The Use of Sediment Traps in High-Energy Environments

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Abstract. A sediment trap is a container deployed in the water column with the aim of providing a representative sample of the material settling through that water column before it passes to a greater depth and ultimately to the seabed or lake bottom. A review of the previous literature shows cylinders and baffled funnels to be the most efficient sediment trap design in flows less than 0.1 m/s. For flow velocities above 0.1 m/s recent evidence suggests upwelling from the trap base, and possible undercollection. The degree of undercollection depends on the flow velocity, the type of trap, the height: diameter (aspect) ratio of the trap, and the type of sediment. Recent experiments suggest that cylinders with an aspect ratio of $\geqslant 3$ may be efficient collectors in velocities up to 0.2 m/s. The use of cylinders is not recommended in velocities above 0.2 m/s. For unbaffled asymmetric funnels a lower limit of 0.12 m/s is suggested.

Introduction

Over the past fifteen years sediment traps have become an increasingly popular tool for investigating particulate flux in oceanic and lacustrine environments. The aim of a sediment trap is to provide a representative sample of the material settling through the water column, before it passes to a greater depth and ultimately to the seabed, or lake bottom. Most of the early sediment trap studies were undertaken in environments in which the current velocities were below 0.1 m/s. Laboratory experiments have verified that in such conditions certain trap designs provided an accurate estimate of the vertical flux. The subsequent deployment of sediment traps in a wider range of conditions, such as the continental slope, submarine canyons, estuaries, and the nearshore zone, meant that assumptions about trap performance were made beyond the hydrodynamic conditions for which they had been tested. Only recently have experiments been conducted to assess sediment trap behaviour in flow velocities above 0.1 m/s. This chapter provides an assessment of sediment trap designs, and reviews recent developments in the use of traps in high-energy environments.

Sediment Trap Shape

Since the first recorded use of a sediment trap by Heim (1900) a variety of designs have evolved to suit individual needs, the designs commonly being based on intuitive assumptions of trap behaviour rather than tested models. Gardner (1980a) classified the designs into the five broad categories below:

i) Cylinders;
ii) Funnels;
iii) Wide-mouthed jars;
iv) Containers with bodies much wider than the mouth (e.g. Flasks and Tauber Traps);
v) Basin/tray-like containers with width much greater than height.

The different shapes are illustrated in Fig. 1.

The earliest studies to investigate the particulate flux values determined from traps of different shapes were simple field comparisons. Pennington (1974) found that the sedimentation rate inferred from cylindrical traps deployed in Lake Windermere agreed closely with known rates from core samples, palaeomagnetic evidence and Pb^{210} dating. Funnel traps deployed simultaneously, however, tended to give sediment accumulation rates of 0.3 to 0.5 of the expected value (i.e. to "undercollect" sediment). This supported the earlier work of Johnson and Brinkhurst (1971) who reported differences in the collection efficiencies of cylinders and funnels deployed in the

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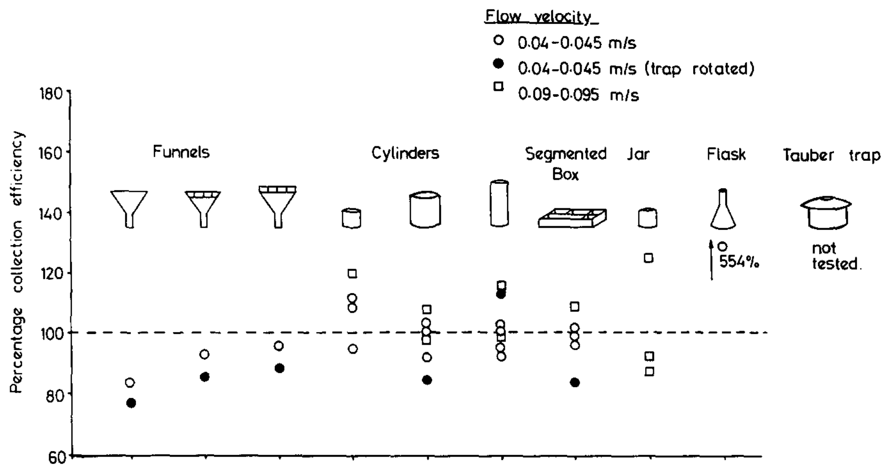

Fig. 1. The collection efficiency of different sediment trap shapes (adapted from Gardner, 1980a).

