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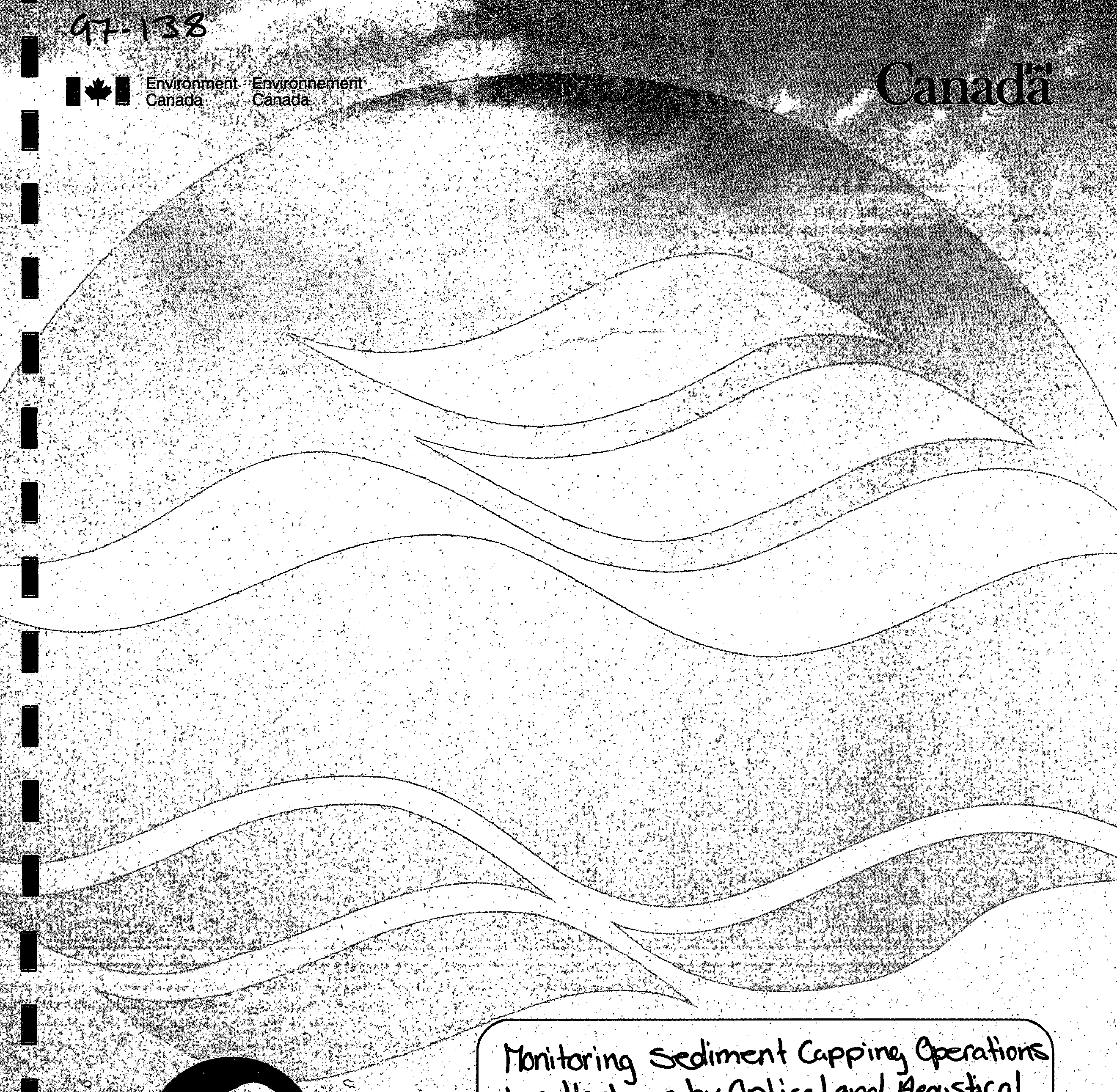

Monitoring Sediment Capping Operations In a Harbour by Optical and Acoustical Methods

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Monitoring Sediment Capping Operations in a Harbour by Optical and Acoustical Methods

by

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97-138

Monitoring sediment capping operations in a harbour by optical and acoustical methods

MANAGEMENT PERSPECTIVE

This work is part of the cleanup of Hamilton Harbour which has been undertaken through the office of the Great Lakes Cleanup Fund. This work was done in order to determine the likelihood of disturbance to in-place contaminated sediments by the sand capping method of sediment remediation. The study was undertaken during the summer of 1995.

This study did not find any evidence of in-place sediment disturbance by the sinking sand jet. Future application of the technology outlined may be to monitor dredging operations of contaminated sediments for potential inadvertent releases. Recommendations for improvement of the monitoring procedures are given.

It is intended to submit this report to a peer reviewed journal for possible publication. The information discussed in this report has been presented at the Great lakes Conference in Buffalo, NY, in June 1997.

Surveillance des opérations de recouvrement des sédiments dans un port par des méthodes optiques et acoustiques

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les présents travaux s'inscrivent dans le cadre de l'assainissement du port de Hamilton entrepris par le bureau du Fonds d'assainissement des Grands Lacs. Ils visaient à déterminer la probabilité de perturbation des sédiments contaminés présents sur place par la méthode d'assainissement qui consiste à les recouvrir de sable. L'étude a commencé au cours de l'été 1995.

L'étude n'a révélé aucun signe de perturbation des sédiments en place par enfoncement du jet de sable. L'application future de la technique décrite pourrait consister à surveiller les opérations de dragage des sédiments contaminés en vue de déceler les libérations accidentelles potentielles. Des recommandations visant l'amélioration des méthodes de surveillance ont été formulées.

On prévoit présenter le rapport à une revue à comité de lecture en vue de sa publication. Les renseignements contenus dans ce rapport ont été présentés à la conférence des Grands Lacs, tenue à Buffalo (N.Y.), en juin 1997.

ABSTRACT

Capping of contaminated bottom sediments is one strategy for immobilizing contaminants. In a pilot-scale project a 0.5 m thick cap of clean sand was deposited over a 100 m^2 area in Hamilton Harbour. The objective of our study was to determine if in-place sediments could be disturbed by the capping operation. In the first of three approaches we monitored the suspended sediment plumes created during the capping operation for evidence of suspension of bottom materials with underway acoustic and optical profilers and other moored instruments. In-lake calibration of the instrumentation is based on the collection of over 300 grab samples. Three-dimensional rendering of a dense network of acoustic backscatter profiles revealed that there was not evidence that bottom sediment was resuspended. We examined the densimetric current flowing downslope close to the bottom caused by the capping material and found that it was too weak to erode bottom sediments. Finally, a quantitative estimation of the amount of sediment suspended in the plumes indicated little evidence for resuspension of in-place sediments. The methodology developed could also be applied to estimate the concentration and quantities of contaminants in sediment suspended by other remedial activities such as dredging.

RÉSUMÉ

Le recouvrement des sédiments de fond contaminés est une stratégie d'immobilisation des contaminants. Dans le cadre d'un projet-pilote, on a déposé une couche de 0,5 m d'épaisseur de sable propre sur une superficie de 100 m^2 dans le port de Hamilton. Il s'agissait de déterminer si l'opération de recouvrement pouvait perturber les sédiments en place. Dans la première des trois approches utilisées, au moyen de profileurs acoustiques et optiques remorqués et d'autres instruments mouillés, nous avons surveillé les panaches de sédiments contaminés formés pendant le recouvrement afin de déceler des signes de mise en suspension des sédiments de fond. L'étalonnage des instruments dans les eaux du lac est fondé sur le prélèvement de plus de 200 échantillons pris au hasard. Le traitement tridimensionnel d'un réseau dense de profils acoustiques rétrodiffusés n'a révélé aucun signe de remise en suspension des sédiments de fond. Nous avons examiné le courant densimétrique descendant près du fond causé par le matériau de recouvrement et constaté qu'il était trop faible pour éroder les sédiments de fond. Finalement, d'après une estimation quantitative, une remise en suspension des sédiments présents ne semble guère probable. La méthode élaborée pourrait également servir à estimer la concentration des contaminants et leur quantité dans les sédiments mis en suspension par d'autres activités d'assainissement comme le dragage.

1. Introduction

Capping of contaminated sediments by sand offers a cost-effective and environmentally sound alternative to dredging and land disposal. Hamilton Harbour has been identified as a water body having substantial areas of bottom sediments with concentrations of deleterious compounds in excess of the severe effects level of sediment quality standards of the Ontario Ministry of Environment and Energy. Toxic substances remaining in the bottom sediments include such metals as lead and zinc and persistent organic compounds such as PAHs and PCBs. An experiment was conducted in Hamilton Harbour during the summer of 1995 at a 100 by 100m (1HA) test site to evaluate the effectiveness of sand capping as a remedial measure.

A concern in the capping of sediments is that contaminants may be released from in-place sediments by disturbances arising from the process of the remedial operation. As a means of monitoring possible release of contaminated sediment into the environment random water sampling around potentially affected zones is slow and has limited spatial resolution. What is needed is some method of rapidly identifying the presence of suspended material around the affected site so that grab samples can be focused on the locations of maximum concentration.

In this study various methods of monitoring suspended sediment are developed and evaluated. Furthermore, in the event that dredging is used to remediate acutely toxic sediments in the Harbour it would be desirable to monitor and quantify the inadvertent release of highly contaminated sediment. Thus, the goal of the present study is to develop not only an effective means of detecting suspended sediment plumes but also to quantify the amount of contaminant released to the environment.

Methods of sediment monitoring may be classified into those associated with moored or unattended instrumentation and into those with attended instrumentation taken underway aboard a motor launch. We first briefly describe the capping project in general, then summarize the main results of a pilot study intended to test the feasibility of the attended optical and acoustical instruments. Next, the data taken underway in the present study are calibrated from suspended sediment samples taken in the field in the sediment plume. The crucial question of whether contaminated sediments can be resuspended by the capping operation is examined in a number of ways. First, the three-dimensional configuration of the sediment plumes is examined for evidence of resuspension. Next, quantitative estimates of the total mass of sediment suspended in the plume arising from the introduction of sand are compared to the quantities expected from the rate of capping to see if additional material is present. For the third method, we examine the strength of near-bottom currents to see if flows induced by the falling sand are sufficient to erode bottom material. Finally, observations from instrumentation moored in the vicinity of the capping site are examined for possible resuspension of the newly deposited sand cap.

2. Sand Capping Description

Figure 1 shows the location of the capping site at a distance of one-half a kilometre from the north shoreline of Hamilton Harbour. This location was carefully selected to be in sufficiently deep water that orbital motions at the bed due to surface waves should be too low to disturb the newly deposited cap but not too close to the southern shoreline where the propeller wash and anchoring activities associated with freighters could be a problem. Shown in more detail in Figure 2 is the bathymetry in the vicinity of the capping site and the locations of additional moored instrumentation. Notable is that the bottom slopes gradually downwards in the southeast direction by about 5m over the area and that the minimum depth is below the thermocline depth of about 10m as indicated in the plot of the history of the thermal structure shown in Figure 3 until September when the upper layer deepens and thermal structure disappears over the capping site.

A continuous supply of sand was introduced to the water column at a depth of approximately 11m depending on the sand load in the barge by a bank of tremie tubes which, in turn, were filled by a front-end loader from the sand stored on the barge as shown schematically in Figure 4. The design depth of the sand cap was 0.5m but subsequent compaction reduced the thickness to 0.35m (7and Patterson, 1996) The rate of supply was nominally 40 tonnes per hour and the capacity of the barge was sufficient for ten hours operation. Figure 4b also shows the arrangement for positioning the tremie tubes. Briefly, the supply barge is winched along an east-west oriented cable at a rate of 1m/min. When the barge reaches either end, the guide cable is repositioned one metre to north and a new swath of sand is deposited. Care was taken to position the corner anchors and moored instruments so that they did not interfere with the sediment cap. In total, the test location was covered with 6600 tonnes of fine sand. The sand capping commenced on a routine basis at the outer edge of the capping site on August 4 and continued weather permitting in ever decreasing water depths until completion on September 20, 1995.

A motor launch equipped with an acoustic doppler current profiler (ADCP) of RDI manufacture, an electronic navigation system of the differential GPS type, a temperature/turbidity profiler of Hydrolabs manufacture and a water sampler made traverses of the capping area during sediment deposition (Figure 4). The ADCP permitted sediment concentrations to be continuously monitored while the boat was underway. When the sediment plume was detected on the screen of an onboard computer displaying backscatter profiles, the launch was stopped and profiles of optical turbidity and grab samples at selected depths were taken. This system of underway monitoring was developed from experience gained during a brief pilot study conducted during the previous field season to be outlined shortly.

The capping took place from July 31 to September 20, 1995 depending on the weather conditions. Capping was monitored on nearly all occasions. Approximately two dozen episodes were selected for detailed analysis to be described below. In a preliminary report (Charlton et al., 1997) the measurements of particulate concentrations near the capping site are documented.

