EVALUATION OF SEDIMENT TRAPS IN LAKE ST. CLAIR, LAKE ONTARIO, AND IN HAMILTON HARBOUR

F.M. Boyce, P.F. Hamblin,
D.G. Robertson and F. Chiocchio

NWRI Contribution No. 89-09

Lakes Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6
Canada

April 1989

EXECUTIVE SUMMARY

Sediment traps are simple, inexpensive devices that yield time-integrated samples of material suspended in the water column. In relatively calm waters, earlier studies have shown the cylindrical settling tube to be a reliable design. In shallow water, where oscillating currents caused by surface waves frequently resuspend bottom material, less confidence can be placed in the interpretation of the trap returns because it is suspected that the quantity of material retained in the traps depends not only on the concentration of material suspended in the water, but also on horizontal water movements. A further complication is that certain sizes of suspended particles may be trapped preferentially. In reviewing the recent literature, the authors could find no previous studies that dealt adequately with these two concerns. Kenney (1985) constructed a vertical array of traps of a novel design that seemed well-suited for studies of sediment movements in shallow, wave-dominated lakes. Kenney's trap was later adapted for our work in Lake St. Clair. During the 1985 and 1986 experiments we collected data that permitted a comparison of the two traps and a first evaluation of the trapping efficiency of the Kenney device. In 1987, a simple and inexpensive settling chamber based on the Kenney

design was constructed from a 1 L plastic sample bottle in response to a need for a device that could be used in rivers. An intercomparison of settling tubes, the Kenney array, and bottle traps was conducted in 1987 in Hamilton Harbour and in the western end of Lake Ontario. These last studies provide rough answers to the central questions of velocity dependence and size fractioning based on field data. We find that the tendency for traps of both the conventional and the Kenney design to sort sediment is only slight, at least for the range of particle sizes from fine sand to clay. On the other hand, we find that catch rates depend strongly on the horizontal water velocity, scaled according to a Reynolds Number based on trap diameter. The Reynolds Number range over which the velocity sensitivity is largest is that associated with laminar and transitional flow. Further study is needed to establish whether there is a range of Reynolds numbers where the catch rates are less sensitive to the velocity scale. It is proposed that such follow-up studies be performed in the controlled conditions of the hydraulics laboratory. Quantitative results inferred from sediment traps deployed in shallow, wave-dominated environments should be viewed cautiously.

RÉSUMÉ

Les pièges à sédiments sont des appareils simples et peu coûteux qui permettent d'obtenir des échantillons intégrés dans le temps des matières en suspension dans l'eau. On a vu lors d'études précédentes qu'en eau relativement calme, les tubes de décantation cylindriques sont d'une conception fiable. En eau peu profonde, là où il y a des oscillations de l'eau entraînée par les vagues en surface, les matières qui se sont déposées au fond sont fréquemment reprises en suspension; alors, on ne peut pas accorder autant de confiance à l'interprétation des résultats fournis par ces échantillonneurs car il est suspecté que la quantité de matières capturées dans les pièges ne dépend pas seulement de la concentration des matières en suspension dans l'eau, mais aussi du mouvement horizontal de l'eau. De plus, pour compliquer davantage la question, il se peut que des particules en suspension de certaines dimensions soient capturées de manière préférentielle. Lors d'une revue de la documentation récente, les auteurs n'ont pu trouver d'études qui s'adressent à ces deux questions de manière satisfaisante. Kenney (1985) a construit une batterie verticale de pièges de conception nouvelle qui semble bien se prêter à l'étude des mouvements de sédiments dans les lacs peu profonds et dominés par les vagues. Le piège de Kenney a ensuite été adapté à nos propres travaux du lac St. Clair. Lors des

expériences de 1985 et 1986, nous avons recueilli des données qui permettent d'établir une comparaison entre les deux types de piège et de procéder à une première évaluation de l'efficacité du dispositif Kenney pour la capture des particules. En 1987, une cuve de décantation simple et peu coûteuse, fondée sur la conception de Kenney, a été fabriquée avec un bouteille d'échantillonnage en plastique de 1 L; cet appareil devait servir dans les cours d'eau. Une étude de comparaison croisée entre les tubes de décantation, le dispositif de Kenney et les bouteilles, a été faite en 1987 dans le port de Hamilton et dans la partie ouest du lac Ontario. Ces travaux apportent des réponses approximatives aux questions centrales de la dépendance vis-à-vis la vitesse et de la distribution granulométrique qui sont fondées sur des résultats obtenus sur le terrain. Il est observé que les pièges classiques et la batterie de Kenney ont à peine tendance à faire un tri, du moins à l'intérieur de la plage granulométrique du sable fin à l'argile. Par ailleurs, il est observé que le taux de capture dépend fortement de la vitesse horizontale de l'eau, en fonction d'un nombre de Reynolds calculé en fonction du diamètre des pièges. La plage des nombres de Reynolds où la sensibilité à la vitesse de l'eau est la plus importante est celle associée à un écoulement laminaire et de transition. Il est nécessaire de procéder à d'autres études pour voir s'il existe une plage de nombres de Reynolds où le taux de capture est moins sensible aux vitesses. Il est conseillé de procéder en milieu contrôlé à ces travaux, dans le laboratoire d'hydraulique. Il faut se méfier des résultats chiffrés qui sont obtenus à partir de pièges à sédiments disposés en eaux peu profondes et dominées par les vagues.

ABSTRACT

Sediment traps are simple, inexpensive devices that yield time-integrated samples of material suspended in the water column. Although many different designs have been proposed, there seems to be general agreement that the cylindrical settling tube is a design capable of yielding quantitative results in (Bloesch and Burns 1980, Gardner 1980a,b) for relatively calm waters. The reliability of these or any other trap in shallow water with significant wave orbital motions is unknown. This paper describes our attempts to assess the field performance of conventional settling tubes and two versions of horizontally-ported chambers in shallow, wave-dominated water.

RÉSUMÉ

Les pièges à sédiments sont des appareils simples et peu coûteux qui permettent d'obtenir des échantillons intégrés dans le temps de matières en suspension dans l'eau. Bien que différentes conceptions ont été proposées, il semble qu'on s'entende pour dire que les tubes cylindriques à décantation sont d'une conception qui permet d'obtenir des résultats chiffrés dans les lacs en eau relativement calme (Bloesch et Burns, 1980, Gardner, 1980a,b). On ignore quelle est la fiabilité de ces pièges ou de tout autre en eau peu profonde et soumise à des mouvements orbitaux des vagues. Cet article décrit comment nous avons tenté d'évaluer la performance sur le terrain des tubes à décantation de conception classique ainsi que deux versions des cuves à partitions horizontales, en eaux peu profondes et dominées par les vagues.

INTRODUCTION

Kenney (1985) devised a vertical array of sediment traps for use in shallow Lake Manitoba (4 to 5 m). His design (Figure 1) embodies a vertical cylindrical chamber connected to the exterior with small horizontal ports. Horizontal water motions (currents, wave orbital motions) move suspended materials in and out of the top part of the chamber; a portion of the suspended material settles into the calm fluid beneath the level of the ports. The design is vertically compact and would seem to be well-suited for the study of near-bottom sediment resuspension and transport. Kenney's results in Lake Manitoba suggest that this phenomenon is poorly understood.

In 1985 and 1986, as a contribution to the Upper Great Lakes Connecting Channel Study, the authors deployed the original 10-compartment (4 m high) Kenney sampler from a tower in Lake St. Clair. Qualitatively, the sampler was succesful, trapping useful amounts of suspended materials. In 1985, a limited intercomparison between the Kenney sampler and conventional settling tubes was made, using apparatus originally designed by Rosa (Rosa _et al_. 1983) while in 1986, time series data of currents and optical transmission were collected at different levels on a nearby tower, permitting an evaluation of the trapping efficiency of the Kenney's design.

A need to trap suspended material in the estuary of the Fraser River, an environment of strong currents and heavy ship traffic, suggested a modification of the Kenney design in which the chambers consist of 1 L Nalgene sample bottles with horizontal ports drilled near the upper shoulders. Such traps are inexpensive, light, and easy to deploy (Figure 2). It was assumed that in strong currents, the top of the chamber would be adequately flushed through small diameter ports, whereas large diameter ports might lead to excessive turbulence within the chamber, precluding the settling of fine material. Thus port diameter and spacing are likely to influence trap performance and their effects should be evaluated.

In July and August of 1987, the frame carrying the five-chamber version of the Kenney sampler and conventional tubes originally assembled for the 1985 experiments was modified to include arrays of bottle traps and deployed in Hamilton Harbour (Figure 3). The ports of the bottle traps were postioned at the same levels as the ports on the five-chamber Kenney sampler. All bottle traps had eight, equally-spaced ports; the three vertical arrays had port diameters of 5, 10, and 15 mm, respectively, and they are known in this study as small, medium, and large-ported bottle traps.

Taking advantage of the wind and wave data collected during the WAVES experiment in Lake Ontario (Donelan <u>et</u> <u>al</u>.

1988), the sediment trap study was shifted to the vicinity of the array of towers located at the western end of Lake Ontario, and operated from late September to early December, 1987. In addition to the array of traps described above, specially designed stands carrying three bottle traps each were deployed in the vicinity of a temporary tower set in 8 m of water. These traps were located 1.5 m above the bottom. At the same level, and attached to the tower, were a Neil Brown "Smart" acoustic current meter and a 25 cm pathlength Seatech optical transmissometer. The transmission data was recorded on a Seadata recorder mounted on the tower 3 m above the surface. The traps were refurbished on a weekly interval, weather permitting. Temperature and optical transmission profiles plus seston samples were collected at the tower site from a launch as often as possible. In the last few weeks of the study, an ISCO automatic water sampler was mounted on the tower, drawing a 1 L sample every eight hours from the level of the current meter and transmissometer. This auxiliary data serves to calibrate the recording transmissometer signal so that it may be used to estimate the time-varying concentration of suspended material.

Previous studies of sediment trap behaviour are reviewed in the next section of this paper. Then, because of their relative completeness, the 1987 experimental results are analysed, and a similar treatment is then applied to the 1985 and 1986 results. It is concluded that for the range of parameters included by the experiments, the preferential sorting of sediments by the various traps is minimal, but that the catches are strongly dependent on the horizontal water velocity. This velocity dependence should be established through a wider range of Reynolds numbers in a controlled laboratory environment.

