusion, advection, and bioturbation) and comparisons to one- and two-layer, one-dimensional models, t = 24 hours.

the flume tests, where the filling procedure was controlled electronically (by the flume pump).

[37] A finite difference numerical scheme was employed to solve the one-dimensional diffusion problem, with two sediment layers, each having a unique diffusivity (*Aller* [1978] presents an analytical solution). A best fit effective diffusion coefficient was computed for the top sediment layer, given layer thicknesses and a value for effective diffusion coefficient in the lower layer.

[38] The diffusion coefficient for the lower layer was obtained from the corresponding no-worm case, using the best fit one-layer solution. Typical worm length was estimated at 6 cm, and this value was selected as the vertical thickness of the top (bioturbated) zone, consistent with *Aller* [1978]. Thus only the (biogenic) diffusion coefficient for the upper layer remains to be adjusted to fit the two-layer solution to the data. A best fit biogenic diffusion coefficient was determined for the upper sediment layer in each case that featured worms (column 5 of Table 3). The dashed curve in Figure 7 shows the best fit, two-layer solution for case B10.

[39] Best fit coefficients were only weakly dependent on assumed thickness for the top sediment layer. Obviously, a higher coefficient is expected in the top layer owing to bioturbation but also because of the increased importance of advection in the upper portions of the bed. This was true for each case.

[40] The two-layer solution slightly reduced RMS differences between measured and modeled percent mass remaining curves (compare columns 6 and 7 of Table 3). Test B2 was a no-flow, no-clay test with worms; the biogenic diffusion coefficient exceeded the molecular diffusion coefficient by an order of magnitude. Test B4 featured the same conditions but included flow. Addition of flow did not appear to increase the rate of flushing of the bed. This may be a byproduct of inadequate test duration; 84% of the initial mass remained at the conclusion of test B4, and the assumed bioturbation zone (the upper 6 cm of the bed) still contained much of its initial salt concentration.

[41] Tests B5–B8 include clay and are more consistent with expectations (Table 3). The best fit coefficients in the upper layers are consistently double the values in the lower layers. This difference is also larger for the case including flow (B6).

[42] The last group of tests (B9–B12) feature conditions identical to tests B5–B8 but were sampled with twice the vertical resolution. Trends are unchanged but the magnitude of the differences between the best fit coefficients for the two layers are reduced. Cases B6 and B10, featuring identical sediment and flow conditions but different sampling schemes, are compared in Figure 7 and serve as an indication of experiment repeatability.

[43] Intuitively, it is expected that advection and bioturbation would exert similar influences after lateral averaging and in either case flush the upper portion of the bed more quickly than the lower regions. Advection and bioturbation will dominate initially, while the upper layer of the bed still contains a high concentration of solute, and diffusion will dominate at later times. Advection and bioturbation will both continue to flush the upper portion of the bed and thus increase the rate of diffusion from the lower layer by maintaining a high vertical concentration gradient.

[44] Comparisons of the measurements and analytical solutions for cases with flow are consistent with this idea. In each case, the initial rate of flushing from the bed exceeds that predicted by the one-layer diffusion model. At later times, the rate of flushing is overpredicted when the best fit diffusion coefficient is used, but this coefficient is typically larger than the molecular diffusion coefficient. *Elliott and Brooks* [1997] reported effective diffusion coefficients for Lissamine that were 25 times the molecular diffusion coefficient and noted that the effective diffusion coefficient should be a function of hydraulic conductivity and head gradient.

[45] Additional results isolate the influences of the different processes affecting contaminant transport. Figure 8 compares two no-flow cases, one with worms (B2) and one without (B1). The initial rate of flushing is much greater for the case including bioturbation. Once the mass of solute within the bed has dropped 25% from its initial value, the rate of change of mass is reduced substantially. Note that the typical length for the species used (6 cm) is roughly 25% of the total bed thickness (23 cm). Advection yields a similar effect, although less pronounced because of the low sediment permeability due to the presence of the clay.

