Sediment trap dynamics and calibration: a laboratory evaluation[1]

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ABSTRACT

The flow dynamics and particle trapping characteristics of several designs of sediment traps were investigated using dye, sea-water, and deep-sea lutite in a recirculating flume and fish tank at velocities of 0, 4, and 9 cm/sec. Particles are collected through a process of fluid exchange rather than falling freely into a trap. The efficiency of a trap is therefore a function of the residence time and circulation pattern of fluid within the trap, processes which are controlled primarily by trap geometry and secondarily by current velocity. Cylinders trap particles in the closest agreement with the sediment deposition rate in the flume. Funnels generally undertrap, but their efficiency may be improved by constructing a baffle at the top of the funnel. Containers with narrow mouths and wide bodies consistently overtrap at an unpredictable rate of many times the actual vertical flux of particles.

1. Introduction

Since the work of Heim (1900) there have been over one hundred papers concerned with sediment traps (see Gardner, 1977, for complete list). Traps can be divided into five categories: cylinders, funnels, wide-mouthed jars, containers with bodies much wider than the mouth, and basin-like containers with width much greater than height.

About half of the published studies were conducted in lakes, where turbulence and mixing are relatively slow, while the other half were in estuaries, bays, and coastal environments where turbulence and advection are stronger. Attempts at using sediment traps beyond the continental shelf have been rare, but their potential for collecting the large-particle flux has been recognized and technology now makes their use in the deep sea practical (Wiebe *et al.*, 1976).

Despite the increasing use of sediment traps and speculation about the effect of turbulence on what they collect, only two papers have reported limited observations of hydrodynamic flow around traps (Patten *et al.*, 1966; Peck, 1972). Most field

inter-comparisons between different shapes of traps have been confined to tranquil waters, as have been attempts to compare collection rates in traps with other means of estimating the vertical flux. This paper reports a series of experiments made on the dynamics of flow around and particle collecting characteristics of several containers while the author was designing sediment traps for use in the open ocean.

2. Previous work on calibration of trapping efficiency

a. Still water. For quantitative studies to be made with sediment traps it is necessary that the flux measured by a trap be equal to the vertical flux across the plane of the trap. Failing this, we must know the biases—deviation from true vertical flux, size distribution or particle density.

Attempts to calibrate fluxes calculated from sediment trap collections have centered on comparison of trap fluxes with accumulation rates in the underlying sediment or with an independently determined production rate of some component in the water column. Pennington (1974) found that sediment collection made with cylinders in an oligotrophic lake (0.26 cm yr^{-1}), compared well with sedimentation rates derived from paleomagnetic evidence (0.20 cm yr^{-1}), Pb-210 dating (0.27 cm yr^{-1}), and with accumulation of sediment above a known horizon in cores (0.23 cm yr^{-1}). This assumes, however, that 1) none of the material entering the trap has been resuspended from anywhere on the bottom; 2) horizontal advection is not affecting the accumulation rate of sediment below the trap; and 3) the dissolution and biodegradation of particles in the trap is quantitatively the same as what affects identical particles falling through the water from the position of the trap until they are a permanent part of the sediment record. These may be reasonable assumptions in a tranquil oligotrophic lake, but must be applied with care elsewhere. Brunskill (1969; and personal communication) found that his trap (a funnel on top of a long tube) yielded a flux which was only 50% of the accumulation rate estimated by C. D. Ludlum (personal communication) from varve dates using ^{210}Pb measurements. This may result from one of the effects mentioned above, or it may result from inefficiencies of funnels. Rigler *et al.* (1974) found close agreement between the production and entrapment of zooplankton exuviae.

Kirchner (1975) tested cylinders with identical heights but whose diameters ranged from 3.2 to 43.2 cm and reported no "statistically significant" differences in their collection rates in a lake. In two of the nine experiments, however, the collection rates of cylinders with different diameters varied by more than 400%. This is much greater than the 8%-23% variation reported by Hargrave *et al.* (1976), and 0-10% reported by Pennington (1974) for pairs of identical cylinders at the same location, suggesting that trap geometry is important.

Davis (1967) reasoned that the sedimentation rate determined from traps with different size openings was correct if the amount of detritus collected was propor-

tional to the trap opening and if the extrapolation of data points intersected the origin. These conditions were met when using cylinders and wide-mouthed jars in the laboratory and in stratified lakes (Davis, 1967; Pennington, 1974) and with funnels moored in lakes (Watanabe and Hayashi, 1971). The interpretation is not unique, however, because the traps used in each experiment could be biased in their collecting efficiency to a degree proportional to their size. Some intercomparisons have been made between the collection rates of cylinders and funnels of different sizes (Johnson and Brinkhurst, 1971; White and Wetzel, 1975; Pennington, 1974). One consistent observation was that cylinders collected more per unit of opening area than funnels.

b. Moving water. The flow pattern around the trap of Tauber (1967) and its ability to remove pollen grains from the water flowing over it was analyzed by Peck (1972), but it is difficult to relate her results to a concept of vertical flux because some of the pollen used was positively buoyant.

Wiebe *et al.* (1976) attempted to calibrate their trap by mooring it in a deep raceway and releasing coffee grounds from fifteen meters above the trap. The results were not conclusive, especially since the fall velocity of the coffee grounds was 20 cm/sec; orders of magnitude faster than most oceanic particles.

Soutar *et al.* (1977) deployed pairs of cone-shaped traps off the California coast in the 580 m deep Santa Barbara Basin, where varved sediments allow the annual, but not seasonal, sedimentation rate to be resolved. Based on deployments of 2-35 days, their collection rate was 22% to 88% of the annual accumulation rate of varves when the trap was 100-150 m below the surface, and 66-190% of the varve accumulation rate with the trap 10 m above the bottom. The difference may result from a breakdown of one or more of the assumptions listed above in section *a*.