Previous Studies of Sediment Trap Performance

Gardner (1980a,b) tested sediment traps of various configurations in the laboratory and independently in a field environment. He noted that sediment traps collect particles through a process of fluid exchange rather than their falling directly into the trap. Somewhere in the trap there must be a zone of calm water through which particles can freely settle without resuspension, and this zone must be in contact with water containing suspended material ideally at the ambient exterior concentration. Assuming that there is a region at the bottom of the trap where the fluid remains non-turbulent, it can be shown via a simple diffusion argument that the fractional increase in concentration of suspended material between the turbulent upper part of the trap and the quiet bottom is roughly equal to the ratio of the settling velocity to the turbulent velocity scale in the upper part of the trap. Since this ratio tends to be small, the trap should catch material at a rate very close to the product of the concentration at the top of the chamber and the settling velocity. The laboratory experiments demonstrated that traps of simple cylindrical geometry (settling tubes open at one end and with vertical axes) came closest to this ideal. Other configurations, such as funnels and pots, can introduce flow-dependent biases. Gardner did not demonstrate that the aspect ratio (ratio of the depth of the trap to its diameter) was an important design parameter; most of his experiments were performed with modest flow velocities. Hargrave and Burns (1979), supported by the laboratory studies of Lau (1979), demonstrated that aspect ratio of settling tubes was a critical parameter in more energetic flow regimes, and recommended that this ratio should exceed five. A thorough review of sediment trap techniques by Bloesch and Burns (1980) suggested that the aspect ratio should exceed ten for turbulent environments. They recommended against a common practice of reducing washout of trapped sediments with the addition of baffling at the top of the traps. Gardner (1985) studied the effect of the tilt of settling tubes away from the vertical on their collecting efficiency. The catch rate increased with tilt angle (both upstream and downstream) up to an angle of 45 degrees, with the maximum catch rate being as much as three times the rate of an identical but vertical trap. This phenomenon may have implications for traps located where elliptical surface or internal wave orbital motions are significant. Hawley (1988) has conducted very detailed laboratory studies of the flow field in cylindrical settling tubes and has delineated the horizontal flow conditions (range of Reynolds numbers) under which a calm zone can be expected at the base of the trap. While this is valuable information, the study does not constitute a calibration of the device for which one must actually trap sediment. Trapping efficiency also depends on the grain-size distribution of the suspended material, in particular on the Reynolds number associated with the particle diameter and its settling velocity. We are assuming for the present that these Reynolds numbers are very small, that the distribution of material away from the boundaries is controlled by the ambient turbulent motions. Depending on the analyses intended for the trapped material, its inevitable alteration due to biological or chemical activity (or indeed due to efforts to reduce such alterations through the use of poisons or preservatives) over the time it remains in the trap may pose problems (Bloesch and Burns 1980).

It should be noted that even in the calmest of natural environments the horizontal flux of suspended material is at least two orders of magnitude greater than the vertical flux due to settling. We consider it unlikely then that a trap should respond only to the vertical component of sediment flux.

Intercomparison of the Kenney Sampler, Bottle Traps, and Settling Tubes in Hamilton Harbour and in Lake Ontario, 1987

The multi-trap array was deployed for four episodes in Hamilton Harbour, and for seven episodes in Lake Ontario. The nominal duration of each episode was seven days but was often longer depending on the availability of servicing vessels or weather conditions. The collected material, a slurry of trapped sediments and water, was decanted while under refrigeration, freeze-dried, and weighed. In Hamilton Harbour, the collected material was dark and flocculated. The harbour samples were ashed in a high-temperature oven to burn off organic components and then reweighed. Only total sample weights are reported here. A complete description of the laboratory techniques used in this study is given by Robertson (1988).

Figure 4 (a through l) shows profiles of the catch rates of the vertical arrays of the bottle traps and the Kenney sampler. The catch rate is expressed in $gm/m^2/day$, the area in this display being the horizontal cross sectional area of the trapping cylinders (in order to compare the catches of both the bottle traps and the cylinders).

Although both the Hamilton Harbour and the Lake Ontario sites have comparable water depths, the wave conditons in the Harbour are much less energetic. The suspended sediment in the Harbour location has a relatively high organic component and appears "fluffy" or flocculated whereas the material collected in Lake Ontario is predominantly inorganic (sands, silts, and clays). During calm periods in the Harbour (Episodes 1 and 2, Figures 4a and 4b), the vertical profiles of catch rates from the Kenney and bottle traps show a minimum at mid depth. Profiles of optical transmission and temperature show uniform properties in the upper two thirds of the water column; the decrease in catch rate with distance from the surface would be consistent with a positive correlation between catch rate and a rms horizontal velocity associated with surface waves. The increase in catch rate approaching the bottom is presumably associated with the resuspension of recently settled material. During windier periods (Episodes 3 and 4 in the Harbour, Figures 4c and 4d) the mid depth minimum in catch rate is not observed; catch rates increase monotonically with depth, and we presume that the gradient of concentration of suspended material controls the shape of the profile. The catch rates observed with the sediment tubes during the Harbour episodes are typically twice those of the large-port bottle traps. Although their vertical spacing is too large to permit a definitive statement, there does not seem to be evidence of a mid-depth minimum in catch rate during the calm episodes.

The catch profiles for the Kenney and bottle traps in Lake Ontario are all similar to those observed in the Harbour during the windier periods (monotonically increasing with depth) (Figures 4e through 4l). The absolute catch rates vary widely, however, and reflect the vigour of the meteorological forcing. Episode 6 (Figure 4k) includes a major storm with onshore winds; some of the deeper traps were overfilled with sediments and the reported catch rates are unreliable. A puzzling feature of the windier Lake Ontario episodes is the erratic behaviour of the settling tubes located 1 m above the bottom. The ratio of catch rate between the tubes and the large-port bottles was at times as large as 40 and there were large variations between two settling tube catches at the same depth (Episode 2, Figure 4f, Table 1). On the other hand, the results from all traps located 2 m above the bottom are relatively consistent with each other through all episodes.

Calibration of Traps Located 1.5 m Above Bottom

A second set of bottle traps mounted on stanchions 1.5 m above bottom near the 8 m auxiliary WAVES tower in Lake Ontario was deployed from October to December. These traps could be serviced from the WAVES tender without lifting a heavy mooring provided the winds were light (Figure 5). Wind conditions and the heavy demand on the launch made it impossible to coordinate the trap refurbishments so that the two trapping sequences were identical. With contemporaneous measurements of current and optical transmission made by tower-mounted instruments at the 1.5 m height above bottom, it was hoped to "calibrate" the bottle traps.

Water samples were collected from the launch at 1.5 m above the bottom as often as possible. These samples were used to determine the concentration of suspended material. At the same time, a depth profile of optical transmission was recorded (Seatech 25 cm pathlength). The transmission at the 1.5 m height above bottom was extracted from this record. An identical transmissometer was mounted on the tower at a height of 1.5 m above bottom and its signal was burst-sampled and recorded at half hour intervals. The launch-based transmission measurements served to correct the _in situ_ transmission measurements for progressive fouling of the instrument. Unfortunately, the _in situ_ transmissometer operated only sporadically because of frequent shutdowns of the WAVES array of which it was a part. An automatic water sampler (ISCO) was placed on the tower from 13 November onwards and collected 1 L samples from 1.5 m above bottom every eight hours. These were used to determine sediment concentration in exactly the same way as the samples collected from the launch. This data was used to construct an empirical relation between _in situ_ optical transmission and suspended sediment concentration. Because the sensitivity of the transmission measurement decreases as concentration of suspended material increases, the relationship is only useful for concentrations less than 20 mg/L.

Data from all sources is assembled to construct a daily averaged suspended sediment concentration 1.5 m above the bottom over the entire sediment trapping period (October 7 to December 10, 1987).

The current meter on the tower operated in a burst-sampling mode, and was active for nine minutes every half hour. During that time it sampled the two components of horizontal current twice each second. An on-board microprocessor calculated and recorded the arithmetic mean and the sum of the squares of both components as well as the sum of the cross products. This information is sufficient to calculate the speed and direction of surface wave orbital motions and a total root mean square speed (Hamblin _et al_. 1987). Episode averages of suspended sediment concentration, good mean square current speed, and the magnitude of horizontal sediment flux are reported in Table 2. With the exception of the 6th trapping interval (that included a major storm), the standard deviation of catch rate for each group of bottles with the same port diameter is less than 10% of the mean rate. The average catch rate expressed as gm/m^2/day, divided by the mean concentration over the trapping interval (expressed in g/m^3) yields a velocity scale (m/day) that for an ideal trap could be equated with the mean settling speed of the collected sample. For the "calm" periods, these apparent settling velocities are between 1 and 5 m/day; for the rougher periods, they may be an order of magnitude larger. Data from the 3rd level (1.2 m above bottom) of the vertical arrays of traps were analysed in the same way. With the exception of the surprisingly large catch rates of the settling tubes, the results are comparable to those of the stanchion traps. The data from the stanchion traps will be further analysed.

We believe that at small horizontal velocities, and for small diameter ports, the catch rate of the bottle traps should depend on the horizontal flux of suspended material. material. The horizontal capture efficiency of each episode was calculated by the formula

$$E_H = \frac{Q_o}{Ad\ \overline{VC}}$$

where Q_o is the total catch rate in gm/day, Ad is the frontal area of the inlet ports to unidirectional flow, and $\overline{VC}$ is an estimate of the daily-averaged magnitude of the horizontal flux of suspended material based on an rms speed (derived from the current meter data) and the estimates of suspended sediment concentration. The microprocessor in the current meter, in addition to storing the algebraic sums of the north and east components of velocity, also computes and stores the sum of their squares. From the sum of the squares a root-mean-square speed is computed for each measurement burst. This number may exceed the mean scalar current speed by as much as 22% for particular cases, but the two measures are generally within 10% of each other. The root mean square speed, directly available from the Neil Brown current meter, can be defended as a rational choice for the velocity scale with which to multiply the burst-averaged concentration because it represents the mean kinetic energy of the flow field due to the combination of steady and oscillating flows. The efficiency is plotted as a function of the mean Reynolds number based on a trapping interval average of the root mean square speed and the outside diameter of the bottle (9 cm) (Figure 6). It is seen that for the range of Reynolds numbers from 3000 to 7000, the efficiencies for traps of common diameter group approximately along straight lines, the smaller the diameter of the port, the higher the efficiency. At the large Reynolds number associated with the major storm, the efficiencies of all traps have diminished from the largest observed values at a Reynolds number of 6840. The dependence of efficiency on Reynolds number at the low speed end of the range suggests that sediment flux to the bottle traps is controlled here by boundary layer effects. A corresponding effect for the sediment tubes cannot be demonstrated here because of the erratic behaviour of these traps at the level for which we possess flow data, but it should not be ruled out. The decreasing capture efficiency for increasing port diameter at low Reynolds numbers could be attributed to the shorter residence time of the larger-ported traps; only a fraction of the material that enters is retained. The nature of the response of the traps in the range of Reynolds numbers between 7,000 and 15,000 is of great interest. Is there, for example, a range of R where the collection efficiency is constant, and for which the traps, in effect, measure horizontal sediment flux? Or, as the evidence suggests, but cannot confirm, is there a region of the response curve where the capture efficency is roughly proportional to the reciprocal of the Reynolds number. In such a range, the catch of the traps would depend primarily on the ambient sediment concentration. In effect, one could argue that the flushing of the top of the bottle traps was sufficient to maintain the ambient concentration inside the trap and the trap would then function very much like the standard settling tube. At very large flows, one expects that the turbulence level inside the trap would become large enough so as to inhibit settling and the capture efficiency should tend to zero.

A "vertical" efficiency, Ev, of capture can be defined in a fashion analogous to that of the horizontal efficiency

$$Ev = \frac{Qo}{A_D Cw}$$

where Qo is the total catch rate in gm/day, A_D is the area of the base of the trap, C is the concentration of the suspended material at the top of the trap, and w is a settling velocity (m/day). Assuming that the ambient concentration is the same as that at the top of the trap, and that the vertical efficiency is unity, an effective settling velocity, w_s can be inferred. Given w_s, and assuming that Stokes' Law applies to the settling particles, the diameter δ_q, of a quartz sphere having settling velocity equal to w_s in water at 20°C may be estimated from data given by Sverdrup *et al.* (1942). δ_q may in turn be related to Wentworth Size scale, by the formula

$$\phi_q = 9.965 - 1.4426 \ln \delta_q$$

where δ_q is expressed in microns (Griffiths 1967). This estimate of the diameter of an equivalent quartz sphere may be compared with the mean ϕ of the actual trapped sediment as determined in the sedimentology laboratory (Duncan 1988).

