MARINE SCIENCES RESEARCH CENTER
STATE UNIVERSITY OF NEW YORK
STONY BROOK, NEW YORK 11794-5000

TURBIDITY DISTRIBUTION IN THE HUDSON RIVER ESTUARY

by

Henry Bokuniewicz and David Ullman
Marine Sciences Research Center
State University of New York
Stony Brook, New York 11794-5000

June 1995

Approved for Distribution

J. K. Cochran, Director

Special Report #109
Reference #95-02

Turbidity Distribution in the Hudson River Estuary

Henry Bokuniewicz
Marine Sciences Research Center
State University of New York
Stony Brook, New York 11794-5000

Introduction

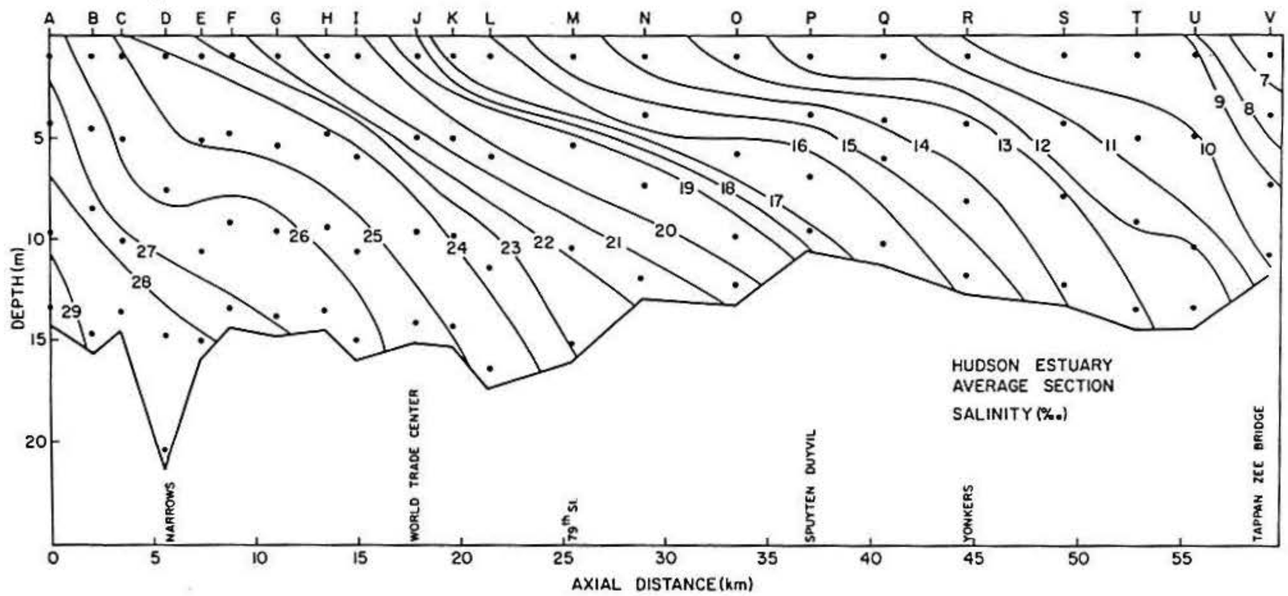
The Hudson River estuary appears to be an effective trap for fine-grained sediment that is capable of absorbing not only fine-grained sediment supplied by its rivers but also a substantial ocean source (Bokuniewicz and Coch, 1986; Olsen et al., 1984; Ellsworth, 1986). Such behavior is common in partially mixed estuaries and has been explained by characteristic estuarine circulations and suspended sediment distribution (Schubel and Carter, 1984) in conjunction with rapid particle settling speeds due to agglomeration. In the Hudson deposition has been enhanced by dredging which creates large areas that are not in equilibrium with the local sedimentary system. Deposition rates in dredged channels may exceed 8 cm/yr based on dredging records.

The Hudson shows characteristics of a salt-wedge estuary in its lower reaches due to the transient intrusion of a salt wedge at the bottom. The upper reaches, however, show characteristics of a partially mixed estuary. The seasonal changes in the supply of sediment from external sources should have little influence on the levels of turbidity. This contention is supported by the observations of Arnold (1982) who found a difference in average concentrations in the estuary of less than 20% between times of high freshwater flow and times of low flow.

The internal processes of resuspension and dispersion, however, may be the estuary's dominant characteristics. Much more sediment is transferred among temporary repositories within the estuary than is supplied annually from external sources. The distribution of turbidity reflects the pathways for these exchanges and the persistence of both turbidity maxima and strong lateral gradients in the suspended sediment distribution implies a resilient coherence to the tidal and non-tidal processes over long-time periods.

Previous Work

There is at least one turbidity maximum along the Manhattan shore and it is likely that there is another near the landward limit of salt. One turbidity maximum was documented in a series of vertical distributions of water temperature, salinity, and suspended sediment concentrations measured along the axis of the Hudson River estuary nine times between November, 1980 and September, 1981 (Hirschberg and Bokuniewicz, 1991). The averaged salinity section and the averaged section of suspended sediment concentrations are shown in Figure 1. The observations did not extend to the limit of sea salt, but a strong turbidity maximum was found near the river bed between 79th Street and the Spuyten Duyvel. Suspended sediment concentrations exceeded 40 mg/l. They reached levels over 100 mg/l and the highest recorded value was 447 mg/l. This turbidity maximum, however, was not present in all the individual transects. On 27 May, 1981, a section was done from an EPA helicopter (Figure 2). Although there was a well developed salinity stratification, no strong turbidity


A B C D E F G H I J K L M N O P Q R S T U V
HUDSON ESTUARY
AVERAGE SECTION
SALINITY (‰)
DEPTH (m)
AXIAL DISTANCE (km)
NARROWS
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE

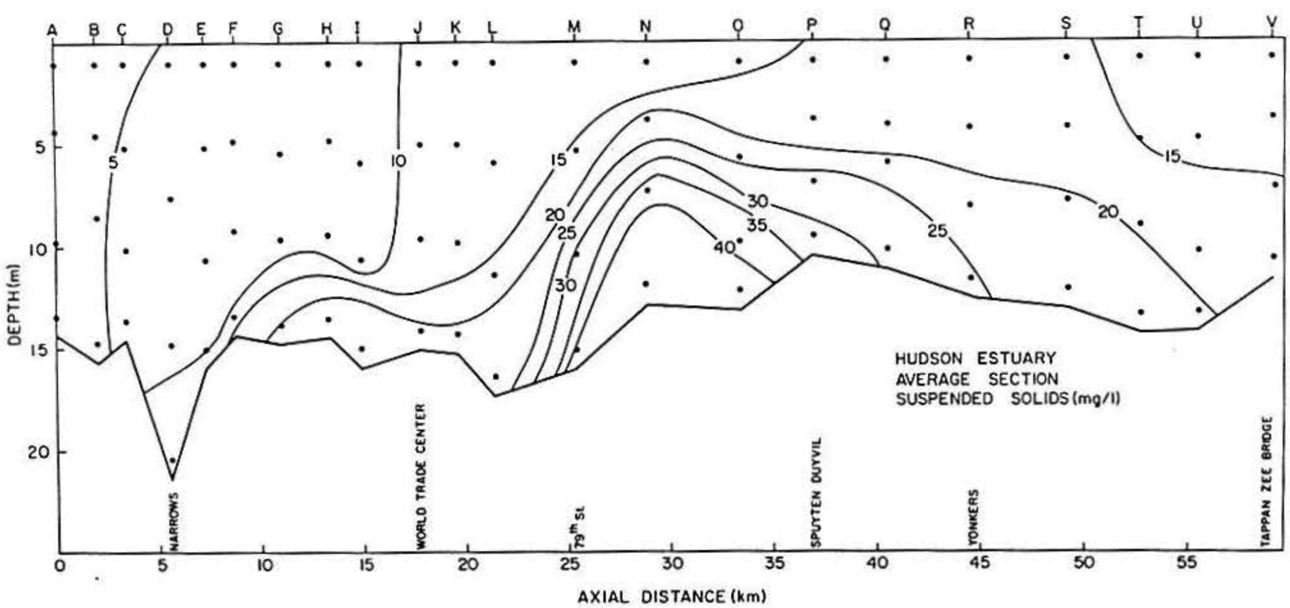

A B C D E F G H I J K L M N O P Q R S T U V
HUDSON ESTUARY
AVERAGE SECTION
SUSPENDED SOLIDS (mg/l)
DEPTH (m)
AXIAL DISTANCE (km)
NARROWS
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE

Figure 1

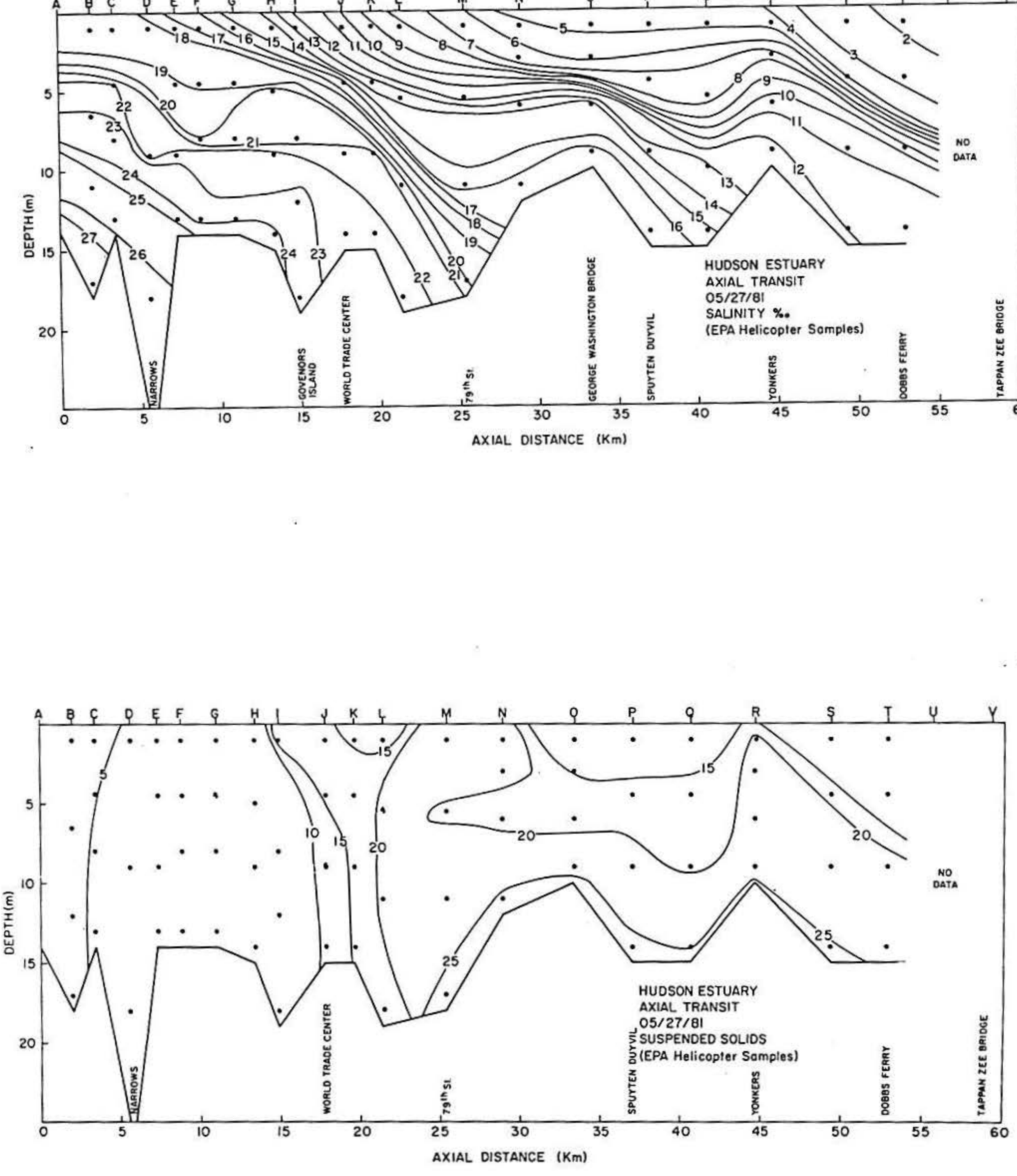

HUDSON ESTUARY
AXIAL TRANSIT
05/27/81
SALINITY ‰
(EPA Helicopter Samples)
DEPTH (m)
AXIAL DISTANCE (Km)
NO DATA
NARROWS
GOVENORS ISLAND
WORLD TRADE CENTER
79th St.
GEORGE WASHINGTON BRIDGE
SPUYTEN DUYVIL
YONKERS
DOBBS FERRY
TAPPAN ZEE BRIDGE
HUDSON ESTUARY
AXIAL TRANSIT
05/27/81
SUSPENDED SOLIDS
(EPA Helicopter Samples)
DEPTH (m)
AXIAL DISTANCE (Km)
NO DATA

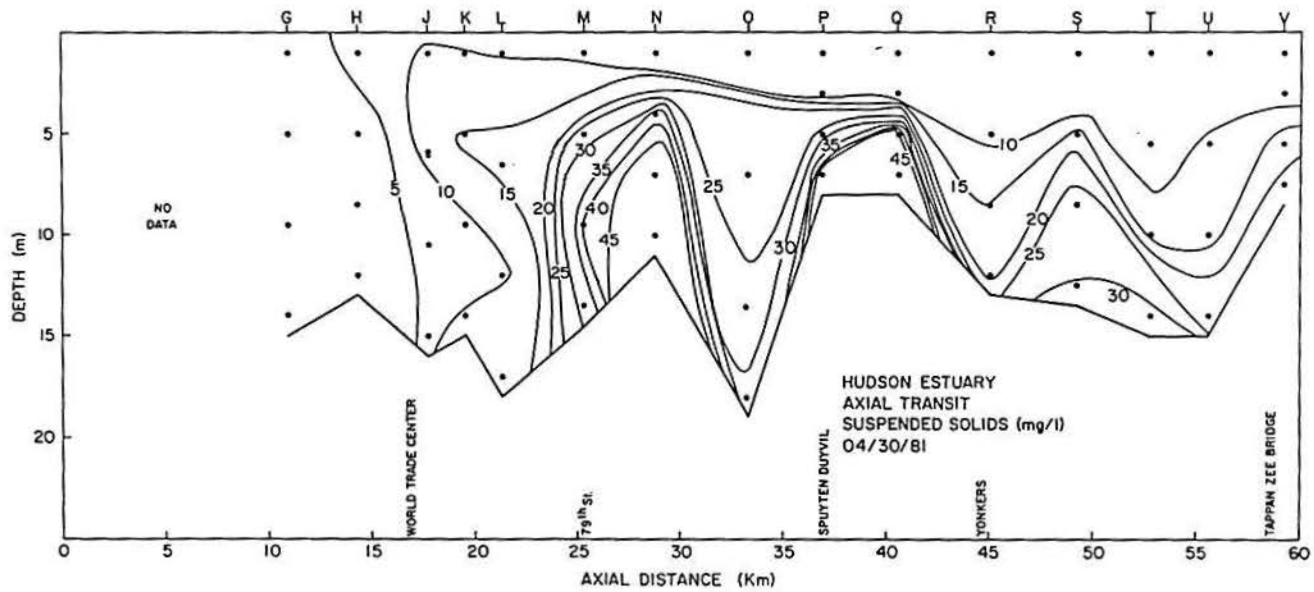
Figure 2

maximum was found. At another time (30 April, 1981, Figure 3), two turbidity maxima were found.

Data has been sparse further up the estuary, but there is some reason to believe a second turbidity maximum occurs near the limit of sea salt intrusion. Five axial sections of the salinity and suspended sediment concentrations were compiled from vertical sampling at between 5 and 11 stations from the Battery to Indian Point between 1975 and 1977 (Olsen, 1979, Figure 4). The high turbidity south of the George Washington Bridge is consistent with these observations and there is some indication of a second turbidity maximum or an extension of the turbidity maximum found along the shore of Manhattan into Haverstraw Bay and, perhaps, beyond.

Between 1978 and 1980, the concentrations of suspended sediment in the surface and bottom water were measured five times at between 9 and 16 stations from the Battery to Albany (Figure 5). The resolution of these data are poor for the purpose of identifying a turbidity maximum but on at least three of the cruises, higher turbidity was found near the limit of sea salt (Figure 5). Another axial section of average suspended sediment concentrations was produced from surface and bottom samples at 18 stations (Gibbs, 1991, University of Delaware, personal communication) showing a turbidity maximum in the bottom water approximately at the head of salt.

