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Dredging Research Technical Notes

Size Dependence in Fine-Grained Sediment Transport

Purpose

This technical note examines particle size effects on sediment transport, describes a method of analysis that can be applied to identify transport paths, and presents case study results for New Bedford Harbor—a system previously studied in relation to dredging and disposal of contaminated sediments. It will be shown that, for systems with substantial silt in transport, dispersed particle size is an appropriate index for transport behavior and a suitable basis for numerical transport modeling.

Background

Under DRP Technical Area 1, Work Unit "Cohesive Sediment Processes," a number of fine-grained sediment transport processes are being studied. Since resources are limited, priority is given to processes most critical to managing dredged material disposal sites, and erosion processes are the area of focus for the work unit. However, predicting long-term transport of materials (an important study area for Technical Area 1) involves suspended transport of both cohesive clays and less cohesive silts. Suspended fine-grained, cohesive particles aggregate so that their transport characteristics do not necessarily depend on dispersed particle characteristics.

An open question, then, is whether dispersed fine-grained particle size has any relationship to transport characteristics. The question is relevant to modeling, which must numerically transport conservative sediment properties and imitate important sediment behavior. Dispersed particles are an intrinsic character of the material, at least over short periods of time, and affect the characteristics of fine-grained suspensions and bed sediments in complex ways. The question is also relevant to sorting of sediment size by field transport processes, and to whether size signatures can be used to trace transport paths in the environment.

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Role of Fine-Grained Sediment Size in Transport Processes

Dispersed particle size can be important to the behavior of fine-grained sediments under some conditions. However, particle size effects on fine-grained sediment transport processes have not been extensively studied by experimentation, nor widely reported in conjunction with laboratory or field transport observations. Fine-grained sediments (here taken as those with dispersed particle diameters less than 0.074 mm) are not only transported as individual particles but as cohesive particle aggregates or flocs. The strength of cohesive, fine-grained sediments depends on their electrochemical properties as well as their physical state. At progressively smaller particle sizes, cohesion has a greater effect on particles than particle mass because of the relative dominance of surface area and clay mineral content. The particle size limit of cohesive sediments, often associated with clays, is not distinct, and can depend on the presence of organic matter and dissolved salts, as well as sediment mineralogy. Descriptions of some observed grain-size effects on fine-grained transport are given in the following paragraphs.

Suspended Transport

Estuarine suspended transport can have a dominant impact on the maintenance requirements of navigation channels. Upstream suspended material transport toward the estuary head is a common feature of low- to moderate-freshwater inflow systems. However, a number of sediment transport processes can operate, depending on the conditions present. Many estuaries display upstream fining and sorting in fine-grained (silts and clays) bed sediments. Only a few studies have correlated suspended material fluxes and particle size spectra (distributions). Kranck (1979 and 1981) has studied the variability and distribution of suspended particle concentrations and size spectra in the St. Lawrence Estuary, and the size spectra and flocculation in the Miramichi Estuary in Canada.

The spatial distributions of various suspended particle size fractions and transport rates in the Wadden Zee, Netherlands, were reported by Postma (1967). He presented a theory explaining landward transport in the presence of landward-decreasing maximum tidal currents, not depending on velocity asymmetry, that involved either of two lags. One lag related to the response time for a suspension to settle, based on its vertical distribution and settling velocity; the other lag was the difference between deposition and erosion critical shear stresses. Since the lags vary with particle size for silts, landward accumulation may be different for different particle sizes. The coarser suspended size fractions of the Wadden Zee showed no concentration effect, the silt fractions showed the greatest effect, and the fine silts showed a moderate effect, although no distinct optimum size was observed with respect to transport.

Aggregate Settling

Settling rates affect the vertical distribution and transport of sediments. Kranck (1980) conducted detailed settling experiments on aggregated and disaggregated marine silt-clay mixed suspensions, and showed how dispersed particle size related to the settling of aggregated cohesive sediments. Settling tests were conducted on 15-cm-deep aggregated and disaggregated suspensions using 3 percent NaCl and 2 percent Calgon solutions, respectively.

Results indicated that suspended aggregates were made up of all particle sizes present, and during the aggregate settling phase, concentrations decreased in all discrete size classes. Kranck proposed that each aggregate contained a representation of the dispersed particle spectrum. However, the coarser end of the spectra decreased fastest, and the spectra modes (initially about 0.016 m) became progressively finer and reached the 0.001-mm limit of analysis during the 12-hr duration of the tests. Aggregation had a significant effect on settling, and Kranck's tests showed that the effect extended well into the silt-sized range.

In the disaggregated suspensions, only the coarsest fraction decreased from the withdrawal level at any given time during the tests, indicating that discrete particle fractions settled independently according to particle size.

