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Sediment trap biases in turbulent flows: Results from a laboratory flume study

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ABSTRACT

Several cylindrical and noncylindrical sediment trap designs were tested in a recirculating steady-flow flume. The laboratory study was conducted to achieve dynamic- and geometric-similarity to conditions in a specific field environment where traps eventually would be deployed. Relative (to a "standard" trap design) particle collection efficiencies of the traps were quantified in ~10 cm/sec turbulent flows that were continuously seeded with particles having fall velocities of about 10^{-2} to 10^{-1} cm/sec (the upper range of silt-sized quartz sediments). The nature of flow through the trap mouths was qualitatively described using dye.

The following trap biases were demonstrated in the study. For unbaffled cylinders, efficiency decreased over a range of increasing trap Reynolds number (R_t) when aspect ratio (H/D) was held constant, and efficiency increased over a range of H/D when R_t was held constant. Baffling cylinders with various H/D, but constant R_t, gave mixed results. Any disturbance to flow near the trap mouth or through the trap tended to increase between-replicate variability. For unbaffled, noncylindrical traps, small-mouth, wide-body traps overcollected particles and funnel-type traps tended to undercollect particles, relative to cylinders of the same height and mouth diameter.

The biases demonstrated here are for specific parameter combinations and cannot be generalized outside the range of values tested. The results do indicate that significant biased collections are possible by a variety of trap designs and may be flow-regime dependent. Trap-users thus are urged to interpret vertical flux results with caution. Further quantitative studies of trap biases for the ranges of conditions common in field trapping environments and process-oriented studies of physical trapping mechanisms are needed to determine the utility of sediment traps for flux estimates in ocean flows.

1. Introduction

Particle-collecting traps are routinely used to determine particulate flux in a wide variety of limnologic and oceanic environments (e.g., see the annotated bibliography of Reynolds *et al.*, 1980). Collection characteristics of sediment traps have been quantified in three published laboratory studies (Gardner, 1980a; Hargrave and

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Burns, 1979; Lau, 1979; but see also the laboratory studies on pollen collectors by Hopkins, 1950; Davis, 1967; Peck, 1972; Tauber, 1974), but there is a more voluminous literature where field collections by a variety of trap designs are compared (e.g., Steele and Baird, 1972; Wahlgren and Nelson, 1976; Wahlgren *et al.*, 1978; Sato and Sawada, 1979; Gardner, 1980b; Blomqvist and Kofoed, 1981; Staresinic *et al.*, 1982) or field comparisons between trap collections and some other measure of particulate flux (e.g., Spencer *et al.*, 1978; Knauer *et al.*, 1979; Brewer *et al.*, 1980; Bruland *et al.*, 1981; Dymond *et al.*, 1981; Lorenzen *et al.*, 1981; Gardner *et al.*, 1983a). Laboratory calibration studies are capable of supplying information on trap accuracy, but the field comparisons can yield only precision estimates or *relative* particle collection efficiencies of the traps tested. In fact, traps collecting marine sediments were calibrated in only two studies (Gardner, 1980a; Hargrave and Burns, 1979), each covering a narrow range of particle types and flow parameters (see Butman *et al.*, 1986). Parameters representative of the bulk of field conditions remain to be experimentally tested.

Specific predictions of sediment trap biases in turbulent flows were made by Butman *et al.* (1986), based on a theoretical analysis of the hydrodynamics of particle trapping and on evidence from the published trap calibration studies. From a dimensional analysis, particle collection efficiency, P/WN_c, was described as a function of six dimensionless parameters, u_f/W, u_fD/ν, H/D, Wd/ν, S, N_cd^3, where P = the number of particles trapped per unit area per unit time (particle trapping rate), W = the nominal particle fall velocity ($([S-1]gd^2/\nu)$), N_c = number of particles in the fluid per unit volume, d = particle diameter, ρ_p = particle density, ρ_f = fluid density, μ_f = fluid viscosity, u_f = flow speed at the height of the trap mouth, g = acceleration due to gravity, D = trap mouth diameter, H = trap height, $S = \rho_p/\rho_f$, $\nu = \mu_f/\rho_f$. Also note that u_fD/ν is the trap Reynolds number (R_t) and Wd/ν is the particle Reynolds number (R_p). From the literature and based on some simple physical models, relationships between three of these parameters (u_f/W, R_t and H/D) and collection efficiency could be predicted. For fixed values of the other two parameters, Butman *et al.* (1986) hypothesized that the collection efficiency of unbaffled, straight-sided cylinders will decrease over some range of increasing R_t, decrease over some range of decreasing W and increase over some range of increasing H/D. In addition, for fixed values of R_t, u_f/W, and H/D, unbaffled, small-mouth, wide-body traps generally will be overcollectors and unbaffled, funnel-type traps generally will be undercollectors, relative to cylinders with the same mouth diameter.

The present laboratory flume study of sediment trap biases tested all these predicted effects, except for W-dependence. The study was carefully designed and conducted to achieve dynamic and geometric similarity for collecting a specific class of particles (see 2.) in a specific shallow-water (15-m depth) turbulent flow environment (Station 35 in Buzzards Bay, Massachusetts, described in Sanders *et al.*, 1980) where the traps eventually were used in field experiments (Hannan, 1984a,b). In addition, the

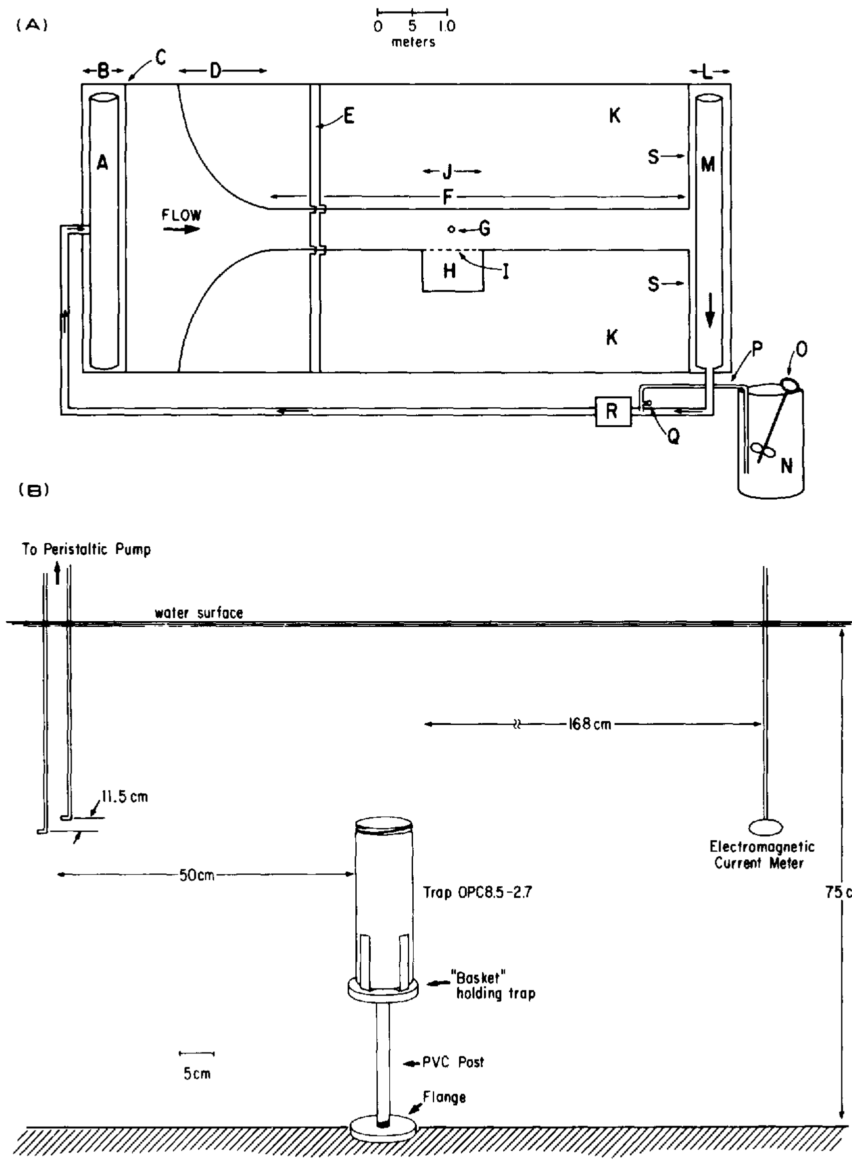

Figure 1. (A) Flume drawn to scale; top view. A = diffuser, B = depressed well where diffuser is located, C = point where flume basin begins, D = flow-straightening area (entrance section to raceway), E = one of five wooden braces holding down the raceway, F = raceway, G = threaded flange to hold PVC post and trap, H = dry box holding mirror, I = window, J = test section, K = areas filled with water during experiments to support raceway, L = sump area, M = pipe returning flow to centrifugal pump, N = bead tank, O = motor to stir bead tank, P = hose connecting bead tank to valve on pipe leading to centrifugal pump, Q = adjustable valve to regulate flow from bead tank, R = centrifugal pump, S = removeable vertical walls to allow water into support areas. (B) Side-view of flume at test section (see J in Fig. 1A), drawn to scale, showing location of a trap in relation to the peristaltic pump water sampling tubes upstream (for all series except 6/7/82, where tubes were located only 10.2 cm upstream of the trap pedastal) and the electromagnetic current meter downstream.

Table 1. Conditions and traps tested during each series of flume experiments.

Series	Date of series	Traps tested (listed by code$^{\alpha}$)	C_{bp} mean ± SD ( ) = N (mg/l)	Height$^{\beta}$ of all trap mouths above bottom (cm)	Time interval when traps were tested (EST$^{\delta}$) ( ) = total no. hrs.	Approx. temp. (°C) range during all trap tests ( ) = mean rate of change in °C/hr	Range of flume water height (cm)	Measured flow speed mean ± SD ( ) = N (cm/sec)	Bead mixture used to seed flow	Approx. range in C_i^{ϵ} (mg/l)
I	6/07/82$^{\gamma}$	OPC8.5-1.0 OPC8.5-1.9 OPF8.5-1.9 OPC8.5-2.7	1.00 ± 0.38 (22)	34	1410–1946 (5.6)	20.5–22.3 (0.3)	58.5–61.0	none	46μm	4.5–8.5
II	6/24/82$^{\lambda}$	OPC8.5-2.7 OPC8.5-3.6	0.51 ± 0.44 (22)	34, 47$^{\mu}$	1322–1922 (6.0)	22.0–24.4 (0.4)	68.5–71.0	11.0 ± 0.8 (98) 11.0 ± 0.9 (25) 11.1 ± 0.7 (52) 10.6 ± 0.8 (40)	25μm	9.0–15.5
III	7/10/82	TBC1.7-3.0 TBC3.6-3.1 TBC7.4-2.9 OPC8.5-2.7 OPC8.5-2.7S$^{\nu}$ OPG8.3-3.0 OPF8.3-1.9	1.39 ± 0.68 (22)	47	1304–1756 (4.9)	23.9–25.8 (0.5)	69.5–71.5	none	25μm	8.5–13.0
IV	7/22/82	TBC1.7-3.0 TBC3.6-3.1 TBC7.4-2.9 OPC8.5-2.7 OPG8.5-3.0 OPF14.1-1.6$^{\pi}$	1.32 ± 1.01 (22)	51	0823–1320 (5.0)	25.9–27.7 (0.4)	69.5–73.5	10.1 ± 0.7 (55) 10.3 ± 0.6 (61)	25μm	7.5–11.0

V	8/24/82	TBC14.7-1.6	1.44 ± 0.33	51	1152–1940	24.9–27.3	69.0–75.0	none	25μm	8.5–11.5
		TBF14.7-1.6S	(22)		(7.8)	(0.3)				
		TBC14.7-2.9								
		OPC8.5-1.0TB[ρ]								
		OPC8.5-1.9TB								
		OPC8.5-2.7TB								
		OPC8.5-2.7BB[σ]								
		OPC8.5-2.7S								
		OPC8.5-2.7								
		OPC8.5-3.6								
		OPP8.3-2.7[π]								
		OPG8.5-3.0								
		OPG8.5-3.0S								
		OPGC8.5-3.6								

α. Trap dimensions and codes are given in Table 2.

β. Heights are given to ± 0.5 cm.

δ. Eastern Standard Time.

ϵ. In each series, less than 10% of the measured bead concentrations were outside this range.

γ. All traps were tested for 4.5-, 6.5-, and 8.5-min intervals.

λ. All traps were tested for 4.5-, 6.5-, 8.5- and 16.5-min intervals.

μ. For trap OPC8.5-2.7, three replicates were tested at each of the two heights (34 cm and 47 cm) for 8.5-min intervals; all other traps were tested at 34-cm.

ν. S = screened; a fine filament (≤ 0.25 mm in diameter) plastic screen having 16-mm^2 openings was secured tightly over the trap mouth during collections.

π. Results not reported here (see Hannan, 1984a).

ρ. TB = top baffled; a "honeycomb" baffle 78 mm tall with cells ~10 mm in diameter was cut to exactly fill the inside diameter of the trap and was placed inside the trap, flush with the trap mouth.

σ. BB = bottom baffled; a honeycomb baffle (described in footnote ρ) was pushed down inside the trap to sit directly on the trap bottom.

variables identified by Butman *et al.* (1986) to be important to the process of particle trapping were closely monitored during flume experiments, allowing detailed estimates of the experimental error underlying calculations of trap collection efficiencies.

The biased trapping effects demonstrated in this study were determined for specific combinations of the dimensionless parameters identified by Butman *et al.* (1986). The applicability of these results outside the range of values tested can only be determined empirically. Thus, while this study clearly demonstrates some biased trapping effects, the generality of these effects for other flow regimes and particle types awaits direct experimentation. However, the results of this study do indicate that it is probably premature to suggest that any trap design accurately estimates particulate flux over a wide range of turbulent field flows (see also conclusions of Gardner, 1980b).

2. Methods

a. Flume design. Collection efficiencies of a variety of trap designs were determined in a freshwater flume located in the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at Massachusetts Institute of Technology. The flume (Fig. 1A) consists of a wood basin 945 cm long, 417 cm wide, and 121 cm deep modified specifically for these experiments. A centrifugal pump recirculates water from a sump-section downstream to an upstream diffuser; the flow is unidirectional.

Model tests of traps in the flume were originally designed for field R_t ranging from 8×10^3 to 1×10^4, based on a predicted mean flow speed in the field of 10 cm/sec, trap mouth diameters ranging from 8 to 15 cm, and $\nu = 1.05 \times 10^{-2}$ cm^2/sec (seawater at atmospheric pressure, 20°C, 30 ppt). Modifications to the flume necessary to achieve these R_t primarily were stipulated by the maximum fluid discharge rate (0.056 m^3/sec) of the pump. To achieve 10 cm/sec laboratory flows, the flume had to be narrowed to ~60 cm at the test section and the water depth reduced to ~75 cm. In addition, full-scale traps were tested in the flume to maintain R_t-similarity between laboratory and field flows.

The rectangular flume basin was modified (see Fig. 1A) by constructing a "raceway" 61 cm wide and 75 cm tall centered in the basin and covering 615 cm of the flume length. To straighten the flow funneled into the raceway, a curved "entrance section" attaches the raceway to the basin walls 79 cm downstream from the diffuser. Defining the test section and located 435 cm downstream from the diffuser is a "dry box" (see H in Fig. 1A); the box is connected to the raceway by a glass window. Observations and photographs of traps during experiments were made from above the box by looking down at the mirror, placed in the box at a 45° angle from the box window. Other details of the flume design and construction are described in Hannan (1984a).

The location of the test section was selected so that traps would be collecting particles in a unidirectional turbulent flow field, above the bottom boundary layer (see Hannan, 1984a). Using the 4/5 power law for boundary-layer thickness (δ) as a function of distance downstream (x), $\delta = (\nu/U_\infty)^{0.2}0.37x^{0.8}$ (see Schlichting, 1979), where U_∞ is the free-stream velocity (of ~10 cm/sec in the flume), $\delta = 13.0$ cm at the test section (where $x = 481$ cm, $\nu \simeq 0.01$ cm/sec^2); trap mouths were well above this height (see Table 1). The flume flow Reynolds number was ~2×10^5 (using the wetted perimeter as the length scale, a flow speed of 10 cm/sec and $\nu \simeq 0.01$ cm/sec^2) and the flume Froude number was subcritical (Froude number $\simeq 0.2$, using a flow speed of 10 cm/sec and a water depth of 60 cm). Trap mouths were positioned a sufficient distance below the water surface (see Table 1) such that no significant free-surface effects of the traps on the flow were observed.