3. Pilot Study

For the pilot study the instruments chosen for the monitoring of the capping operation were a 600 Khz broad band ADCP and a 1.2Mhz narrow band ADCP. While these devices were developed primarily for current measurement they do provide a measure of the backscatter intensity of the acoustical energy. To test their feasibility for the detection of suspended material 100kg of fine sand was mixed to a slurry and rapidly pumped into the surface water at the proposed capping site in December, 1994. It is evident from the size fractions presented in Figure 5 that the introduced material is composed mainly of fine sand (phi=3) and coarse silt (phi=4-6). Next, a survey launch equipped with an ADCP and an electronic navigation system (GPS) criss-crossed the area as depicted in Figure 4 for approximately one hour until the sediment plume had settled out. In order to demonstrate the sinking of the slurry the period is segmented into three episodes. The ship track for each portion is shown in Figure 6 along with some associated examples of concurrent backscatter intensity with depth and distance along the track. Each individual backscatter profile (not shown) represents an average of a large number of individual pings averaged over 5s or approximately 10m of horizontal excursion at the usual speed of the boat. The contours of backscatter intensity in Figure 6 suggest a rapid sinking and dispersion of the introduced material based on an assumed relation between sediment concentration and backscatter intensity. Fine sand falling at a nominal rate of 0.3mm/s would reach the bottom in somewhat more than an hour's time. From a comparison of similar transects across the sediment plume with both models of the ADCP it was apparent that the 1.2Mhz narrow band model yielded stronger backscatter returns than the lower frequency model. Although the pilot experiment demonstrates that sand in suspension is detectable acoustically the question of the quantitative calibration remains to be resolved.

For this reason a number of grab samples were collected in the sediment plume and filtered for the total sediment concentration as well as the organic and inorganic components of each sample Scatter plots of the backscatter intensity of each sample against its concentration suggest in Figure 7 a relation between scatter and concentration. However, it is considered that there is too much scatter to attempt to fit a regression equation. Of the three plots in Figure 7 the inorganic component of the sediment sample gives the closest agreement visually. An interpretation of this plot (7c) is that there is a background level of backscatter from 75 to 80db and a response which is roughly three times the difference between the backscatter intensity and background.

4. Calibration

Clearly, if the monitoring method is to provide quantitative estimates sediment concentrations and mass, a more precise means of relating acoustical backscatter to sediment concentration than in the pilot study must be found. Based on the results of the pilot study grab samples in the present study were taken over the side of the survey vessel by means of a mechanically operated bottle sampler when the onboard computer screen monitoring acoustic backscatter indicated the presence of a turbidity plume. A one litre subsample was filtered aboard the boat through a preweighed glass fiber filter which was subsequently returned to the laboratory for final determination of the sediment concentration (referred to as " seston") and its inorganic and organic fractions.

First, the profiler's turbidity sensor was calibrated. For the present set of monitoring experiments the total seston was plotted as a function of the turbidity at the depth closest to the seston sample depth. This comparison of data shown in Figure 8 demonstrates a similarly poor correspondence with a scatter of values of comparable magnitude to the scatter of the pilot study (Figure 7). After manipulating the data it was discovered that the scatter could be reduced by consideration of only the inorganic fraction of the seston and by eliminating grab samples with depths less than 10m. This is justified on the basis of the contribution to turbidity from high levels of suspended organic material found in the epilimnion. Furthermore, a background value of turbidity which was thought to be due to dissolved rather than suspended material was subtracted from the turbidity observations. When the data of Figure 8 are replotted in Figure 9 with the above modifications, the scatter is much reduced and supports a regression analysis yielding a reasonable coefficient of variation (r^2) of 0.83.

The next calibration step was to plot continuous profiles of suspended sediment concentration along with concurrent acoustic backscatter profiles. The calibration of backscatter was made more difficult than the turbidity profiler by the necessity of employing two ADCPs both having an acoustic frequency of 1.2MHz but based on differing operating principles, a broad band and narrow band type. While the vertical resolution of the broad band profiler is user selectable within the range from 0.25 to 2m, the narrow band is fixed at 1m. We first used a broad band ADCP but instrument availability for the second half of the monitoring dictated the use of the same narrow band device as in the pilot study. However, it was found that both versions could be calibrated similarly. First, a background intensity representing the response when no introduced material is in suspension is subtracted from the observed intensity and then the result is scaled by a gain of 5 mg/l/ db where db (decibel) is the unit of backscatter intensity. The gain of 5mg/l/db was obtained from visual inspection of the agreement between the acoustically and optically derived profiles. Profiles of suspended sediment concentration based on this calibration are compared to those obtained from the turbidity profiler and direct seston samples in Figure 10 for both types of ADCPs. It should be borne in mind that only depths below 11m are important as the capping material is not expected to occur at shallower depths. It may be noted in Figure 10a that the turbidity profile does not peak but continues to increase with depth unlike the acoustic backscatter profile. In other examples the acoustic profiles did not peak as is evident for those shown in Figure 14. These differences are likely due to slightly differing water masses that each method sampled, despite efforts made to co-ordinate the samples.

The sampling problems noted above suggest that improvements in the in situ calibration of both the optical and acoustic instruments should be made before future application of the monitoring method. In particular, a seston sampler that could be triggered from a command from the surface and mounted directly on the optical profiler would reduce the temporal and spatial uncertainty of the seston sample with respect to the plume and acoustic beams. Secondly, a logger that records both the acoustic and optical data in the same time base would greatly facilitate the co-ordination.

5. Sediment Plume Configuration

Were the erosion of bottom material to occur due to the force of the sinking plume of sand, it is expected that the shape of a sediment plume originating from the eroded material would be similar to an inverted mushroom with the cap being an indication of the material eroded at the bed. In order to examine the form of the sediment plume surfaces of constant sediment concentration were plotted in three dimensions for all experiments. Briefly, the analysis is summarized as follows. First, the raw backscatter profiles were corrected for beam spreading and acoustic attenuation which is a function of frequency and water temperature (Urick, 1967). The region sampled is subdivided into a three-dimensional array of up to 5000 cells and all samples falling into an individual cell are averaged. The corrected backscatter intensity is much higher in the upper layer or epilimnion than it is in the lower layer or hypolimnion which is considered to be due to the higher concentrations of organic material found in the epilimnion. In the lower layer the background intensity is relatively uniform except where it impinges on the bottom. In this case reflected acoustical energy overwhelms the backscattered energy. For this reason, in all analyses, care has been taken to disregard the acoustic returns from the two intervals next to the bed. Data from cells containing valid averaged data are interpolated and extrapolated to empty cells. Next, backscatter readings were converted to concentrations. Finally, visualization software was employed to display perpective views of the concentration surfaces defining the plume.

An example of typical ship track similar to those shown in Figure 6a is seen in Figure 11 for the case of August 16, 1995 to be composed mainly of east-west traverses as the guide cable constrains the trajectory of the boat. In Figure 12 an example of the concentration iso-surfaces for four values of concentration for the same case are compared for the identical plume and viewing angle. In this perspective view and that of the following figure the viewer is located near the water surface looking downwards into the water column in a shoreward direction. It is apparent that the plume has the shape of a cone with a vertex located at the end of the tremie tube. The plume appears to be elongated in the direction of travel of the sand supply barge. In this example as well as the other cases examined there is little evidence of resuspension of bottom material. This is supported in Figure 13 where three additional samples of mapping of the sediment plume demonstrate similar shapes. Over the capping period a number of control surveys were made when no capping took place as shown in Figure 13 for the July 26 case. As expected no plume is evident. The remaining panels in this figure display the same value of the concentration surface but with varying vertical resolution of the acoustic profilers over the experimental period. As might be expected there is a general elongation of the plume along the direction of the barge track. All cases show some evidence of subsidence of the plume into deeper water as well as a small deflection of the centre of mass of the plume in the downstream direction in the bottom current flow. Current vectors which are also measured by the ADCP are not shown in Figures 12 and 13 for the sake of simplicity. Figure 13 demonstrates the obvious superiority of the broad band over narrow band in monitoring sediment plumes as the broad band has a higher and more flexible resolution.

6. Suspended Sediment Mass

In this section computations of the total mass of the sediment suspended in the plume are outlined. To apply the above calibration procedure it is first necessary to determine the background value of the backscatter intensity. One method is to display profiles of backscatter as presented in the example of Figure 14 and estimate the background value below 11m. The staggered profiles clearly show several traverses of the sediment plume at profiles 133 to 138 and 181 to 188. Another is to contour the intensity at depths below 11m and choose the contour which best represents the background. For example, in the plot of Figure 14 an appropriate hypolimnetic background is 72db. Once the background is specified for a monitoring survey the concentration is estimated and integrated from the bottom minus two intervals up to 11m, the depth of the tremie opening. Finally, areal integration of the mass per unit area distribution as shown in Figure 15 provides an estimate of the total material suspended in sediment plume.

The results for the application of the procedures described above to nine cases of sediment monitoring and to four cases when no sediment was added are listed in Table I. Such ancilliary data as the duration of the monitoring episode, the background intensity assumed and the average current speed at the level of the end of the tremie tube and the amount of silt added during the sampling period are also provided in Table I.
For a summary of the estimates of the total mass in the turbidity plume for the nine capping cases see Figure 16. Despite the scatter in mass with distance to the bed it is apparent that there is trend to less mass as the bed is approached. This is reasonable as the receiving volume is less and the time required for the particles to settle to the bottom is less as the depth decreases. On average about 900kg of silt are measured in suspension. In the seston samples we did not observe sand grains unless samples were taken immediately beside the tremie tubes. The amount of material would be about one third the silt released over the average duration of our coverage based on a reported silt fraction of eight per cent. Thus, there is little indication of additional material being scoured from the bottom during capping. Because of the higher resolution the 0.25 cases are judged to have less error than the 1.0m cases observed with the narrow band profiler. On account of the poorer resolution of this device it could not be employed effectively once the receiving depth was less than 3m. As a result no useful data were logged during the September period. Even with the better resolution there is considerable variability from one day to the next.

7. Induced Bottom Current

The question arises of possible erosion of bottom material due to scouring of the bottom by a localized turbidity current induced by the heavier layer of introduced material. Turbidity currents are known to be caused by the downslope flow of suspended sediments on slopes as low as several degrees (Akiyama and Stefan, 1985). While it is unlikely that the low bottom slope of 3° in the capping area is sufficiently steep to generate strongly erosive turbidity currents it is nontheless instructive to examine observations of current for their possible existence. Zeman (1995) has estimated that nearbed flows of 20cm/s would be necessary to initiate resupension of bottom material.

Up to this point the current measuring capability of the ADCP has not been exploited. Unlike sediment concentration, flow calibrations are factory supplied. Despite the low bottom slope across the experimental site there is enough variation of the flow with height above the bed that current on a level surface will be strongly influenced by the vertical current structure. For this reason current and suspended sediments have been plotted with reference to a height of one metre above the bottom in the example shown in Figure 17. Weak flow with a general tendency parallel to the bottom contours and in a southwest direction is seen in Figure 17. No evidence of offshore flow or elongation of the sediment plume is evident in the offshore direction that would be expected if the capping material were to trigger a density current. This case of August 23 was one of the largest bottom flows encountered. In all cases, measured flows near the bottom were substantially less than the threshold speed required for erosion.

In contrast to the situation with the detection of suspended sediment plumes the narrow band ADCP proved to be superior to the broad band for measurement of flow in the hypolimnion. Broad band flows were random whereas narrow band flows were more organized. Vertically averaging of as many as seven levels of broad band data did not appear to remove the noisy appearance of the horizontal flow vectors. Since we chose a maximum vertical resolution of 0.25m for the broad band profiler less acoustic energy is imparted to the water column than in the 1m vertical resolution narrow band. Thus, a decrease in the range of current detection for the broad band device is not unreasonable.

8. Unattended Monitoring

A possible disadvantage of the attended method of monitoring described so far is its expense. In cases where the potential for disturbance of bottom material exists and it is not necessary to undertake immediate emergency cleanup, unattended monitoring offers a cost effective alternative. Four bottom mounted supports at the locations shown in Figure 2 and as close to the capping site as logistics permitted a self-recording optical backscatter sensor (DNA Instruments) and two optical transmissometers of Seatech manufacture and of path lengths of 10 and 25cm. Data were recorded at one metre above the bottom at 10-min intervals. From previous experience light extinction in units of m^{-1} was converted to suspended sediment concentration in mg/l by a gain factor of 1.6 and an offset of -1.25 concentration units. Regrettably, the two offshore moorings, numbers 67 and 68 were either upset in the deployment or sank into the soft bottom sediments and failed to yield usable data.

Fortunately, data were successfully obtained at the two inshore stations. Optical backscatter appeared to be saturated for much of the period, likely due to immersion in a thin layer of highly concentrated material close to the bottom. At both moorings the two transmissometers demonstrated nearly identical responses with the 25cm path length being slightly more sensitive and station 65 having higher concentrations than mooring 64. All records contained spikes of high concentration which nearly always coincided with capping activities as seen in Figure 18. Spikes occurred at both stations during a capping period but not necessarily at the same time. There is only one major spike which is not associated with capping at station 65 on September 17, thus indicating that occasionally some other mechanism besides capping is responsible for elevated sediment concentrations.

9. Discussion and Recommendations

We have assembled a suite of moored and attended instrumentation which we assert is capable of remotely detecting sediments in suspension due to a capping operation. The rapid sampling of the acoustic profiler followed by a direct readout of optical turbidity has allowed us to collect water samples at the location of maximum concentration thus conserving our sampling effort. When the plume is small, however, we found that it is still difficult to locate the maximum concentration. In such cases improvements could be made by co-ordination of acoustic and optical profiling by displaying both types of data on the same computer screen concurrently. Furthermore, a grab sampler mounted beside the turbidity sensor that could be triggered from a command from the surface instrument operator would permit more precise water sampling. While the broad band ADCP is the instrument of choice for monitoring suspended sediment plumes, especially the higher of the two frequencies examined, it appeared to lack the range of the narrow band in the measurement of flow.

