Building the Turbidity Maximum in the Hudson River Estuary

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INTRODUCTION

Turbidity maxima are common characteristics of estuaries although their formation has been ascribed to various, different mechanisms. Floculation, tidal asymmetry, and gravitational, or estuarine, circulation have all been implicated as agents. Turbidity maxima formed at the limit of sea salt in an estuary has been attributed to the retardation of particle settling due to upwelling near the limit of the inflow of saline bottom water (Festa and Hansen, 1978). This characteristic, estuarine circulation proceeds at horizontal velocities of a few centimeters per second and vertical velocities of about 0.01 cm/sec. These are difficult to measure when superimposed on strong tidal flows, but the postulated vertical velocities would be sufficient to inhibit settling . Such a characteristic estuarine circulation has been found in the Hudson River estuary (Hunkins, 1981).

In many estuaries along the northern European coast, asymmetric tidal resuspension appears to be the cause of turbidity maxima. In shallow water, the tidal wave is distorted having shorter, more rapid flooding tides and longer, slower ebbs (LeBlond, 1978). Sediment resuspension has a non-linear dependence on flow velocity and local maxima in turbidity can be generated when this response is superimposed on an asymmetric tide. Turbidity maxima produced by this mechanism could exist anywhere within the estuary, not just at the head of salt, or even in freshwater, tidal rivers.

In this paper, we will discuss the turbidity structures in the Hudson River estuary and propose a new mechanism for the genesis of turbidity maxima. It appears that one turbidity maximum in the Hudson River estuary is caused by tidally modulated and bathymetrically controlled incursion of salt-water fronts. A second maximum appears at the head of salt.

PREVIOUS WORK

The Hudson River estuary has been described as a partially mixed estuary. It exists in a glacially overdeepened channel. The Hudson is a tidal river for 250 km of its length to the locks at Troy, NY, but the geochemical estuary only occurs in the lower third of this stretch. Salt is rarely found more than 120 km from the estuary mouth at the southern tip of Manhattan (the Battery) during times of low freshwater discharge.

The freshwater discharge to the estuary averages 550 cubic meters per second (Abood, 1978; Olsen, 1979). Most of the total annual flow occurs during the spring, usually in April, when discharges can exceed 1200 cubic meters per second. In the lower estuary the tidal discharge is about 20 times the freshwater flow. Sediment input is also seasonally modulated (Olsen, 1979).

Turbidity is largely controlled by resuspension in the lower estuary and the seasonal signal is weak. Average concentrations of suspended sediment differ by less than 20% between times of high freshwater flow and low flow (Arnold, 1982).

There is evidence of two turbidity maxima in the Hudson River estuary. One of these is at the head of salt and the other is mid-estuary. The mid-estuary maximum was first defined by a series of axial sections of salinity and suspended sediment concentrations in 1979-80. Eleven monthly sections were constructed from sampling at five water depths at 22 stations from the Lower Bay to the Tappan Zee Bridge, about 59 km above the Battery. Salinities were measured with a Beckman salinometer and suspended sediment concentrations determined by filtering water samples through 0.45 millipore filters (Hirschberg and Bokuniewicz, 1991). The average section shows a turbidity maximum about 32 km above the Battery (at about the location of Grant's Tomb). Concentrations within the maximum reached levels of 447 mg/l and it was found at the position of a strong salinity gradient at salinities between 17 and 19 parts per thousand (Figure 1). This turbidity maximum was not always detected during individual, monthly cruises. Sometimes it was well defined, at other times it was absent (Figure 2), and sometimes two maxima were found (Figure 3). No explanation for this variety was offered at the time, but now we believe that the observations can be explained by the frontogenesis mechanism discussed here.

The evidence for a turbidity maximum at the head of salt is less compelling because available measurements were neither frequent nor closely spaced. Five axial sections of salinity and suspended sediment concentration were compiled from vertical sampling at between 5 and 11 stations from the Battery to Indian Point between 1975 and 1977 (Figure 4; Olsen, 1979). High turbidity south of the George Washington Bridge is consistent with these observations and there is some indication of a second turbidity maximum in Haverstraw Bay.

Suspended sediment concentration in the surface and bottom water were measured five times at from 9 to 16 stations between the Battery and Albany between 1978 and 1980. The resolution of these data is poor. At least three cruises showed higher near bottom concentrations near the limit of sea salt but the "maximum" is defined by only one or two samples (Arnold, 1982; Figure 5). A persistent turbidity maximum at the head of salt could not be generated by tidal asymmetry since the limit of salt migrates along the axis of the estuary with variations in freshwater discharge while the tidal currents persist well into the freshwater reaches regardless of the salinity structure.