At maximum pumping rate, the diffuser supplies to the raceway a flow field containing numerous turbulent eddies. The turbulence arises because the pumping system is not completely water-tight so air bubbles are introduced with the water (the bubbles rise in the upstream section of the flume, mixing the water mass) and because the diffuser ports point downward in a depressed well upstream (see Fig. 1A) so that the flow rebounds off the sides of the well. The flume is not long enough to allow complete dissipation of these eddies downstream. No steps were taken to baffle the flume flow because the flow near (within two meters of) the bottom at the field study site was expected to be smooth-turbulent during most of the tidal cycle. Visualizations of the flume flow using dye showed that the eddies in the flow approaching a trap were small, on-the-order-of trap diameter or less (see Hannan, 1984a); the flow at the test-section was not dominated by any large-size eddies that may result purely from secondary-flow phenomena generated at the entrance section.

The size of the test section permitted testing of only one trap at a time if possible trap-induced, secondary-flow effects were to be avoided. From hydrodynamic arguments concerning flow acceleration around bluff bodies, a distance of approximately three trap radii between the trap and the flume side walls would result in minimal interactions between the trap-induced flow field and the walls of the flume (see discussion in Hannan, 1984a). This criterion was satisfied for all traps tested. Each trap was raised above the bottom on a PVC (polyvinyl chloride) pedestal (1.9 mm diameter) (see Fig. 1B); the lengths of the pedestals were adjusted so that all trap mouths were raised to approximately (± 0.5 cm) the same height above the bottom, during a given "series." (A "series" of experiments includes three replicates of all trap designs tested during a single day, a continuous 6- to 10-hr interval.) The pedestal screwed into a threaded flange centered in the test section 481 cm downstream of the diffuser well and equidistant from the side walls (see Fig. 1A). Another flange was screwed onto the top of the pedestal and the trap was held vertical in a stainless steel "basket." The orientation of a trap during a collecting interval could be viewed through the mirror in the box; care was taken to insure that trap mouths were horizontal to the flume bottom (and thus, to the unidirectional mean flow) during all collections.

Flow speed was monitored in the water column with a Marsh-McBirney electromagnetic current meter positioned 168 cm downstream of the trap pedestal at the height of the trap mouth (see Fig. 1B). The meter averages current speed over a vertical distance of about 4 cm and is accurate to about ±1 cm/sec under these steady-flow conditions (Aubrey and Trowbridge, 1985; Aubrey *et al.*, 1984). Because the pump was set at the maximum discharge rate during all series, flow speed was monitored in detail only during a few trap collection intervals. Flow speed, recorded by an observer every 10 sec for 4 to 10 min intervals, varied between 8 and 12 cm/sec over these short intervals due to flow turbulence; however, the mean flow speed varied only by 1.1 cm/sec, ranging from 10.0 to 11.1 cm/sec (coefficient of variation [CV] varied between 5.9 and 8.2%) and decreased with increasing flume water height. The approximate flow speed during each trap collecting interval was calculated, from conservation of mass, for the range of flume water heights that occurred during all series (see Table 1); measurements and calculations are given in Hannan (1984a).

Detailed velocity profiles were not possible using this current meter because it averages velocities over a large vertical distance (~4 cm) relative to the estimated thickness of the bottom boundary layer at the test section (~13 cm), it is accurate only to ±1 cm/sec, and it is sensitive to the presence of solid boundaries. While turbulent eddies were observed to mix the dye vertically and horizontally over small spatial scales (of centimeters or less), significant deviations from a unidirectional flow (e.g., due to flume artifacts) were not present at any height above the bed at the test section (see photographs in Hannan, 1984a).

b. Seeding the flow with particles and sampling the water column. The flume was filled with freshwater from the Cambridge City water system. During the fill, the water was filtered through a diotomaceous earth filter. The flume was drained, cleaned, and refilled for each new series. The water was at ambient outside air temperature when it entered the flume, so it warmed considerably during each series. Thus, water temperature was measured (to 0.1°C) in the flume test section, at the height of the trap mouths, approximately every hour during a series. To limit bacterial action on particles in the flume water, 3.8 liters of bleach (5.25%, by weight, of sodium hypochlorite, NaClO) was added to the flume during each fill. This resulted in NaClO concentrations ranging from 0.353 millimolar (mM) for a flume water height of 50 cm (or ~7600 liters of water) to 0.235 mM for a flume water height of 75 cm (or ~11,400 liters of water).

The flow was seeded with spherical glass beads (Ferro Class IVA "Uni-spheres," claimed by Ferro to contain ≤15% irregularly shaped beads and to have a density of 2.42 g/cm^3). The Coulter Counter size-class distributions of the two bead mixtures are shown in Figure 2. The size-frequency distributions of both mixtures were unimodal; hereafter, the mixtures are referred to as the "25 μm beads" and the "46 μm beads," indicating the mean bead diameters in the two mixtures, respectively. These means were determined by assigning the frequency of beads in a Coulter Counter size class to the midpoint of that class, summing over the size classes and then calculating the average bead diameter. For bead sizes between 13 and 63 μm (which includes 94% of

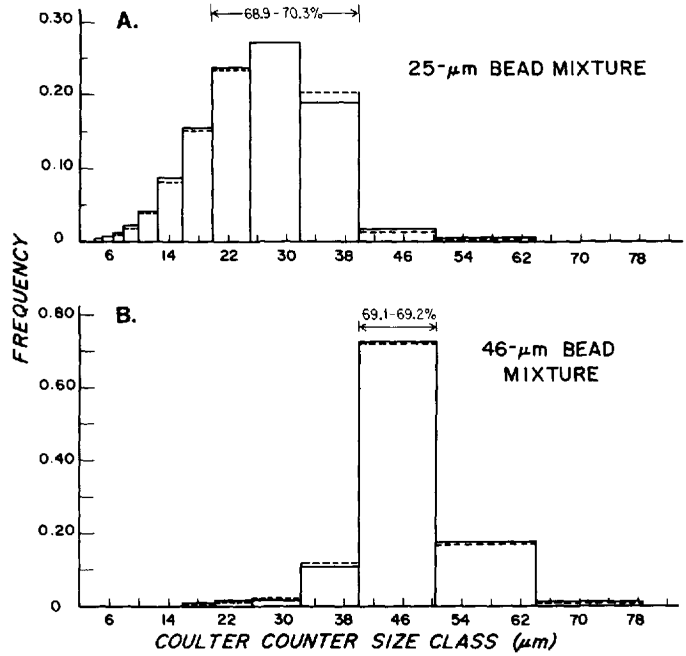

Figure 2. Size-frequency histograms of the 25 μm bead mixture (A) and the 46 μm bead mixture (B) used to seed the flume flow. Two samples from each bead mixture were analyzed using a Coulter Counter. Mean bead diameters were 24.9 μm (dashed line in A), 24.8 μm (solid line in A), 46.4 μm (dashed line in B), and 46.7 μm (solid line in B). Modal size-classes and percentage of beads in these classes are indicated by the arrows above the histograms.

the 25 μm mixture and 97% of the 46 μm mixture), Stokes' theoretical fall velocities (Stokes, 1851) are between 0.015 cm/sec and 0.35 cm/sec (for freshwater at 24°C). For comparison, silt-sized (4-63 μm), quartz ($\rho_p = 2.65$ g/cm^3) sediments have theoretical fall velocities ranging from 0.0013 cm/sec to 0.33 cm/sec (for 30 ppt seawater at 20°C). Thus, the bead mixtures used here have fall velocities covering the upper range of silt sediments and the lower range of very fine sands (Fig. 3).

The beads were mixed with water in a separate "bead tank" (95.3 cm diameter, 121.9 cm tall, 874.4 liter capacity, see Fig. 1A) by sprinkling preweighed amounts of dry beads onto the water surface. For one series (8/24/82), preweighed lots of the 25 μm beads were ensonified, in clean glass jars containing deionized water, several days prior to the series. These ensonified beads, maintained in suspension by manually shaking the jars, were poured into the bead tank during the course of the series. A homogeneous bead suspension was attempted by continuous rigorous mixing with a motor.

The flume flow was seeded with the bead-tank suspension through an adjustable valve on the pipe leading from the flume into the centrifugal pump (see Fig. 1A); the

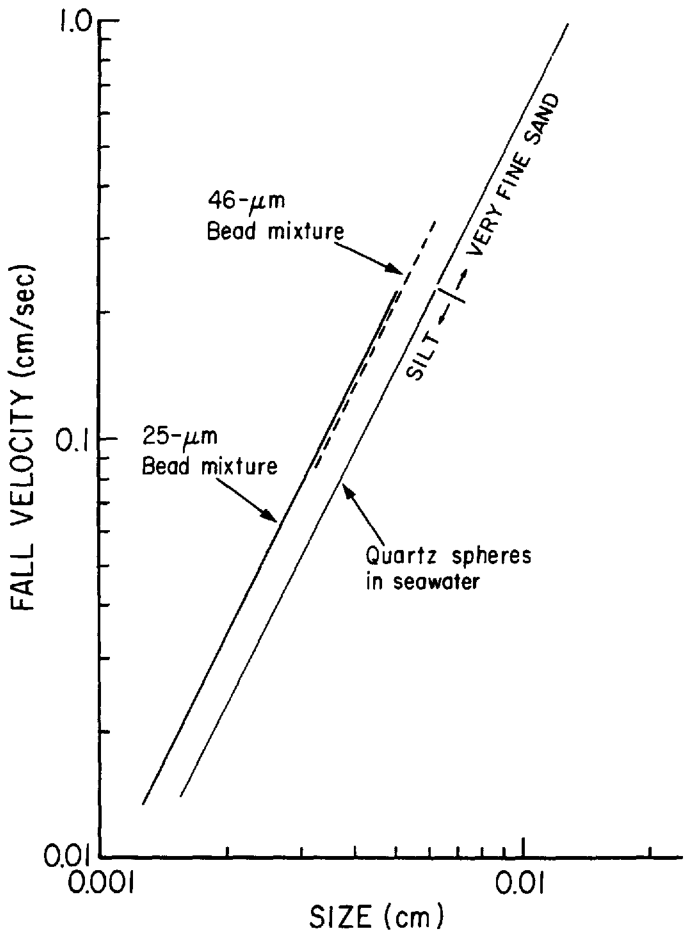

Figure 3. Relationship between fall velocity and size (particle diameter) for the beads used to seed the flume flows and for quartz spheres falling in seawater. Solid line is for beads in ~94% of the 25 μm mixture (see Fig. 2A) and dashed line is for beads in ~97% of the 46 μm mixture (see Fig. 2B). The sediment classification of the quartz particles as "silt" or "fine sand" also is shown on the figure.

combined forces of pump suction and the pressure head on the bead tank carried the bead suspension into the pipe. A manometer on the hose leading from the bead tank into the pipe was used to monitor the supply of beads to the flume. From theoretical calculations of the settling loss rate of beads over the length of the flume and from several experiments where loss-rate was determined directly, it was eventually possible to seed the flow such that flume bead concentrations during most trapping experiments were maintained roughly between 8 and 12 mg/l (actual ranges in bead concentrations are given in Table 1), with very gradual changes ($\leq$0.1 mg/l/min).

Bead concentrations during flume experiments were monitored using a peristaltic pump water sampler. A pair of glass tubes (2.5 cm long, 11.1 mm diameter), separated cross-stream by 11.5 cm, were positioned on a frame so they were parallel to the flume bottom and faced directly into the flow. Each tube connected to a flexible hose (11.1 mm diameter) leading through one of the two peristaltic pump drums and into a collection jar. The frame holding the tubes was clamped onto a point gauge with a vertically traversing vernier scale and was lowered into the water only during sampling, thus minimizing disturbance to the flow during trapping. The tubes were centered equidistant from the flume walls and, for all series except one, the tubes collected water 50 cm upstream of the trap pedestal (see Fig. 1B). In one series (6/7/82), the tubes collected water 10.2 cm upstream of the pedestal. Water samples to determine bead concentrations during a given trap collecting interval were always taken at the height of the trap mouth. In addition, vertical profiles of bead concentrations were made three times during each series by taking discrete water samples as quickly as possible (over 4 to 6 min time periods) at consecutive 10 cm intervals above the bottom.

Particle concentrations using the peristaltic pump sampler initially were compared with collections using several other water-sampling techniques. No statistically significant differences were detected among particle concentrations estimated by all the sampling methods tested (see Hannan, 1984a), suggesting that biased sampling by these methods is unlikely. Of the methods tested, the pump sampler was selected for use in this study because it results in the least amount of flow disturbance, it is quick and can be positioned accurately, and it yields replicate samples.

Water samples were pumped from the flume at mean sampling speeds of 28.8 cm/sec (standard deviation [SD] = 1.2 cm/sec, for $N = 12$ measurements). The maximum pumping rate of the apparatus was chosen to minimize the sampling interval, and thus, the duration of upstream disturbances to the flow field. Because this water sampling speed was nearly three times the flume flow speed, possible oversampling of particles at these high sampling speeds was tested by taking water samples at slower pumping rates. No statistically significant differences could be detected in particle concentrations among samples taken at speeds ranging from 6.5 to 28.8 cm/sec, an empirical observation which is supported theoretically (see Hannan, 1984a).

The volume of water collected in peristaltic pump samples during trapping experiments usually varied between 200 and 250 ml (9–10 sec pumping time). For each sampling operation, the pumping apparatus was in the flume for ≤30 sec. The water was pumped into glass jars that were prewashed and rinsed twice with prefiltered (using 0.45 μm Metricel filters) deionized water. These samples were stored in a cold box at 6 ± 1°C until filtering (within 10 days of the experiment). For processing, the samples first were measured for water volume to ±1 ml, and then were filtered through preweighed 0.45 μm Millipore filters using a vacuum pump. The filters were air-dried and weighed to ±0.001 mg and then rounded to .01 mg due to the precision of the scale. The weights also were corrected for changes in humidity (see Hannan, 1984a).

Short water sampling times were required to minimize disturbances to the upstream water mass during trap collections and small sample volumes were required to minimize sample-processing time (filtering water samples). However, samples large enough to minimize analytical error and to accurately represent the variability in particle concentration also were necessary. The sample size chosen in this study represented a compromise among these considerations. Most importantly, analytical error was held to $\leq$10% if samples $\geq$200 ml were processed and sampling during about 6% of a trap collecting interval (9 sec samples at the beginning, midpoint and end of an approximately 8.5 min period) was sufficient to represent the variability in particle concentration (see Hannan, 1984a).

Prior to seeding the flow with beads in each series, the flume flow was sampled every 2 min for a 22 min interval. These 11 pairs of concentration estimates were used to determine the mean background concentration for the series, to allow for possible differences between series in Cambridge City water quality and flume cleanliness. Estimates of the mean background concentration were not significantly improved if the water was sampled for a continuous interval longer than 22 min (see Hannan, 1984a).