In the evaluation of the monitoring methodology attention has been focused on sand capping. Three approaches to the question of the disturbance to the contaminated sediment by the capping operation have indirectly supported the conclusion that there is no measurable disturbance. We advocate the use of such monitoring during sediment remediation in general and, in particular, attended monitoring during the dredging of severely contaminated sediments in harbours. As it is likely that there is a quantifiable relation between the suspended sediment concentration and the concentration of deleterious compounds in the sediment it should be possible to estimate the mass of noxious material that may be released into the environment should an accidental spill occur during the cleanup operation. As flow is also recorded the transport of material could be estimated as well.

Acknowledgments

The assistance of F.M.Boyce in conducting the pilot study and the efforts in the field of R. Rowsell and J. Gabriel are greatly appreciated. This report was sponsored by the Great Lakes 2000 Cleanup Fund and addresses sediment quality issues in Hamilton Harbour Area of Concern in Hamilton, Ontario. Although the report was subject to technical review, it does not necessarily reflect the views of the Cleanup Fund of Environment Canada.

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List of Figure Captions

1. Study location in Hamilton and the location of meteorological and water temperature stations. Inset shows location in the Great Lakes region.
2. Bathymetry in metre near the capping site and location the moored optical instrumentation.
3. Isotherm depth history nearby the capping site during the capping period. Tics on right axis represent the measurement depths.
4. (a) Schematic sectional view of the survey vessel and underway acoustical monitoring system, tremie tubes, sand supply barge and sand cap. (b) same as (a) but plan view.
5. Particle size analysis of (a) pilot study and (b) present study. Phi is the negative logarithm to the base two of particle diameter in mm.
6. Pilot study survey data for three periods: (left) 17:00-17:10, (centre) 17:25-17:39 (right) 17:44-18:03, December 12, 1994; (a) track of survey boat during the pilot experiment; (b) acoustic backscatter intensity in decibel (db) from the 1.2 Mhz narrow band ADCP over depth and horizontal distance.
7. Suspended sediment concentration of seston samples versus backscatter intensity for (a) total seston, (b) organic fraction and © inorganic for the pilot experiment for the1.2Mhz narrow band ADCP.
8. Seston concentration versus optical turbidity ratio for all samples of present experiment.
9. Optical turbidity ratio minus background value versus the inorganic fraction of seston of all samples below 10m depth and regression line.
10. Profiles of suspended sediment concentration based on seston samples, optical turbidity and acoustic backscatter for (a) the broad band (Cbb) on August 11 and (b) the narrow band (Cnb)ADCP on August 22. Ctub and Ctr refer to the concentration as determined from the turbidity meter. Tot is the total seston concentration while inorg is the inorganic portion.
11. Ship track (triangles) and barge positions from 14:50 to 15:24 UCT August 16, 1995. Barge positions during the survey period are indicated by a solid line in a east-west direction in the centre of the capping area. Horizontal positions (easting and northing) are relative.
12. Same as Figure 11 but perspective view in a northwest direction of surfaces of constant suspended sediment concentration for four vales of concentration. The bottom depth in metres is indicated by a gray scale between 19.22 and 11.81m. Vertical resolution indicated by the horizontal lines is 0.25m.
13. Same as Figure 12 but for a value of sediment concentration of 30mg/l. July 26 is for no capping, August 4 for broad band ADCP with vertical resolution of 0.5m, August 9 with 0.25m and August 23, narrow band with vertical resolution of 1.0m. Note varying depth ranges.
14. Staggered broad-band profiles of acoustic backscatter intensity for August 9. Each profile is offset by 10db.
15. Vertically integrated sediment mass per unit area for the case of Figure 14. The origin is a relative position. Contour units are kg/m^2.
16. Computed mass of sediment in plumes for two resolutions of broadband ADCP, 0.25 and 0.5m and narrow band of resolution of 1.0m as a function of distance of the tremie to the bottom for nine cases during the experiment.
17. Plan view of currents and suspended sediment concentrations at one metre above the bed for August 23, 16:53 to 17:53. Two current reference arrows are 5cm/s Concentration contours range from 0. mg/l to 50mg/l in the centre of the plume.
18. History of near bottom sediment concentration as determined from a recording transmissometer of path-length of 25cm. Sediment capping times are indicated by solid dashes, (a) at mooring 64; (b) at mooring 65.

Date (1995)	Survey Time (UCT)	Capping Times (UCT)	ADCP Resolution(m)	Background Intensity (db)	Current Speed (cm/s)	Direction	Distance of Tremie to Bottom (m)	Capping Mass Added (KGx1000) over Survey	Estimated Mass(KG x1000) in Suspension
July 26	13:00-14:25	-	0.5	72			no capping	0.	0
Aug. 4	13:29-14:47	12:40-19:30	.5	72	5	as sw	6.	4.6	1.5
Aug. 4	16:47-17:14	“	.5	72	5	as ne	6.3	1.4	1.5
Aug. 9	16:54-17:43	12:45-21:03	.25	69	8	as ne	5.8	2.6	.5
Aug9	18:11-18:51	“	.25	69	8	as ne	5.5	2.1	1.2
Aug. 10	18:11-19:19	-	.25	69			no capping	0.	0
Aug 16	14:51-15:25	14:51-15:25	.25	69	5	as sw	6.2	1.8	.5
Aug. 17	16:48-18:09		.25	69			no capping	0.	0
Aug. 22	15:59-16:48	12:33-22:03	1	70	4	as ne	4	2.6	.21
Aug 22	17:59-18:54	“	1	70	5		3.5	3.0	.23
Aug 23	13:36-14:23	12:32-22:34	1	70	4	ons	4.2	2.5	1.0
Aug. 23	16:54-17:54	“	1	70	6	as sw	3.0	3.2	.9
Sept. 14	13:15-14:41		1	78			no capping		0
Average of capping cases									.83

Table I: Various data used in the estimation of mass in the sediment plumes and verification of the estimates. Current directions are either alongshore (as) or onshore-offshore (os).

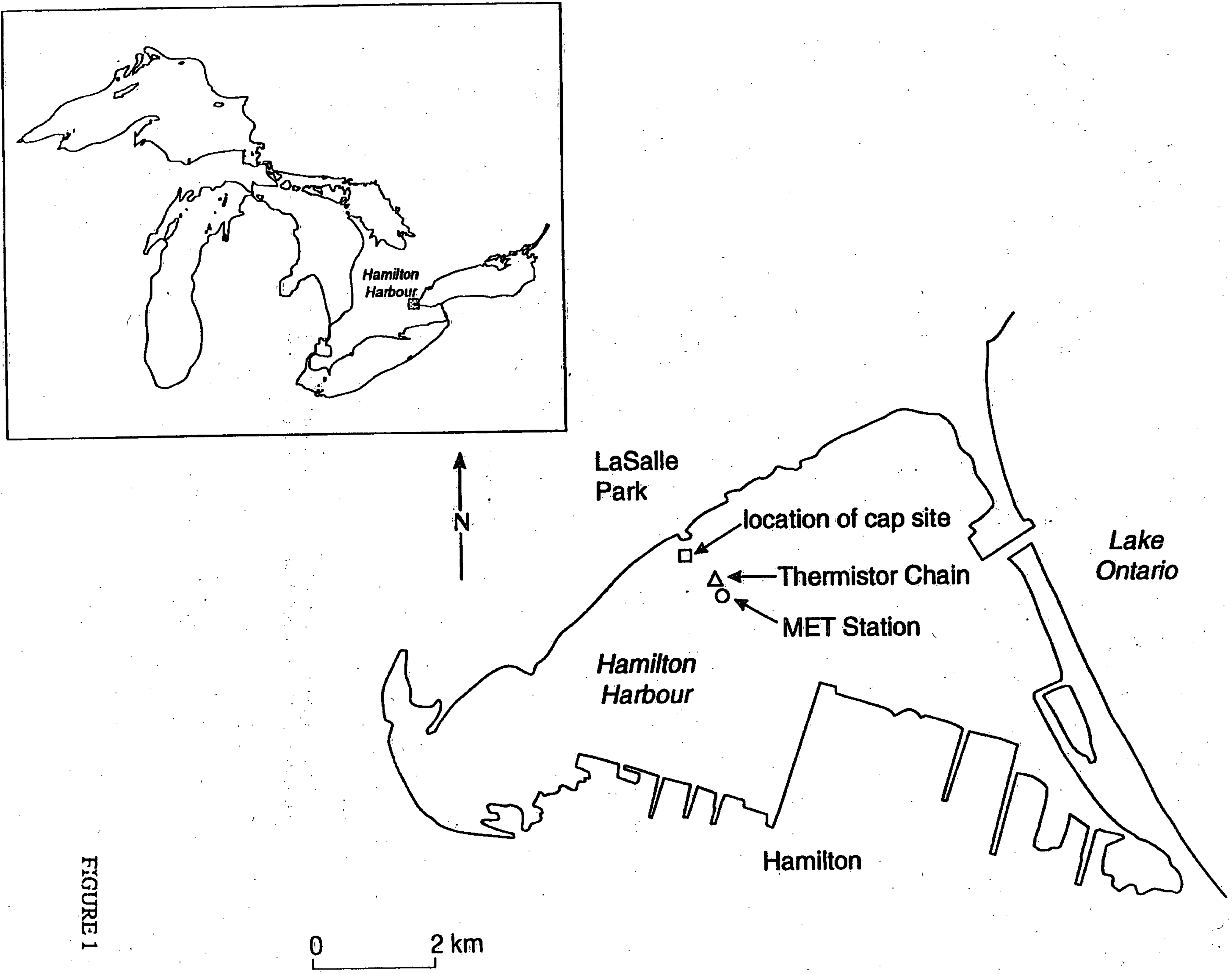

Hamilton Harbour
N
LaSalle Park
location of cap site
Thermistor Chain
MET Station
Lake Ontario
Hamilton Harbour
Hamilton
0
2 km

