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Variability of entrainment of cohesive sediments in freshwater

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Abstract. Estimates of sediment entrainment are required for models of particle transport in lakes and estuaries but are difficult to make because of the multiplicity of factors affecting cohesiveness of surficial sediments. We present results of sediment resuspension studies performed in an annular flume calibrated with laser-Doppler velocimetry. In our experiments, using sediments collected from two sites in the R. Raisin which flows into L. Erie and from one site in the western basin of L. Erie near the mouth of the R. Raisin, we applied shear stresses at the sediment-water interface in steps from 2 to 12 $dyne/cm^2$. Percent water content at the surface of the sediments was either 77 or 74%, and trials were run with and without oxygenating the water overlying the sediments. Entrainment rates as a function of shear stress at the sediment-water interface were best described by a power-law relationship. All but 14% of the variability in the power law expression was due to shear stress and percent water content; the variability not accounted for was due to differences in particle size distributions, chemical properties, and biological activity in the sediments.

Introduction

Changes in the quantity of suspended material affect the physical, chemical and biological processes occurring in lakes (Melack 1985; Kirk 1985). The distribution of radiant energy is altered with consequent effects on the distribution of heat, of light available for photosynthesis, and on the visibility of predators and prey. Absorption and desorption of nutrients, heavy metals, and organochlorides occur on the surfaces of particulates which thus act as sources or sinks for these materials depending on rates of reaction and on residence times. Water quality management programs require estimates of the change in particle concentration over time. Transport models incorporating current speeds and bottom stresses can supply these estimates but, because no general model of sediment entrainment exists, require that the supply of particulates from the sediments be determined from laboratory or field experiments from specific sites.

The eventual goal of sediment entrainment studies is to develop a model of sediment entrainment, that is, to predict changes in concentration of suspended sediments as a function of shear stresses at the sediment–water interface and to explicitly include the effects of properties of the sediments and the sediment bed. This problem is especially complicated for cohesive sediments, the dominant sediment type in lakes, estuaries, and the offshore ocean, because the strength of bonds between particles depends upon sediment chemistry and the near ubiquitous organic coatings on the particles. Laboratory experiments designed to determine the physical and geological mechanisms affecting entrainment of cohesive sediments have shown that it depends upon shear stress and water content at the sediment-water interface, the mineralogy of the sediments (Fukuda & Lick 1980; Lee, Lick & Kang 1981), particle size distributions (Massion 1982), and bed shear strength (Mehta et al. 1982). The situation is made more complex because the sediment-water interface is chemically and biologically active (Holland et al. 1974; Frostick & McCave 1979; Nowell et al. 1981; Tsai & Lick 1985). This multiplicity of factors makes developing predictive equations difficult. Lavelle et al. (1984) did attempt to find a general expression relating entrainment to shear stress by reanalyzing a number of field and laboratory experiments. They found that entrainment rates are a power law function of shear stress but there was considerable variation in the function partly becuase of the different factors affecting entrainment and partly because of different experimental techniques.

In this paper, our primary purpose is to present the results of laboratory experiments designed to determine rates of entrainment of cohesive sediments for different shear stresses and percent water content of the surficial sediments. The shear stresses are those likely to be encountered at the sediment–water interface of lakes and rivers. The percent water contents selected are those likely when storms disturb the sediments with either a 2 or an 8 day periodicity. Furthermore, we address the variability of entrainment induced by oxygenation or deoxygenation of the overlying water and differences in particle size distribution. We compared sediments from three nearby sites with comparable cation exchange capacities and percent organic matter but slightly different particle size distributions. We describe entrainment rate as a power law function of shear stress and compare our findings with Lavelle et al.'s (1984).

Another of our goals was to determine if concentrations of suspended sediments at steady state in the laboratory flume closely approximate the total mass of material that can be eroded. This mass is the quantity of material that would be introduced into the water column of a lake. It is not clear that the two are equal because at steady state, when the rate at which material is being entrained equals the rate at which it returns to the bed by deposition, entrainment rates are concentration dependent. In a lake where turbulence in the overlying water acts to move the particulates away from the boundary, sediment concentrations at the interface would be less than in the flume. Our approach to this problem was to take the system away from steady state by diluting the water in the flume, to collect all the material that was entrained, and to compare the mass entrained with that entrained at steady state.

Laboratory experiments to study sediment entrainment have traditionally been carried out in one of two types of flume (Nowell & Jumars 1987). Linear flumes have simple flow fields but the sediment bed is not continuous and studies are limited to determining the shear stress at which sediment movement is initiated (Lavelle & Mofjeld 1987). Annular flumes have flows complicated by secondary motions due to the curvature of the sidewalls but the bed is continuous and entrainment rates and steady state concentrations can actually be measured. We performed our measurements in an annular flume and tested three configurations to determine the one with the least spatial variation in shear stress. The calibrations, using laser–Doppler velocimetry, show the extent of varations in longitudinal shear stress radially across the flume because of the presence of the flume's side-walls and curvature.

Materials and methods

Sediments used in this study were obtained from the western basin of Lake Erie and the River Raisin (Fig. 1), one of its inflowing rivers. The River Raisin, a moderately-sized river which discharges 6–70 $m^3 s^{-1}$, is situated in an industrial–agricultural region whose lower drainage basin is composed of clay-rich soils. The Monroe Harbor, at the mouth of the R. Raisin, is one of the more heavily polluted regions of Lake Erie. It was chosen by the Environmental Protection Agency for an investigation of the loading, transport and fate of toxic substances as well as their effect on the ecology of the region. The results from this study are to be used in modelling the transport of toxic substances (e.g. PCB's).