Bay of Quinte and Lake Ontario which appeared to depend upon the size of the funnel or cylinder used. Tauber traps tested by Pennington (*op. cit.*) tended to "over collect" sediment at an average of 2.3 times that collected in cylinders. When compared against basin/tray traps however, Reynolds and Godfrey (1983) found Tauber traps in Lake Windemere to collect up to 25 times more sediment. In the oceanic environment, Dymond *et al.* (1981) observed only a factor of two variation in the amount of sediment collected by cylindrical, funnel and basin/tray traps in the Santa Barbara Basin.

It is only through laboratory investigations that a reliable measure of the response characteristics of different types of sediment trap has been obtained. The turning point in sediment trap methodology came with the work of Gardner (1977), later summarized in Gardner (1980a and b). Models of the five different sediment trap shapes were tested in a recirculatory flume for flow velocities in the range 0–0.095 m/s. The trapping efficiency was calculated by comparing the sediment flux measured in the trap (mass/cm^2 of trap opening/per unit time) with the sedimentation rate on the flume bed. The results (Fig. 1) show cylinders, segmented boxes and baffled funnels to be the most efficient trap shapes. The effect of rotating the traps through 180°, 45°, and 135° during the experiments, to simulate a change of current direction is also shown in Fig. 1. Since the work of Gardner (1977) subsequent laboratory tests, e.g. those of Hargrave and Burns (1979) and Butman (1986), together with other reviews of existing data, such as those of Bloesch and Burns (1980), Reynolds *et al.* (1980) and Blomqvist and Hakanson (1981) have recognized cylinders to be the most efficient sediment trap shape.

The experiments of Butman (op. cit) have verified that in flows up to 0.1 m/s baffled funnels also provide a good estimate of particulate flux. Baffled funnels have been used extensively in deep oceanic environments, for example by Honjo (1980) in the Sargasso Sea and E. Hawaii Abyssal Plain and Jickells (1984) also in the Sargasso Sea. Funnels have the distinct advantage of concentrating the collected material in a sample container at the funnel base from which resuspension is unlikely during retrieval.

Sediment Trap Size

The earliest investigations into the effect of sediment trap size on collection efficiency considered different sediment trap designs. Davis (1967) found in laboratory experiments that the amount of material collected in cylindrical jars with openings varying between 25 and 100 cm^2, was directly proportional to the area of the trap mouth (Fig. 2). Field experiments using funnels by Watanabe and Hayashi (1971) in a lake environment yielded similar results. These results indicate that for fixed relative dimensions of the trap, i.e. height: diameter ratio or "aspect ratio", the cross-sectional area of the trap will not affect the amount of sediment per unit area.

The collection efficiency of traps is significantly affected, however, if the relative dimensions (aspect ratio) are changed. Most of the work in this field has