FIGURE 1

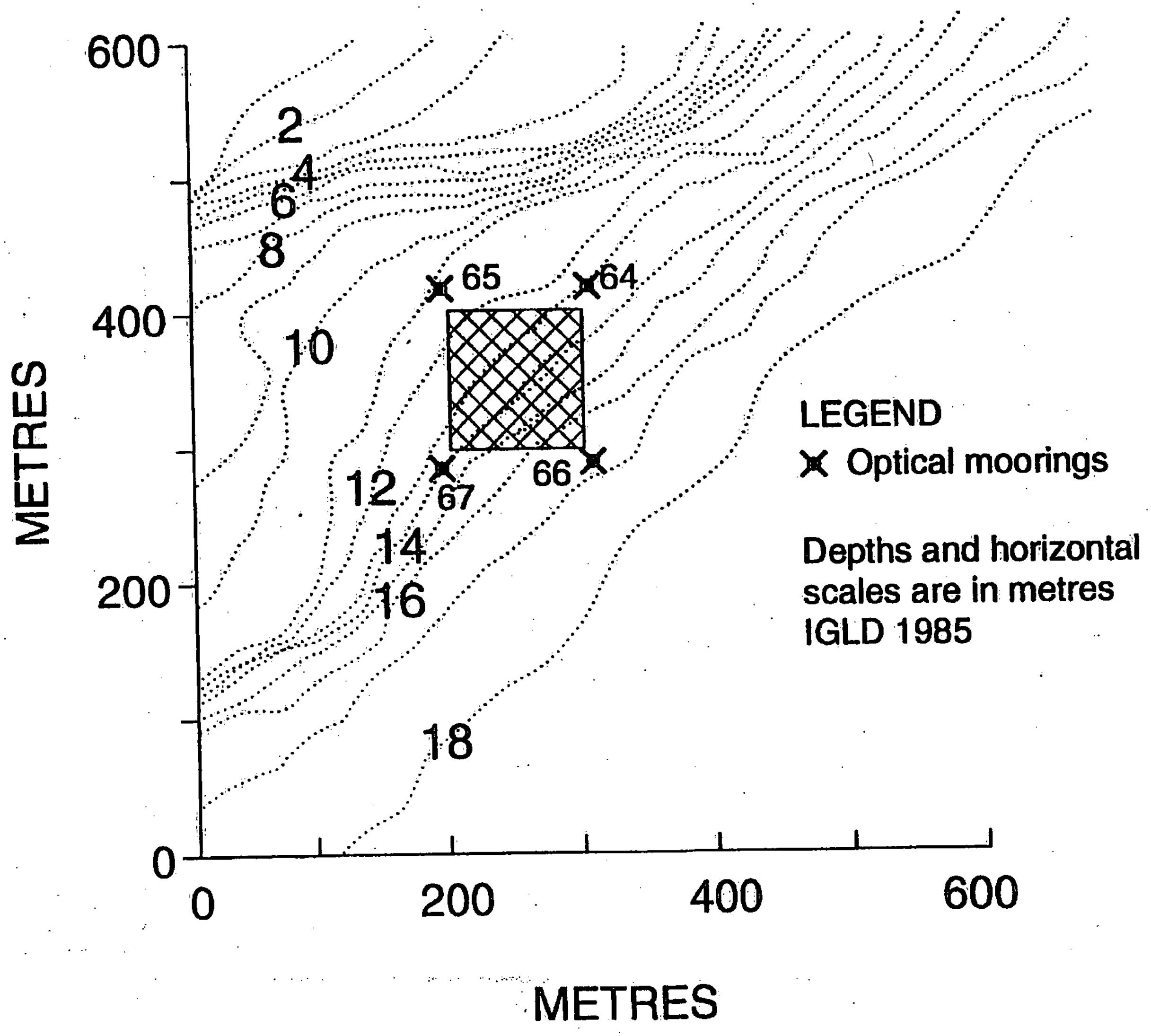
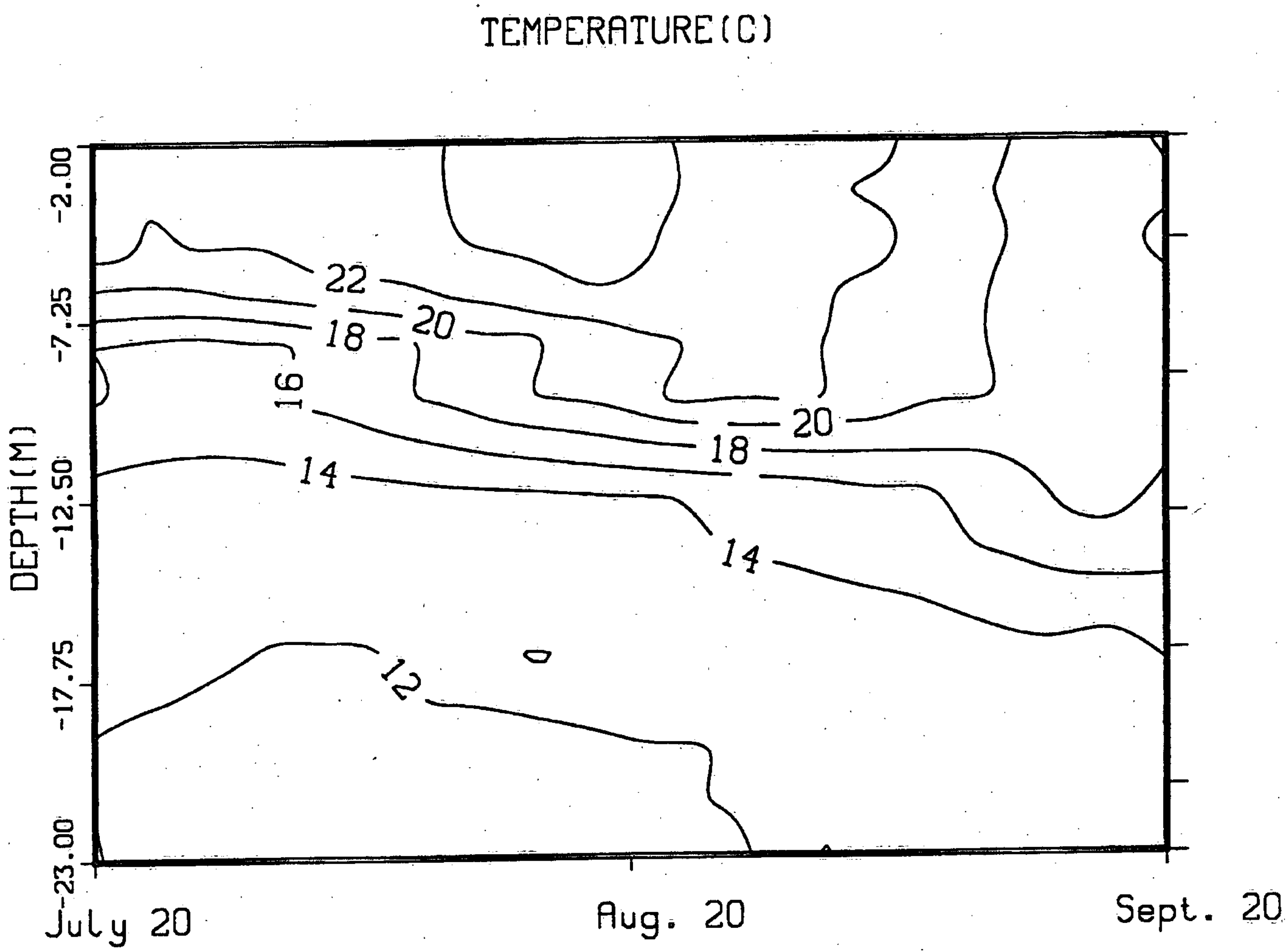

600
400
200
0
METRES
0
200
400
600
METRES
2
4
6
8
10
12
14
16
18
65
64
66
67
LEGEND
✕ Optical moorings
Depths and horizontal scales are in metres
IGLD 1985

FIGURE 2



TEMPERATURE(C)
DEPTH(M)
-2.00
-7.25
-12.50
-17.75
-23.00
July 20
Aug. 20
Sept. 20
22
20
18
16
20
18
14
14
12

FIGURE 3

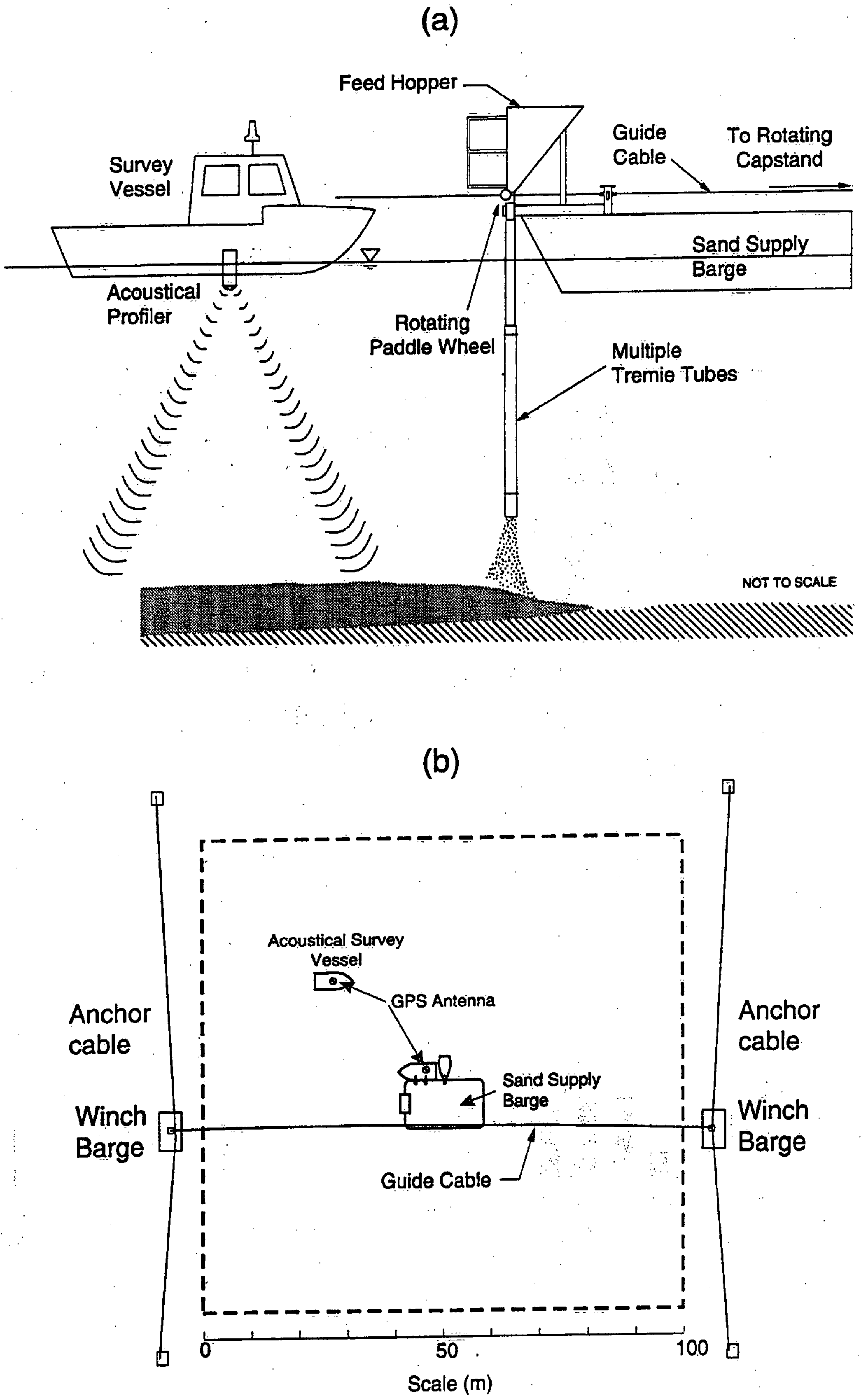

(a)
Feed Hopper
Survey Vessel
Guide Cable
To Rotating Capstand
Sand Supply Barge
Acoustical Profiler
Rotating Paddle Wheel
Multiple Tremie Tubes
NOT TO SCALE
(b)
Acoustical Survey Vessel
GPS Antenna
Anchor cable
Anchor cable
Sand Supply Barge
Winch Barge
Winch Barge
Guide Cable
0
50
100
Scale (m)

FIGURE 4

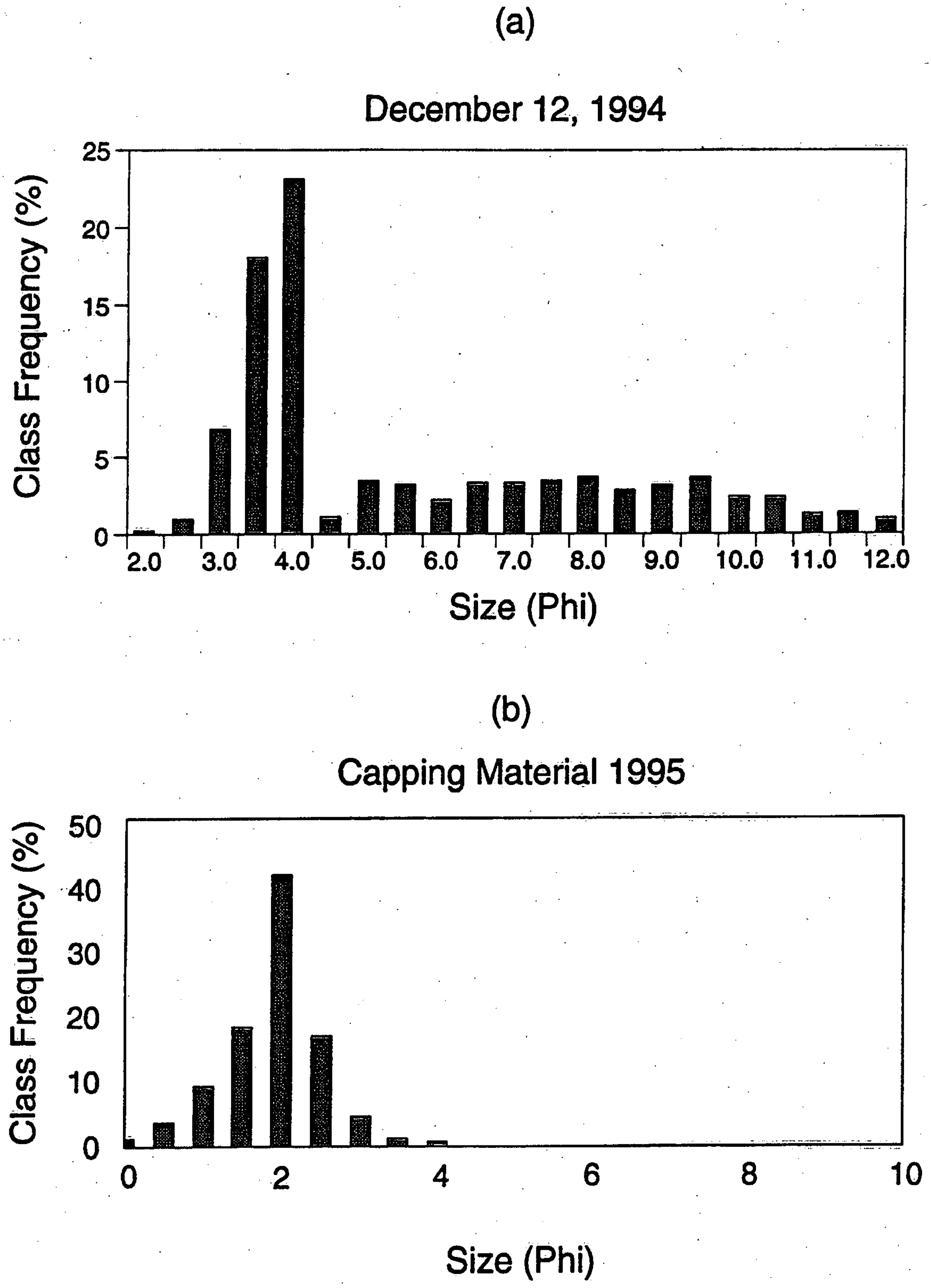
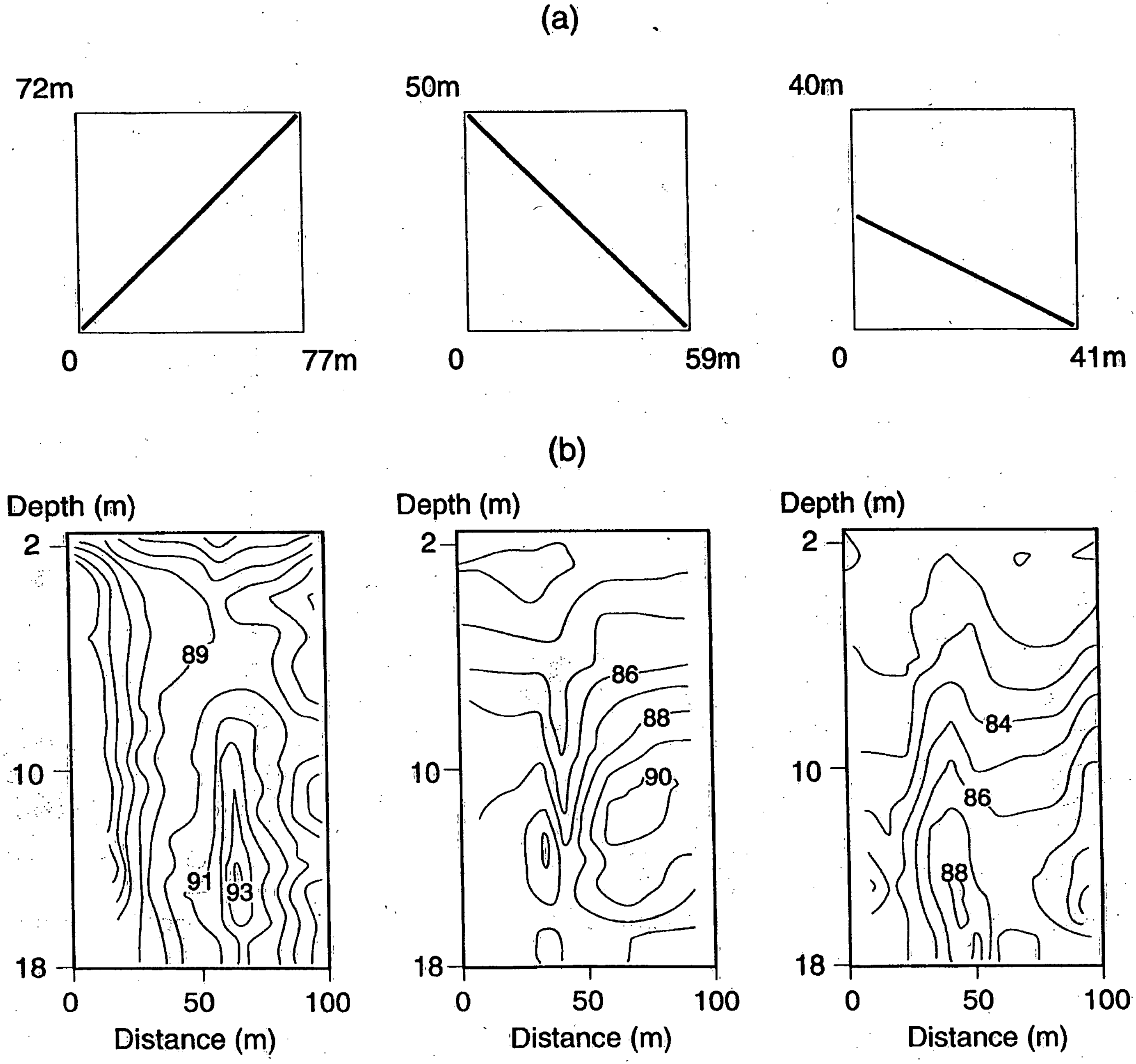
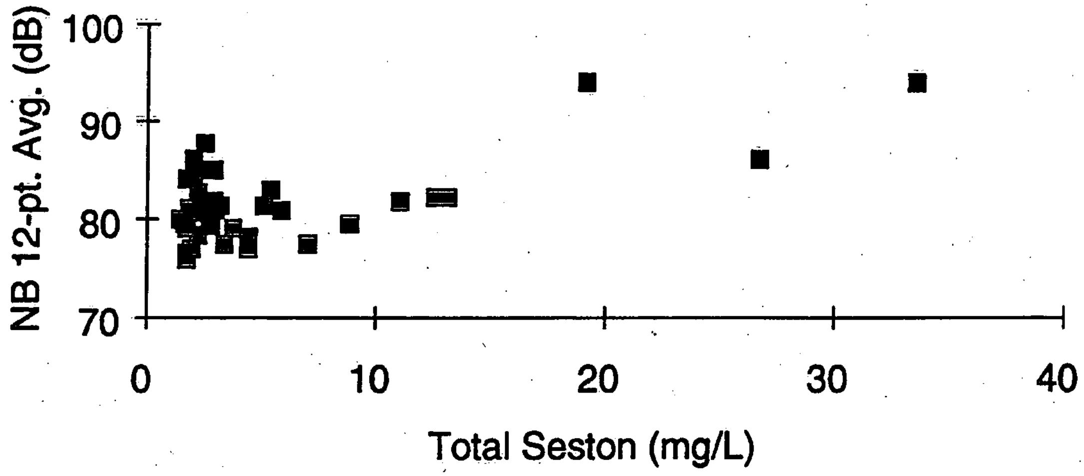