Samples were collected by box coring in May 1984. Percent organic matter was determined by the Walkley-Black procedure and cation exchange capacity by the ammonium acetate method (Page et al. 1982). Particle sizes were obtained by treating the sediments with H_2O_2 and seiving to determine the size fraction 53 μm or larger and by a particle sizer employing laser diffraction light scattering (Malvern Instruments) for the smaller

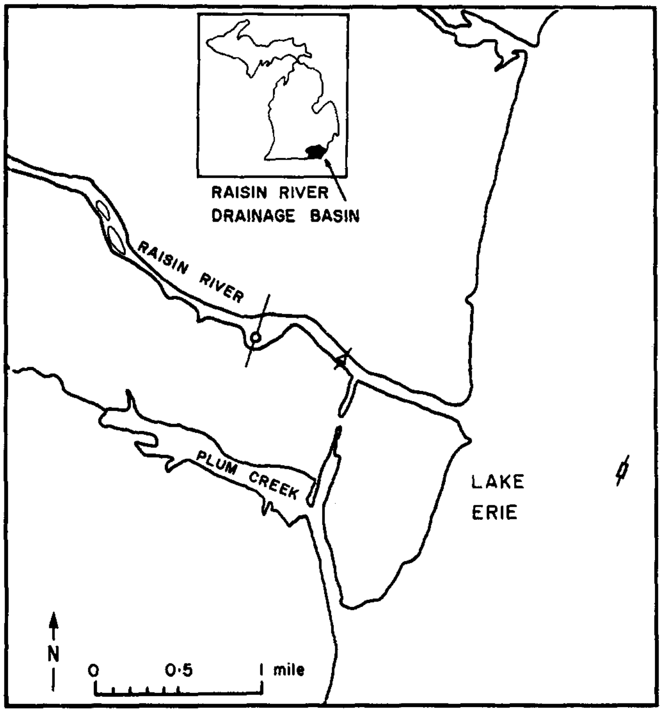

Fig. 1. Map of the River Basin as it flows into Lake Erie. Site 1 (○), site 2 (△), site 3 (||).

fraction. Percent water content of the deposited sediments was determined by sampling a well-mixed sediment suspension (step 1 in preparing the sediment bed, see following), letting it settle for 2 or 8 days, removing the overlying water, and determining the percent water content from the weight of wet and dry sediments. The sediments were dried at an oven temperature of 100–105 °C.

Calibrations

Experiments were performed in an annular flume with a rotating lid (Fukuda & Lick 1980). The flume is 2 m in diameter; the annulus is 0.15 m in cross-section and 0.21 m high. The flume was calibrated using a one-dimensional laser–Doppler velocimeter (LDV) in backscatter mode to quantify the relation between shear stress and the rotation rate of the lid. Because velocity measurements using laser–Doppler velocimetry are nearly impossible with even moderate particle concentrations, calibrations were made without sediments in the flume.

Previous calibrations by Fukuda (1978), using a smaller flume, had shown that shear stress varied across the flume as a function of the radial Reynolds number. He concluded that reducing the variations in radial Reynolds number (i.e. the variations in azimuthal velocity across the flume) would reduce the variation in shear stress. In consequence, we performed our calibrations with three different water depths, 5.1 cm, 7.6 cm, and 10.2 cm, to determine if variations in velocity and shear stress depended on water depth.

Shear stress, $\tau = \rho\mu^2{}_*$ where ρ is density and u_* is the friction velocity, was calculated from the equation valid for flow over smooth surfaces:

$$u_z = (u_*/\kappa)\ln(zu_*/v) + 5.56 \tag{1}$$

where u_z is horizontal velocity at a height z, v is kinematic viscosity, and κ is von Karmon's constant (Schlichting 1968). To solve for u_*, u_z must be measured within the logarithmic boundary layer. To determine the height of the logarithmic boundary layer, we made vertical profiles of azimuthal velocity (Fig. 2). The logarithmic layer is the region where the velocity changes linearly with the logarithm of height; in this figure the region extends from ca. 0.15 to 0.5 cm above the bottom. The viscous sublayer is the region below it. The presence of a viscous sublayer justifies using the above equation for smooth flow to solve for shear stress. We observed a viscous sublayer in every vertical profile obtained. A viscous sublayer occurs when the roughness Reynolds number, $Re_k = k_s u_*/v$, where k_s is the roughness height, is everywhere less than 5 (Schlichting 1968). The bulge in the velocity profile near 1 cm depth indicates the presence of an Ekman layer due to the rotation of the fluid; the mixed layer extends from approximately 2–4 cm, and the region above this is affected by the shear stress from the rotating lid, which in this case was 5.1 cm above the substrate. The vertical position of the logarithmic layer was determined for 5 different rotation rates of the lid at a distance of 3 cm from the inside of the outer wall of the flume and occasionally at distances of 8 or 10.5 cm; subsequently a horizontal transect across the flume was made at a height determined to be within the logarithmic layer and shear stresses were computed using the above equation.

We observed that the variations in velocity across the flume were least when the lid was positioned at a height of 7.6 cm above the substrate, and maintained a water column 7.6 cm in depth in our experiments with sediments.

We were able to use these calibrations even with sediments in the flume because the small grain size of the sediments (Table 1) ensured that Re_k is always less than 5. The roughness height is approximated by the height of