[46] The one- and two-layer models can be used to describe concentration versus depth for comparison to the laboratory data. The best fit coefficients for each solution, determined previously using the solutions for percent mass remaining, were substituted into the analytical solutions for concentration versus depth. Figure 9 shows results for one case at t = 24 hours. Both models give a reasonable description of the variation of concentration versus depth, with the two-layer solution providing a slightly better fit.

[47] With proper choices for velocity and length scales, a Peclet number $\gg 1$ indicates dominance of advection, whereas $Pe \ll 1$ indicates dominance of diffusion. An estimated Darcy velocity, the product of the sediment hydraulic conductivity and the head gradient, was taken as the velocity scale. The head gradient was estimated on the basis of the bed surface pressure observations made by *Vittal et al.* [1977] for flow over dunes. Dune height was

taken as the length scale since it strongly influences the pressure gradients driving the advection. The molecular diffusion coefficients derived from the laboratory observations served as the final parameter. Results suggest that advection is important for all cases involving flow (Table 2). Note that a large range of values will be found in nature, depending on dune height, flow speed, and sediment properties.

5. Summary and Conclusions

[48] Many contaminant transport problems in nature involve combinations of advection, diffusion, and bioturbation (the latter process defined here to incorporate all contaminant transport attributable to the presence or activity of biological organisms). Data describing the combined effects of all three are sparse. A laboratory study was performed in a recirculating flume, with Peclet numbers ranging from 0 to 1.5, to isolate each process. *Lumbriculus variegatus*, a small aquatic worm, was selected as bioturbator. Test sediments included combinations of medium sand (d_{50} = 0.31 mm), topsoil, and kaolinite. Both flow and no-flow tests were included. All tests with flow included dunes.

[49] Conductivity probes were used to monitor temporal and spatial variations in the concentration of a NaCl tracer solution within a test box. Longitudinal periodicity was evident in the results, controlled by the bedform wavelength.

[50] Other observations may be summarized as follows.

1. Inclusion of 30% kaolinite in the sediment mixture drastically reduced hydraulic conductivity but exerted little influence on diffusion of tracer out of the bed.
2. The one-layer, one-dimensional, analytical diffusion solution provides a reasonable description of the contaminant exchange process when a suitable effective diffusion coefficient is used but typically underpredicts initial rate of response and overpredicts rates of change at later times. A two-layer solution improves agreement slightly.
3. Bioturbators typically reduced tracer concentrations by 5–40% in the top layer of the bed until advection and bioturbation reduced concentrations in this region to insignificant levels.
4. Bioturbators can increase vertical concentration gradients and thereby increase the rate of diffusion of a contaminant out of the bed even after their home area has become "clean."
5. Effective diffusion coefficients for experiments including advection and/or bioturbation were typically 2–5 times values for diffusion-only cases. The significance of bioturbation will depend on sediment characteristics, bed thickness, organism size and activity level, overlying flow speed, and presence and size of bedforms. Bioturbation effects will be minimized under conditions that favor advection of pore water.

[51] The experiments described here represent an idealization of conditions in nature. Flow was steady and uniform, initial tracer concentrations were uniform, and boundary conditions were relatively simple. Yet the relative significance of advection, diffusion, and bioturbation is revealed, as is the dependence of these processes on flow and sediment properties. A one-dimensional description of tracer transport processes, modeled together as a diffusive process, provided reasonable results for tracer half-life in the bed. A more realistic description would require the use of a two-dimensional, numerical model for flow and contaminant transport, but the simpler one-dimensional approach may be suitable for many applications.

Notation

C concentration.
C_o initial concentration.
d_{50} median grain size.
D diffusion coefficient.
D_b effective diffusion coefficient including influence of bioturbation.
D_e effective diffusion coefficient.
h vertical thickness of sediment layer.
L length scale.
N number of laboratory sample times.
P percent mass remaining (calculated).
P' percent mass remaining (from laboratory observations).
P_e Peclet number.
t time.
V mean flow speed.
V_p pore water volume.
V_r overlying water volume.
z vertical coordinate.
ε RMS difference between measurements and model results.
ε_1 value of ε from one-layer model.
ε_2 value of ε from two-layer model.

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