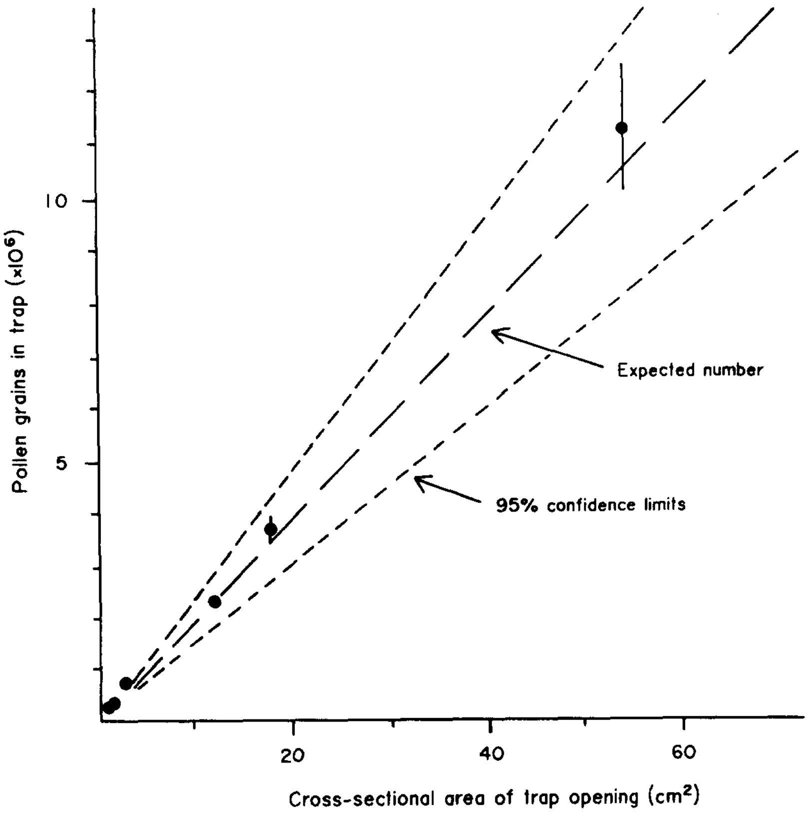

Fig. 2. Relationship between amount of material collected and trap cross-sectional area (adapted from Davis, 1967).

been concerned with defining the optimum aspect ratio for cylinders in any given hydrodynamic region. The flume experiments of Gardner (1980a) over the velocity range 0–0.095 cm/s showed the aspect ratio to have no apparent influence on the trapping efficiency for cylinders with aspect ratios of 1, 1.1 and 2.3. In field conditions near the Woods Hole Oceanographic Institution, however, where the velocity occasionally reached 0.5 m/s, an increase in the material collected was observed with increasing aspect ratio, and Gardner (1980b) suggested an optimum aspect ratio of between 2 and 3. This relationship was also investigated in the laboratory by Hargrave and Burns (1979) at velocities of 0.04–0.05 m/s for aspect ratios of 1.2, 2.6, 3.6, 5 and 20.4 and by Blomqvist and Kofoed (1981) in the Baltic Sea for ratios of 0.5, 1, 2, 3, 4, 6, 8 and 10. The results indicate that the apparent flux rate of material into the trap (i.e. the amount of material trapped per unit area, per unit time) increases with the aspect ratio up to a value of about 3 (Blomqvist and Kofoed, 1981) or 5 (Hargrave and Burns, 1979). After this the flux rate tends to a constant value which depends upon the prevailing hydrodynamic regime (Fig. 3).

Cylindrical sediment traps are thought to collect sediment by:

(i) Particles falling directly into the trap; and

(ii) Particles being carried into the trap by trap-induced turbulence.

The asymptotic relationship between collection efficiency and aspect ratio is thought to mark the dominance of the process of particles being carried into the trap by trap-induced turbulence. The critical aspect ratio marks the point at which a quiescent zone is formed at the base of the trap. Above this aspect ratio there is very little change in the amount of material collected; below this limit however, eddies may resuspend material from the trap base.

The Relationship between Trap Collection Efficiency and Flow Velocity

All the aforementioned work was conducted in flows less than 0.1 m/s. The encouraging results from sediment trap deployments in these environments lead to