Non-tidal, gravitational circulation has been found to generate a turbidity maximum at the landward limit of saline waters in several estuaries on the east coast. Earlier authors had suggested this mechanism as the cause of higher turbidity



G H J K L M N O P Q R S T U V
DEPTH (m)
NO DATA
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE
HUDSON ESTUARY
AXIAL TRANSIT
SUSPENDED SOLIDS (mg/l)
04/30/81
AXIAL DISTANCE (Km)

Figure 3

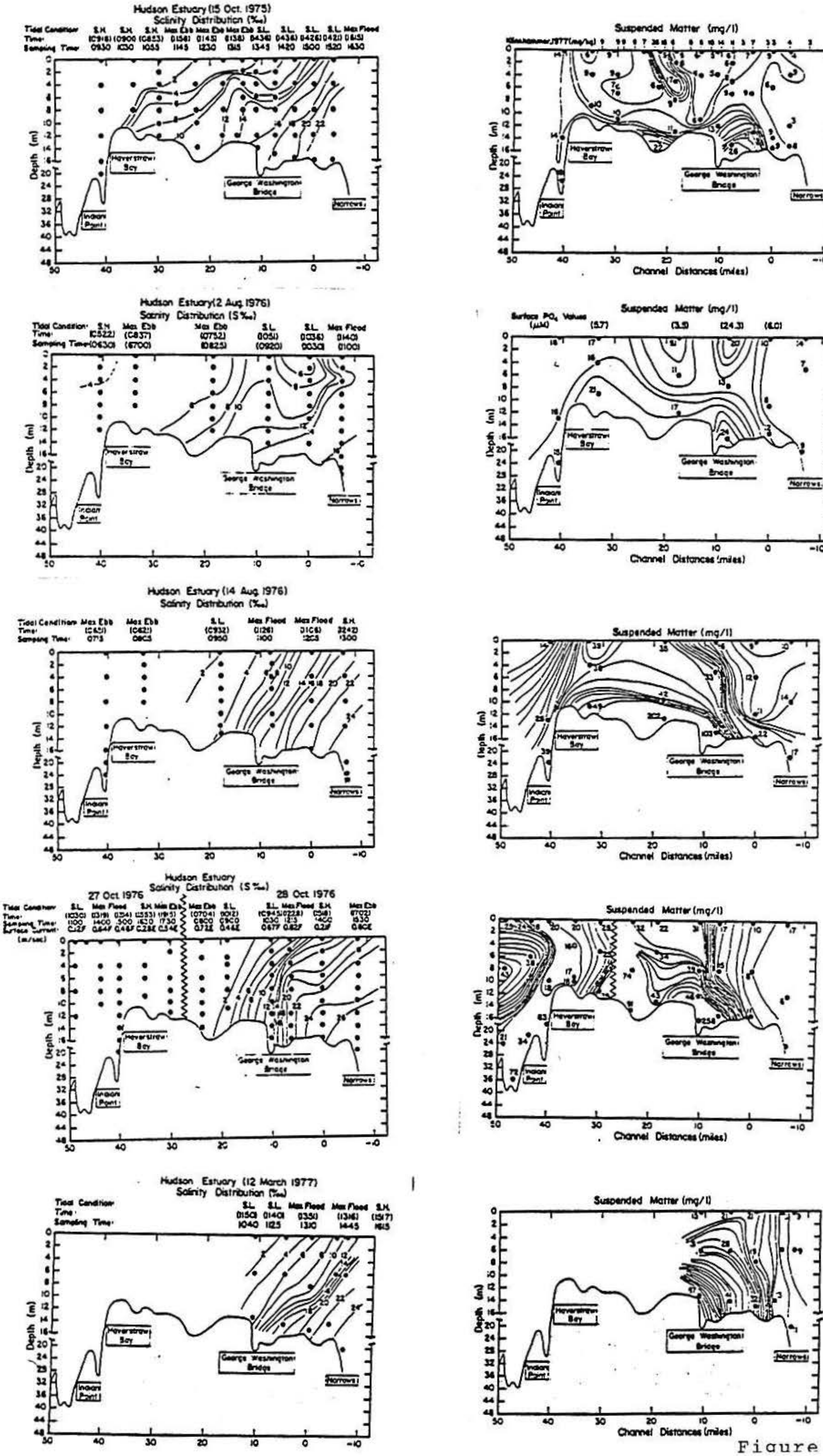
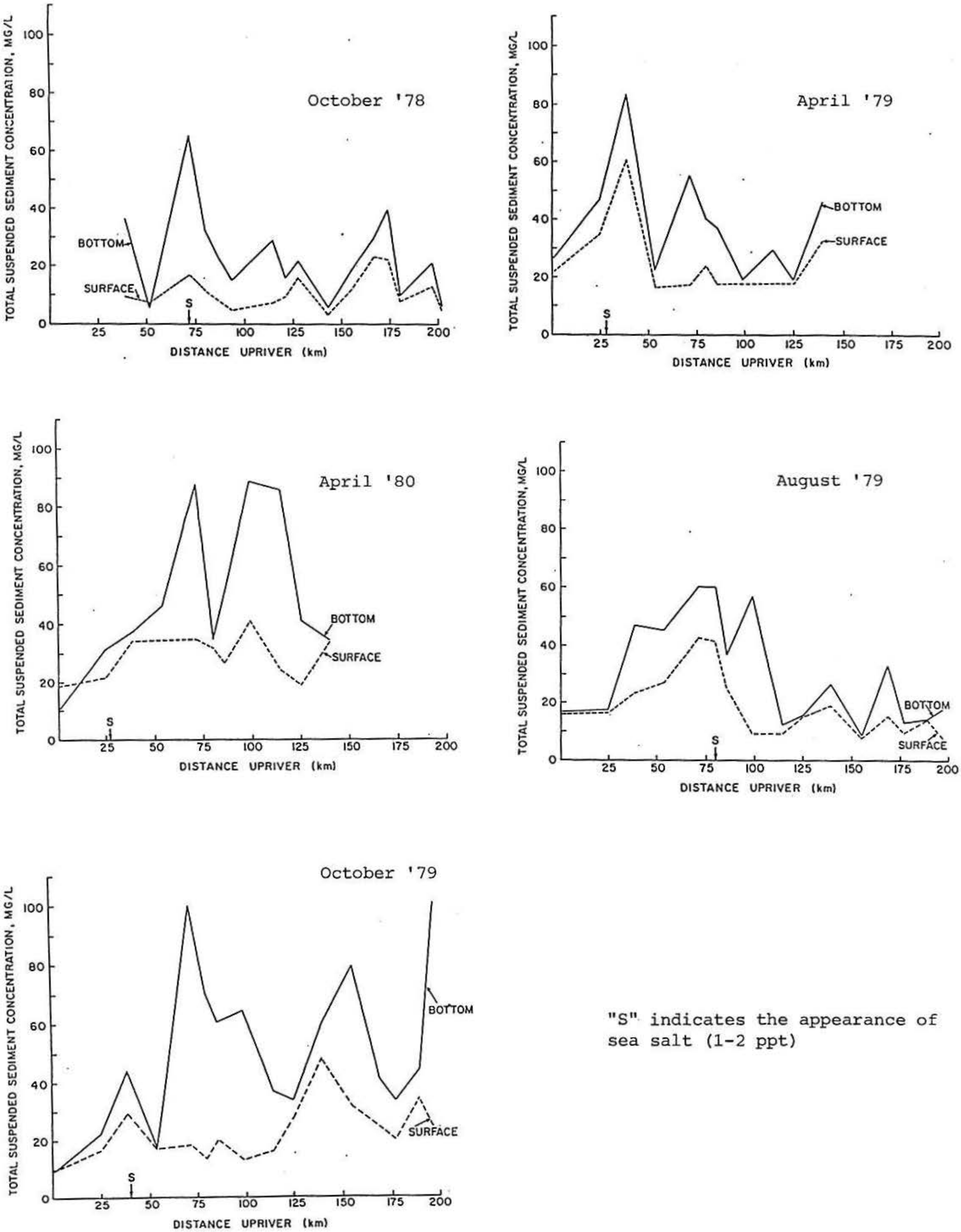

Hudson Estuary (15 Oct. 1975)
Salinity Distribution (‰)
Tidal Condition
Time
Sampling Time
Depth (m)
Haverstraw Bay
George Washington Bridge
Indian Point
Narrows
Suspended Matter (mg/l)
Channel Distances (miles)
Hudson Estuary (2 Aug. 1976)
Salinity Distribution (S ‰)
Surface PO4 Values (μM)
Hudson Estuary (14 Aug. 1976)
Salinity Distribution (‰)
Hudson Estuary
Salinity Distribution (S ‰)
27 Oct. 1976
28 Oct. 1976
Surface Current (m/sec)
Hudson Estuary (12 March 1977)
Salinity Distribution (‰)

Figure 4



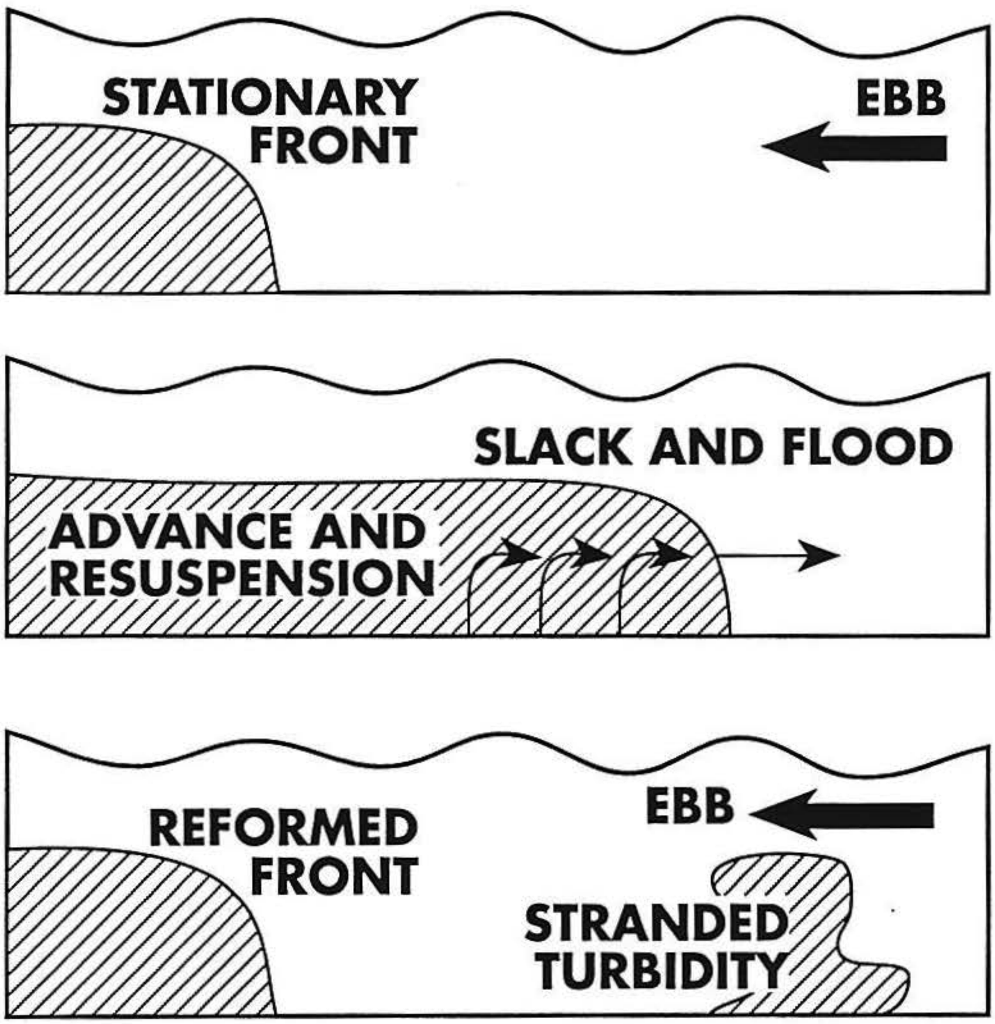
"S" indicates the appearance of sea salt (1-2 ppt)

Figure 5

levels found in the vicinity of Haverstraw Bay in the Hudson. The intense turbidity maximum south of the George Washington Bridge was more difficult to explain by the conventional wisdom although it was pointed out that the highest turbidity on the average section was found in the vicinity of strong salinity gradients.

In estuaries of the coastal plain of northern Europe, turbidity maximum have been found to be generated by asymmetry in the tidal resuspension and transport. Resuspension and transport of fine-grained sediment is highly non-linear so that distortion of the tidal signal can have a disproportionately large effect on the suspended sediment concentrations. Shallow water tidal constituents (e.g., M_3 tides) have a substantial amplitude in the Hudson and modify the basic semi-diurnal tidal behavior. However, this mechanism has not been suggested as the cause of turbidity maxima in the Hudson River estuary.

Recent research suggests another mechanism, that is the importance of frontogenesis on the formation of intense, local turbidity. A tide ebbing through a constriction in the channel's cross-sectional area arrests a bottom, salinity front in a highly stratified water column. As the tide relaxes and reverses, this front moves forward due to its higher density, resuspending sediment as it travels upstream. Resuspended sediment is trapped below the pycnocline. As the ebb tide begins again the excess turbidity is stranded and a new front forms in the original position (Figure 6). This dynamic process could explain why the turbidity maximum was not seen on some of the earlier cruises;



STATIONARY
FRONT
EBB
SLACK AND FLOOD
ADVANCE AND
RESUSPENSION
REFORMED
FRONT
EBB
STRANDED
TURBIDITY

Figure 6

their sampling distribution merely missed the sharp front. The appearance of more than one turbidity maximum could also be explained by the stranding of turbid water masses on successive tides. The data presented in this report supports this hypothesis.

Methods

The data described in this report were gathered as part of a project whose focus was the description of the suspended sediment distribution within the Hudson estuary. The data derive from two sets of cruises in the lower Hudson, in early September 1992, and in late April 1993. Measurements included vertical profiles of salinity and optical backscatter with water bottle (500 ml) sampling at specific depths. Water samples were filtered completely through preweighed 0.45 micrometer nucleopore filters, rinsed with distilled water three times, air dried and desiccated, then weighted to one hundred-thousandth of a gram. In this report, we present contour plots of salinity, optical backscatter, and suspended sediment concentration quantities over different transects. Finally, the relationships between suspended sediment concentration and salinity and optical backscatter are investigated. (Vertical profiles of salinity, optical backscatter, and suspended sediment concentrations are presented in an accompanying data report.)

The study area for this series of cruises encompasses the lower Hudson estuary and Upper New York Bay (Figure 7). The September 1992 sampling program consisted of two transects on each of two days, September 8 (Figure 8) and September 10 (Figure

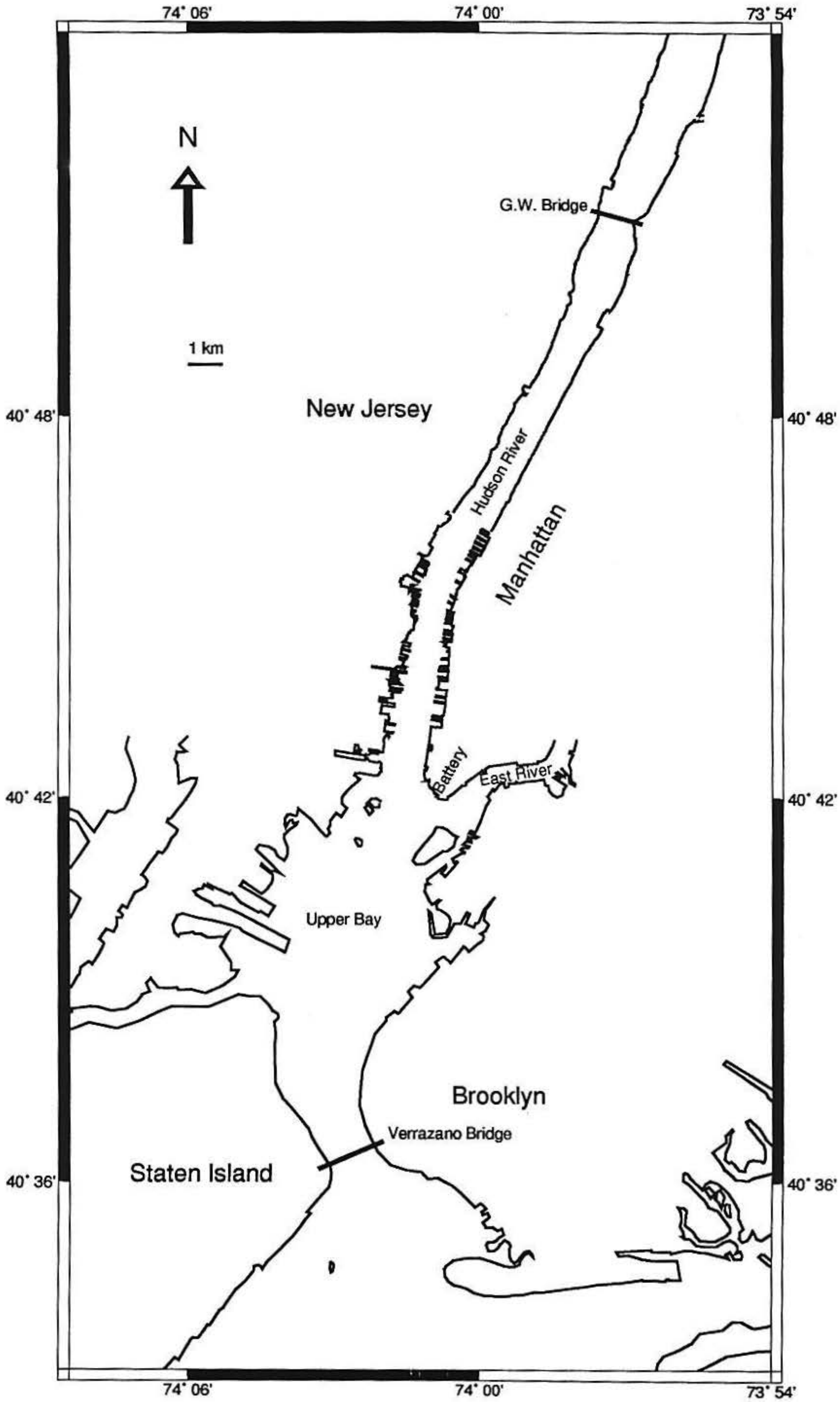

74° 06'
74° 00'
73° 54'
N
G.W. Bridge
1 km
New Jersey
40° 48'
Hudson River
Manhattan
Battery
East River
40° 42'
Upper Bay
Brooklyn
Verrazano Bridge
Staten Island
40° 36'