Particle Size Distributions of Selected Samples from Lake Ontario

Sixty-three samples of trapped sediments were analyzed for grain-size distribution (Duncan 1988). In this discussion we shall refer to percentages of sand (PHI scale of 1.5 [smallest PHI number reported] to 3.5), silt (PHI scale of 3.5 to 8.0), and clay (PHI scale greater than 8).

Samples from the array of bottle traps at the 8m depth tower site (all at 1.5 m above bottom) were examined to study the degree of reproducibility of catches with this type of trap and also to determine if the port diameter introduced a bias into the size distribution. Episodes A4, A5, A6, A7 were examined (see Table 2). Data from three of the stanchion arrays were assembled for episode A5, an interval that contained two modest wind events (Table 3). This table shows that reasonably consistent results were obtained among traps of the same port diameter. For traps of differing port diameter, the fraction of sand caught decreases slightly as trap diameter decreases for episode A5 only, but the silt and clay fractions are comparable. Episode A6, which contained a major storm produced anomalous results in that the large port diameter trap caught the least amount of sediment, most likely because the turbulence levels in the container were large enough to inhibit settling. For these trials, the correspondance between the mean particle size determined from grain-size analyses in the laboratory and the size inferred from the effective settling speed of the sample is reasonably good (Table 2). To summarize, the results from the stanchion arrays 1.5 m above bottom suggest very little size sorting according to port diameter.

In the next suite of samples, attention is focussed on the differences between tube and bottle traps, as well as on the vertical distribution of catch. In Table 4, grain size data is presented for three levels (nearest bottom, 1.2 m and 1.97 m above bottom) for the four types of trap on the multi-trap array (Episode 4, 8/11 to 15/11). All the horizontally ported traps show a decrease in the sand fraction moving away from the bottom. Surprisingly, the largest sand fraction is consistently reported for the 1.0 cm (medium) port diameter bottles. The smallest sand fraction is reported for the 0.5 cm (small) port chambers. The variability among traps is greatest at the bottom; at the 1.2 and the 1.97 m levels the grain-size distributions are quite similar. The uppermost sediment tube (1.97 m above bottom) yielded a result very similar to that of the bottle traps, and the result from the lowest level tubes (0.8 m above bottom) is comparable to the results obtained for the lowest bottle traps. However at the intermediate level, the two tubes caught sediments of very different composition. One tube caught 116 g of material dominated by sand, a material like that caught next to the bottom by the other traps. The second tube, at the same 1.2 m level, caught 6 g of a material quite similar to that caught by the other traps at that level. This anomaly is not isolated; it is confirmed by an identical analysis of Episode 7 (29 November to 6 December, 1987) not reported here. Even during the very high energy event of Episode 6 (22 November to 29 November, 1987), the traps at 1.97 m above bottom yielded comparable results, although the 0.5 cm port traps caught proportionately less sand, and the sediment tube caught the most sand. Our tentative conclusion for the sporadic overtrapping by the tube chambers, reinforced by the grain-size data that suggests that the extra material comes directly from the bottom, is that eddies induced by the structure of the array itself cause a local upward billowing of the near-bottom material. The tube traps, opening upwards, would tend to catch fast-sinking sand particles, whereas the nearby bottle traps, with horizontal ports, would not capture as much of this vertical flux of sand. The tube traps are located close to the large and potentially interfering Kenney Sampler, whereas the bottle traps are situated outboard, a distance equal to at least five diameters of the Kenney sampler.

1985 and 1986 Experiments in Lake St. Clair

The original Kenney sampler was deployed by us for the first time in Lake St. Clair in the autumn of 1985. The catch rates for seven episodes are reported in Figure 7. The three episodes where the measured catch rates exceed a background level are associated with significant meteorological forcing. Grain-size analyses show that the more energetic trapping intervals yield a sediment that has a bi-modal size distribution (Figure 8). The bottom-mounted array described in Figure 3 was also deployed for the first time in 1985, but without the bottle traps. A comparison between the Kenney sampler and the settling tubes over two episodes is depicted in Figure 9. Here the tubes indicate a marked decrease in trapping rate moving away from the bottom that is not echoed in the Kenney sampler results. In contrast to the 1985 results, the 1987 results from the Kenney sampler show an increase in catch near the bottom in all cases. The 1985 episodes coincided with very calm conditions; horizontal water motions may have been insufficient to maintain near-ambient suspended sediment concentrations at the top of the Kenney chambers, although the settling tube profiles are indicative of active resuspension from the bottom (Rosa et al. 1983). Unfortunately, the array was lost for a year when a marker float broke loose so that there is no intercomparison data from Lake St. Clair for windy (and wavy) conditions.

In 1986 (Hamblin et al. 1987) the Kenney Sampler was again deployed in Lake St. Clair. During four of the eight trapping episodes, current meters and optical transmissometers on a nearby tower provided a record of horizontal flow and an estimate of suspended sediment concentrations, the latter from an empirical relation established between extinction coefficient and concentration of suspended material. Transmission measurements were made at three heights and horizontal velocities were interpolated to these heights from current meters positioned at four levels. The catch from the Kenney sampler chamber nearest each transmissometer level was used for comparison. For each data level and each trapping episode, the observed sampler catch (expressed in grams per day), the mean suspended sediment concentration, an rms velocity scale, and the averaged product of sediment concentration and rms horizontal velocity were computed, first over each measurement burst and then over the trapping episode (Table 5). Multiplying the mean velocity-concentration product by a scaling factor that includes the frontal area of the chamber ports yields the catch rate of a "perfect" trap that retains all the material flowing into it in the absence of boundary layer effects. As before, we can calculate a horizontal trapping efficiency, an apparent vertical settling speed, and a mean Reynolds number for horizontal flow about the trap (Table 5).

Figure 10 shows the observed total catch rate plotted against averaged suspended sediment concentration. These results are very similar to the Lake Ontario results. The estimates of horizontal capture efficiency as a function of Reynolds number are shown on Figure 7. Episode B, C, and D plot close to the curve for the large-port chambers in the 1987 experiment. Episode A seems to have a lower trapping efficiency than would be expected from the observed values of mean concentration and rms speed. This episode is marked by a relatively large mean current and by small waves; the low catch rates suggest that oscillating flow may result in a more "efficient" particle capture, a possibility worthy of further exploration. The difference between the mean particle diameter inferred from the mean settling speed in the Kenney sampler and the mean particle diameter determined from the grain-size distribution is much larger for the 1986 Kenney sampler trials than for the 1987 data. Generally, the observed particle sizes are somewhat larger than those inferred from the effective settling speed. This is consistent with the concentration of suspended material inside the Kenney sampler being less than the exterior or ambient concentration, and indeed, Figure 7 indicates that the sampler, with the exception of episode C (where ϕ_q and ϕ_ρ agree most closely), was operating in the flow-sensitive regime.

CONCLUSIONS

The good news from this study is that for the range of material encountered (PHI 1.5 and greater) there is no strong tendency for the traps of any design to sort the sediment differentially. That is not to say that the material trapped has been demonstrated to be the same as the material actually suspended in the water column, but given the wide range of trap geometries, it does seem likely that the results are insensitive to size distribution, and that the catch rate is mainly controlled by hydrodynamic effects. Very near the bottom, where a coarser material is found, the results may depend more strongly on the size distribution.

The bad news is that the catch rates for the bottle traps are strongly velocity dependent at Reynolds numbers (based on overall trap diameter)up to 10,000 and possibly beyond. This behaviour is indicative of boundary layer and wake effects at the trap itself. Figure 6 suggests that the sensitivity of catch rate to horizontal velocity may diminish with increasing Reynolds number but additional data in the Reynolds number range of 7,000 to 15,000 are needed to confirm this. Away from the bottom (where a combination of vertical gradients of suspended material and the interference of structural elements produce uneven results) the sediment tubes and the bottle traps catch in approximately constant ratios. Although we lack direct measurements of flow velocity at this level, because of the large contribution from surface waves, it is reasonable to suppose that the bottle traps are operating at higher effective Reynolds numbers and are behaving more like sediment tubes. There is no reason to suppose that boundary layer phenomena do not in any way affect the catch rates of the sediment tubes. In view of the widespread use of the tubes as the "standard" sediment trap, it would be prudent to check this out.

The horizontally ported chambers appear to be better suited to turbulent, high-velocity environments than the conventional traps. However, until a more thorough investigation is made of the effects of horizontal velocity (both steady and oscillating) on all types of sediment traps, quantitative evaluation of sediment trap results in moving water requires caution.

ACKNOWLEDGEMENTS

We acknowledge the generous assistance of H. Savile (construction of equipment, diving support), Y. Desjardins (fieldwork), and G. Duncan (grain-size analyses).

REFERENCES

Bloesch, J. and Burns, N.M. 1980. A critical review of sedimentation trap technique. Schweiz. Z. Hydrol. 42: 15-55.

Donelan, M.D. et al. 1988. Reference describing WAVES experiment - to be supplied.

Duncan, G. 1988. Particle Size Report, Hamilton Harbour. NWRI Research Applications Branch RAB-88-08A.

Gardner, W.D. 1980a. Sediment trap dynamics and calibration: A laboratory evaluation. J. Marine Research 38: 17-39.

Gardner, W.D. 1980b. Field assessment of sediment traps. J. Marine Research 38: 41-52.

Gardner, W.D. 1985. The effect of tilt on sediment trap efficiency. Deep Sea Res. 32: 349-362.

Griffiths, J.C. 1967. Scientific Method in Analysis of Sediments. McGraw-Hill, New York, 1967, 508p.

Hamblin, P.F., Boyce, F.M., Chiocchio, F. and Robertson, D.G. 1987. Physical processes in Lake St. Clair relating to the transport of dissolved and suspended materials: Overview and preliminary analysis of field experiments of 1985 and 1986. NWRI Contribution 87-76, 33p, illus.

Hargrave, B.T. and Burns, N.M. 1979. Assessment of sediment trap collection efficiency. Limnology and Oceanography 26: 1124-1136.

Hawley, N. 1988. Flow in cylindrical sediment traps. J. Great Lakes Res. 14: 76-85.

Kenney, B.C. 1985. Sediment resuspension and currents in Lake Manitoba. J. Great Lakes Res. 11: 85-96.

Lau, Y.L. 1979. Laboratory study of cylindrical sediment traps. J. Fish. Res. Board of Canada 36: 1288-1291.

Robertson, D.G. 1988. Data and field report: 1987 sediment trap development in Hamilton Harbour and Lake Ontario. NWRI unpublished report.

Rosa, F., Nriagu, J.O., Wong, H.K. and Burns, N.B. 1983. Particulate flux at the bottom of Lake Ontario. Chemosphere 12: 1345-1354.

Sverdrup, H.U., Johnson, M.W. and Fleming, R.H. 1942. The Oceans, Their Physics, Chemistry, and General Biology. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

TABLE CAPTIONS

Table 1.	(a) Catch rates per unit horizontal area for the large-port bottle traps at 0.8, 1.2, and 2.0 m above bottom together with ratios of catch rates of settling tubes and small-port bottle traps at the same levels relative to the catches of the large-port bottles. This data for the Hamilton Harbour episodes.
	(b) Data from the Lake Ontario episodes; same information as (a).
Table 2.	Data from the stanchion arrays of bottle traps 1.5 m above bottom near the 8 m WAVES tower.
Table 3.	Particle size data for Episode A5 (Julian days 309 - 321) of the stanchion array series for the three stations near the 8 m WAVES tower.
Table 4.	Particle size data for Episode LO 4 (Julian days 312 - 319) for the multi-trap array showing variations with depth and with type of trap.

Table 5. Basic data and derived quantities for the Kenney sampler evaluations of 1986.

