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PHYSICAL MEASUREMENTS IN LAKE ST. CLAIR: OVERVIEW AND PRELIMINARY ANALYSIS

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MESURE DE PARAMÈTRES PHYSIQUES AU LAC SAINTE-CLAIRE : APERÇU ET ANALYSE PRÉLIMINAIRE DES RÉSULTATS

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EXECUTIVE SUMMARY

Although the residence time of water in Lake St. Clair is of the order of a week, the trajectory of suspended material through the basin is more complex and takes much longer. Net accumulation of sediment in the St. Clair basin itself must be small, since the maximum thickness of post glacial sediments there is only 3 m. However, sediment must undergo several, if not many, cycles of settling and resuspension before it reaches the Detroit River and is carried into Lake Erie. Given the affinity of many organic contaminants to suspended sediments, the transport of contaminants through the system, and indeed the eventual flushing or purging of the system following curtailment of loading, depends on sediment processes. This report documents efforts made in 1985 and in 1986 to measure sediment resuspension and transport in Lake St. Clair. New equipment and new approaches were required to deal with episodes of large wave orbital motion, a consequence of the shallow water environment. The time frame of the Upper Great Lakes Connecting Channel Study necessitated the simultaneous pursuit of instrument development and field measurements, a potentially dangerous overlap. Despite the inevitable difficulties with new equipment, data were collected that will lead to improved models of sediment transport in Lake St. Clair.

RÉSUMÉ ADMINISTRATIF

Même si la durée de séjour de l'eau dans le lac Sainte-Claire est généralement d'une semaine, la trajectoire des matériaux en suspension à l'intérieur du bassin est beaucoup plus complexe et se mesure sur une période beaucoup plus longue. L'accumulation nette de sédiments dans le bassin du lac Sainte-Claire doit être faible, car l'épaisseur maximale des sédiments de l'époque post-glaciaire n'y est que de trois mètres. Les sédiments doivent par contre subir plusieurs, voire de nombreux, cycles de dépôt et de remise en suspension avant d'atteindre la rivière Detroit et d'être finalement déversés dans le lac Érié. Compte tenu de la relation étroite entre de nombreux contaminants organiques et les sédiments en suspension, le transport des contaminants à travers le système, et même la classe ou la purge possible du système découlant d'une baisse de la contamination, dépend des processus auxquels les sédiments sont soumis. Le présent rapport expose les efforts déployés en 1985 et en 1986 pour mesurer la remise en suspension des sédiments et leur transport dans le lac Sainte-Claire. Il a fallu recourir à un nouvel équipement ainsi qu'à de nouvelles méthodes pour contrer les périodes de fort mouvement orbital des vagues, attibuables à la faible profondeur de l'eau. Le calendrier de l'Étude sur les voies d'eau reliant les Grands Lacs d'amont a obligé les chercheurs à mettre au point leurs instruments tout en procédant aux mesures sur le terrain, soit un chevauchement d'activités pouvant présenter des dangers. Malgré les problèmes inévitables qu'a soulevés le nouvel équipement, les données recueillies permettront d'améliorer les modèles de transport des sédiments dans le lac Sainte-Claire.

ABSTRACT

The pathways of nutrients and contaminants through Lake St. Clair are strongly influenced by the transport, distribution, and fate of particulate material. This report describes both field and modelling studies of sediment resuspension and transport undertaken in Lake St. Clair in 1985 and 1986. Among the topics discussed are:

- circulation measurements of 1985
- sediment trap expriments
- sediment characteristicsd and suspended sediment concentrations derived from optical transmission
- measurements of vertical velocity profiles (1985 and 1986)
- wave orbital velocities; direct measurements and velocities inferred from surface wave measurements (height and period)
- export of sediments from the Lake
- evaluation of the Kenney sediment trap.

The overall goal of this work is to develop an overall sediment transport model in order to form a lakewide picture of sediment/water column interactions and of sediment export.

RÉSUMÉ

Les trajectoires des substances nutritives et des contaminants dans le lac Sainte-Claire sont grandement influencées par le transport, la répartition et l'évolution des substances particulaires. Le présent rapport décrit les études sur le terrain et les études simulées réalisées en 1985 et en 1986 sur la remise en suspension et le transport des sédiments dans le lac Sainte-Claire. On y traite notamment des points suivants :

- les données recueillies en 1985 concernant l'écoulement
- les expériences menées au moyen de collecteurs de sédiments
- les caractéristiques des sédiments et les concentrations des sédiments en suspension déterminées par transmission optique
- les profils verticaux des vitesses (1985 et 1986)
- la vitesse orbitale des vagues (mesures directives et vitesses établies à partir de mesures à la surface - hauteur et période)
- la façon dont les sédiments sortent du lac
- l'évaluation du collecteur de sédiments Kenney

Les travaux visaient à mettre au point un modèle global de transport des sédiments afin d'obtenir un aperçu des interactions entre les sédiments et les colonnes d'eau dans l'ensemble du lac, ainsi que de la façon dont les sédiments sortent finalement du lac.

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INTRODUCTION

The pathways of nutrients and contaminants through water bodies is strongly influenced by the transport, distribution, and fate of particulate matter. The physical processes of settling, resuspension, and transport of particles determine the effective exposure times of particles to the water column. In deep, sheltered lakes, resuspension may not occur; the distribution of sediments, in the simplest terms, depends on three parameters (time scales), a hydraulic flushing time, the settling speed of the particles (or settling time scale), and a horizontal mixing timescale (Figure 1). In shallow lakes, where resuspension of sediment occurs from time to time, a fourth parameter, the fraction of the time that the kinetic energy of the water column is sufficient to resuspend particles and maintain them in suspension, must also be considered. When that fraction approaches unity, the sediment moves with the water and settling is unimportant; when it becomes small, the basin behaves like a deep lake.

The hydraulic residence time of Lake St. Clair is of the order of 6 days; the settling timescale for the fine material resuspended during major storm events is about 2 days. Thus flushing, mixing, settling, and resuspension are all important processes in the sediment balance of Lake St. Clair.

Our first major field experiment got underway in June, 1985. A network of current meters was maintained (see below), and measurements aimed at documenting and understanding sediment resuspension and transport were centred on a mid-lake tower. From our preliminary assessment of that data, and drawing on the results of a workshop held at NWRI in the spring of 1986, we designed a second field experiment for the fall of 1986 which was carried out from September 15 to 7 November, 1986. Satellite images of Lake St. Clair indicated more active resuspension along the southeast shore of the lake; for this reason the central tower location was shifted from mid-basin in 1985 towards the mouth of the Thames river in 1986 (see Figure 4).

TOPICS FOR FURTHER STUDY

To summarize the conclusions of the modelling studies mentioned above, and to form a context in which the measurements of 1985 and 1986 can be discussed, we list the areas/topics where further work is needed:

1) Selection of the optimum parameterization of vertical mixing through study of the vertical distribution of mean and fluctuating velocities.

2) Reassessment of the empirical sediment resuspension model with a more accurately calibrated relation between optical transmission and suspended sediment concentration, more rapidly sampled velocities near the bottom, knowledge of the sediment characteristics, and assessment of horizontal advection.

3) Improved predictions of near-bottom wave orbital motions and/or turbulent fluctuations. One component of this work is the development of a wave model specifically for shallow water, the other is a verification of the relation between the predicted wave field and the velocity parameter used in the resuspension model.

4) From improved transport and resuspension models, to develop an overall sediment transport model for the lake in order to form a lakewide picture of sediment/water-column interactions and sediment export.

In this paper, the components of the physical studies of 1985 and 1986 will be discussed, particularly as they relate to the items in the foregoing list.

CIRCULATION MEASUREMENTS OF 1985

An array of 9, vector-averaging Neil Brown "Smart" acoustic current meters was maintained from June 4 through November 11 at the locations shown in Figure 2. The meters, the first operational deployment of them at NWRI, were bottom mounted with their sensing volumes at one meter above the lake bottom. They collected a sample of current components and temperature every 20 minutes, a sample that was vector averaged over a burst of 240, 1 second subsamples. This data has been the backbone of the transport modelling studies. Figure 2 shows a vector for each current meter representing the mean run of the current over 24 hours. The box at the base of the arrow represents the dimensions of the rms excursion of a pseudo-particle with respect to the mean 24 hour current. Figure 2a shows the 24 hour currents on October 4, 1985 under light winds; this distribution is typical of the river-dominated circulation. Figure 2b, the currents for October 5, represent the largest storm event of the measurement period. Note that the dimensions of the "meander box" increase somewhat but that the 24 hour currents increase only a little in magnitude. The insensitivity of current speeds to wind stress has been explained by Simons and Schertzer (1986).

SEDIMENT TRAP EXPERIMENTS

The sediment trap experiment described here uses apparatus designed and built by B. Kenney of the NHRI (JGLR 11: 85-96). It is shown in Figure 3. The trap comprises an array of 10 compartments separated vertically by 40 cm. It was deployed at Station 24 during the 1985 experiment and at site 501 during the 1986 experiment (see Figure 4). The collection intervals ranged from 3 to 7 days. Figure 5a shows the average catch per day at the 10 levels for the 1985 experiments. These may be interpreted as a horizontal flux (gm $m^{-2} s^{-1}$) by multiplying the catch per day by 0.03, as the geometry of the trap suggests. On three occasions the catch rises above a background level of 18 mg $m^{-2} s^{-1}$, the highest occasion brackets the strong wind episode of October 5. Figure 5b shows similar results for 3 trap intervals in 1986 at location 501, in which the catch rises above background.
The sediment catch in both years responds to meteorological forcing. Data collected in 1986 is useful in "calibrating" the Kenney sampler; see Appendix A.

SEDIMENT CHARACTERISTICS AND SUSPENDED SEDIMENT CONCENTRATIONS DERIVED FROM OPTICAL TRANSMISSION.

Laboratory analyses of samples from the Kenney trap show that during the most energetic events the particle size distribution is bimodal (Figure 6a) with the fine sediment being most frequent in the size range 4 to 7 microns, while the coarse fraction is associated with sizes of 50 microns or greater. Figure 6b shows the vertical distribution of the percentage of coarse material having dimensions of 22 microns or greater. The sand fraction varies widely from episode to episode but generally increases towards the bottom. The sinking speeds corresponding to the modal sizes are 150 m day for the coarse material, and 2.6 m day for the fine fraction. Suspended sediments are composed primarily of inorganic material.

From simultaneous observations of seston concentrations (filtered normally from 1 litre water samples) and optical transmission, empirical relations were developed relating optical transmission to suspended sediment concentrations, both total sediments and the organic fraction (Figure 7a). The relation between transmission and the organic component of the suspended sediments contains less scatter than the relation for total dissolved solids, possibly because of the bimodal distribution of the inorganic component of the suspended material; the size distribution, and hence the optical properties would change as the coarse fractions settled out. This work was performed by Y. Marmoush and is described in his contract report (Marmoush, 1986). The project was extended in 1986. Because the sediment characteristics differed at the new site, the correlation between suspended sediment concentration and extinction coefficient was redrawn (Figure 7b).

1985 VELOCITY PROFILES AND MCATS EXPERIMENT.

As opportunities arose, vertical profiles of lake current were taken with a Neil Brown remote reading acoustic current meter at the mid lake tower (Site 24). A numerical model using a finite element scheme in the horizontal and a constant eddy viscosity vertical structure was run with observed winds corresponding to the times of the measured velocity profiles. Figure 8 shows modelled and observed profiles of current in mid-lake. Agreeement is reasonable near the bottom but beyond error limits near the surface. These results suggest that the simple, constant eddy viscosity model is inadequate and that a more elaborate scheme, perhaps including the effect of surface waves is needed. Simons and Schertzer (1986) draw similar conclusions from their modelling study.

The MCATS system (Figure 9), deployed at Station 24 from September 11 to October 2, 1985, comprises three 10 cm Marsh McBirney EM current meters suspended 20, 30, and 40 cm above the lake bottom on an aluminium tripod. The recording schedule was a burst of 1200 one-second samples (20 min) every 3 hours. Although the system returned data through its entire deployment, the results raise many difficult questions. Verification of the MCATS data against the information from a nearby Neil-Brown current meter located 1m above the bottom showed some general correspondence in direction but poorer agreement in speed. Comparison of the horizontal current spectrum calculated from linear surface wave theory and observations of surface wave heights with that observed at the MCATS current meters shows that the wave orbital motions appear to be submerged in the turbulence of the bottom boundary layer much of the time. When the hydraulic flow opposes the wind-driven component and mean bottom shear is reduced, wave orbital motions are detectable as close as 20 cm to the bottom. These tend to be overestimated by the motions predicted from near-surface pressure fluctuations and linear wave theory. Aubrey and Trowdridge (1985) raise doubts as to the ability of Marsh-McBirney EM Current Meters to track rapidly varying oscillatory flows in the presence of a mean flow. A paper discussing the performance of these instruments has been written (Hamblin et al., 1986).

1986 MID LAKE ARRAY.

Figure 10 shows the disposition of equipment on the central tower situated at station 501. At two "satellite" positons , stations 505 and 506, a single Neil Brown acoustic current meter and a Sea-Tech transmissometer were deployed on weighted platforms with their sensing volumes approximately 1 m above the lake bed. A tripod bearing a current meter and transmissometer was placed at station 502 by GLERL. The current meters on the central tower (Neil Brown "Smart" Acoustic) were reconfigured for the application. Four of the curent meters measured horizontal flow, two current meters at 1 m above bottom were arranged to measure a horizontal and a vertical current component. Transmissometers were placed at 3 levels on the tower. Both the transmissometers and the current meters on the tower were controlled by a common clock. In the early phase of the experiment, the transmissometer signals (sampled every 0.5s for a burst of 8 minutes every 2 hours) were recorded on a Sea Data recorder (together with wind speed and direction). The current meters recorded vector averaged components of current for each burst in their internal memories. At a later stage, the current meters were upgraded by the addition of more elaborate internal processing program that recorded not only averages of the two components but also mean square velocity components, mean cross-products, and the number of zero-crossings of the current meter component. Finally, a high speed surface-mounted recorder was added to the system that recorded the instantaneous current data as well. The satellite systems recorded currents and optical transmission one metre above the bottom every two hours. A summary catalogue of the data collected is given in Appendix B.

The Ohio State acoustic suspended sediment profiler was installed at station 501 from October 10 to October 20.

The time series plots of uncorrected extinction coefficients measured on the tower point to progressive fouling of the instruments. Fortunately, transmission profiles were made from a launch at the intrument sites as often as possible. The launch-based data was used to estimate a correction to the tower data, and the corrected results now look reasonable (Figure 11). The satellite transmission data was treated similarly.

Prior to October 24, current meter records were incomplete due to an unforseen sensitivity of the instrument to power supply voltages and operator error. The high speed recorder, a new and untested development also proved erratic, although its failure to record clean data did not compromise the averages stored in the current meter memories. Data collected at the 1m level (above bottom) where the current meters were oriented to collect both horizontal and vertical components is suspected of being contaminated much of the time by eddies shed by the instrument cases. Selected episodes where the currents are aligned with the axes of the instruments may prove worthy of analysis. Figure 12 shows profiles of current (including standard deviations) constructed from the 4 instruments that measured horizontal currents. Samples from two days are chosen, November 1 (calm), and November 4 (windy).

WAVE ORBITAL VELOCITIES.

Wave orbital velocities are inferred from near-surface pressure measurements and are directly measured by a near bottom current meter at the central tower site in 1986 (Station 501). Wind speed and direction measured on the tower are also examined. It is seen that the suspended sediment concentration correlates closely with the orbital velocity of the waves and less directly with the wind speed or mean shear stress, (vel)**2 (Figure 13). The two estimates of orbital velocity compare well during extreme conditions. Similar comparisons and conclusions are drawn for the satellite stations.

WATER INTAKE TURBIDITIES

An auxiliary data set was obtained from turbidity readings collected at several water intakes along the Candadian shore of Lake St. Clair (Figure 14) in 1986. Note that the turbidity at Tilbury intake, located close to the mouth of the Thames river, correlates well with the discharge from the river.

EXPORT OF SEDIMENTS.

The question of the conditions required for the export of suspended sediment into the Detroit River is raised in the analysis of the 1986 data set is examined further with reference to the 1985 data. High turbidities at Windsor during the study period are seen in Figure 15 on October 21, November 2, and on June 12 (not shown). The waves on these occasions ranged from 45 to 60 cm. As was the case in 1986, these were not the maximum wave events occurring on June 1 and October 6; on these two occasions winds were from the southwest. It is tentatively concluded that the conditions required for export of material to the Detroit River are waves in excess of 40 cm in height directed onshore in the vicinity of the entrance to the Detroit River. Since the conditions favouring removal of sediment from the Lake are fairly restricted, this suggests that sediment export may be mainly from the nearshore area.