The technique for seeding the flow with beads, coupled with the turbulence in the flow, provided a well-mixed (in terms of total particle concentration, but see 5.a.) water mass to the test section. Vertical profiles of bead concentration taken near the beginning, midpoint and end of each series (Fig. 4) show haphazard oscillations in bead concentrations with respect to sample height. If the water column is well mixed, then there should be no significant differences among particle concentrations at each depth. This null hypothesis (H_o) could not be rejected at $\alpha \leq 0.05$ using the nonparametric Kruskal-Wallis test (see Siegel, 1956). The water column was well mixed for particle concentrations from 3 to 15 mg/l. The mean CV for the profiles was 6.1% (SD = 2.9%, range = 2.1–13.1%), well within the range in CV for particle concentrations taken over 8.5 min intervals at a single depth (see Hannan, 1984a).

c. Trap tests. The relevant dimensions of the traps tested in the flume are given in Table 2; hereafter the traps will be referred to by the code numbers listed and explained in this table. The "tenite butyrate" traps were cut from lengths of clear tenite butyrate tubing. The trap bottoms were cut from clear acrylic plastic (8 mm thick) for traps TBC14.7-2.9, TBC14.7-1.6, and TBF14.7-1.6, and polyethylene plastic caps were used for traps TBC1.7-3.0, TBC3.6-3.1 and TBC7.4-2.9. The "opaque polyethylene" traps were screw-cap jars with threaded trap mouths, while the tenite butyrate traps were straight-sided all the way to the trap mouth. Several trap designs were made by gluing (using silicone sealant or waterproof epoxy) two jars together: trap OPC8.5-2.7 consisted of trap OPC8.5-1.0 glued on top of trap OPC8.5-1.9; trap OPC8.5-3.6 was made from trap OPC8.5-1.9 glued to another trap OPC8.5-1.9; a funnel was glued inside trap OPC8.5-1.0 and then taped on top of another trap OPC8.5-1.0 to make trap OPF8.3-1.9; and trap OPC8.5-1.0 was glued on

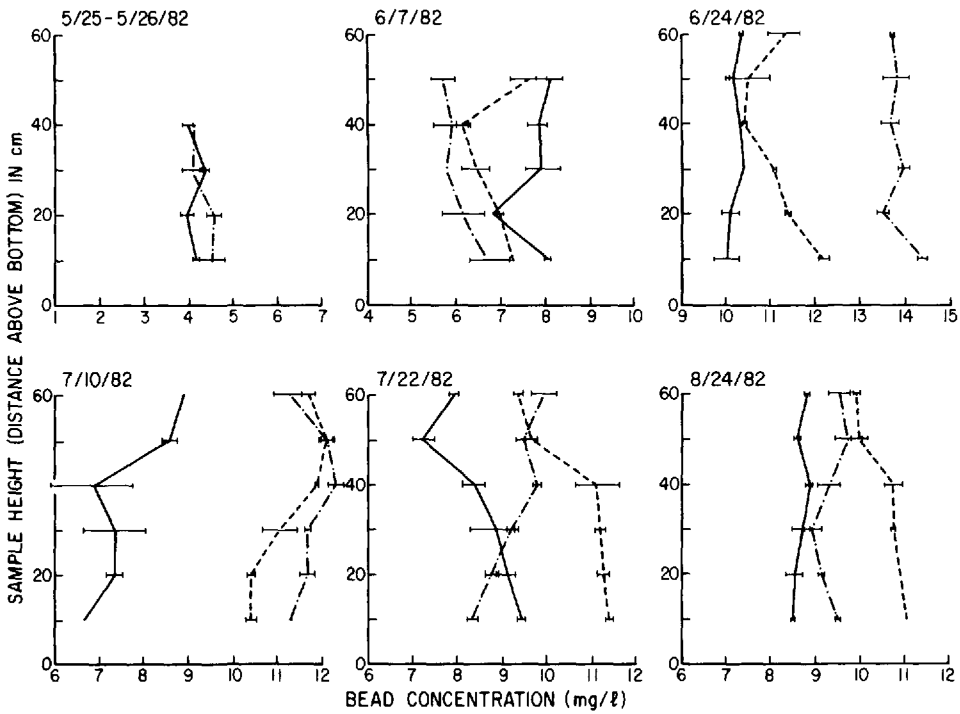

Figure 4. Vertical profiles of bead concentrations at the test section during all series. Horizontal bars connect the paired water samples taken at each depth. Vertical lines connect mean concentrations. Profiles were taken near the beginning (solid lines), midpoint (dashed lines) and end (dot-and-dashed lines) of each series. Plotted values are C_i (see 3. in text) for all series, except series 5/25–5/26/82, where C_{ap} (see 3. in text) is plotted. Series 5/25–5/26/82 does not appear in Table 1 because it was a preliminary run where no traps were tested.

top of trap OPG8.3-3.0 to make trap OPGC8.5-3.6. Jars were affixed together by cutting the bottom off the upper jar and sliding it over the threaded mouth of the lower jar; the glue was applied between the two jars and inside the trap creating a ridge (~1 mm wide and ~2 mm thick) on the inside perimeter of the trap. Jars were affixed in this way so the traps would still present a smooth surface to the oncoming flow; however, the effect of the inside ridge on eddies circulating inside the traps is unknown.

The specific trap designs tested in a given series are listed in the third column of Table 1. During each series, three replicates of each trap design were tested. During series 7/10/82, 7/22/82 and 8/24/82, the order of testing replicates of all trap designs was determined from a random-number table. For series 6/24/82, replicates of the two trap designs (see Table 1), tested for each of the 4.5, 6.5, 8.5, and 16.5 min intervals, were randomized over the whole series. However, during series 6/7/82, all traps

Table 2. Trap dimensions.

Trap design	Trap code[a]	Wall thickness (cm)	Height (cm)	Inside mouth diameter (cm)	Maximum outside diameter at trap mouth (cm)	Average measured trap volume (ml) ( ) = N
tenite butyrate cylinder	TBC1.7-3.0	0.1	5.2	1.7	1.9	13 (6)
tenite butyrate cylinder	TBC3.6-3.1	0.1	11.2 ± 0.1	3.6	3.8	116 (6)
tenite butyrate cylinder	TBC7.4-2.9	0.15	21.8 ± 0.1	7.4	7.7	909 (5)
tenite butyrate cylinder	TBC14.7-2.9	0.4	43.9	14.7	15.5	7179 (6)
tenite butyrate cylinder	TBC14.7-1.6	0.4	23.6 ± 0.2	14.7	15.5	3705 (3)
tenite butyrate cylinder with funnel inside	TBF14.7-1.6	0.4	24.0 ± 0.2 (funnel = 6.2 ± 0.2)	14.7 (funnel = 7.8 ± 0.2)	15.5	3698 (3)
opaque polyethylene cylinder	OPC8.5-1.0	0.1	8.7 ± 0.1	8.5 ± 0.1	8.7	478 (12)
opaque polyethylene cylinder	OPC8.5-1.9	0.1	16.0 ± 0.1	8.5 ± 0.1	8.7	939 (11)

opaque polyethylene cylinder with funnel inside	OPF8.5-1.9	0.1	16.0 ± 0.1 (funnel = 6.5 ± 0.1)	8.5 ± 0.1 (funnel = 1.1 ± 0.1)	8.7	459 (9)
opaque polyethylene cylinder with funnel inside	OPF8.3-1.9	0.1	16.0 ± 0.1 (funnel = 7.5 ± 0.1)	8.3 ± 0.1 (funnel = 1.1 ± 0.05)	8.7	388 (3)
opaque polyethylene cylinder	OPC8.5-2.7	0.1	22.8 ± 0.2	8.5 ± 0.1	8.7	1349 (43)
opaque polyethylene[β] cylinder with plate surrounding mouth	OPP8.3-2.7	0.1	22.9 ± 0.3	8.3 ± 0.1	15.2 ± 0.1	1457 (3)
opaque polyethylene cylinder	OPC8.5-3.6	0.1	30.2 ± 0.1	8.5 ± 0.1	8.7	1820 (15)
opaque polyethylene[β] cylinder with funnel on top	OPF14.1-1.6	0.1	22.8 ± 0.2	14.1 ± 0.1	14.5	1788 (3)
opaque polyethylene gallon jar	OPG8.3-3.0	0.1	24.9 ± 0.1	8.3 ± 0.1	8.5[δ]	3787 (12)
opaque polyethylene gallon jar with cylinder on top	OPGC8.5-3.6	0.1	30.7 ± 0.1	8.5 ± 0.1	8.7[δ]	4150 (3)

α. Traps will be referred to in the text and in tables and figures by these "trap codes"; the first two letters refer to the material the trap is made of, the letter(s) that immediately follow refer(s) to the trap geometry, the number before the hyphen refers to the inside mouth diameter, and the number following the hyphen refers to the aspect ratio (the ratio of trap height to inside mouth diameter).

β. Results not reported here (see Hannan, 1984a).

δ. Maximum body diameter = 15.2 cm.

collecting for 4.5 min intervals were tested successively, followed by all traps collecting for 6.5 min intervals, and then for 8.5 min intervals; replicates of the four trap designs (see Table 1) were randomized, separately, within these three blocks of time.

Before testing, all traps were scrubbed and rinsed several times with prefiltered (through 0.45 μm Metricel filters) deionized water and then capped. A trap first was secured in the basket on the pedestal and then the cap was removed to mark the start of the collecting interval. At the end of the interval the trap was capped in place and then removed from the flume. Traps were stored in a cold room at 6 ± 1°C and processed as for the water samples.

Traps collected beads for intervals of ~8.5 min; this collecting interval was experimentally determined as the minimum period of time necessary for trap collections to reach steady state (see Hannan, 1984a). Three pairs of water samples were taken, at intervals ~4 min apart, during each trap collecting interval: one pair immediately after the trap was uncapped in the flume, one pair at the midpoint of the interval, and one pair immediately before capping the trap at the end of the interval. Doubling the sampling frequency during an interval did not significantly improve estimates of the mean concentration or of the variability in particle concentration (see Hannan, 1984a). Care was taken to slowly and smoothly lower and raise the pump sampling apparatus during trap collections to minimize these disturbances to the flow. Usually 2 min lapsed between adjacent trap collections.

3. Calculations of relative particle collection efficiencies and error estimates

The particle collection efficiencies (E) of the traps were calculated by dividing the corrected weight of beads collected in a trap (B_t) by a predicted collection estimate (B_p). The relative particle collection efficiencies (E_r) were obtained by normalizing the particle collection efficiencies for all trap designs tested in a given series by the mean particle collection efficiency (E_s) for trap OPC8.5-2.7 in that series. Trap OPC8.5-2.7 was the only trap design tested in all series. Variability in conditions between the series (probably in the bead mixtures, see 5.a.) resulted in different mean efficiencies for this trap design. Thus, normalizations of the data were required if meaningful between-series comparisons of collection efficiencies for different trap designs were to be made. Justification for and implications of this practice are discussed elsewhere (see 5.a.).

B_t, the weight of beads collected by a trap, is the final measured weight of beads in a given trap, B_f (the beads collected on the 0.45 μm filters), minus a correction term, B_w. B_w corrects for beads in suspension in the trap, based on the mean concentration (C_{ap}, mg/l) in the water approaching it during the trap collection interval. This correction was necessary because of the short trap collecting intervals in the flume relative to the field (see Hannan, 1984a) and because V_t (trap volume, ml) differed among the trap designs. An underlying assumption for this calculation is that the concentration of particles in V_t equals the concentration of particles in the oncoming flow.

Table 3. Definitions, approximate ranges in values, and measurement precision for measured terms used in calculating particle collection efficiency.

Measured term	Definition	Approximate range in values	Measurement precision[α]	Range in percent error
T_i	Length of trap collecting interval	510 sec	± 5 sec[β]	1.0
V_{wc}	Volume of water in a water column sample	200–250 ml	± 1 ml[δ]	4.0–5.0
V_t	Volume of water in a trap	12–7179 ml	± 1–5 ml[ε]	0.4–8.3
D	Inside trap diameter	1.9–15.5 cm	± 0.05 cm[γ]	0.3–2.6
		8.3–14.4 cm	± 0.01 cm[λ]	0.7–1.2
AP	Weight of all particles in a water sample collected during seeded flow	1.5–3.0 mg	± 0.14 mg[μ]	4.6–9.3
BP	Weight of all particles in a water sample collected before flow was seeded with beads (Background Particles)	0.1–0.4 mg	± 0.14 mg[μ]	35–140
B_f	Total weight of beads in a trap	1.0–71.5 mg	± 0.14 mg[μ]	0.2–14.0

α. If accuracy is greater than precision, then only precision is given here.

β. T_i was not timed exactly, but standardized procedures were used to maintain T_i at about 510 sec.

δ. Volume measured with a 250-ml graduated cylinder.

ε. Measurement precision depended on size of graduated cylinder used to measure sample volume: for $V_t < 250$ ml, precision = ± 1 ml, for $250 \leq V_t < 500$ ml, precision = ± 2.5 ml, for $V_t \geq 500$ ml, precision = ± 5 ml.

γ. Replicates of these traps were cut from same piece of tubing so precision corresponds to accuracy of ruler (see Table 2 for traps involved).

λ. Replicates of these traps actually varied in size (see Table 2 for traps involved).

μ. This error associated with the humidity correction factor (see Hannan, 1984a).

B_p was calculated as (W_c) (T_i) (A_t) (C_i), where W_c = the calculated fall velocity (cm/sec) of the mean bead diameter in the bead mixture used to seed the flow, T_i = the length (sec) of the trap collecting interval, A_t = the inside trap mouth area (cm^2), and C_i = the mean bead concentration (mg/10^3 cm^3) during the trap collecting interval. $C_i = C_{ap} - C_{bp}$, where C_{bp} is the mean background particle concentration for the series. All of these quantities, except particle fall velocity (W_c), were measured in the study. W_c was calculated from Stokes' equation for the mean bead diameter (24.8 or 46.8 μm) of the bead mixture used to seed the flow and for the water temperature (to 0.1°C) during the collecting interval.

Table 4. Definitions, approximate average values and average percent error for derived terms used to calculate particle collection efficiency.

Derived term	Definition	Approximate average value$^{\alpha}$	Average percent error
A_t	$\pi (D/2)^2$	54.11 ± 1.31 cm^2	2.4
C_{ap}	AP/V_{wc}	10 ± 0.72 mg/l	7.2
C_{bp}	BP/V_{wc}	1.0 ± 0.64 mg/l	64
C_i	C_{ap}-C_{bp}	9.0 ± 0.72 mg/l	8.0
W_c	$\dfrac{d^2 (\rho_p-\rho_f)g}{(0.75)(24)\mu_f}$	0.525 ± 0.0052 cm/sec	10.0
B_p	$(W_c)(T_i)(A_t)(C_i)$	13.36 ± 1.39 mg	10.4 (range = 0.2–22.9)
B_w	$(V_t)(C_{ap})$	14.50 ± 1.04 mg	7.2
B_t	B_f-B_w	15.50 ± 0.88 mg	5.7
E	B_t/B_p	1.16 ± 0.12 mg	10.3 (range = 4.3–18.1)

α. For 25 μm bead mixture, a trap 8.3 cm in diameter and 14.50 ml in volume and for B_f = 30 mg.

β. An approximately 10% error between Stokes' fall velocities and measured fall velocities of various spheres (with known d and ρ_p, but not the particles used here) with fall velocities between 0.0566 and 2.80 cm/sec was determined in Hannan (1984a).

A summary of definitions, average values and precision estimates for the measured and derived terms involved in calculating E are listed in Tables 3 and 4, respectively. Sources of error could be determined and estimated in this study for all terms, except W_c. For W_c, only the accuracy of Stokes' fall velocities could be estimated (see footnote β to Table 4). This approximately 10% error seems reasonable, albeit conservative, regarding the calculation of a Stokes' fall velocity for a sphere of a given size; however, for calculating B_p, a potentially much larger source of error arises from using W_c for only the mean bead diameter in a mixture when a spectrum of bead sizes were actually available to and collected by traps. For example, error that may vary between traps and between series and that could not be estimated in this study would result if, (1) the bead mixtures contain other dominate modes that were not detected in the Coulter Counter size analysis, such that their probability distributions are not described by a normal curve, (2) the flume water approaching the traps and the trap contents contained particle mixtures with size-frequency distributions that differed from those determined by the Coulter Counter (i.e., if particle sorting occurred during experiments so that certain particle sizes were rendered unavailable to the traps), and/or (3) traps differentially collect certain particle sizes (see Butman *et al.*, 1986) from the range of particles available in the bead mixture used in this study. These potential problems are evaluated and discussed in detail later (see 5.a.).

The mean measurement error in E, for the average conditions listed in Table 4, is 10.3%, ranging between about 4.3 and 18.1% if all possible combinations of the error terms for B_t and B_p are used in separate calculations of E. Thus, the coefficient of variation (CV) surrounding the mean value of E determined for replicate tests of an "average" trap design is expected to be about 10% *due to measurement error alone.* Errors greater than about 10% must result from either the hydrodynamic characteristics of the trap or from another unknown source of error (i.e., an undetected methodology problem).

4. Results

a. Particle collection efficiencies of one trap design tested in all series. Replicates of trap OPC8.5-2.7 were tested during all of the series, for comparative purposes. Mean efficiencies (E) of this trap design varied significantly between some series (Fig. 5), requiring normalizations of collection efficiencies for between-series comparisons (as discussed in 3.). For the series with 25 μm bead mixtures (series 6/24/82, 7/10/82 and 7/22/82) that were not ensonified, the ranges in replicate particle collection efficiencies overlapped among the three series; however, collection efficiencies tended to be higher in the 7/22/82 series than in the other two. The range in replicate particle collection efficiencies for the 6/7/82 series overlapped only with the range of values for the 7/22/82 series. All particle collection efficiencies in series 8/24/82 (the only series where bead mixtures were ensonified) were about twice the values of the collection efficiencies during the other series. However, the percent CV for replicate collections during each series (Fig. 6) varied between 5.3 and 22.6 (mean = 14.0, SD = 6.6), and thus, was close to the estimated 4.3 to 18.1 average percent measurement error (see Table 4).

b. Measured particle collection efficiencies: variability between replicates. The variability surrounding the mean E_r values calculated for all traps tested in this study ranged from CV = 0.1% to CV = 42.0% (mean = 16.1 for N = 37). This mean 16% imprecision is higher than the estimated average total measurement error of 10%, but is within the predicted 4 to 18% total range in measurement error. However, the CV for the mean E_r values of over a third of the traps tested was between 20 and 42% suggesting that factors, other than just those included in measurement-error calculations, contributed to the variability in replicate particle collections by these trap designs. For determining statistically significant differences between or among trap designs, the nonparametric Mann-Whitney U (Siegel, 1956) and Jonckheere (Hollander and Wolfe, 1973) tests were used.

c. Effect of trap Reynolds number on particle collection efficiency. Butman *et al.* (1986) hypothesized that, for a given trap aspect ratio and particle size class, collection efficiency will decrease over some range of increasing R_t. This hypothesis was supported by the results of trap tests during two different series over R_t (defined in caption to Fig. 7) ranging from 2.2×10^3 to 1.9×10^4. Three cylindrical trap designs

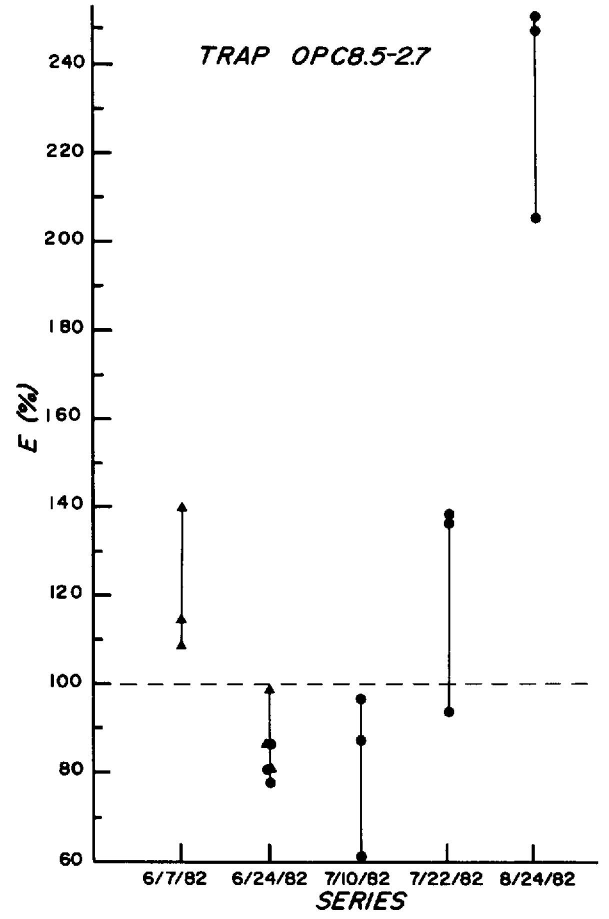

Figure 5. Particle collection efficiencies (E) of trap OPC8.5-2.7 during all five series. These efficiencies have not been normalized (see 3. in text). Solid triangles are for traps positioned 34 cm above the flume bottom and solid circles are for traps positioned 47 or 51 cm above the bottom (see Table 1). Vertical bars connect replicate values.