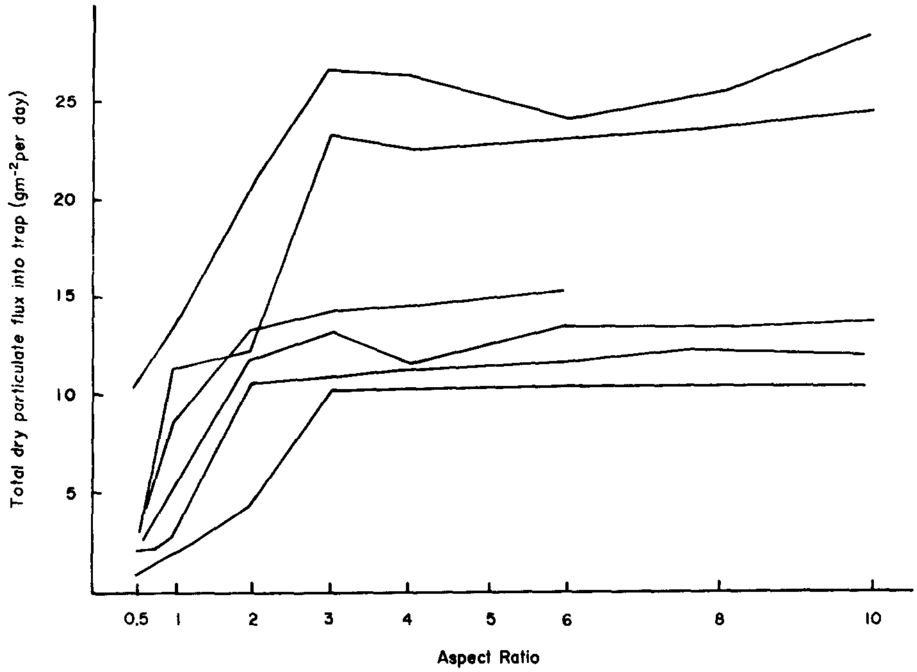

Fig. 3. Evidence for asymptotic relationship between amount of material collected in trap and aspect ratio, for cylindrical traps (after Blomqvist and Kofoed, 1981).

their use in a wider range of hydrodynamic conditions. Parmenter *et al.* (1983) used traps in flows with a mean speed of 0.3 m/s off Georges Bank, Gardner *et al.* (1983) deployed traps in the "Hebble" area where mean current speeds ranged between 0.08 m/s and 0.32 m/s, and recently Gardner (1989) investigated resuspension in the Baltimore Canyon where the mean velocities were up to 0.19 m/s, with maximum velocities of 0.8 m/s. It is only very recently however, that the relationship between collection efficiency and flow velocity has been fully examined.

The first investigation of the relationship between trap efficiency and aspect ratio under a wider range of hydraulic conditions was undertaken by Lau (1979), who considered the aspect ratio, h/d, in relation to the trap Reynolds number R_t, Ud/v, where;

h = height of trap
d = diameter of trap mouth
U = velocity of fluid at trap mouth
v = kinematic viscosity.

In a series of flume experiments the motion of oil droplets at the trap base was observed over velocities between 0.03 and 0.75 m/s in cylinders with aspect ratios of between 4.7 and 10 i.e., a range of R_t values between 2×10^3 and 3×10^4. By observing whether the oil droplets stayed or escaped from the traps, Lau (*op. cit.*) determined the aspect ratio at which upwelling would occur for any given hydrodynamic conditions (Fig. 4). Unfortunately, the range of conditions and aspect ratios tested by Lau (*op. cit.*), and the use of oil droplets rather than sediment particles, limits the extent to which these results can be applied to natural sedimentary environments.

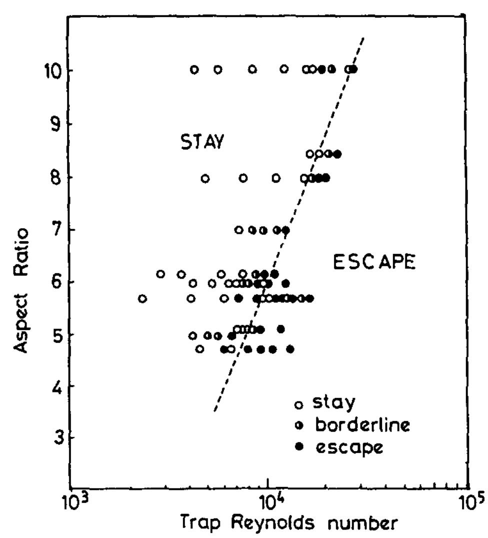

Fig. 4. The influence of aspect ratio and trap Reynolds number on oil droplet movement from a cylinder's base. Line indicates stay/escape boundary (after Lau, 1979).