CONCLUSIONS.

This paper is in effect an annotated catalogue of most of the data sets available from the 1985 and 1986 experiments. We look forward in particular to a thorough examination of the data from the current meters and transmissometers at the central tower. These promise new information about flow and resuspension in a shallow lake. The experiments have provided valuable technical experience that will be useful elsewhere.

ACKNOWLEDGEMENTS.

The support of J. Bull in all phases of the experiment is gratefully acknowledged. S. Smith coordinated the field logistics and provided valuable field support. M. Kerman assisted with the reduction of the current meter data. This paper draws freely on the reports listed below:

Marmoush, Y.M.R. 1986. Measurement and analysis of suspended sediment in Lake St. Clair. Report submitted to NWRI in fulfillment of contract 09SE.KW404-5-1075, March, 1986.

Marmoush, Y.M.R., and Smith, A.A. 1986. Analysis of suspended sediment in Lake St. Clair. Report submitted to NWRI in fulfillment of contract 09SE.KW404-6-0071, June, 1986.

Marmoush, Y.M.R., and Smith, A.A. 1986. Analysis of suspended sediment in Lake St. Clair. Report submitted to NWRI in fulfillment of contract 09SE.KW404-_-____, August, 1986.

McCrimmon, R.C. 1987. Plots of Lake St. Clair data. Report submitted to NWRI in fulfillment of contract KW405-6-2637/01-SE.

Hamblin, P.F., Boyce, F.M., Bull, J, Chiocchio, F., and Robertson D. 1987. Report to sediment work group, Upper Great Lakes Connecting Channel Study: Physical measurements in Lake St. Clair. April, 1987.

Chiocchio, F. 1987. Documentation of main tower data from 1986 Lake St. Clair experiment. NWRI unpublished report.

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Aubrey, D.G., and Trowbridge, J.H. 1985. Kinematic and dynamic estimates from electromagnetic current meter data. J. Geophys. Res. 90(C5): 9137-9146.

Hamblin, P.F., Marmoush, Y.M.R., Boyce, F.M., and Smith, A.A., 1986. Fiels evaluation of an electromagnetic current meter based vertical profiler. NWRI Contribution 86-204.

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

Simons, T.J., and Schertzer, W.M. 1986. Hydrodynamic models of Lake St. Clair. NWRI Contribution 86-10.

FIGURES

Figure 8. Comparison between observed and calculated velocity profiles near the main tower on September 17, 1985.

Figure 9. Sketch of bottom mounted array of electromagnetic current meters (MCATS) used in 1985.

Figure 10. Dispostion of current meters and transmissometers on main tower, 1986 Lake St. Clair experiment.

Figure 11. Time series of wind and suspended sediment concentrations from tower data.

Figure 12. Current profiles from tower for two days, November 1 (calm), and November 4 (windy), 1986.

Figure 12. Wind speed, wave heights, measured and inferred orbital velocities (near bottom), and suspended sediment concentrations at the tower site (Stn. 501). (Fig 10 rept to sed grp)

Figure 14. Time series of turbidity from water intakes located long the Canadian shore of Lake St. Clair.

Figure 15. Time series of turbidities measured at the Windsor water intake during the field season of 1985.

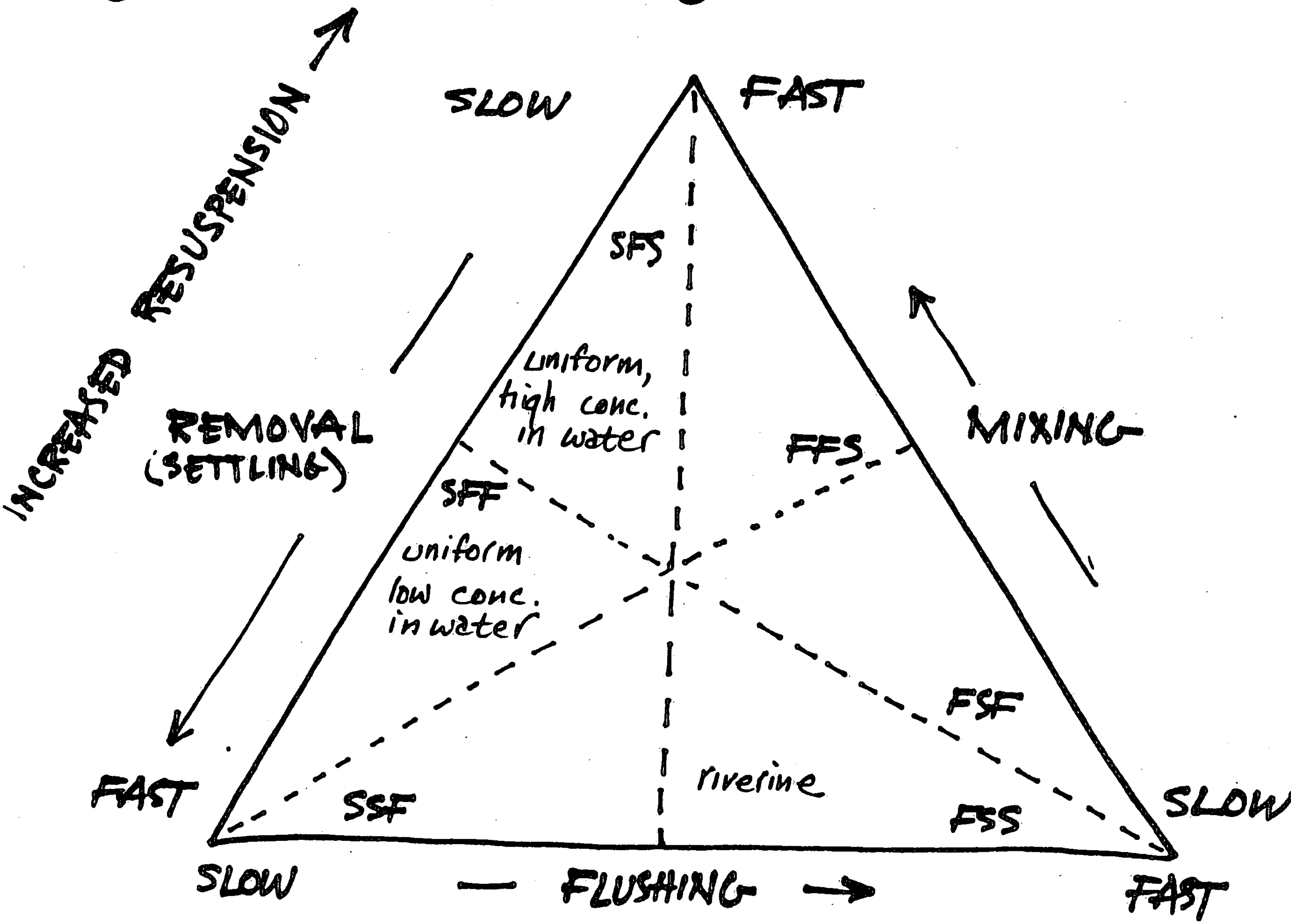


Figure 1. "Contaminant concentrations" as a function of flushing time, mixing time, and settling time.

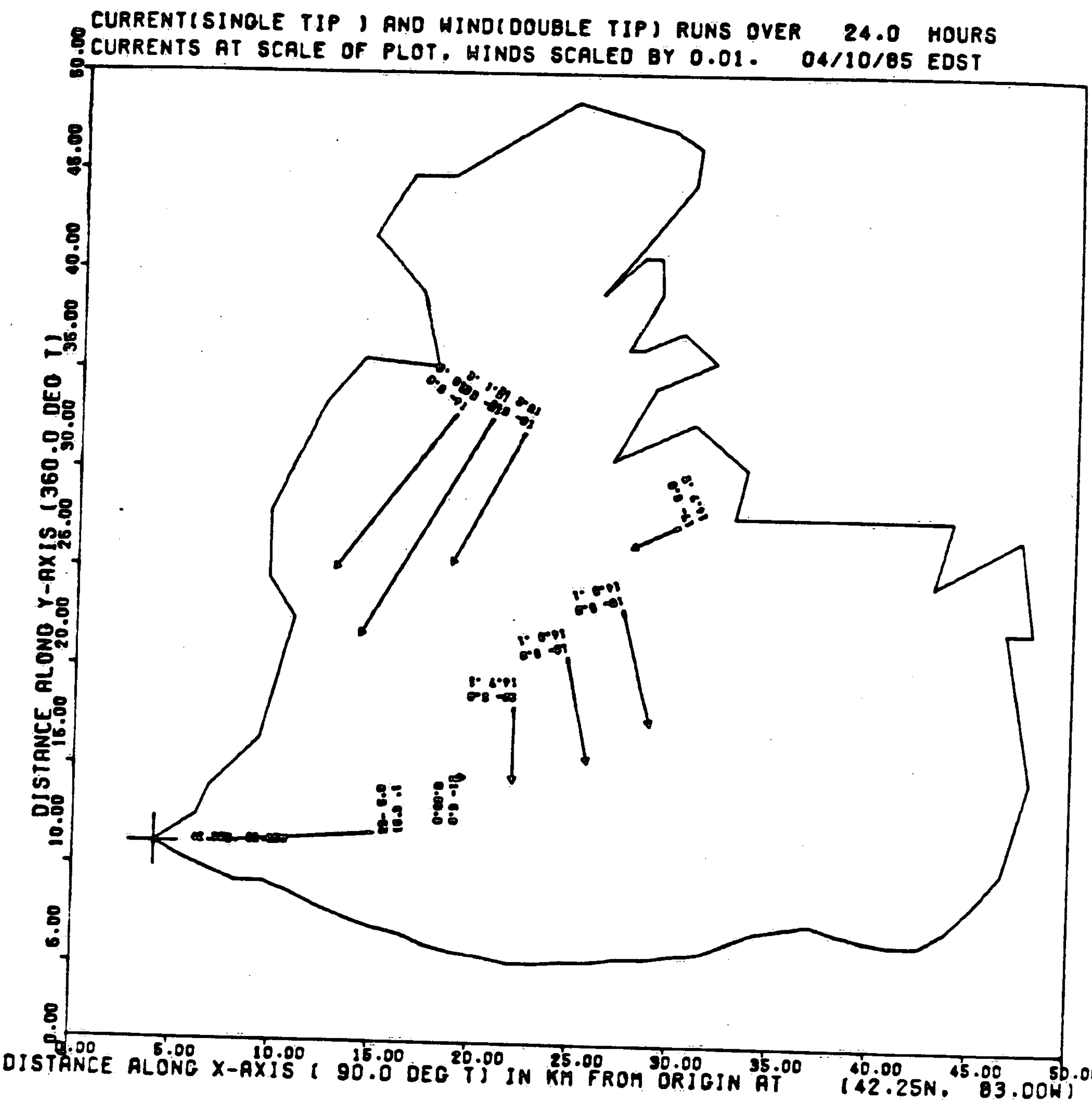


Figure 2a. ARVEC diagram of NB currents for October 4, 1985

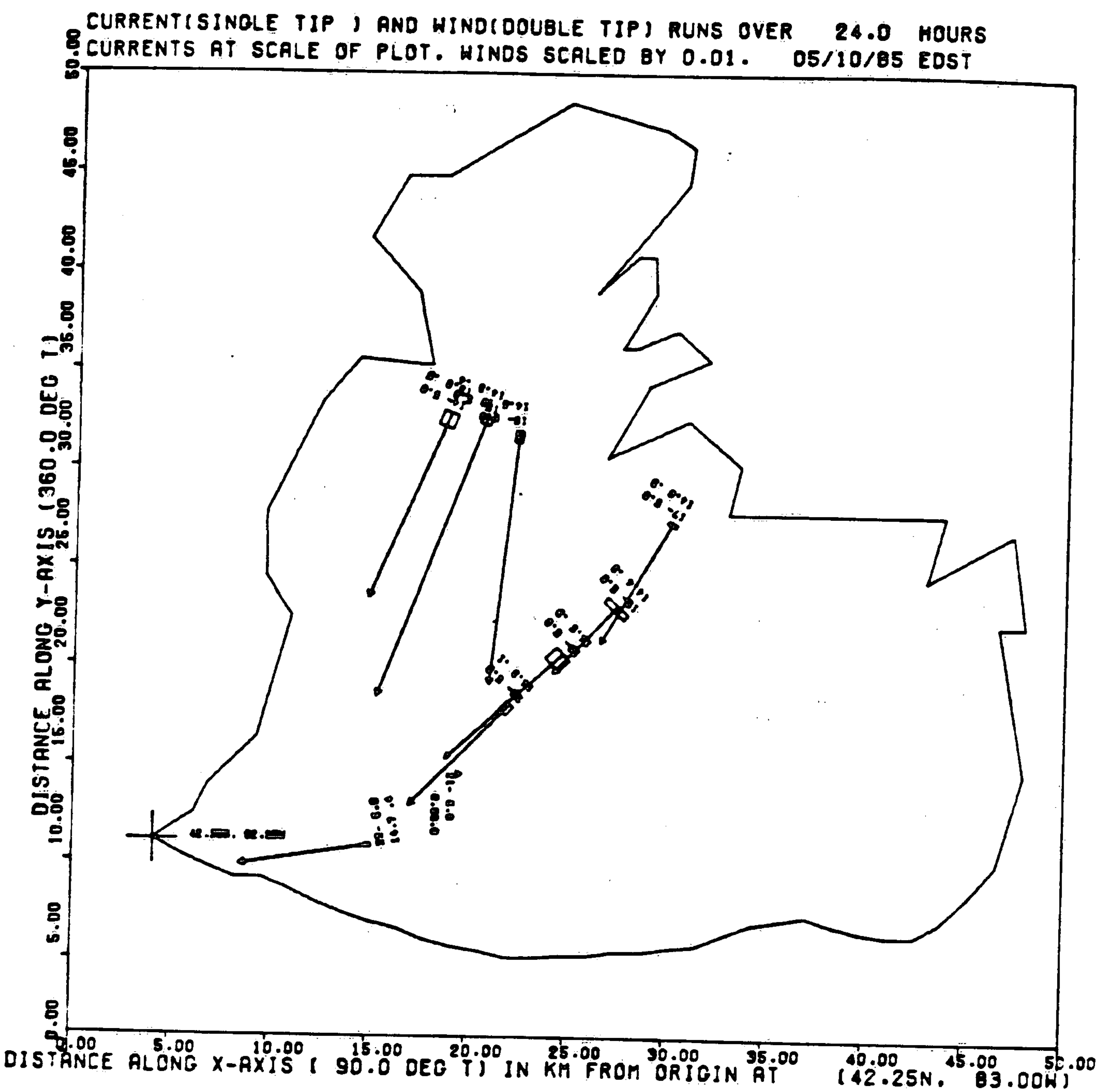
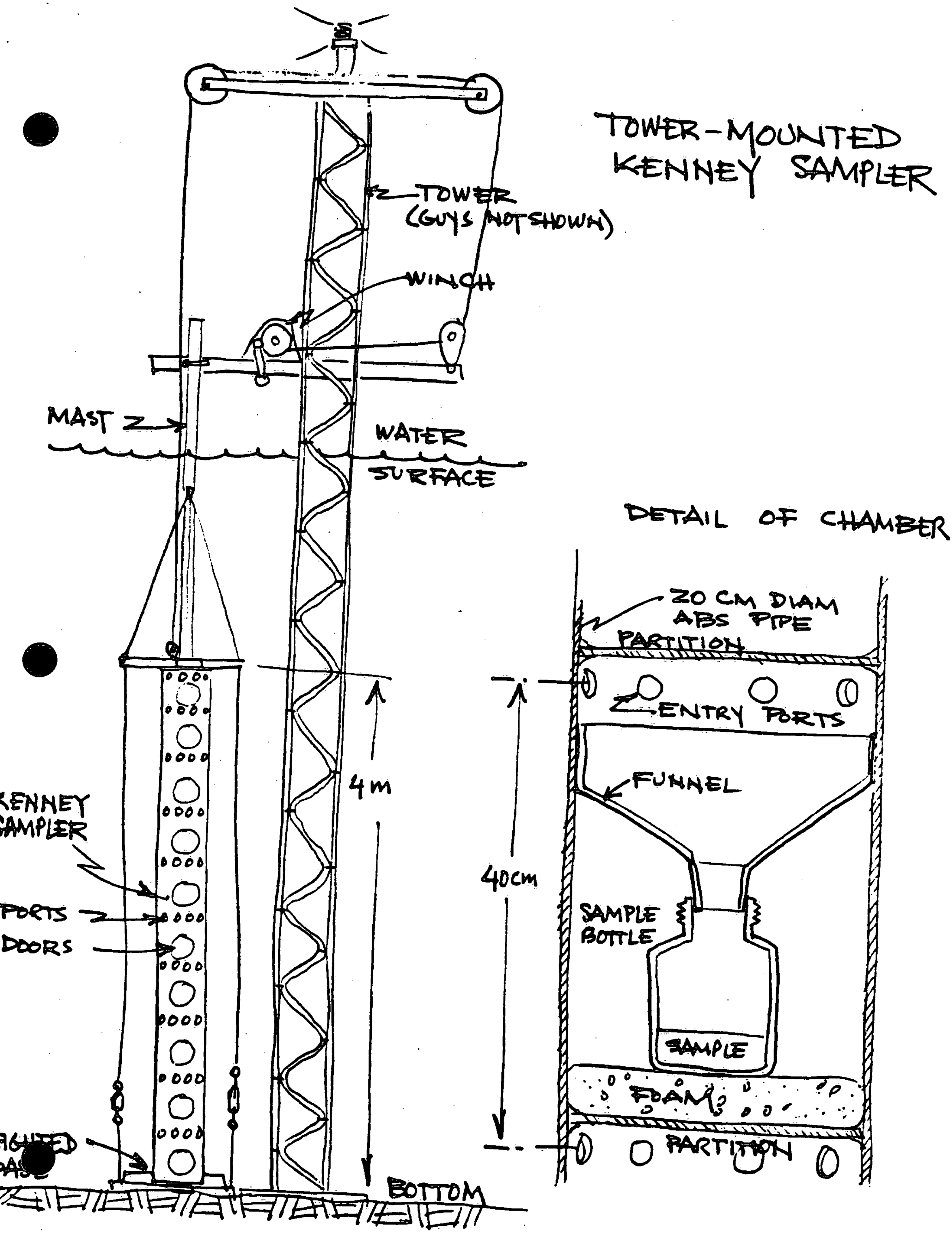