Two sampling programs were undertaken to elucidate the mechanism by which the mid-estuary turbidity maximum was formed and to explore the existence of a turbidity maximum at the landward limit of sea salt. The first of these was a series of observations of salinity, current structure, and suspended sediment concentrations at a dense array of stations around the mid-estuary turbidity maximum at various stages of the tide (Bokuniewicz and Ullman, 1995). Only the second will be described in this report. It consisted of a series of long, axial transects to map out the longitudinal structure of salinity and suspended sediment distribution over an 18 month period.

METHODS

Salinities and temperatures were usually measured with a Sea Bird, Sea Cat CTD fitted with a half-liter water bottle. On one cruise (16 June, 1994) the CTD malfunctioned and salinities were determined on water samples with a refractometer. The entire volume was filtered on 0.45 micrometer, preweighed filters, washed, dried, and weighed. Axial transects of between 40 and 44 stations were made on 3 May, 16 June, 30 August, 18 October, 1 December, 1994, and 11 January, 9 March, 6 April, 16 May, 27 June, and 27 September, 1995. The spring of 1994 was a time of exceptionally high discharge due to an unusually large snowmelt, but the summer of 1995 was a drought with minimum rainfall in August, 1995. The flow at Hadley, NY on 8 August, 1995 was 300 million gallons per day which was 60% below the average flow for August of 773 million gallons per day (U.S. Geological Survey, Public Affairs Office, Reston, Virginia, 29 August, 1995). Station locations and sampling depths are shown in Figure 6.

RESULTS

May, 1994 (Figures 7-8). This was a time of unusually high freshwater discharge. Sea salt had been pushed to below Km 60 near the George Washington Bridge. Both horizontal and vertical salinity gradients were sharp and there turbidity maxima were seen. One was at the landward limit of sea salt (Km 60 on Figure 7). This may be the accumulation of high-discharge, sediment load at the head of the geochemical estuary due to the estuarine circulation. The mid-estuary turbidity maximum was between Kms 28 and 46 on Figure 8, south of its expected position. A third, weaker maximum was found south of the Battery (Km 20-26).

June, 1994 (Figures 9-10). The salinity structure had dispersed north of the George Washington Bridge and a very intense and broad turbidity maximum was found mid-estuary between Km 33and 67 on Figure109.

August, 1994 (Figures 11-12). By August, 1994, sea salt had penetrated thirty kilometers further north (to Km 95 on Figure 11). Only the intense mid-estuarine turbidity maximum has survived between Km 35 and 50 on Figure 12.

October, 1994 (Figures 13-14). Salt had spread to Km 120 on Figure 13, into the narrow deep gorge of the Hudson River. The mid-estuary turbidity maximum maintained its position near Km 46 on Figure 14, while a broad maximum was found at the head of salt.

December, 1994 (Figures 15-16). The salinity gradients were fairly uniform. The mid-estuary turbidity structure seemed to be broken up. A relatively intense maximum in turbidity was found north of its expected position near Km 57 on Figure 16 and a second one south of the expected position at Km 32. The broad, northern maximum was again seen in the gorge at the head of salt. As we will discuss, we believe that the northern feature was a remnant of the previous tidal cycle and salinity intrusion and that the southern feature marked the formation of the next high turbidity area behind a salt front.

January, 1995 (Figures 17-18). The winter was a mild one with little snowfall. By January, the freshwater, vertical stratification was starting to form. The turbidity maximum near the head of salt was irregular, perhaps due to the instability of the front in combination with higher fluvial discharges of both freshwater and sediment. The intense maximum in mid-estuary persisted.

March, 1995 (Figures 19-20). In March the salinity was below 90 km with strong vertical and horizontal gradients in the vicinity of the mid-estuarine turbidity maximum. A second turbidity maximum was found at the head of salt. There was a third turbidity maximum above the head of salt, perhaps due to local tidal resuspension.

April, 1995 (Figures 21-22). By April the salinity structure showed signs of weakening. The gradients are less intense than they were in March and exhibited some instability (waviness). Maxima are again found in the mid-estuary position and the head of salt.

May, 1995 (Figures 23-24). Salt has penetrated to the northern limit of the transect and there is little vertical structure except at the mid-estuary position. Turbidity maxima were found at the mid-estuary position, slightly northward of this position and at the head of salt.