Subsequent experiments examining the relationship between hydrodynamic conditions, aspect ratio and collection efficiency have used the R_t value to characterize the flow. In flow visualization experiments Gardner (1985) observed a tranquil zone at the base of cylindrical sediment traps with aspect ratios of 5, in velocities of up to 0.22 m/s. The corresponding R_t value was 8.4×10^3, which compares favourably with the value of 8×10^3 in Lau's experiments. Recent flow visualization experiments by Hawley (1988) have shown that upwelling of a layer of dye at the trap base in cylinders with aspect ratios of 5 starts at $R_t = 4.9 \times 10^3$, and is almost continuous at $R_t = 8.5 \times 10^3$.

At lower aspect ratios the upwelling in cylinders occurs at lower R_t values. The results of Butman (op. cit.) suggest that cylinders with aspect ratios of 3, accurately collect sediment at $R_t = 2.2 \times 10^3$, but at 4.6×10^3 significantly less sediment is collected (Fig. 5). Hawley (*op. cit.*) has shown that in a cylinder with an aspect ratio of 3, upwelling starts at $R_t = 3.5 \times 10^3$ and is almost continuous at $R_t = 5.1 \times 10^3$.

Information regarding the performance of other trap designs at velocities above 0.1 m/s is scant. For R_t values of 1.0 to 1.2×10^3 Butman (*op. cit.*) showed that wide-mouth jars overcollected sediment and funnels undercollected sediment as compared to cylinders, supporting the earlier work of Gardner (1980a). In the same experiments, baffled funnels and cylinders collected similar amounts.

Recently Baker *et al.* (1988) tested an unbaffled asymmetric funnel over a range of velocity conditions in Colvos Passage, Puget Sound. A Flow Activated Sediment Trap (FAST) was developed, capable of partitioning the collections according to the velocity regimes in which the collection occurred. The velocities were <0.12 m/s, 0.12 – 0.3 m/s, 0.3 – 0.5 m/s, and 0.5 m/s. The results were compared to similar free drifting sediment traps deployed simultaneously, considered to give an accurate estimate of the vertical particle flux since there is little velocity shear across the trap mouth. Figure 6 shows the results of the moored traps and the free drifting traps plotted against the velocities. Clearly less sediment is collected at velocities above 0.12 m/s in the moored traps. Taking the collections at 0.12 m/s to represent 100% efficiency Baker *et al.* (op. cit.) have shown the drastically reduced efficiency of asymmetric funnels at higher R_t values (Fig. 7).

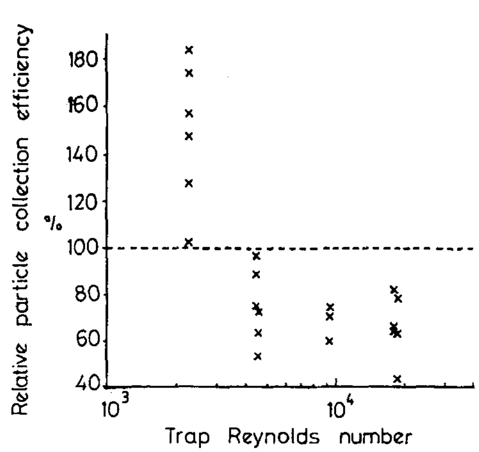

Fig. 5. Relative particle collection efficiency vs trap Reynolds number for cylinders with aspect ratios of ~3 (from Butman, 1986).

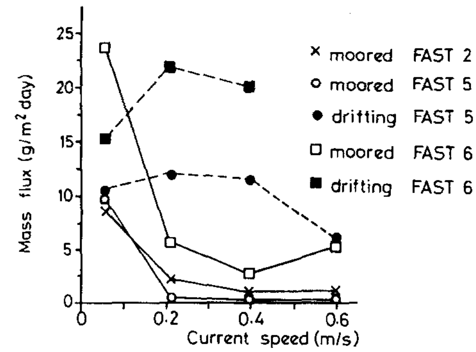

Fig. 6. Amount of material collected in asymmetric funnels at different velocities (from Baker *et al.* 1988).