Deposition

Deposition can vary widely for fine-grained sediment. Under conditions of a sufficiently wide particle size distribution, fine-grained sediment suspensions sort by particle size during deposition. Both settling velocities and critical shear stresses for deposition vary sharply between clay and silt fractions. While a well-sorted cohesive suspension will steadily deposit in a flow below a critical shear stress, a suspension of silts and clays will partially deposit to a steady-state constant suspension concentration level. At a given shear stress level, the particles remaining in suspension are generally finer than those which deposit (Mehta and Lott 1987).

Erosion

Particle size has not been found to be well correlated to the erodibility of cohesive fine-grained sediments in general. Krone (1963) described how individual suspended particles first formed primary aggregates and then formed successively higher order aggregates under various shearing conditions. Aggregate strength and density varied inversely with the order of aggregation. Thus, aggregate strength has the most pronounced effect on the erodibility of recently deposited sediments, rather than particle-size characteristics. However, Dash (1968) and Hunt (1981) found that, for a given sediment mixture, increases in clay content increased the mixture's resistance to erosion, indicating that particle size has an indirect effect on erosion through its effect on cohesion.

Dispersed particle size is most important when sediment size distributions include substantial amounts of both silts and clays. Under these conditions, dynamical sediment behavior can vary widely between particle size fractions, and sorting can occur during settling, deposition, and transport. Therefore, numerical sediment transport models must accommodate varying particle size distributions to accurately describe overall sediment behavior.

Size Spectra Trend Analysis for Suspended Material

A trend analysis was recently adopted to identify temporal and spatial changes in suspended sample size-distributions which might be correlated with transport. McLaren and Bowles (1985) proposed two trends in particle-size summary statistics associated with general transport. Based on a simple transfer function model in which transport is related to size classes, these investigators suggested that the mean, sorting, and skewness of transported sediment grain-size spectra follow progressive trends which indicate direction of transport and sedimentation conditions. Lag deposits formed by the transport process were predicted to have similar trends in size distribution statistics.

Swift, Ludwick, and Boehmer (1972) used a Markov chain model to test assumptions about continental shelf sediment transport systems, and also found progressive sorting of transported and deposited sediments along transport systems. Various input sand-sized distributions and transition probability matrices were tested. Distributions were broken into size classes of differing transport characteristics. Standard deviation tended to decrease, and skewness increased, especially if transport competence declined across the system.

Two statistical trends associated with transport were described by McLaren and Bowles (1985). Case B was defined as progressive fining, better sorted, and skewed more toward larger sizes along a line in the direction of transport. Coarsening, better sorted (a smaller sorting value), and skewed more toward finer sizes in the direction of transport was defined as Case C. Case B is associated with deposition (reduced transport capacity in the direction of transport), and Case C is associated with erosion or winnowing (increased transport capacity in the direction of transport).

Although this technique was proposed for sediments in transport, it has previously been applied only to bed sediments. However, the underlying model was developed without specific assumptions about the mode of transport, and should apply equally well to fine-grained suspended transport. It is critical that samples used in the analysis represent sediment that is subject to transport. Suspended sediment is under transport at the time of its sampling, while bed sediments reflect some earlier transport or, more problematical, some relict transport. Conditions of transport associated with suspended samples can be more easily defined in relation to those of bed material samples.

The size spectra trend analysis is an empirical technique used to identify statistically significant changes in size spectra. Spectra statistics used in the trend analysis were calculated by an extended graphical method in phi units. Sizes were interpolated at 5, 10, 16, 25, 37, 50, 63, 75, 84, 90, and 95 percentiles on cumulative frequency curves, and used to compute means, sorting (standard deviation), and skewness. The method was tested against analytical functions, compared with other methods, and appears to be accurate. It is anticipated that the method minimizes the effects of local variations in experimentally determined spectra as compared with graphical methods that use only three or five points from the spectrum. The method excluded the extreme 5 percent from both ends of the spectrum, reducing the effects of spectra tails on central tendencies as compared to the method of moments. The particle size analysis covered only part of the entire spectrum (0.004 to 0.100 mm), and excluded the portion between 0.00045 and 0.0039 mm. Size spectrum statistics are therefore considered comparative rather than absolute.

Trends in size spectra statistical mean, sorting, and skewness were analyzed by a method similar to McLaren and Bowles (1985). The method tests for finer or coarser, better or poorer sorting, and positive or negative skewness trends along sequences. Eight combinations of changes in the three summary statistics are possible, including Cases B and C described earlier. Every possible pair along the sequence was compared, resulting in a single-tailed, paired analysis of the three statistics. A Z score was calculated for each of the possible eight trends along a line as follows:

$$Z = \frac{x - Np}{(Npq)^{1/2}}$$

where x is the number of pairs in the sequence with the trend, N is the total number of pairs, p is the random probability of the trend (0.125), and $q = 1 - p$. The greater the Z score, the more pronounced the trend. A sequence of at least eight samples, containing 28 total pairs, is required to obtain meaningful results. McLaren and Bowles (1985) indicated that a Z score of 1.65 has only a 0.05 probability of occurring randomly, and a Z score of 2.33 has a probability of 0.01 of occurring at random. However, numerical experiments conducted by the author indicated that a Z score of 3 had a probability of 0.05 for uniformly distributed random sequences of statistics. Thus, a Z score of 3.0 was used as an indication of statistical significance.