June, 1995 (Figures 25-26). Salt continued to be found at the north end of the transect along with a turbidity maximum. The salinity structure is unusual, however, in that the strongest gradients are north of the George Washington Bridge. There is no maximum in turbidity associated with these gradients. This may imply that strong salinity gradients themselves are not sufficient to generate the maximum; the flow structure over changes in channel geometry may also be required. The mid-estuary turbidity maximum is very weak.

September, 1995 (Figure 27-28). The estuary remained well mixed with salt penetrating to the northern edge of the transect. The mid-estuary turbidity maximum was north of its usual position and rather weak. The turbidity maximum near the head of the geochemical estuary was south of the head of salt but well-defined.

DISCUSSION

There does appear to be a persistent turbidity maximum in the Hudson River estuary at the head of salt. The feature migrates through the river with the landward limit of sea salt although its position seems to be modified in the gorge where a combination of bathymetry and tidal currents may be influencing its location.

The turbidity maximum found at mid-estuary is most often found south of the George Washington Bridge in the vicinity of Grant's Tomb. It is most intense in the presence of strong salinity gradients when the estuary is relatively well stratified. At times of extremely high discharge, its position can be further south. At times of low discharge when sea salt penetrates to its northern limit and the estuary is well mixed, the mid-estuary turbidity maximum is not as intense and may be found further north in the vicinity of the George Washington Bridge. Occasionally two mid-estuary turbidity maxima are found. One is north of the expected position and generally weaker than its counterpart.

Other evidence suggests the following mechanism for the formation of the mid-estuarine turbidity maximum (Bokuniewicz and Ullman, 1994). During an ebbing tide, a salt front is found downstream of the George Washington Bridge as a result of the downstream expansion of the channel below the construction at the Bridge. This front is characterized by strong horizontal salinity gradients that intersect the bottom and a strong halocline. Suspended particles settling through the halocline become trapped in the lower water layer. As the ebb tide relaxes and the flood begins, the salt wedge moves northward into the estuary gravitationally. As it transgresses, additional sediment is resuspended and trapped behind the front under the halocline. The front progress apparently is arrested on the bathymetry south of the George Washington Bridge even as the flood continues and the halocline rises. As the flood tide ends and the ebb begins, the salinity gradients become unstable and the front breaks down. This event can strand turbid water near the northernmost position of penetration of the salt wedge while a new front is generated further downstream to begin the process again. The second mid-estuary turbidity maximum sometimes seen north of the first may be turbid water formed on the previous tide and stranded as the next ebb began.

Conclusion

The Hudson River estuary has two turbidity maxima formed by different mechanisms. One is associated with the landward limit of sea salt. It is apparently formed by the estuarine circulation although its location may be modified by bathymetric influence in the deepest parts of the estuary (the gorge). The second is formed at mid-estuary by the tidally modulated and bathymetrically controlled formation and migration of salt fronts into the estuary. Secondary mid-estuarine turbidity maxima are sometimes seen; these seem to be residuals from the previous tide.