Intercomparisons of the collection rates of cylinders have also been made in moving water (Young and Rhoads, 1971; Hoskin *et al.*, 1975; John Davies, Aberdeen, personal communication), but there is not enough information about trap dimensions or collections or currents to evaluate the results properly. Collection rates appear erratic when using cylinders less than 2 cm in diameter.

c. Comparison with rain and snow gauges. An obvious corollary to the calibration of sediment traps is the calibration of rain and snow gauges. Precipitation collectors have been used for hundreds of years (Kurtyka, 1953), but only in the last hundred years has it been realized that the collecting efficiency of rain and snow gauges decreases with an increase in wind speed, the primary source of error (Wilson, 1954).

Any object placed in a moving fluid (air or water) is an obstruction around which the fluid must flow. Hydrodynamically the flow characteristics of air and water around a container are qualitatively very similar. However, due to differences in particle size and relative density, and fluid velocity and viscosity, the path of rain drops or snow flakes around a container may be very different from the path of

falling detritus in water. Raindrops of 0.5-5 mm diameters fall at 2.3-9.3 m/sec, and snow falls around 0.5 m/sec (Kurtyka, 1953). If most winds are less than 10 m/sec, then the fall velocity of rain and snow is seldom more than one order of magnitude less than the horizontal wind speed and may be one order of magnitude greater. In the marine environment, however, a one-micron particle falls at about 10^{-4} cm/sec, a 40 μm particle falls at 10^{-1} cm/sec ($\rho < 2$ g/cm^3) and zooplankton fecal pellets fall at 0.04-1.0 cm/sec (Smayda, 1969; Fowler and Small, 1972), whereas current velocities are generally less than 200 cm/sec in estuarine and surface waters and less than 20 cm/sec in deep ocean water. Thus the fall velocity of most particles in water is between one and six orders of magnitude less than normal horizontal currents. Rather than descending nearly vertically, particles settling through water generally follow the fluid path lines and enter traps by being carried passively in the turbulent eddies produced by traps. Thus it is important to understand how traps disturb the flow field and what are the resulting flow patterns around and inside sediment traps. Some of the important variables affecting trapping efficiency may include current velocity and turbulence, trap size and geometry, and particle size, concentration, and composition.

3. Methods and instrumentation used in flume experiments

A variety of traps were exposed to steady, uniform flow in a recirculating flume six meters long and 17 cm wide with a flow depth of 15 cm. Observations were also made in a flume one meter wide with 45 cm of water. Flat plates, cylinders, wide-mouthed jars, funnels, narrow-necked wide-bodied bottles (Erlenmeyer flasks and salinity bottles), and a segmented basin were among the geometries tested (Table 1). Patterns of fluid flow around and inside the different traps were observed in fresh water by using fluorescein dye as a tracer. Subsequently, three series of experiments were made using sea water and fine-grained sediments in the same flume to calibrate the traps.

Flow velocities were determined by timing dye streaks 3 cm below the surface down the center 2 meters of the flume with traps in place. A second measurement was made with a small drogue which integrated the velocity over the top 3 cm. The two methods agreed within 5% and five measurements with the drogue were always within ± 5%.

a. Dye experiments. Each trap was observed 3.5 m from the head box in the center of the flume with flow velocities ranging from 1-15 cm/sec. Fluorescein dye was released from a hypodermic needle upstream of each trap. Flow lines and zones of turbulence were observed, sketched, and photographed with still and movie cameras. Fluid exchange observations were made by filling traps with dilute fluorescein dye. The fluid residence time—defined here as the time required for dye inside the trap

TABLE 1

Dimensions of Traps Tested

TRAP DESIGN								
Height (cm)	4.0	4.8	3.9	8.7	6.5	4.0	4.5	0.8
Diameter (Inside)								
Mouth (cm)	4.5	10.5 x 0.11	3.7	3.8	6.4	3.8	1.8	
Body (cm)	5.0	10.5 x 4.8	3.7	3.8	6.4	3.8	4.5	10.2 x 14.5
Height/Width	0.8	1.2	1.0	2.3	1.0	1.1	2.54	
Area (Mouth) (cm^2)	15.9		13.7	11.3	32.2	11.3		148
Volume (ml)	71	180	54	99	209	45	58	

TRAP DESIGN									
Height (cm)	7.8	10.3	23	8.9	8.9	9.9	7.5	8.8	10.8
Diameter (Inside)									
Mouth (cm)	6.3	10.0	23	6.3	6.3	6.3	1.6	1.2	1.5
Body (cm) (at the neck)	0.5	0.5	2	1.2	1.2	1.2	4.6	3.5	4.5
Wall angle (deg.)	60	60	50	60	60	60			
Area (Mouth) (cm^2)	31.2	78.5	360	31.2	31.2	31.2	2.0	1.13	1.77
Volume (ml)	61	230	4570	57	55	102	60	64	1.29
Baffle size									
Height (cm)			5.0		1.0	1.0			
Width (cm)			2.5		1.0	1.0			

to be diluted to the concentration in the flume—was measured for most trap designs (Table 2).

b. Sedimentation experiments. Filtered Sargasso Sea water was used with flow depths of 11 cm in the first experiment and 15 cm in all other experiments. Abyssal

TABLE 2

Fluid residence time and vortex shedding rate for traps

Trap	Velocity (cm/sec)	*Fluid residence time (min)	**Vortex shedding rate (#/sec)	Velocity (cm/sec)	*Fluid residence time (min)	**Vortex shedding rate (#/sec)
	5.7	5	1.3	7.8	0.8-1.0	2.4
	5.7	10-15	1.5	7.8	1.7-2.0	2.4
	5.7	3-4	1.4	7.8	1.2-1.3	2.4
	5.7	>>20	1.4	7.8	several 10's of min.	1.8
	4.5					
1		20-30[1]				
2		3				
3		5-7[2]				
4		5-6[2]				
5		2-3[3]				
	6	2				
	6	5-6				
	6	2				
	not reported[4]	< 12 hrs.				