Figure 2b. Same for currents of October 5, 1985, strongest wind event of the measurement period



TOWER-MOUNTED KENNEY SAMPLER
TOWER (GUYS NOT SHOWN)
WINCH
MAST
WATER SURFACE
4m
KENNEY SAMPLER
PORTS
DOORS
BOTTOM
DETAIL OF CHAMBER
20 CM DIAM ABS PIPE
PARTITION
ENTRY PORTS
FUNNEL
40cm
SAMPLE BOTTLE
SAMPLE
FOAM
PARTITION

Figure 3.

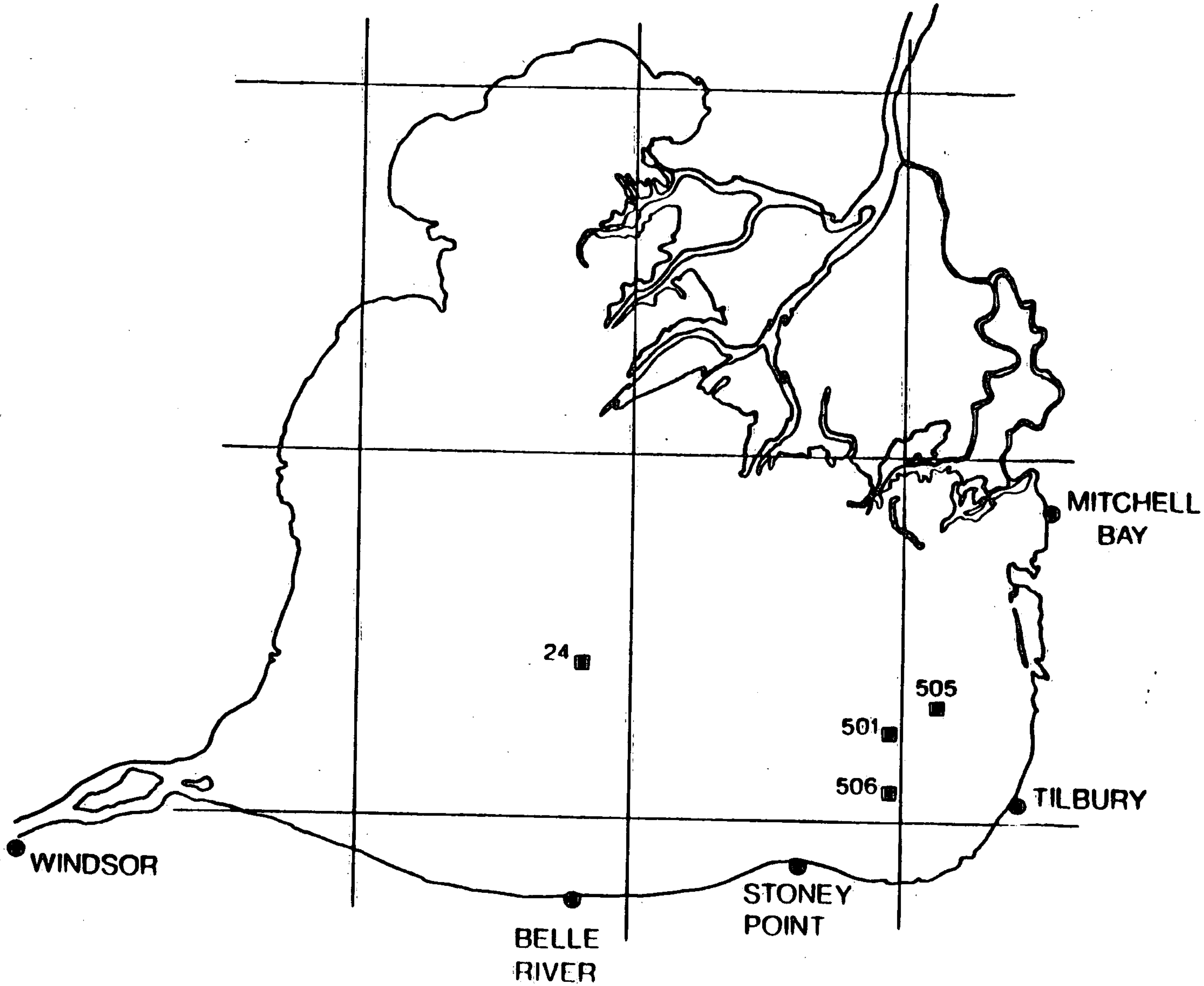

MITCHELL
BAY
24
505
501
506
TILBURY
WINDSOR
STONEY
POINT
BELLE
RIVER

Figure 4.

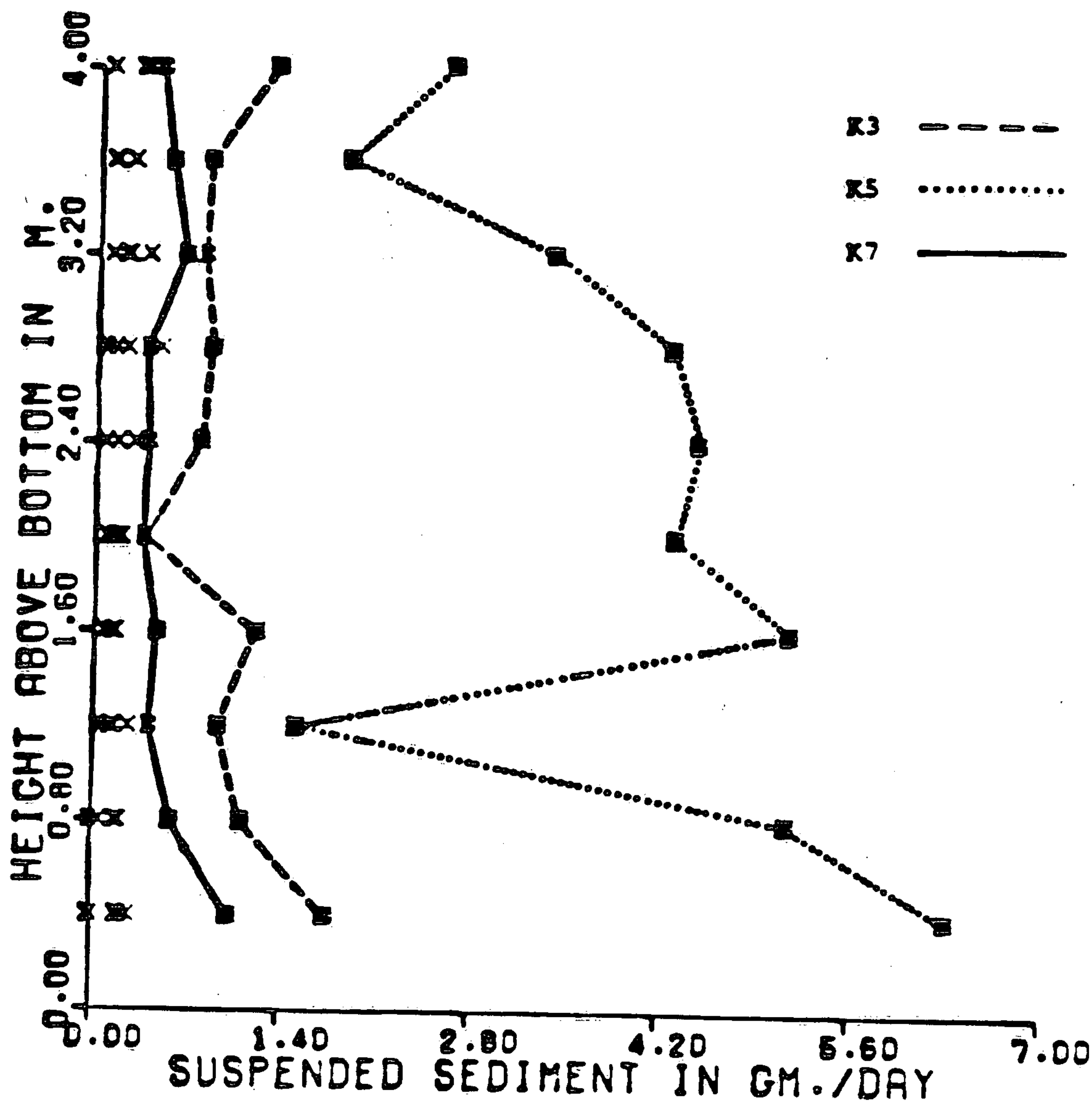
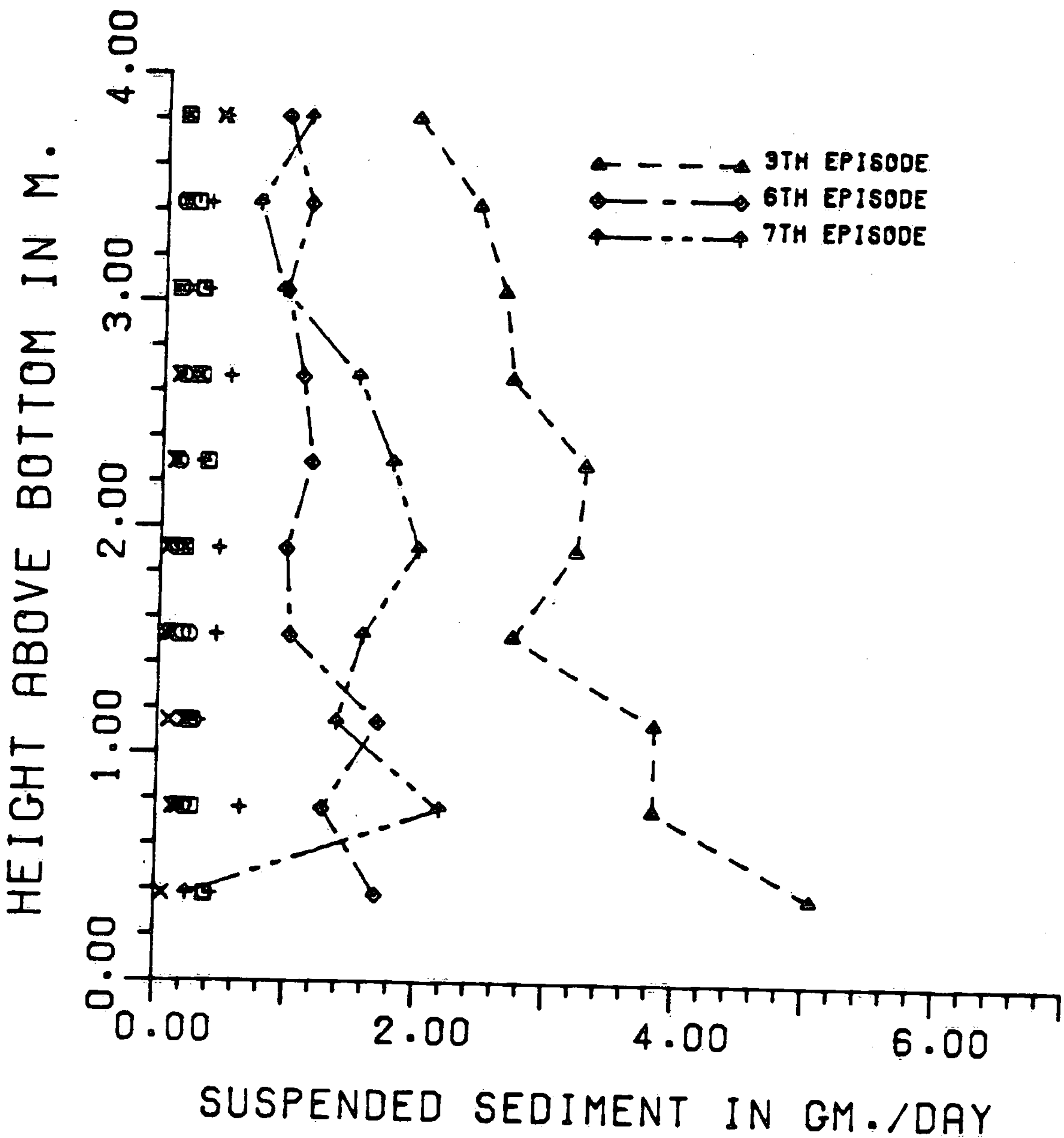

HEIGHT ABOVE BOTTOM IN M.
0.00
0.80
1.60
2.40
3.20
4.00
SUSPENDED SEDIMENT IN GM./DAY
0.00
1.40
2.80
4.20
5.60
7.00
K3
K5
K7

Figure 5a.



HEIGHT ABOVE BOTTOM IN M.
0.00
1.00
2.00
3.00
4.00
3TH EPISODE
6TH EPISODE
7TH EPISODE
0.00
2.00
4.00
6.00
SUSPENDED SEDIMENT IN GM./DAY

Figure 5b.

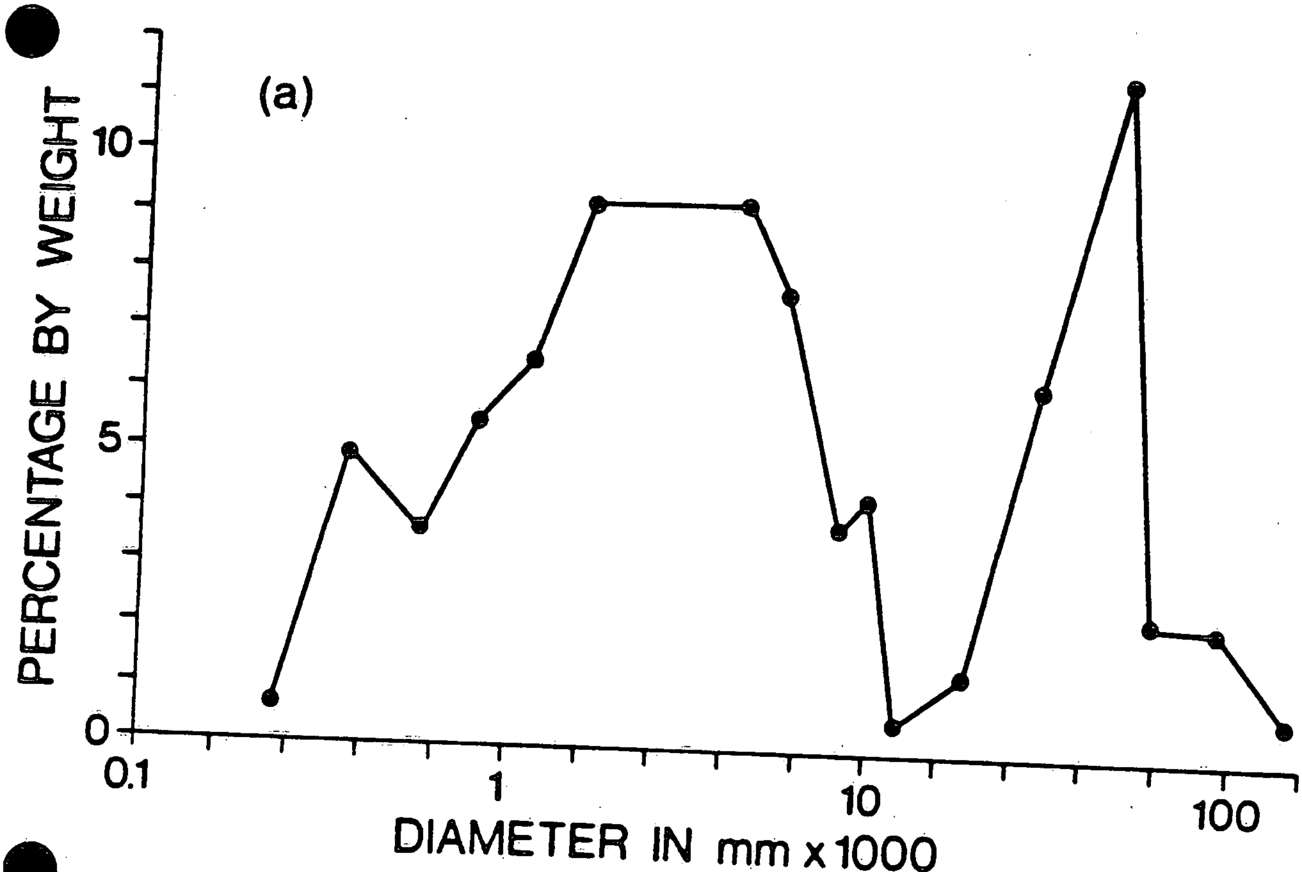


Figure 6a.