Application to New Bedford Harbor

Site Description and Background

New Bedford Harbor is located on the north shore of Buzzards Bay and is the estuary of the Acushnet River. As shown in Figure 1, the harbor is about 6.4 km long from the hurricane barrier to the Saw Mill Dam, the limit of tide and the point of greatest freshwater inflow. The harbor is divided by two artificial constrictions, the hurricane barrier and Coggeshall Street Bridge. The upper harbor has an average depth of only about 1 m mean low water, and bed sediment contaminant concentrations are highest there. The Acushnet River drains 48 sq km, has an average freshwater discharge to the harbor of about 0.85 cu m/sec, and carries relatively little suspended material compared to the tidal flow at the Coggeshall Street Bridge. The mean tide range at New Bedford Harbor is 1.1 m, and the spring range is 1.4 m. Little tidal damping or phase shift appears to occur between the outer and upper harbor areas, or around Buzzards Bay. Current speeds generally decrease upstream, except at constrictions. Surface-to-bottom salinity differences are generally less than 0.5 ppt.

Fine-grained bed sediments in the Buzzards Bay area are composed primarily of chlorite, mica, and minor amounts of quartz (Summerhayes, Ellis, and Stoffers 1985). Clays are mostly illitic. Pruell and others (1990) found that the total organic carbon of the upper 5-cm bed sediments increased steadily from 2.9 percent by dry weight near the hurricane barrier to 12 percent near the location of station 9 (Figure 1), and then decreased sharply farther up the Acushnet River.

Bed sediment characteristics vary widely over the harbor. The clay fraction is nil at the hurricane barrier, but increases rapidly to about 40 percent in the inner harbor navigation project west of Popes Island. Outside the project, the clay fraction is typically 10 percent for the inner and upper harbor areas. Sand fractions are about 30 percent for the inner harbor navigation project, and 30 to 70 percent elsewhere. A small fraction of gravel occurs near the hurricane barrier opening. Bed-surface bulk wet densities are typically 1.5 g/cu cm in the upper harbor, and sediments classify as organic sandy, clayey-silt, or silty-clay.

Suspension Sampling and Measurements

Water samples were drawn by pump, stored in 250-ml plastic bottles, iced down, and analyzed within 7 days. Total suspended material was determined according to a standard nonfilterable solids method using Nuclepore 0.00045-mm pore-size filters. About half of the middepth water samples from stations 3, 5, 7, and 8 were analyzed using a Particle Data, Inc., model 80XY ELZONE particle analyzer. This instrument electronically measures the current displacement of particles as they pass through an orifice and resolves the displacements into 128 channels. Since silt particles dominated bed sediments, a 0.240-mm orifice was used for these analyses,