*Time for dye to reach background concentration in most of the trap.
**Average of 3-5 measurements of 100 vortices.
[1] Some dye still in corners after 70 minutes.
[2] Some dye still in corners after 15 minutes.
[3] Some dye still in corners after 30 minutes.
[4] Patten et al., 1966.

mud from the North American Basin was wet sieved to remove particles >63 μm and used as the particle source. Coulter counter measurements showed that after sieving 95% of the material was less than 25 μm; the median grain size was 2.6 μm. Less than 10% of the mud was carbonate, and illite was the predominant clay mineral (60%). The sediment was disaggregated ultrasonically for one hour in 250 ml of distilled water and added to the flume at the beginning of each series of experiments. The water and sediment were allowed to mix for 10-20 minutes before each experiment during which time the channel surfaces were wiped two or three times to resuspend all particles while the pump was at maximum discharge. The

TABLE 3

Series I flume conditions and trap efficiencies

Experiment No.	_1_	_2_
Time (hr.)	39.3	42.7
Velocity (cm/sec)	9.0	8.9
Flow Depth (cm)	12	11.0
Initial Conc. (mg/ℓ)	11.8	11.5
Final Conc. (mg/ℓ)	2.8	2.3

TRAP		EFFICIENCY	
⬜	Identical Containers	106%	163%
⬜		94%	
⬜	(1mm nylon mesh over mouth)		266%
⬭		391%	994%
⬭			6850%
◇	flat Plexiglas plate		31%

flow velocity was lowered to the desired speed and the containers were positioned in the flume.

The water in the flume was recirculated through two-inch PVC pipe. The return velocity was therefore much higher than the flume velocity, so sediment could not deposit in the return flow system. The system was free of dead spaces where sediment could accumulate, so all sediment was assumed to be deposited on the flume bed or collected in the traps. Initial and final concentrations for each experiment are shown in Tables 3-5.

One experiment used a fish tank (25 cm × 50 cm with 24 cm of water) to test trapping efficiencies in still water using the same sea water and sediment used in the flume. Sediment and water were mixed thoroughly and the water was allowed to calm down. The traps were then arranged in the tank so all trap openings were at the same depth (12 cm). The tank was covered to eliminate circulation caused by air currents or evaporational cooling and had equilibrated with room temperature

TABLE 4

Series II flume conditions and trap efficiencies

Experiment No.	3	4	5	6
Time (hrs.)	32.7	11.1	11.1	11.0
Velocity (cm/sec)	4.4	4.4	9.5	4.4
Flow Depth (cm)	15.0	15.0	15.0	15.0
Initial Conc. (mg/l)	51.0	55.0	58.2	53.0
Final Conc. (mg/l)	8.3	25.9	30.7	23.2

TRAP		EFFICIENCY		
1	78%	88%	105%	86%
2	128%	114%	152%	105%
3	106%	101%	130%	98%
4	108%	110%	121%	89%
5	97%	92%	115%	83%
Σ 1-5	102%	99%	123%	91%
	101%	106%	139%	88%
	101%	107%	120%	79%
	123%	130%	148%	88%
	413%	550%	651%	508%

for 24 hours prior to the experiment to reduce thermal convection, but no attemp
was made to control room temperature.

1. *Determination of flume sedimentation rates and trap fluxes.* The rate o
deposition in the flume was determined by measuring the concentration of suspender
particles at the beginning and end of each experiment. The difference in the sus
pended load was assumed to have been deposited on the flume bed. At the end o
each experiment the traps were covered and removed from the flume. The content
were washed onto a preweighed Nuclepore filter. In funnels it appeared that mos
sediment accumulated on the walls; this material was included in the mass collected
The filter handling was similar to that described in Brewer *et al.* (1976). The weigh
was corrected for particles suspended inside each trap based on the trap volum
and final flume concentration. The flux (the mass of sediment collected per squar
centimeter of trap opening per unit of time) was then calculated for each trap, a
shown in Tables 3-5. Deposition rates with traps in the flume were within the rang
measured without traps under similar conditions (Gardner and Southard, 1975ε

TABLE 5

Series III flume conditions and trap efficiencies

Experiment No.	8*	9	10**	Fish Tank
Time (hrs.)	10.8	11.3	17.3	17.3 hrs.
Velocity (cm/sec)	4.3	4.0	4.0	0
Flow Depth (cm)	14.3	14.8	14.8	24.2
Initial Conc. (mg/1)	34.4	31.2	82.4	46.1
Final Conc. (mg/1)	18.5	17.8	36.2	5.4

TRAP		EFFICIENCY			
	1	64%			
	2	67%			
	3	59%			
	4	60%			
	5	56%			
	Σ 1-5	60%			
		44%	60%		
		65%	84%	82%	89%
		71%	90%		
		136%	80%	81%	98%
		62%			94%
		>264%***	550%		322%
			60%		
			65%		
				554%	
				743%	231%
				896%	

*A clockwise rotation of 180°, 45° and 135° was made on all traps at 3.0, 5.3 and 9.2 hours into the experiment.

**Sediment which was mostly between 2-62μm was added to increase initial concentration.

***Unknown amount lost during filtration.

1975b), indicating that the obstruction to flow caused by the traps did not significantly alter the deposition rate on the flume bottom.