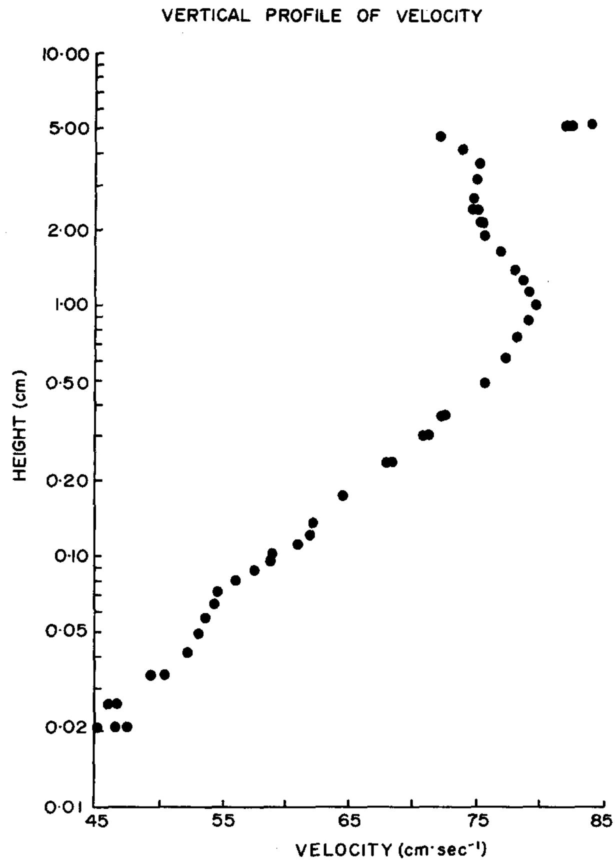

Fig. 2. Vertical profile of velocity measured 3 cm from the outer wall of the flume. The lid was 5.1 cm from the bottom and the period of rotation of the lid was 4.8 s. The logarithmic layer was assumed to begin when $u_* z \nu^{-1} > 30$.

protrusions (i.e. sediment particles) in the boundary layer. However, if entrainment caused the sediments to be scoured unevenly or to form waves, these calibrations would be invlid. We observed scouring occasionally but only at the highest stresses. An additional problem could arise if drag reduction occurs when clay sediments are suspended in freshwater (Gust 1976); the importance of this problem has not been resolved (Fukuda & Lick 1980; Fukuda 1978; Lavelle et al. 1984).

Horizontal transects of shear stress for four periods of rotation of the lid are presented in Fig. 3. Stresses varied by a factor of two at each rotation rate, but the range was considerably more at the higher stresses. An average value of shear stress was obtained by integration across the flume to the last position at which shear stress could be obtained due to interference from

Table 1. Percent organic carbon, cation exchange capacity (CEC), and percent by weight of particles finer than the given particle diameters for samples from the three sites.

	Size	Sites		
		1	2	3
% Organic carbon		3.7	2.8	3.0
CEC (meq. 100 g^{-1})		18.3	15.1	10.6
Weight % finer				
	250	98.8	99.7	92.6
	149	96.1	98.7	80.9
	90	9.10	95.3	75.0
	53	86.3	88.7	70.1
	33.7	82.4	83.0	68.5
	23.7	77.5	74.7	66.0
	13.6	62.0	59.5	57.8
	8.2	45.0	46.6	45.2
	5.0	20.3	30.4	23.6
	3.0	8.1	17.4	8.3
	1.9	1.9	6.5	1.8

CEC was determined from the mean of two replicates. Size discrimination for particles 53 μm or larger was by seiving, the size distribution for the smaller particles was with a non-destructive particle sizer using laser diffraction.

refraction for the LDV. In an attempt to more accurately average the shear stress ($\bar{\tau}$) given its radial variation, we computed $\bar{\tau}$ with the equation

$$\bar{\tau} = \frac{1}{A} \sum_{i=0}^{n} \tau_i \mathrm{d}A(i)$$

where A is the surface area and n is the number of measurements of τ. The values of stress at the boundaries were obtained by fitting the curve (Fig. 3) by eye. We did this computation at the two higher shear stresses and found the difference between the two procedures was only 3%.

If the magnitude of secondary motions (velocity in the radial direction) is sufficient, they will contribute to the boundary shear stress. Dye experiments by Fukuda (1978) showed these motions occur, but he concluded that they are minor because he couldn't distinguish the radial velocity component from the azimuthal. Deardorff & Yoon (1984) performed extensive radial and azimuthal velocity measurements in an annular flume comparable in dimensions and operating principle to ours. Their data support Fukuda's contention that the contribution of the radial velocity to the bottom shear stress is minor, since, in measurements near the density interface in their flumes, the ratio of the radial velocity to the azimuthal velocity is everywhere

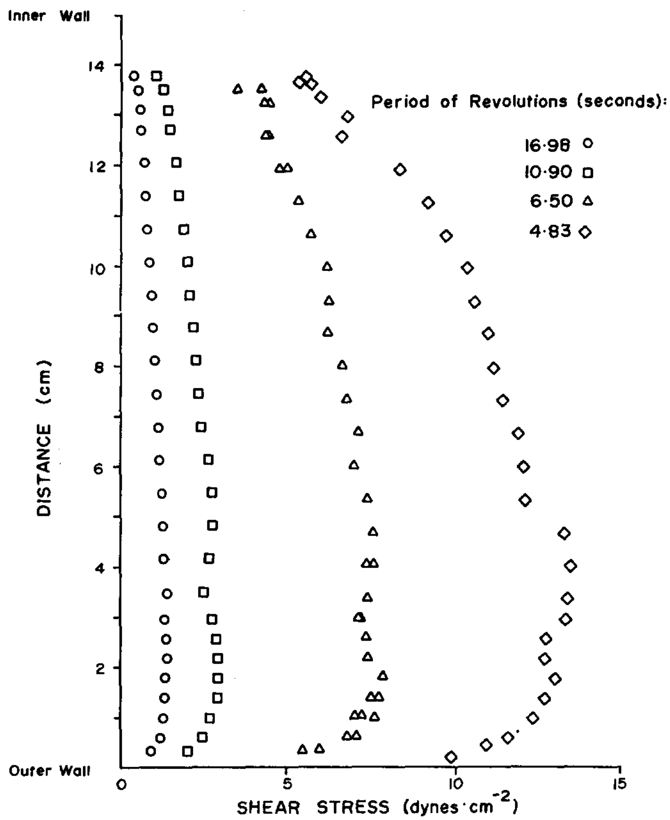

Fig. 3. Horizontal transect of shear stresses from the inner wall to the outer wall of the flume for four periods of revolution of the lid.

less than 0.1. Further evidence for similarity of behavior between their flumes (operated in their mode 1) and ours is that we both observed 35–40% reductions of turbulent intensities, u'^2, in the mixed layer compared to the logarithmic layer. These reductions in turbulence in the mixed layer, when considered in the force balance of the flume, attest to the importance of the secondary motions to the overall circulation (Deardorff & Yoon 1984). The circulation induced by the secondary motions is inward near the bottom, upward near the inner wall of the flume, outward near the upper boundary, and downwards near the outer wall and serves to mix materials within the flume (Deardorff & Yoon 1984).