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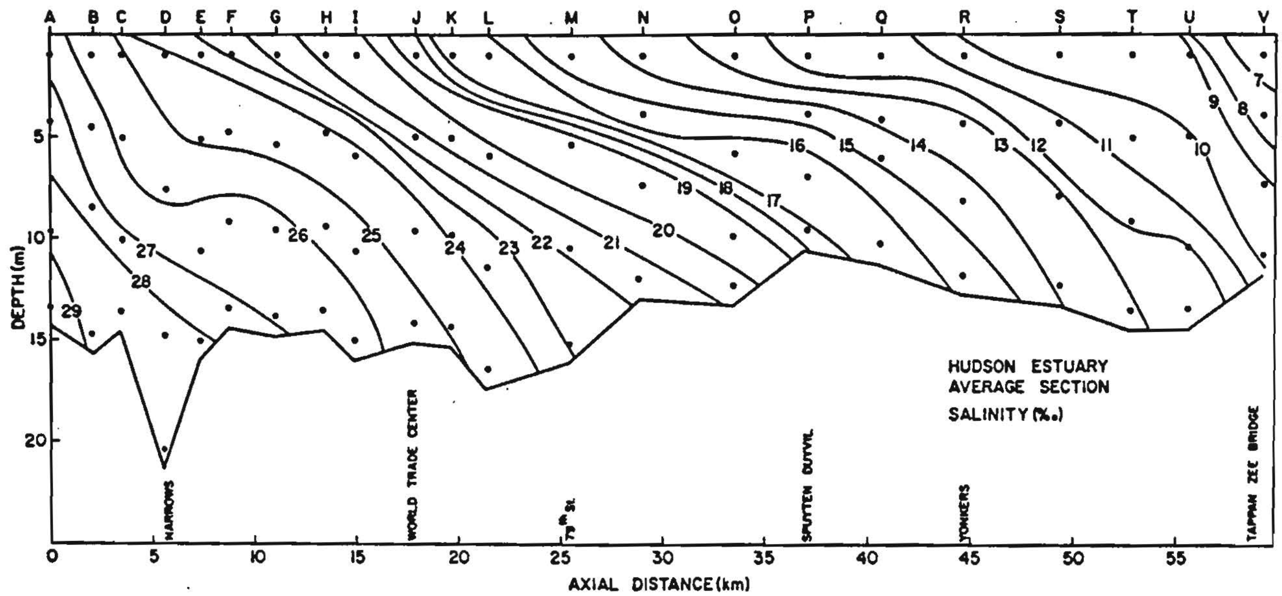
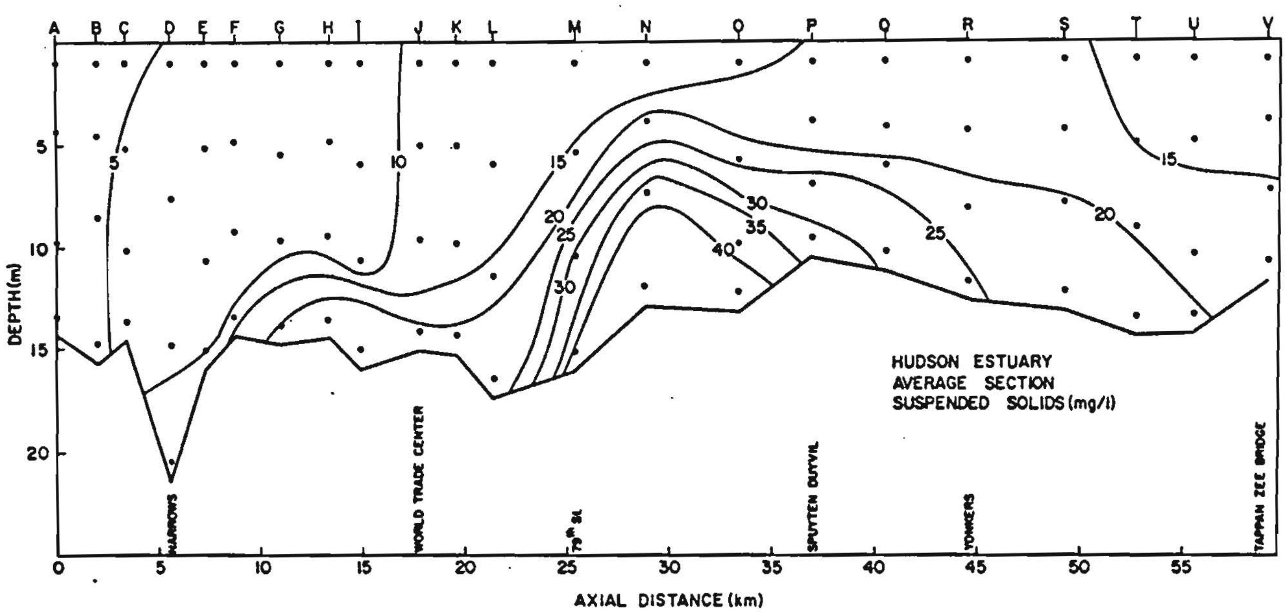