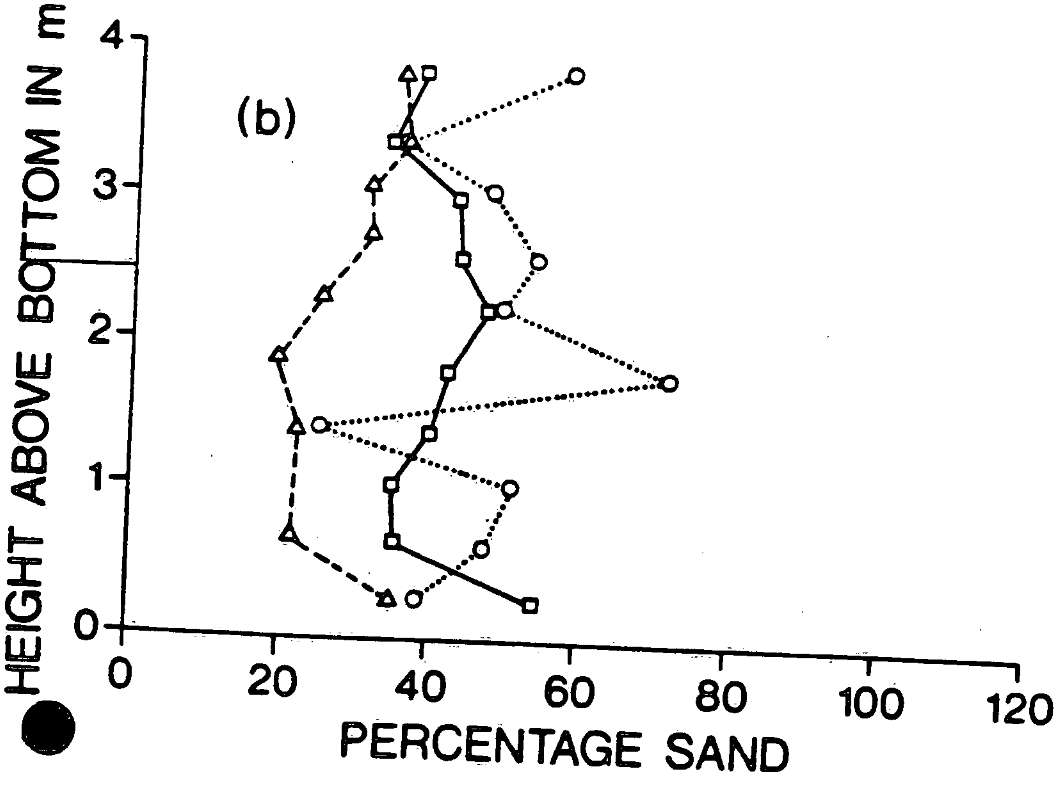


Figure 6b.

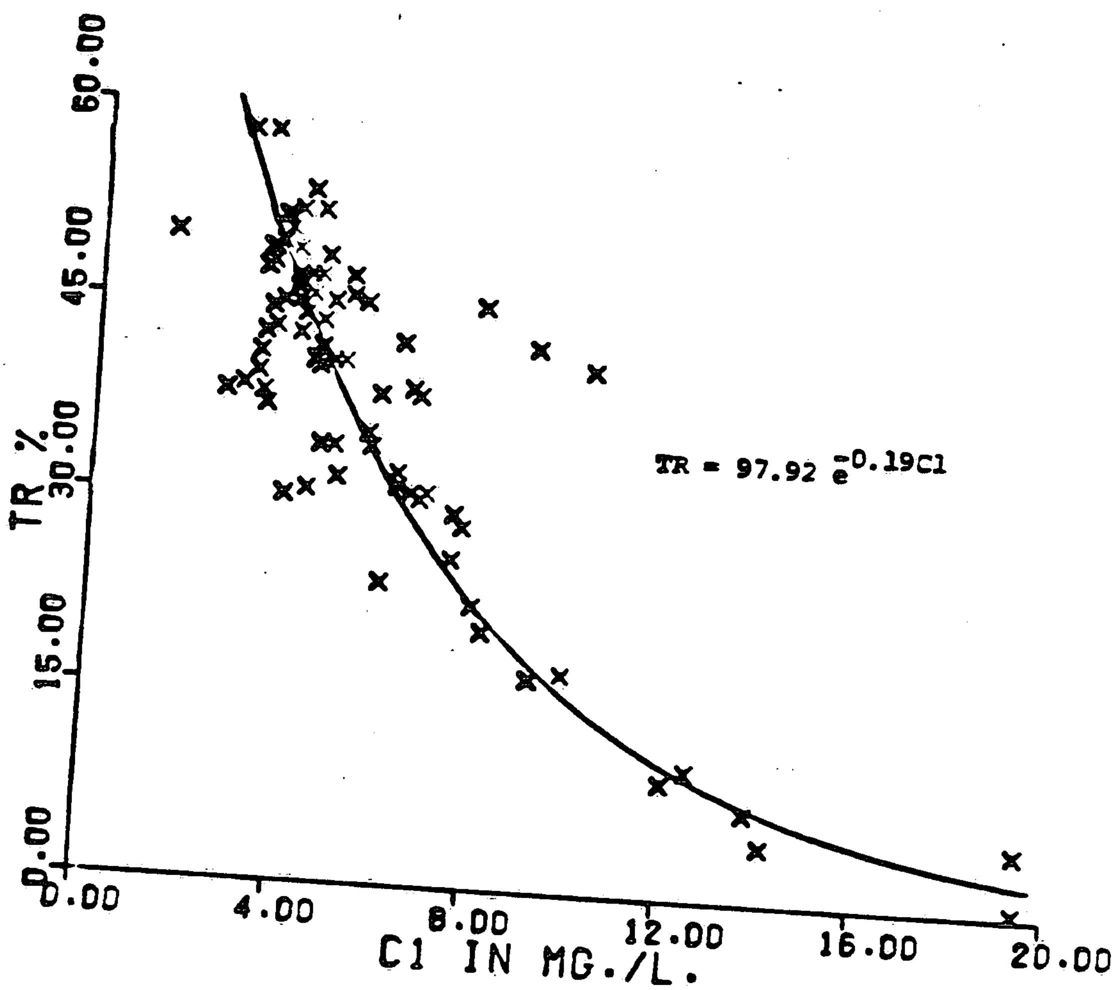
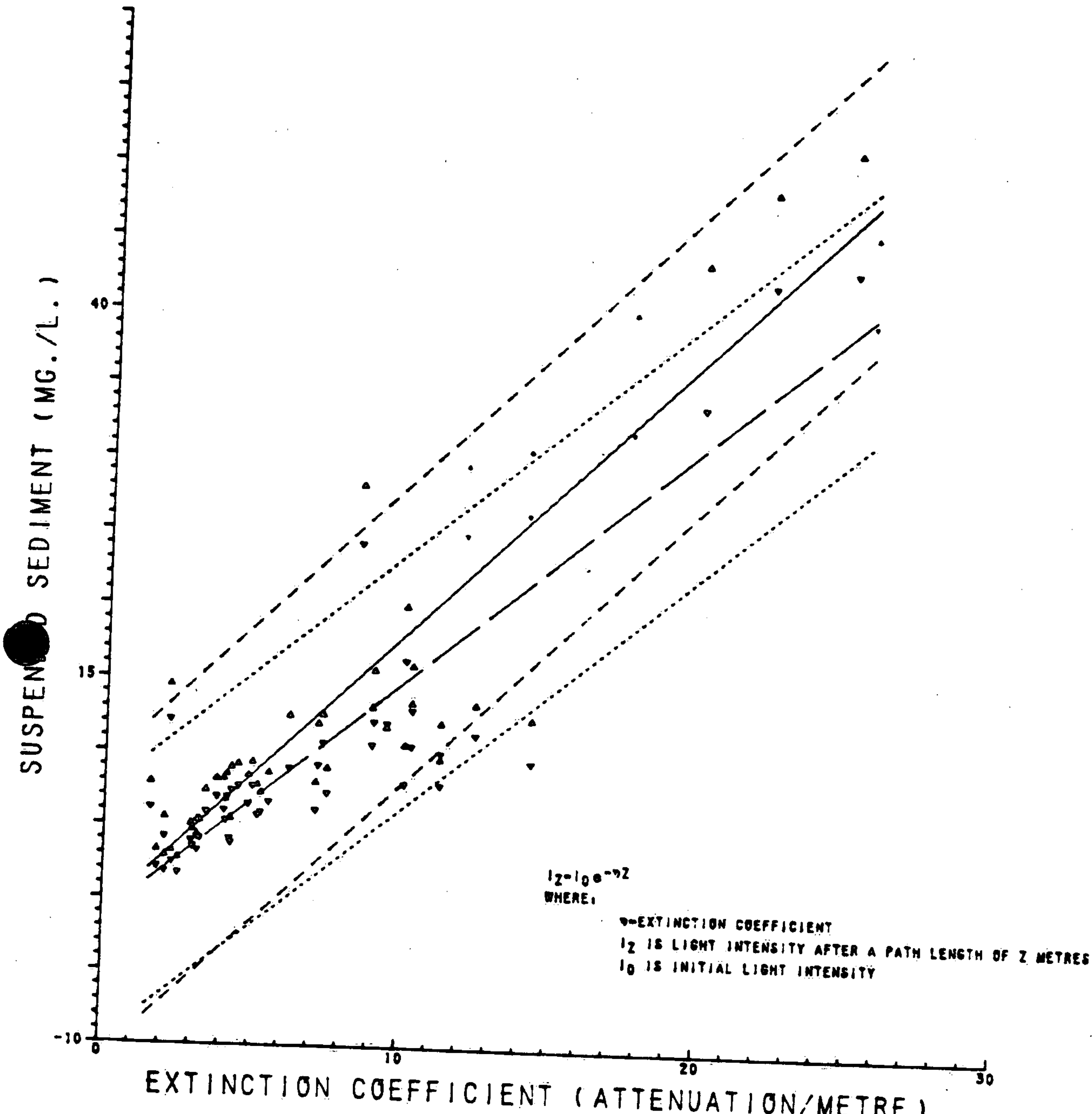
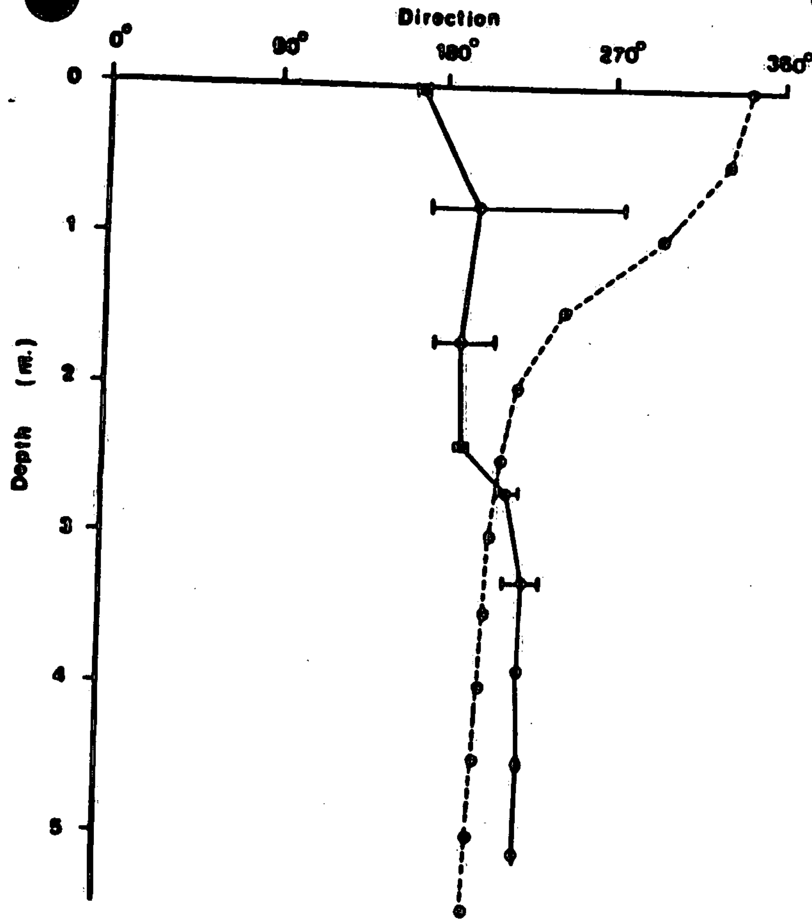


Figure 7a. : Relationship between percentage of transmittance, TR, and total concentration, Cl..

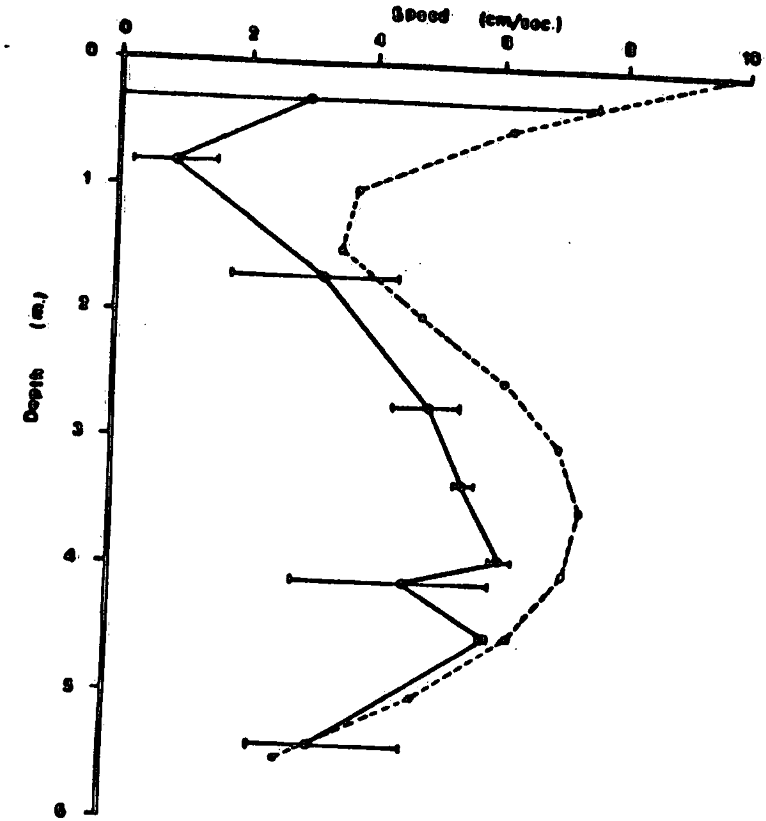


▲ TOTAL SEDIMENT SOLID LINE WITH SMALL DASHED LINE AS 95% PROBABILITY LIMIT
SUSPENDED SEDIMENT (MG/L)=-0.90347+1.90756η r=0.91183
▼ ASHED SEDIMENT LARGE DASHED LINE WITH DOTTED LINE AS 95% PROBABILITY LIMIT
ASHED SUSPENDED SEDIMENT (MG/L)=-1.25136+1.62387η r=0.91130

Figure 7b.