Experimental protocol

The goals of the experiments were to determine entrainment rates, concentrations of sediment at steady state, and the total mass of material that could be eroded from the sediment bed. Measurements were performed using shear stresses typically found at the sediment–water interface and were conducted using sediment beds of two different shear strengths as determined by the length of time since previous resuspension. We present entrainment rates for two different time periods: the first 30 s and the first hour. We use the results from the initial period to compare our results with those of other workers; results for the first hour are more useful for numerical models.

The first step of an experiment was to prepare the bed. Sediments were wet seived through a 500 μm Nytex screen and introduced into the flume as a well-mixed slurry. The proportions of tap water and sediment were adjusted to give a sediment height of approximately 6 cm and a water height of 7.6 cm after settling. At this water level, bottom shear stress had the least variation radially across the flume. The sediments from each site remained in the flume throughout each phase of the experiments. On the first day of an experiment, the sediments were mixed into the overlying water to create a homogeneous slurry first by manual stirring and then by rotating the lid at a speed sufficient to generate a stress at the bed of 12 dyne cm^{-2}. The sediments then settled to create what is known as a deposited bed (Mehta et al. 1982), analogous to a bed formed in a lake after sediments are resuspended by storms and subsequently deposited during calmer periods. In such a bed the bulk density and shear strength of the sediments is least at the surface and increases with depth (Mehta et al. 1982). Although we did not test the physical properties of the bed, we do present values of cation exchange capacity which can be used to predict bed shear strength (Krone 1983). We allowed deposition to occur for 2 or 8 days to simulate the periodicity of storms on the Great Lakes.

We ran two types of experiments. In the first, which we call a single stress experiment, the applied shear stress remained constant throughout the course of an experiment. From these experiments, we can compute initial and hourly entrainment rates, steady state concentrations and the total mass of sediment which could be entrained. During an experiment, we determined initial concentration before applying the shear stress, then rotated the lid at a rate that caused the desired shear stress. We repeatedly sampled the water in the flume using a piece of tubing inserted into the side of the flume. From these samples we determined concentrations of suspended matter gravimetrically using Millipore HA 0.45 μm filters and expressed the results as mg dry weight per unit volume. Entrainment rates were determined using the expression $E = h(C_t - C_0)/\Delta t$ where h is the height of water overlying the sediments, C_0 is the concentration at the beginning of the time interval Δt, and C_t is the concentration at the end of the time interval Δt. Initial entrainment rates were computed for the first 30 s; hourly entrainment rates for the first hour. C_0 is the concentration in the overlying water before the shear stress was applied.

To find the total mass of sediment that could be entained, we gradually replaced the water overlying the sediments with clear water after steady state had been attained. We continued replacing the water until the concentration of particles was similar to that at the beginning of the experiment or until it no longer decreased, with the expectation that no further material would be entrained once these criteria were met. At this time, we computed the total mass entrained as the sum of the mass of sediment that remained suspended in the flume and the mass of sediment in the overlying water which we had collected. However, to test whether further entrainment occurred, we maintained the shear stress at the sediment-water interface for another 4–6 h after we had stopped replenishing the water and computed the entrainment rate for this final period. Any material entrained during this test was not considered to be part of the total mass entrained.

We called the other type of experiment a multi-stress experiment. The sediments were exposed in a stepwise manner to four shear stresses; a higher stress was applied after steady state was reached at the previous stress. From these experiments, we could determine steady state concentrations of suspended sediment and entrainment rate for the first hour. Experiments conducted by Tsai & Lick (1985) and Lee et al. (1981) showed that steady state concentrations at a given shear stress are approximately the same in multi-stress and single-stress experiments.

The method of preparing a sediment bed in the laboratory is critical. When field measurements of turbidity have been contrasted with turbidities predicted from models whose data on entrainment rates were obtained from experiments done comparably to ours, results have been comparable and validate the laboratory procedures we follow (Sheng & Lick 1979; Paul et al. 1982; Lick & Kang 1987).

Results

Entrainment experiments were performed on sediments from two sites in the River Raisin (1 and 2) and one nearshore site (3) from the Western Basin of Lake Erie (Fig. 1). Particle size distribution, percent organic matter and cation exchange capacity are presented in Table 1. Particles were predominantly in the size range of silts and clays (i.e. 53 μm in size or less) although the sediments from the lake were somewhat sandier. X-ray diffraction of the sediments from site 1 showed them to be comprised of chlorite, kaolinite, illite, and possibly a small amount of smectite. Cation exchange capacities (CEC) for samples from all three sites are typical of values found for illite, chlorite, and kaolinite clays (Lerman 1979). Because of the similarity in percent organic carbon and CEC at the three sites, we do not expect great differences in surface aggregation and consequent resistance to shear stress at the sediment-water interface. Krone (1983) has suggested CEC is related to Bingham shear strength of the sediments; this measure should be a good predictor of the resistance of a bed to shear stresses.

Variability at one site

The sediments from site 1 were used to examine physical mechanisms and biological and chemical processes affecting entrainment. The results obtained from these sediments will be described first. We then describe the differences observed in sediments from the three sites.

After a deposition period of two or eight days, sediments were exposed to shear stresses ranging from 1 to 12 dyne cm^{-2}. The general features of our experimental results are illustrated in Fig. 4, which shows that at low shear stresses entrainment did not occur or was minimal, but that at moderate and high stresses, entrainment proceeded rapidly, reaching a steady state within 3 h.

The differing response to shear stress of sediments that have deposited for two and eight days is shown in Fig. 5. Entrainment rates from sediments that have been resuspended recently are considerably higher than those that have not been resuspended for nearly a week. Similarly, the length of time between resuspension events has a pronounced effect on the total mass of sediments that can be entrained at each stress (Table 2).