HUDSON ESTUARY
AVERAGE SECTION
SALINITY (‰)
DEPTH (m)
AXIAL DISTANCE (km)
NARROWS
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE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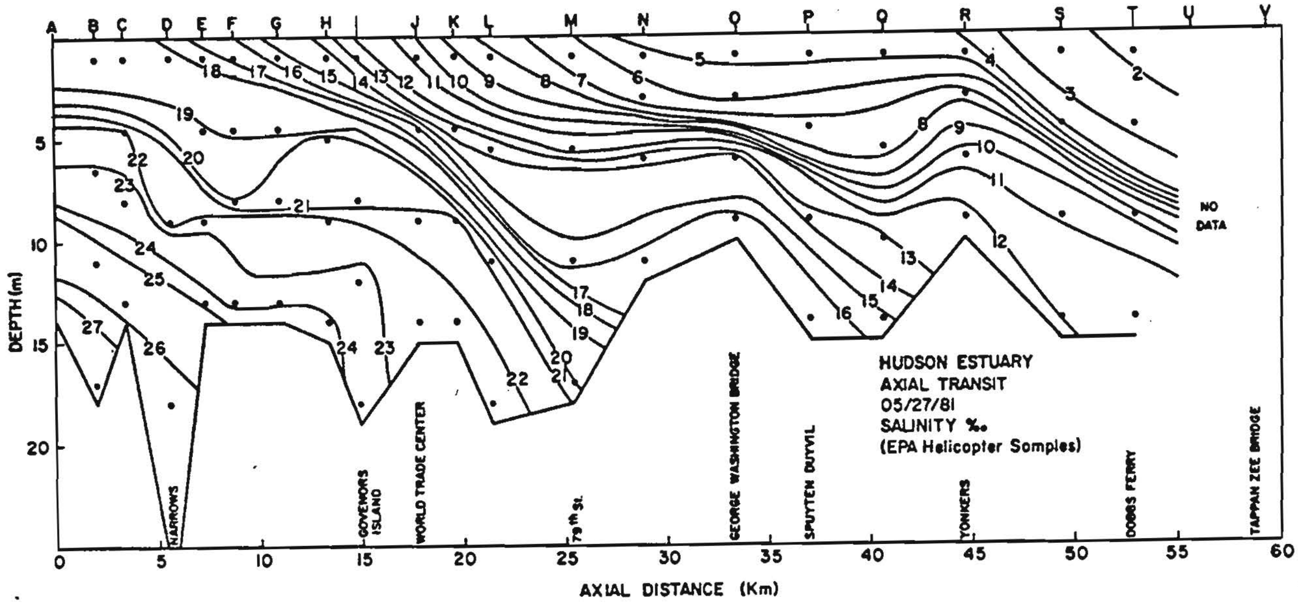
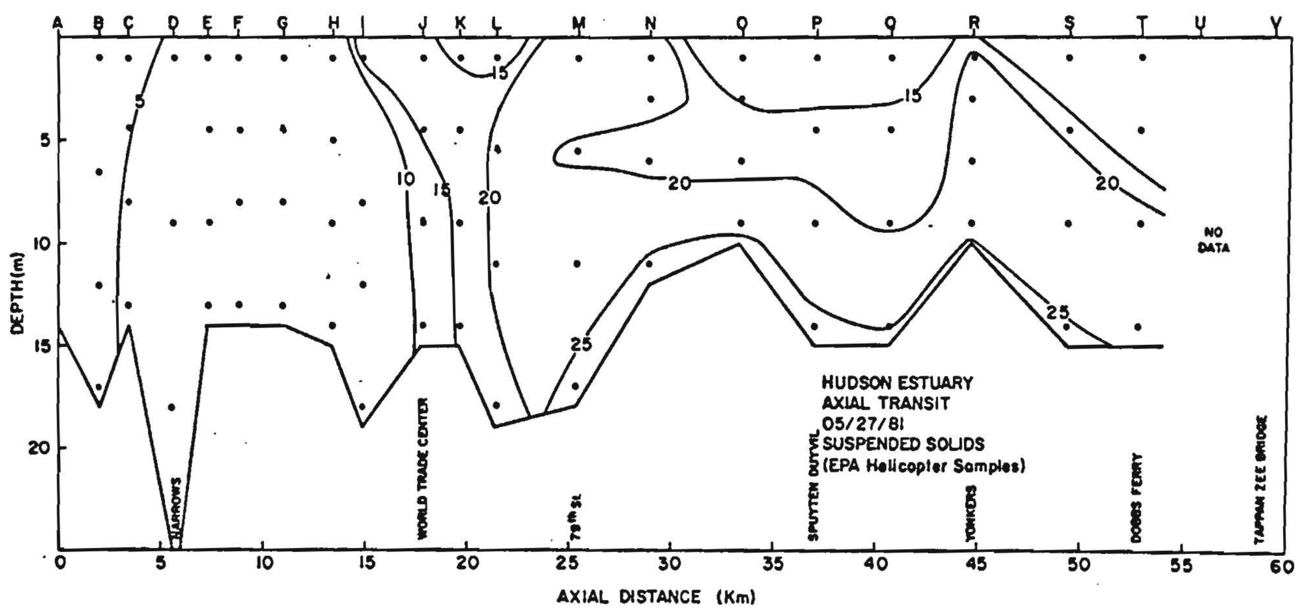
AVERAGE SECTION
SUSPENDED SOLIDS (mg/l)
DEPTH (m)
AXIAL DISTANCE (km)
NARROWS
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE

Figure 1


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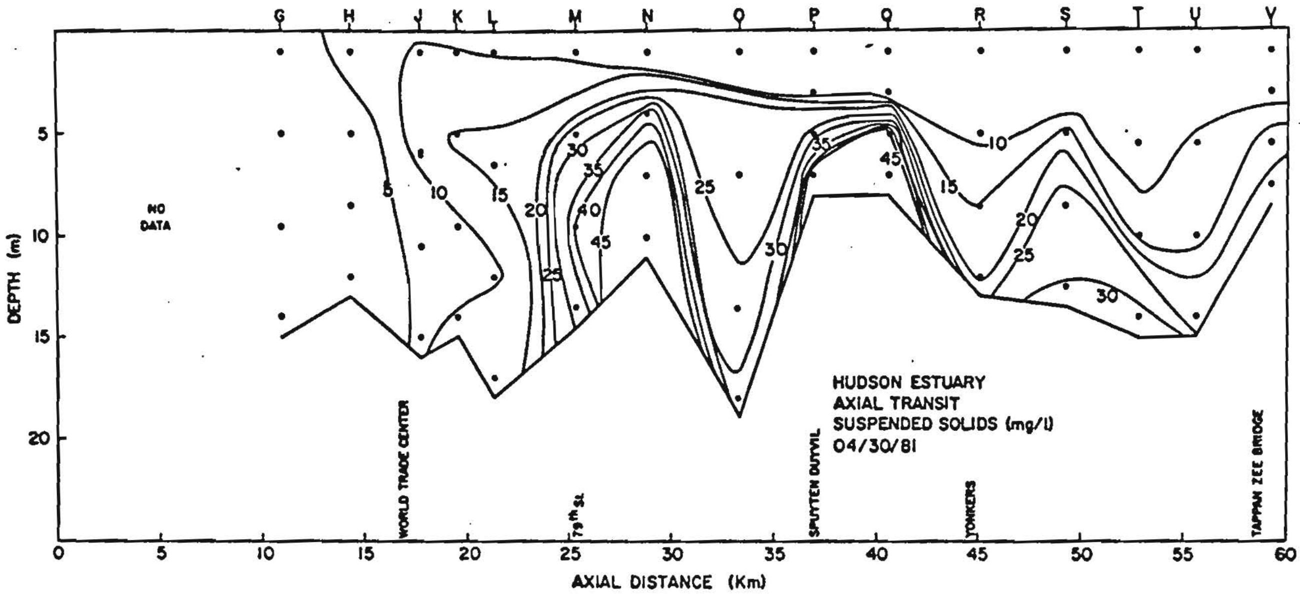
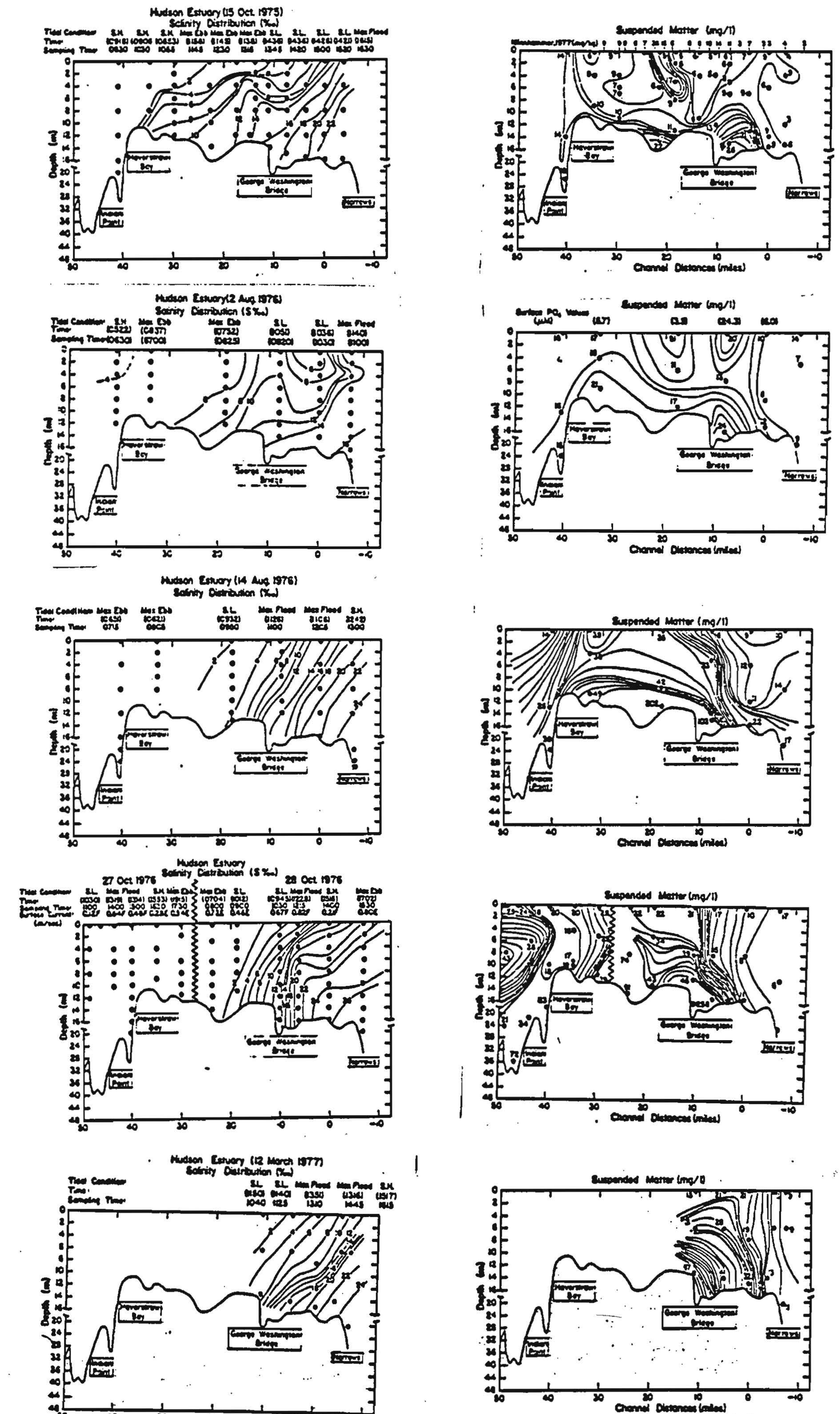
AXIAL DISTANCE (Km)
NARROWS
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
DOBBS FERRY
TAPPAN ZEE BRIDGE