Comparison between the observed (as solid lines) and calculated (as dashed lines) values for the vertical current direction near the main tower on Sept 17-1985.



Comparison between the observed (as solid lines) and calculated (as dashed lines) values for the vertical current speed near the main tower on Sept. 17-1985.

Figure 8.

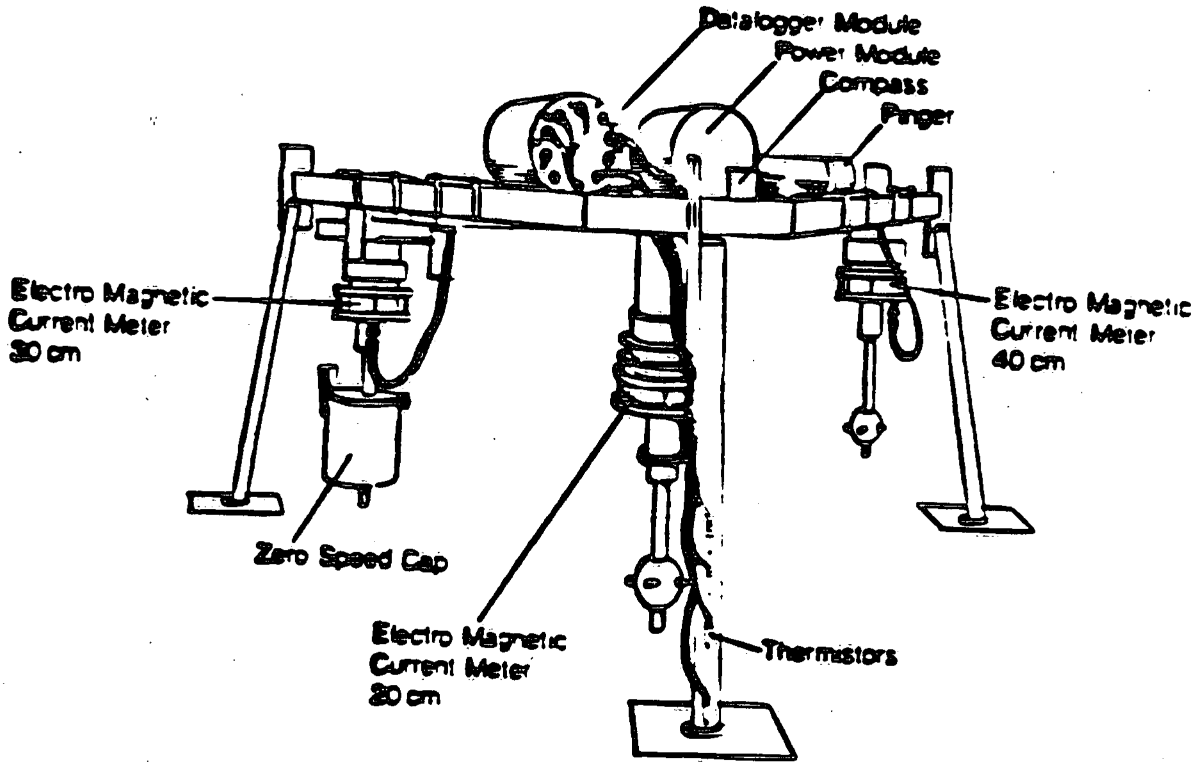


Figure 9. Sketch of bottom mounted array of electromagnetic current meters (MCATS) used in 1985.

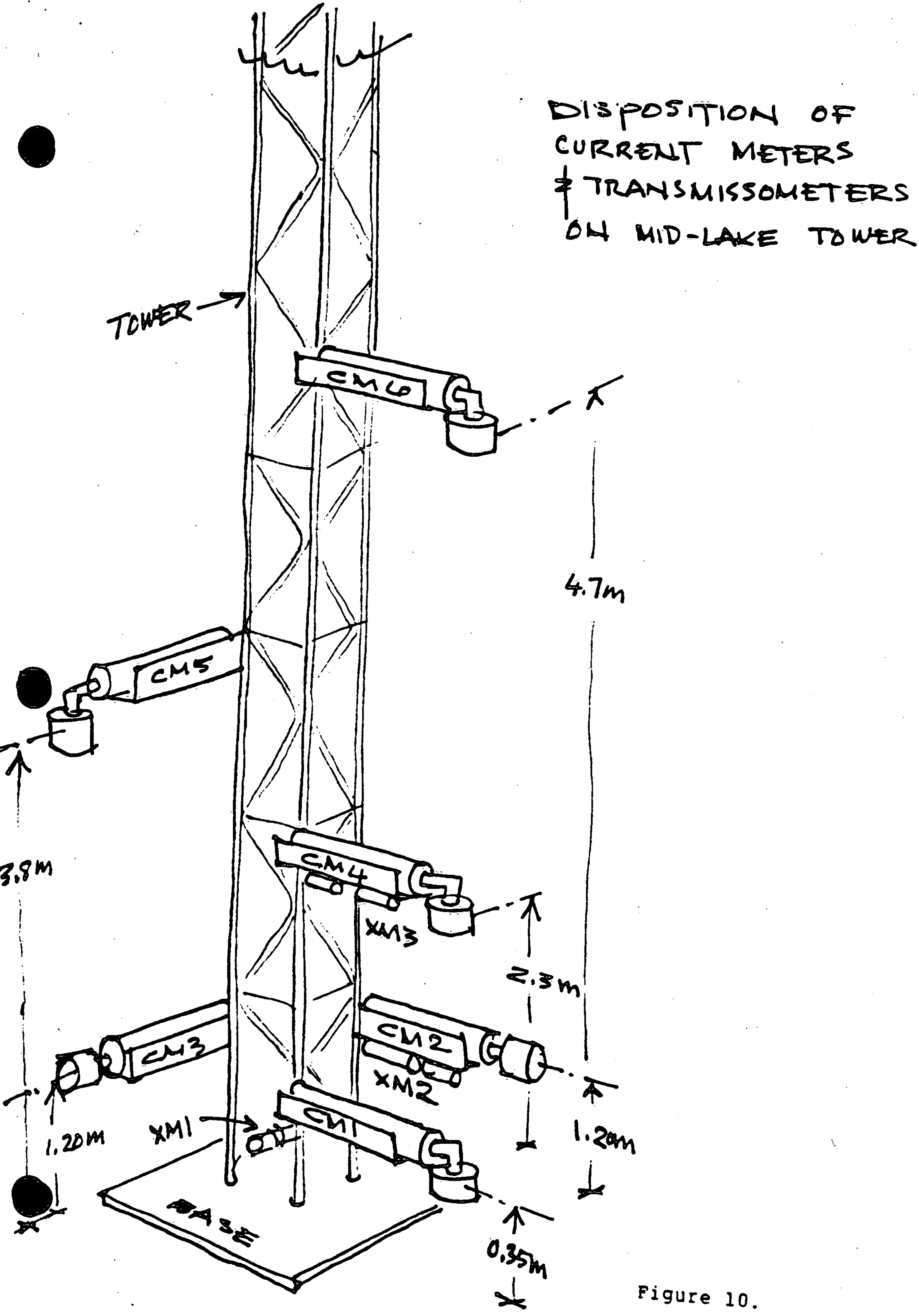

DISPOSITION OF
CURRENT METERS
& TRANSMISSOMETERS
ON MID-LAKE TOWER
TOWER
CM6
4.7m
CM5
3.8m
CM4
XM3
2.3m
CM3
CM2
XM2
1.20m
XM1
CM1
1.20m
BASE
0.35m

Figure 10.

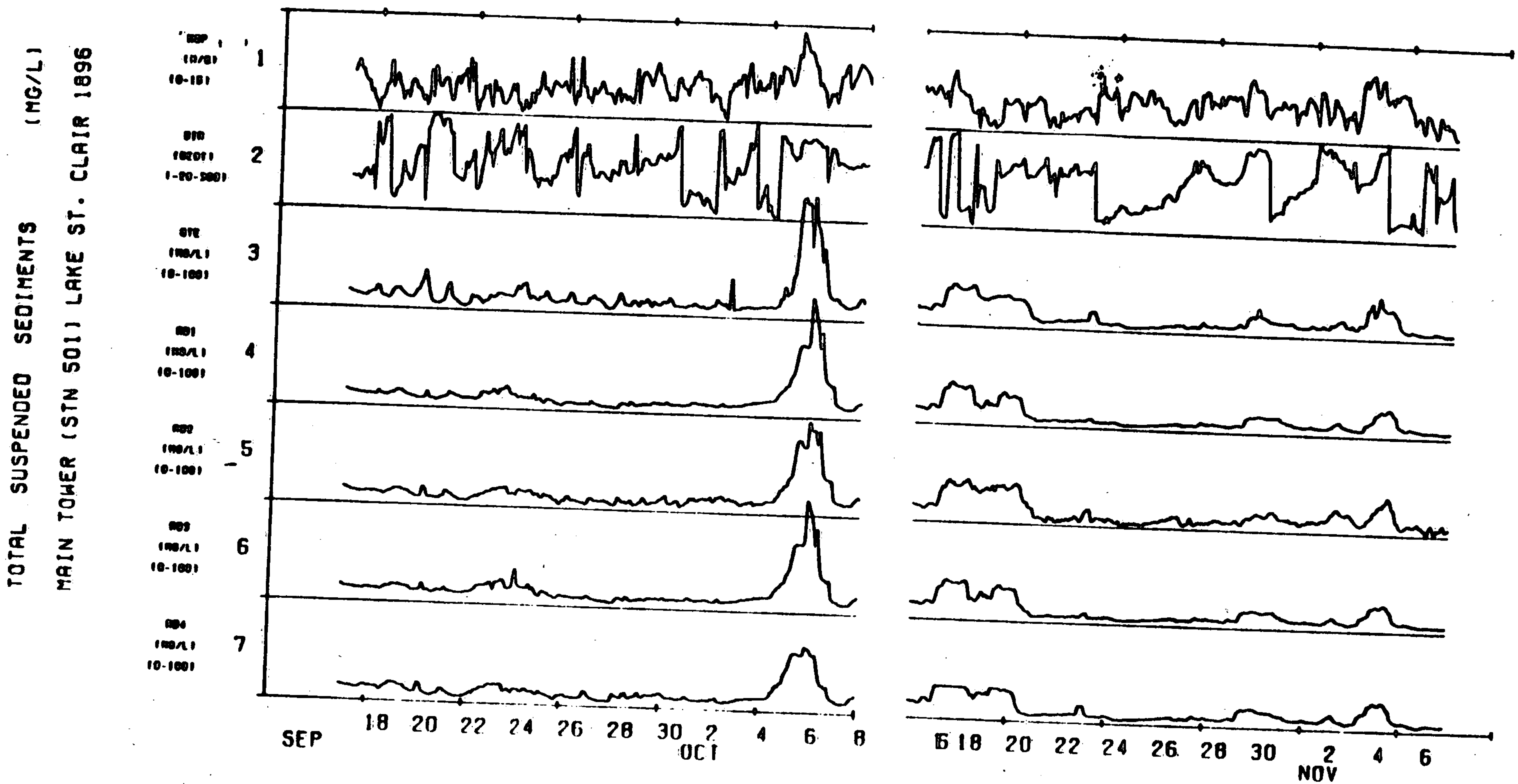
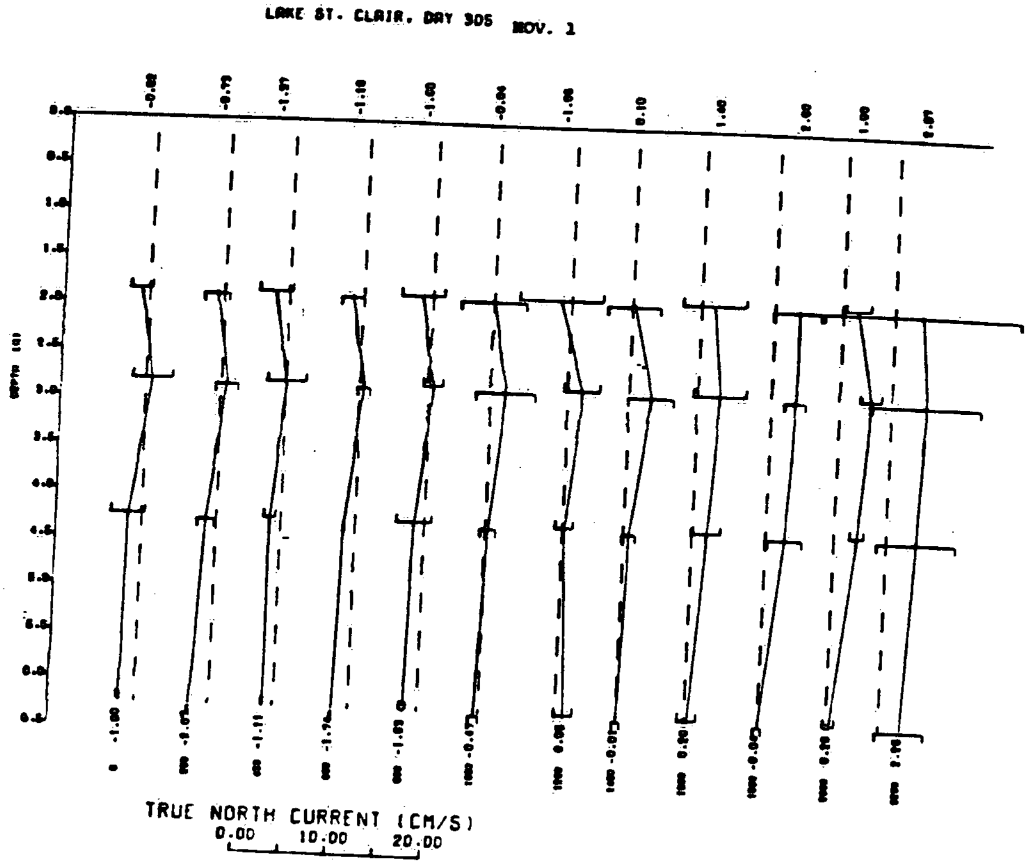
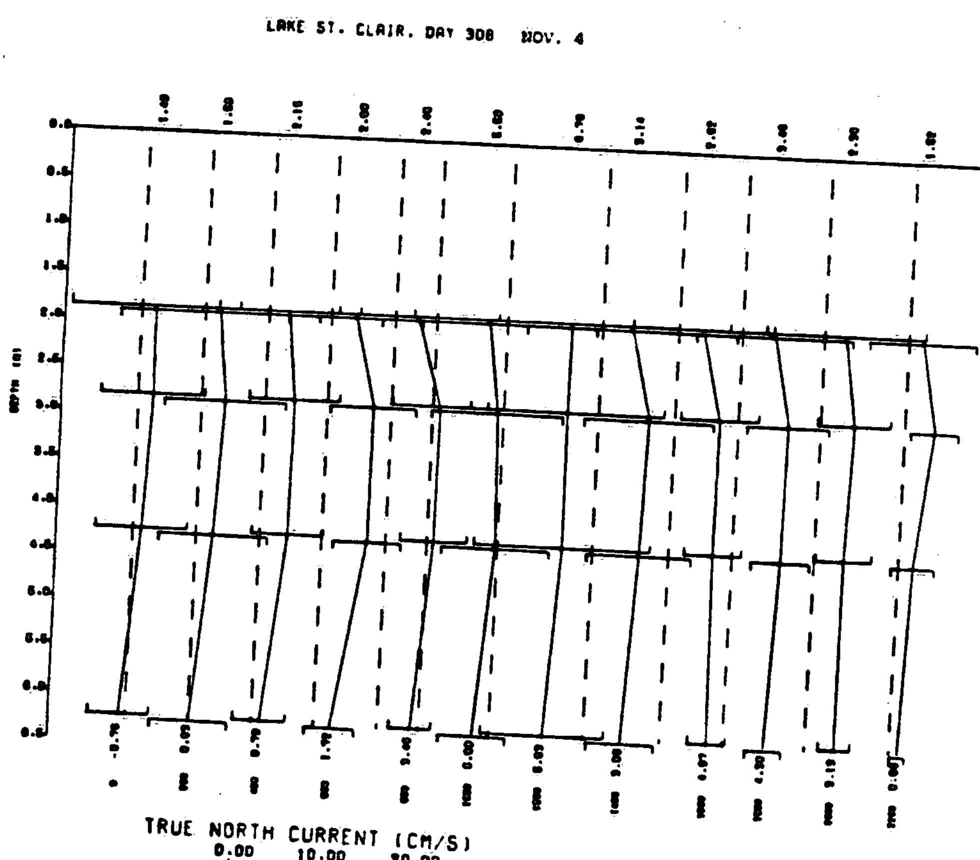


Figure 11. Time series of wind and suspended sediment concentrations from tower data.