By chance, a population of tubificid worms had survived in the sediments from site 1 and, by the time we ran our experiments with eight days of deposition, had reached densities above the sediment–water interface of 50–670 m^{-2}. The worms were not observed in the two day deposition experiments with sediments from site 1, nor were they present in the sediments from sites 2 and 3. Because the chemical and biological interactions that occur at the sediment-water interface can effect entrainment by either stabilizing or destabilizing the bed, we made an assessment of this effect by varying the degree of oxygenation of the water column and thus stimulating the activity of the worms and altering the chemical conditions at the interface. We oxygenated the water column by bubbling in air through a hose and created deoxygenated conditions merely by reducing atmospheric exchange by placing the lid on top of the water after initially preparing the bed and then keeping it there for eight days. Oxygen concentrations were

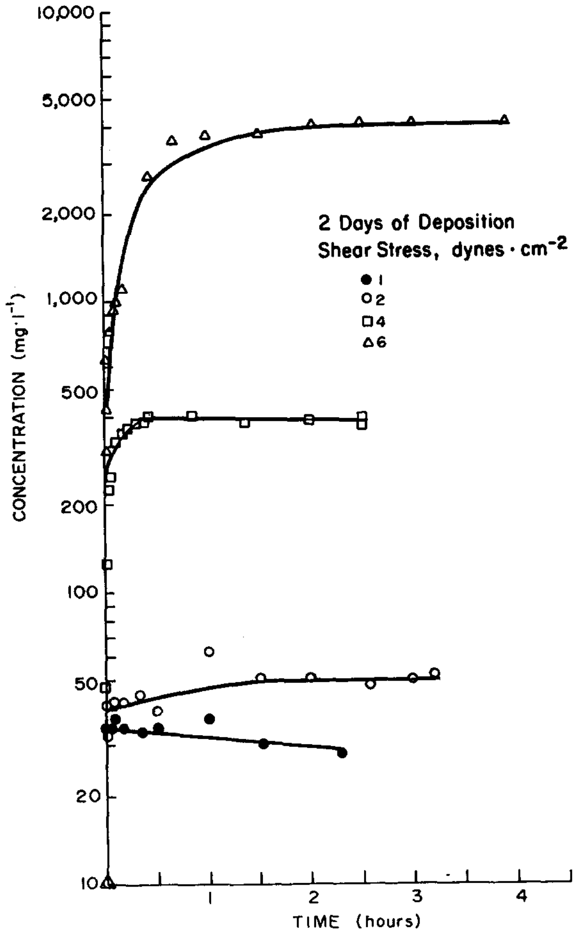

Fig. 4. Concentration of suspended matter plotted against time for 4 shear stresses and 2 days of deposition of the sediments at station 3. The percent water content was ca. 77% at the surface; the integrated value was 72%.

measured with a polarographic oxygen electrode, and the water was considered deoxygenated at concentrations less than 0.4 mg L^{-1}. Oxygenating the water column did not guarantee a change in the redox state of the sediments. We determined the effect of the treatment on the sediments by changes in their color. In only one experiment did the sediments develop the reddish cast indicative of oxygenated conditions at the interface; in the other three experiments the upper 2 mm of sediments were gray-brown as they were in experiments from site 1 with two days of deposition, and from sites 2 and 3. In one experiment a dense cover of flocculent material formed at the sediment–water interface possibly as the result of a shift from

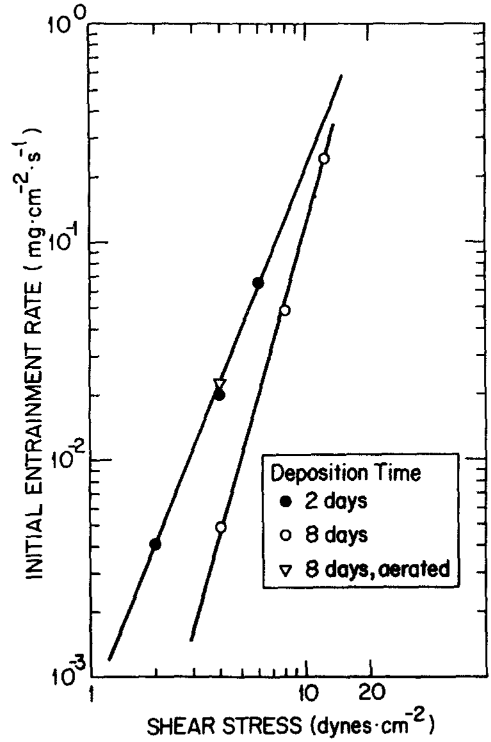

Fig. 5. Log–log plot of initial entrainment rates versus shear stress at site 1. The lines were drawn based on the regression equations in Table 3.

Table 2. Total mass per unit area (M_T, mg cm^{-2}) of sediment entrained, ratio (R) of total mass entrained to the mass entrained at steady state, and entrainment rates (E_f, mg cm^{-2} s^{-1}) during the final period as a function of shear stress (τ, dyne cm^{-2}) and two or eight days of consolidation. Sediments are from site 1.

τ	M_T		R		E_f	
	2 days	8 days	2 days	8 days	2 days	8 days
1	–		–		0	
2	0.60	–	1.57	–	0	0
4	3.21	1.71	1.05	1.02	0	7.4×10^{-6}
6	46.09		1.45		1.4×10^{-4}	
8		9.48		1.09		9.2×10^{-6}
12		56.25		1.05		8.08×10^{-4}
4+		5.65				

The + indicates that the sediments were reddish brown. By definition, the total mass does not include the mass entrained during the final flushing period.