Figure 2



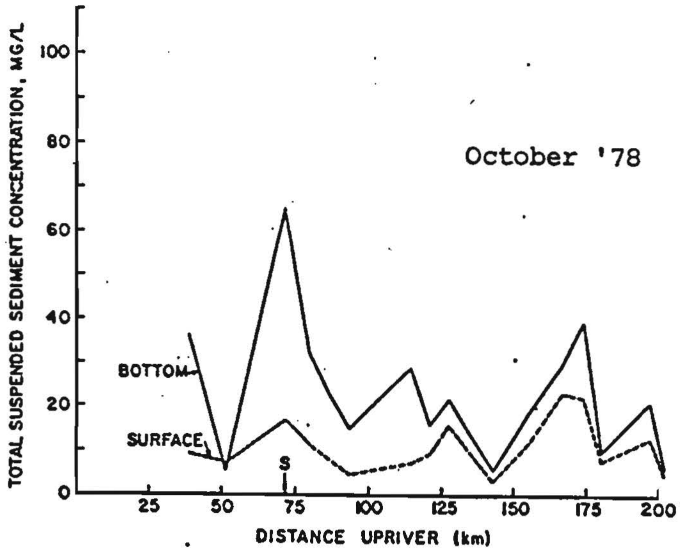
G H J K L M N O P Q R S T U V
NO DATA
DEPTH (m)
AXIAL DISTANCE (Km)
HUDSON ESTUARY
AXIAL TRANSIT
SUSPENDED SOLIDS (mg/l)
04/30/81
WORLD TRADE CENTER
79th St.
SPUYTEN DUYVIL
YONKERS
TAPPAN ZEE BRIDGE