(a)
December 12, 1994
Class Frequency (%)
0
5
10
15
20
25
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
Size (Phi)
(b)
Capping Material 1995
Class Frequency (%)
0
10
20
30
40
50
0
2
4
6
8
10
Size (Phi)

FIGURE 5

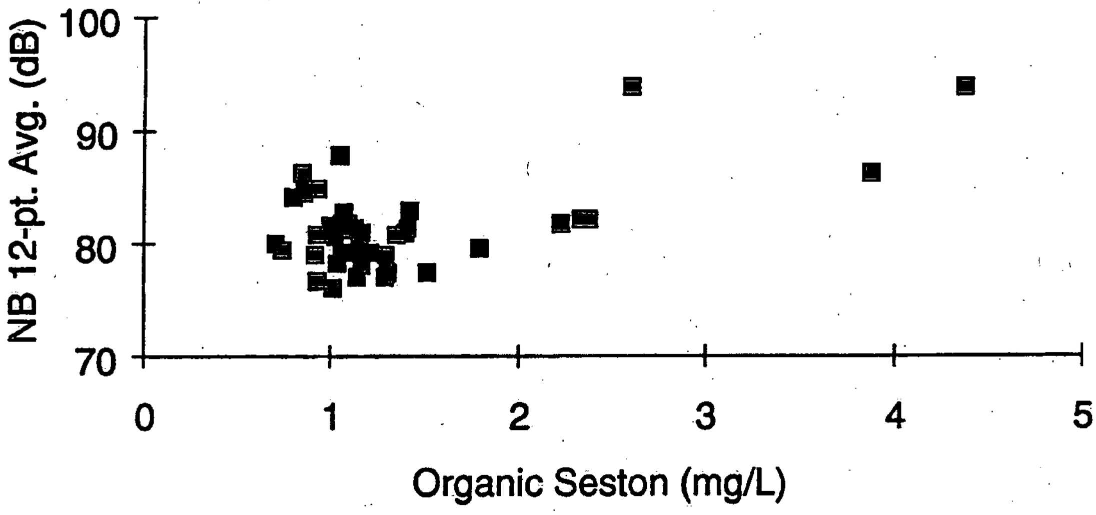
FIGURE 6


(a)
72m
0
77m
50m
0
59m
40m
0
41m
(b)
Depth (m)
2
10
18
89
91
93
0
50
100
Distance (m)
Depth (m)
2
10
18
86
88
90
0
50
100
Distance (m)
Depth (m)
2
10
18
84
86
88
0
50
100
Distance (m)

a) NB 12-pt. Average vs. Total Seston



b) NB 12-pt. Average vs. Organic Seston



c) NB 12-pt. Average vs. Inorganic Seston

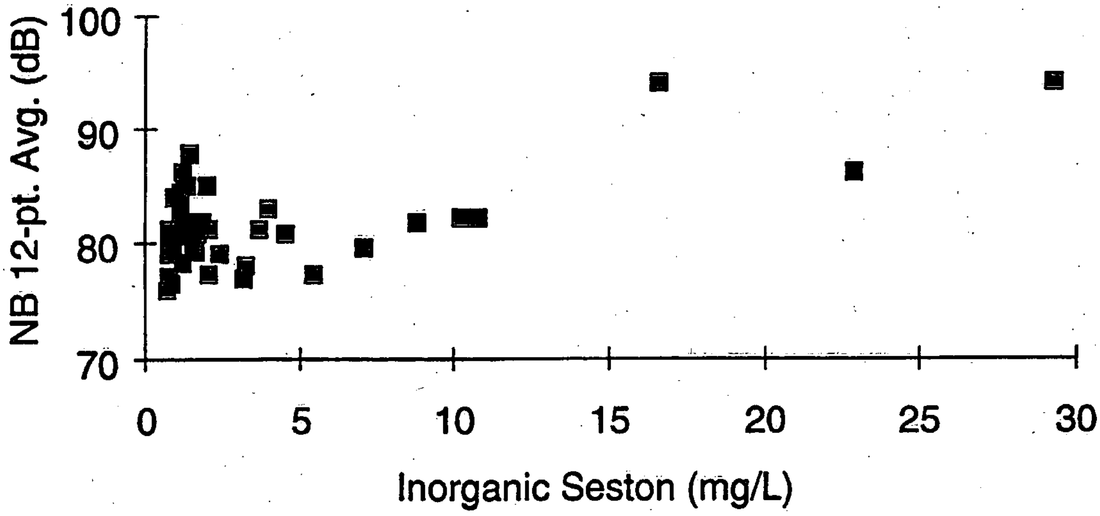


Figure 7

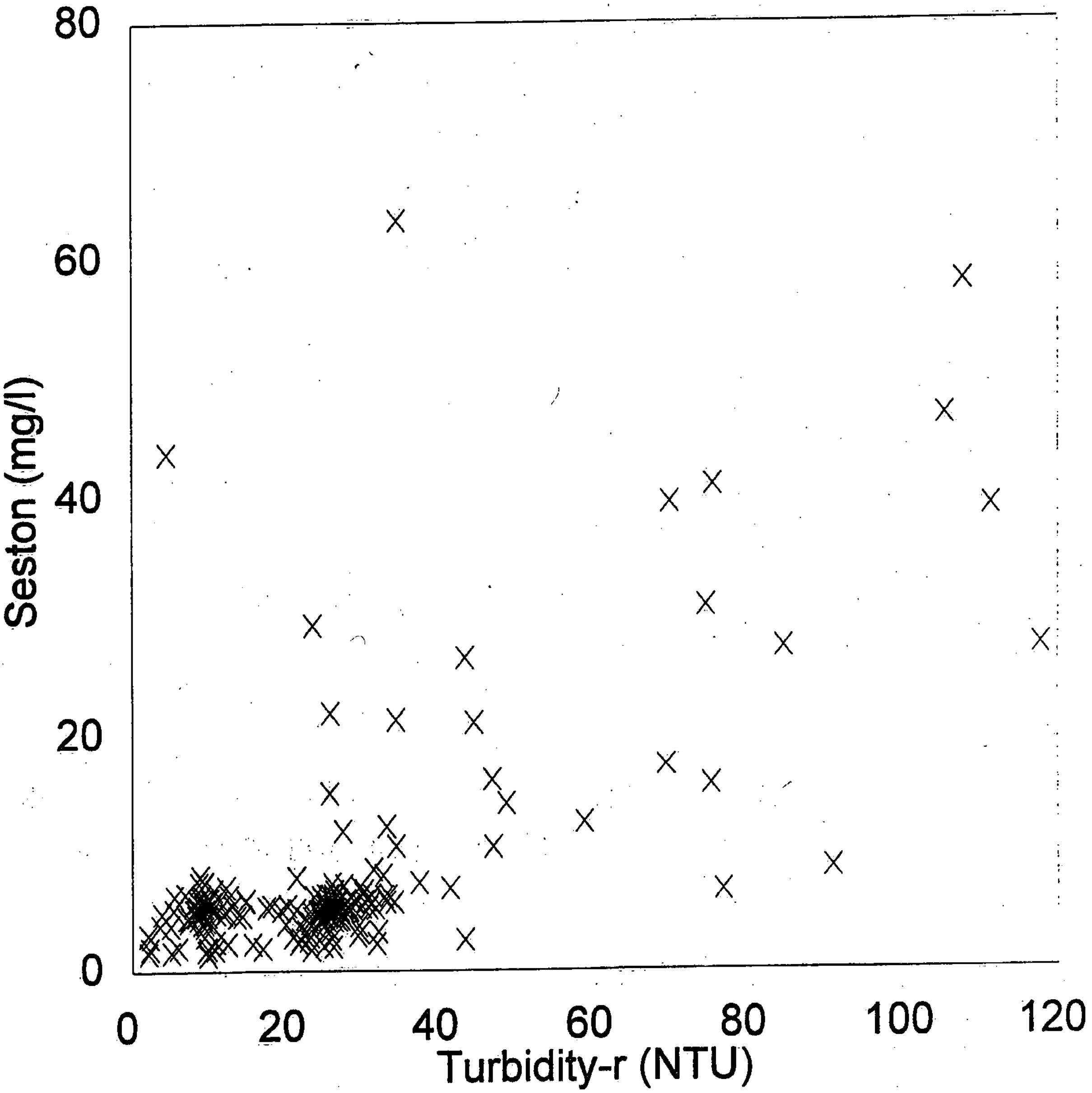
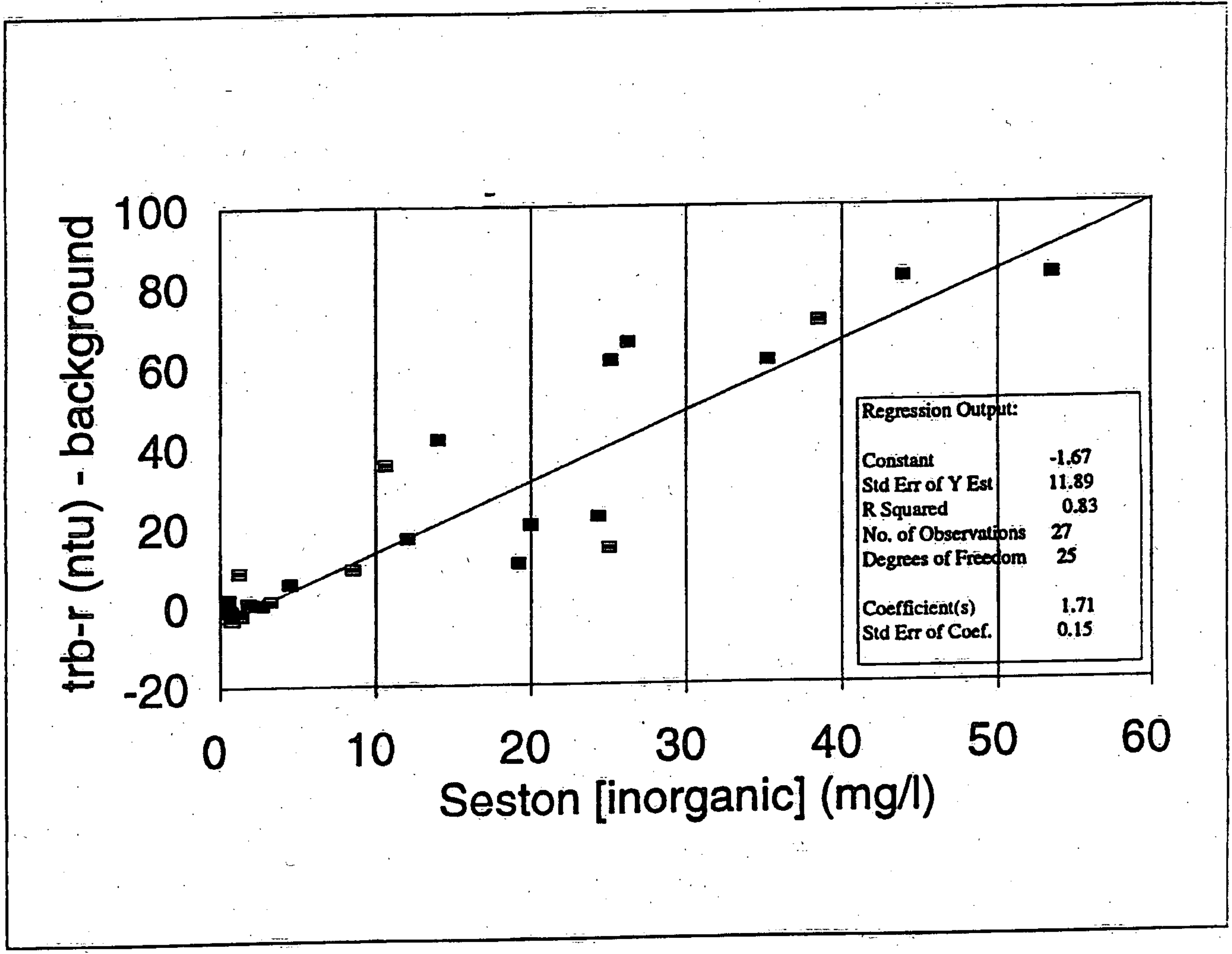