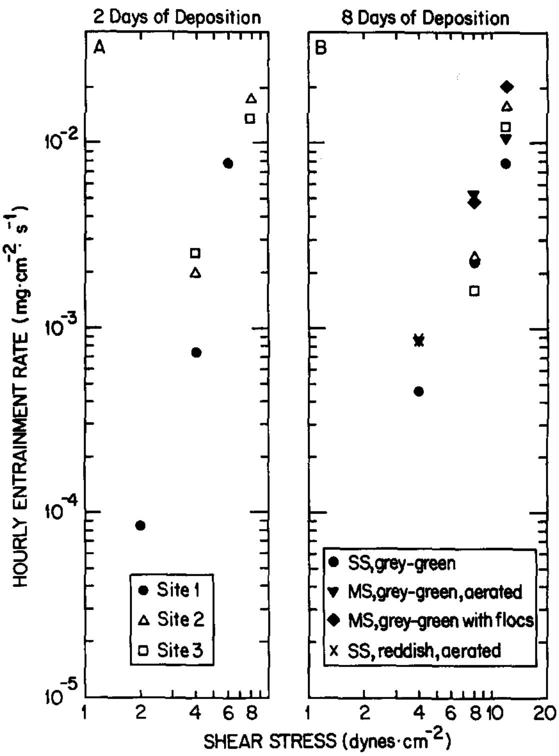

Fig. 6. Log–log plot of hourly entrainment rates versus shear stress at all three sites for 2 and 8 days of deposition. In panel B, the symbols for sites 2 and 3 are as in panel A and the key refers only to experiments at site 1. For site 1, ms and ss indicate multi-stress and single stress experiments respectively, the colors given refer to the color of the sediments at the sediment–water interface with only reddish sediments assumed to be oxygenated, and aerated indicates that air was bubbled into the water column. The equation for hourly entrainment rate for 2 days of deposition is $E_{hr} = 4.45 \times 10^{-6}\tau^{4.01}$ where the units are as in the figure. $r^2 = 0.97$, and the predicted value of E_{hr} is 1.88×10^{-2} mg cm^{-2} s^{-1} at 8 dyne cm^{-2}, (site 1).

oxygenated to deoxygenated conditions. Such flocs are common at the sediment-water interface in Lake Erie in the summer (WL, pers. observ.).

The experiments in which the sediment-water interface was not oxygenated show the variability in results from one sediment (Figs. 6 and 7). Steady state concentrations and entrainment rates for the first hour varied by as much as a factor of three.

The sediments became oxygenated only in a single stress experiment at 4 dyne cm^{-2}. Initial entrainment clearly was higher than it was at the same stress in the other single stress experiment; in fact it was comparable to that at 4 dyne cm^{-2} and only two days of deposition (Fig. 5). The total mass entrained was not only higher than in the other experiment but was also

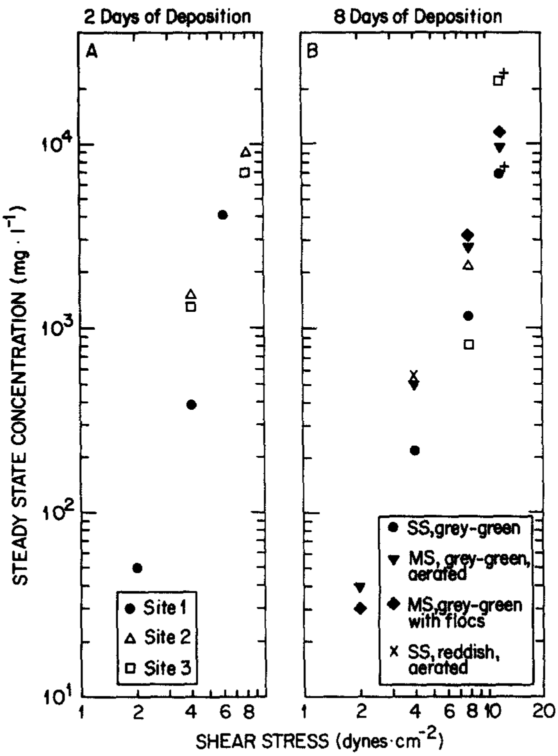

Fig. 7. Log–log plot of steady state concentrations of suspended matter versus shear stress for all three sites. The + indicates that in 2 of the experiments steady state was not attained at 12 dyne cm^{-2}. The description of the symbols at site 1 is the same as for Fig. 6. The equation for steady state concentration, site 1, deposition period 2 days, is $C_s = 2.82\tau^{3.90}$ where the units are as in the figure. $r^2 = 0.96$, site 1, and the predicted value of C_s at 8 dyne cm^{-2} is 9336 mg l^{-1}.

higher than when the sediments had consolidated for two days (Table 2). When the results are contrasted with those at 4 dyne cm^{-2} from an experiment in which the water column was oxygenated but the sediments maintained their gray-green cast, the steady state concentrations and hourly entrainment rates are nearly identical (Figs. 6 and 7). The higher oxygen levels in the overlying water may have stimulated the tubificid worms, causing more burrowing and a decrease in the compaction of the surficial sediments. However, given the variability in entrainment from site 1 seen at 8 and 12 dyne cm^{-2}, these results from 4 dyne cm^{-2} may be another expression of the variability of the system.

A power law fit was obtained to relate shear stress to initial entrainment rate (Table 3) determined from the single stress experiments and to both steady state concentration and hourly entrainment rate (Table 4).

Table 3. Initial entrainment rates for sediments from the western basin of Lake Erie.

Reference	Sediment location	% Water content	Days of deposition	Initial entrainment rate, $E = \alpha\|\tau\|^n$			
				α	n	r^2	#
This study	River Raisin, site 1	77,* 72†	2	7.01×10^{-4}	2.5	0.996	3
This study	River Raisin, site 1	73–75,* 67–71†	8	3.43×10^{-5}	3.5	0.997	3
Lee et al. (1981)	Western Basin, sediment 1	76–78	2	6.59×10^{-6}	3.2	0.99	3
Lee et al. (1981)	Western Basin, sediment 2	76–78	2	1.08×10^{-5}	3.2	0.87	5
Lee et al. (1981)	Western Basin, sediment 3	76–78	2	8.9×10^{-5}	3.0	0.59	5
Lee et al. (1981)	Western Basin, sediment 4	76–78	2	3.04×10^{-5}	2.8	0.88	3

* Surface

† Integrated

In the equation for entrainment rate, τ is shear stress in dyne cm^{-2}, n is an exponent, α is a coefficient with units mg cm^{-2} s^{-1} and r^2 is the coefficient of determination. # indicates the number of observations.