2. *Calculation of trap efficiency.* A trapping ratio is determined by dividing the
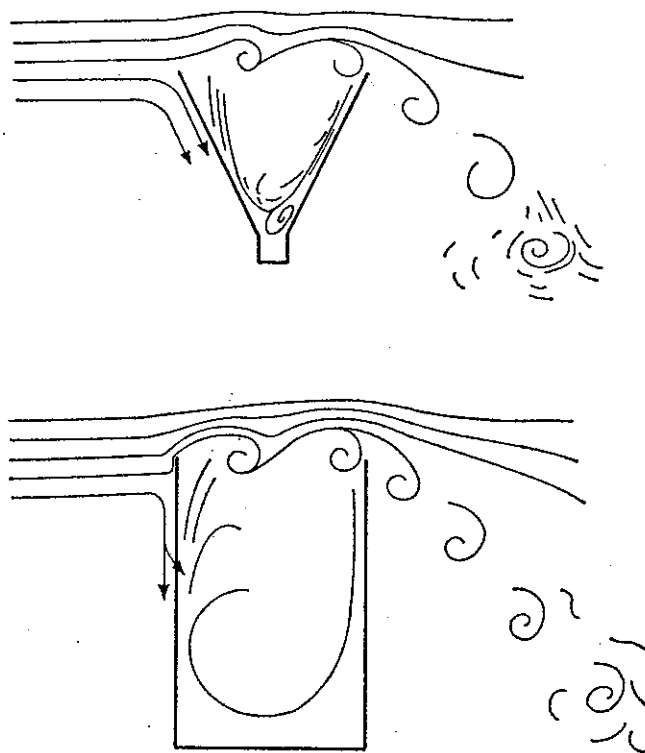
Figure 1. Flow lines around a funnel and cylinder are idealized from photographs. The fluid enters the boundary layer of the outside cylinder wall and creeps up the side. The edge of the cylinder produces pressure instabilities which cause vortices to be shed and move downstream. Only fluid approaching the cylinder *below* the top edge (1-4 cm below in these tests) is entrained in eddies entering the trap. Each vortex forms a spiral consisting of fluid leaving the cylinder from the upstream portion sandwiched by new fluid entrained from the outside boundary layer of the cylinder. This sandwiched vortex breaks on the downstream edge of the cylinder sending part of the fluid beyond the container while the rest is propelled down into the cylinder. If eddies reach the bottom of the cylinder, sediment is preferentially deposited in the corners, where circulation is reduced. Otherwise, deposition is relatively uniform over the bottom. Funnels also produce eddies, but the sloping wall decreases the updraft of fluid moving over the container. Sediment preferentially accumulates on the upstream wall of the funnel and in the funnel neck.

flux measured by the trap (mass/cm²/time) by the sedimentation rate on the flume bed (mass/cm²/time). The ratio is multiplied by 100 and defined as the trapping efficiency. In this system the ideal trap has an efficiency of 100% which means it collected particles at the same rate as the flume bed, though the dynamics of particle collection in the trap is very different from the way particles pass through the boundary layer to the flume bed (e.g., Kline *et al.*, 1967; Corino and Brodkey, 1969). Deviations from 100% are from over- or under-trapping.

3. *Traps and conditions tested.* Figures and dimensions of all traps tested are
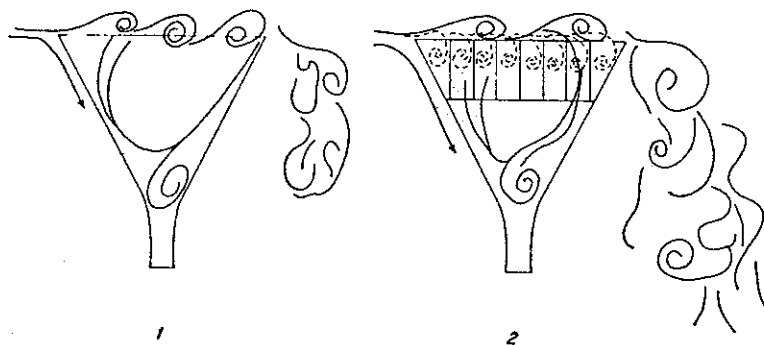
Figure 2. Flow lines around and inside a funnel (1) without a baffle and (2) with a baffle at the top are idealized from photographs. The intent of baffles is to reduce the scale of turbulence and mixing to approximate the dotted lines shown so that particles would be retained inside. The baffles do reduce the rate of mixing, but even with velocities as low as 4 cm/sec, the general circulation within the funnel remains unchanged (solid lines in 2). Making the cells taller and narrower reduces the overall flow more, but not completely.

given in Table 1. The first experiments (Table 3) included a diversity of geometric forms and yielded a range of two-orders-of-magnitude in trapping efficiencies between containers used. Based on these results, a second series of experiments (Table 4), in which collection time and flow velocity were varied, tested five containers (mostly cylinders). The third series of experiments (Table 5) primarily involved funnels under various flow conditions. Two experiments were made in a fish tank to test efficiency in still water.

4. Observations of flow visualization

a. General: The most notable features of flow are the vortices produced by the trap (Figs. 1 and 2), internal patterns of circulation, and the rate of fluid exchange within the trap. The primary control on the fluid exchange and fluid residence time in a container is its shape, with stream velocity playing a secondary role. All containers produced eddies at the leading edge which plunged into the container at the downstream edge. It was not clear whether the entering eddies forced fluid out at the leading edge, or the higher velocity at the leading edge caused a low pressure zone which sucked fluid from the container and helped form the eddy.

The rate at which vortices are shed across the top of cylinders and the dome increases with velocity, but at a constant velocity the vortex shedding rates are very similar for all traps tested (Table 2). The residence time, however, ranged from less than one minute to several tens of minutes, indicating that the size and depth of penetration of the vortices were controlled by the shape of each trap. Containers with long residence times (generally containers with small openings and large bodies) can still have rapid circulation and exchange near the opening, but a sharp boundary develops between an area of rapid circulation and a nearly stagnant re-

gion below. A cylinder might also develop this type of boundary layer if it is tall enough to keep eddies from penetrating too deeply.

b. Cylinder: The flow lines around a cylinder are shown and discussed in Figure 1. The depth of fluid penetration into a vertical cylinder is a function of a Reynolds number $Re = \dfrac{VD}{\nu}$, where V is the stream velocity, D is the cylinder diameter, and ν is the fluid viscosity. In a 9 cm/sec flow the depth of penetration ranged from $1.5D$ to $2D$ in a cylinder with $H/W = 2.3$. However, it was observed that tilting a cylinder will change vortex mixing more than will a change in the Reynolds number. For instance, a cylinder ($H/W = 1$) whose residence time was 2-3 minutes when vertical was flushed out in half the time when tilted 15° into the current. Tilting the cylinder 15° downstream drastically reduced the penetration of eddies, and after 15 minutes a boundary layer of dye still remained in three-fourths of the cylinder.