Figure 7

September 8 transects

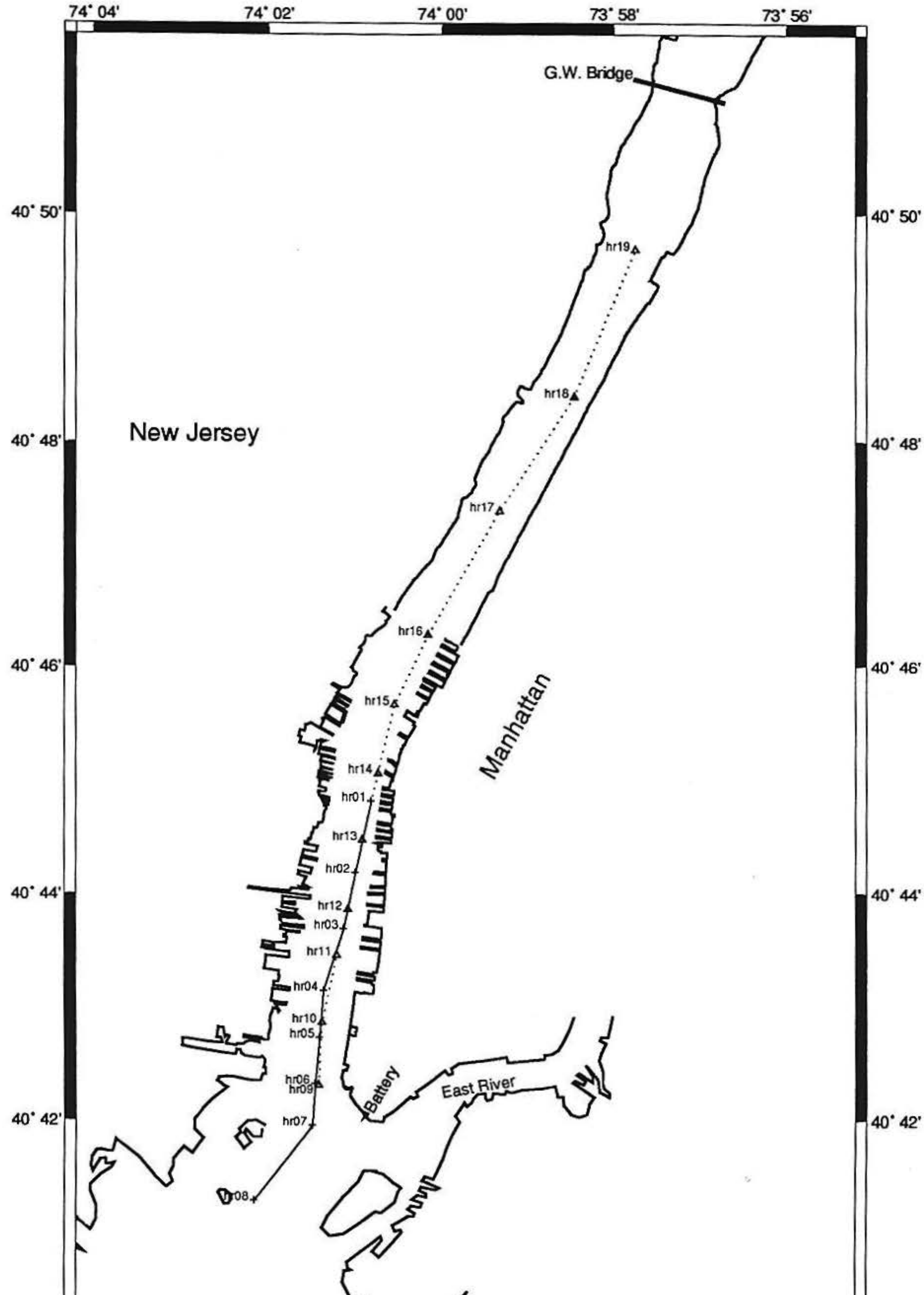


Figure 8

9). The April 1993 program involved two transects on April 28 (Figure 10), three transects on April 29 (Figure 11), and three transects on April 30 (Figure 12). Information about start times and end times for each transect can be found in Table 1.

At each station, suspended sediment concentrations were measured by taking water samples at 4 or 5 depths, then filtering and weighing the filtered sediment. Profiles were measured with a Seabird, Seacat CTD, which is equipped with a pumped conductivity cell and an optical backscatter sensor. In this report, optical backscatter is given in relative units because no *in sutu* calibration was performed.

Contour plots and scatter plots were constructed from vertical profiles (downcasts) of salinity, optical backscatter, and suspended sediment concentrations, except for Stations HR02, HR03, HR04, and HR05 on September 8, 1992 for which CTD data were not obtained. Examination of these plots reveals occasional instances of unrealistic profiles, typically involving salinity. These are thought to be due to clogging of the conductivity cell pump system. Table 2 lists those stations for which data corresponding to one or more variables were determined to be in error. These data were not included in this report.

RESULTS AND DISCUSSION

Figures 13-16 are contour plots of salinity, optical backscatter and suspended sediment concentrations on a vertical depth-distance plane for each of the four September transects. Distances were measured from the Verrazano-Narrows Bridge (VZB). Transect 1 on September 8 (Figure 13) was sampled at the end of