Table 4. Power law relation describing hourly entrainment rate (E_{hr}, mg cm^{-2} s^{-1}) and steady state concentration (C, mg L^{-1}) versus shear stress (τ, dyne cm^{-2}) for site 1 and for sites 1, 2, and 3.

Site	Days of deposition	Hourly entrainment $E_{hr} = \alpha_0 \tau^{n_0}$				Steady state concentration $c = \alpha_1 \tau^{n_1}$			
		α	n_0(SE)	r^2	#	α_1	n_1(SE)	r^2	#
1	8	2.24×10^{-5}	2.51 (0.32)	0.90	9	4.91	3.01 (0.20)	0.96	11
1, 2, 3	8	1.77×10^{-5}	2.59 (0.32)	0.86	13	4.14	3.10 (0.23)	0.93	15

All the experiments performed at site 1 are included in both regressions. The units of α are mg cm^{-2} s^{-1}. In parenthesis are the standard errors for n; r^2 is the coefficient of determination; # indicates the number of observations.

Experiments from sites 2 and 3

Multi-stress experiments were performed on sediments from the other sites in the River Raisin and in Lake Erie. The sediments were grey-green and no tubificid worms were observed. The results are compared with the results from site 1 (Figs. 6 and 7).

Entrainment did not occur at the lower shear stress for which entrainment had occurred at site 1. For this reason, the data from sites 2 and 3 cannot be used in a regression analysis, and variability between sites can only be assessed by comparing the magnitude of entrainment rates and steady state concentrations at comparable shear stresses. For two days of deposition, results are quite similar for sites 2 and 3, but a direct comparison with site 1 can only be made at 4 dyne cm^{-2}, where steady state concentrations were two times less and hourly entrainment rates were three times less. However, when the data from site 1 are extrapolated to 8 dyne cm^{-2}, the results, both for hourly entrainment rates and steady state concentrations, are within 40% (Figs. 6 and 7).

For eight days of deposition the results from sites 2 and 3 varied by as much as a factor of three and, given the variability of results from site 1, could not be distinguished from it.

The power law regressions relating shear stress to both hourly entrainment rate and to concentrations at steady state for all three sites are presented in Table 4.

Discussion

The relation between entrainment rates and bed shear stress

One of the goals of research on sediment resuspension is to determine the factors affecting sediment entrainment and to develop predictive equations based on these factors. The results of our experiments confirm the dependence of entrainment rate and steady state concentrations on shear stress and degree of consolidation of the surface sediments expressed as percent water content (Fukuda & Lick 1980; Lee et al. 1981). It is important to determine a general relationship between these factors and to assess its general applicability. Although linear and exponential expressions have been used to express the relationship between entrainment rate and shear stress (Sheng & Lick 1979; Fukuda & Lick 1980; Mehta et al. 1982), Lavelle et al. (1984) found that a power law relation applied not only to their data from Puget Sound, but also to data obtained from Lake Erie, San Francisco Bay, and the Thames River. We plotted our results to determine the applicability of a linear (not shown), exponential (not shown) and power law relation to describe the relation between initial entrainment rate and shear stress. With only three data points, it is only possible to obtain a suggestion of the more appropriate fit, but over the broad range of stresses we tested, a departure from both linear and exponential relations was evident. The applicability of the power law is evidenced in Fig. 5. We also examined the plots of shear stress versus the logarithm of initial entrainment rate in Fukuda and Lick (1980), Lick & Kang (1987), Lee et al. (1981), and Tsai & Lick (1985). When their results included experiments with shear stresses greater than 4 dyne cm^{-2}, entrainment rates at the higher stresses tended to be less than would be predicted based on an exponential relation.

We suggest that the initial near exponential rise is not maintained because of the non-uniformity of particle size distributions with depth and because of the increase in bed shear stress with depth.

Because the power law relation appears to have general applicability, we present the results of the regression of initial entrainment rates versus shear stress for our experiments in Table 3 along with that for experiments by Lee et al. (1981) for four sediments from different regions of the western basin of Lake Erie which had not been analyzed by Lavelle et al. (1984). All had the same percent water content.

The exponent (n) in the regressions using Lee et al's (1981) data only varied from 2.8 to 3.2. We calculate a similar value, 2.5, for the same percent water content. This confined range contrasts highly with the range presented in Lavelle et al. (1984) for 5 sediment types, n ranged from 1.2 to 5. In fact, when Lavelle and Mofjeld (1987) contrasted a range of sediment types from dredge spoil to unconsolidated sediment, n ranged from 0.23 to greater than 10. Some of the spread can be explained by a change in the water content of the surficial sediments; as the percent water content at the surface for the Lake Erie sediments increased in 5 steps from 74–75% to 81–82%, n increased from 1.2 to 5. We do not observe the same pattern for our experiments with two different percent water contents, but given that these regressions are based on three data points each, it is likely that the two slopes are statistically indistinguishable. Similarly, the regressions from the Lake Erie data are based on at most 5 data points and are often biased with most of the data for shear stresses less than 2 dyne cm^{-2}.