c. Flat plate: In moving water a plate disturbs the flow and generates eddies from the upstream edge of the plate. If the plate is tilted down toward the oncoming flow, a favorable (negative) pressure gradient develops along the plate and a critical angle is reached at which eddies are no longer shed along the plate. The critical angle is a function of a Reynolds number $\dfrac{VL}{\nu}$, where L is the plate thickness. A 0.8 cm thick plate was observed to have a critical angle of 13° at a flow velocity of 5 cm/sec.

d. Domed cylinder: From observations of the effect of an inclined plane on fluid motion, it appeared that placing a sloping surface upstream of a cylinder would reduce the turbulence inside the cylinder, as noted by Tauber (1965). This approach resulted in the dome-shaped container shown in Table 1. The time required for complete exchange of fluid in the dome-shaped container was more than an order of magnitude greater than for a straight cylinder at the velocities tested (Table 2). The small ratio of trap opening to trap volume was partially responsible for this effect, but more important, the dome shape produced different boundary layer and pressure effects which restricted the mixing depth of vortices.

e. Narrow-necked, wide-bodied traps: A container with a narrow neck and a flared body, like an Erlenmeyer flask, restricts total fluid exchange more than the domed cylinder. A salinity bottle, whole body flares out at a much larger angle than that of an Erlenmeyer flask, was even more effective in preventing fluid exchange. Residence time of water in a salinity bottle may be up to 12 hours (Patten *et al.*, 1966).

f. Horizontal cylinder with narrow slit: This container (Table 1) has the least amount of internal circulation, and also uses the idea of a sloping surface in front of an opening where particles are collected. The cylinder, which has a narrow slit

parallel to the axis, rests horizontally and is oriented perpendicular to the direction of flow. If the slit is upstream of the point of flow separation, virtually no fluid exchange occurs. With the slit at the point of flow separation there is a pulsating exchange with fluid entering along one end of the slit and forcing fluid out the other end. When the slit is in the zone of separated flow, fluid exchange is erratic.

g. Funnel: Funnels have the apparent advantage that fluid approaching the funnel below the lip will be swept down and around the funnel, thus reducing updrafts which may lift large particles past the trap. Only fluid at or slightly above the lip can enter a funnel, as discussed in Figure caption 1.

In an attempt to reduce the energetic mixing inside the funnel, a cube-shaped grid of baffles was fitted inside one funnel and on top of another funnel of the same size (Table 1). The first arrangement noticeably decreased the fluid velocities within the funnel and increased the residence time from about two minutes to six minutes. The second arrangement appeared to have little effect on fluid velocities or residence time (Table 2).

The flow within a much larger funnel (25 cm at top) was the same as in smaller funnels. When a baffle whose cell height was twice its diameter was placed on top of the funnel, the overall circulation was essentially unchanged (Fig. 2). Baffles whose cells were ⅜" wide and 2" high reduced the primary circulation but did not eliminate it.

h. Segmented basin: If a trap is divided into shallow isolated compartments, the mixing in one compartment is influenced by the presence of the other compartments. In the trap tested, compartmentalization caused a range of two to thirty minutes in the residence time of different compartments. Compartmentalization is similar to locating traps too close together. When traps are less than about three diameters apart the internal flow patterns are altered.

5. Results of sedimentation experiments

a. Variables affecting trap efficiency. The efficiency of a trap may depend on variables such as concentration of suspended particles, size and density of particles, trap geometry, or current velocity. The number of variables and combination of variables is far greater than the number of experiments made, so trapping effects cannot always be conclusively attributed to a given variable. Some first-order observations can, however, be made.

The most important correlation between the dye and sedimentation experiments is that at a given velocity there is a positive correlation between the trapping efficiency of a container and the residence time of the dye within the container. Each trap also has pockets where dye remains much longer than the mean residence time, and the particles tend to collect at these stagnation points.

1. *Reproducibility*. No experiment was duplicated because of time constraints, but experiments 4 and 6 (Table 4) differed only in the relative position of the traps in the flume. Traps were always spaced 60-70 cm apart in the center of the flume. The second arrangement of traps resulted in slightly lower efficiencies, but the relative ranking of efficiency among the traps remained the same. When all unidirectional and still-water experiments were combined, the coefficient of variation was 17% for cylinders and funnels and 41% for containers with wide bodies and small openings. The funnels were not tested above 4.5 cm/sec. Considering the complex flow around traps, the consistency of the results was encouraging.

2. *Concentration of suspended sediment*. The concentrations used in these experiments (12-82 mg/1) are at least an order of magnitude higher than that of continental shelf waters and up to three orders of magnitude greater than in the open ocean. This was necessary to obtain measurable amounts in a reasonable time period. The flux calculated from traps increased when the initial concentration was increased, but at a rate directly proportional to the increased flux to the flume bed. Thus, a trap's efficiency (% of vertical flux) is not a function of particle concentration over the range tested. If the fall velocity of particles were increased (because of larger or denser particles), the flux of particles to the traps would also increase, but there is no evidence that the efficiency of a trap would change. Although it is difficult to separate, the effects of increased particle concentration and fall velocity on the vertical flux trap experiments by Richardson *et al.* (1978) appeared to conform to the above observations at oceanic concentrations.

3. *Duration of run*. Two experiments (No. 3 and 4, Table 4) were identical except in duration (33 hours vs. 11 hours). The trapping efficiencies were virtually the same for all containers except the dome, whose collection rate was generally more erratic than that of other traps.

4. *Size distribution of particles trapped*. A snow-fence effect could be created by sediment traps and cause large particles to be carried up and over the entire trap, or to be carried up and over the leading edge of the trap and be dropped into the trap. The result could be not only an over- or under-collection of sediment, but also an unnatural differentiation by size and density of the particles collected. It is to be expected that particles collected in the trap have a larger size distribution than the total suspended particles because the larger particles contribute more to the flux, but it is important not to skew the size distribution of settling particles.