September 10 transects

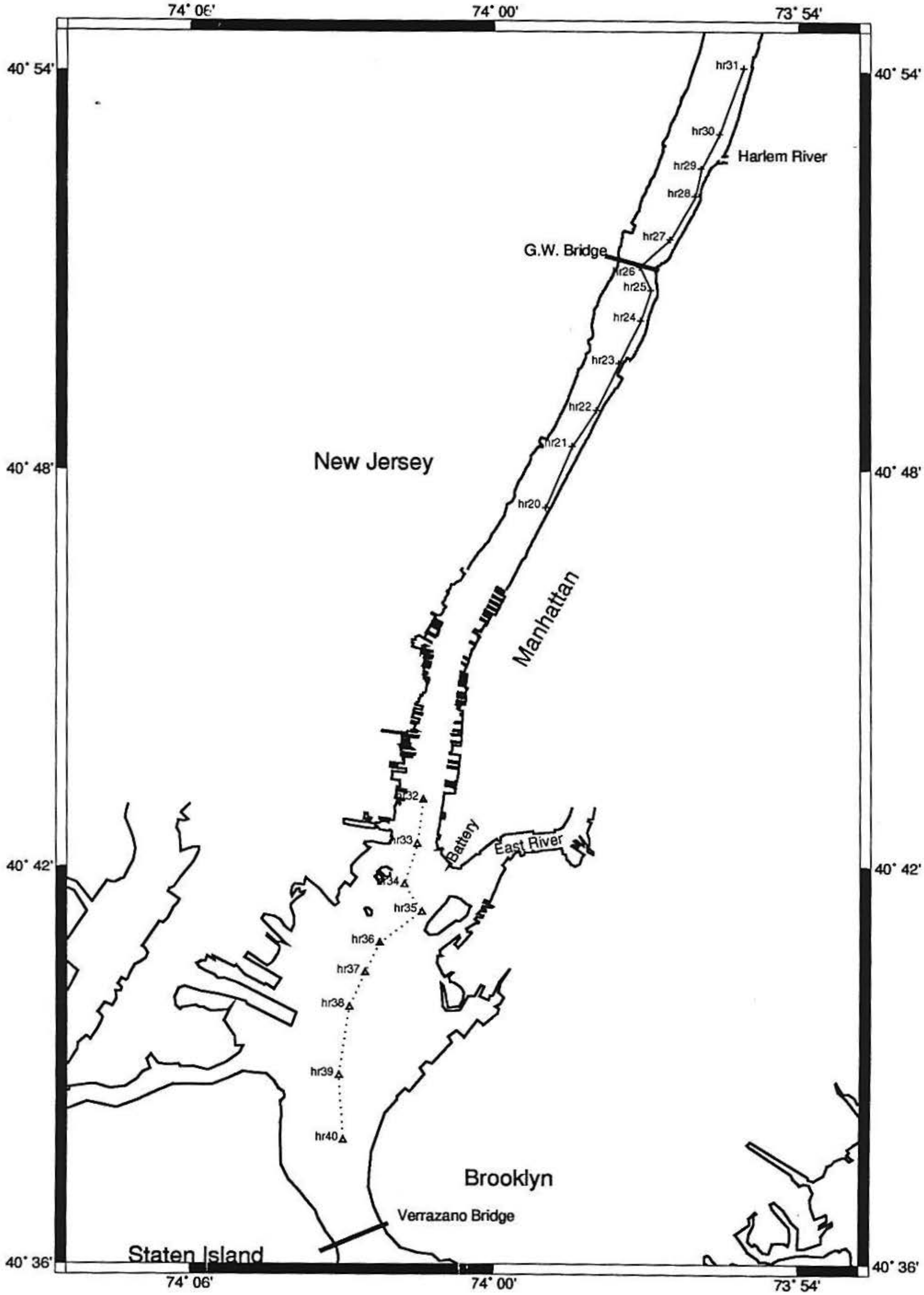


Figure 9

April 28 transects

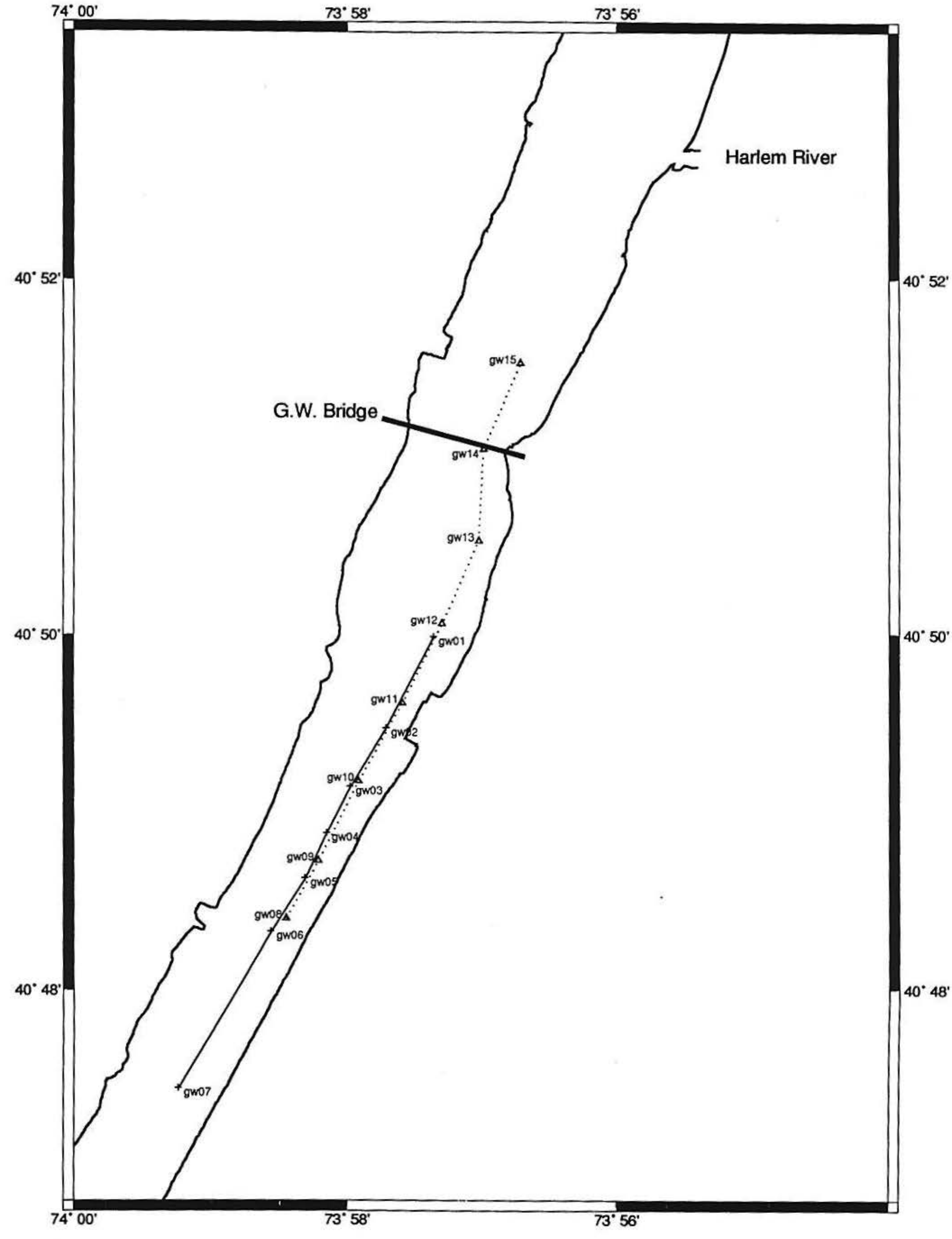


Figure 10

April 29 transects

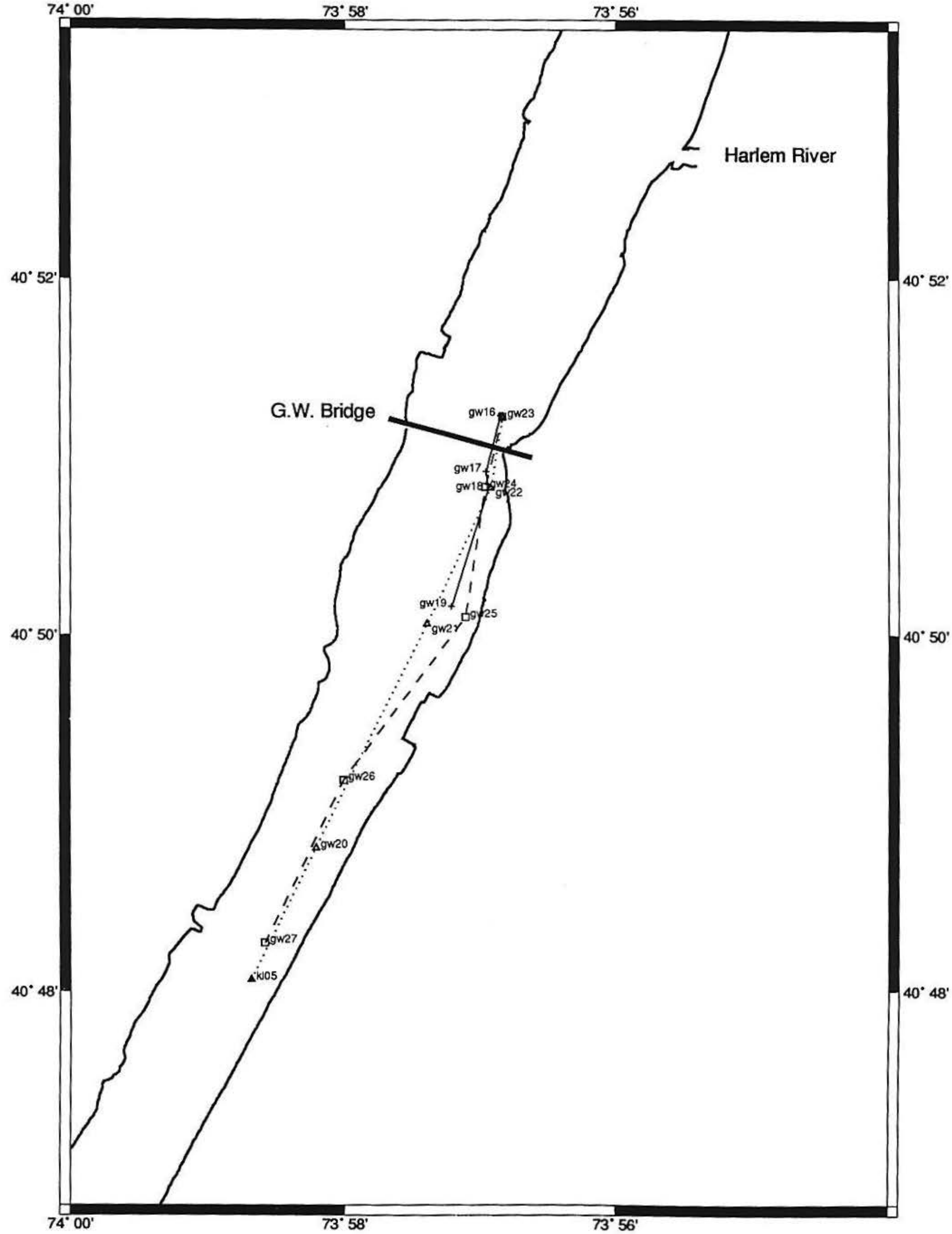


Figure 11

April 30 transects

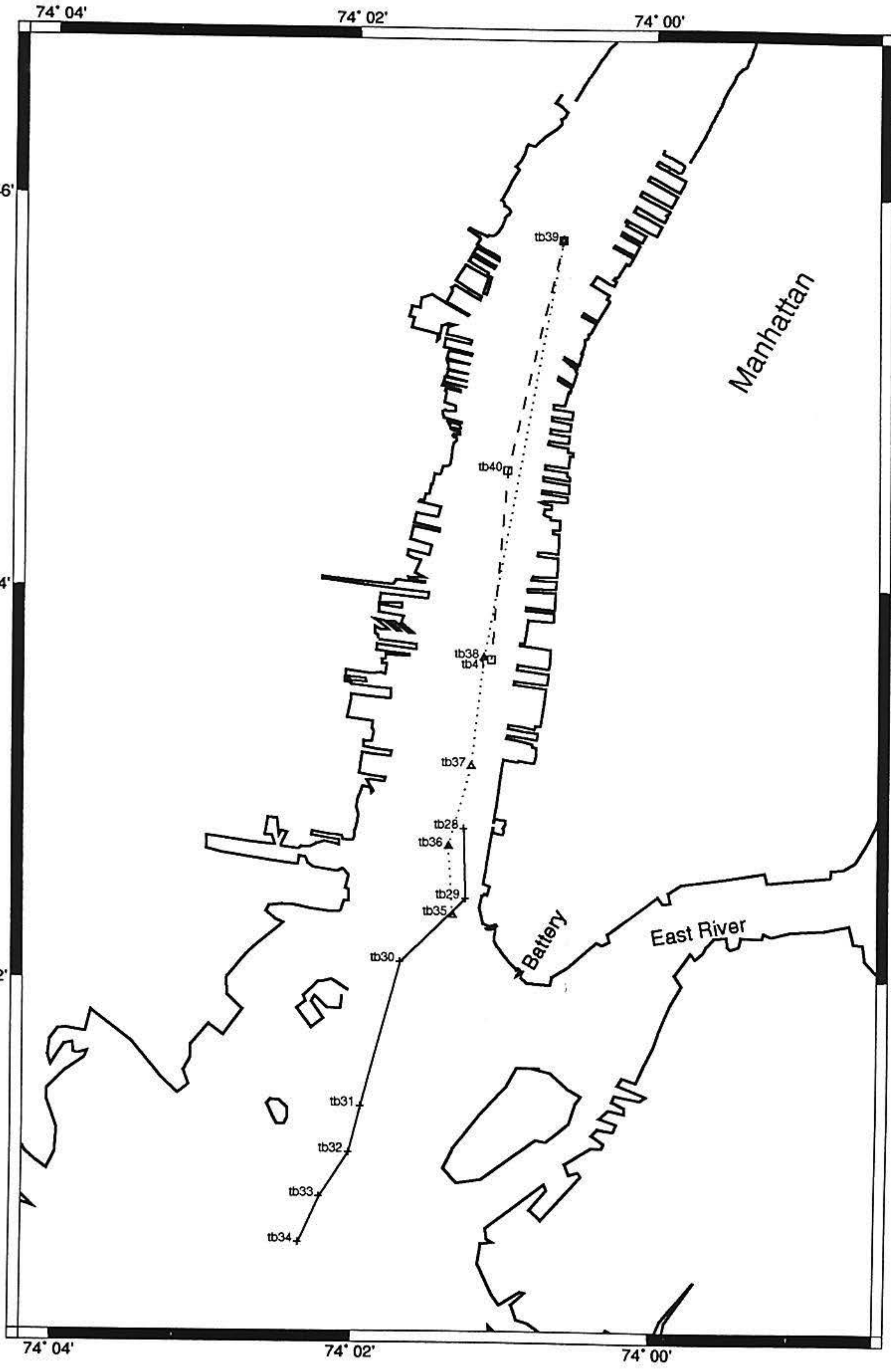


Figure 12

Table 1. Transect Information

date	transect #	start time (EDT)	end time (EDT)	direction
Sept. 8, 1992	1	14:00	16:15	south
Sept. 8, 1992	2	16:28	18:40	north
Sept. 10, 1992	1	07:20	10:11	north
Sept. 10, 1992	2	11:45	13:38	south
Apr. 28, 1993	1	07:58	08:52	south
Apr. 28, 1993	2	13:10	14:11	north
Apr. 29, 1993	1	09:20	10:30	south
Apr. 29, 1993	2	13:16	14:34	north
Apr. 29, 1993	3	14:34	15:20	south
Apr. 30, 1993	1	10:28	11:30	south
Apr. 30, 1993	2	12:25	13:37	north
Apr.30, 1993	3	13:37	14:08	south

Table 2. Questionable profiles

date	station	measured quantity
Sept. 8, 1992	hr01	OBS
Sept. 8, 1992	hr14	salinity
Sept. 8, 1992	hr17	salinity
Sept. 10, 1992	hr36	salinity
Apr. 28, 1993	gw01	salinity
Apr. 29, 1993	gw16	salinity
Apr. 29, 1993	gw17	salinity
Apr. 29, 1993	gw22	salinity

09/08/92 transect 1
14:00 - 16:15
Battery low: 12:48
Battery high: 19:04

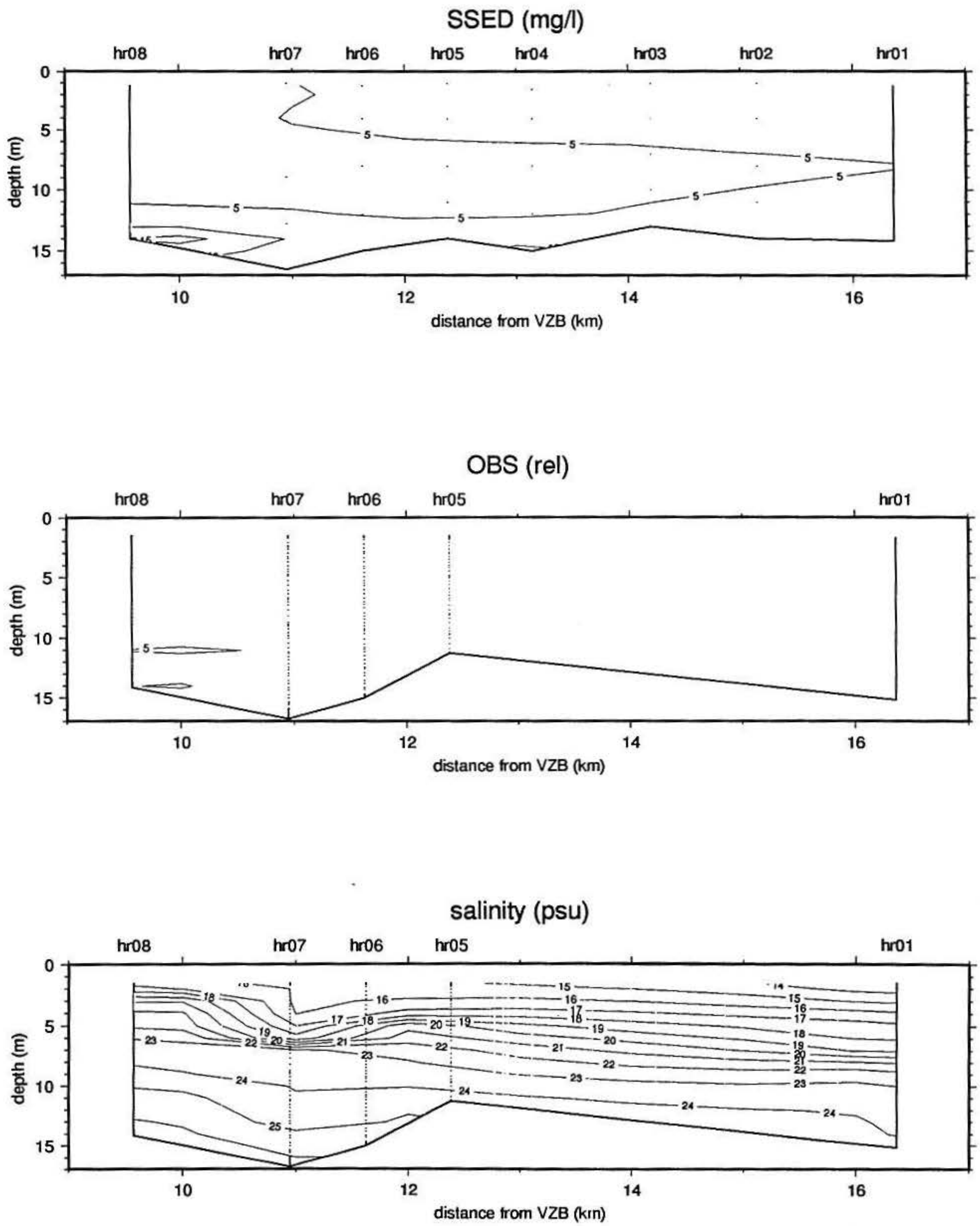
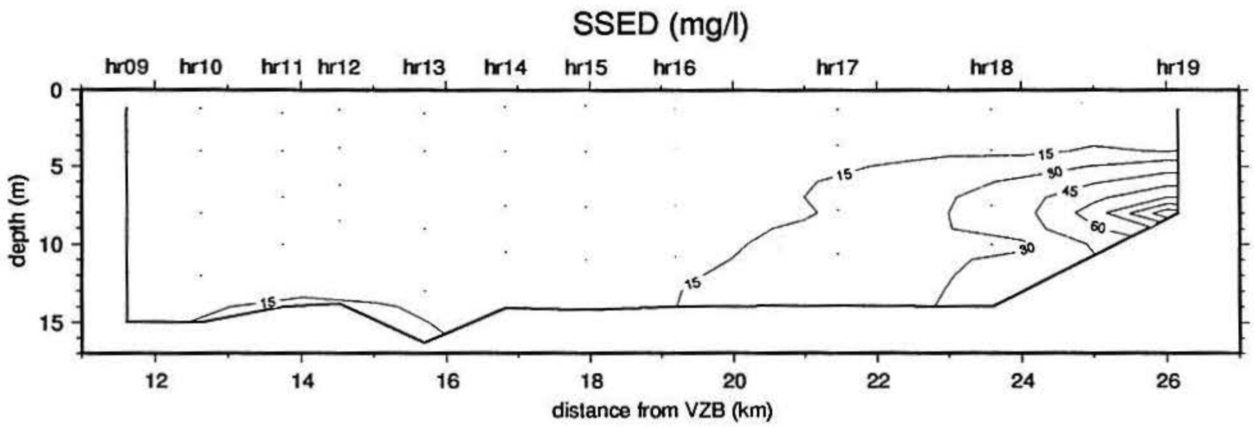


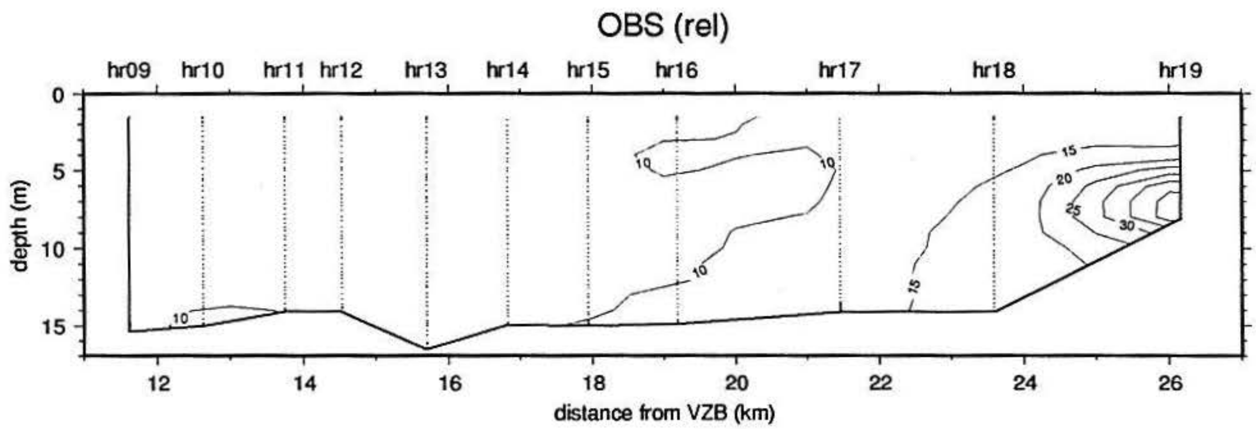
Figure 13

ebb. Stratification was moderate and extended to the bottom. Optical backscatter values and suspended sediment concentrations were low throughout, with highest values being associated with the saltiest water at Station HR08. Transect 2 (Figure 14) on the same day was occupied during early flood. The salinity field showed that a bottom well mixed layer has started to develop with strong stratification above. Optical backscatter values and suspended sediment concentrations were low except at the northernmost end of the transect, several kilometers south of the George Washington Bridge, where values near the bottom reached about 50 mg/l. We interpret this to be the beginning of the salt-front intrusion on the bottom and associated resuspension. The feature was better captured on September 10.

Transect 1 on September 10 (Figure 15) corresponds to approximately maximum flood current. Stratification was reduced relative to September 8, possibly due to increased tidal mixing associated with stronger spring tidal currents. Highest optical backscatter and suspended sediment concentrations were again found in the region just south of the George Washington Bridge. At this time, well into the flooding tide, the salinity front would have spread itself upstream as shown by the near bottom salinity contours. The turbidity maximum near a salinity of 19 psu may have also been beginning to be dispersed by the strong tidal currents. It appeared that the suspended sediment distribution may be more vertically well mixed than on September 8. Transect 2 (Figure 16) in the upper bay during early ebb displays the same reduced stratification observed in Transect 1. Optical backscatter and suspended sediment concentrations were