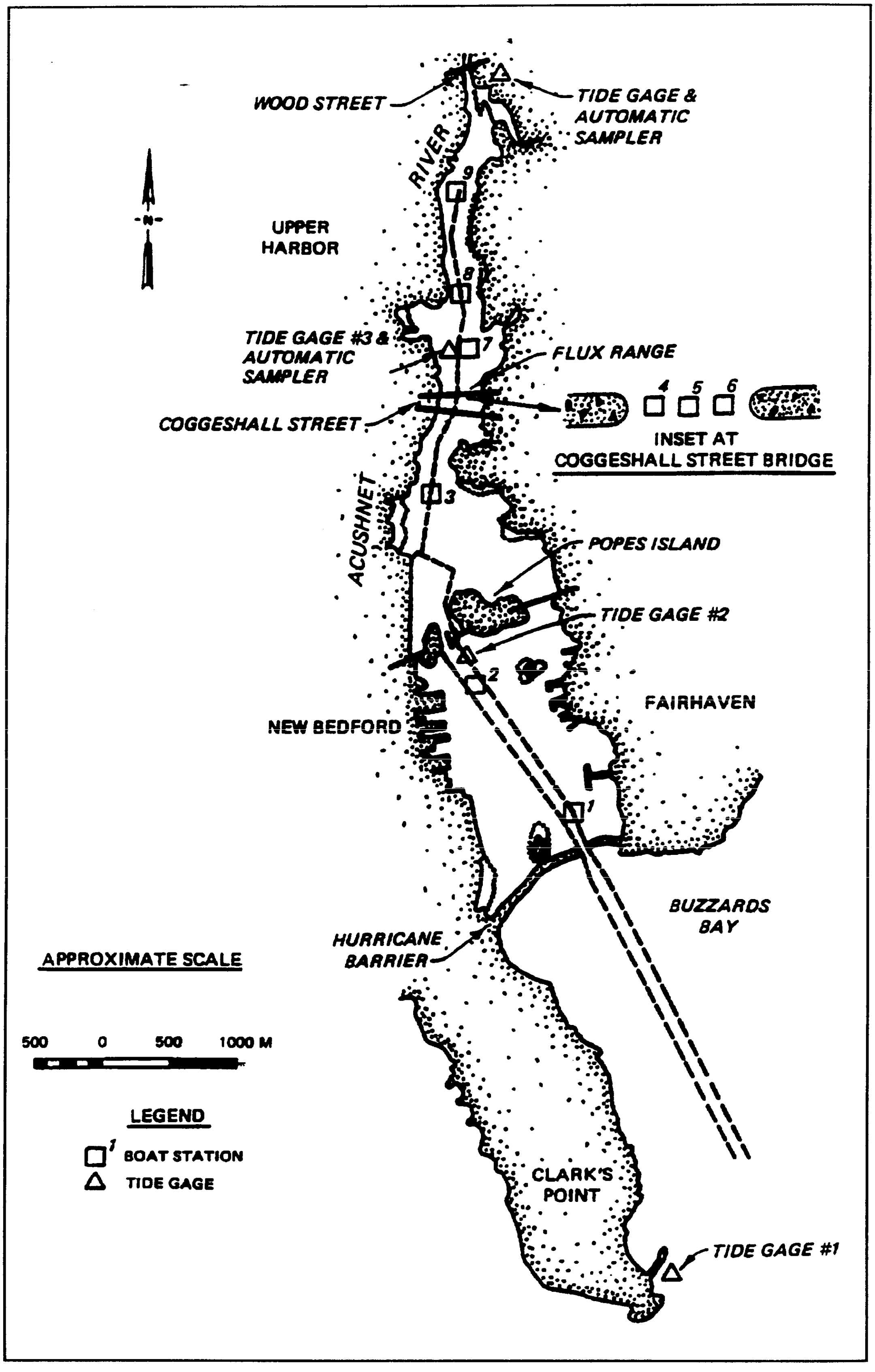

Figure 1. Layout of New Bedford Harbor, showing sampling and gaging stations

providing a size measurement range of 0.0039- to about 0.100-mm equivalent spherical diameter. Analyses were performed on disaggregated samples without removal of any organic component present. The analytic method generally followed the manufacturer's recommendations, and a standard particle analyzer method was used for sediment samples (Plumb 1981). Subsamples were mixed with 100 ml of 1 percent NaCl electrolyte for analysis. Sample particle counts lasted 43 sec, during which 3,000 to 8,000 particles were counted and sized. The particle sizer calculated the total sediment volume analyzed, which was converted into volume concentration.

Laboratory Sediment Tests

Settling, deposition, and erosion testing were carried out on a composite sediment sample from the upper harbor. The composite sample was collected at four locations in the upper harbor using a box corer, and then homogenized for use in a suite of feasibility study tests to assess the behavior of dredged sediments and contaminants in various disposal environments. The composite contained 30 percent sand, 2.5 percent organic carbon, and only 2.5 percent clay (< 0.004 mm). Laboratory tests were performed on the sediment material that was less than 0.074 mm, or about 68 percent of the composite. The test sediment was therefore an organic silt, highly plastic, and contained less than 5 percent clay-sized material.

Erosion, deposition, and settling tests were performed by progressive additions of sediment to a water tunnel. The water tunnel had a uniform cross section of about 342 sq cm, which changed from rectangular in the horizontal, depositional/resuspension sections to circular in the vertical settling and pumping sections. Settling tests were performed in one of the water tunnel's vertical tubes at the end of the tests immediately after the flow was stopped. Details of the sediment water tunnel tests are described in Teeter (1988) and Teeter and Pankow (1989). In addition to the settling tests performed in the sediment water tunnel, two additional high-concentration settling tests were performed to fractionate the sediment and study contaminant-particle association. Composite sample sediment was mixed with site water to about 2.4 and 17 g/L initial concentration, and allowed to settle for 24 hr. Samples were drawn by pipette from the 20-cm depth.

Solids concentration and dispersed particle size spectra, in addition to contaminant concentration, were determined on the samples. Settling velocities were calculated for 0.25-phi size intervals using time-series volume concentrations from the particle analyzer, similar to a standard pipette analysis. (Phi sizes are the negative log-base-2 of the particle diameter in millimeters.) Settling velocities were calculated based on the settling times and test suspension height for each size class. The result was estimated aggregate settling velocities associated with each dispersed particle size class.

Results

Particle size effects were observed. Steady-state suspensions, as described earlier, were observed as suspended sediment concentrations in the sediment water tunnel reached constant values during deposition and erosion tests. The cause was sorting and winnowing according to particle size. Sediment water tunnel tests were interpreted as the superposition of three sediment size fractions with varying depositional and erosional characteristics to describe sediment behavior.

The main water tunnel test results are shown in Table 1. Deposition velocities (from flowing deposition tests) were almost an order of magnitude lower than settling velocities (from quiescent settling tests), similar to previous test results. Settling and deposition velocities were found to increase with concentrations greater than about 75 mg/L, which is above levels normally expected to occur in the upper harbor. Therefore, aggregation had a small effect on natural suspensions, and the constant values in Table 1 apply.