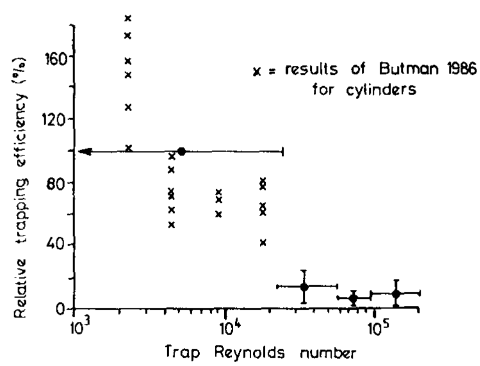

Fig. 7. Decrease in relative trapping efficiency with increasing trap Reynolds number for an asymmetric funnel (from Baker *et al.* 1988).

Laboratory Experiments of Trap Efficiency versus Velocity

As a precursor to the deployment of cylinders in an estuarine environment where the current velocities

TABLE 1

Dimensions of the cylinders tested in laboratory calibrations

External diameter (ED) (mm)	Internal diameter (ID) (mm)	Internal height (mm)	Aspect ratio Internal (height/ diameter
100	94	282	3
100	94	188	2
100	94	194	1
75	69	276	4
75	69	207	3
75	69	138	2
75	69	69	1
50	44	220	5
50	44	176	4
50	44	132	3
50	44	88	2
50	44	44	1

reached up to 0.4 m/s White (1989), conducted a series of laboratory experiments to investigate the collection efficiency of 12 cylinder types (Table I) at velocities of 0.1, 0.2, 0.3, and 0.38 m/s. The laboratory experiments were conducted in a 22.5 m long, 1.37 m wide and 0.6 m deep recirculatory flume. The freshwater of the flume was "seeded" with natural sediment taken from Port Hamble Marina, Hamble UK, to a concentration of approximately 60 mg/1. For each experiment, 24 cylinders were tested simultaneously, as shown in Fig. 8 with the mouth of each cylinder at 0.3 m above the bed in a water depth of 0.52 m. Before the start of each run the sediment was stirred into suspension within the flume by producing a current of 0.38 m/s in the channel and sweeping the entire length of the channel bed with a weighted domestic broom. The mean mid-channel velocity was adjusted to the desired setting, monitored with an electromagnetic current meter, and the cylinders were placed within the flume.

Concentration profiles were measured at either end of the test section, at the beginning and end of each run. Since there were no closed spaces in the system, and it was assumed that the flow velocity in the pumps and pipes was too great for particles to settle, the difference between the two sets of concentration values gives a measure of the total amount of sediment to have settled either on the flume bed or in the traps.

Each trap was removed after 24 hours, the trapped sediment was filtered through a preweighed glass microfibre filter, dried at 105°C, desiccated, and then weighed to determine the dry sediment weight in the trap. This was then corrected for the amount of material remaining in suspension within the trap at the time of its retrieval, to specify the total dry weight of sediment collected on each trap base. This was then compared to the calculated amount of material collected on the flume bed per unit area. For a 100% efficient trap in any given flow, the amount of sediment collected on the trap base and that collected on the flume bed (per unit area) would be equal. The procedure was similar to that performed by Gardner (1980a).

Figures 9a and b show the collection efficiencies plotted against velocity for cylinders with different aspect ratios at 0.1 and 0.2 m/s respectively. The

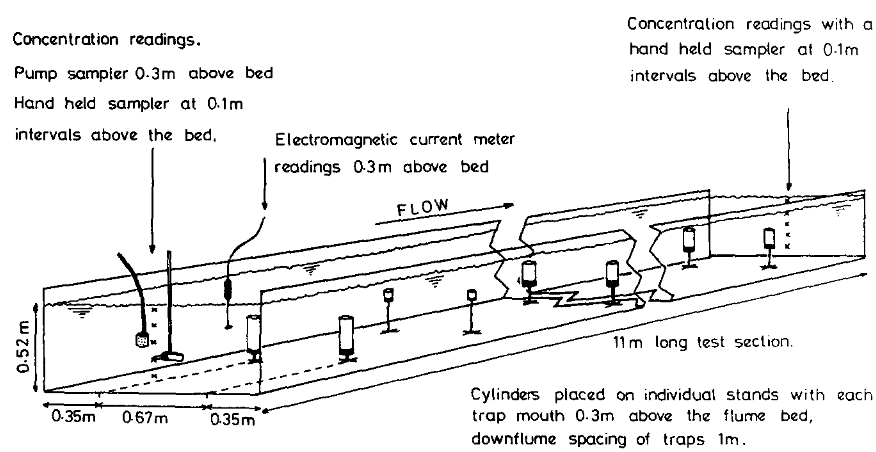

Fig. 8. Flume layout for experiments testing the effect of velocity on the collection efficiency of cylinders.