(traps TBC1.7-3.0, TBC3.6-3.1, and TBC7.4-2.9) with similar aspect ratios (of ~3.0), but different mouth diameters (and thus, with R_t ranging from 2.2×10^3 to 9.2×10^3) tested during series 7/10/82 showed a significant decrease in E_r with increasing R_t (Fig. 7). The null hypothesis (H_0) of no difference in E_r among these trap designs was rejected at $\alpha \leq 0.0018$ in favor of the ordered alternative hypothesis (H_a) that E_r decreased with increasing R_t, using the Jonckheere test. During series 7/22/82, these three trap designs were tested again, along with even a larger-diameter cylindrical trap (trap TBC14.7-2.9, with an R_t of 1.8 to 1.9×10^4 during this series). Again, E_r decreased with increasing R_t (Fig. 7), but the H_0 could be rejected only at $\alpha \leq 0.0907$,

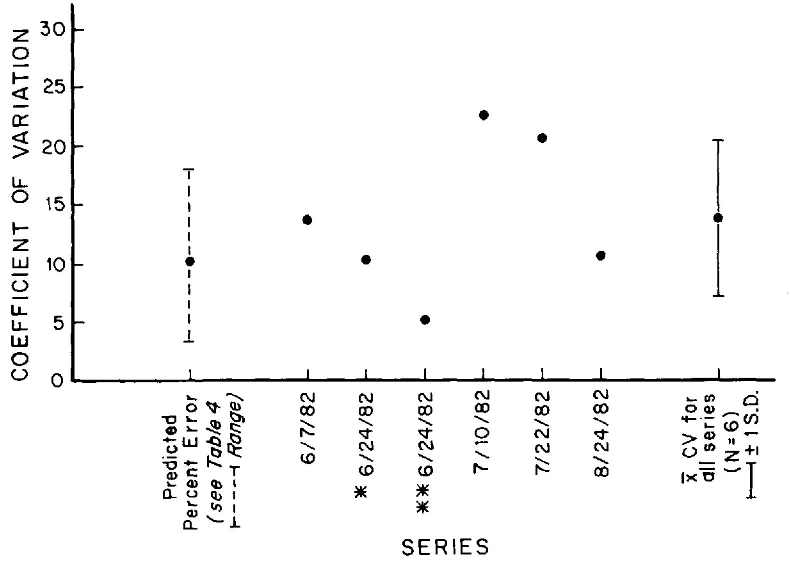

Figure 6. Coefficient of variation for collections by trap OPC8.5-2.7 during all five series and the predicted percent error, based on the error analysis (see Tables 3 and 4). $N = 3$ for each series, except for 6/24/84 where 3 traps were tested at 34 cm above the flume bottom (*) and 3 traps at 47 cm above the flume bottom (**).

in favor of the ordered H_a (Jonckheere test) for tests during this series. It appears that, after a sudden drop in E_r between $R_t = 2.2 \times 10^3$ and $R_t = 4.6 \times 10^3$, an asymptotic value of E_r is approached for R_t between 4.6×10^3 and 1.9×10^4 (Fig. 7). A second test of trap TBC14.7-2.9, during series 8/24/82, yielded E_r values within the range of those determined in series 7/22/82 (Fig. 7). Thus, for nearly an order of magnitude increase in R_t, the mean E_r dropped by about a factor of two.

Results for the standard cylinder, trap OPC8.5-2.7, are not plotted on the R_t-figure because it is constructed of thinner-walled plastic (see Table 2) with a different surface roughness (the tenite butyrate is much smoother than the polyethylene) and because of the threads at the trap mouth, all of which may result in different collection efficiencies between the cylindrical trap designs. The relatively large difference of 25–30% in mean collection efficiency between OPC8.5-2.7 and TBC7.4-2.9, both collecting at an $R_t \sim 1 \times 10^4$, must be explained mechanistically, however, for the R_t-effect demonstrated in Figure 7 to be upheld. Possible explanations are discussed later (see 5.b.).

d. Effects of trap aspect ratio and baffles on particle collection efficiency. Butman *et al.* (1986) hypothesized that, for a given trap Reynolds number and particle size class, collection efficiency will increase over some range of increasing trap aspect ratio, as shown in several previous studies (see reviews of Bloesch and Burns, 1980; Blomqvist

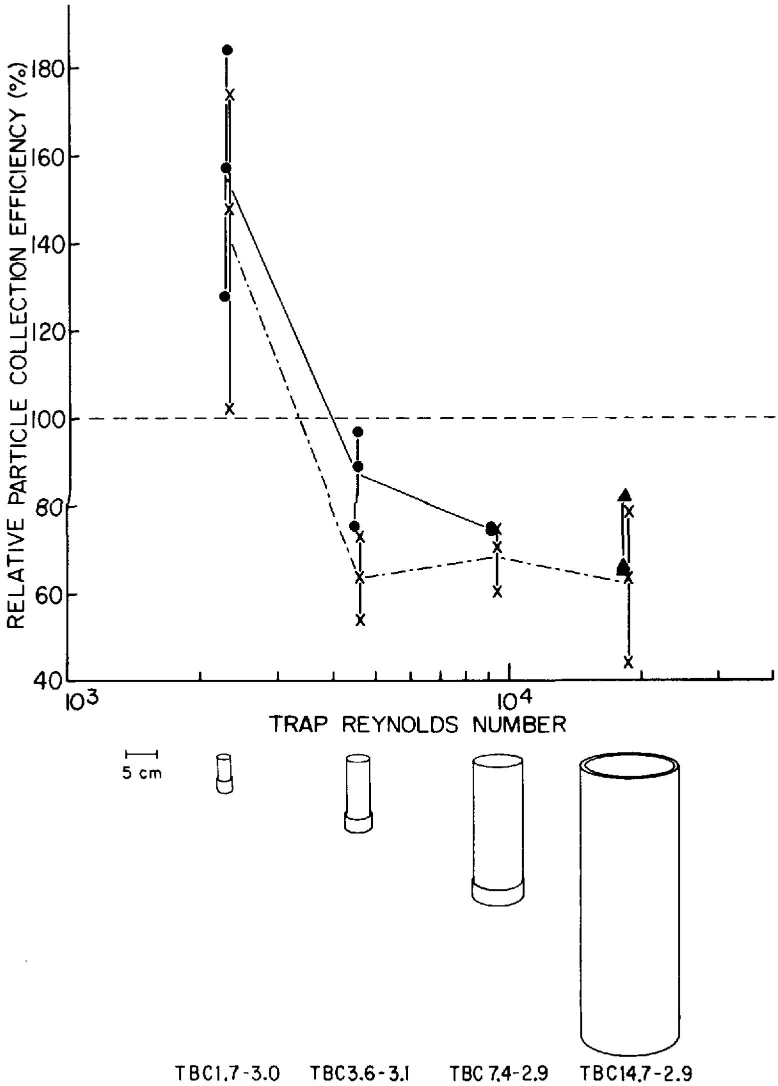

Figure 7. Relative particle collection efficiency (E_r) versus trap Reynolds number (R_t) for straight-sided cylinders. The traps are drawn to scale below the figure. R_t was calculated as DV/ν, where D = outside trap diameter at the trap mouth, V = flow speed at the trap mouth during the trap collecting interval and ν = kinematic viscosity for freshwater at the water temperature that occurred during the trap collecting interval. Solid circles show traps tested during series 7/10/82, crosses for during series 7/22/86 and solid triangles for during series 8/24/82. Vertical bars connect replicate values. The solid line connects mean values for series 7/10/82 and the dot-and-dashed line connects mean values for series 7/22/82.

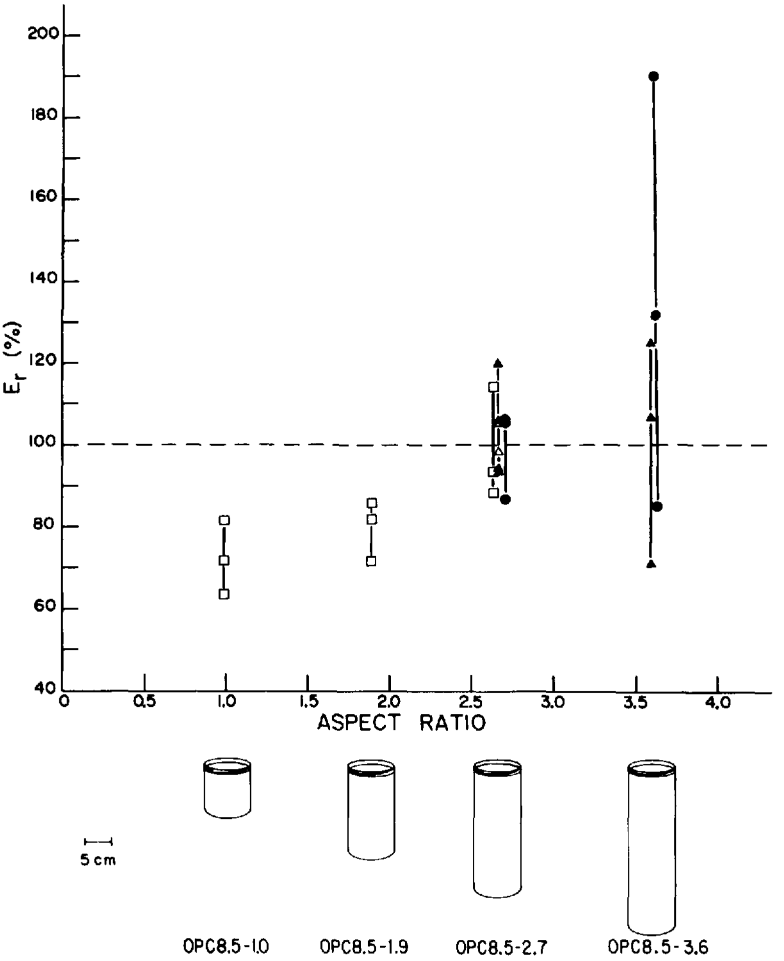

Figure 8. Relative particle collection efficiency (E_r) versus trap aspect ratio (H/D) for cylinders with screw-cap mouth openings. The traps are drawn to scale below the figure. Traps OPC8.5-1.0, OPC8.5-1.9 and OPC8.5-2.7 were tested during series 6/7/82 (open squares). Traps OPC8.5-2.7 and OPC8.5-3.6 were tested during series 6/24/82 (solid triangles for 47 cm above the bottom, open triangles for 34 cm above the bottom) and during series 8/24/82 (solid circles). Vertical bars connect replicate values.

and Hakanson, 1981). This hypothesis was supported for tests of traps with $R_t \sim 1 \times 10^4$ and aspect ratios ranging from 1.0 to 2.7, where E_r increased 40% (Fig. 8). For series 6/7/82, the H_0 of no difference in collections between the trap designs (see Fig. 8) could be rejected at $\alpha \leq 0.039$ in favor of the ordered H_a that E_r increases with increasing aspect ratio, using the Jonckheere test. However, the mean E_r values are not significantly different between the aspect ratios of 2.7 and 3.6, again for $R_t \sim 1 \times 10^4$.

In Mann-Whitney U tests, the H_o could be rejected only at $\alpha \leq 0.452$ during series 6/24/82 (using all six replicates of trap OPC8.5-2.7, see Fig. 8) and the H_o could be rejected only at $\alpha \leq 0.350$ during series 8/24/82, so the H_o was accepted in both cases. However, replicate collections by trap OPC8.5-3.6 were more variable than replicate collections by trap OPC8.5-2.7, even if the one anomalously high E_r for OPC8.5-3.6 during series 8/24/82 (see Fig. 8) is excluded. For example, the CV was 21.3% for trap OPC8.5-3.6 compared to 5.3 and 10.4% for the two sets of three replicates of trap OPC8.5-2.7 during series 8/24/82.

For the range of aspect ratios tested here, 2.7 may represent the smallest ratio at the asymptotic mean E_r of ~100%; however, careful scrutiny of laboratory processing techniques to determine if this data point was spurious due to technician error (= author error, in this case) revealed no justification for its dismissal. There is also a suggestion from the data that between-replicate variability may increase with increasing aspect ratio, but certainly more experiments are needed.

Several researchers (e.g., Soutar *et al.*, 1977; Gardner, 1980b and see also review by Bloesch and Burns, 1980) have implied that inserting baffles with high aspect ratios into traps with low aspect ratios should increase the collection efficiency of these traps relative to the unbaffled case, by reducing turbulence at the trap mouth. Baffles can be viewed as a collection of individual, but adjacent, traps having relatively high aspect ratios. If particle collection efficiencies of unbaffled cylinders increase with increasing aspect ratio until some asymptotic value of collection efficiency is reached, then an improvement in particle collection efficiency by baffling is expected only for traps with aspect ratios below this asymptotic range. In addition, the aspect ratio of the baffle cells must be larger than the smallest trap aspect ratio at the asymptotic value of particle collection efficiency.

To test this baffling hypothesis, honeycomb baffles (described in footnote ρ to Table 1) with individual cell aspect ratios of 7.8 were inserted into traps OPC8.5-1.0, OPC8.5-1.9, and OPC8.5-2.7 during series 8/24/82. The top of each baffle was precisely flush with the trap mouth. During this series, two other modifications to trap OPC8.5-2.7, as well as the unmodified trap, also were tested: screened (see footnote ν to Table 1) traps and traps where the baffle was pushed down to sit on the bottom of the trap. For the top-baffled traps, E_r values again significantly increased with increasing aspect ratio, this time by ~180% between the aspect ratios of 1.0 and 2.7 (Fig. 9). The H_o of no difference in collections among the traps could be rejected at $\alpha \leq 0.0048$ in favor of the ordered H_a that E_r increases with increasing trap aspect ratio, using the Jonckheere test.