Table 1
Summary of Erosion and Deposition Test Coefficients

Variable	Fraction		
	1	2	3
Critical shear stress for deposition, N/sq m	0.42	0.33	0.043
Depositional velocity, mm/sec	2.02	1.04	0.006
Critical shear stress for erosion, N/sq m	> 0.6	0.38	0.060
Grain diameter, mm	0.074-0.028	0.028-0.014	< 0.014

The sediment identified as the slowest to settle and deposit and easiest to erode (fraction 3) is the most mobile. The size of the mobile fraction was less than 0.014 mm. Other, larger sized fractions had progressively higher critical shear stresses, and are relatively immobile. While the relatively mild variation in critical shear stress for deposition was adequately described by fractions 2 and 3, the sharp increase in critical shear stress for erosion was not well described by only two fractions. Critical shear stress for erosion was a continuous function of grain size above 0.014 mm.

Median settling velocities for several tests representative of the whole composite sediment are shown in Figure 2, along with field settling velocity tests. Median values for high-concentration laboratory settling tests are also shown in Figure 2. Figure 3 shows the time-series of concentration by particle volume plotted against dispersed grain size for one of the high-concentration settling tests. The initial spectrum was very well graded.

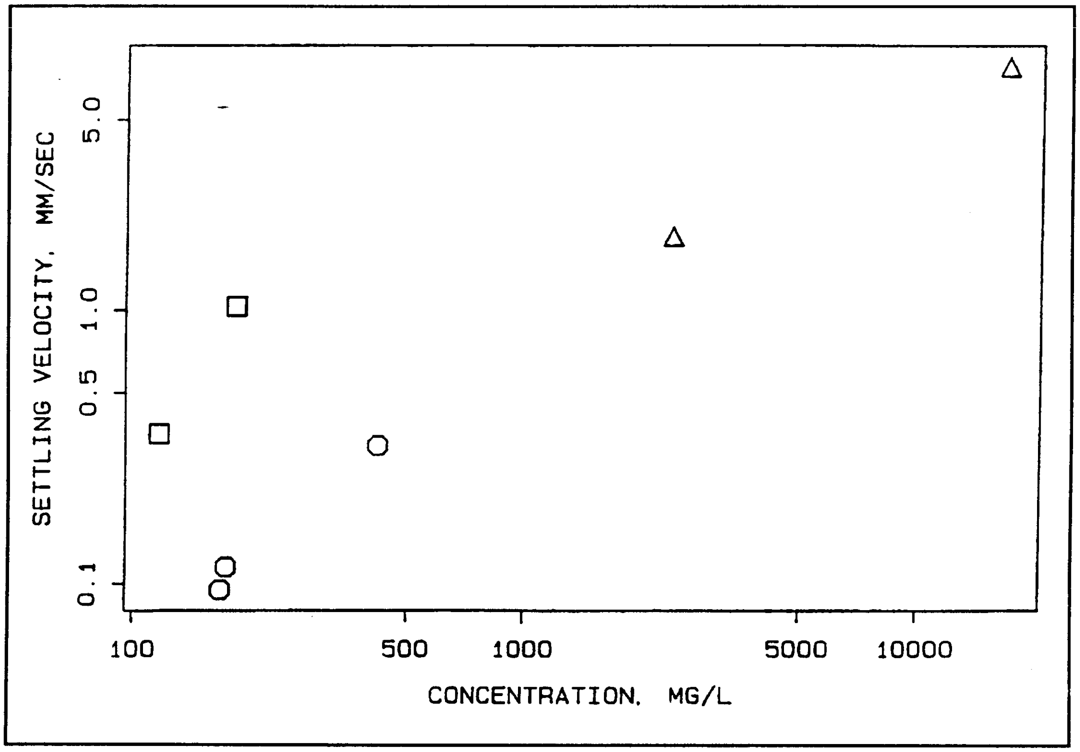

Figure 2. Median settling velocities for the composite sediment observed in the sediment water tunnel (○) and in high-concentration laboratory tests (Δ), and for resuspended bed material tested in a field settling tube (□)