If no differentiation occurs in a given trap, the particles collected on the flume bottom should have the same size distribution as the particles collected in the trap. At the end of experiment No. 2, samples were taken from the dome, wide-mouth jar, horizontal cylinder, and the flume bottom and analyzed for size distribution with a Coulter counter. The size distributions of the particles between 0.8 μm and

63 μm were compared in both their flocculated state and, after two minutes in an ultrasonic bath, in their unflocculated state. It was not possible to determine the size distribution of particles at the time they entered the trap. However, the size distributions of particles removed from the wide-mouthed glass jar and dome trap were nearly identical to that obtained for the particles on the flume bed both before (median size = 6.9 μm) and after (median size = 3.2 μm) sonication. The cylinder with the slit trapped particles which were slightly larger than those on the flume bed (median size = 9.1 μm before sonication and 3.7 μm after). During the experiment large flocs had been seen entering and piling up at one end of the horizontal cylinder.

In a test with larger particles it was seen that the primary circulation around traps can affect even very large particles. For instance, in a current of 7 cm/sec, plastic beads with a fall velocity of 0.8 cm/sec (690 m/day), which is twice the fall velocity of any fecal pellets measured by Smayda (1969), were carried into the downstream end of a 25 cm wide, baffled funnel in the flow pattern seen in Figure 2-2. The upward circulation at the upstream side of the funnel was sufficient to carry two of about sixty beads out of the funnel, indicating that, depending on trap design, not even all large particles entering a trap are necessarily retained.

5. *Construction material of the trap.* There was no obvious correlation between the material used to make the traps (glass, Plexiglass, PVC, and polyethylene) and the trap efficiency that could not be explained by the geometry of the trap. If trap surfaces are rough or develop an organic surface layer, the likelihood that particles will be trapped on that surface increases. While some sediment adhered to the walls of containers, more sediment accumulated on the bottom than on the walls of all containers except the funnels.

6. *Current velocity.* In order to see if the trapping efficiency of a container was a function of velocity the trapping efficiency was plotted against velocity for several containers (Fig. 3). The maximum velocity tested in the flume was 9.5 cm/sec, because flocs were seen moving along the bottom at higher velocities and would have been re-entrained in the return flow. It is therefore uncertain whether the slight increase in collection efficiency with increasing velocity is a velocity effect for cylinders or a result of resuspension. Assuming that particles in the traps could not be resuspended, re-entrainment of sediment from the bed would provide another chance for particles to enter a trap and increase its apparent efficiency.

The collection efficiency of small-mouthed, large-bodied traps such as the dome and salinity bottle increased substantially between still water and 4 cm/sec. The efficiency of funnels decreased over this velocity range.

7. *Omnidirectional flow.* All of the results discussed so far have been for steady, unidirectional flow, which is an anomalous situation in large bodies of water. There-
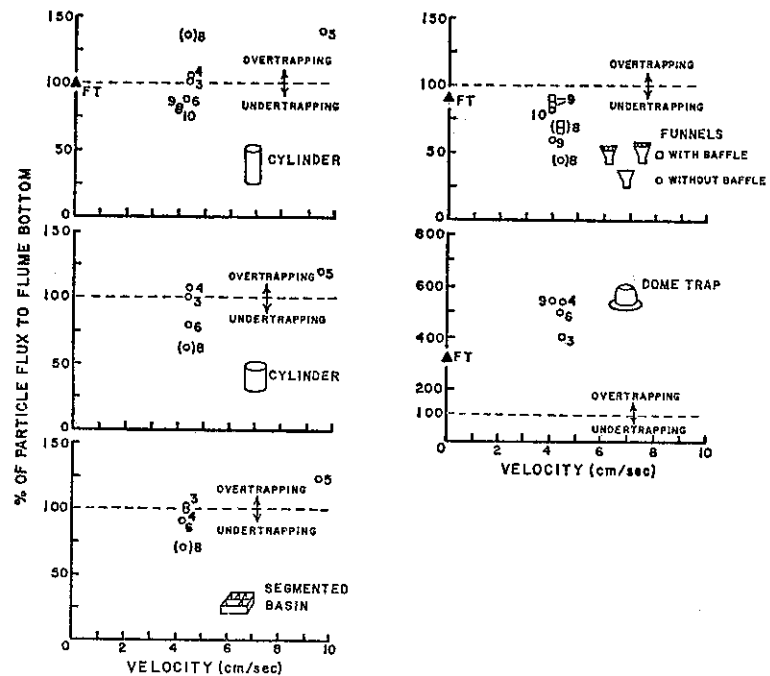
Figure 3. Trapping efficiency of containers versus current velocity. Numbers next to symbols refer to experiment numbers (Tables 3-5). FT is for still water Fish Tank experiment (Table 5). Experiment #8 (set off in parentheses) was different in that traps were rotated during the experiment (Table 5).

fore, during experiment No. 8, traps were turned three times (Table 5). Rotation of the funnels decreased their efficiency (compare experiments 4 and 8, Tables 4 and 5). Visual observations indicated that the decrease was due to resuspension of material which had been preferentially deposited on the upstream wall of the funnel before rotation.

The trapping efficiency for shallow, straight-walled containers (cylinders and flat basins) also decreased when exposed to changing current direction. In unidirectional flow the sediment preferentially accumulated at the upstream base of the shallow containers. When the current shifted, the deposited sediment was exposed to incoming eddies and was resuspended. The increase in the tall cylinder during rotation may have been caused by the currents pushing sediment accumulated on the lip of the trap wall into the trap.