A comparison of the results for baffled traps tested during series 8/24/82 and unbaffled traps tested during series 6/24/82 (Fig. 9) indicates that only results for trap OPC8.5-1.0 violated the predictions. E_r values were significantly (i.e., the ranges in E_r values did not overlap) different for baffled versus unbaffled versions of trap OPC8.5-1.9. In fact, baffling this trap design brought the E_r values for trap

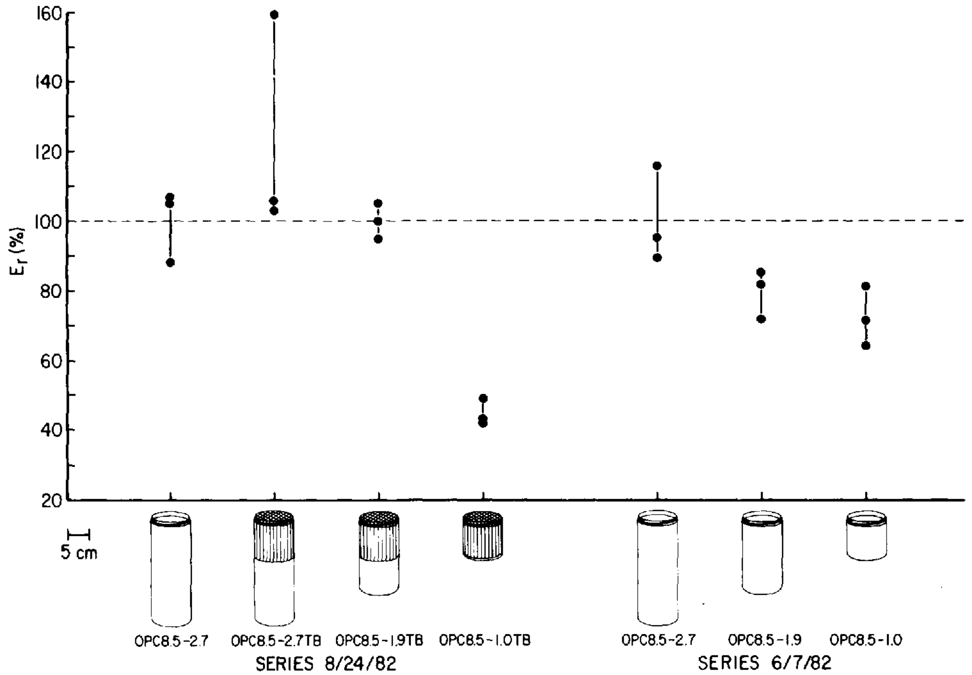

Figure 9. Relative particle collection efficiency (E_r) for baffled cylinders with different aspect ratios (H/D). The traps are drawn to scale below the figure. Vertical bars connect replicate values. Note that the 46 μm bead mixture was used during series 6/7/82 and the ensonified 25 μm mixture during series 8/24/82 (see Table 1).

OPC8.5-1.9 within the range of the E_r values for trap OPC8.5-2.7, as would be expected for traps below the asymptote. E_r values overlapped for baffled versus unbaffled versions of trap OPC8.5-2.7, as is consistent with the baffling argument for traps at the asymptote. However E_r values for baffled versions of trap OPC8.5-1.0 were significantly (i.e., the ranges in E_r values did not overlap) lower, by a factor of about two, than for unbaffled traps.

Tests of the four versions of trap OPC8.5-2.7 during series 8/24/82 (Fig. 10) indicate that any obstruction to flow at or through the mouth of this trap increases the between-replicate variability in collections, but does not significantly change the mean E_r values. While the ranges in E_r values overlapped for all four trap designs, the percent CV increased from 10.8 for the unmodified version, to 20.2 for the screened version, to 25.6 for the top-baffled version, and to 42.0 for the bottom-baffled version. There also is evidence (Fig. 10) that the threads at the mouth of the opaque plastic cylinders enhance both the mean E_r and the CV for these traps relative to the tenite butyrate traps, which are straight-sided at the mouth; however, as mentioned previously (see 4.c.), there are other differences between these trap designs. During series 7/10/82

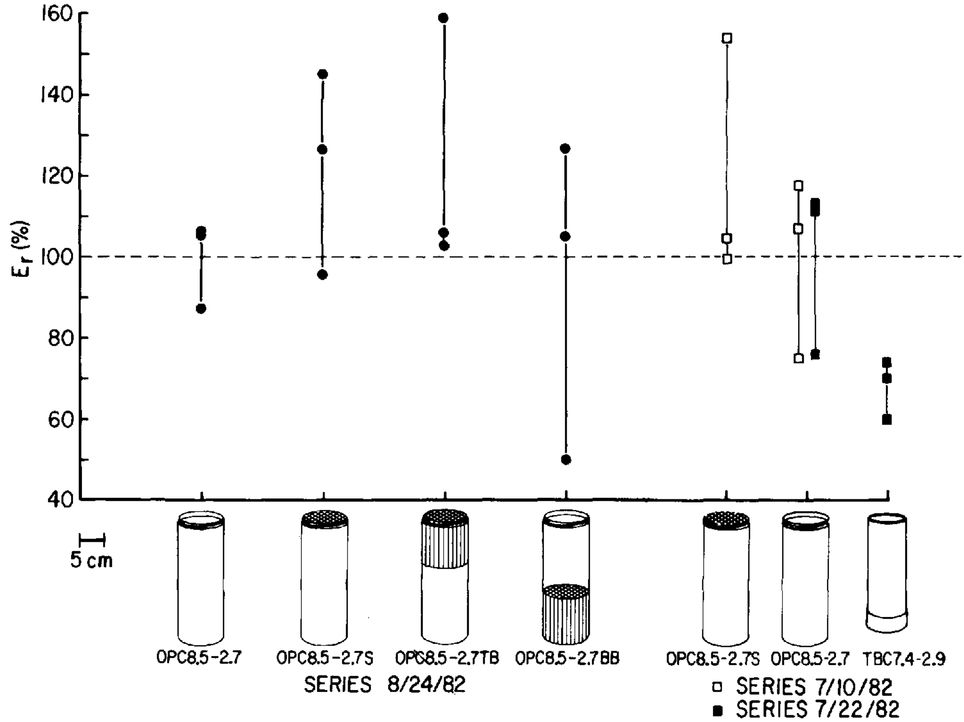

Figure 10. Relative particle collection efficiency (E_r) for cylinders with aspect ratios (H/D) of ~3.0, showing effects of obstructions to flow through the mouth opening (e.g., by screening or baffling). Traps are drawn to scale below the figure. Vertical bars connect replicate values.

and 7/22/82, the mean E_r for trap TBC7.4-2.9 was 25.2 and 31.7% lower, respectively, than the mean E_r for trap OPC8.5-2.7.

e. Effects of trap geometry on particle collection efficiency. Butman *et al.* (1986) hypothesized that, for a given trap Reynolds number, trap aspect ratio and particle size class, small-mouth, wide-body traps generally will be overcollectors and funnel-type traps generally will be undercollectors, relative to cylinders with the same mouth diameter, as demonstrated by others (see previously cited reviews). Their theoretical analysis also indicated that small-mouth, wide-body traps could be undercollectors and funnel-type traps could be overcollectors for a very limited range of parameter combinations (see Table 4 in Butman *et al.*, 1986). In the present study, the two small-mouth, wide-body traps tested were overcollectors and two of the funnel-type traps tested were undercollectors, but collections by a screened version of one funnel-type trap design did not significantly differ from collections by a cylinder with the same mouth diameter.

The small-mouth, wide-body trap, OPG8.3-3.0, tested during three series with R_t

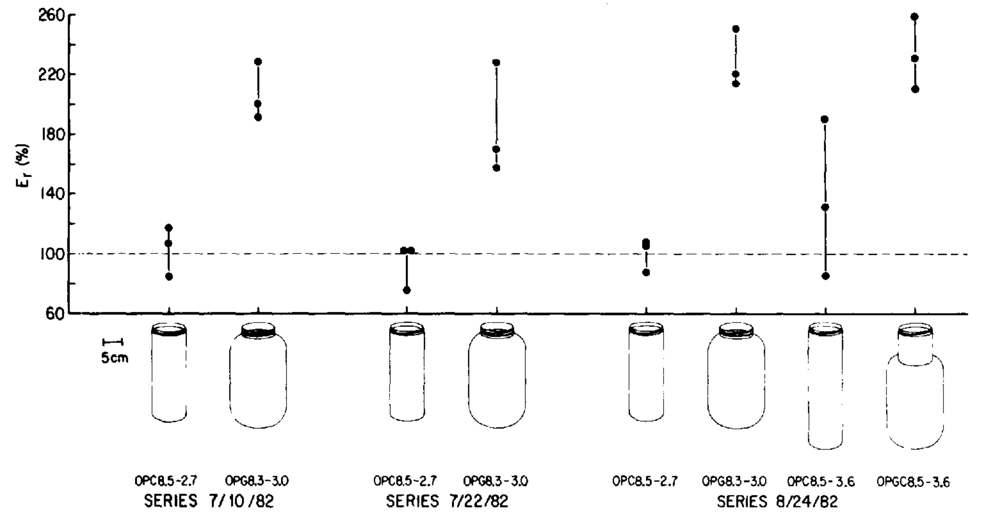

Figure 11. Relative particle collection efficiency (E_r) for cylindrical versus small-mouth, wide-body traps. Traps are drawn to scale below the figure. Vertical bars connect replicate values.

from 1.0×10^4 to 1.1×10^4, always overcollected particles relative to cylinders with a similar height and mouth diameter (trap OPC8.5-2.7, $R_t = 1.0 \times 10^4$ to 1.1×10^4 for these three series) (Fig. 11). To determine to what extent the geometric shape of the trap directly below the trap mouth determines particle collection efficiency, another small-mouth, wide-body trap design (OPGC8.5-3.6) was tested. This trap had a cylindrical trap geometry (with an aspect ratio of 1.0) for a distance of 8.7 cm below the trap mouth, but then flared into the wider body of trap OPG8.3-3.0 (see 2.c.). The *a priori* hypothesis was that relative particle collection efficiencies of this new trap (OPGC8.5-3.6) should be similar to the efficiencies of a straight-sided cylinder of similar height and mouth diameter (trap OPC8.5-3.6) if trap geometry within the cylindrical-trap distance of the trap mouth determined particle collection efficiency. This H_o was rejected at $\alpha \leq 0.05$ (Mann-Whitney U test) in tests of these two trap designs during series 8/24/82 (Fig. 11), for R_t ranging from 1.0×10^4 to 1.1×10^4. In fact, values of E_r for trap OPGC8.5-3.6 encompassed the range in values for trap OPG8.3-3.0, tested during this series.

At R_t ranging from 1.1×10^4 to 1.2×10^4, the funnel-type traps, OPF8.5-1.9 and OPF8.3-1.9, were undercollectors relative to the cylinder, OPC8.5-1.9 (Fig. 12), as long as the washings from the walls of the funnel (hereafter called "funnel-washings") were not considered part of the trap contents; this is consistent with the efficiency definition used by Butman *et al.* (1986). At R_t ranging from 1.8×10^4 to 2.0×10^4, collections by the screened funnel-type trap, TBF14.7-1.6S, were not significantly different from collections by the cylinder, TBC14.7-1.6, whether or not the funnel-

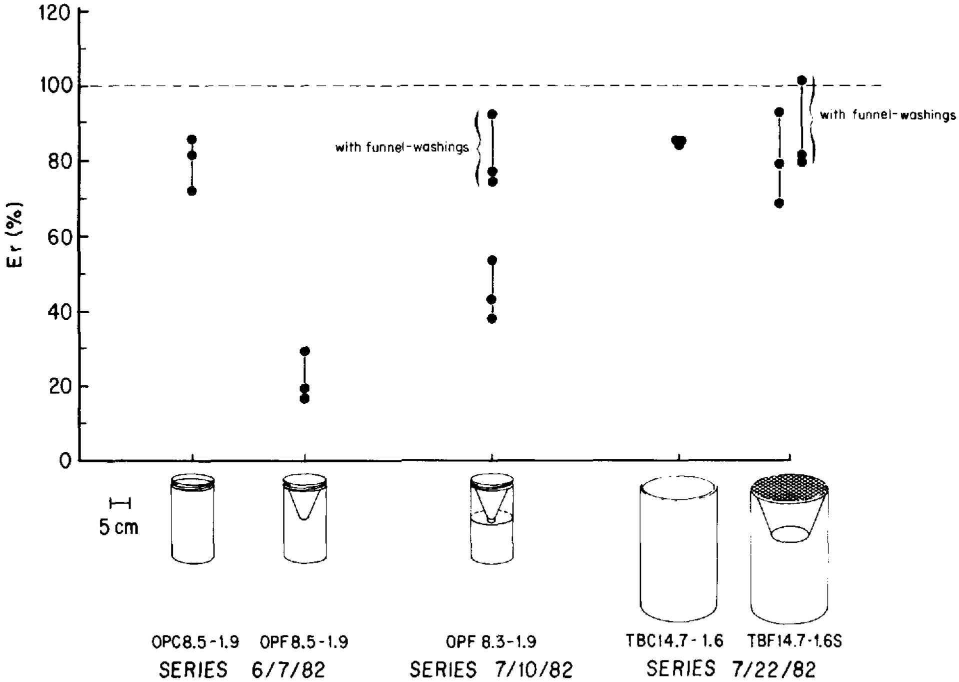

Figure 12. Relative particle collection efficiency (E_r) for cylindrical versus funnel-type traps. Traps are drawn to scale below the figure. For funnel-type traps, OPF8.3-1.9 and TBF14.7-1.6S, E_r was calculated both for when the material adhering to the interior funnel walls was included as part of the trap collection ("with funnel-washings" on the figure) and when only material collected on the trap bottom was included.

washings were included as part of the trap contents. The presence of a screen (described in footnote ν to Table 1) on the funnel-type trap may have increased the mean E_r value and the between-replicate variability in collections by this trap design, relative to collections by unscreened versions of this trap. However, when screened versus unscreened versions of trap OPC8.5-2.7 and trap OPG8.3-3.0 were tested simultaneously (see Table 1), the mean E_r values for screened and unscreened traps were not significantly different, and the percent *CV* was substantially higher for a screened trap versus an unscreened trap only in one case (shown in Fig. 10).

f. Visualization of flow patterns near the mouths of several trap designs. The general pattern of flow through all trap designs tested was similar to that observed at lower R_t (by about an order of magnitude) by Gardner (1980a) and at similar R_t by Gardner (1985). Large eddies (on-the-order-of trap diameter or smaller) were shed over the trap mouth and circulated counter-clockwise (for a flow moving from right to left) (see Figs. 13B, 14A, 14B, 15A). Dye was observed entering only the downstream inside

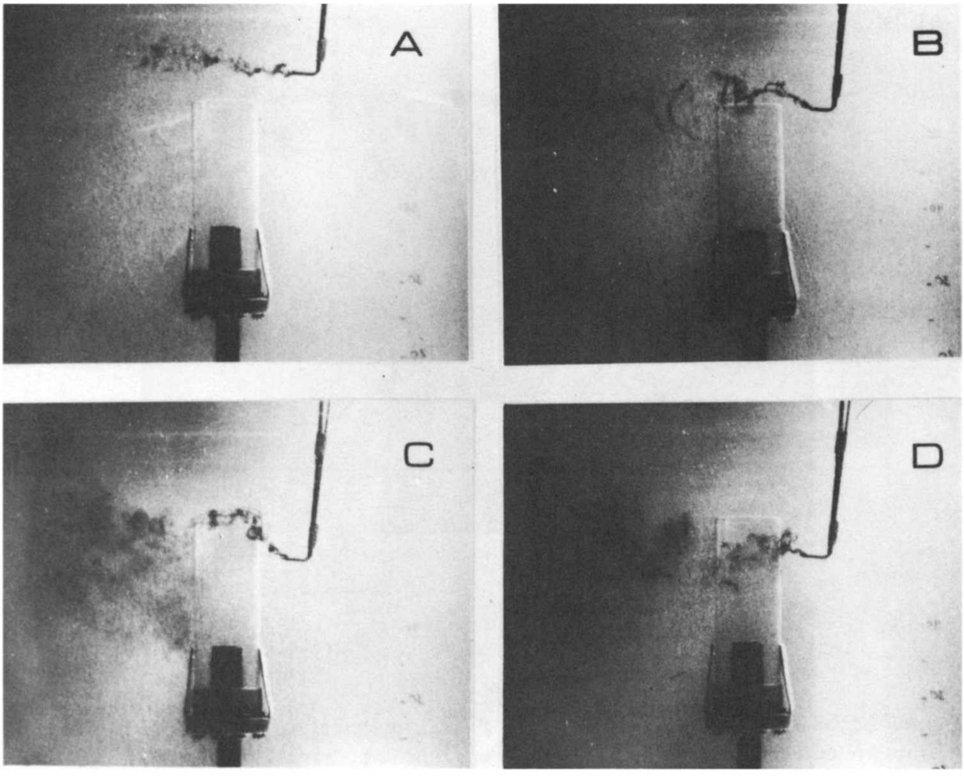

Figure 13. Patterns of flow near the mouth of trap TBC7.4-2.9. The vertical distance between the probe and the trap mouth was 3.1 cm in (A), 1.0 cm in (B), 4.2 cm in (C) and 4.7 cm in (D).

perimeter of the trap mouths (e.g., see Fig. 14A); it circulated through the traps in a counter-clockwise cell (e.g., see Fig. 15C) and then exited the trap mouths at their upstream perimeter (e.g., see Fig. 15D), as also noted in Gardner (1985). Only fluid within a distance of about 1 cm above the trap mouths was entrained by the traps (compare Figs. 13A and 13B), although quantitative estimates were made only for some of the trap designs. The distance below the trap mouth for which the oncoming fluid veered up over the trap, rather than moving around it, apparently differed, depending on the trap geometry or, perhaps, on the dimensions of the trap tested. For the cylindrical trap, TBC7.4-2.9, fluid 4.2 cm below the trap mouth veered up over it (Fig. 13C), while fluid 4.7 cm below the trap mouth (or a distance of about a fifth of the trap height) moved around it (Fig. 13D). For a small-mouth, wide-body trap (similar in design to trap OPG8.5-3.0, but having slightly different dimensions), fluid 8.7 cm below the trap veered up over it (Fig. 15A), and fluid 11.4 cm below the trap (a distance of about a third of the trap height) moved around the trap (Fig. 15B). Since