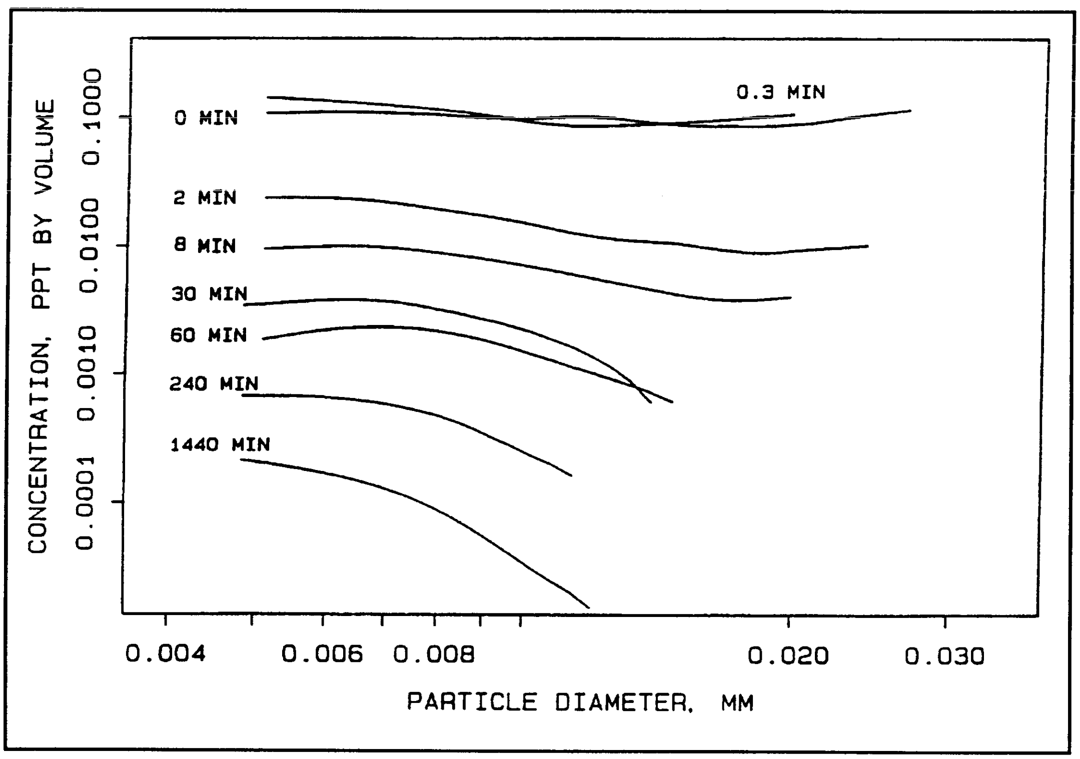

Figure 3. Volume distribution of particle sizes during a laboratory settling test, starting from an initial suspension concentration of 2.4 g/L

All sizes decreased with time, although the coarse sizes decreased fastest, and the spectra became progressively finer. Increases in settling velocity with concentration indicated that aggregation took place in these tests. Results for dispersed size-class mean settling velocities, shown in Figure 4, represent the aggregate settling rates for individual grain size classes. The greatest concentration effect can be seen at the smallest grain sizes.

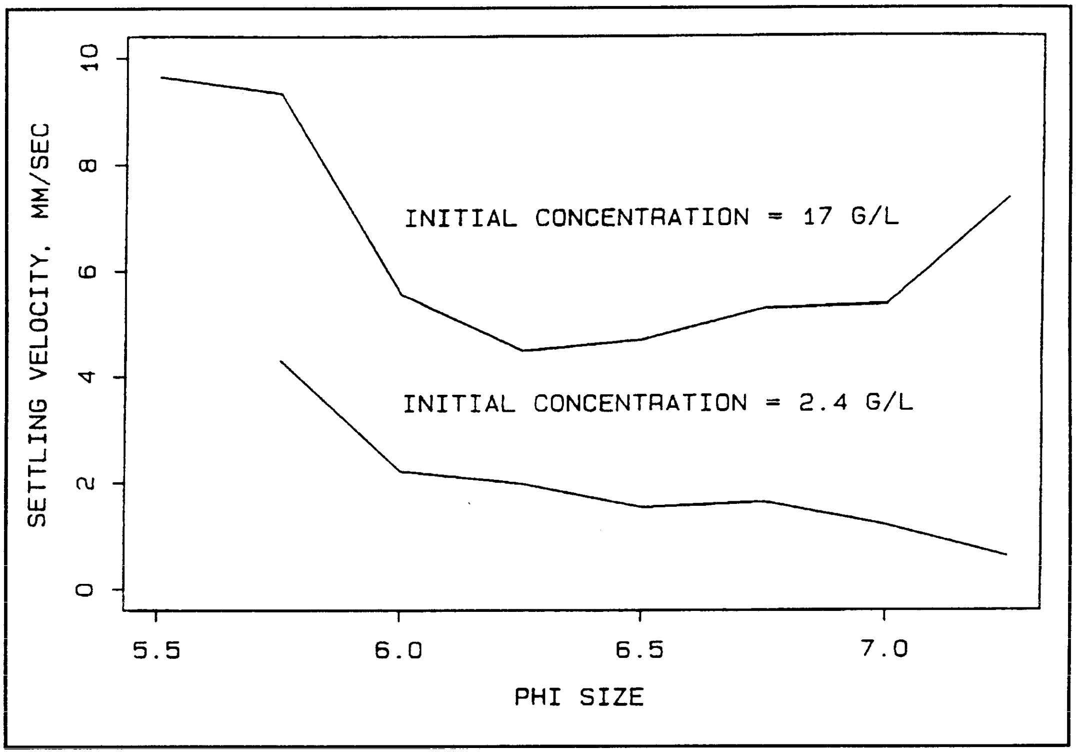

Figure 4. Aggregate settling velocities by dispersed grain size for two high-concentration laboratory settling tests