09/08/92 transect 2
16:28 - 18:40
Battery low: 12:48
Battery high: 19:04





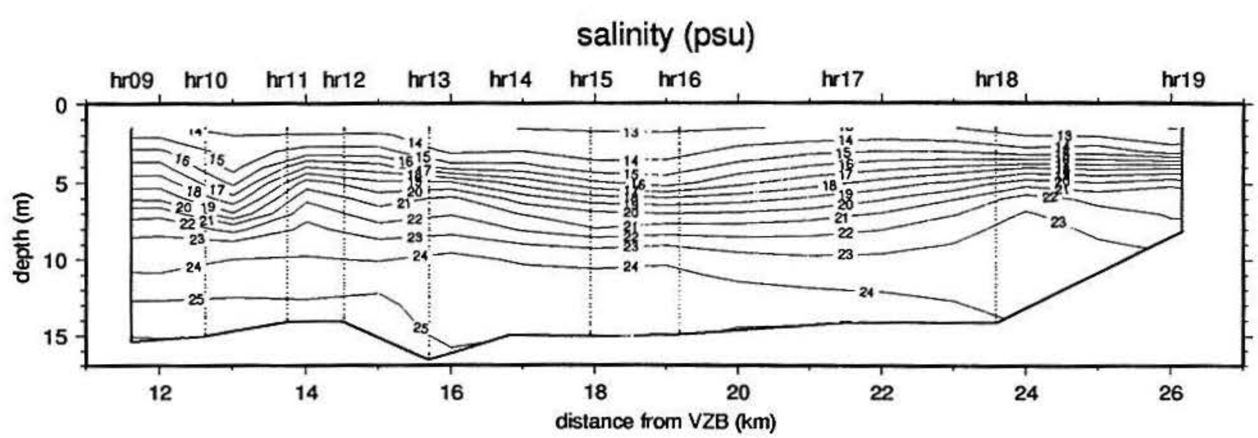


Figure 14

09/10/92 transect 1
07:20 - 10:11
Battery high: 08:12
Battery low: 14:17

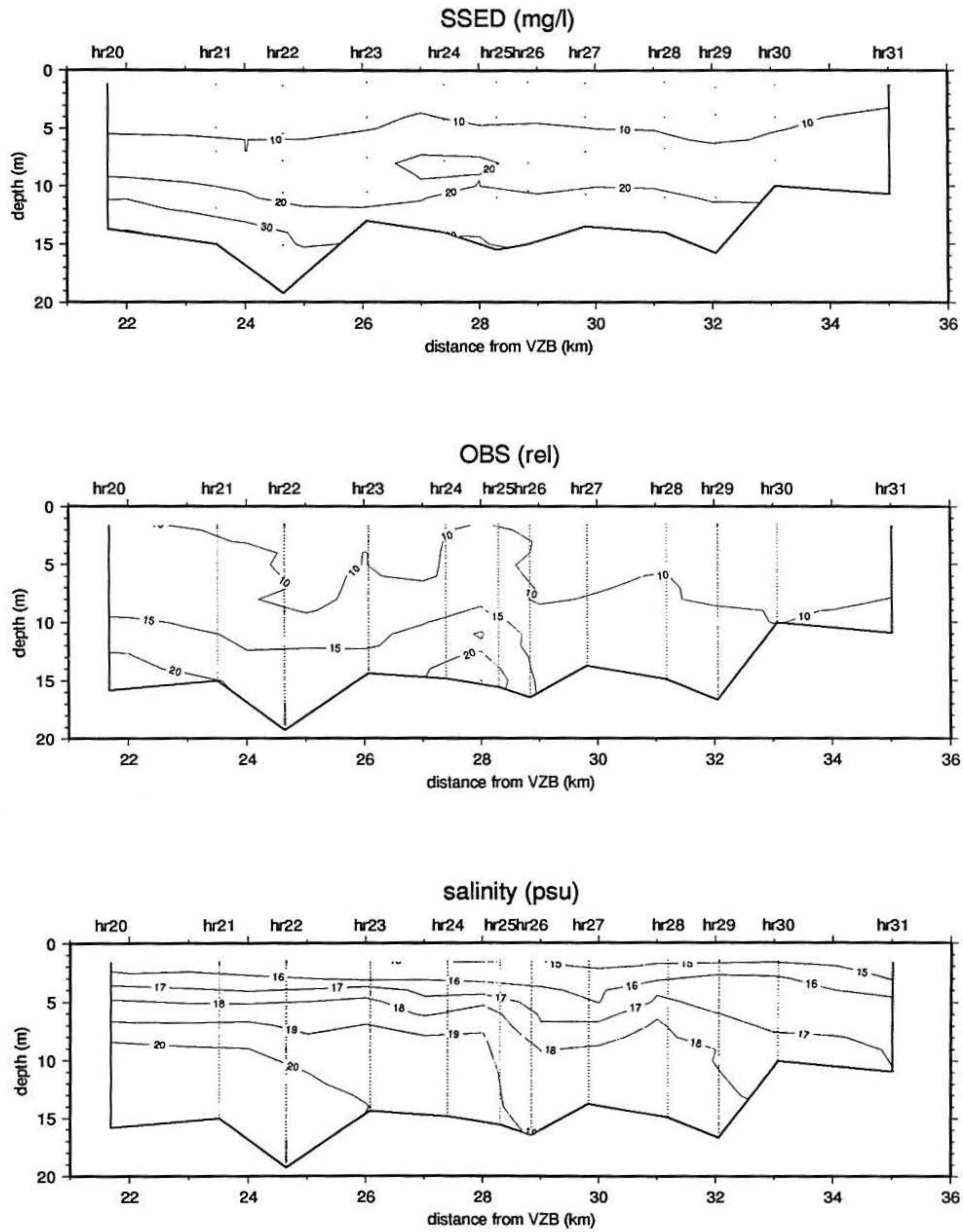
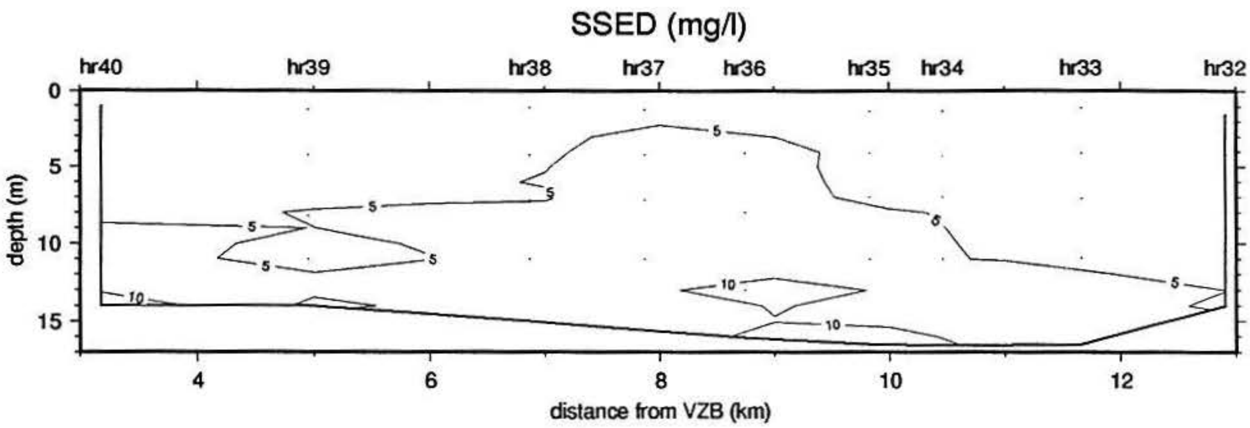
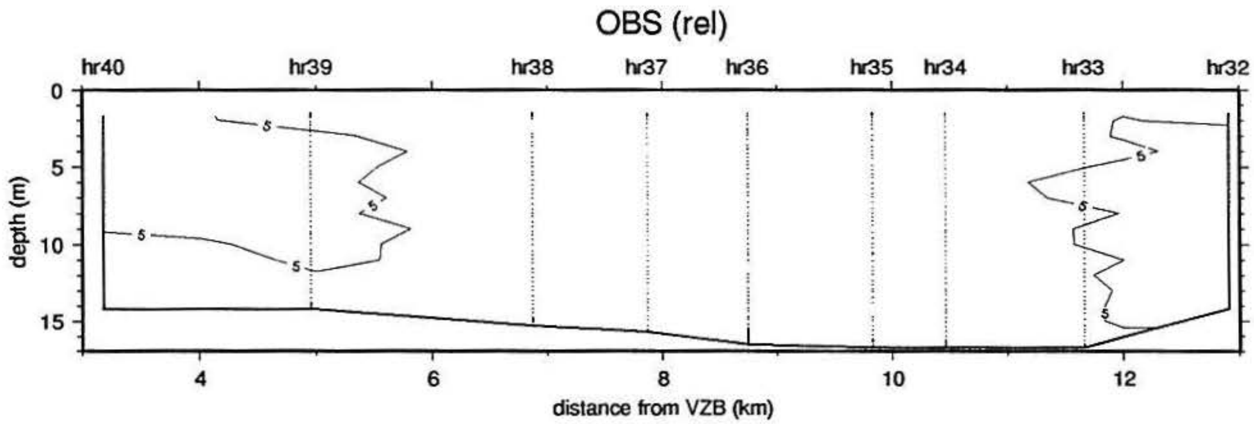


Figure 15

09/10/92 transect 2
11:45 - 13:38
Battery high: 08:12
Battery low: 14:17





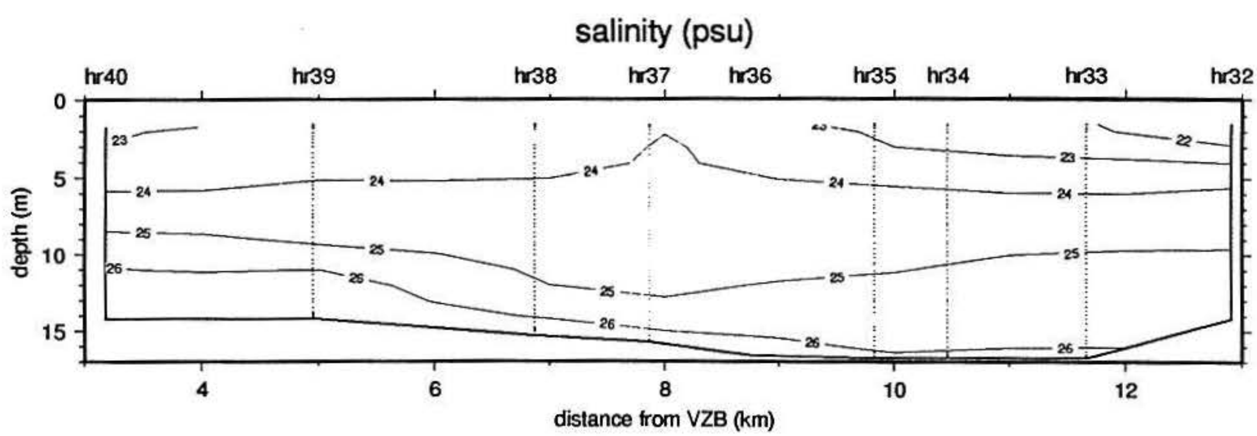


Figure 16

very low throughout. This section was near the Battery and the salinity and turbidity structure seen further up-estuary on the previous transect either had not developed or had been dispersed by the flooding tide.

Contour plots for the April 1993 cruise (Figures 17-24) reveal much stronger salinity stratification than was observed in September 1992. Near surface water is nearly fresh reflecting the strong, spring river flow.

Transect 1 on April 28, 1993 was located just south of the George Washington Bridge and was sampled at approximately maximum ebb (Figure 18). Optical backscatter and suspended sediment concentrations were generally higher than those recorded in September, perhaps reflecting contributions from increased river runoff. As in September, highest values are seen several kilometers south of the bridge near Grant's Tomb. They were associated with a bottom salinity front and strong vertical stratification. Transect 2 (Figure 19) on the same day is a longer transect in the same area during early flood tide. There is evidence of the development of a bottom, well-mixed layer in the northernmost part of the transect, with very strong stratification above. Very high suspended sediment concentrations values were observed near the bottom particularly at the southern end of the transect. Presumably, this was sediment resuspended by the intruding front and trapped beneath the pycnocline. Optical backscatter values were also high, but the increase observed from Transect 1 was less than that observed in suspended sediment concentrations.

04/28/93 transect 1
07:58 - 08:52
Battery low: 07:44
Battery high: 14:03

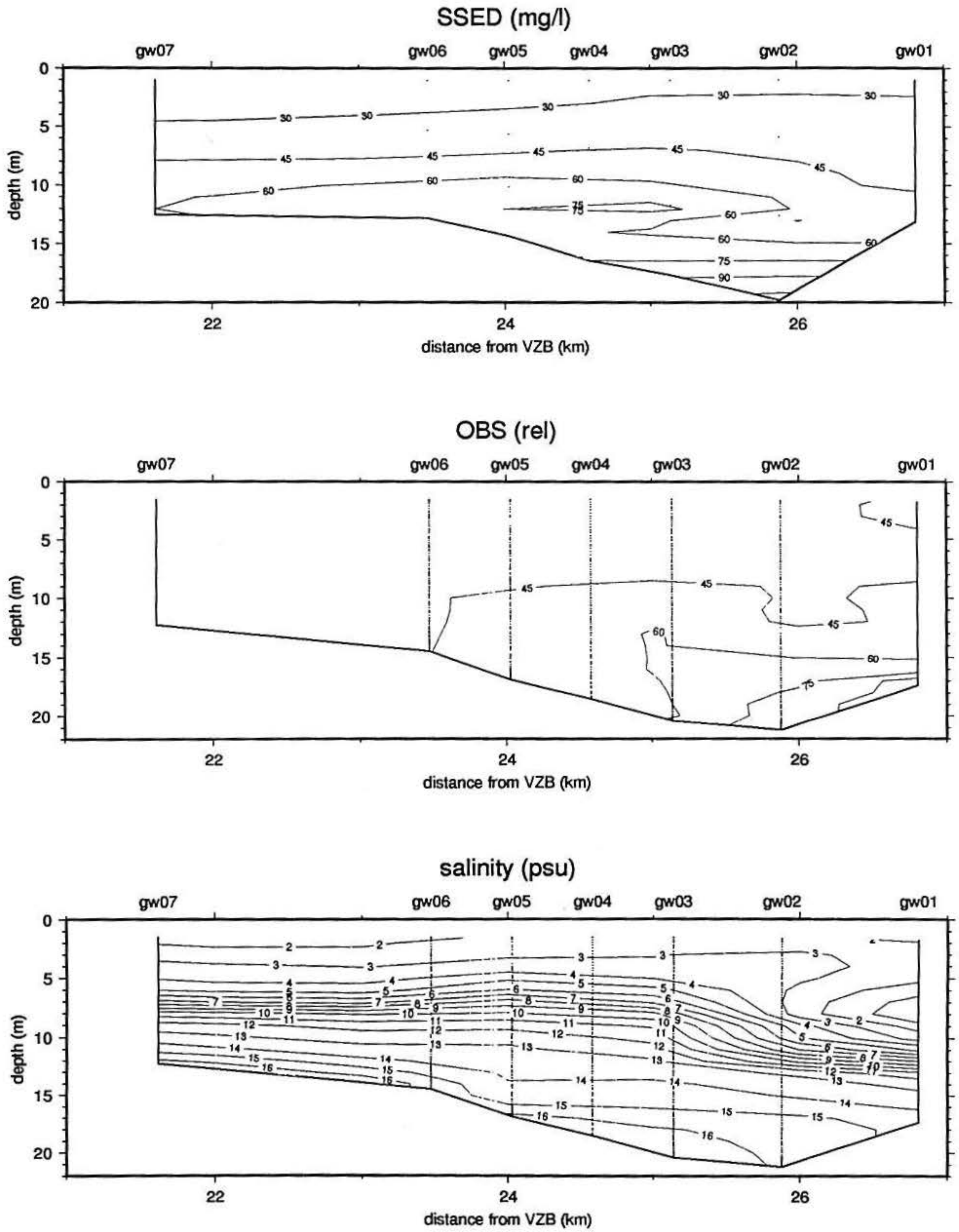


Figure 17

04/28/93 transect 2
13:10 - 14:11
Battery low: 07:44
Battery high: 14:03

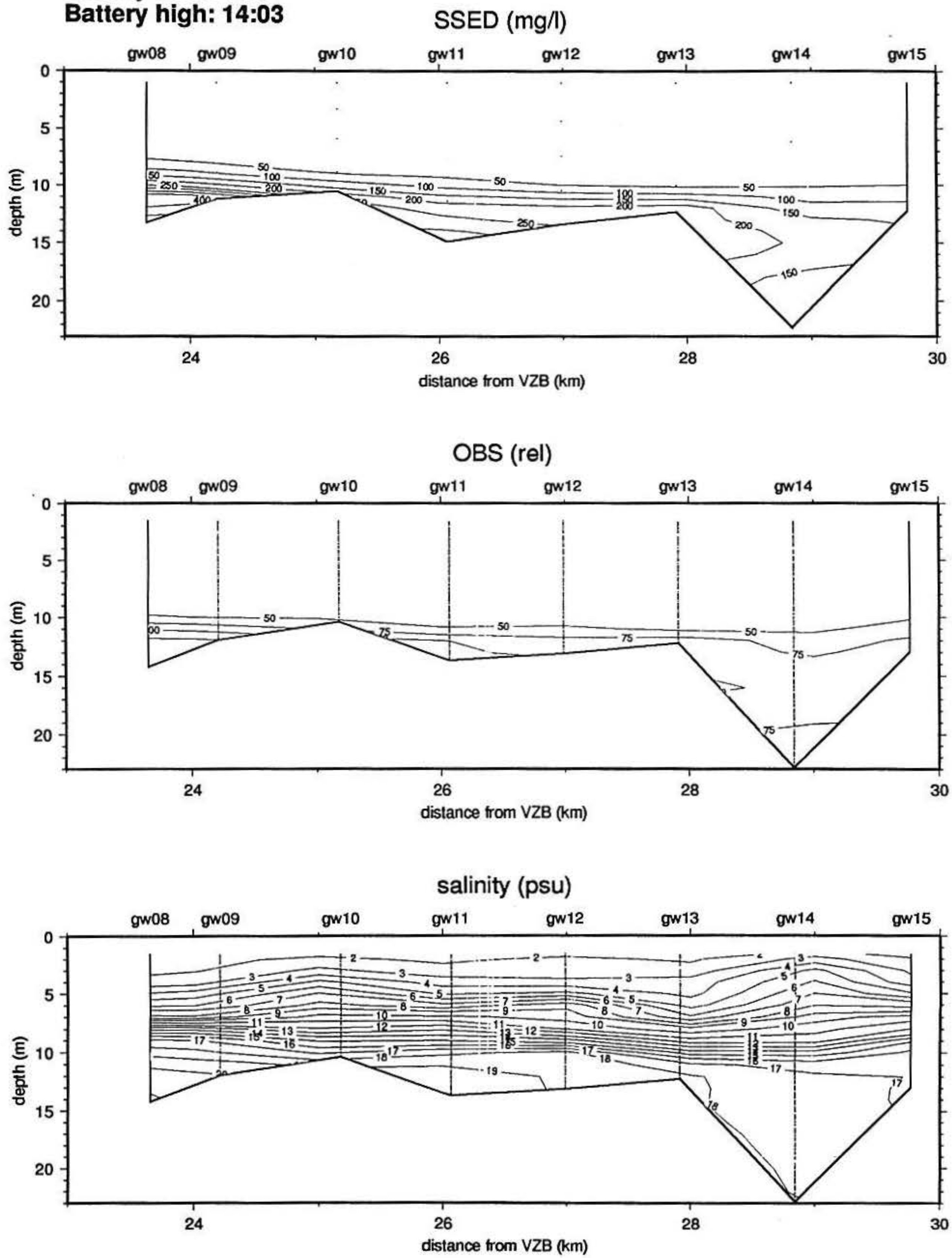
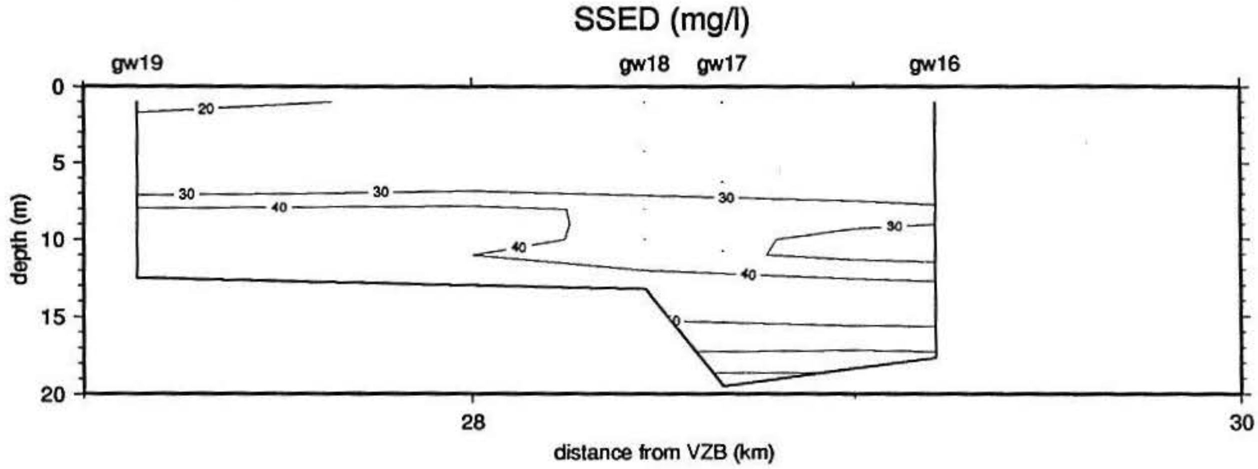
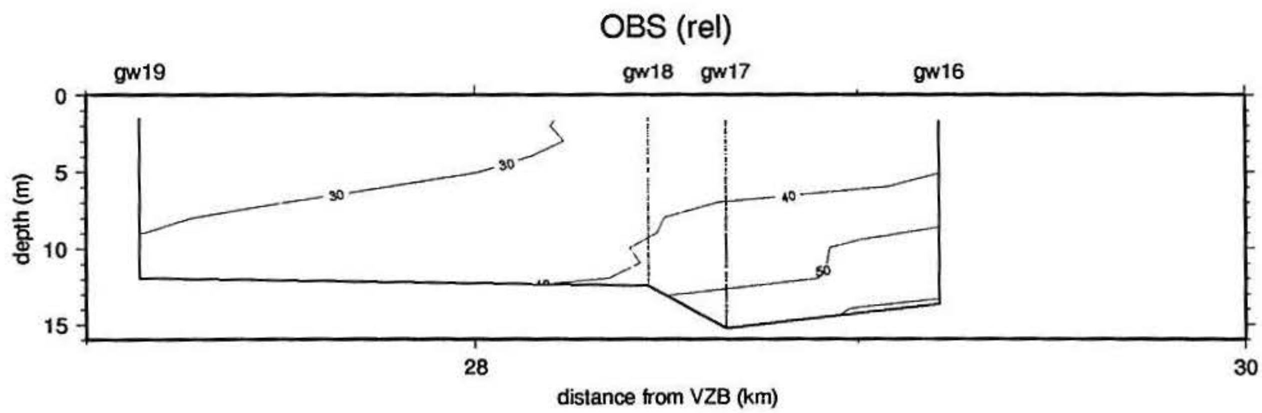