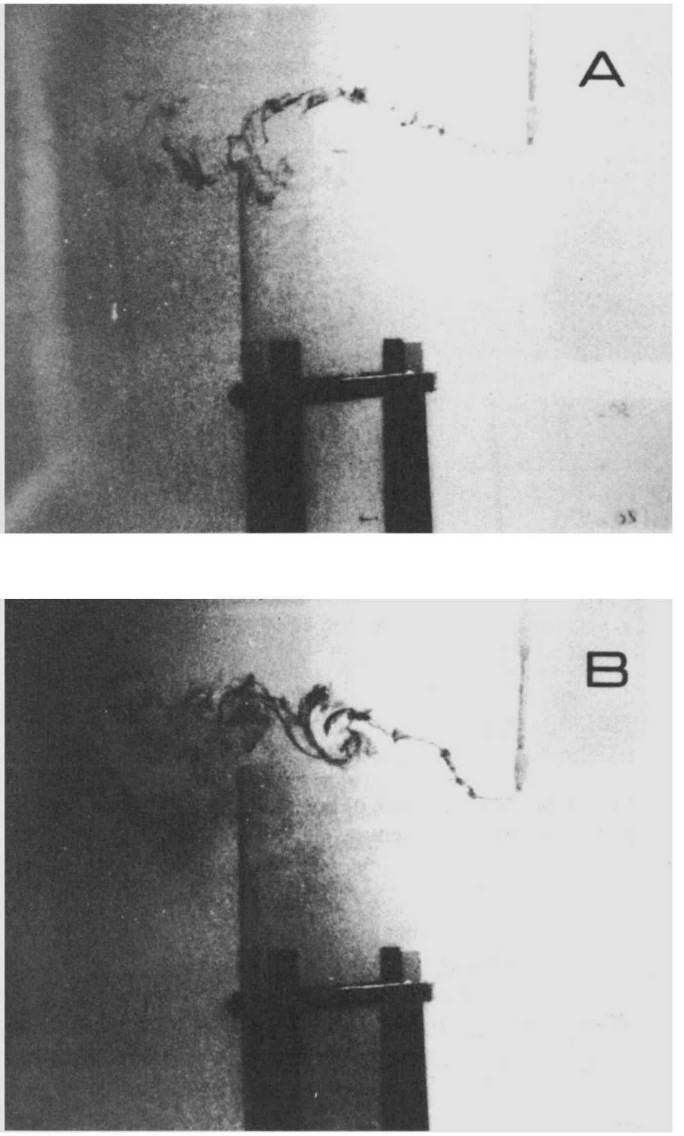

Figure 14. Patterns of flow near the mouth of trap TBC14.7-1.6. The probe was about level with the trap mouth in (A) and was 3.2 cm below the trap mouth in (B).

these two traps had similar mouth diameters and heights, these fluid entrainment differences are most likely attributed to differences in trap geometry. This phenomenon was not quantified for any other trap designs, so the importance of differences in mouth diameter or height cannot be assessed.

It was difficult to observe the flow through the two small-diameter cylinders (traps

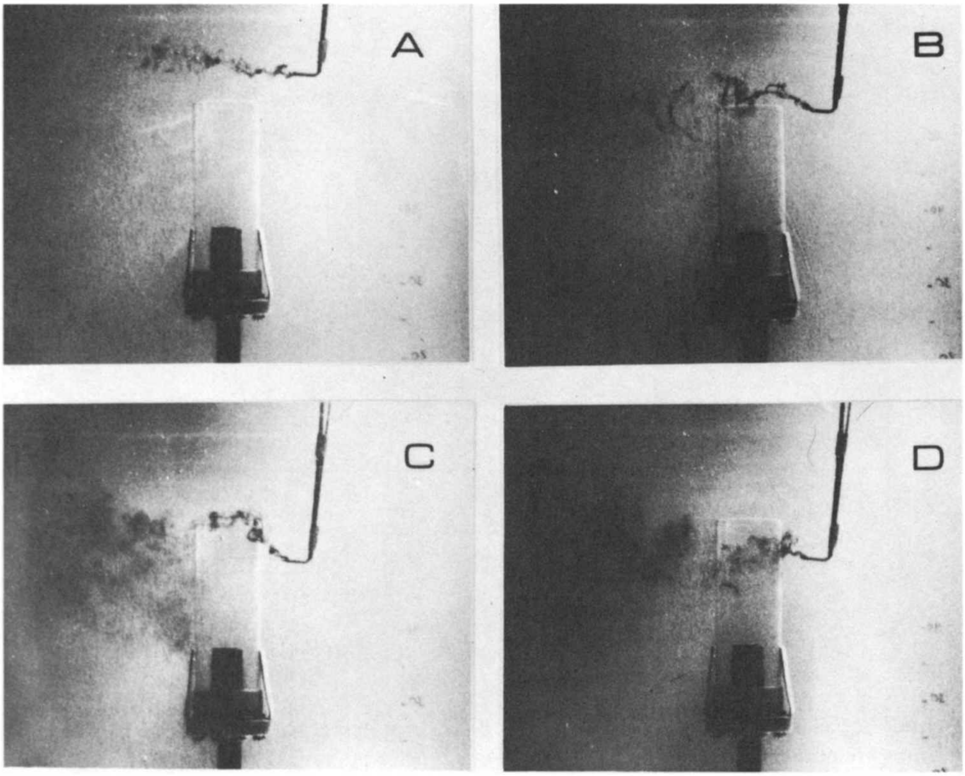

Figure 15. Patterns of flow near the mouth of a trap similar in design to trap OPG8.3-3.0. The vertical distance between the probe and the trap mouth was 7.0 cm in (A), 11.4 cm in (B), 9.7 cm in (C) and 17.8 cm in (D).

TBC1.7-3.0 and TBC3.6-3.1) because the dye streak produced by the probe was thick, compared to these mouth diameters, such that the flow was quickly mixed inside the traps. However, the author did observe that eddies, on-the-order-of trap diameter and even larger, were often shed in the lee of these traps rather than over the trap mouth. This was not observed for the larger trap designs.

The pattern of flow at the mouth of a funnel-type trap (shown in Hannan, 1984a) was similar to the pattern of flow at the cylinder mouths and also similar to flow patterns observed in funnels by Gardner (1980a, 1985). The funnel severely limited the exchange of dye between the funnel and the trap interior. Thus, a circulating cell of fluid penetrating to the trap bottom was not observed inside the cylinder below the funnel, though eddies certainly penetrate to the neck of the funnel proper.

5. Discussion

a. The problem of estimating absolute efficiency to calibrate traps. While this study originally was designed to calibrate sediment traps collecting a specific class of particles in a specific flow regime, it eventually was possible to obtain only *relative* and not absolute particle collection efficiencies. Estimates of absolute efficiencies require knowledge of the vertical flux of particles through an area at the height of and the same size as the trap mouth and of the particulate flux collected by the trap. The total concentration of material can be used to calculate these fluxes only if it can be demonstrated that there is no significant difference in the distribution of fluxes for the various particle sizes and types present in the water mass approaching the trap and in the water collected by the trap (i.e., that traps do not differentially collect certain particle sizes or types). Thus, in addition to total concentration of material, detailed knowledge of the frequency distribution of particle fall velocities in the oncoming flow and in trap collections is required to calculate absolute collection efficiencies.

No flume study of sediment traps, including the present, has made such measurements. The two previous sediment trap calibration studies (Gardner, 1980a; Hargrave and Burns, 1979) have assumed that the particle fall velocity-frequency distributions within their particle mixtures did not differ over both vertical and horizontal scales in their flumes, with time, and with trap design. Both studies used the total change in suspended particle concentration during flume runs to calculate predicted collections by each trap design. In addition, particles within their natural sediment mixtures theoretically (i.e., calculating Stokes' fall velocities for the range of particles in their sediment mixtures) spanned three or four orders of magnitude in fall velocity. The assumption that no hydrodynamic sorting of particles in the oncoming flow occurred during the course of these flume experiments (e.g., larger particles settling out upstream, and thus, being unavailable for collection by downstream traps) was not tested in these studies and seems particularly important because several trap designs were tested in these flumes simultaneously (see Hannan [1984a] for further discussion). However, Gardner (1980a) did test the hypothesis that traps collected particle sizes in proportion to their availability in the flow (assuming that samples of material deposited on the flume bottom represented particle size-class distributions approaching the traps) for noncylindrical trap designs, with encouraging results.

Several measures were taken to decrease the likelihood of hydrodynamic sorting of particles in the flume and of particle size selection in trap collections during this study. (1) The flow was seeded with particle mixtures having relatively narrow ranges in fall velocity, spanning about a factor of two for the 46 μm mixture and about an order of magnitude for the 25 μm mixture. (2) Only one trap was tested in the flume at a time. (3) Particle concentration was measured in the water mass just upstream and at the height of the trap mouth three times during *each* trap collecting interval. (4) The flow regime was turbulent such that total particle concentrations (but not necessarily particles in all size classes) were well-mixed vertically. (5) The flow was *continuously* seeded with rigorously mixed particle suspensions. (6) Trap placement was selected to avoid possible hydrodynamic sorting of particles before the water mass reached the trap; even for laminar flow (i.e., no mixing), the fastest-falling particle in each bead mixture could not fall below any trap mouth before reaching the trap, if the bead began falling from the water surface at the flow entrance. Thus, well-mixed particle concentrations approached the test section. These measures were aimed at eliminating sources of variability or unaccountable error that would prohibit calculations of absolute collection efficiencies. It eventually was clear, however, that such calculations were not possible because I did not directly determine particle fall velocity-frequency distributions in the water approaching the traps and in trap samples, and because efficiencies varied considerably between approximately replicate series for the one trap design (the "standard" trap, OPC8.5-2.7) that was tested in all series.

In the present study, the predicted collection by each trap (B_p) was estimated using the calculated bead fall velocity (W_c) for the mean bead diameter of the mixture used to seed the flow (see 3.). Then, the mean efficiency of the "standard" trap for a given series was used to normalize the data for collections by other traps in that series. This would accurately represent the average vertical flux of particles through the trap mouth if, (1) particles in the flume were present in the same relative abundances as in samples analyzed by the Coulter Counter and if the means of these distributions are equivalent to the arithmetic means calculated here, (2) particles fell individually (i.e., no aggregation or cohesion occurred) and according to Stokes' law, and (3) traps did not differentially collect certain particle sizes from those available (note that particles in the mixtures varied only in size because all were glass spheres). While I have no direct evidence that these three criteria were met, indirect evidence (discussed below) suggests that deviations from each criterion were small and probably did not substantially affect the outcome of this study (e.g., the demonstrated trap biases). However, trap calibration studies where particle fall velocities are closely monitored throughout experiments are required to test this tenet.

If values of B_p calculated in this study are a true representation of vertical flux at the height of the trap mouth, then for an unbiased collector, it is expected that variability in replicate collections during any series would be within the precision estimates calculated for the experiments (see Table 4) and that mean efficiencies would not significantly differ between series. Clearly, there is circularity in these arguments since the goal of this study was to determine which trap designs act as biased or unbiased collectors. However, a conclusion of nearly all previous studies of trap biases is that cylindrical traps with some minimum aspect ratio (to prevent resuspension of the trap contents) should be the least-biased collector (e.g., see reviews by Bloesch and Burns, 1980; Reynolds *et al.*, 1980; Blomqvist and Hakanson, 1981). The aspect-ratio experiments in the present study suggested that this minimum value was 2.7 at R_t of 1×10^4 (Fig. 8); thus, replicates of trap OPC8.5-2.7 were tested in all series to indirectly determine the reliability of the B_p estimates. The percent errors (expressed as CV) for mean collections by this trap design in each series were remarkably similar to the predicted percent error for average conditions during the experiments (see Fig. 6, Table 4 and 4.a.). Thus, the first assumption regarding the reliability of the B_p estimates seems to be upheld, at least for this trap design.

At first glance, it appears that the second and third assumptions are not supported by data for this trap design because efficiencies (E) varied by as much as a factor of two among the series (Fig. 5). However, these results may be explained by the error bars that bracket calculations of the mean bead diameters in the mixtures used to seed the flow, rather than by hydrodynamic sorting of particles in the flume or by differential trapping of specific particle sizes. A small change in bead diameter results in a much larger change in fall velocity, and thus, in collection efficiency because $W \alpha d^2$ in Stokes' equation and $E \alpha 1/W$ (see 3.). I calculated the mean bead diameter of the two bead mixtures by averaging frequencies per size-class interval that were assigned to the arithmetic mean size in each interval. In fact, the distributions of bead sizes within each size-class interval are unknown. For a Coulter Counter size-frequency analysis, if one size class completely dominates a unimodal distribution (i.e., if the mode is narrow, see the 46 μm mixture in Fig. 2b), then the mean is well-bracked within that interval. However, when the mode is broad, consisting of several size-class intervals (e.g., see the 25 μm mixture in Fig. 2a), then the true mean actually could lie within any of the dominate modes. Thus, the true mean is expected to be between 20 and 40 μm in the 25 μm mixture and between 40 and 50 μm in the 46 μm mixture (see Fig. 2).

For lack of any better choice, collection efficiencies were calculated here using the fall velocity for the arithmetic mean bead diameters of the mixtures. However, given the uncertainty in the true means, discussed above, it is interesting to back-calculate the mean bead fall velocity (and thus, the mean bead diameter) required for each series so that collection efficiencies of trap OPC8.5-2.7 would be a constant 100% (see Fig. 5). The results (Fig. 16) are encouraging. For series 6/7/82, involving the 46 μm mixture, the required bead diameters for two of the three replicates are within the modal size-class interval. For the other four series, involving the 25 μm mixtures, the required bead diameters for all replicates, except one, are within the three size-class intervals comprising the mode.

While the required bead diameters for 100% efficiency of trap OPC8.5-2.7 in the five series are within the uncertainty of the mean bead diameter calculations, there also is a trend of increasing bead diameter with increasing Julian date for the 7/10/82, the 7/22/82 and the 8/24/82 series (see Fig. 16). An equivalent trend of increasing collection efficiency with increasing Julian date is even more pronounced (see Fig. 5). 25 μm bead mixtures were used in all three series, but in the 8/24/82 series the beads were sonified in water before they were added to the bead tank. Sonifying the beads was expected to insure that particles fell as individuals and not as aggregates; however, the trend in the data suggests that bead fall velocity may have increased rather than decreased in the ensonified series. Even though the trend is within the error bars for calculating mean bead diameter, and thus, does not bias the results of this study, there are two explanations for this trend: (1) ensonifying the beads may have caused aggregation, rather than eliminating it, or (2) the mean bead diameter actually may have differed slightly in each 25 μm mixture used to seed the flow, due to slight

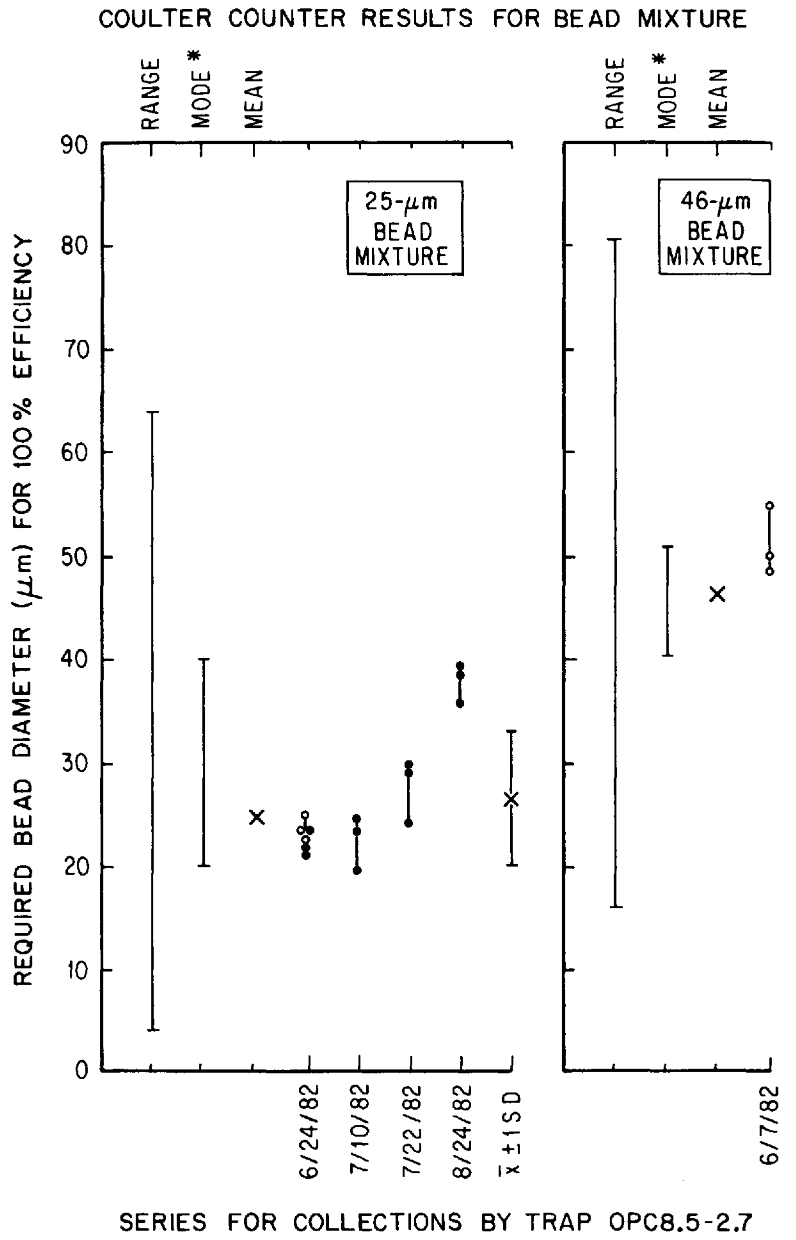

Figure 16. Calculated required bead diameters for each measured collection by trap OPC8.5-2.7 to have an efficiency of 100 percent (see 3. and 5.a. in text). Trap collections at 34 cm above the bed are plotted as open circles and collections 47 or 51 cm above the bed are plotted as closed circles. The range, modal and mean particle sizes for the two bead mixtures (see Fig. 2) are plotted on the left-hand side of the graphs, for comparison with calculated values. *The "mode" for each bead mixture is shown by arrows above the histograms on Figure 2.

differences between shipments of beads (one shipment was used for the Coulter Counter analysis and for series 6/24/82 and 7/10/82, while a different shipment was used for series 7/22/82 and 8/24/82) or to sorting or grading of beads within the shipping container (e.g., beads for the 7/22/82 series were taken from the top of the container, leaving the bottom beads for the 8/24/82 series).