These observations show that traps should be designed so that incoming eddies do not impinge on depositional surfaces and resuspended particles already collected. Traps should also be axially symmetric so that the hydrodynamic response is not a function of current direction.

b. Evaluation of trap shapes as measurers of vertical flux. The results of all the flume sedimentation experiments show that a range of two orders of magnitude in sedimentation rates can be obtained from using different types of traps (Fig. 4).
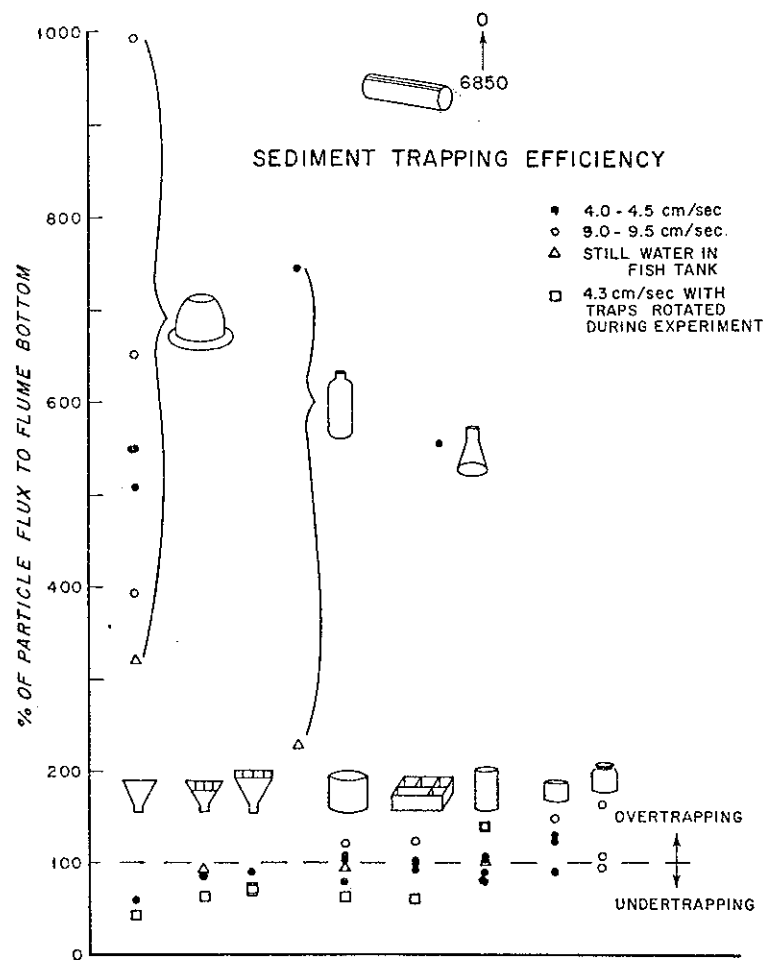
Figure 4. A compilation of the trapping efficiency of traps tested under a variety of conditions differing in flow velocity, length of experiment, initial concentration, and orientation of the container to the flow.

1. *Cylinders.* The average efficiency of cylinders was closer to 100% than other configurations tested in both flowing water (4.0-9.5 cm/sec) and still water. The H/W ratio showed no definite influence on the trapping efficiency of cylinders, but the ranges of dimensions and velocities tested were not very great due to physical limitations of the flume.

2. *Flat plates.* A flat plate in moving water was a highly inefficient collector, because particles landing on the plate were unprotected from currents. Had the Plexiglas plate had a rougher surface, more sediment might have remained, but recovery of such a collector without losing sediment was difficult.

3. *Funnels.* In still water the trapping efficiency of funnels was close to the calculated flux (Table 5). In a current of 4 cm/sec the open funnel collected only 60-

Figure 5. Cross section of domed trap shows sequence of events causing over-trapping of par-
ticles in containers with overhanging walls. Visualization of this process is described in text.

65% of the calculated flux, but the addition of baffles improved the efficiency.
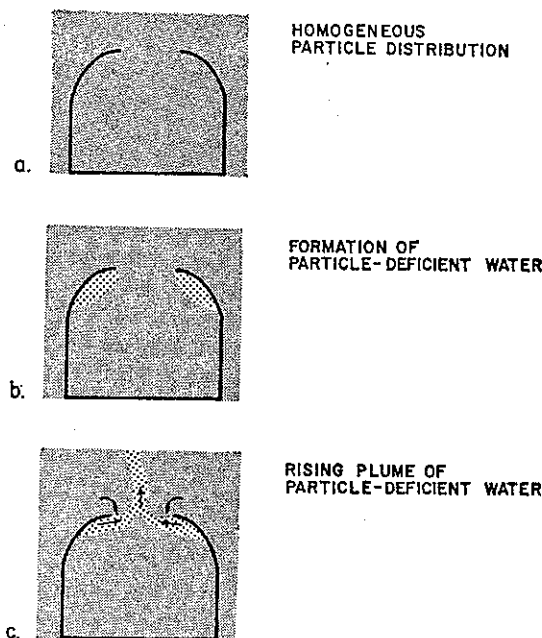Whether the baffle was located on top of or just inside the funnel made no significant
difference in the trapping efficiency. Rotation decreased the efficiency of all funnels.
In these experiments the accumulation of particles has been predominantly on the
funnel walls. In the natural environment there may be enough agitation of a funnel-
shaped trap to cause most particles to roll down the funnel wall and into the neck
and not be resuspended (Brunskill, 1969; Gardner, 1979), but some fine-grained
particles may remain on funnel walls.

4. *Segmented basin.* Each segment of the basin collected sediment at a different
rate, although the relative ranking of each segment's efficiency in different experi-
ments was consistent. The average collection rate was in close agreement with the
calculated flux except when the trap was rotated.

5. *Narrow-necked, wide-bodied traps.* Containers with bodies larger than their
openings had high trapping efficiencies, even in still water. The horizontal cylinder
overcollected so drastically the design could prove useful in removing suspended
particles for pollution control or for industrial purposes.

6. Dynamics of particle entrapment in still water

Observations in a fish tank where suspended particle concentrations ranged from
3-40 gm/l provided insight as to how overtrapping can occur in still water. Parti-

cle-laden water under an overhanging wall lost particles due to gravitational settling (Fig. 5). The overhanging wall prevented new particles from entering the particle-depleted zone. The water eventually became less dense than surrounding water and slowly rose in a narrow, continuous plume. The plume was made visible with back scattered light and by dropping tiny dye pellets into the traps and watching the dyed water rise. (The dye is slightly *negatively* buoyant.) The particle-deficient water was replaced by water of a higher particle concentration from outside the container, and the cycle continued. Thus, particles were "pumped" into containers at a rate which depended on the particle characteristics (sinking rate, concentration) in the fluid and the proportion of overhanging wall area to trap-opening area. A plume also rose from a tall cylinder in still water ($H/W = 3$), but not from a short ($H/W = 1$) cylinder. It may be that horizontal diffusion and Brownian motion did not allow the fluid at the bottom of the tall trap to remain homogeneous, so as particles fell out at the trap bottom a less dense fluid developed which rose.