Figure 18

04/29/93 transect 1
09:20 - 10:30
Battery low: 09:02
Battery high: 15:05





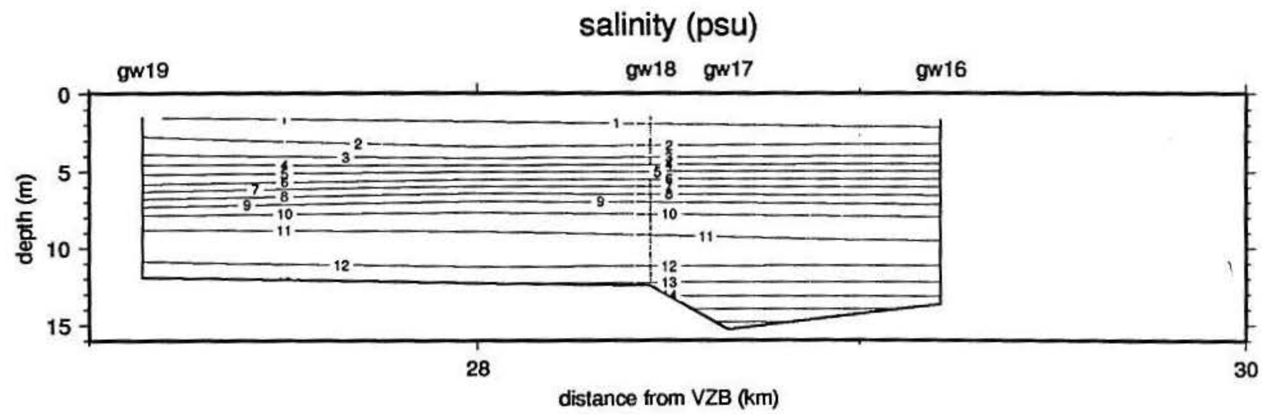
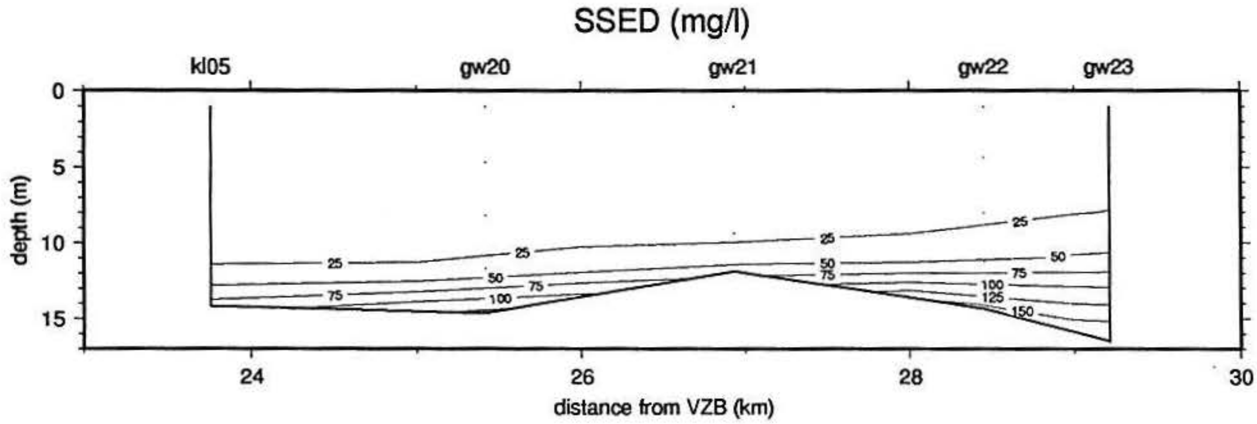


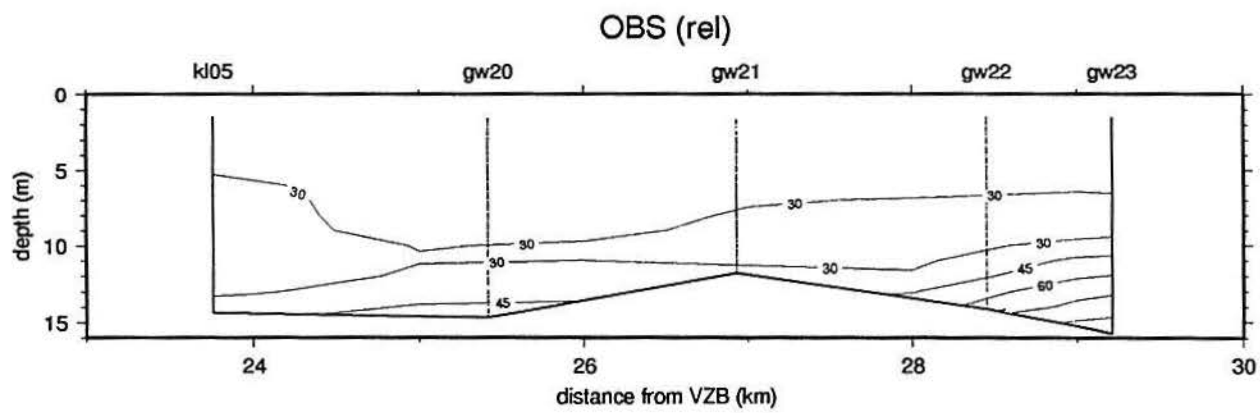
Figure 19

Transect 1 on April 29 (Figure 19) was carried out in the vicinity of the George Washington Bridge slightly after the time of maximum ebb current. Salinity contours are unreliable since salinity profiles at Stations GW16 and GW17 were rejected as unrealistic. Highest optical backscatter and suspended sediment concentrations were found near the bottom at the George Washington Bridge. Transect 2 (Figure 20) in the same vicinity during early flood revealed strong stratification extending to the bottom. Optical backscatter and suspended sediment concentrations were high near the bottom (100 mg/l) with the maximum found near the Bridge as before. Transect 3 (Figure 21) around maximum flood, also in the same area, reveals evidence of a bottom mixed layer at each end of the transect. The absence of a well mixed layer near the bottom at Station GW25 is puzzling, but may be due to the fact that this station is very close to shore. Very high (300 mg/l) suspended sediment concentrations were observed in the southernmost part of the transect.

Transects on April 30 were all made near lower Manhattan (Figures 22-24). Transect 1 in the vicinity of the Battery at approximately maximum ebb exhibited strong stratification throughout the water column and generally low optical backscatter and suspended sediment concentrations (less than 15 mg/l). Interestingly, however, the suspended sediment concentration was relatively uniform with depth. Transect 2 on the same day reached further north than Transect 1 and was occupied during late ebb. Vertical stratification was again uniform while optical backscatter and suspended sediment concentrations exhibited a maximum at Station TB39. These values (100 mg/l) are