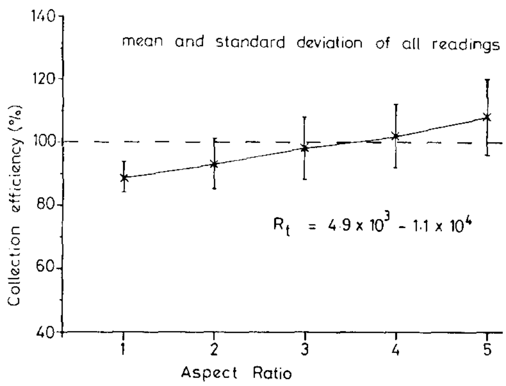

Fig. 9(a). The collection efficiency of cylinders with different aspect ratios at 0.1 m/s (from White, 1990).

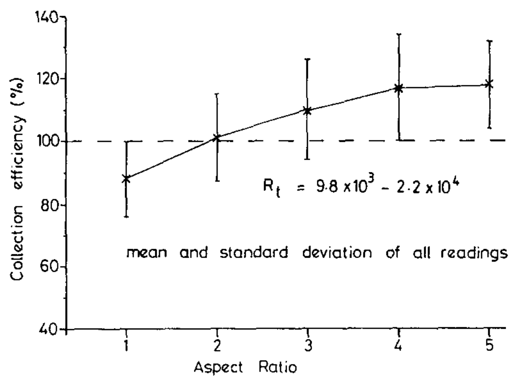

Fig. 9(b). The collection efficiency of cylinders with different aspect ratios at 0.2 m/s (from White, 1990).

results suggest that at velocities up to 0.2 m/s cylinders provide a reasonably accurate estimate of vertical flux.

The flow visualization experiments from previous literature suggest that for the range of R_t values tested (given on Figs. 9a, b) upwelling should have occurred from virtually all traps, particularly at 0.2 m/s. The fact that undercollection did not appear significant in cylinders with aspect ratios greater than 1 suggests that upwelling does not necessarily produce particle resuspension.

Butman (*op. cit.*) also found that traps with aspect ratios of 2.7 collected efficiently at 1×10^4 R_t, whereas Hawley's experiments suggest upwelling should be complete at 5.1×10^3 R_t for this aspect ratio. Clearly further work is needed to verify the limit at which resuspension occurs rather than upwelling of fluid.

Unfortunately the results of White (1990) for flows of 0.3 and 0.38 m/s are inconclusive due to resuspension of material from the flume bed at these velocities.

Conclusions

Laboratory experiments and field investigations have suggested that cylinders and baffled funnels are the most efficient sediment trap designs for estimating the vertical flux in velocities up to 0.1 m/s. At higher velocities (or R_t values) recent work suggests that upwelling from a trap base may occur although the point at which particle resuspension and hence undercollection occurs is still unclear. The point at which resuspension occurs depends upon the trap type, the trap aspect ratio, the ambient velocity, and the sediment type. Recent laboratory experiments suggest that cylinders with an aspect ratio of 2 may be efficient collectors in velocities up to 0.2 m/s. As a precaution it is suggested that an aspect ratio of at least 3 and preferably 5 is used in deployments in such environments. The use of cylinders in flows above 0.2 m/s is not recommended. Unbaffled asymmetric funnels have been shown to seriously undercollect sediment at velocities above 0.12 m/s.

Further work is needed to investigate resuspension of particles from the trap base, and any biasing effects that resuspension may have on the composition of the particles collected. If sediment traps are to be used in high-energy environments such as the continental slope, estuaries, and the nearshore zone, the limitations outlined in this paper must be considered when the results are interpreted.

Acknowledgement

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