Raw and tide-corrected total suspended material (TSM) fluxes at the Coggeshall Street Bridge are shown in Table 2. The net flux of TSM was always found to be in the upstream direction. Ebb and flood fluxes were at least twice the net values. Average upstream flux, corrected for tidal asymmetry, was about 2,200 kg per tidal cycle. On average, 26 percent of the suspended sediment load carried upstream past the Coggeshall Street Bridge deposited in the upper harbor. A corresponding accumulation of sediments in the upper harbor has been reported (Summerhayes, Ellis, and Stoffers 1985).

Table 2 Survey Conditions and Fluxes of TSM at Coggeshall Street Bridge						
Survey Date	Freshwater Inflow cu m/sec	Tide Range m	Tidal Phase	Total Suspended Material ppm	TSM Flux,[1] kg	
					Raw	Tide-Corrected
3/06/86	1.3	1.1 (mean)	Ebb Flood Total	3.9 7.2	-4,400 6,400 2,100	3,100
4/24/86	1.5	1.7 (spring)	Ebb Flood Total	5.9 8.1	-8,700 12,800 4,000	2,900
6/05/86	0.3	1.0 (neap)	Ebb Flood Total	6.6 7.4	-4,400 6,500 2,100	605

[1] Flow × concentration.

Tidal average mean particle sizes are presented in Table 3 in both millimeters and phi units, along with phi values for sorting and skewness averages. Figure 5 shows an example time-series of particle spectra from station 5.

Table 3 Summary of Tidal-Averaged TSM Size Statistics and Trends								
Survey Date	Mean		Sorting phi	Skewness	Dominant Trend			TSM Flux Direction[1]
	mm	phi			Case	Z	Direction	
3/03/86	0.013	6.21	0.73	0.25	C	3.3	+	NA[2]
3/05/86	0.015	6.06	0.82	0.29	C	3.9	+	+
6/03/86	0.010	6.71	0.61	0.08	B	6.6	-	-
6/05/86	0.010	6.59	0.66	0.12	B	5.5	+	+
6/07/86	0.010	6.70	0.62	0.10	C	3.3	+	0
6/08/86	0.010	6.58	0.60	0.16	B	5.6	-	+

[1]Symbols are defined as follows: + = upstream toward the head of the estuary, - = seaward, and 0 = neutral.
[2]Not available.