TABLE 1a. Harbour episodes.

Episode H = Harbour LO = Lake Ontario (Julian Days)	Level Above Bottom (m)	Catch BL gm/m^2/day	Ratios		
			S_1/BL	S2/BL	BS/BL
H_1	0.8	28.9	1.89	1.90	0.22
(200 - 217)	1.2	26.3	2.19	1.81	0.25
	2.0	28.6	1.10	1.42	0.35
H_2	0.8	24.9	2.23	2.07	0.23
(217 - 230)	1.2	24.1	1.88	1.88	0.27
	2.0	28.7	1.26	1.45	0.36
H_3	0.8	50.47	2.26	2.40	0.34
(230 - 245)	1.2	41.95	1.96	2.53	0.39
	2.0	34.24	1.88	1.66	0.41
H_4	0.8	16.7	1.86	2.10	0.37
(245 - 257)	1.2	13.6	2.21	2.21	0.45
	2.0	11.6	1.88	1.82	0.49

TABLE 1b. Lake episodes.

Episode	Level (m)	Catch BL gm/m^2/day	Ratios		
			S1/BL	S2/BL	BS/BL
LO_1 (287 - 298)	0.8	7.7	1.95	2.08	0.61
	1.2	6.7	2.12	1.88	0.58
	2.0	5.4	1.40	1.39	0.57
LO_2 (298 - 307)	0.8	67.9	40.86	13.5	0.58
	1.2	42.1	25.5	33.5	0.39
	2.0	18.7	1.78	1.79	0.48
LO_3 (307 - 312)	0.8	6.55	5.91	4.54	0.63
	1.2	5.23	3.42	5.42	0.64
	2.0	3.22	3.34	3.89	1.01
LO_4 (312 - 319)	0.8	272	3.50	3.49	0.47
	1.2	211	33.2	1.70	0.48
	2.0	156	1.53	1.33	0.45
LO_5 (319 - 326)	0.8	46.4	2.42	2.96	0.65
	1.2	40.7	3.58	1.90	0.60
	2.0	23.4	1.91	2.02	0.45
LO_7 (333 - 340)	0.8	583	1.17	1.23	0.23
	1.2	163	7.02	26.3	0.61
	2.0	137	1.53	1.66	0.62

TABLE 2.

								%				
Episode		$\overline{C}$	R_D	$\overline{VC}$	E_H	W_S	δq	Sand	Silt	Clay	ϕp	ϕq
A_1 (280-287)	S	1.9	4140	7165	0.037	1.16	3.5					
	M	1.9	4140	7165	0.015	1.82						
	L	1.9	4140	7165	0.0074	2.12	4.6					
A_2 (288-295)	S	1.6	4320	6652	0.101	3.31	6.0					
	M	1.6	4320	6652	0.035	4.60	7.8					
	L	1.6	4320	6652	0.017	5.18	8.0					
A_3 (295-302)	S	1.7	3780	6652	0.034	0.98	3.2					
	M	1.7	3780	6652	0.010	1.14	3.5					
	L	1.7	3780	6652	0.0036	0.92	3.1					
A_4 (302-309)	S	2.60	5040	12614	0.116	4.45	7.5	1.45	69.3	29.2	6.6	7.1
	M	2.60	5040	12614	0.045	6.90	9.1	0.38	69.5	30.1	6.7	6.8
	L	2.60	5040	12614	0.020	7.20	9.2	1.46	71.9	26.6	6.4	6.8
A_5 (309-321)	S	2.70	6840	17712	0.339	17.5	13.5	4.74	72.9	22.3	6.0	6.2
	M	2.70	6840	17712	0.143	29.3	16.8	5.98	69.1	24.8	5.9	5.9
	L	2.70	6840	17712	0.078	36.5	19.0	6.49	69.9	23.5	5.9	5.7
A_6 (321-334)	S	16.9	15750	255571	0.190	22.6	14.6	8.28	71.9	20.6	6.0	6.1
	M	16.9	15750	255571	0.061	29.1	17.0	11.83	67.3	20.9	5.8	5.9
	L	16.9	15750	255571	0.019	17.6	13.5	7.99	69.9	22.1	6.1	6.2
A_7 (334-341)	S	7.0	6570	44064	0.271	12.7	11.6	3.94	64.4	31.7	6.7	6.4
	M	7.0	6570	44064	0.111	21.9	14.2	5.56	65.6	28.8	6.3	6.1
	L	7.0	6570	44064	0.052	23.6	14.6	1.44	66.3	32.2	6.9	6.1
A_8 (342-344)	S	6.0	2970	17107	0.0300	0.67	2.6					
	M	6.0	2970	17107	0.0085	0.76	3.0					
	L	6.0	2970	17107	0.0033	0.67	2.6					

cont'd.../

TABLE 2 (cont'd).

$\overline{C}$ mean concentration suspended material over trapping interval (gm/m^3).

$R_D = \frac{\overline{V}_D}{Z}$ = Reynolds number, based on mean flow (rms) in trapping interval ($\overline{V}$), trap diameter D, and viscosity z.

$\overline{VC}$ = average horizontal transport of suspended material gm m^{-2} day^{-1}.

E_H horizontal trapping efficiency $= \frac{\text{catch rate/day}}{\text{horizontal flux/day}} = \frac{Q_o}{\overline{VC}\ A_D}$

Ao = area of opening presented to flow.

w_s apparent settling velocity m day^{-1}) $\quad w_s = \frac{Q_o}{\overline{C}\ A_v}$ $\quad A_v$ = area of bottom of trap.

% sand, silt, clay - results from particle size distribution.
ϕ_ρ mean particle size (Wentworth scale) of sample (sedigraph).
ϕ_q mean particle size (Wentworth scale) inferred from w_s (quartz equivalent).

TABLE 3.

		%			
Site	Port	Sand	Silt	Clay	ϕ
A_1	L	6.2	64.2	29.6	6.34
A_2	L	6.1	71.9	21.9	5.50
A_3	L	7.1	73.8	19.0	5.92
A_1	M	5.2	68.9	25.9	6.23
A_2	M	6.1	69.4	24.5	6.60
A_3	M	6.6	69.1	24.2	6.04
A_1	S	4.2	75.4	20.2	6.10
A_2	S	4.9	71.3	23.8	5.80
A_3	S	5.0	72.0	23.0	6.12

TABLE 4. Episode L04 (312-319).

Trap Type	Level	Q_T	% Sand	% Silt	% Clay	ϕ
KS	0.44	110	53.4	34.1	12.6	4.46
	1.12	23	11.5	67.5	21.0	5.92
	1.97	7.0	8.6	67.6	23.8	6.18
BL	0.44	29	35.1	48.0	16.9	5.11
	1.12	9	10.7	68.8	20.6	6.07
	1.97	7.0	9.4	71.4	19.2	6.04
BM	0.44	73	65.5	22.1	12.4	4.05
	1.12	10	18.9	60.1	20.9	5.70
	1.97	6	10.0	69.6	20.4	5.62
BS	0.44	12	29.3	52.7	19.0	5.41
	1.12	4.5	8.0	68.1	23.9	6.18
	1.97	3.2	7.2	68.2	24.6	6.15
ST	0.82	5	47.2	30.7	22.9	4.61
	1.20	116	77.4	12.1	10.4	3.50
	1.20	6	19.4	57.1	23.4	5.73
	1.97	7.5	13.04	65 6	21 3	5 90

KS	Kenney sampler.
BL	Large port (1.5 cm) bottle trap.
BM	Medium port (1.0 cm) bottle trap.
BS	Small port (0.5 cm) bottle trap.
ST	Sediment tubes.
Q_T	Total Catch (gm)
ϕ	Mean particle size PHI scale.
Level	Trap opening location distance above bottom (m).

TABLE 5.

Sample	Q_o	$\overline{C}$	R_D	E_H	w_s	δ_q	%			ϕ_q	ϕ_p
							Sand	Silt	Clay		
A_1	1.91	6.9	8280	0.007	0.28	2.0	15	45	40	8.9	6.7
A_2	4.14	6.4	8280	0.018	0.65	2.8	11	67	22	8.5	5.9
A_3	2.54	6.2	8280	0.010	0.47	2.2	13	69	18	8.8	4.8
B_1	54.1	13.3	8740	0.078	4.1	7.2	27	36	37	7.1	6.6
B_2	41.4	12.4	8740	0.072	3.3	6.2	31	39	30	7.3	5.3
B_3	54.1	12.4	8740	0.088	4.4	7.3	42	28	30	7.1	4.6
C_2	70.1	12.4	9860	0.095	5.9	8.6	25	38	30	6.9	6.9
C_3	44.6	12.4	9860	0.075	3.7	7.0	24	41	35	7.2	7.0
D_2	5.09	6.5	5600	0.027	0.87	3.0	10	51	39	8.4	5.3
D_3	6.69	6.5	5600	0.033	1.09	3.2	19	51	30	8.3	4.7

Kenny sampler evaluations 1986.

Q_o Catch rate of sampler gm m^{-2} day^{-1} (horizontal cross-section of trap.

$\overline{C}$ Suspended sediment concentration averaged over trapping interval (gm m^{-3}).

R_D Reynolds number based on external diameter of trap (21 cm), rms velocity over trapping interval.

E_H Horizontal trapping efficiency (see Table 2).

w_s Apparent settling velocity (m day^{-1}) (see Table 2).

% Sand, Silt Clay Results from grain-size analysis.

ϕ_q Mean particle size (Wentworth scale) (quartz) deduced from W_s.

ϕ_p Mean particle size (Wentworth scale) from sedigraph analysis

FIGURE CAPTIONS

Figure 1. Cross-section of one chamber of the original Kenney sampler. A vertical array of chambers is formed by partitioning a length of plastic (ABS) drain pipe. Sample bottles are replaced through doors at the base of each chamber (not shown).

Figure 2. Details of the sediment tubes (left) and bottle traps (right) mounted on the frame with the Kenney sampler (Figure 2). Port diameters on the bottle traps were 0.5 (small), 1.0 (medium), and 1.5 (large) cm. The rubber bands fold up over the ports to reduce spillage when handling.

Figure 3. Diagram of the array of sediment traps deployed in Hamilton Harbour and in the western end of Lake Ontario in the summer and fall of 1987. The entire array was lifted to the surface for refurbishing.

Figure 4. (a through d)

Vertical profiles of sediment capture rate (both inorganic and total) for the bottle chambers, the Kenney Sampler, and the sediment tubes for the four harbour episodes. Catch rates are expressed as the amount of material settling per unit area of the bottom of the chamber.

Figure 4. (e through 1)

Same as above except for locale which is now the western end of Lake Ontario.

Figure 5. Details of stanchion-mounted bottle traps.

Figure 6. Efficiency of capture of horizontal particle flux of the bottle traps as a function of horizontal flow velocity (Reynolds number) and port diameter.