FIGURE 8



Regression Output:

Constant	-1.67
Std Err of Y Est	11.89
R Squared	0.83
No. of Observations	27
Degrees of Freedom	25
Coefficient(s)	1.71
Std Err of Coef.	0.15

FIGURE 9

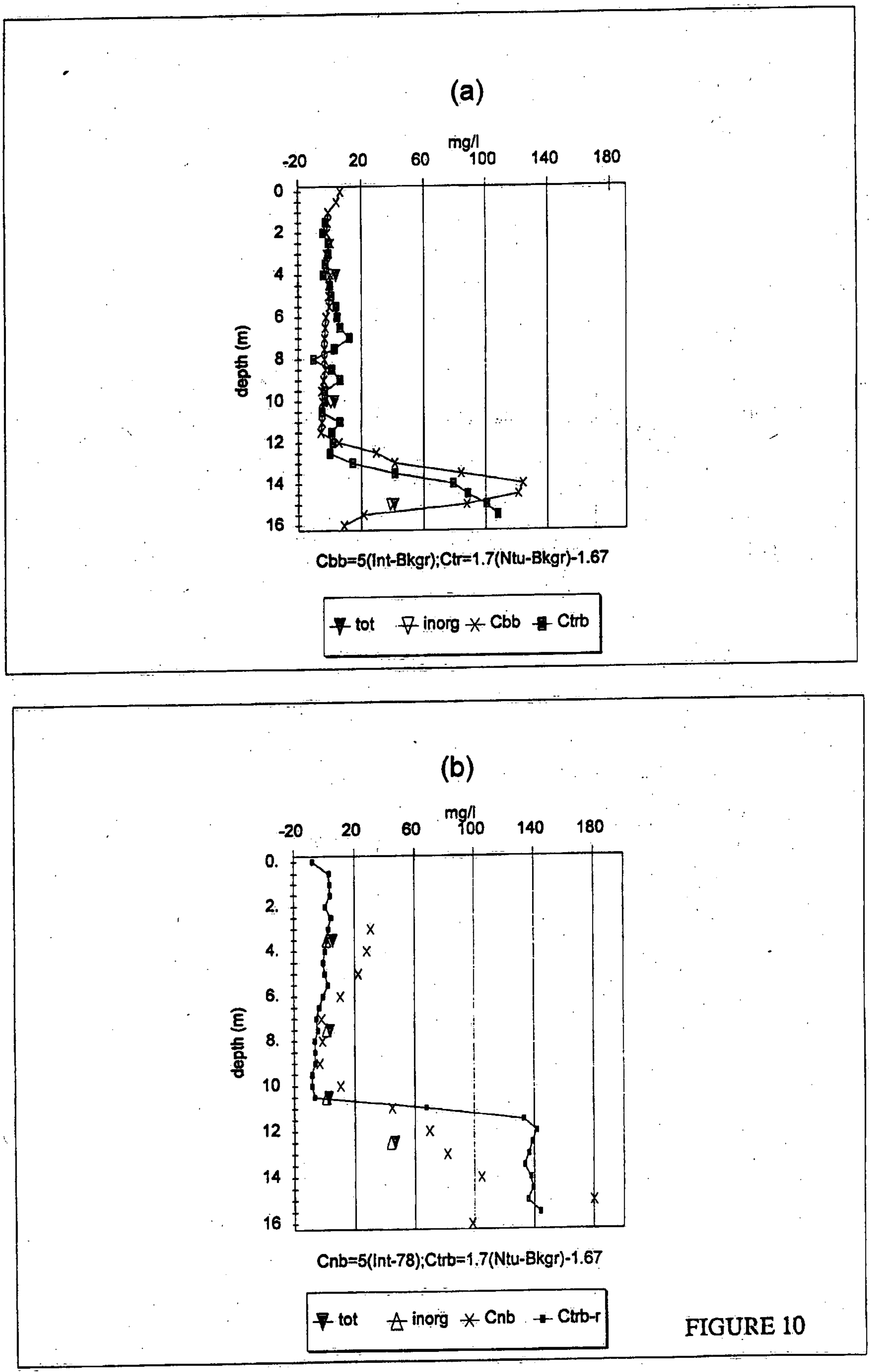

(a)
mg/l
-20
20
60
100
140
180
depth (m)
0
2
4
6
8
10
12
14
16
Cbb=5(Int-Bkgr);Ctr=1.7(Ntu-Bkgr)-1.67
tot
inorg
Cbb
Ctrb
(b)
mg/l
-20
20
60
100
140
180
depth (m)
0.
2.
4.
6.
8.
10
12
14
16
Cnb=5(Int-78);Ctrb=1.7(Ntu-Bkgr)-1.67
tot
inorg
Cnb
Ctrb-r

FIGURE 10

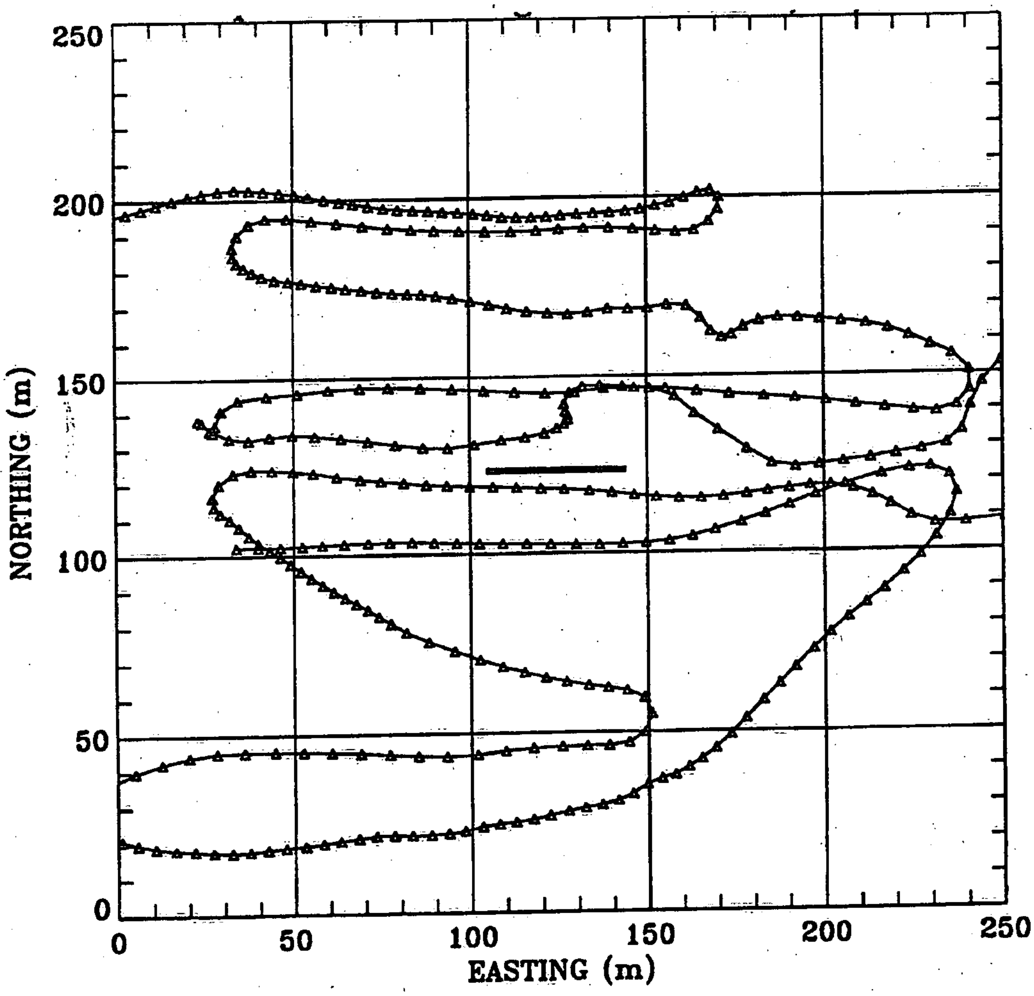


FIGURE 11

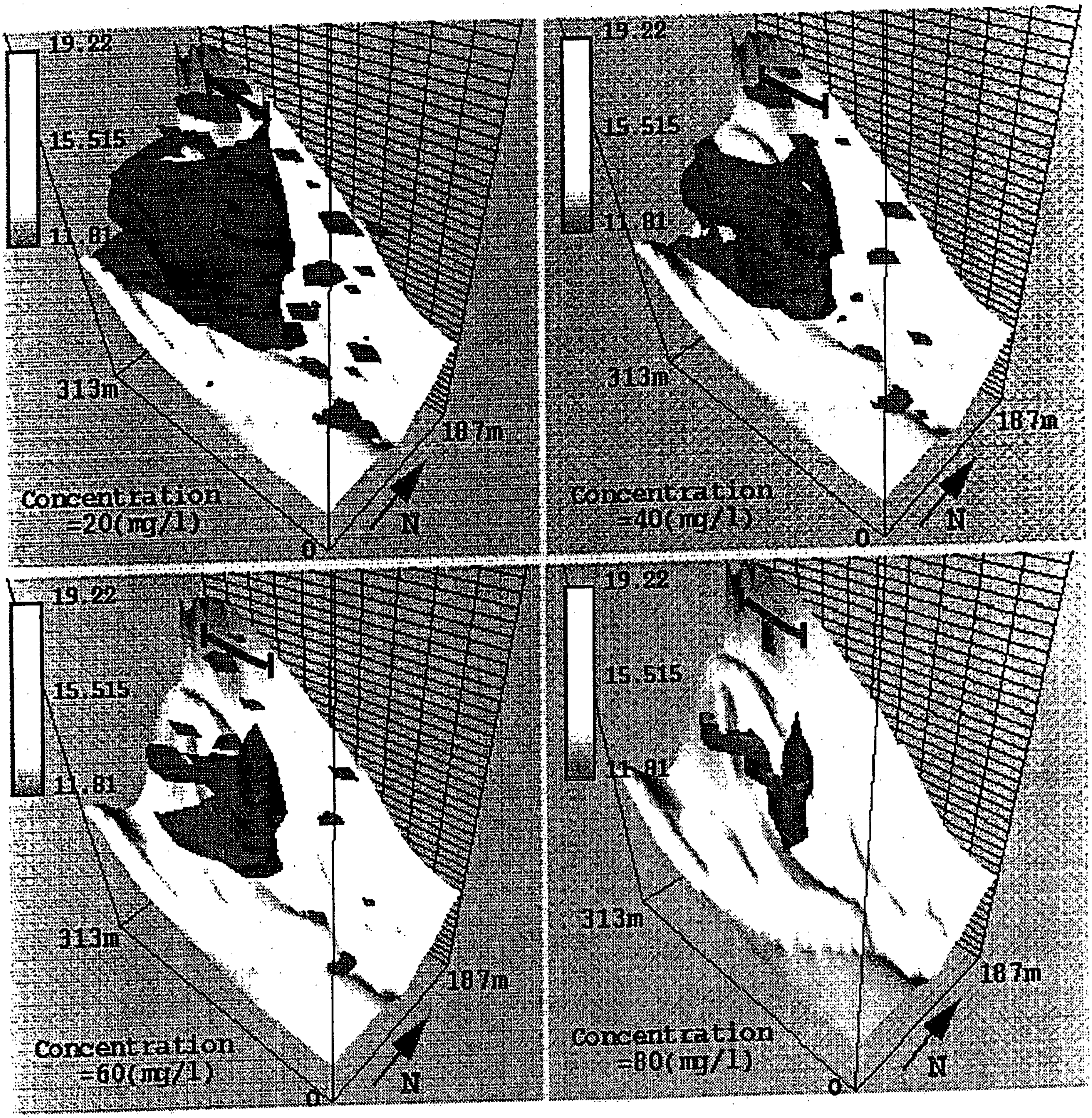

19.22
15.515
11.81
313m
187m
Concentration
=20(mg/l)
O
N
19.22
15.515
11.81
313m
187m
Concentration
=40(mg/l)
O
N
19.22
15.515
11.81
313m
187m
Concentration
=60(mg/l)
O
N
19.22
15.515
11.81
313m
187m
Concentration
=80(mg/l)
O
N