In addition to explaining much of the variability in efficiency between series, this error analysis also demonstrates the difficulty in determining accurate absolute particle collection efficiencies when a spectrum of particle sizes is available for trapping. The indirect evidence presented here indicates that beads probably were present in the flume and in traps in the relative abundances similar to those identified in the Coulter Counter analysis, but it was not possible to precisely pinpoint the true mean diameter of these mixtures to use in efficiency calculations. Thus, I used the conservative procedure of normalizing the data and reporting only relative efficiencies.

b. Biases of cylinders traps. Experiments were designed to determine the influence of trap Reynolds number, trap aspect ratio, and various baffle arrangements on particle collection efficiencies of cylinders. Each of the statistically significant results from these experiments is discussed below. The dye study (Figs. 13–15) shows that water flow around, over and inside traps is complex and is dependent, in part, on trap dimensions and geometry. As observed in other dye studies (Gardner, 1980a; 1985), trap-induced turbulence, in the form of large eddies developing at the trap mouth and circulating through traps, dominate the trap flow environment, and thus, physical mechanisms to account for observed trap biases are likely to involve eddy effects. Relevant features of particle behavior in eddies and turbulence-related particle trapping mechanisms are discussed in detail in Butman *et al.* (1986). The focus of the following discussion is on the quantitative results.

(1) *Trap Reynolds number.* Results for tests of a single trap design (cylinders), trap aspect ratio and particle mixture over an order-of-magnitude change in R_t show a significant decrease (by about a factor two) in collection efficiency between $R_t \sim 2 \times 10^3$ and $R_t \sim 5 \times 10^3$ and then efficiency appears to level-off for R_t up to $\sim 2 \times 10^4$ (Fig. 7). The range in R_t tested in this study are encompassed by the range in R_t for field environments where traps are typically deployed (Fig. 17). For the most common trap diameters used in the field, however, these results are relevant only for relatively slow-flow areas. For example, unbaffled cylinders with aspect ratios of ~ 3.0 and mouth diameters of 5 and 30 cm would be expected to show a significant decrease in efficiency between the flow speeds of 4 and 10 cm/sec and of 0.7 and 2.0 cm/sec, respectively (see Fig. 17). Traps collecting particles in any variable flow environment where currents regularly (e.g., tides) or periodically (e.g., wind-driven flows) go to zero would be particularly vulnerable to an R_t-related trap bias.

The quantitative results on R_t-effects from this flume study apply *only* for the range of parameter values (which include fluid, flow, trap and particle variables, see Butman

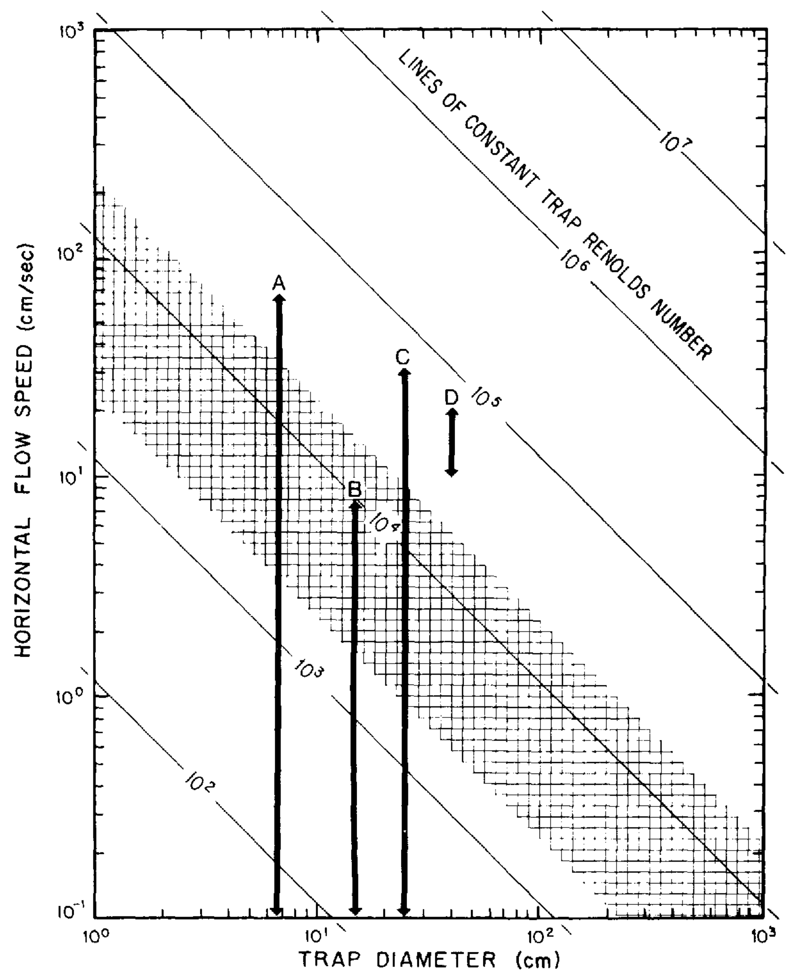

Figure 17. Relationship between flow speed and trap diameter for lines of constant trap Reynolds number, for traps collecting in a typical flow environment (15°C, 30 ppt seawater, $\nu = 1.18 \times 10^{-2}$ cm²/sec). The hatched area shows the range in R_t tested in the present study. Solid vertical bars indicate the range in flow speeds occurring during collections by some cylindrical traps deployed in the field. A = Parmenter *et al.* (1983), Station LCS in Lydonia Canyon, MA, water depth = 560 m, trap depth ~460 m; B = Lorenzen *et al.* (1981), Puget Sound, WA, water depth = 110 m, trap depth = 50 m; C = Rowe and Gardner (1979), North Atlantic, water depths = 2192–3577 m, trap depths = 2156–3459; Staresinic *et al.* (1982), Peru upwelling, water depth ~150 m, trap depth = 30 m.

et al., 1986) tested here. Collection efficiencies for R_t higher and lower than those tested must be determined empirically because the precise physical mechanism responsible for the observed trap biases is unknown, though several testable hypotheses exist (e.g., Butman *et al.*, 1986). Once the mechanism has been determined, it may be possible to theoretically model the general case for particle trapping over a large range of R_t, and thus, to make testable predictions for specific values of the physical parameters involved. At this time, more empirical studies are needed. Two recent studies (Parmenter *et al.*, 1983; Baker *et al.*, 1985) indicate R_t-effects in the field, however, suggesting that the phenomenon may be wide spread and certainly merits further study.

The results presented here may be used to interpret data from field-deployed traps only if the field studies meet the following criteria. (1) Traps must be unbaffled, straight-sided cylinders (i.e., without threads at the trap mouth) with aspect ratios of ~3.0. (2) Trap moorings must be rigid so there are no high-frequency oscillations and no tilt of the trap with respect to the mean flow (see Gardner, 1985). (3) Traps must be collecting in a relatively steady-flow environment (e.g., no waves), where flow speeds change gradually over long time periods and where trap collections can be separated for different flow-speed intervals. (4) Particles available for collection must have fall velocities between about 10^{-2} and 10^{-1} cm/sec (e.g., silt to very-fine sand sized quartz sediments, see Fig. 3). (5) Continuous measurements of current velocities at or near the trap mouth during collections must be available to allow R_t calculations.

These stringent criteria are not met in any published field study known to the author. While several studies (e.g., Rowe and Gardner, 1979; Dymond *et al.*, 1981; Staresinic *et al.*, 1982; Gardner *et al.*, 1983a,b, 1984, 1985) using Gardner's unbaffled 25 cm diameter cylinder, with an aspect ratio of 3.0 (see description in Rowe and Gardner, 1979), may meet the first three criteria, it probably is impossible to satisfy the fourth criterion in any field study and concurrent flow measurements near traps (criterion 5) are rare (but see Table 2 in Butman *et al.*, 1986; also Baker *et al.*, 1985). In fact, the possibility of biased collections due to particle sorting by traps (see 5.a., Gardner 1980a; Butman *et al.*, 1986) must be tested before *any* of the results of the present flume study can be applied to traps collecting particle mixtures in the ocean, because the range of fall velocities of suspended particles spans many orders of magnitude.

Several physical mechanisms were outlined by Butman *et al.* (1986) to account for a decrease in collection efficiency over some range of increasing R_t. The quantitative results presented here are most easily explained by a resuspension mechanism; for a given trap aspect ratio, resuspension of particles from the trap bottom will occur when the bottom shear stress (in the trap) exceeds the critical stress to initiate motion of the collected particles. At some critical R_t for a given particle type, the particles will be removed from the trap bottom and potentially could be carried out with the mass flux leaving the trap. From conservation of mass, Butman *et al.* (1986) showed that $E < 1$ when resuspension is occurring. The resuspension mechanism can operate only at relatively high R_t, when eddies are formed over the trap mouth. The relationship between E and R_t at very low R_t (e.g., in the limit, where u_f goes to zero and separation of the flow does not occur over the trap mouth) is unknown, but because $E = 1$ for a trap collection particles in no flow (see Butman *et al.* 1986), as R_t gets very small, E may approach one from below (i.e., from $E < 1$); however, a more complex function also is possible (see below).

In the present study (see 3.), only particles settling onto the trap bottom (and assuming no adhesion of particles to the trap walls, but see later discussion) were considered to be "collected" by the trap, as is consistent with Butman *et al.'s* (1986) efficiency definition and the definition used by most field-trap users. Since $E < 1$ for $R_t > 4.6 \times 10^3$, resuspension may be removing mass from the trap bottom at these relatively high R_t. This suggests that for this trap geometry, aspect ratio and particle mixture, the critical R_t for resuspension is somewhere between 2.2×10^3 and 4.6×10^3. The fact that $E > 1$ at $R_t < 4.6 \times 10^3$ suggests that E may go through an inflection point for some range of relatively low R_t in order to decrease to $E = 1$ at $R_t = 0$. However, only the shape of the curve and not the actual values of E can be interpreted with confidence at this time, since the entire curve shown in Figure 7 may be shifted up or down, depending on the value of W used in the calculations (see 5.a. and Fig. 16).

It follows from physical arguments (see Butman *et al.*, 1986) and from Lau's (1979) study of water motion near the trap bottom as a function of R_t and aspect ratio that, for a given particle mixture, the trap aspect ratio required to prevent significant particle resuspension increases with increasing R_t. In this study, an aspect ratio of ~3.0 appears to be sufficient at R_t of 2.2×10^3, but not at $R_t > 4.6 \times 10^3$ (Fig. 7). This is difficult to resolve, however, with the aspect ratio results (Fig. 8), where at an R_t of $\sim 1 \times 10^4$, a significant decrease in collection efficiency was observed only for aspect ratios < 2.7 (but see aspect ratio discussion that follows). It is possible that other physical mechanisms (e.g., direct eddy effects, trap-wall adhesion, or particle-particle interactions; see Butman *et al.* [1986]) are operating concurrent with resuspension, making physical interpretations difficult. Quantification of only trap collection efficiencies are not sufficient to determine the precise mechanisms responsible for demonstrated trap biases. Measurements of specific parameters in the mass balance equation (e.g., particle concentration of fluid inside and outside the traps and shear stress at the trap bottom; see Butman *et al.* [1986]) are needed to unequivocally determine the specific physical processes that explain observed trends in the data.

A practical implication of the observed R_t-dependent particle collection efficiencies is that flux estimates from one trap design deployed in a wide variety of flow regimes may not be comparable, of collection efficiency changes over this range of fluid and flow properties (i.e., because $R_t = u_f D/\nu$, if D = constant, then R_t is proportional to u_f/ν). The modest data (Fig. 7) presented here do suggest, however, that for a given range of u_f/ν and particles, there may be a minimum trap size (diameter and aspect ratio of straight-sided cylinders) for which collections would be independent of R_t (e.g., $R_t > 4.6 \times 10^3$ in Figure 7 for the parameter combinations tested here). Unfortunately, it also appears that in areas where flow speeds approach low or near-zero values a significant portion of the time, R_t-dependent collection efficiencies may be inevitable.

While the trend of decreasing E with increasing R_t demonstrated in this study is statistically significant in replicated experiments using completely straight-sided, tenite butyrate cylinders, it is interesting that efficiencies of the standard, screw-cap cylinder, OPC8.5-2.7, do not fall on these E versus R_t curves (as discussed in 4.c.), but are 25–30% higher than efficiencies of trap TBC7.4-2.9, which had a similar R_t (see Fig. 7). One explanation is that, because of the greater surface roughness and, perhaps, differences in surface charge, more particles adhered to the side walls of the polyethylene trap than to the very smooth walls of the tenite butyrate cylinders. Since the interior trap walls were washed, filtered and weighed as part of the trap sample in this study, an increase in trap-wall adhesion would result in an increase in efficiency. This is in contrast to the trap-wall adhesion effects discussed in Butman *et al.* (1986), where particles retained on the walls were not considered to be "collected" by the trap according to their efficiency definition; thus, enhanced adhesion would lead to a decrease in efficiency. The importance of trap-wall adhesion was not addressed in the present study and its role in accounting for any of the observed trap biases must be addressed in the future. An alternative explanation for the differences in collections between traps OPC8.5-2.7 and TBC7.4-2.9 is that enhanced turbulence generated by the threads at the mouth of OPC8.5-2.7 resulted in the observed differences (see also 4.d.); however, the mechanism(s) are unclear. These results underscore the necessity for mechanistic studies of particle trapping and indicate the remarkable variability in efficiency that is possible even among very similar trap designs.

The R_t-effects observed in this study resulted from changes in D when u_f was held constant and some trap-users have argued that I actually tested a D-effect (or an aspect ratio-effect) and not an R_t-effect. There seems to be considerable confusion as to why R_t was tested in this study and what it represents physically. Since this paper is directed primarily at trap-users, it may be helpful to briefly discuss the significance of R_t to particle trapping.

There is a standard technique in physics and engineering, called dimensional analysis, which is used to reduce the number of variables that must be tested for a given physical phenomenon by identifying a set of dimensionless parameters which adequately represent the process. The analysis only identifies a sufficient set of independent parameters, not physical mechanisms. Once all the relevant dimensional variables and physical constants which may affect the process have been identified (and this is the key to the success of a dimensional analysis), then groups of dimensionless parameters are formed according to certain theorems and principals in physics (e.g., see Taylor, 1974; Isaacson and Isaacson, 1975). There is generally more than one set of dimensionless parameters that are independent and sufficient to describe the process and it takes some physical insight to select the set which is likely to be dynamically meaningful.

The dimensional analysis technique was used by Butman *et al.* (1986) to identify parameters which physically represent the process of particle trapping. The result was that a dimensionless particle collection efficiency was identified to be a function of six dimensionless parameters, including R_t and aspect ratio (see 1.). The specific functions (i.e., whether each parameter is positively, negatively, or otherwise correlated with E) are unknown; a dimensional analysis cannot identify these functions, but empirical studies are useful for this purpose.