LAKE ST. CLAIR, DAY 305 NOV. 1
TRUE NORTH CURRENT (CM/S)
0.00 10.00 20.00



LAKE ST. CLAIR, DAY 308 NOV. 4
TRUE NORTH CURRENT (CM/S)
0.00 10.00 20.00

Figure 12.

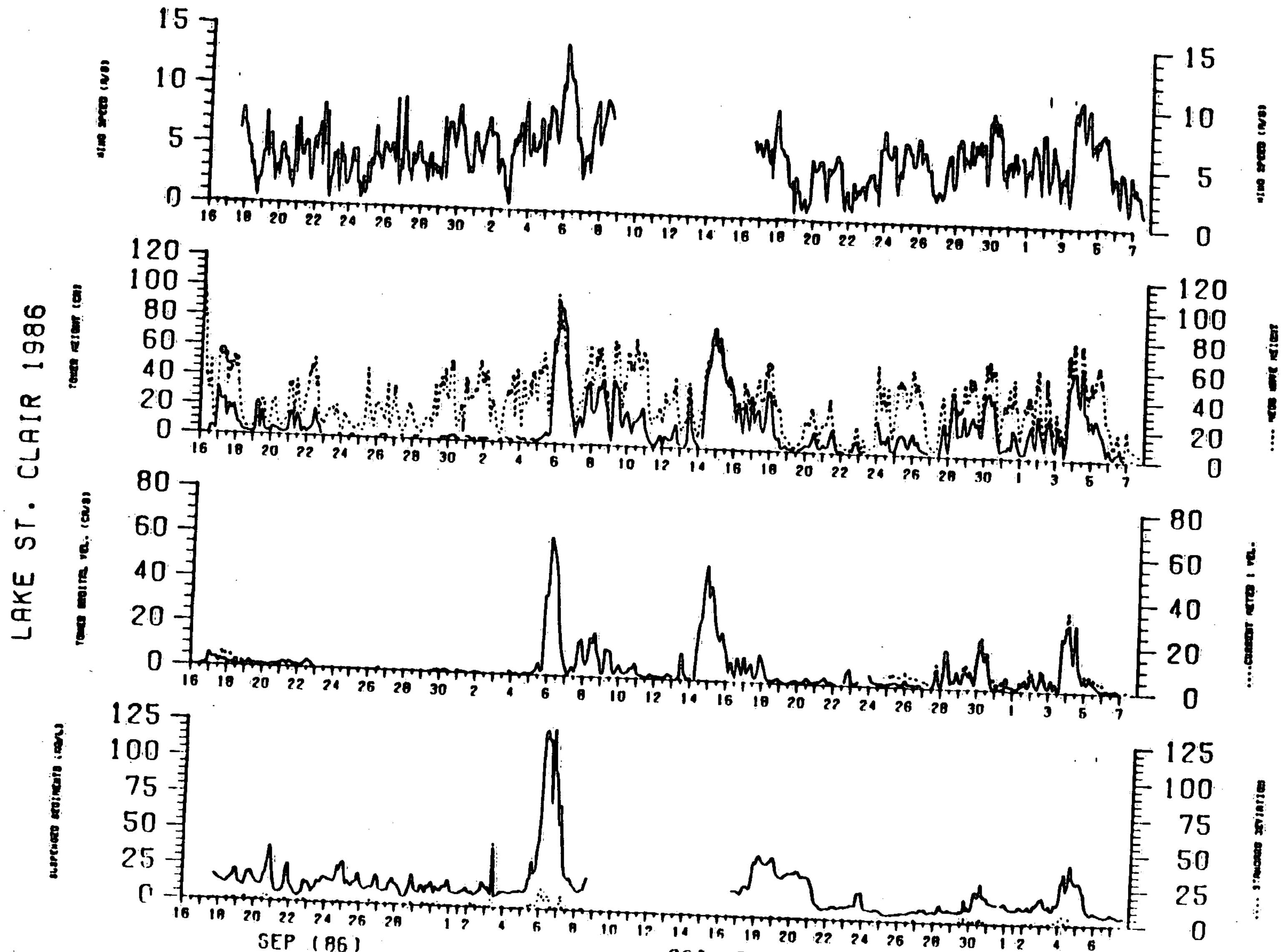


Figure 13.

ST. CLAIR TURBIDITY (FTU)

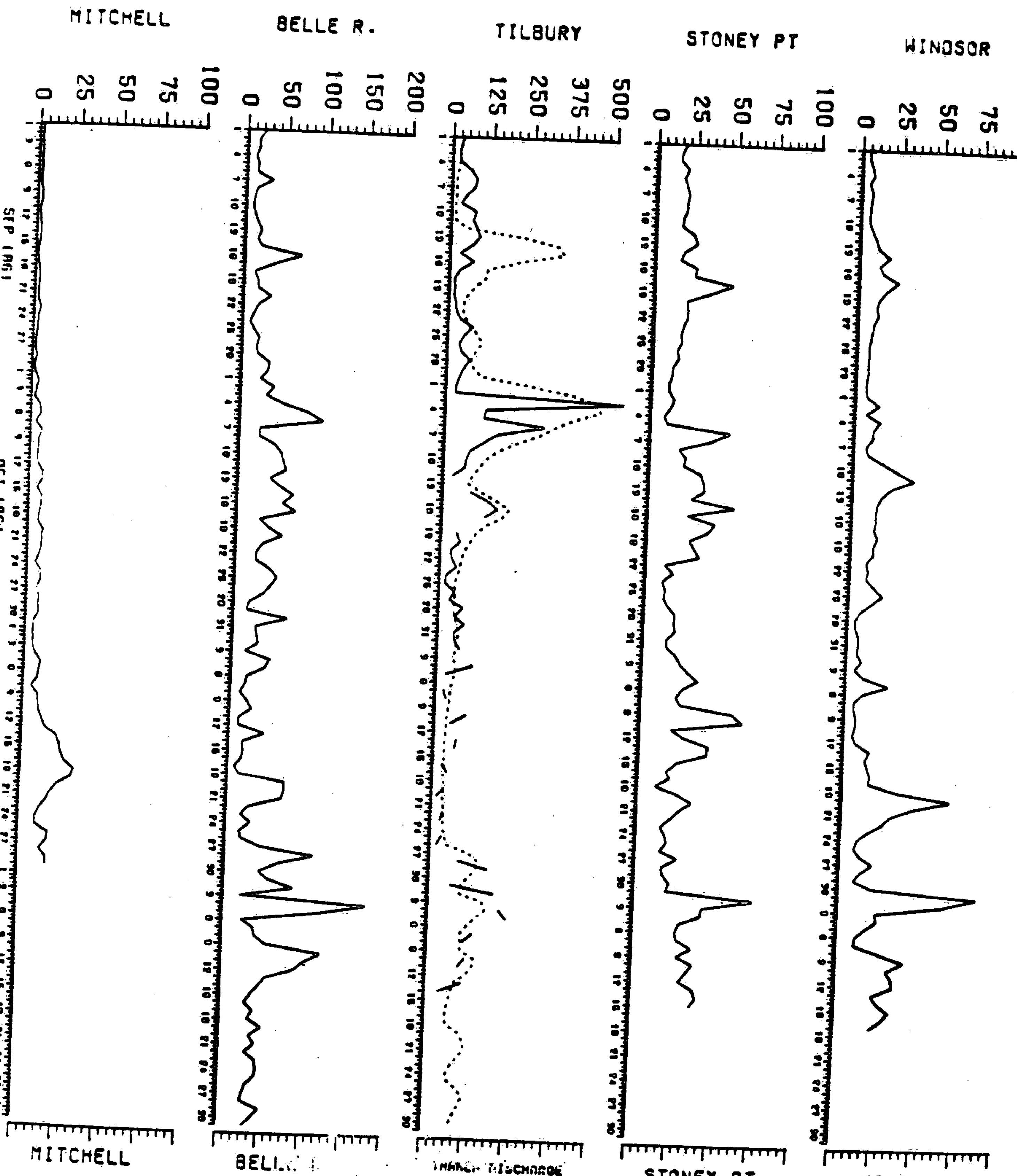


Figure 14.

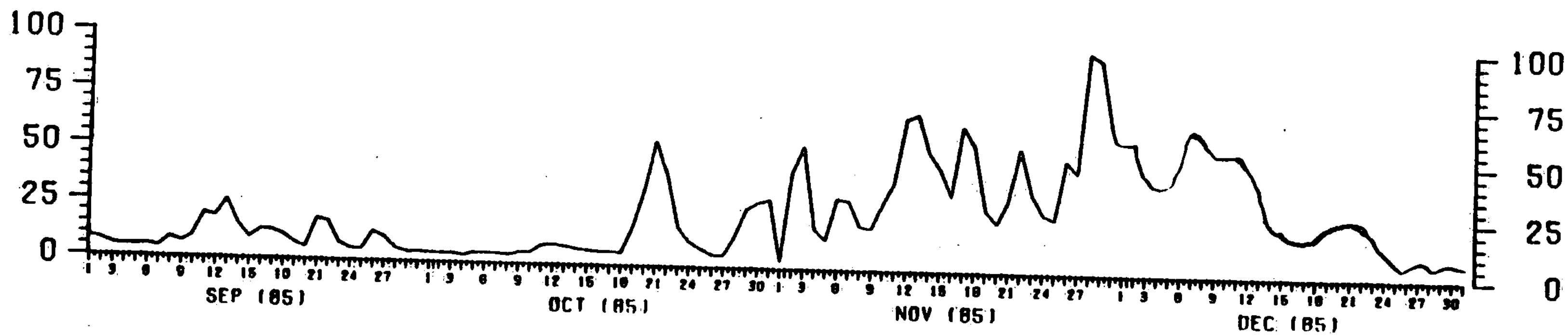


Figure 15. Time series of turbidities measured at the Windsor water intake during the field season of 1985.

APPENDIX A: PRELIMINARY EVALUATION OF THE KENNEY SAMPLER

Selection of Data.

The trapping episodes selected were those for which accompanying measurements of flow and optical transmission were made (4 of 8 episodes). Optical transmission measurements were converted into estimates of suspended sediment concentration using the empirical relation developed earlier in this report. The catch from the chamber nearest in height to each of three transmissometers was chosen; horizontal velocities were interpolated to these heights from 4 levels of current meters.

Calculated Quantities.

Since horizontal water movements are necessary to introduce suspended sediments into the Kenney Sampler chambers through the ports, it is reasonable to suppose that the catch must in some way depend on an average of the horizontal sediment transport (product of concentration times horizontal velocity). If this term is zero, then the catch will be zero. On the other hand, if the horizontal flow is particularly vigorous, the flushing of the top compartment of the trap may be rapid enough so that the concentration of suspended material inside the trap at the level of the ports is essentially that of the ambient, exterior fluid.

In this situation, the catch might depend on the product of the sinking speed and the concentration of the sediment. The data is sufficient to test both hypotheses.

For each of the four Kenney Sampler episodes, the following quantities relating to the above interpretations were calculated.

a) Qdi Sampler catch at level i = 1, 2, 3. expressed in gm day

b) Qfi = $\frac{fac}{N} \sum_{j=1}^{N} \sigma_{V_{ij}} \overline{C_{ij}}$

$\sigma_{V_{ij}}$ is the rms current speed of the jth measurement burst at the ith level (the burst samples consist of 480, velocity readings over an interval of 8 minutes (sampling frequency = 2.0 hertz); bursts are initiated either every 2 hours or every 0.5 hours, depending on the configuration of the controller);

$\overline{C_{ij}}$ is the mean suspended sediment concentration for the jth burst at the ith level. There are N bursts in a trapping interval (N ~ 24 - 100). *fac* is a conversion factor having the dimension L^2 so that the quantity Qfi has units of catch rate, gm day^{-1}, and the area is the projected area of the sample ports facing into the flow. For the

Kenney samplers used, fac takes the value $0.33\ m^2$.
when C is in gm/m³ and velocity is measured in cm/s

Qfi may be interpreted as the theoretical catch of the sampler assuming that (i) all the suspended material entering the ports remains in the sampler, (ii) that the flow into the port is the normal component of velocity in the absence of the trap itself, (iii) that both the mean and the fluctuation velocities accomplish the trapping, and (iv), that the fluctuations of concentration are much smaller than the mean.

c) Qmi $= \frac{fac}{N} \sum_{j=1}^{N} \overline{V_{ij}}\ \overline{C_{ij}}$

This quantity is similar to Qfi except that the velocity scale is $\overline{V_{ij}}$, the burst-averaged mean speed (wave orbital motions, for example, would be averaged out).

d) $Cavg_i = \frac{1}{N} \sum_{j=1}^{N} C_{ij}$ Average observed suspended sediment concentration over the trapping interval.

These and other quantities (explained below) are displayed in Table A1.

Results.

Figure A1 shows Qd plotted as a function of Qf. Qd appears to correlate positively with Qf. The slope of the line that fits the points is apporoximately 0.08, a rough measure of the trapping efficiency of the sampler under the hypothesis that all the flow pulses inject material into the trap.

Figure A2 is similar to Figure A1 but with Qm as the independent variable. Again, there is a reasonable correlation between Qd and Qm. The slope of the line joining the points is close to unity. The capture effciency of the trap in steady flow is unknown, but would certainly be less than one. If one accepts the hypothesis that the trap responds to horizontal sediment flux, then the large efficiency indicates that some portion of the velocity fluctuations augment the capture.

Another interpretation suggests that the fluid motions external to the trap are sufficient to cause turbulent mixing near the top of the chamber which is strong enough to equalize suspended sediment concentrations inside and outside the trap - at the level of the ports. If the fluid below the ports in the trap interior remains calm, then the trap catch should be proportional to some averaged product of the settling velocity and the concentration. In Figure A3 the observed catch is plotted against averaged sediment concentration over the trapping interval. Intuitively one would argue that the larger catches associated with storm events should contain a higher fraction of coarse-grained material and thus have a larger mean sinking speed. Analysis of the trapped material shows this to be true;

the percentage of sand-sized material is shown on figure A3 and ranges from 14 to 28%. Using the dimensions of the trap, Qd and C, estimates of the mean sinking speed can be formed. These are shown on Figure A3, and they vary in the anticipated fashion from a minimum of 0.64 m day for a low-energy, small catch period to 5.6 m day for the largest catch. The estimates of settling speed are in a physically reasonable range, but they are smaller than the settling speeds measured in the laboratory, a feature we could interpret as mixing inefficiency in the trap.

Conclusions.

Although the available data are few, the patterns they suggest are individually persuasive. The data seem best explained by the third hypothesis - that the impinging flow induces enough mixing at the top of the settling chamber that the sediment concentrations there are similar to those outside the trap and that the trap measures downward settling flux. Of course, the results relate only to the grossest of overall averages, and we need to know more about the behaviour of this apparatus.

Further Experimental Work.

a) Visualization of trap behaviour. The pattern of flow immediately outside the trap will depend on the nature of the imposed flow field and the diameter of the trapping chamber, D.

For steady and slowly varying flows, the parameter of interest is the Reynolds Number $R_D = UD/\nu$ where D is the overall trap diameter, U is the external fluid velocity (relative to the trap) and ν is the kinematic viscosity of water (0.01 cm^2/s, nominally). For most applications, this will be in the transition turbulence range with values of a few thousand. Another Reynolds number (R_d) can be defined by the external flow speed and the diameter, d, of the inlet ports (of order 1 cm). This number will typically be several hundred, a regime generally associated with laminar flow. By locating the inlet ports immediately under the roof of the chamber, vertical mixing by the entering jet will be inhibited. Port spacing should be such to create horizontal shear; 8, equally spaced holes would appear about right. With appropriate design, it is possible that the flushing of the top of the chamber at the level of the ports may be rapid compared with the settling time of the particles across this zone so that the concentration of material at the top of the chamber is close that observed immediately outside. At the same time, the turbulence created by the inlet jet is strongly damped by viscosity and by the presence of the horizontal partition immediately above the ports. On the other hand, it may also be possible to design a trap with a long residence time, responding effectively to horizontal transport. It would be useful to confirm these conjectures by visualization of the flow.