Suspended particle concentration in the fish tank was initially 46 mg/l, so if 75% of the particles settled out of a parcel of water, the density difference would be 35 ppm; this corresponds to about a .035‰ change in salinity, which is sufficient to cause a density instability. Particle-deficient plumes were still visible when the total concentration had decreased to 3-5 mg/l. Concentrations of this magnitude are often found in estuaries (Krone, 1972; Meade, 1972; Schubel, 1968) and lakes (Hutchinson, 1957), but are unlikely anywhere in the open ocean.

7. Particle entrapment in flowing water

The mechanism by which particles are collected in any trap in flowing water is related to the process described above. Particles settle out of the water inside a trap. At varying rates the water is replaced by incoming eddies and particles in the "new" water can settle out. Thus, the trapping efficiency of a container is a balance between particle settling velocity, angular velocity of eddies, rate of fluid exchange of "stagnant water" in the trap, and hydrodynamic factors influencing the way fluid enters the trap, all of which may possibly be parameterized by the "residence time."

If a wide lip precedes the trap opening, particles can collect on the lip and be swept into the trap. This may account for some of the overtrapping of the dome and horizontal cylinder, but even if all of the area leading to the hole in the container were used to calculate trapping efficiency, it is not great enough to account for the degree of overtrapping that occurred. If the widest area of the trap body were used to calculate the efficiency instead of the trap opening, there is a better, though still erratic, correlation with the accumulation rate on the flume bed.

Particles are collected in traps through a process of fluid exchange, so it could be argued that traps just collect particles advected past, and by exchange, through the trap. The flux of particles through the trap can be estimated from the particle

concentration and flow velocity through the trap. For instance, the cylinder with H/W ratio of 2.3 had a trapping area of 11.3 cm². In one experiment the velocity was 4.0 cm/sec, and the average concentration was 25 mg/l over the 11.3 hours of the experiment. To a first approximation it was observed that fluid entered the down-stream half of the cylinder (also see Peck, 1972) and exited the upstream half at nearly the velocity of the mainstream flow. For the above example the mass of particles passing through the trap would then be 23.0 g. The mass actually collected during that experiment was only 0.0026 g, so the cylinder gives a very poor esti-mate of the "horizontal flux," but yields a surprisingly accurate measurement of what is collecting on the flume bed. More importantly, the results are reproducible under a variety of conditions.

8. Summary

Sufficient field and laboratory work has been done to instill confidence in the results of sediment traps deployed in tranquil waters (Davis, 1967; Pennington, 1974; Rigler *et al.*, 1974; Kirchner, 1975; Moore, 1931; Deevey, 1964). The ob-jectives of the experiments described here were to analyze flow around traps in moving water, to calibrate different trap geometries, and determine whether traps could be designed to collect particles at the same rate as the vertical flux.

Flow visualization made it immediately apparent that sediment traps in advective flows must not be thought of as "rain gauges" which simply catch the particles falling nearly vertically through a water column, because the particle fall velocity is usually small compared to horizontal current velocity. Thus, sediment is collected through a process of fluid exchange where particles are carried into the trap by eddies. A particle is "trapped" if it has a fall velocity which allows it to settle or be catapulted from the eddy into a stagnant area of the trap before it can be re-en-trained and carried out.

The results of these experiments using fine-grained sediment (95% <25 μm) in currents up to 9 cm/sec indicated that:

(1) At a given velocity the collecting efficiency of a trap is a function of the resi-dence time and flow pattern of fluid around and within the trap;

(2) The dominant control of the fluid residence time and flow pattern in any trap is its geometry;

(3) Particles collect in the stagnant regions of a trap where dye remains the longest;

(4) Particles are collected through a process of fluid exchange rather than falling freely into a trap;

(5) The collection rate of cylinders was closest to the accumulation rate of sedi-ment on the flume bed, and the cylinder with H/W ratio of 2.3 (or in this range) appears to have been deep enough to prevent resuspension of sediment in currents up to 9 cm/sec;

(6) Open funnels underestimate the actual flux in moving water, but yield an accurate measurement in still water;

(7) Placing baffles on top of a funnel can improve the trapping efficiency to a degree dependent upon the baffle design:

(8) Containers with body diameters greater than the mouth openings constantly overtrap sediment by a factor which depends on the geometry of the trap and current velocity (and therefore fluid residence time);

(9) The trapping efficiency of cylinders may increase slightly with increasing current velocity, while the efficiency of funnels decreases;

(10) The efficiency of a trap is reduced, especially in omnidirectional currents, if incoming eddies impinge upon the sites of sediment accumulation and resuspended particles (such as in shallow containers or inadequately-baffled funnels);

(11) Trapping efficiency is not a function of particle concentration;

(12) There was no apparent size differentiation between particles accumulating on the flume bed and in cylinders or the domed trap, but flocs and particles trapped in the horizontal cylinder with a narrow slit were slightly larger than on those of the flume bed.

The results of these empirical experiments should be viewed as exploratory into a method which has been used extensively, but whose working principles have received more speculation than investigation. Hopefully, these results will provoke more experimentation and hydrodynamic analysis (see Soo, 1969; Jobson and Sayre, 1970) of the behavior of particles around sediment traps.

Additional controlled tests need to be made at higher velocities, with larger particles, and with lower concentrations of sediment. Cylinders with larger H/W ratios and different types of baffles should also be tested. Although a larger flume would help meet some of these requirements, the problem of resuspension and bed-load transport in the flume remains and prevents using velocities above 17 cm/sec even in a large system (Krone, 1972; Partheniades, 1965). Also, as particles become larger, it is difficult to maintain an even distribution through the length and depth of the flume. Lower concentrations of particles make it difficult to conduct experiments in reasonable time periods. Further experimentation was therefore moved to the field (Gardner, 1979).

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