FIGURE 12

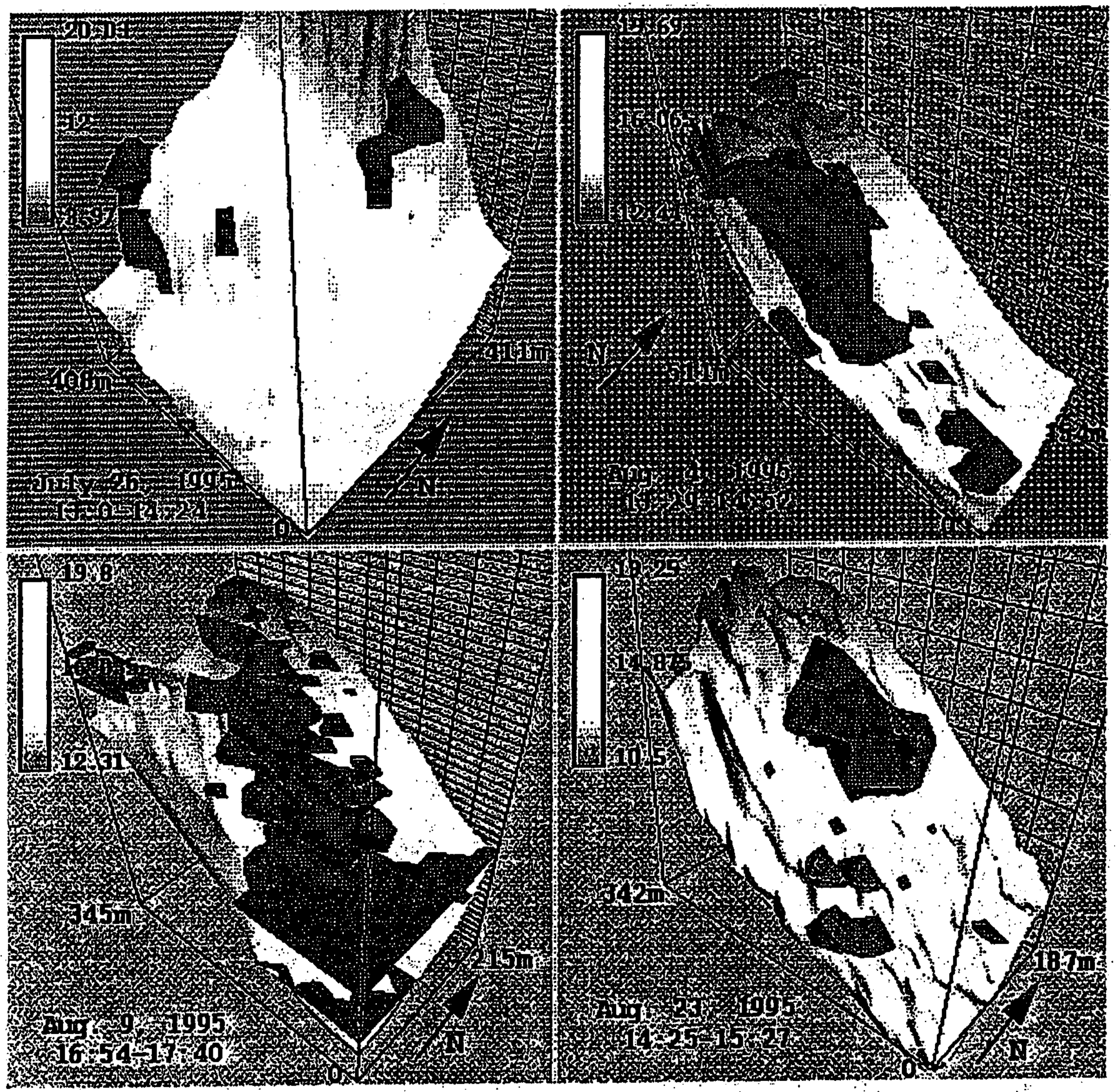
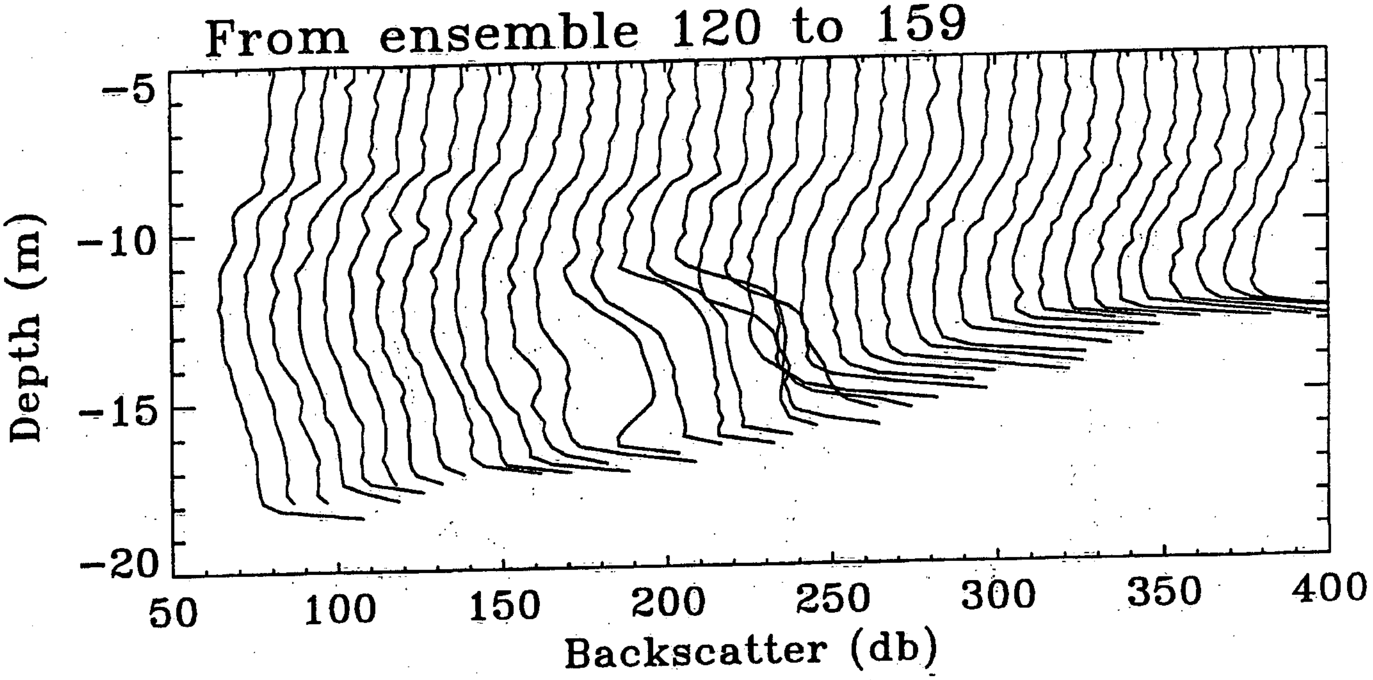

20.04
12
3.97
408m
411m
July 26, 1995
13:0-14:24
0
N
17.69
16.065
12.44
N
511m
Aug. 4, 1995
13:20-14:52
0
19.8
12.31
345m
215m
Aug. 9, 1995
16:54-17:40
0
N
19.25
14.875
10.5
342m
187m
Aug. 23, 1995
14:25-15:27
0
N

FIGURE 13


From ensemble 120 to 159
Depth (m)
-5
-10
-15
-20
50
100
150
200
250
300
350
400
Backscatter (db)

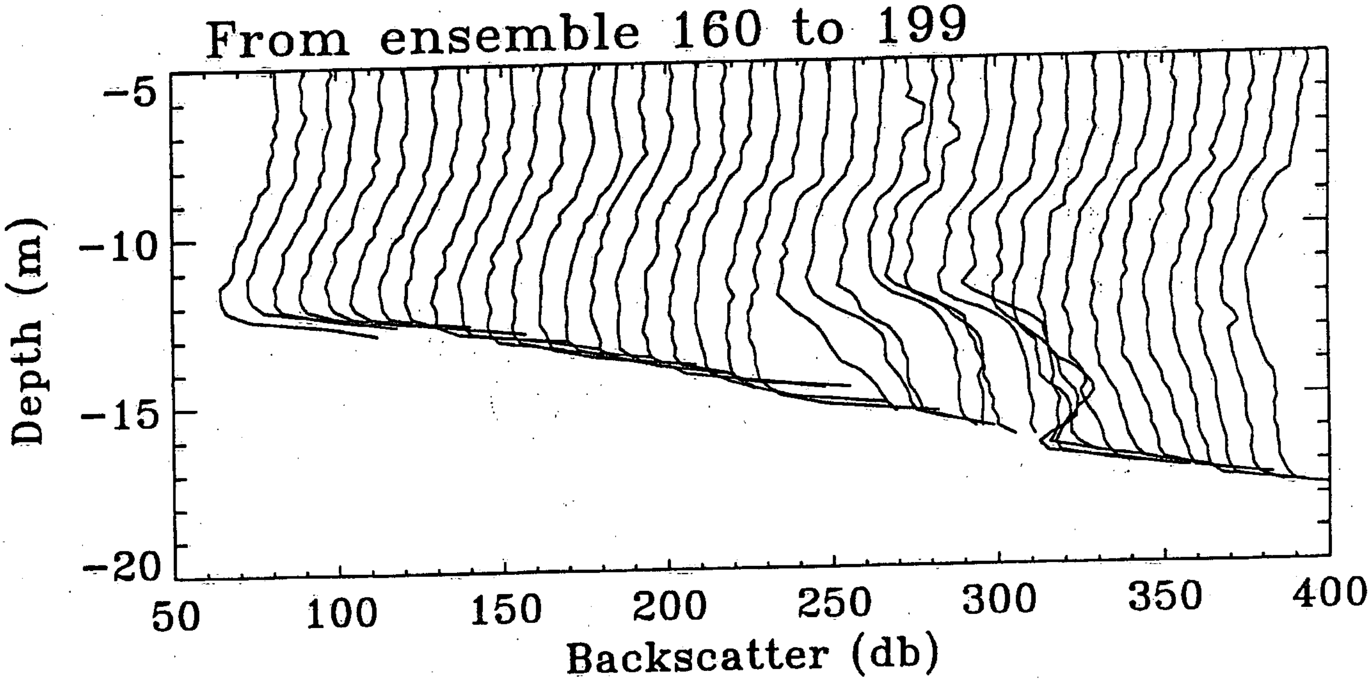

From ensemble 160 to 199
Depth (m)
-5
-10
-15
-20
50
100
150
200
250
300
350
400
Backscatter (db)