Three test traps would be made from clear plastic tube (nominal diameter 10 cm or greater). The traps would differ in the diameter of the inlet ports, 0.5 cm, 1.0 cm, and 1.5 cm. The traps would be tested in a glass-walled hydraulic flume where steady flow velocities of up to 50 cm/s could be provided. If possible, the flume should have a wave-maker so that an oscillating flow component can be introduced. The traps would be filled initially with dyed water, their ports sealed with a removeable sleeve. After installation in the flume and the attainment of steady flow conditions, the sleeve would be removed and the flushing of the trap chamber observed. While quantitative estimates of flushing from this experiment would be difficult, the experiment may nevertheless provide useful guidance in the design of apparatus for the field.

b) Quantitative measurement of flushing.

The essential feature of the experiment is to fill a trap initially with distilled water (or water of substantial conductivity contrast with respect to water in the flume) and to expose it for a brief period to flowing water in the flume. The average conductivity of the water in the trap at the end of the exposure period will then be a measure of the flushing of the chamber by the flow. The details are potentially more complicated:

- Some means of blocking the ports prior to and following after the flume exposure must be devised. A close-fitting, O-ring equipped sleeve may be appropriate (Figure A4).

- To eliminate flow start-up effects, two identical chambers could be employed, but exposed for different lengths of time. This would only prove necessary if the start-up time scale were comparable to the exposure time. A very rough estimate of a flushing time-scale for the top of a 10 cm diameter trap with 1 cm diameter ports in a 5 cm s flow is 20 s.

- We also need to know the distribution of flushing in the vertical. A small conductivity probe such as those used by Gibson and Schwartz (1963) could be employed to profile the conductivity in the trap immediately following the flume exposure (Figure A5). Although the mixing would continue to evolve somewhat after the closure of the ports, the vertical scale of the mixing should be apparent. The chamber should be filled initially with a fluid very slightly more dense than the ambient flume water.

c) Field Experiment.

Following successful laboratory experiments, and guided by the understanding obtained, we would propose to test the system under field conditions. The "satellite" system developed for the 1986 Lake St. Clair Study is the heart of this experiment. It carries a Neil-Brown vector averaging "smart" current meter and a Sea-Tech transmissometer coupled to a Seadata logger, all on a lakebed platform. The measuring head of the current meter is nominally 1m above the bottom, while the transmissometer is located 70 cm above the bottom. The system operates in a burst-sample mode. This system would be deployed near the Waves Tower in October/November at a time when suspended material in the water column would be resuspended from the bottom and mainly inorganic. The height of the transmissometer will be the reference height for the experiment. Using the conventional sediment trap stands for support (or equivalent), an array of sediment trap chambers would be situated at the reference height in the vicinity of the current meter station. Some of these (at least two) would be of the conventional, vertical-tube type, others would be Kenney Sampler chambers, both large and small, the former being cut from the short array attached to the Rosa tripod (see above) or else fabricated from the basic components. Again these traps would be deployed in pairs, with one pair differing from another in the size of the entry ports. Using the original 13 mm diameter holes as standard, the other hole sizes would be 6 mm and 20 mm. An array of the Fraser River traps would also be deployed, again with varying diameters of entry ports. Figure A6 describes the array of instruments. A minimum of 4, week-long deployments of the array should be attempted. At more frequent intervals (once a day would be ideal), a transmission profile should be taken near the satellite system using a comparable, if not identical transmissometer, and a seston sample should be collected at the reference level for filtering and weighing. The launch-based transmission profiles and seston samples will provide an empirical relation between suspended sediment concentrations and optical transmission, as well as providing data for correcting the in-situ transmissometer readings for fouling.

Table A1. Basic data and derived quantities for the Kenney Sampler evaluations.

Sample	Qd	Qf	Qm	c	w	%sand	%silt	%clay
A1	0.06	8.5	0.78	6.9	0.28	15	45	40
A2	0.13	7.2	0.68	6.4	0.65	11	67	22
A3	0.08	7.7	0.71	6.2	0.47	13	69	18
B1	1.7	21.7	1.5	13.3	4.1	27	36	37
B2	1.3	18.0	1.3	12.4	3.3	31	39	30
B3	1.7	19.3	1.4	12.4	4.4	42	28	30
C2	2.2	23.0	1.9	12.4	5.9	25	38	30
C3	1.4	18.5	1.5	12.4	3.7	24	41	35
D2	0.16	5.8	0.57	6.5	0.87	10	51	39
D3	0.21	6.3	0.53	6.5	1.09	19	51	30

Qd = catch rate of sampler gm day^{-1}

Qf = estimate of horizontal flux into trap (rms speed) gm day^{-1}

Qm = estimate of horizontal flux into trap (mean speed) gm day^{-1}

c = suspended sediment concentration averaged over the trapping interval gm m^{-3}

w = estimate of settling speed m day^{-1}

%sand = percentage (by weight) of sand-sized particles in sample

%silt = percentage (by weight) of silt-sized particles in sample

%clay = percentage (by weight) of clay-sized particles in sample

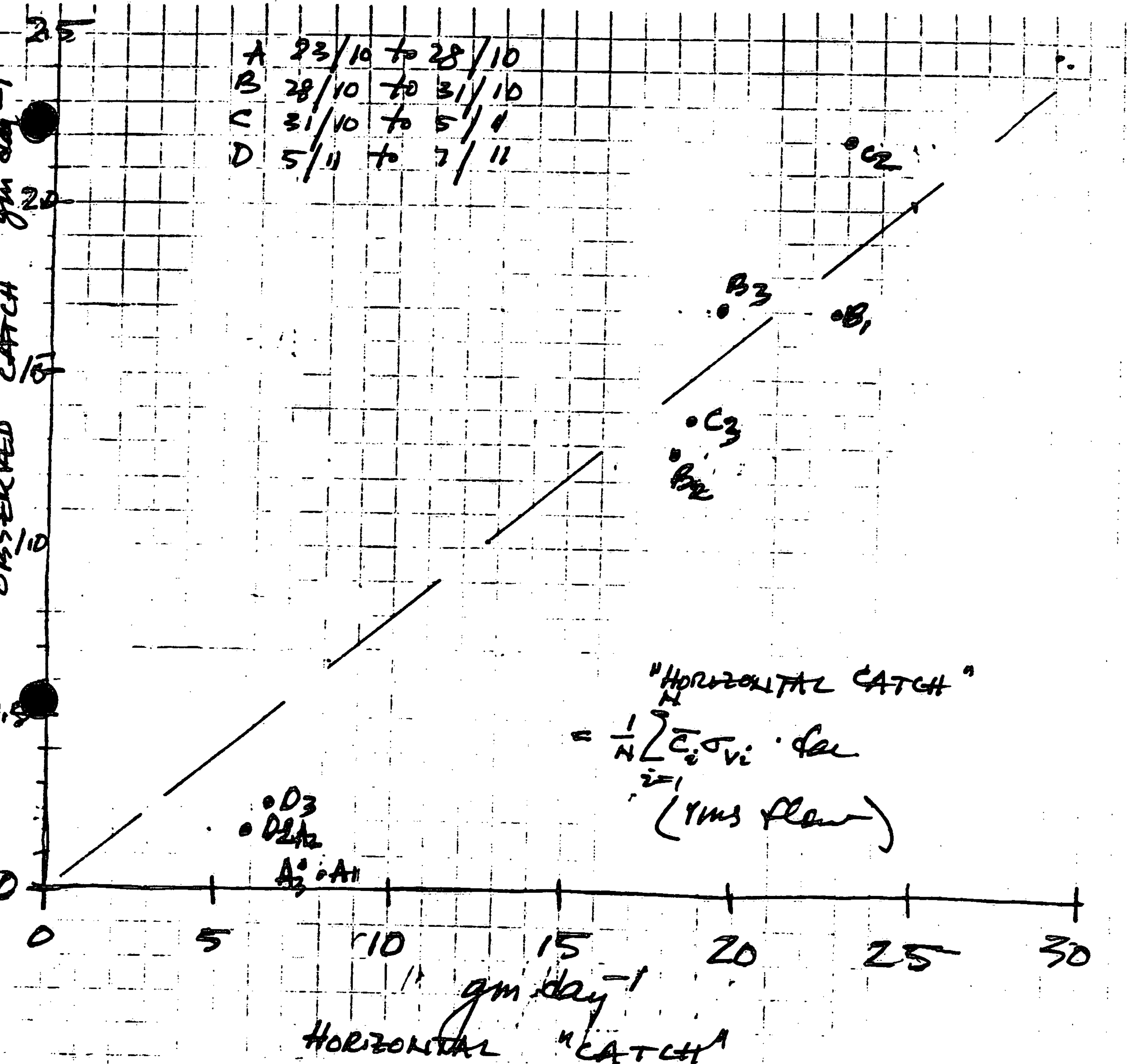

A 23/10 to 28/10
B 28/10 to 31/10
C 31/10 to 5/11
D 5/11 to 7/11
OBSERVED CATCH gm day^{-1}
C2
B3
B1
C3
B2
D3
D2 A2
A3 A1
"HORIZONTAL CATCH" $= \frac{1}{N}\sum_{i=1}^{N} \bar{C}_i \sigma_{vi} \cdot fac$
(rms flow)
0
5
10
15
20
25
30
gm day^{-1}
HORIZONTAL "CATCH"

FIGURE A1

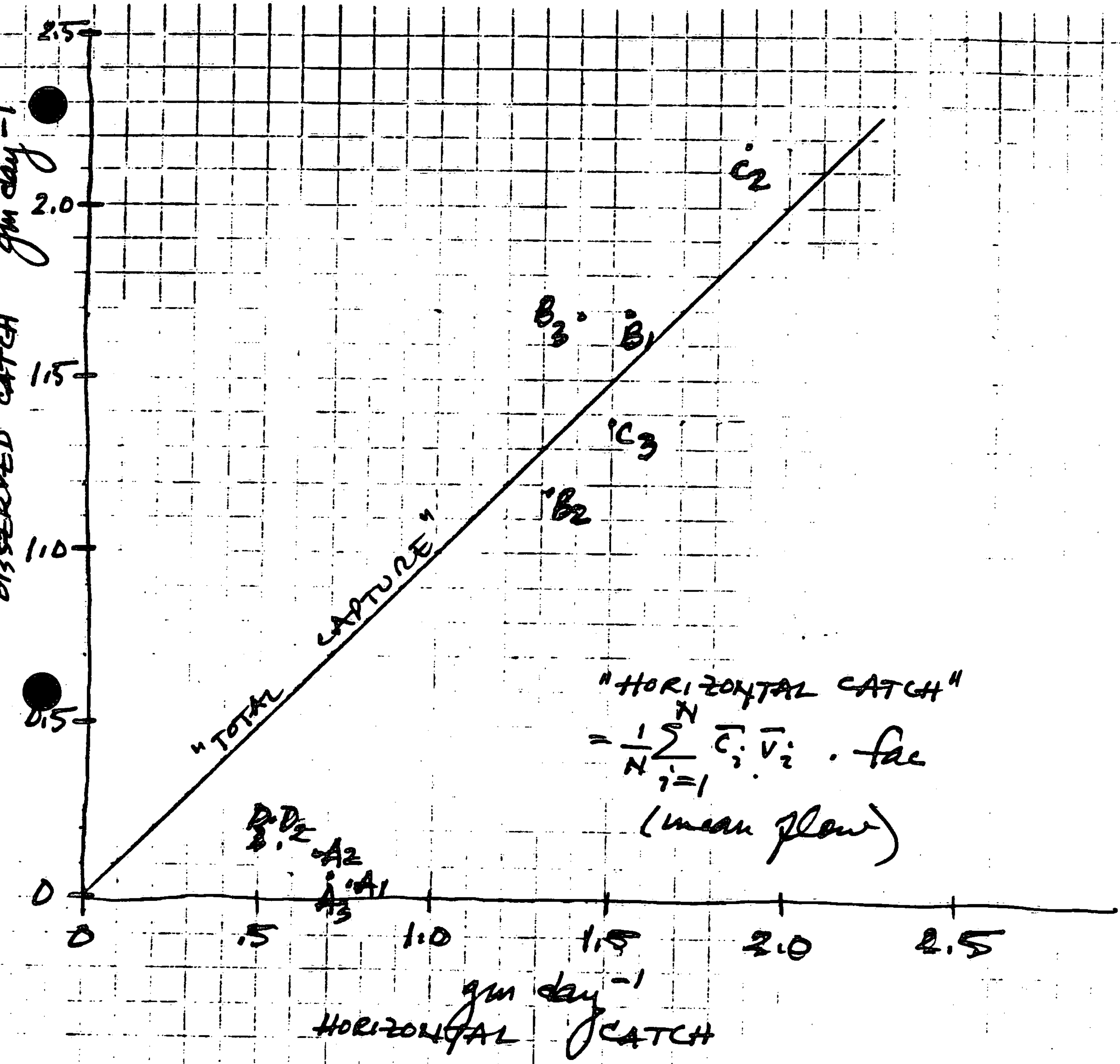
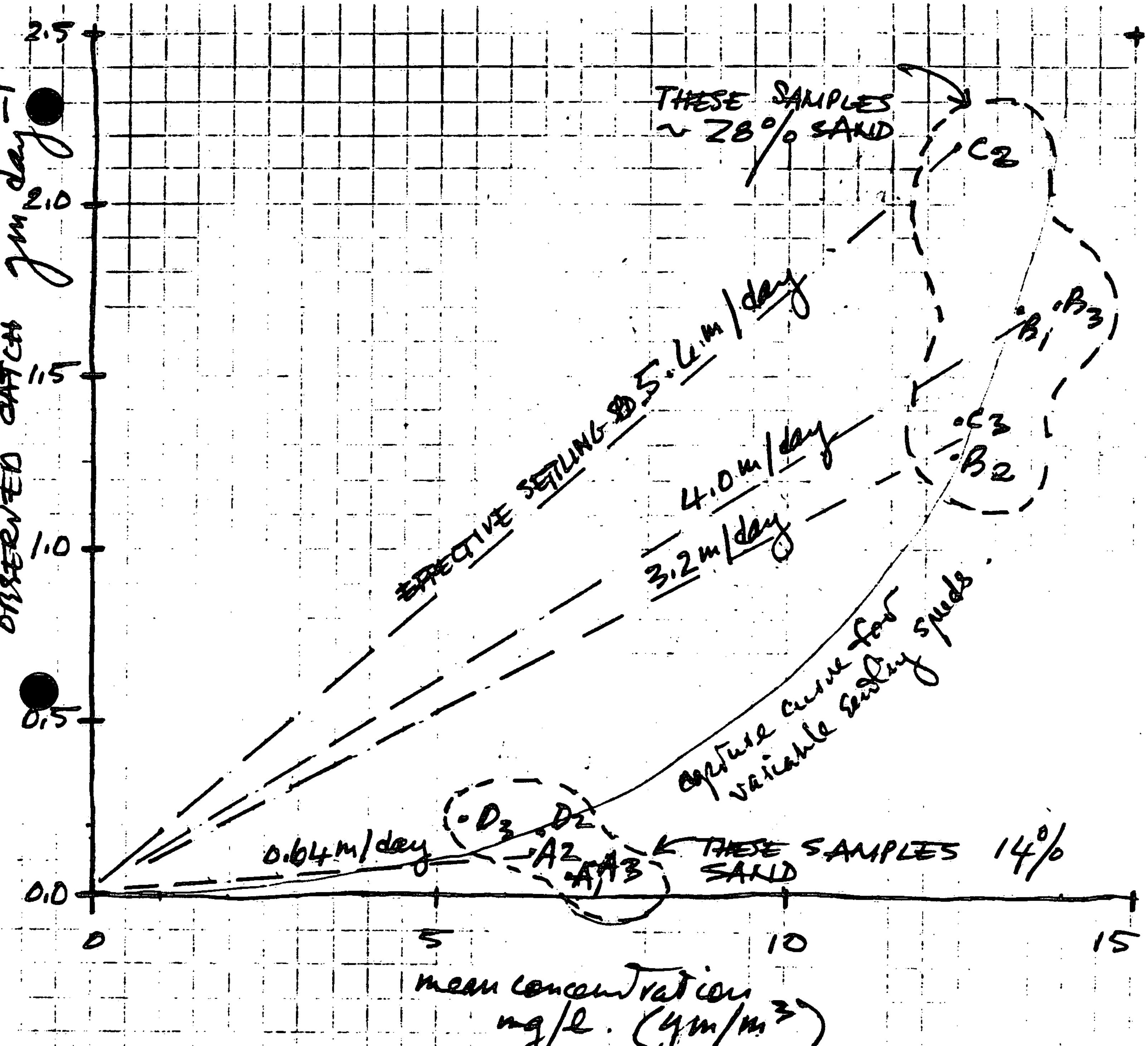
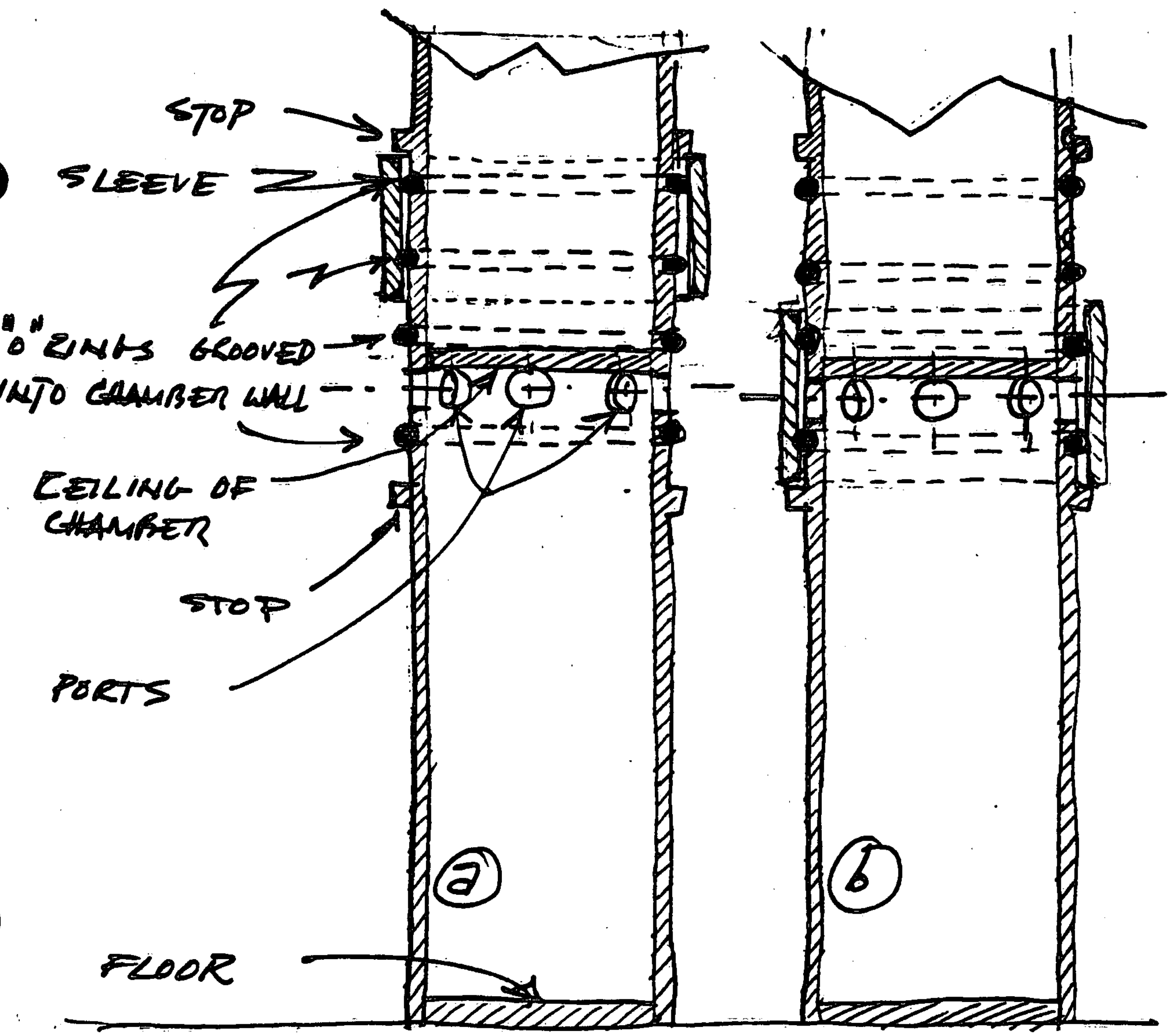