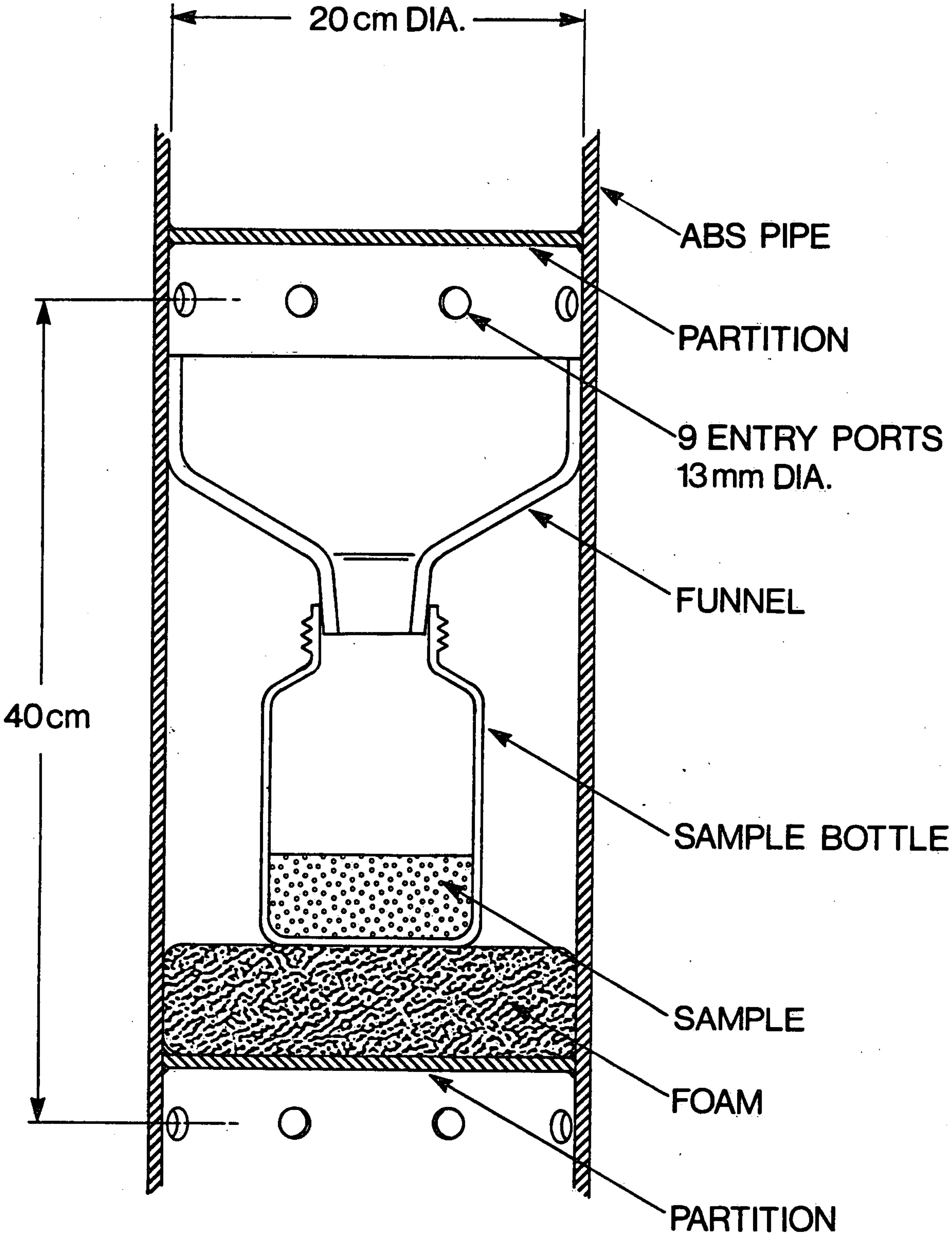
Figure 7. (a) Vertical profiles of the Kenney sampler catches in Lake St. Clair in 1985.

(b) Vertical profiles of the Kenney sampler catches in Lake St. Clair in 1986. In both seasons, calm periods result in small "background" catches. Catch rates are greatly augmented during windy periods.

Figure 8. Grain-size distribution of a sample collected by the Kenney device during one of the windy episodes in 1985. A bimodal distribution is typical for such samples.

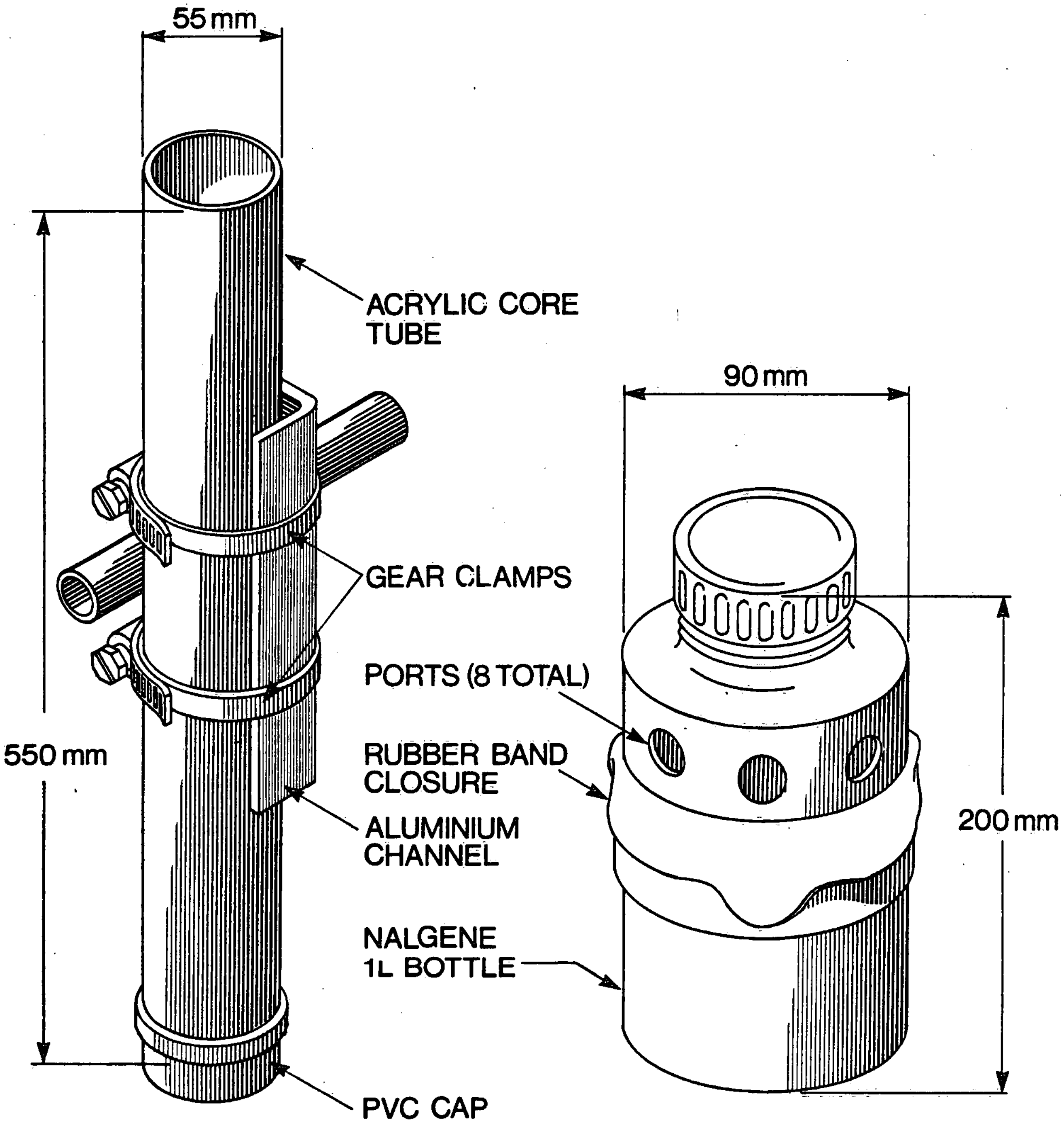
Figure 9. Comparison between Kenney sampler and sediment tube catch rates made with the botom-mounted frame (see Figure 3) during two short, calm episodes in Lake St. Clair in 1985.

Figure 10. Observed catch rate of the Kenney sampler versus the observed mean concentration of the suspended material over the trapping interval. The slope of the line joining each point to the origin can be interpreted as a measure of the mean settling velocity of the material. It is seen that this "velocity" correlated positively with percentage of sand-sized material in the samples.