The value of the coefficient α in Lee et al.'s (1981) experiments ranges from 7×10^{-6} mg $cm^{-2} s^{-1}$ to 9×10^{-5} mg $cm^{-2} s^{-1}$. The sediment with the highest coefficient had the highest entrainment at lowest stresses; it had the largest percentage of fine grained material. With our data, we compute a value of α of 7×10^{-4}, one order of magnitude higher. This is not surprising since Lee et al. added a second step to their procedure for settling the bed which involved resuspending the top 0.5 cm of sediments after initial settling. This step reduced the probability of the very uppermost layer of sediments being comprised of the smallest sediment size fraction. When Lee et al. compared the two methods, they found the extra step causes an order of magnitude decrease in steady state concentrations. These results indicate that for the same percent water content, particle size distribution near the sediment water interface is a key factor determining the coefficient α.

Our results confirm Lavelle et al.'s (1984) finding of the applicability of a power law relation. We conclude that comparable sediment types of the same percent water content at the surface have similar slopes in the relation, but the coefficient α depends upon particle size distribution at the bed. The exponent in the power law expression changes with the percent water content of the surface. Further experiments, with a factorial design, are required to test these conclusions. For these experiments to be useful, the problem of adequately assessing bed shear strength and particle size distributions must be addressed. These characteristics of the bed near the interface optimally would be determined in situ or with carefully taken sediment cores and replicated in the laboratory. As mentioned, we use percent water content as an indication of bed shear strength; bed shear strength is a difficult parameter to measure given the weakness of deposited beds (Mehta et al. 1982). An additional parameter, cation exchange capacity, may prove useful in the analysis as it is a chemical measure of the strength of the bonds likely to form between sediment flocs and thus provides a measure of potential bed shear strength. The advent of in situ particle sizers based on laser-diffraction (Weiner 1973; Bale & Morris 1987) permits rapid, nondestructive sizing of particles. Inclusion of these other two key physical variables in the power law relation will permit prediction of entrainment from key sediment properties.

It will be much more difficult to parameterize different properties at the sediment–water interface due to different chemical and biological conditions. For example, in many eutrophic lakes, changes in the anoxia of the sediments, with potential changes in bonding between particles, occur seasonally. The biological organisms which are present in the sediments and their activity change concommitantly. An alternate approach to parameterizing the many chemical and biological factors is to incorporate the variability which they induce into the mathematical expression describing entrainment. In Table 4, we present the power law relation between shear stress and hourly entrainment rate and between shear stress and steady state concentrations. We have combined data from the different experiments in order to assess the variability in the regression as expressed through r^2, the coefficient of determination. At site 1, when the data for hourly entrainment rates from the four experiments is considered together, all but 10% of the variance is explained by the regression. When the data from all the experiments at all three sites is considered, all but 14% of the variation is explained by the regression. When steady state concentrations are considered, even more of the variation is explained by the power law relation. This variation is manifested as a three-fold difference in the magnitude of concentrations or entrainment rates at each shear stress. That so much of the variation in entrainment for three nearby sites can be attributed to shear stress and percent water content alone is encouraging.

For this analysis to definitively show the observed variability was due to different conditions, replication of experiments with identical conditions would have been appropriate. We attempted to do this but were not successful. For instance, flocs formed at the sediment water interface on one of our experiments with anaerobic conditions but not at the other. However, in experiments with sediments from Long Island Sound, one of us (CHT) obtained steady state concentrations for three different shear stresses that differed by at most 25% in triplicated experiments without organisms and at most 14% in duplicated experiments with organisms. Because of these results, we attribute the observed variability in entrainment of sediments from the R. Raisin to differences in properties of the sediments from different sites and to differences in experimental treatments for the sediments from site 1.

Limitations on the total mass that can be entrained

An assessment of the total mass of sediment that can be supplied to the water column is valuable when modelling sediment transport. It is relatively easy to measure the steady state concentrations in laboratory experiments, but because of deposition, we questioned whether steady state concentrations might be underestimates of the total mass that can be entrained. However, when we contrasted the two (Table 2), we found only a slight difference. The extremely low entrainment rates at all but the highest stresses (Table 2) during the final time period when we had stopped replenishing the overlying water verified the near equality of steady state concentration and total mass that can be entrained. In fact, the measurable entrainment rates at the high stresses were at least two orders of magnitude less than the initial entrainment rates. These results indicate that the quantity of material that can be eroded at a given shear stress is limited, a result also obtained by Lick & Kang (1987).

We attribute the limitation to three factors. One, the bed increases in consolidation with depth; this increase results in more interparticle bonds. Evidence for the consolidation is the smaller percent water content for the integrated than the surface sample (Table 3). Two, the particle size distribution becomes skewed towards larger particles deeper in the bed because they settle out first during bed preparation. Three, particle size distributions at the surface change over the course of reaching steady state as the larger particles that are entrained are the ones most likely to be returned to the sediment surface. These three factors all make the bed more resistant to erosion with depth. In contrast, if the bed shear stress and particle size distribution are uniform with depth, the total mass of cohesive sediments that can be entrained does not reach a limit at each shear stress (Mehta et al. 1982). Certainly in field situations, unless organisms mix the sediments and erase the differences in size distribution due to settling and in shear strength due to consolidation, the quantity of cohesive sediments that can be entrained at a given shear stress can be expected to be finite. We conclude that a determination of steady state concentrations is an adequate assessment of the total mass of sediment that can be entrained.

Summary

Laboratory experiments can be used as a basis for mathematical models to predict entrainment. Sediment resuspension has been shown to be dependent on shear stress, percent water content, particle size distribution and sediment type.

A power law relation between entrainment rate or steady state concentration and shear stress at the sediment water interface describes the observations more accurately than an exponential fit. At present, entrainment rates used in models have been site specific and have not included any of the variability due to changing biological and chemical conditions. We observed that this variability is not excessive; entrainment rates and steady state concentrations varied only by a factor of three for one sediment type exposed to different degrees of oxygenation. In fact, we observed the same degree of variability for sediments from three different, through nearby sites, despite the presence of active turbificid worms at one of the sites. Lee et al. (1981) and Lick & Kang (1988) observed 6-fold and 4-fold differences between sites with comparable sediment types. This variability must be incorporated into the modelling of entrainment. We observed that it caused at most 14% of the variation in a power law expression describing entrainment.

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