04/29/93 transect 2
13:16 - 14:34
Battery low: 09:02
Battery high: 15:05





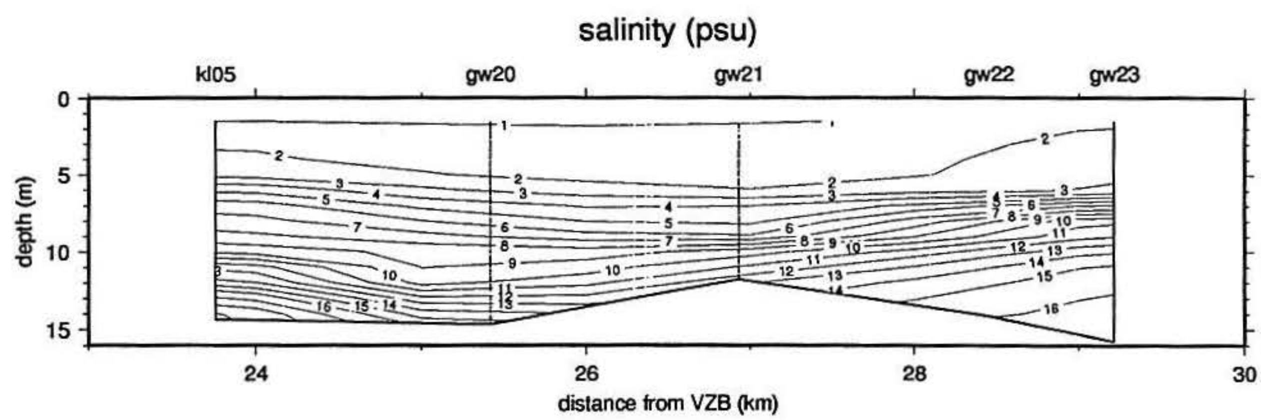


Figure 20

04/29/93 transect 3
14:34 - 15:20
Battery low: 09:02
Battery high: 15:05

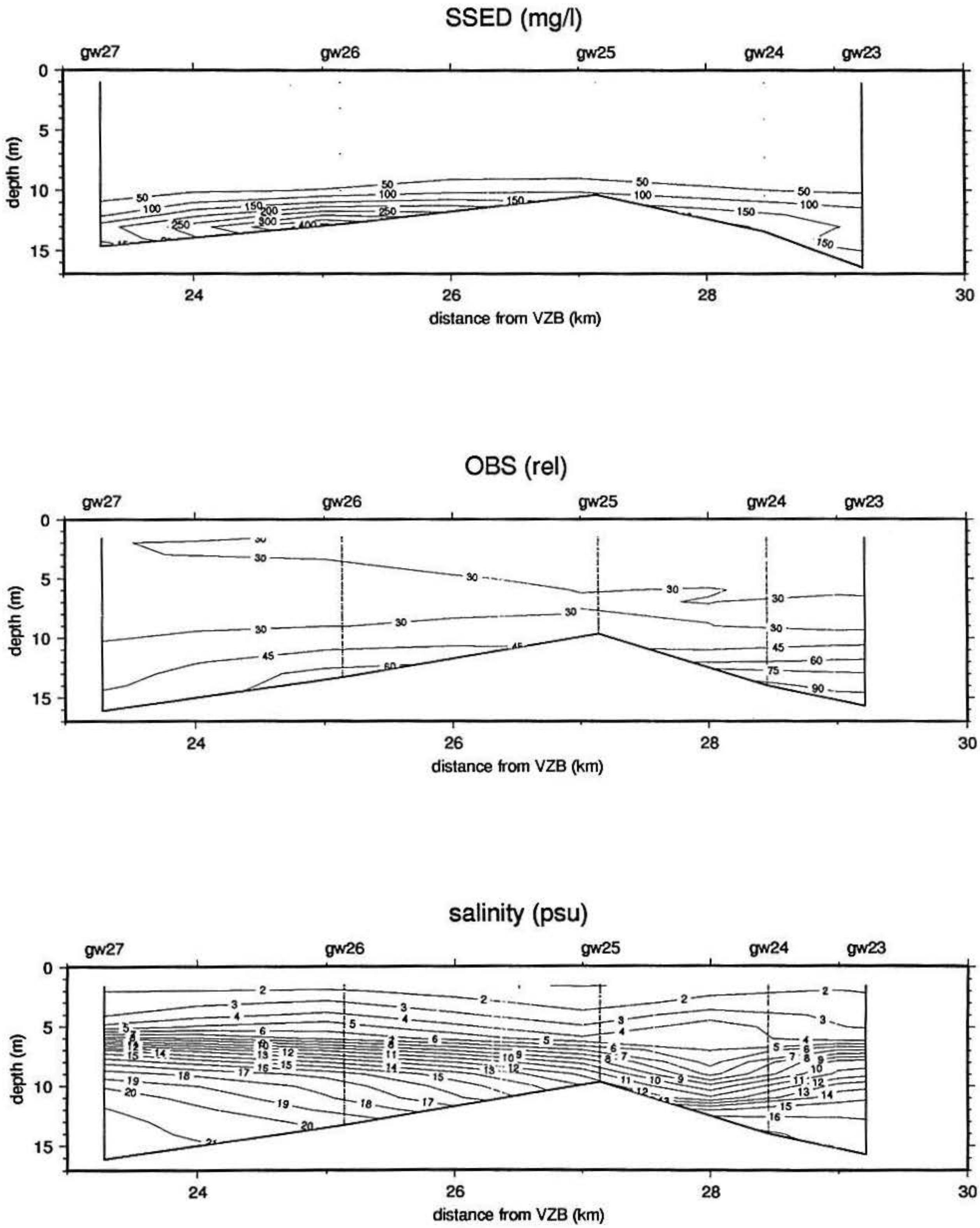


Figure 21

04/30/93 transect 1
10:28 - 11:30
Battery low: 10:08
Battery high: 16:08

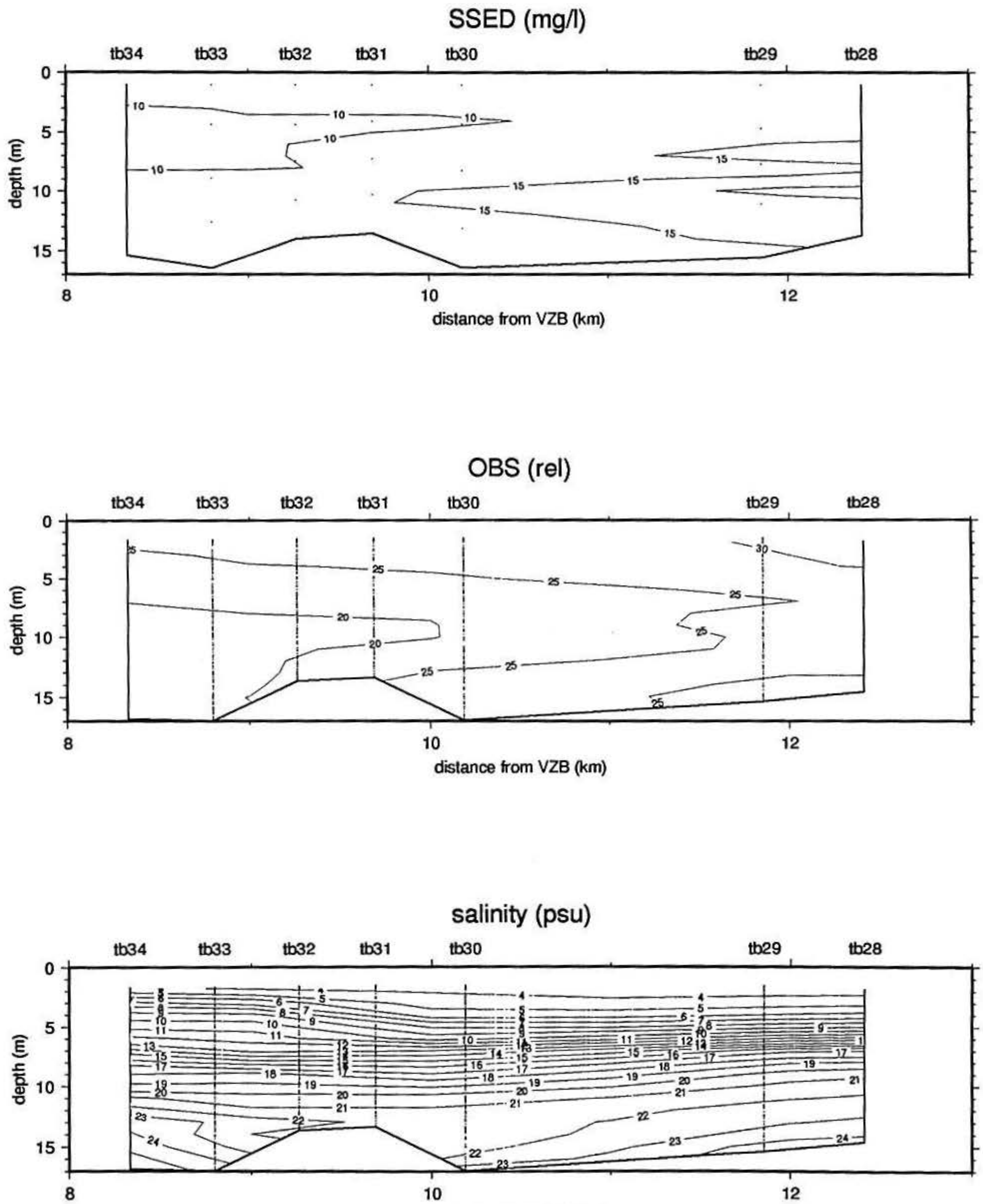


Figure 22

04/30/93 transect 2
12:25 - 13:37
Battery low: 10:08
Battery high: 16:08

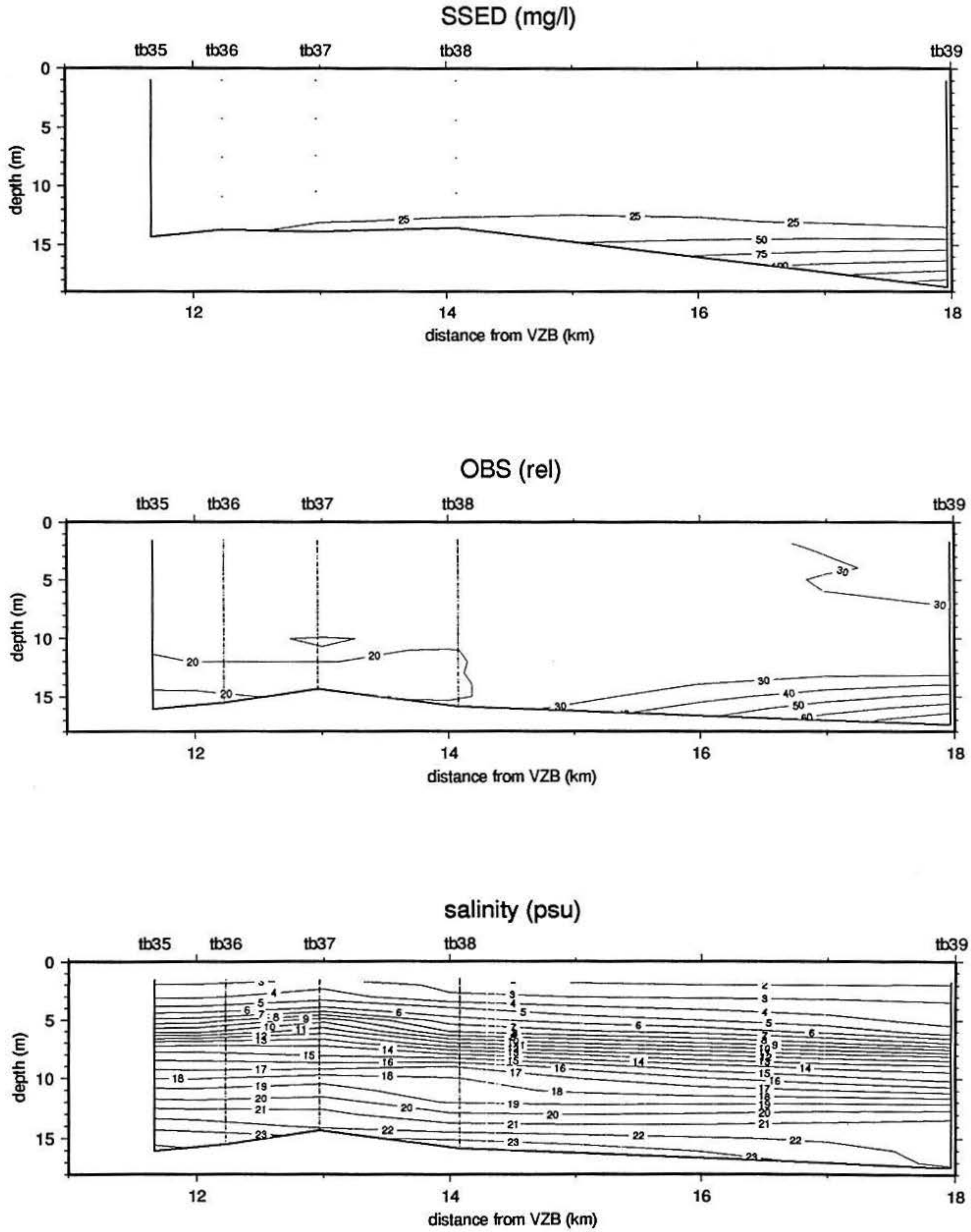
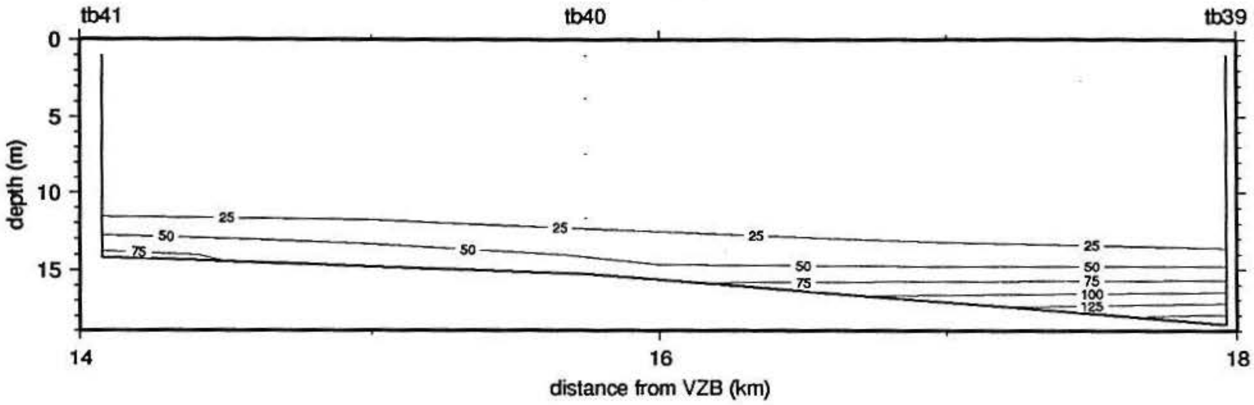


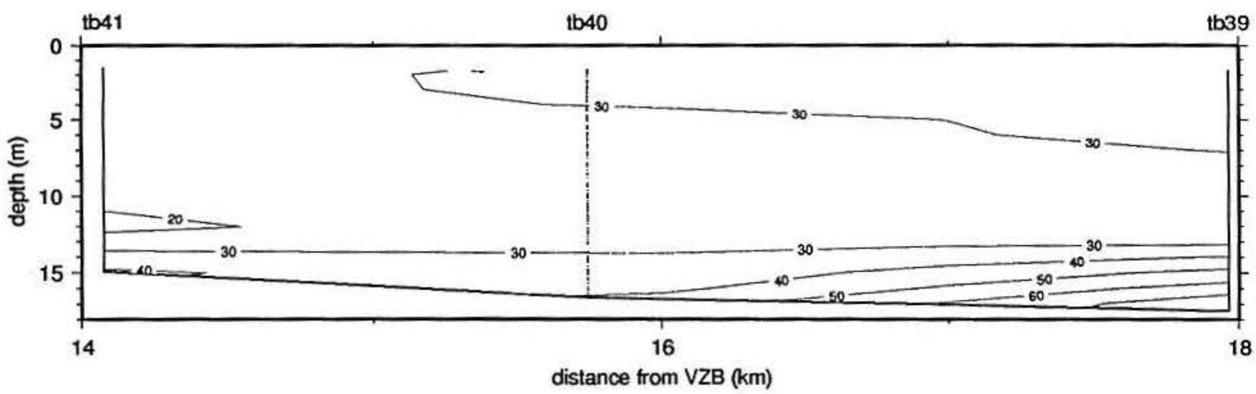
Figure 23

04/30/93 transect 3
13:37 - 14:08
Battery low: 10:08
Battery high: 16:08

SSED (mg/l)



OBS (rel)



salinity (psu)

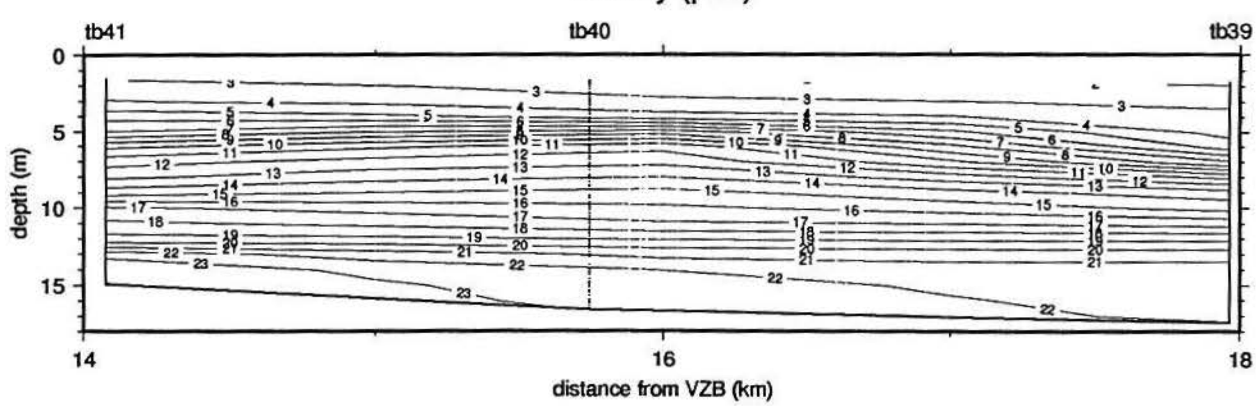


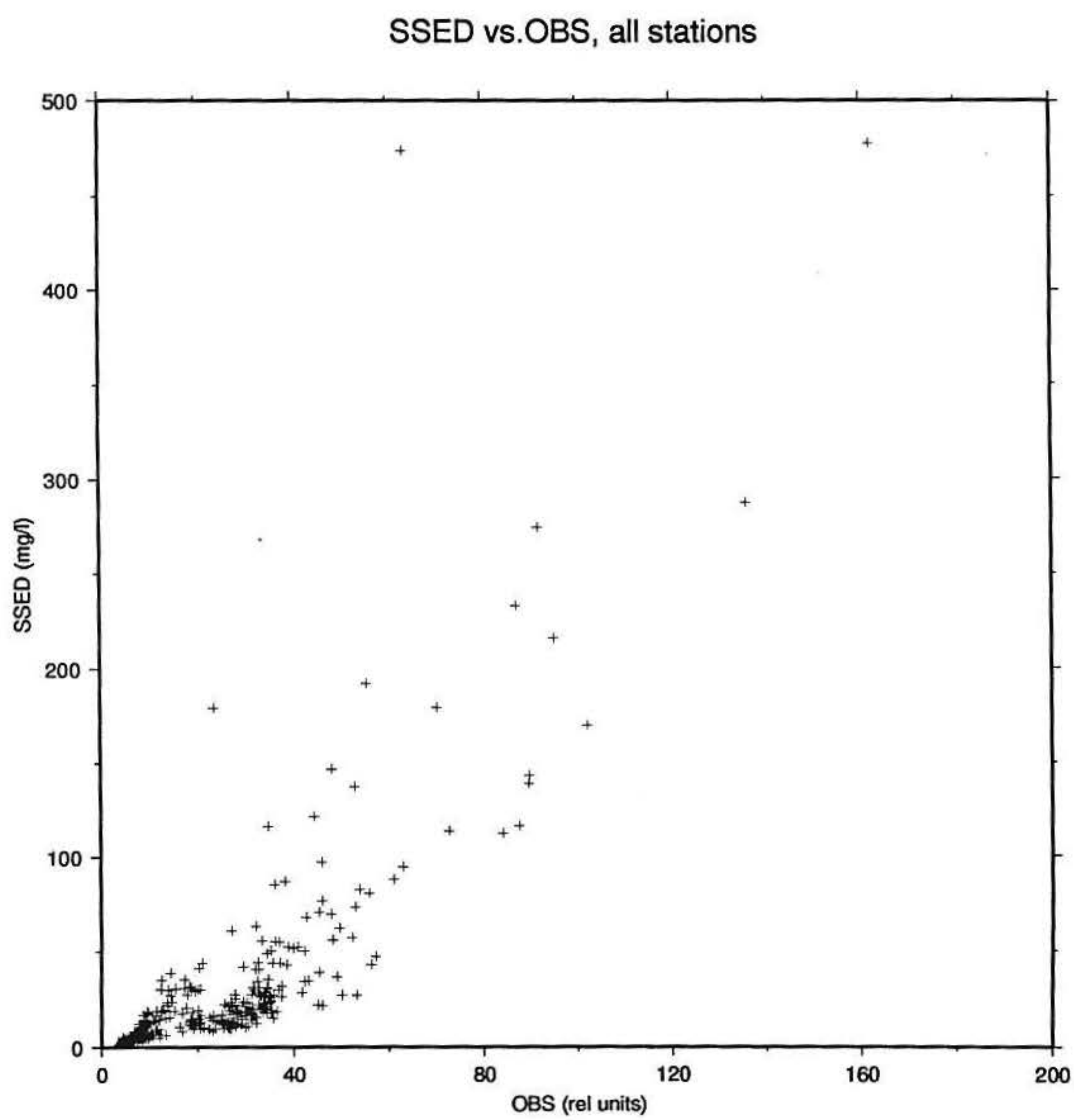
Figure 24

much greater than observed on the previous transect. Transect 3 on early flood exhibits much the same patterns, with the region of high suspended sediment concentration being found somewhat further down estuary than on the previous transect.

Measurements of optical backscatter is typically used as an easily measured surrogate for the measurement of suspended sediment concentration. To test this, suspended sediment concentrations were plotted against values of the optical backscatter for all stations over both cruises (Figure 25). The relationship is positive, indicating qualitatively that high optical backscatter indicates high suspended sediment concentrations, but the scatter is large.

Plotting the data for September 1992 and April 1993 separately (Figures 26 and 27) show that some of the scatter is due to differences between the two sampling periods. Generally, the April samples had higher suspended sediment concentrations than did the samples from September. Additionally, for a given suspended sediment concentration, the April data generally had higher optical backscatter than do the September data (note the different scales on Figures 26 and 27).

Figure 28 shows the relationship between suspended sediment concentrations and salinity for all stations over both cruises. Highest suspended sediment concentrations occurred for a range of salinities centered on about 19 psu, with lower concentrations at higher and lower salinities. This peak seems to be a manifestation of the high suspended sediment concentrations observed just south of the George Washington



SSED vs.OBS, all stations
SSED (mg/l)
OBS (rel units)
500
400
300
200
100
0
0
40
80
120
160
200