DETAIL OF CHAMBER

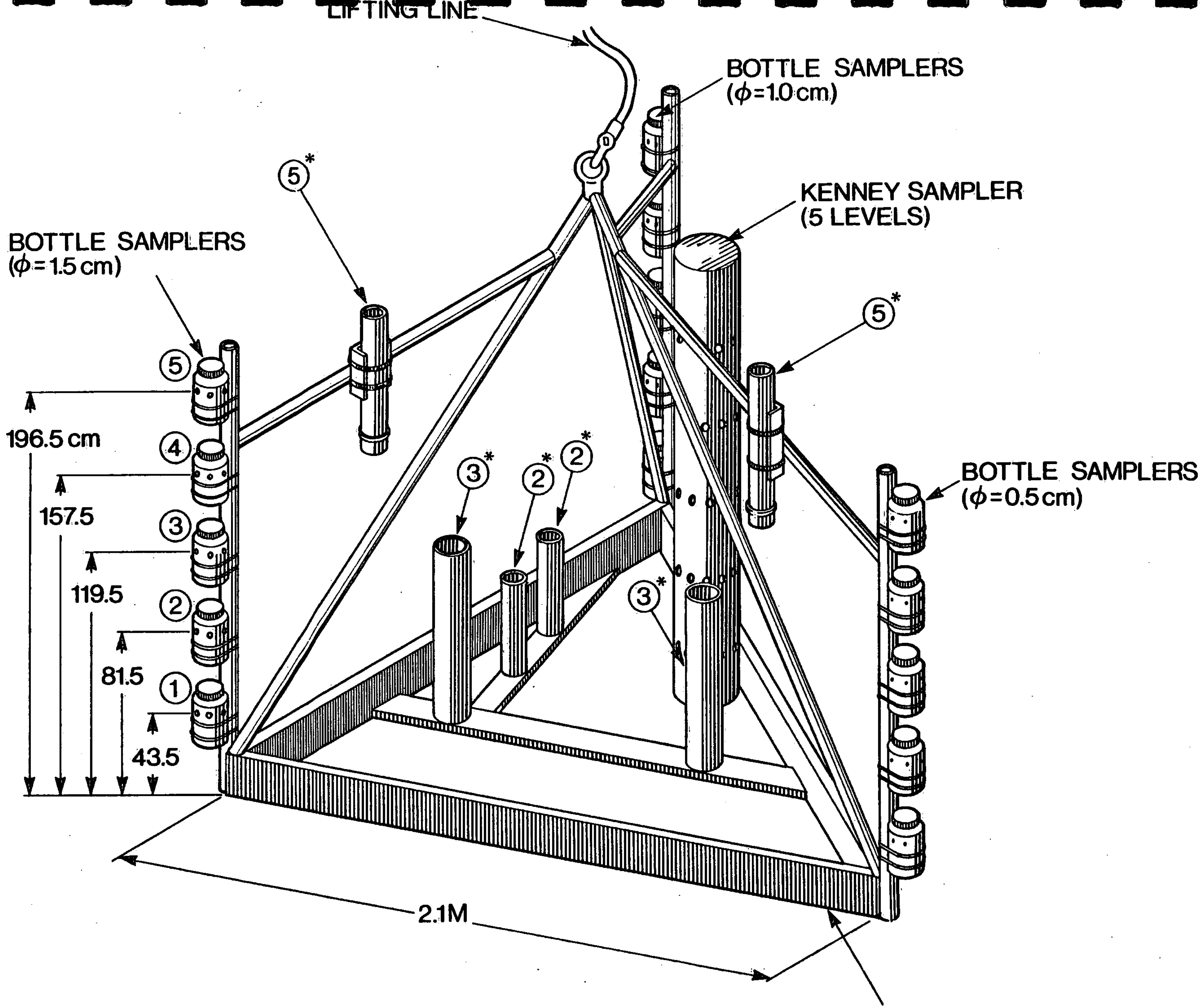
FIGURE 1



SEDIMENT TUBE

BOTTLE TRAP

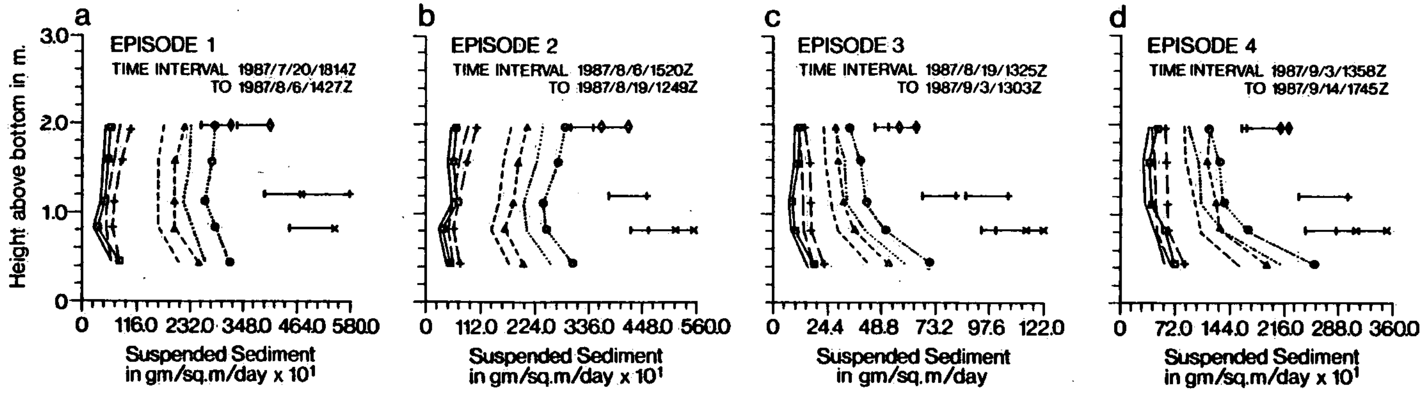
FIGURE 2



*SEDIMENT TUBES AT LEVELS 2,3 AND 5

FIGURE 3

Sediment deposition rate profiles for Hamilton Harbour based on the inside cross-sectional area of the sediment trap.



Sediment deposition rate profiles for Lake Ontario based on the inside cross-sectional area of the sediment trap.

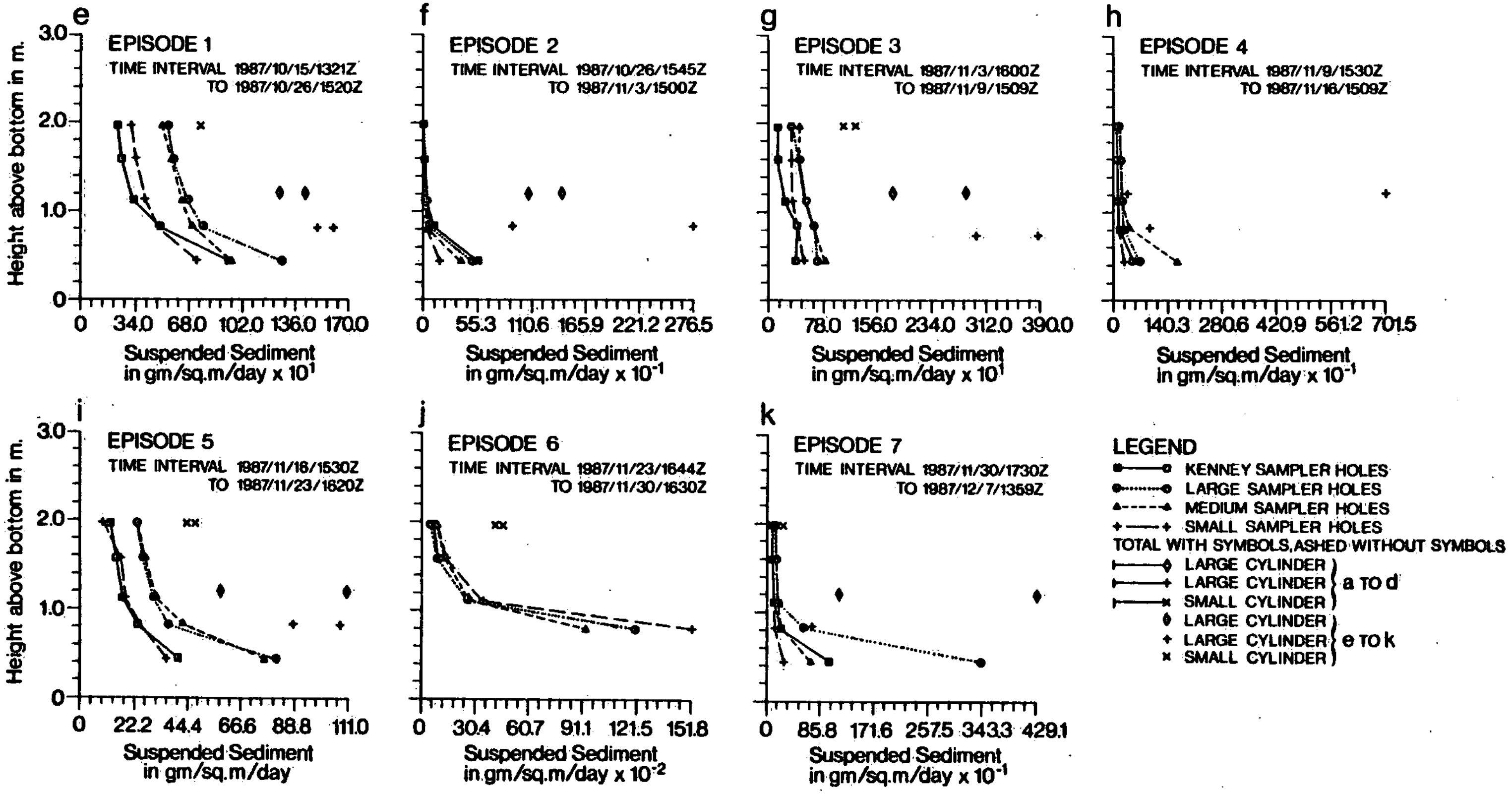
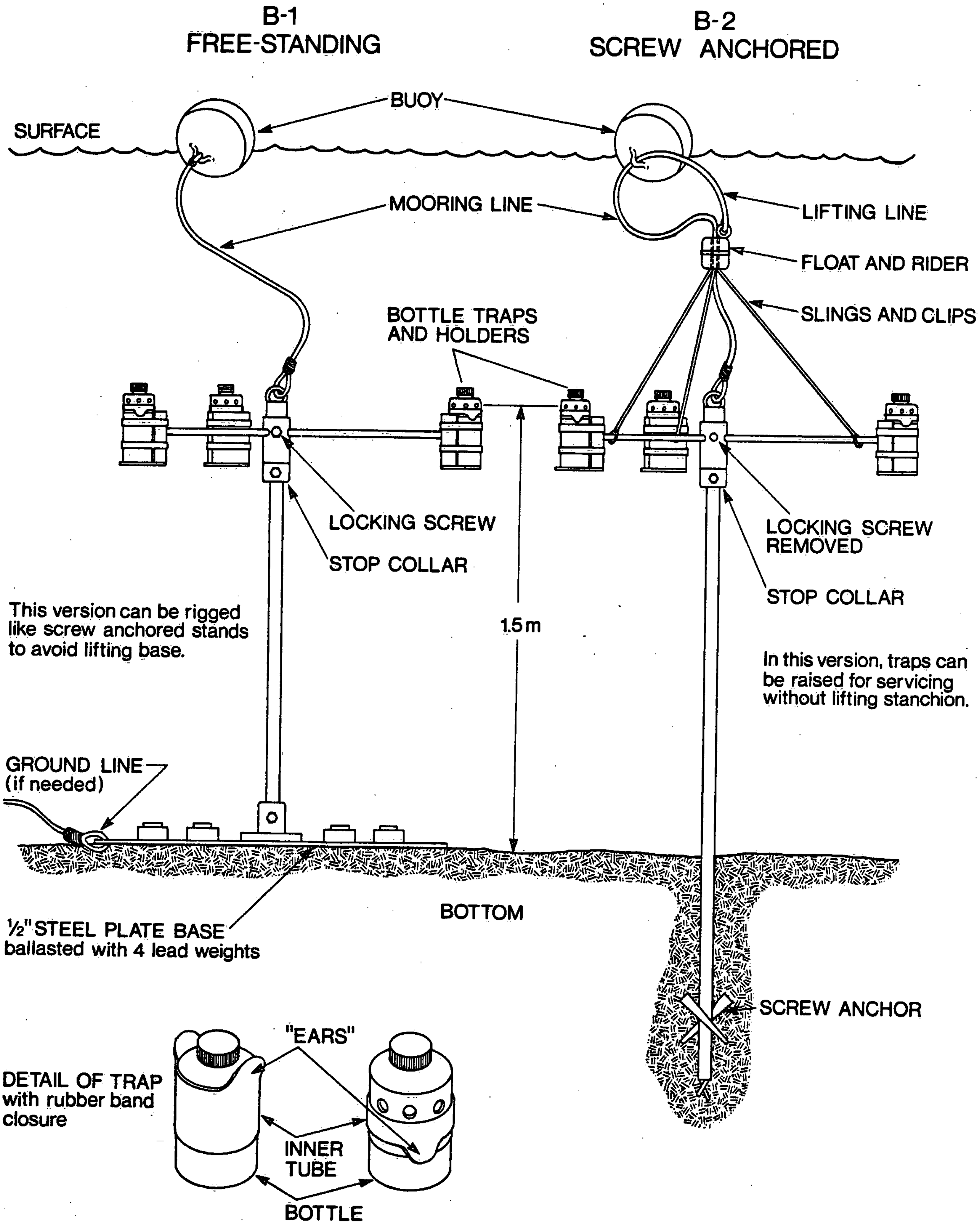