FIGURE 14

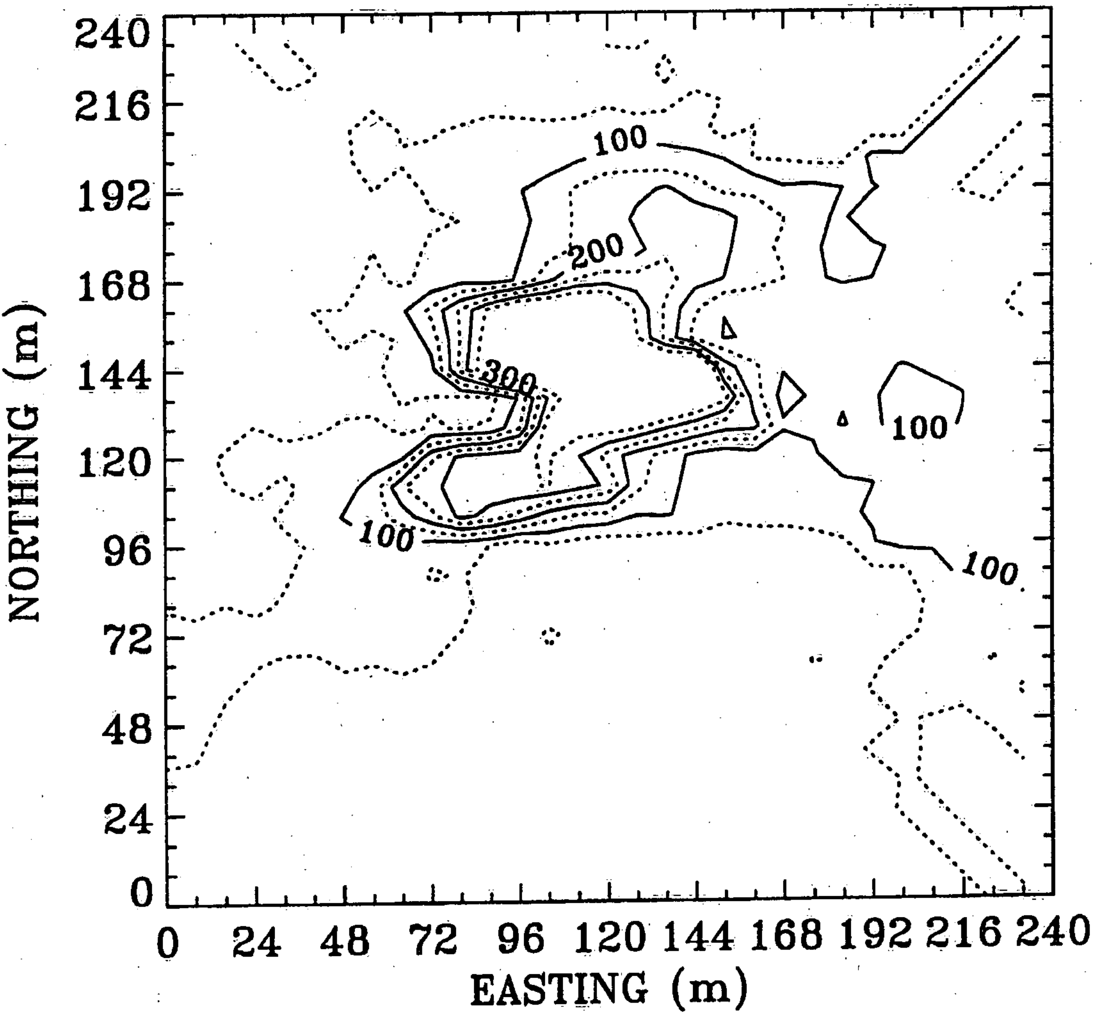
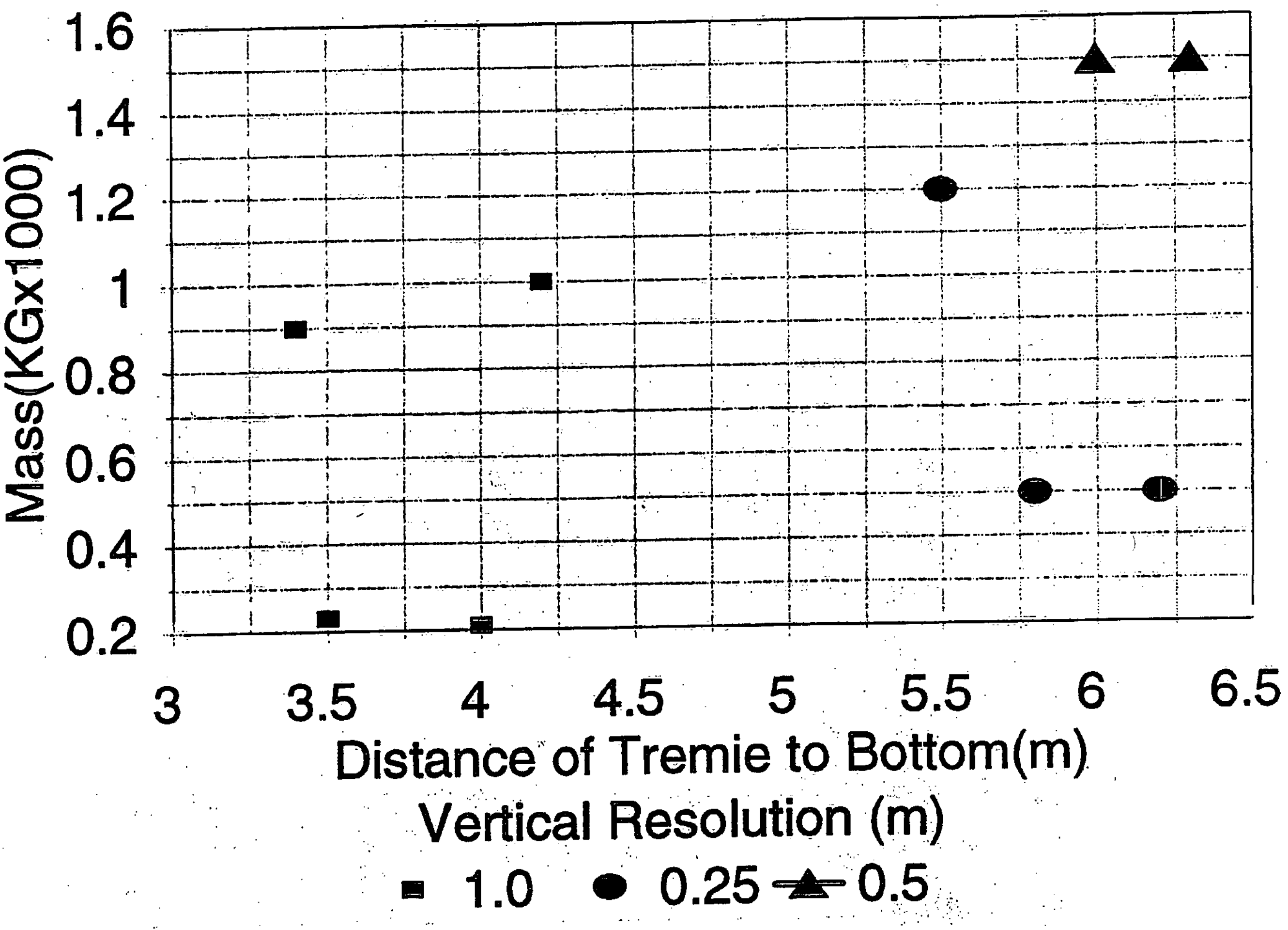

240
216
192
168
144
120
96
72
48
24
0
NORTHING (m)
0
24
48
72
96
120
144
168
192
216
240
EASTING (m)
100
200
300
100
100
100

FIGURE 15



1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Mass(KGx1000)
3
3.5
4
4.5
5
5.5
6
6.5
Distance of Tremie to Bottom(m)
Vertical Resolution (m)
■ 1.0
● 0.25
▲ 0.5

FIGURE 16

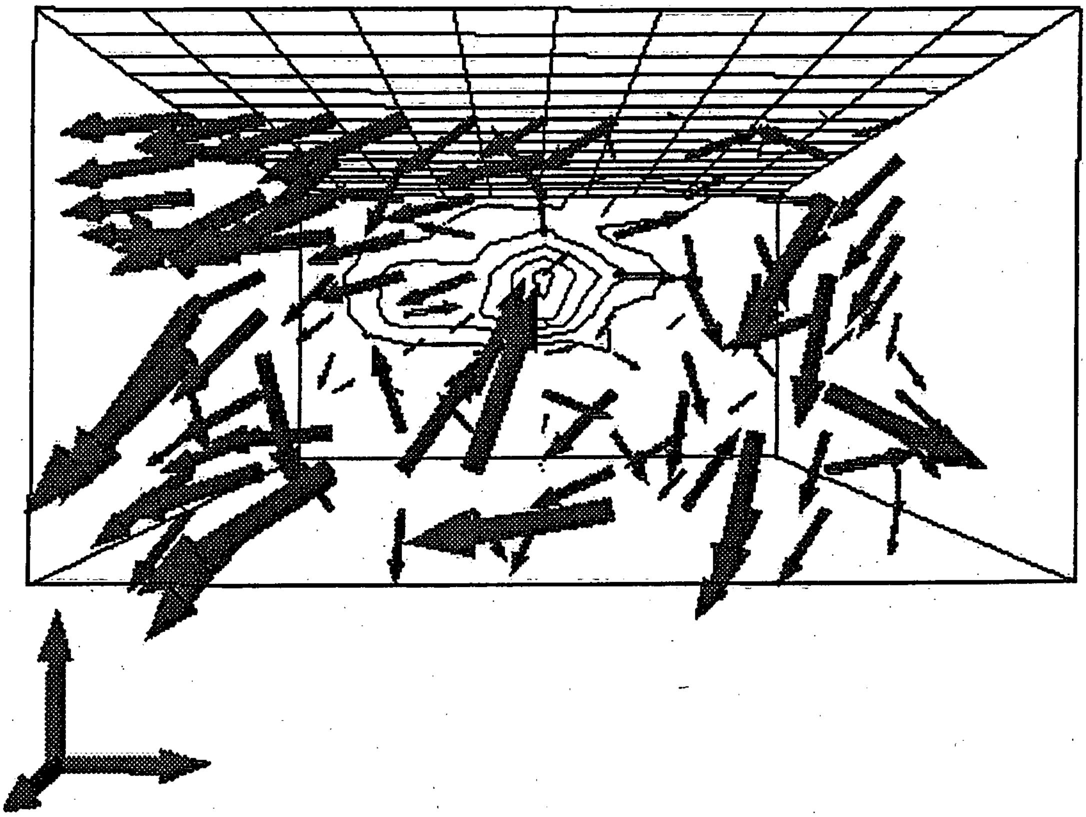


FIGURE 17

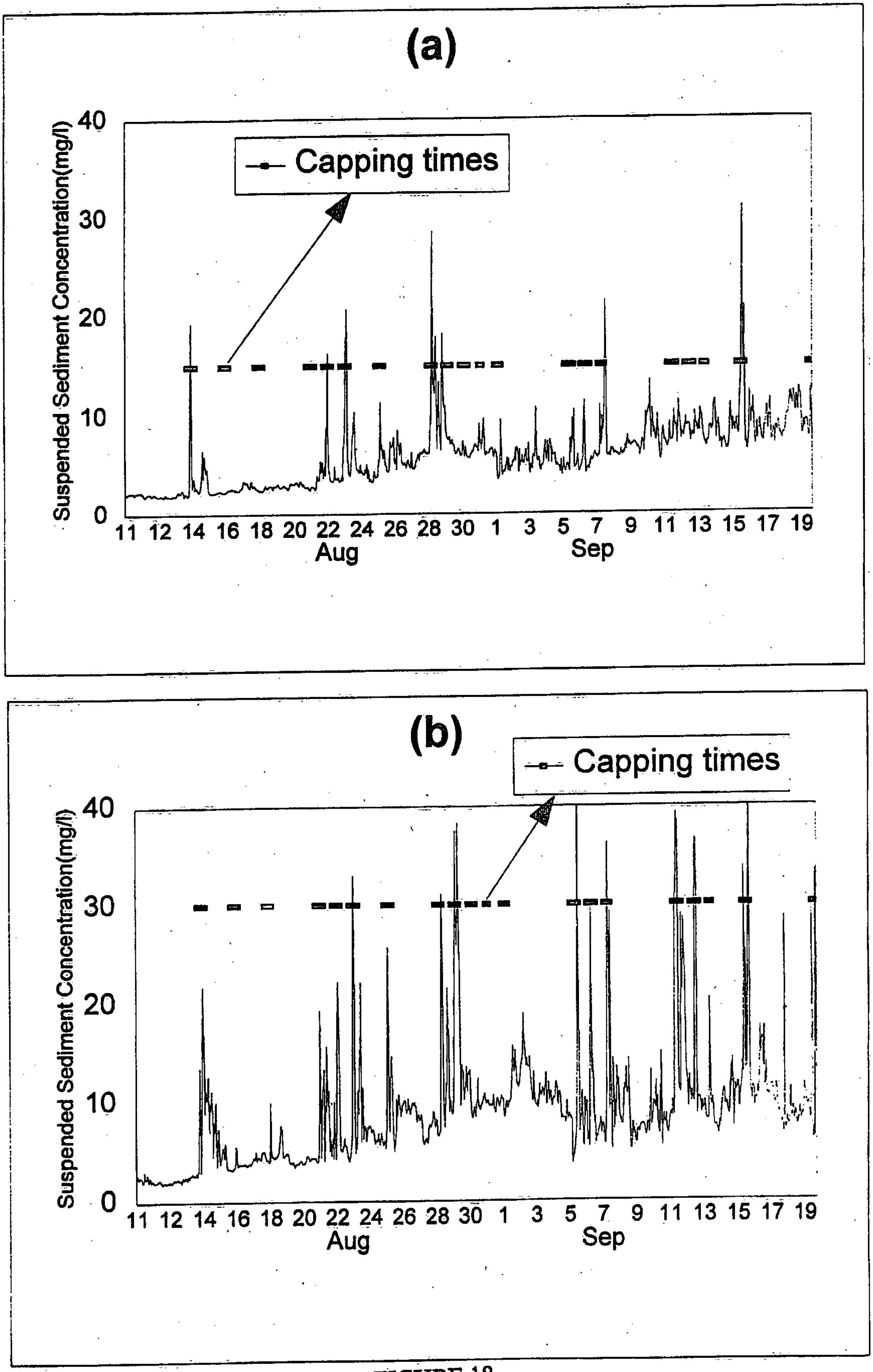

(a)
Capping times
Suspended Sediment Concentration(mg/l)
0
10
20
30
40
11 12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15 17 19
Aug
Sep
(b)
Capping times
Suspended Sediment Concentration(mg/l)
0
10
20
30
40
11 12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15 17 19
Aug
Sep

FIGURE 18

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