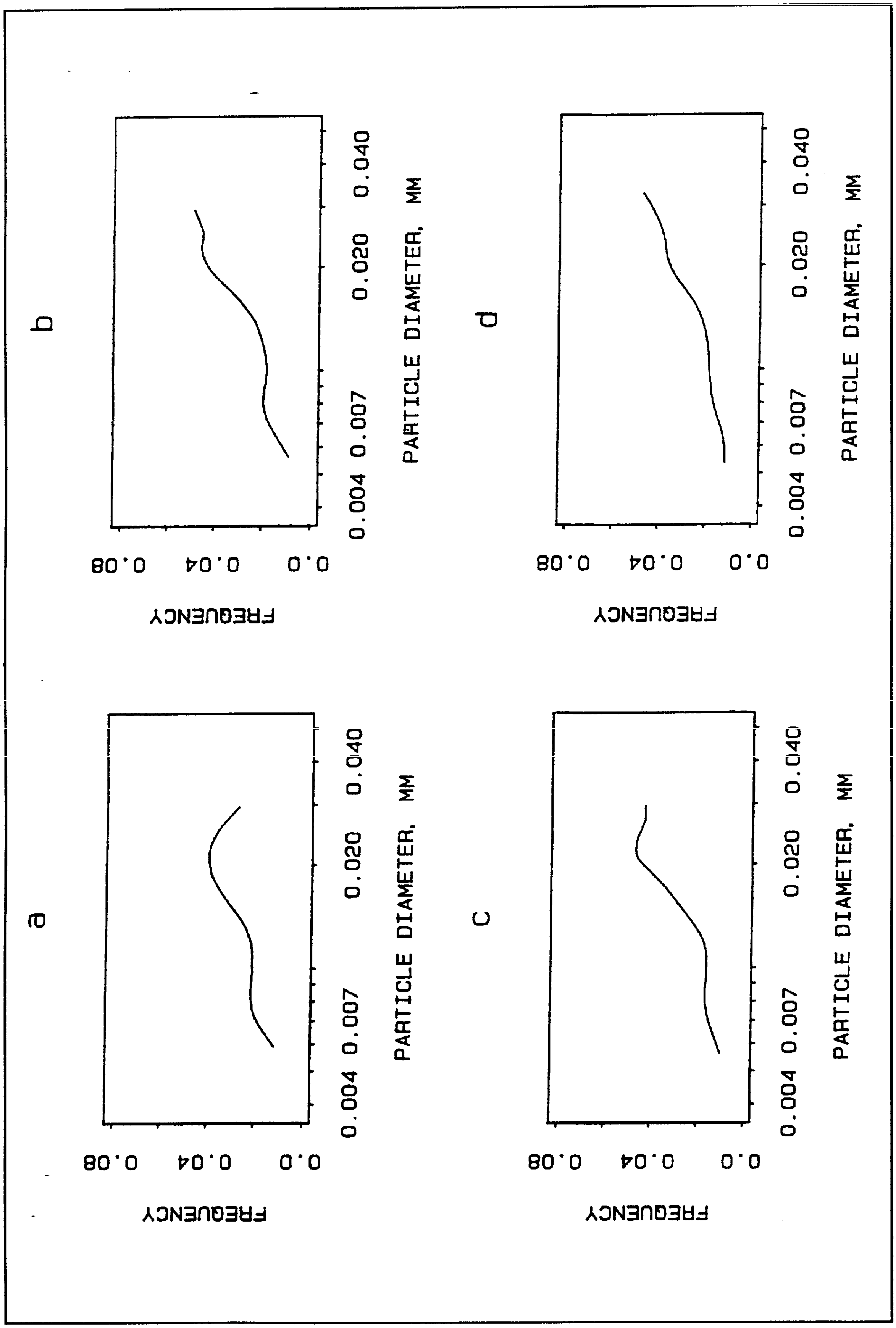

Figure 5. Example time-series of suspended size spectra for March 6 survey approaching low-water slack at station 5: (a) 0608 EST, (b) 0707 EST, (c) 0806 EST, and (d) 0908 EST

Size Spectra Trends

Size spectra trend analysis was applied to the high-concentration settling tests as a test of the method. The initial spectra were very well graded, decreased from the coarse end, and became finer, better sorted, and more skewed toward the larger sizes during the tests. This trend was consistent with Case B, and indicates that the aggregate settling removed larger dispersed particles faster than fine ones. The suspension became more well sorted and skewed as the coarser end of the distribution was depleted by settling. The example presented in Figure 3 for the 2.4-g/L test had a Z score of 6.3. These tests demonstrated that the trend analysis was capable of detecting at least extreme cases of deposition in a progression of measured suspended grain-size spectra and that, even under high-concentration, aggregated conditions, these sediments have size-related behaviors. This might be explained if, for example, like-sized particles had a greater probability of colliding and aggregating together than dissimilar-sized particles.

For application of size spectra trend analysis to tidal samples, spectra were arranged from high water to low water by time. Thus, the ebb tidal phase samples were used in the temporal sequence as collected, and the flood tidal phase samples were used in reverse order, starting with the flood-tide sample closest to high water. These sequences represent both upstream sequences of the water column passing the station, and high- to low-water sequences at a station. Table 3 shows the results for the dominant (highest Z scores) trends for the tidal sequences, and also compares the indicated directions of transport with TSM flux directions.

Conclusions

Dispersed particle size was found to have important effects on fine-grained sediment transport in a system with a large amount of silt. As expected, upstream tidal pumping was found to dominate transport, and TSM concentrations increased upstream. The largest TSM source was Buzzards Bay. Mean particle sizes of suspended material generally increased slightly upstream, and size spectra trend analysis at stations also indicated mean sizes increased upstream and toward low water under average tidal conditions. Suspended spectra generally had modes slightly above the 0.014-mm size, and reached about 0.030 mm. No distinct optimum transport size was observed, but even the slight upstream suspension coarsening that was observed may be noteworthy where deposition is occurring.

Size spectra trend analysis was found to be a sensitive indicator of transport, and may be useful in evaluating suspended sediment transport mechanisms. That significant trends were found indicates transport varied with dispersed particle size (the underlying assumption of the model). The field suspended sediment size data were limited to only about 12 samples per station per tide, only a small fraction of the number of suspended samples collected. Conclusions drawn from such a small sampling should be considered tentative. However, the correlation of size spectra trend results to direct flux measurements is considered to be good, indicating that size spectra variability may be less that TSM variability. Most suspended sediment size spectra trends corresponded to the observed direction of TSM transport, and indicated better (smaller valued) sorting in the direction of transport. Upstream suspension coarsening in the direction of depositional transport, while not always observed (at lower current speeds), could arise from tidal-pumping transport in which deposition and resuspension lags play a role.

Water tunnel tests indicated that deposition and erosion could be described adequately by a few size-classes for modeling purposes. About 27 percent of the finest sediment behaved as a distinct, easily transportable fraction. This fraction was found to consist of sediment material less than 0.014 mm and possessed the greatest cohesion. Other investigators have found similar size boundaries for cohesive sediments. The critical shear stress values for deposition and erosion were similar, 0.043 and 0.06 N/sq m, respectively, for the finest transport fraction. Coarser material had sharply higher depositional velocities, critical shear stresses, and an increasing gap between the critical shear stresses for deposition and erosion (Table 1).

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