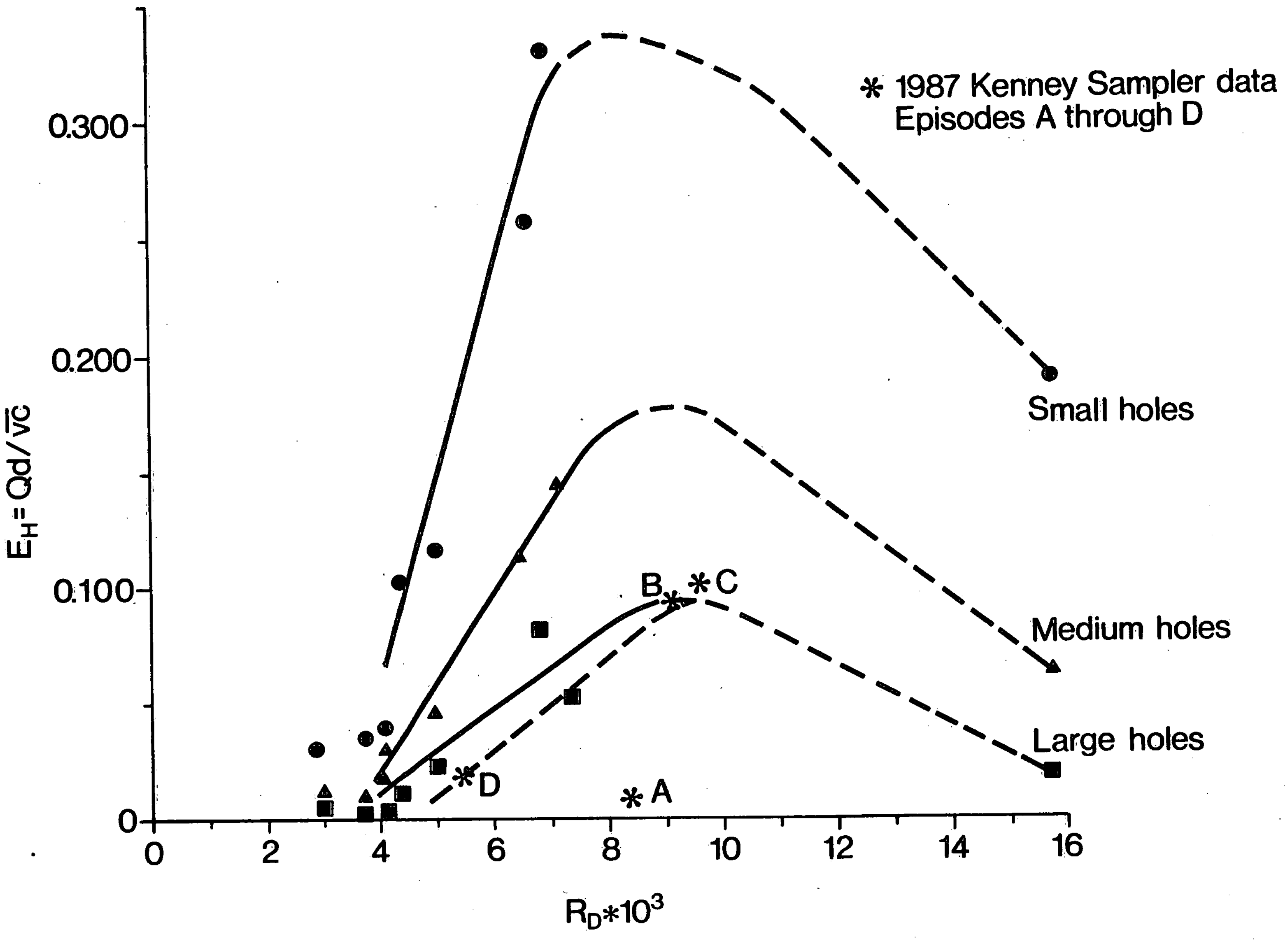
FIGURE 4



This version can be rigged like screw anchored stands to avoid lifting base.

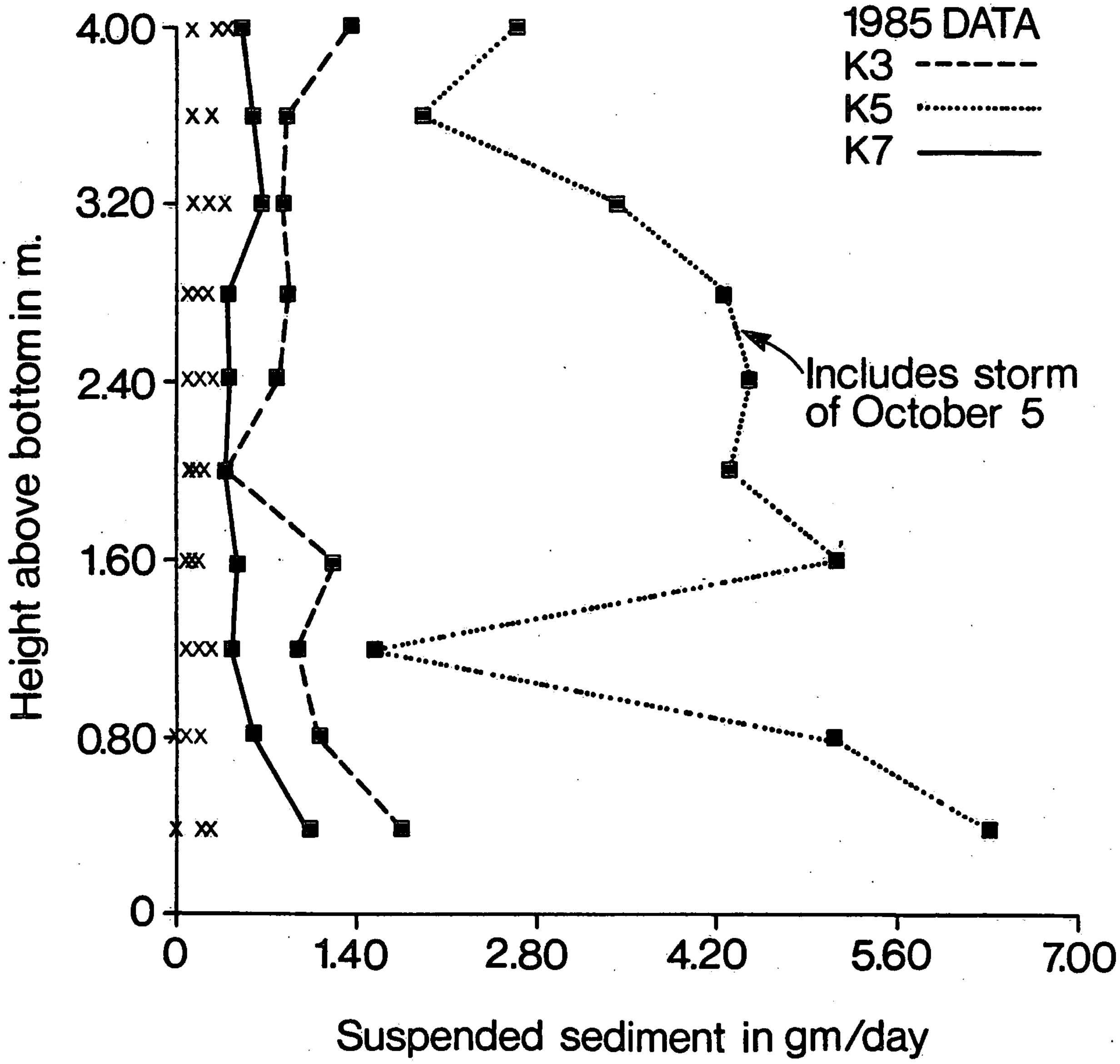
In this version, traps can be raised for servicing without lifting stanchion.

FIGURE 5



Horizontal efficiency of trap as function of the Reynold number

FIGURE 6



1985 DATA
K3 ------
K5 ....
K7 ———
Includes storm of October 5
Height above bottom in m.
4.00
3.20
2.40
1.60
0.80
0
0
1.40
2.80
4.20
5.60
7.00
Suspended sediment in gm/day

FIGURE 7A

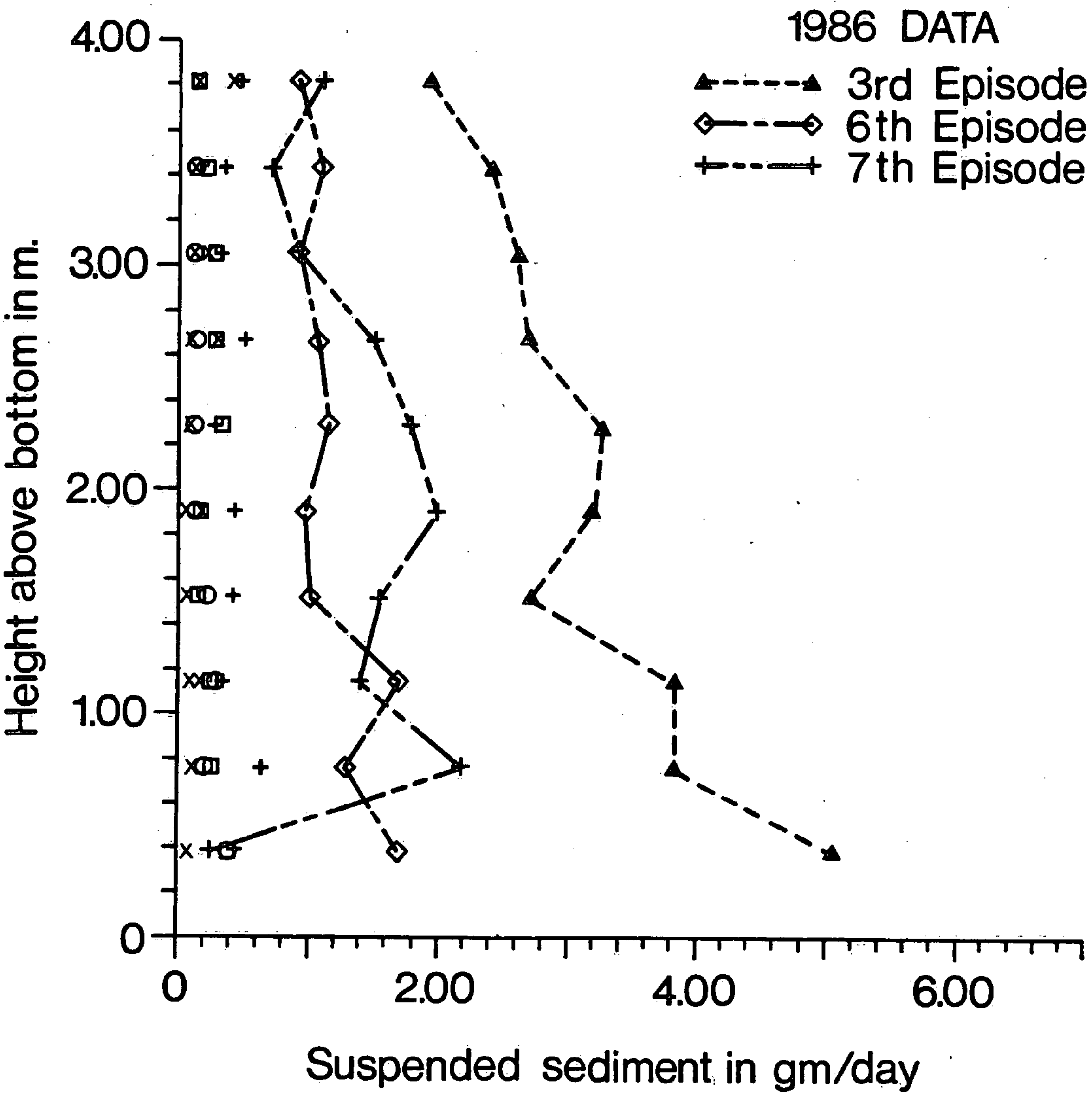

1986 DATA
3rd Episode
6th Episode
7th Episode
Height above bottom in m.
4.00
3.00
2.00
1.00
0
2.00
4.00
6.00
Suspended sediment in gm/day