Figure 25

SSED vs. OBS, September 1992

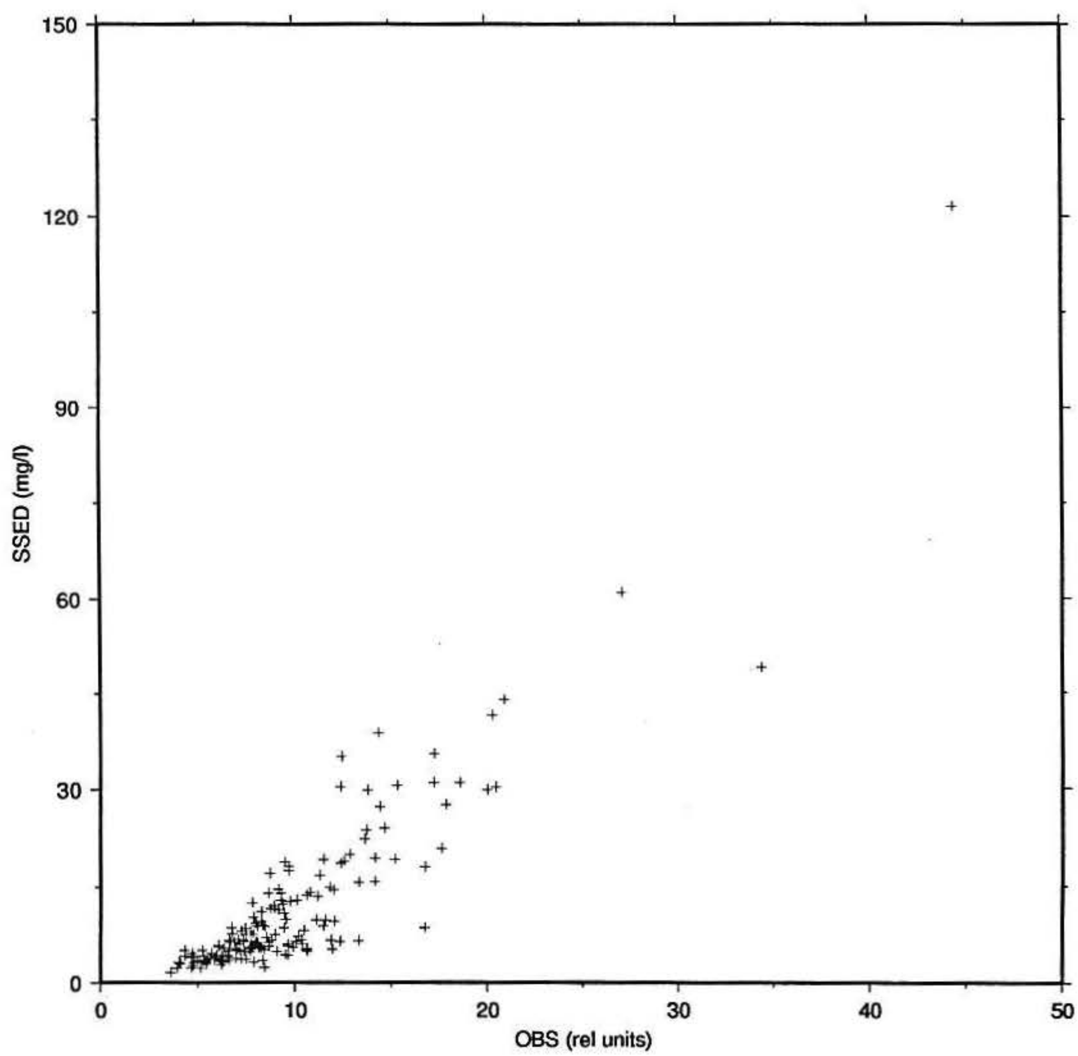


Figure 26

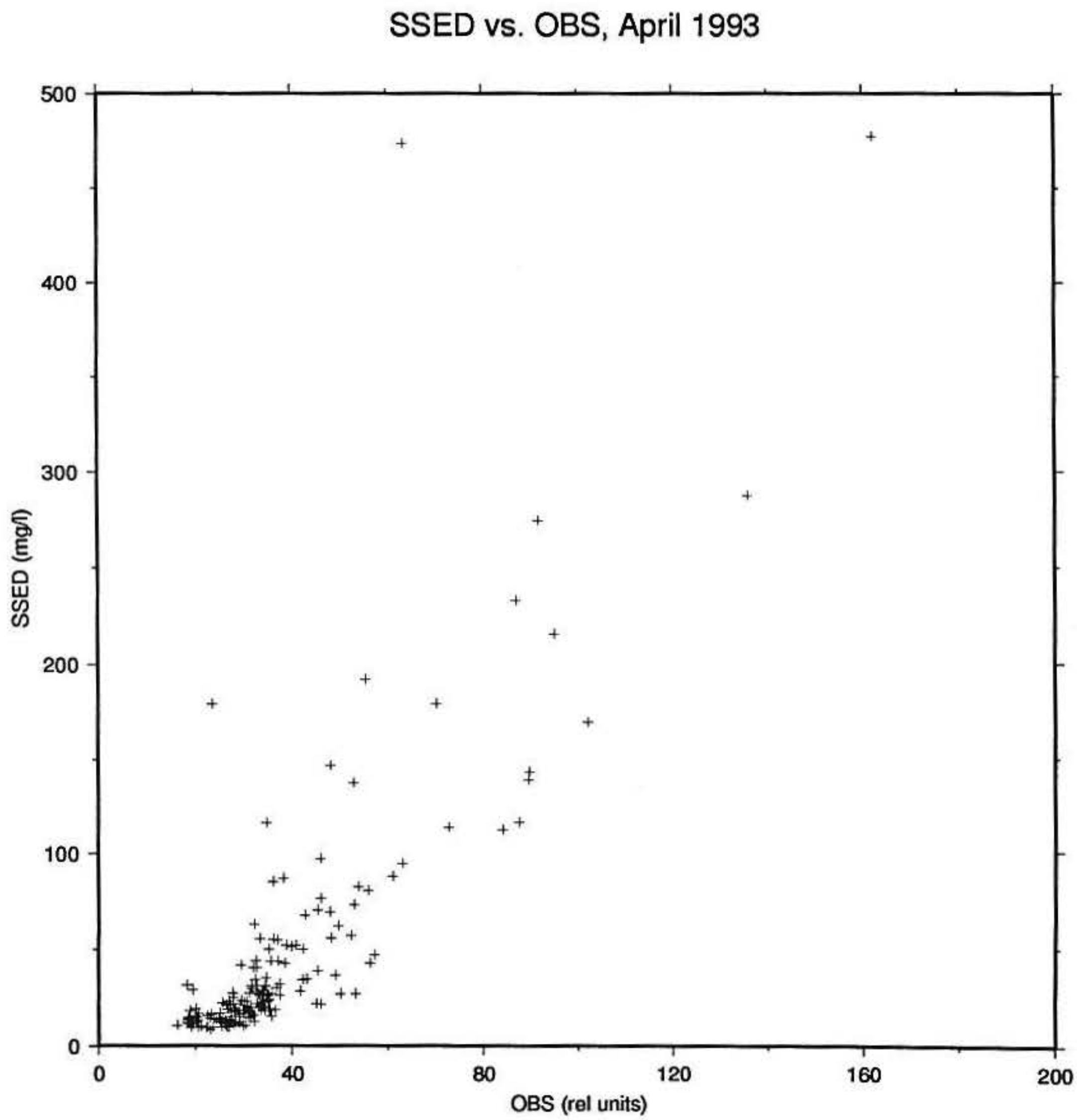

SSED vs. OBS, April 1993
SSED (mg/l)
OBS (rel units)
0
100
200
300
400
500
0
40
80
120
160
200

Figure 27

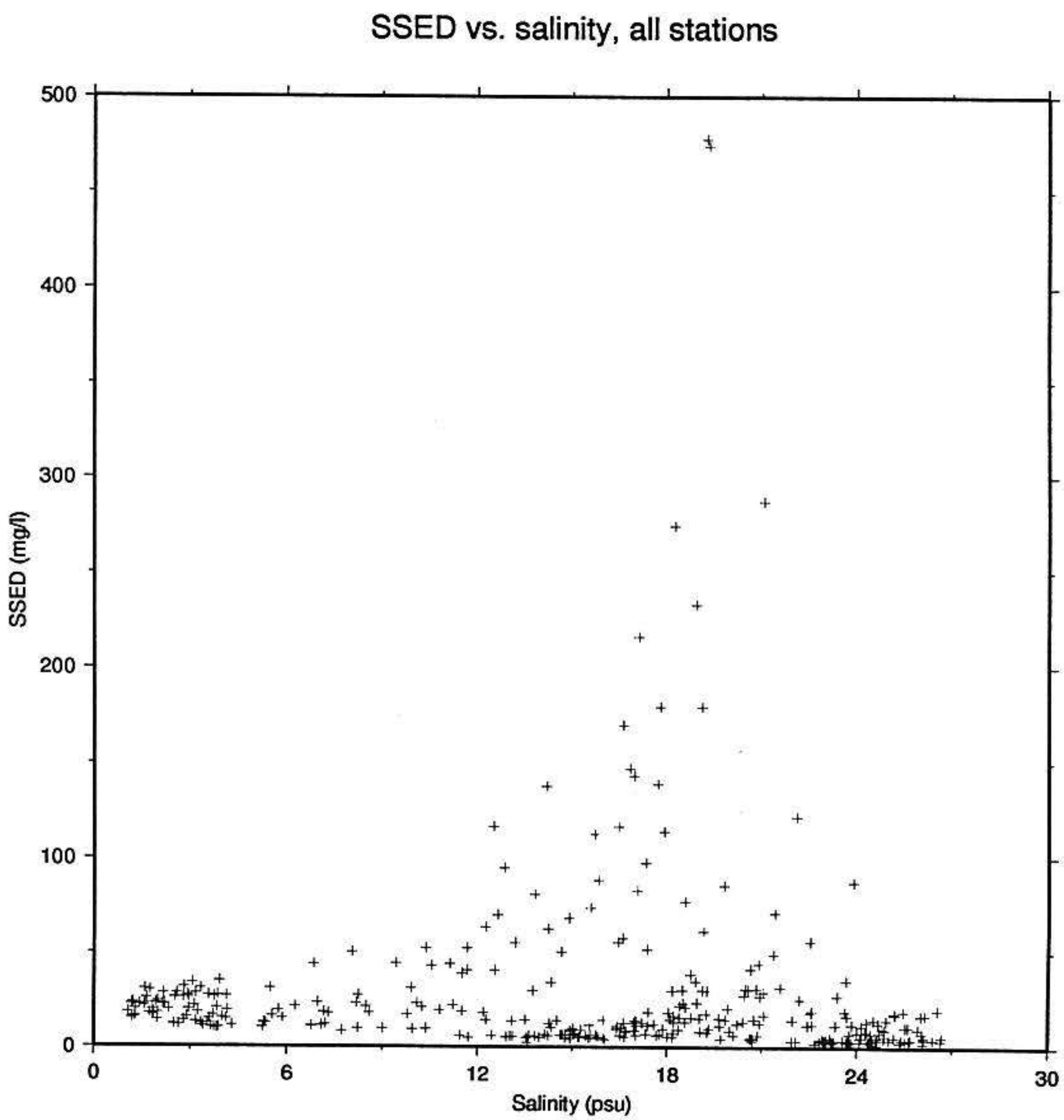

SSED vs. salinity, all stations
SSED (mg/l)
500
400
300
200
100
0
0
6
12
18
24
30
Salinity (psu)

Figure 28

Bridge in the vicinity of Grant's Tomb.

Plotting the data from each of the cruises separately (Figures 29 and 30) shows that the peak at around 19 psu occurs in both data sets. However, the plot of the September data (Figure 29) shows a smaller peak centered at a salinity of about 25 psu. Mechanism that create the turbidity maximum along the side of Manhattan are apparently not effective at the Battery. There is evidence, however, that the processes of frontogenesis are active at the Narrows (R. Wilson, 1991, Marine Sciences Research Center, State University of New York, Stony Brook, NY, personal communication). Perhaps turbidity associated with higher salinity waters is generated by salinity intrusion into the Upper Bay.

SSED vs. salinity, september 1992

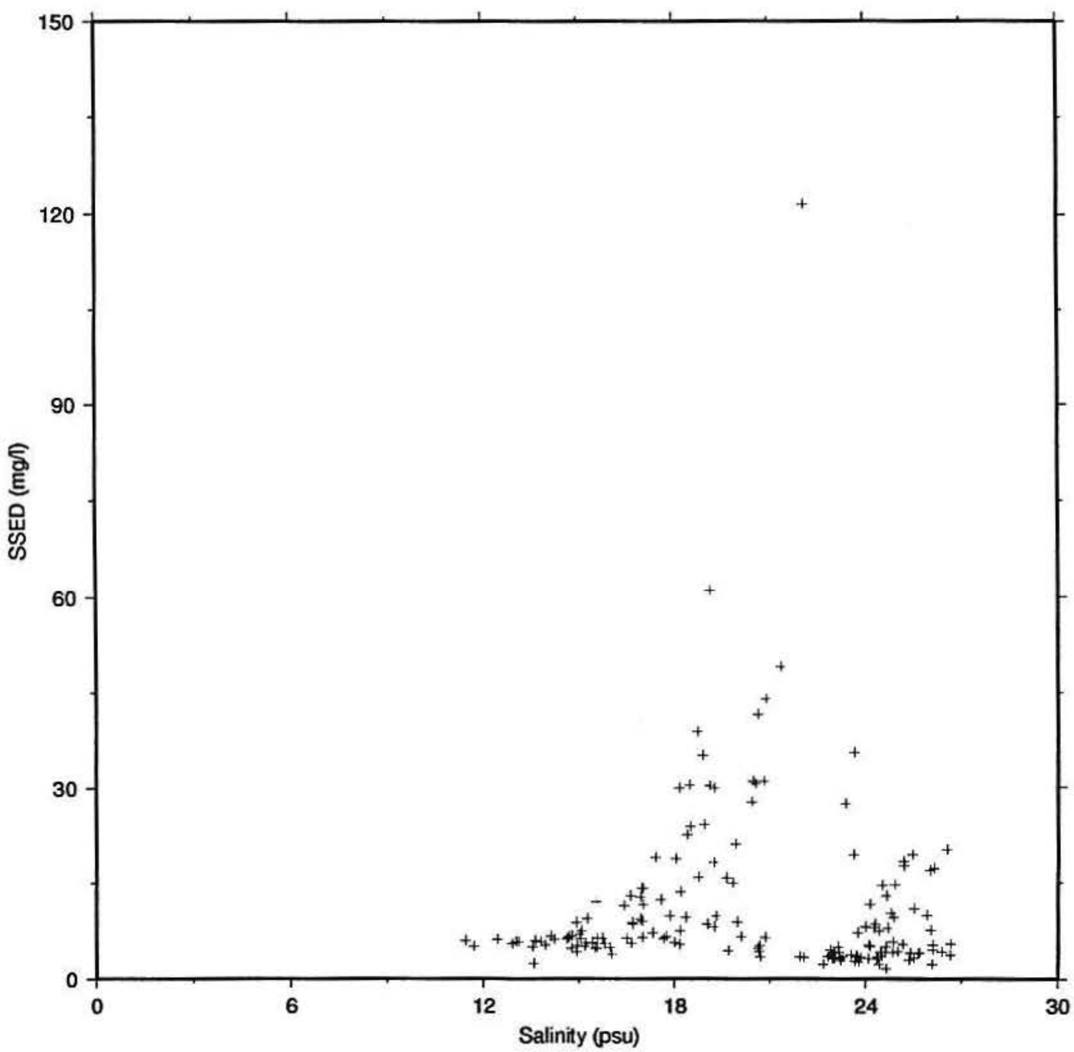


Figure 29

SSED vs. salinity, april 1993

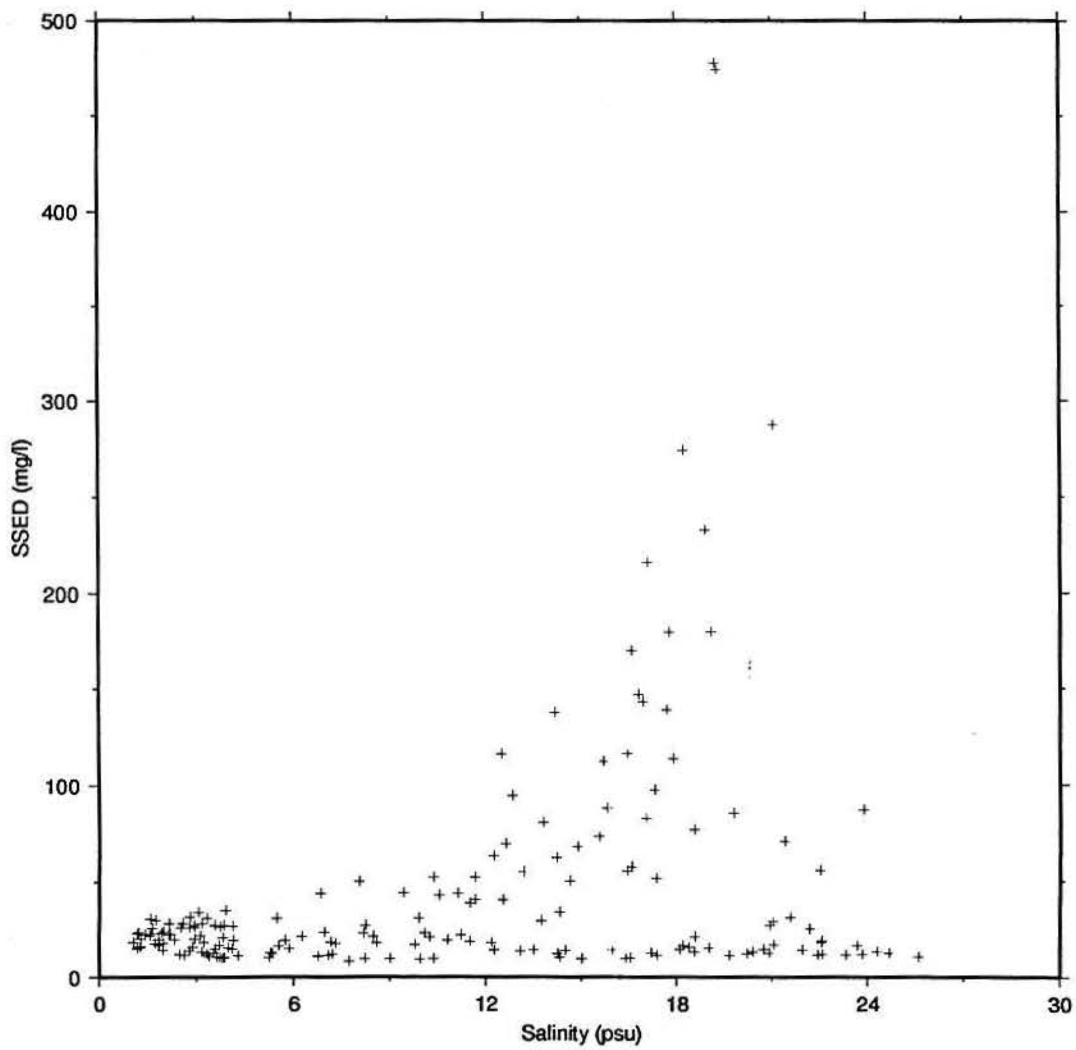


Figure 30

REFERENCES

Arnold, C.L. 1982. Modes of fine-grained suspended sediment occurrence in the Hudson River estuary. M.S. thesis. Marine Sciences Research Center, State University of New York, Stony Brook, NY: 102 p.

Bokuniewicz, H.J. and N.K. Coch. 1986. Some management implications of sedimentation in the Hudson-Raritan system. Northeastern Geology 8: 165-170.

Ellsworth, J. 1986. Sources and sinks for fine-grained sediment in the lower Hudson River. Northeastern Geology 8: 141-145.

Hirschberg, D. and H. Bokuniewicz. 1991. Measurements of water temperature, salinity and suspended sediment concentrations along the axis of the Hudson River estuary: 1980-81. State University of New York at Stony Brook. Marine Sciences Research Center. Special Report 11: 38 p.

Olsen, C.R., I.L. Larsen, R.H. Brewster, N.H. Cutshall, R.F. Bopp, and H.J. Simpson. 1984. A geochemical assessment of sedimentation and contaminant distributions in the Hudson-Raritan estuary. NOAA Tech. Rpt. NOS OMS 2: 101 p.

Olsen, C.R. 1979. Radionuclides, sedimentation and the accumulation of pollutants in the Hudson Estuary. Ph.D. thesis, Columbia University, NY: 343 p.

Schubel, J.R. and H.H. Carter. 1984. The estuary as a filter for fine-grained suspended sediment in "The Estuary as a Filter". V.S. Kennedy, editor, Academic Press, NY: 81-105.