OBSERVED CATCH gm day⁻¹
2.5
2.0
1.5
1.0
0.5
0
"TOTAL CAPTURE"
C2
B3
B1
C3
B2
D1
D2
A2
A1
A3
"HORIZONTAL CATCH"
$= \frac{1}{N}\sum_{i=1}^{N} \bar{C}_i \cdot \bar{V}_i \cdot fac$
(mean flow)
0
.5
1.0
1.5
2.0
2.5
gm day⁻¹
HORIZONTAL CATCH

FIGURE A2



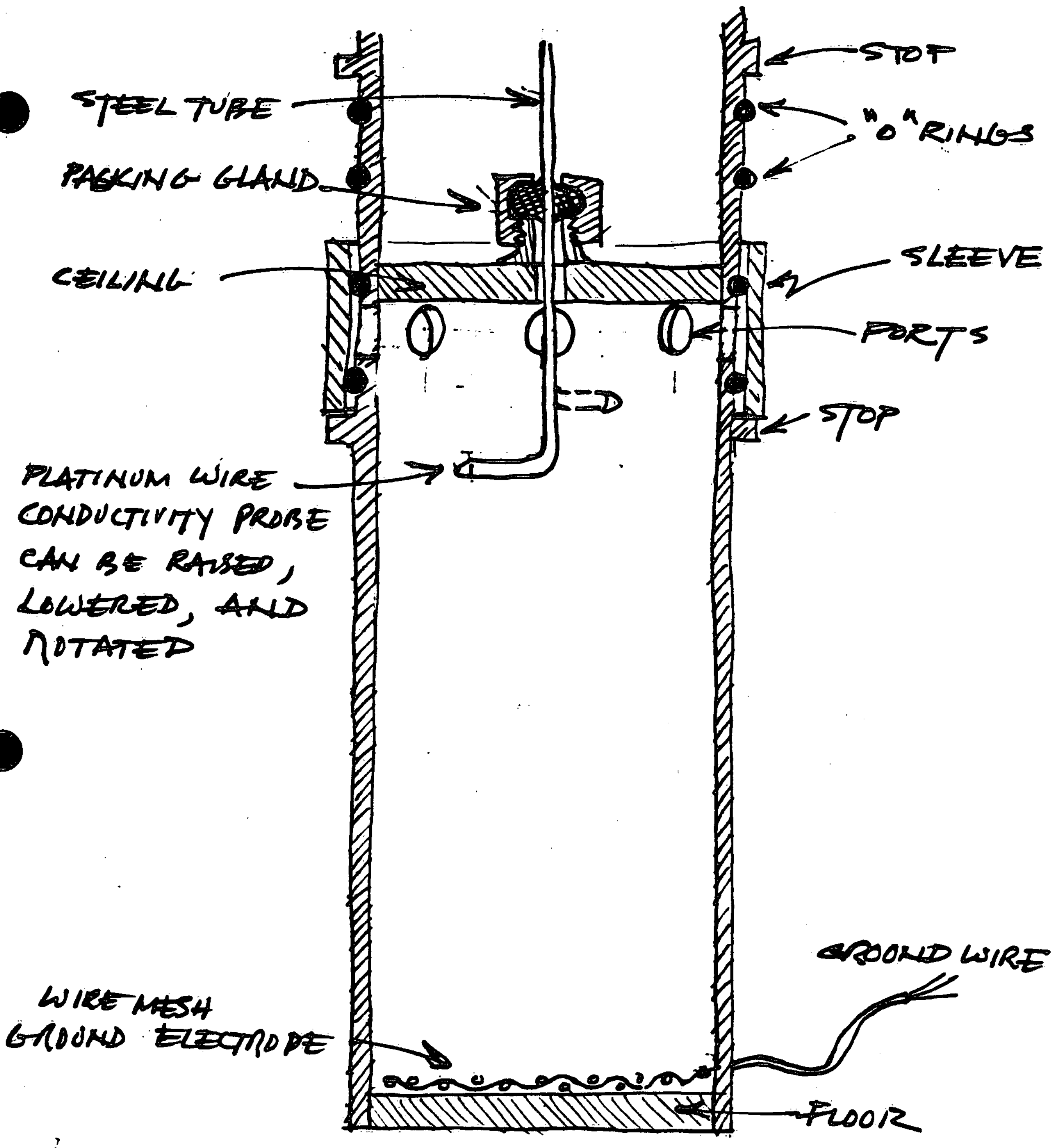
2.5
2.0
1.5
1.0
0.5
0.0
OBSERVED CATCH gm day⁻¹
0
5
10
15
mean concentration
mg/l. (gm/m³)
THESE SAMPLES ~ 28% SAND
C2
B1
B3
C3
B2
EFFECTIVE SETTLING 5.6 m/day
4.0 m/day
3.2 m/day
0.64 m/day
capture curve for variable settling speeds
D3
D2
A2
A1
A3
THESE SAMPLES 14% SAND

FIGURE A3



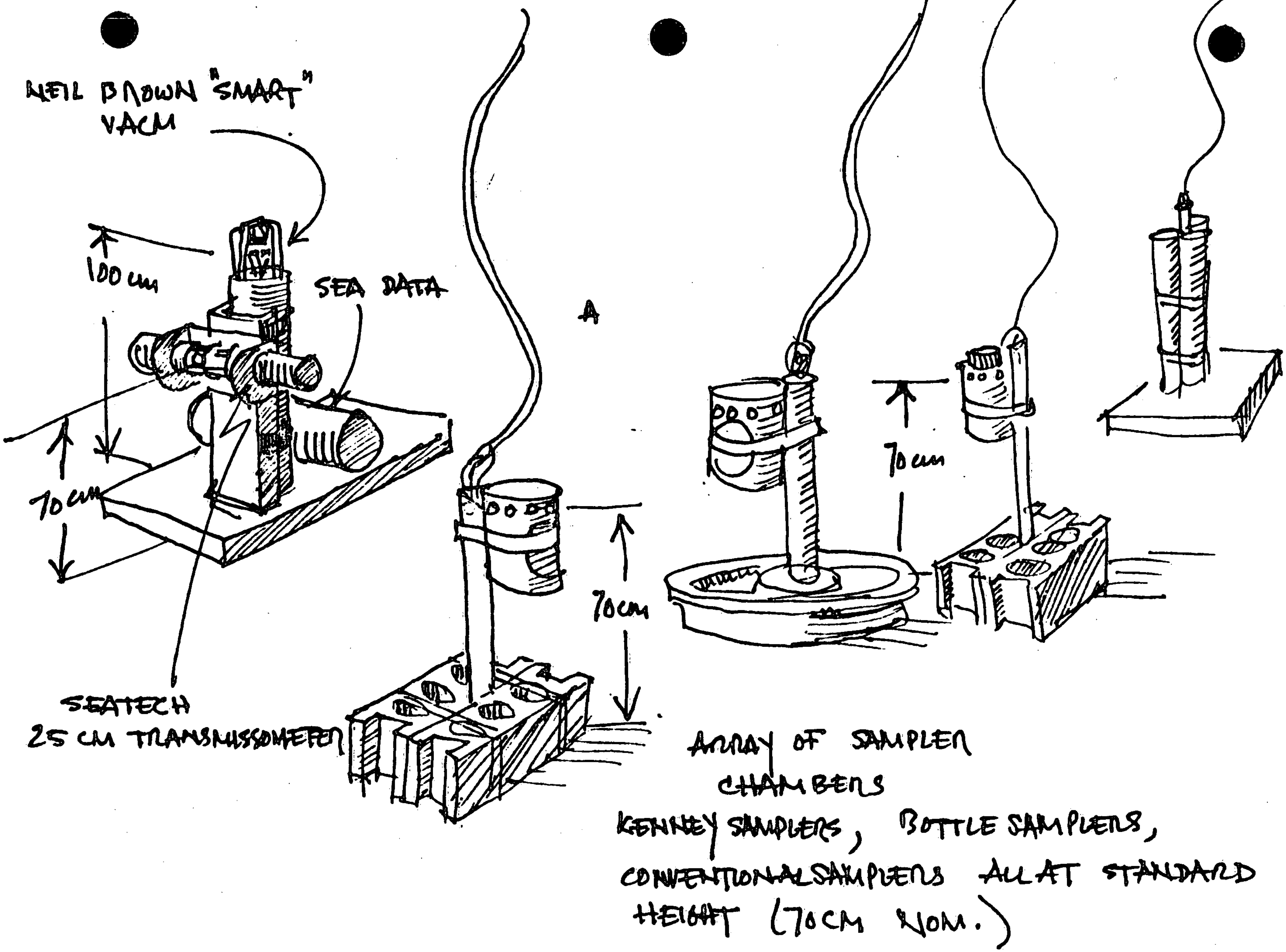
SECTIONAL VIEW OF TRAP WITH SLEEVE
(a) TRAP OPEN (b) TRAP CLOSED

FIGURE A4



TEST TRAP WITH CONDUCTIVITY PROBE FOR FLUSHING EXPT

FIGURE A5



NEIL BROWN "SMART" VACM
100 cm
SEA DATA
70 cm
SEATECH
25 CM TRANSMISSOMETER
A
70cm
70 cm
ARRAY OF SAMPLER CHAMBERS
KENNEY SAMPLERS, BOTTLE SAMPLERS, CONVENTIONAL SAMPLERS ALL AT STANDARD HEIGHT (70CM NOM.)

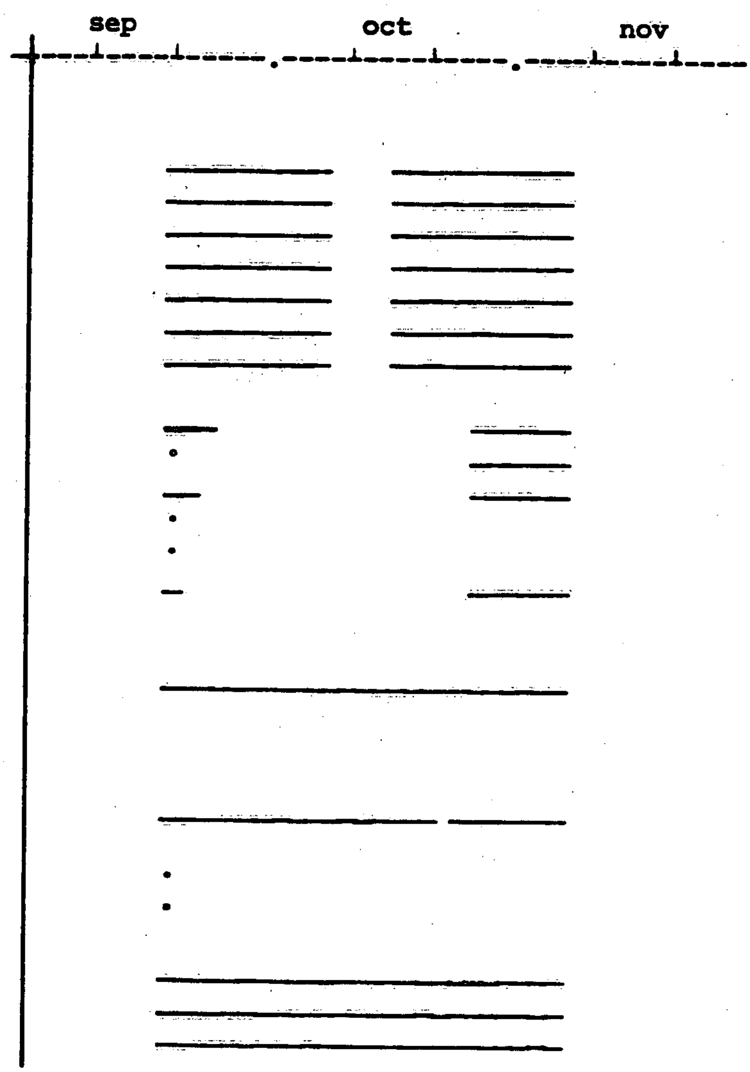
FIGURE A6

APPENDIX B: Summary data catalogue.

LAKE ST. CLAIR 1986

Resume of data return

Mooring Number	sens	depth (cm)
Main Tower (86-04r-06a)	ws	-300
	wd	-300
	tr	550
	tr	552
	tr	598
	tr	598
	tr	643
	cm	188
	cm	283
	cm	427
	cm	542
	cm	542
	cm	625
Kenny Sampler	ss	275 to 617
Satellite data (86-04c-11a)	cm	560
	tr	610
(86-04c-13a)	cm	560
	tr	610
Wave-Tide (86-04r-07a)	wht	250
	tide	250
	temp	250



legend

ws=wind speed
wd=wind direction
tr=transmissometer data
cm=current meter data
wht=wave height
ss=suspended sediment
depths are from the surface