The specific group of parameters presented by Butman *et al.* (1986) was chosen because each parameter is physically meaningful. R_t represents the ratio of inertial to viscous forces in the flow, and thus, the relative importance of eddy versus purely frictional effects. In fact, this parameter can be derived, using scaling arguments, from the equations of motion (e.g., see any standard fluid dynamics text, such as White, 1979). By definition, at higher R_t, inertial effects are relatively more important than viscous effects to the process under study; also, by definition, whether a high R_t results from an increase in D or an increase in u_f, the physical implications are the same.

It is important to remember that R_t is but one of the scaling parameters for the process of particle trapping. Changes in D or u_f may affect other parameters and other physical mechanisms as well. In fact, D and u_f each occur in two parameters (see 1. and Butman *et al.*, 1986). In addition, a single physical mechanism may vary as a function of more than one parameter.

The resuspension mechanism underlying certain observed trap biases appears to be a function of both R_t and aspect ratio, as well as of the particle parameters (see Butman *et al.*, 1986, for complete discussion). R_t and aspect ratio provide physically distinct information regarding the effect of resuspension on particle trapping. R_t carries information on the relative importance of eddy effects and their characteristics (e.g., velocities and shedding frequencies). Aspect ratio carries information concerning whether or not eddies will penetrate to the trap bottom. The two parameters are related through D, since it sets the maximum eddy diameter. However, the trap-induced turbulence is a function of the oncoming flow and D alone cannot scale this dynamical phenomenon; R_t contains the additional flow and fluid information required. Likewise, aspect ratio includes H, as well as D, indicating if the eddy penetration depth set by D (and also by R_t) is sufficient to reach the trap bottom.

The concept of aspect ratio as a scaling parameter for particle trapping mechanisms evidently is more tangible than R_t, since the phenomenon of aspect ratio-dependent trap collection efficiencies is widely accepted. In the literature, there seems to be no argument concerning whether or not the same physical effect is achieved if a given aspect ratio results from changes in H or changes in D. Just as a given aspect ratio indicates a particular physical situation (e.g., whether an eddy penetrates to the trap bottom or a stagnant layer of fluid exists) and can result from a variety of values for H and D (in effect, the specific values of H and D are immaterial; it is the ratio that is significant), a given R_t also indicates a specific physical situation (e.g., whether or not an eddy is formed at all and, if formed, the relative eddy strength) and can result from a variety of values for D, u_f and ν. Thus, it follows from the physics, that the R_t-effects observed in this study would occur over the range of R_t tested for any combination of values for D, u_f and ν that achieve this range.

(2) *Trap aspect ratio.* Results for test of trap aspect ratios spanning about a factor of four when R_t and particle mixture were held constant suggest that collection efficiency reaches an asymptotic value of ~100% at an aspect ratio of 2.7 and that between-replicate variability may increase above this value (Fig. 8). Aspect ratio

effects on efficiency are most easily explained by the resuspension mechanism, as discussed in Butman *et al.* (1986), as well as by many previous authors (e.g., Gardner, 1980a,b; Hargrave and Burns, 1979; Lau, 1979; Bloesch and Burns, 1980). While these data suggest that an aspect ratio of 2.7 is sufficient to prevent resuspension of the particle mixtures used here from screw-top polyethylene cylinders at $R_t \sim 1 \times 10^4$, the R_t-results discussed earlier indicate that an aspect ratio >3.0 is required to prevent resuspension at $R_t > 4.6 \times 10^3$ for the completely straight-sided, tenite butyrate cylinders (see Fig. 7). It is possible that the R_t- or the aspect ratio-results may prove spurious upon further testing. For example, the high between-replicate variability for trap OPC8.5-3.6 (see Fig. 8) may be obscuring true differences in mean collections between this trap and trap OPC8.5-2.7; further experiments which reduce this variability could provide different results that are more easily resolved with the R_t-data. Alternatively, the differences in collections between tenite butyrate cylinders and screw-top polyethylene traps may be real, indicating that more than one physical mechanism may be operating simultaneously to produce the observed trap biases (e.g., see previous discussion for R_t-effects).

As with the R_t-data discussed earlier, the aspect ratio-results presented here cannot be used to interpret most existing field results because of differences in trap types, moorings and particles collected and because of the lack of flow measurements during trap collections in the field. Many trap-users (see Reynolds *et al.,* 1980) have chosen an aspect ratio of either 3.0 or 5.0 as the minimum value to prevent particle resuspension in traps. Both of these values have been perpetuated in the literature without statistical justification based on trap calibration studies in the laboratory. Identification of the minimum aspect ratio of 3.0 is credited to Wahlgren and Nelson (1976) or, more commonly, to Gardner (1980b); both studies took place in the field where the true sedimentation rate was unknown, and therefore, are comparisons not "calibrations." The minimum aspect ratio of 5.0 is based on the laboratory flume study of Hargrave and Burns (1979) and actually is not substantiated by their flume data. In addition to the fact that R_t varied with each aspect ratio they tested, a statistically significant result actually is evident only between the ratios and 1.2 and 2.6 (see Fig. 7 in Butman *et al.,* 1986).

The results of Lau's (1979) study of water motion in traps, the theoretical and literature analysis of Butman *et al.* (1986), and the results presented here suggest that the minimum trap aspect ratio to prevent particle resuspension depends on the bottom shear stress inside the trap (and thus, on R_t) and on the particles collected (see also Gardner, 1980a; 1985). Given this, it is not particularly fruitful to examine the published field data on aspect ratio-dependent collection efficiencies at this time, since velocity was rarely measured and particle mixtures varied widely both within and among the studies. Quantitative studies of trap collection efficiency are needed where a range of trap aspect ratios is tested for various fixed values of R_t, covering the range in R_t that occurs in field trapping environments (see Fig. 17). In addition, the dependence of the results on the particle mixtures collected (see Butman *et al.*, 1986) must be assessed.

(3) *Baffling*. Baffling traps was originally proposed to decrease turbulence at the trap mouth, creating a more laminar flow which, presumably, would increase collection efficiency (e.g., see Soutar *et al.*, 1977; Gardner, 1980b). Flow through baffled funnels was studied with dye in Gardner (1980a) and showed that the general pattern of flow was similar through baffled and unbaffled traps. Depending on the baffle design and the funnel size, Gardner (1980a) also found that the baffles either increased the residence time of the fluid in the funnels or had no effect on this quantity. In field experiments, Gardner (1980b) found a slight increase in trapping rate for baffled funnels and a slight decrease for baffled cylinders. In the present study, inserting a baffle into the trap mouth opening significantly improved collection efficiency in only one case (trap OPC8.5-1.9, see Fig. 9). Otherwise, baffling either decreased collection efficiency (trap OPC8.5-1.0, Fig. 9) or resulted in considerably higher between-replicate variability (see Fig. 10).

The effects of baffling on collection efficiency undoubtedly depend on the size and the shape of the baffle and of the trap, as well as on flow and particle characteristics. Results of this study suggest that the effects of baffling are not straightforward and must be tested for each particular trap design. The results for baffled traps presented here also may be confounded by the fact that they were used on the screw-top cylinders; as discussed earlier, the threads at the trap mouth also may affect the flow over and in these traps (see Fig. 10). Any solid surface which disturbs the flow path through the mouth opening can introduce another turbulence scale for the trap-induced flow and also extracts momentum from the flow due to surface drag. Since any disturbance to the flow near the trap mouth (e.g., the threads on the polyethylene cylinders) or through the trap (e.g., screening the top or placing baffles in the top or on the bottom of the trap) in this study appears to increase between-replicate variability (Fig. 10), baffling arrangements should be scrutinized, based on empirical data, to determine if they are worth this enhanced variability.

c. Biases of noncylindrical traps. Results from tests in this study of small-mouth, wide-body traps and of funnel-type traps generally support the results of all previous studies of similar trap designs collecting in flows (e.g., see review by Bloesch and Burns, [1980]). When collections are normalized to trap mouth area (A_m), then small-mouth, wide-body traps are overcollectors (Fig. 11) and funnel-type traps are undercollectors (Fig. 12). For traps collecting in advecting fluid, these results could be predicted from conservation of mass arguments (Hargrave and Burns, 1979; Bloesch and Burns, 1980; Butman *et al.*, 1986), but Butman *et al.* (1986) also predicted a variety of other outcomes, for certain specific parameter combinations.

Hargrave and Burns (1979) and Bloesch and Burns (1980) suggested that normalizing noncylindrical trap collections by the trap base area (A_b), rather than by A_m,

Table 5. Mean collection efficiencies of noncylindrical traps normalized by trap mouth area (E_r) or by trap base area ($E_r[A_m/A_b]$).

Trap design	Ratio[α] A_m/A_b	Series	$\bar{x}E_r$	Ratio[β] NC/C	$(\bar{x}E_r)(A_m/A_b)$	Ratio[β] NC/C
		Small-mouth, wide-body traps				
OPG8.3-3.0	0.30	7/10/82	207	2.1	62	0.62
		7/22/82	186	1.9	55	0.56
		8/24/82	228	1.9	68	0.56
OPGC8.5-3.6	0.31	8/24/82	233	1.7	73	0.54
		Funnel-type traps				
OPF8.5-1.9	59.7	6/7/82	22	0.27	1307	16.3
OPF8.3-1.9	56.9	7/10/82	42	0.53	1644	22.0
TBF14.7-1.6S	3.6	8/24/82	81	0.94	290	3.4

α See Column 5 in Table 2.
β NC = noncylindrical trap; C = cylindrical trap with similar A_m and height (the appropriate cylinders are shown next to the noncylindrical traps on Figs. 10 and 11).

should make them unbiased collectors when there is "complete and continuous fluid exchange" (Hargrave and Burns, 1979; page 1125). However, when flows are unsteady, such that conditions alternate between calm and turbulent, then the actual collecting surface alternates between A_m and A_b, making it difficult to calculate the true particulate flux from the trap contents. Such relatively erratic collection efficiencies of noncylindrical traps was noted in Gardner (1980b). While the traps tested here were collecting under conditions of steady 10 cm/sec turbulent flow, where traps appeared to be steadily well-flushed (see dye results, Fig. 15), normalizing the data by A_b, rather than by A_m, still results in biased trap collections (Table 5). In this case, however, the small-mouth, wide-body traps are undercollectors and the funnel-type traps are overcollectors.

The accuracy of collections by noncylindrical traps is difficult to assess because of problems in defining the collecting surface, even in steady flows (see also Hargrave and Burns, 1979; Bloesch and Burns, 1980). The trap-induced eddies which circulate through traps (see 4.f.) undoubtedly set the length scale for the collecting surface. The eddy scales depend on trap geometry (in this case, particularly on A_m/A_b) and on flow characteristics; however, it cannot be assumed that well-flushed traps in steady flows have a collecting surface equal to A_b. Turbulent trap-induced eddies are inherently unstable and their length scales are varied, even during steady-flow trap collections. Unless the collecting surface can be defined, it is impossible to evaluate collections by noncylindrical traps for possible biases or to determine the roles of other physical mechanisms (e.g., resuspension, trap-wall adhesion, or particle-particle interactions, see Butman *et al.* [1986]) in particle collections by these trap designs. Quantification of other terms in the mass balance for noncylindrical trap collections, as well as of collection efficiency under various flow conditions, may help clarify trap accuracies since *a priori* predictions of biased collections for specific parameter combinations have been made (see Butman *et al.*, 1986).

d. Recommendations. The present empirical study of sediment trap biases was motivated by the need to estimate particulate flux in the ocean and by the weaknesses in the existing data on trap collection efficiencies, as identified by Butman *et al.'s* (1986) theoretical and literature analysis. The goal of this study was to determine, under controlled laboratory conditions, if there were statisically significant differences in particle collection efficiencies of sediment traps when specific parameters (R_t, aspect ratio and trap geometry) were systematically varied. Butman *et al.'s* (1986) study suggested some hypotheses to test and indicated the physical variables and parameters that must be monitored and measured during an empirical laboratory study to achieve a physical understanding of trap biases. The present study is somewhat crude in this regard, because only *relative* particle collection efficiencies could be estimated and not the individual terms in Butman *et al.'s* (1986) mass balance. Even so, these results advance the field by providing evidence of specific trap biases that merit further investigation.

Results of this study alone cannot be used to directly interpret results from most (if any) field-deployed traps because of the stringent limitations to the measurements made here (e.g., see 5.b.). Traps were tested in a 10 cm/sec steady-flow environment for R_t between $\sim 2 \times 10^3$ to $\sim 2 \times 10^4$; traps collected approximately medium to coarse silt- and very fine sand-sized particles spanning only one order of magnitude in fall velocity and available in concentrations of $\sim$10 mg/l. Furthermore, traps were bottom-moored on rigid posts and the traps were positioned so the plane of the trap mouth was parallel to the mean flow (i.e., there was no trap tilt). Results for different trap types, flow environments, R_t, particle mixtures, particle concentrations, mooring arrangements and trap tilt must be determined empirically in the laboratory flumes. In addition, mechanistic studies must be done of the physical processes that result in particular trap biases.

It is only through these kinds of tedious, systematic studies of trap biases that we may understand the generalized behavior of traps as particle collectors in natural ocean flows. Claims often are made that a particular trap design deployed in a particular flow regime and collecting particular types of particles accurately estimates particulate flux. Such claims *may* be true; however, it is the conclusion of this study that the empirical data, from controlled laboratory studies where traps were calibrated, do not exist to support such tenets. Results from any field study where traps are used to estimate particulate flux in ocean flows should be interpreted with caution.

Certainly our understanding of particle trapping mechanisms will improve with each additional suite of systematic studies. Yet, there is no guarantee that it eventually will be possible to identify a truly unbiased collector, especially for near-shore, shelf or slope environments where flow and particle dynamics are complex. It thus seems apropo to also investigate alternative methods for measuring vertical flux, especially remote techniques that do not interfere with flow dynamics.

6. Summary and conclusions

Relative particle collection efficiencies (E_r) of a variety of cylindrical and noncylindrical trap designs were quantified in a recirculating, steady-flow flume to test some specific hypotheses regarding sediment trap biases (as presented in Butman *et al.* [1986]). Studies in the laboratory were designed to achieve dynamic and geometric similarity to a specific field environment where traps eventually would be deployed. Three replicates of each trap design were tested in the flume for turbulent flow speeds of about 10 cm/sec and R_t between about 2×10^3 and 2×10^4. The flow was seeded with spherical glass beads having fall velocities of about 10^{-1} to 10^{-2} cm/sec and in concentrations of about 10 mg/l. Particle concentrations in the water mass approaching the traps was monitored during each trap collection. An error analysis of the methodologies and calculations indicated an average 10% (range = 4 to 18%) imprecision for the "average" trap design tested, setting the limit of statistical resolution for the experiments. Between-replicate variability for this average trap design fell within the predicted range.

The following trends were statistically significant for the flow regime and particles tested. (1) For aspect ratio (H/D) held constant (at ~3.0), E_r of cylinders decreased over a range of increasing R_t (between $\sim 2 \times 10^3$ and 5×10^3) and then leveled-off at $R_t \sim 2 \times 10^4$. (2) For R_t held constant (at $\sim 1 \times 10^4$), E_r of cylinders increased between H/D of 1.0 and 2.7, and then appeared to level-off (largest H/D tested was 3.6); however, between-replicate variability considerably increased for the highest H/D tested. (3) For R_t held constant (at $\sim 1 \times 10^4$), baffling screw-top cylinders increased E_r for $H/D = 1.9$, decreased E_r for $H/D = 1.0$ and resulted in no change in the mean E_r, but a considerable increase in the between-replicate variability for $H/D = 2.7$. In fact, any disturbance to the flow at the trap mouth or inside the trap enhanced between-replicate variability. (4) At $R_t \sim 1 \times 10^4$, small-mouth, wide-body traps overcollected particles, relative to cylinders of the same height and mouth diameter. (5) At $R_t \sim 1 \times 10^4$, funnel-type traps undercollected particles, relative to cylinders with the same height and mouth diameter. At $R_t \sim 2 \times 10^4$, however, collections by a funnel-type trap did not significantly differ from those by a screened version of a similarly sized cylinder.

Physical mechanisms that result in specific biased collections were outlined in Butman *et al.* (1986), but could only be casually discussed here because many of the relevant terms in their mass balance equation were not measured in this study. Particle resuspension from the trap bottom is the favored mechanism to explain the R_t- and aspect ratio-results, but some ambiguities in the data remain to be explained. Collections by the noncylindrical traps cannot be simply explained; a problem exists in defining the collecting surface area of these traps when fluid is advecting through them.

The results of this study are limited by the specific parameter combinations tested, and therefore, are not generalizable. It is important to continue to test wide ranges of the relevant parameters and variables that are representative of field environments where traps commonly are deployed. Given the results of this empirical study, it may be premature to suggest that any trap design unbiasly collects particles for a range of ocean flows and flux estimates from trap collections should be interpreted with caution.

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