FIGURE 7B

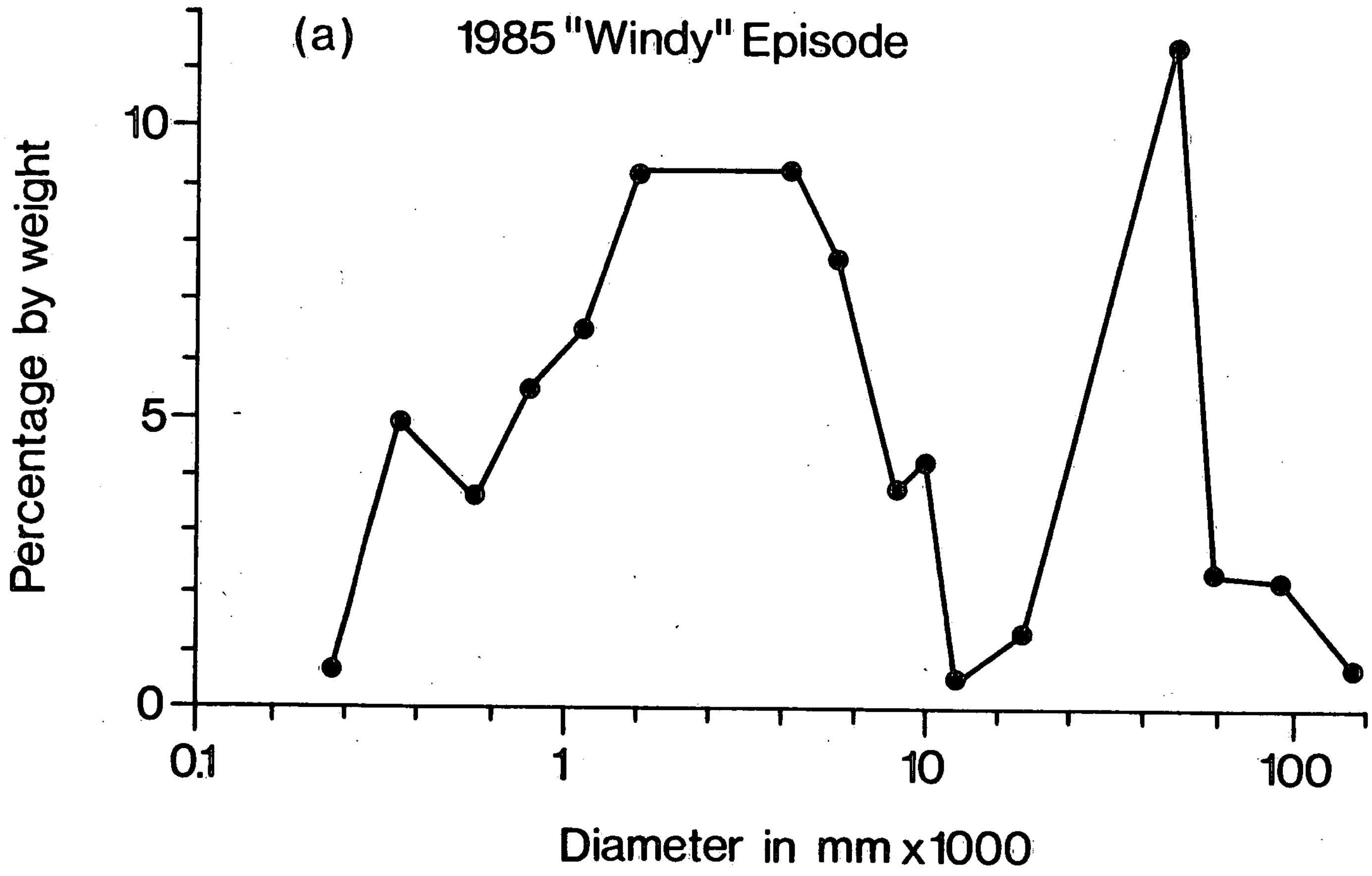
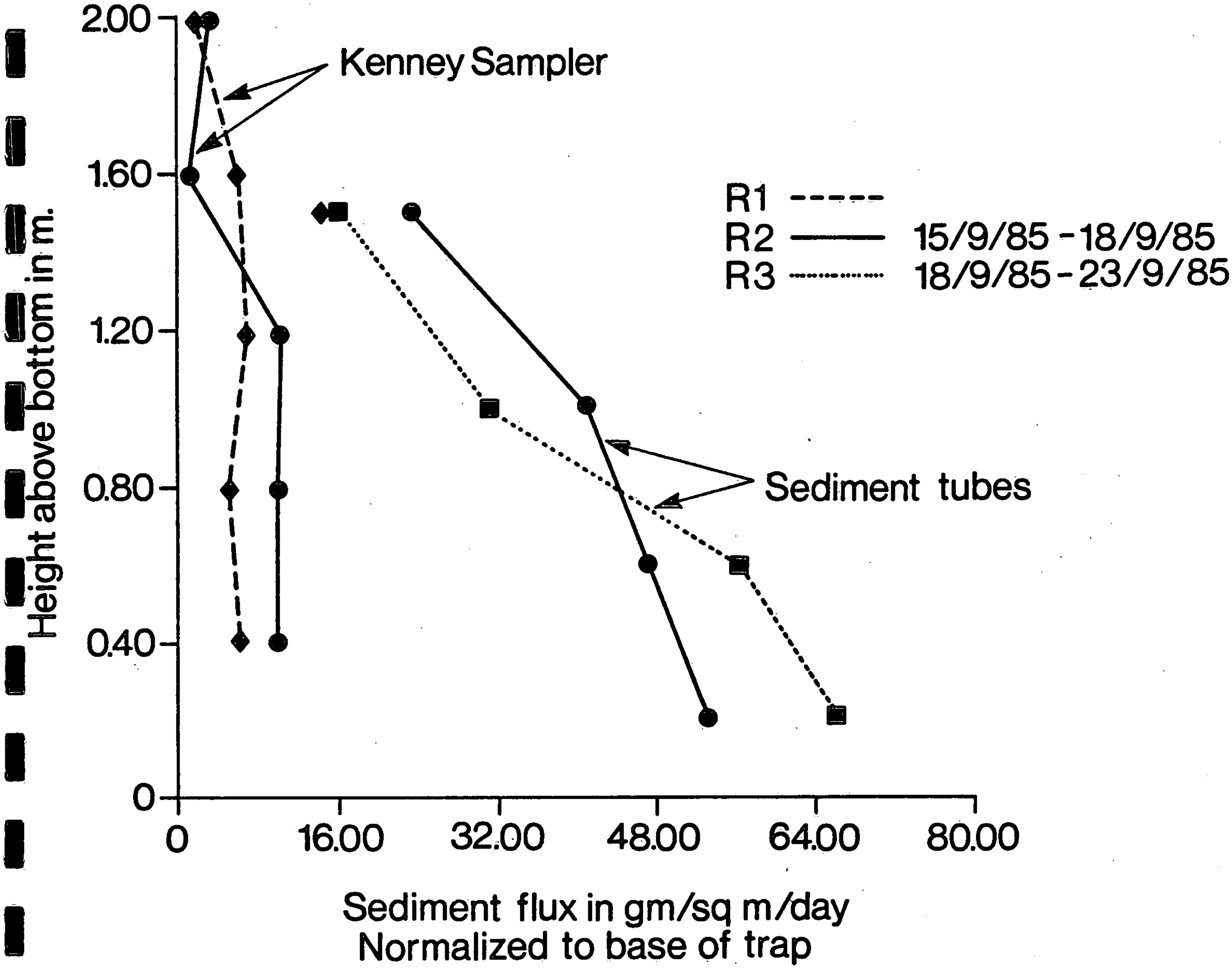
(a)
1985 "Windy" Episode
Percentage by weight
10
5
0
0.1
1
10
100
Diameter in mm x1000

FIGURE 8



2.00
1.60
1.20
0.80
0.40
0
Height above bottom in m.
Kenney Sampler
R1
R2 15/9/85 - 18/9/85
R3 18/9/85 - 23/9/85
Sediment tubes
0
16.00
32.00
48.00
64.00
80.00
Sediment flux in gm/sq m/day
Normalized to base of trap

FIGURE 9

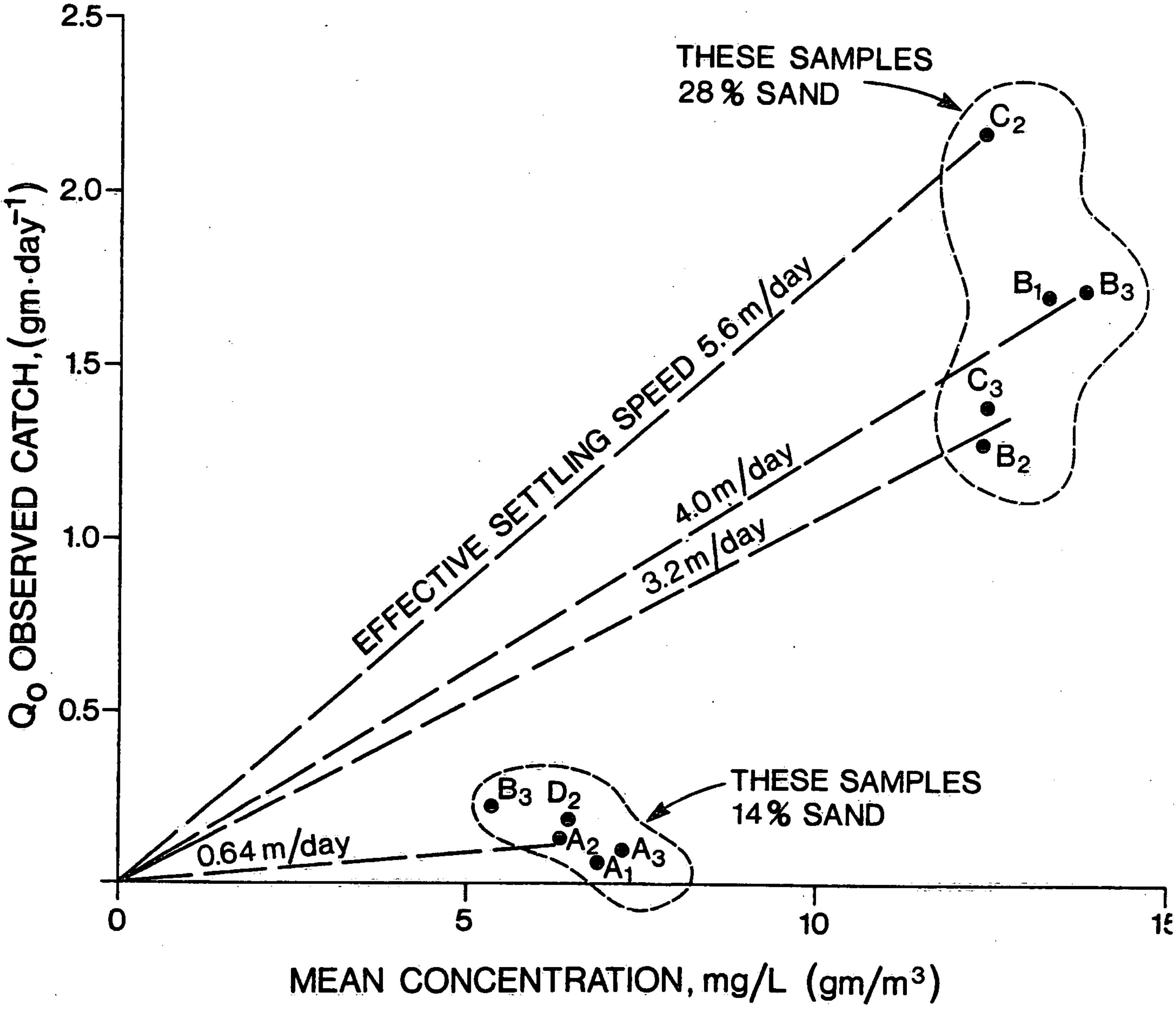

THESE SAMPLES
28 % SAND
C2
B1
B3
C3
B2
EFFECTIVE SETTLING SPEED 5.6 m/day
4.0 m/day
3.2 m/day
0.64 m/day
B3
D2
A2
A3
A1
THESE SAMPLES
14 % SAND
Q_O OBSERVED CATCH, (gm·day^{-1})
2.5
2.0
1.5
1.0
0.5
0
5
10
1
MEAN CONCENTRATION, mg/L (gm/m^3)

FIGURE 10