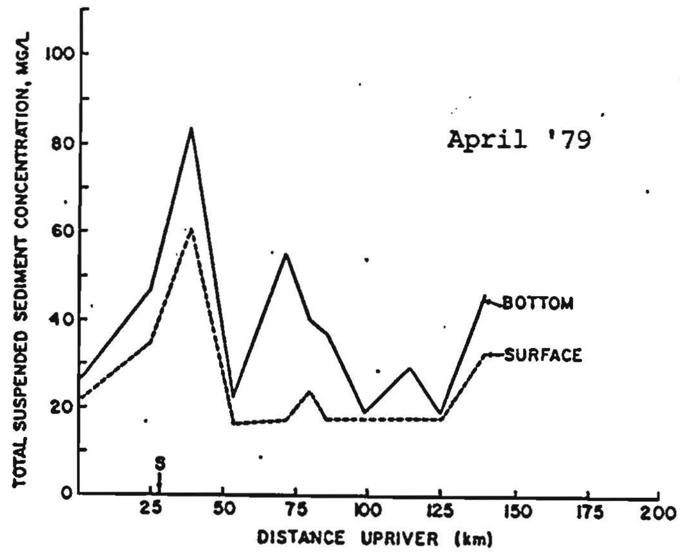
Figure 3

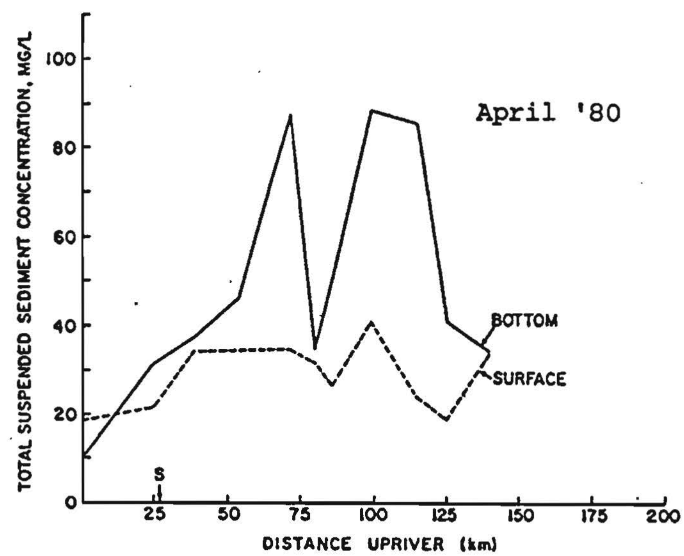


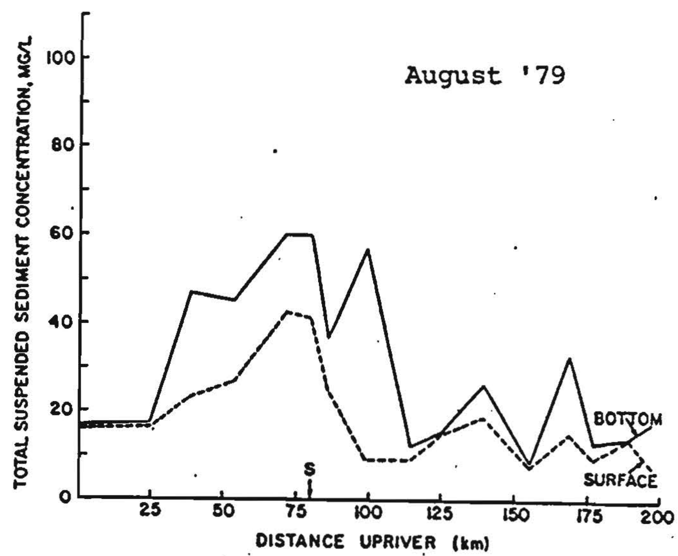
Hudson Estuary (15 Oct. 1975)
Salinity Distribution (‰)
Suspended Matter (mg/l)
Hudson Estuary (2 Aug. 1976)
Salinity Distribution (S ‰)
Suspended Matter (mg/l)
Hudson Estuary (14 Aug. 1976)
Salinity Distribution (‰)
Suspended Matter (mg/l)
Hudson Estuary
Salinity Distribution (S ‰)
27 Oct. 1976
28 Oct. 1976
Suspended Matter (mg/l)
Hudson Estuary (12 March 1977)
Salinity Distribution (‰)
Suspended Matter (mg/l)
Depth (m)
Channel Distances (miles)
Haverstraw Bay
George Washington Bridge
Indian Point
Narrows

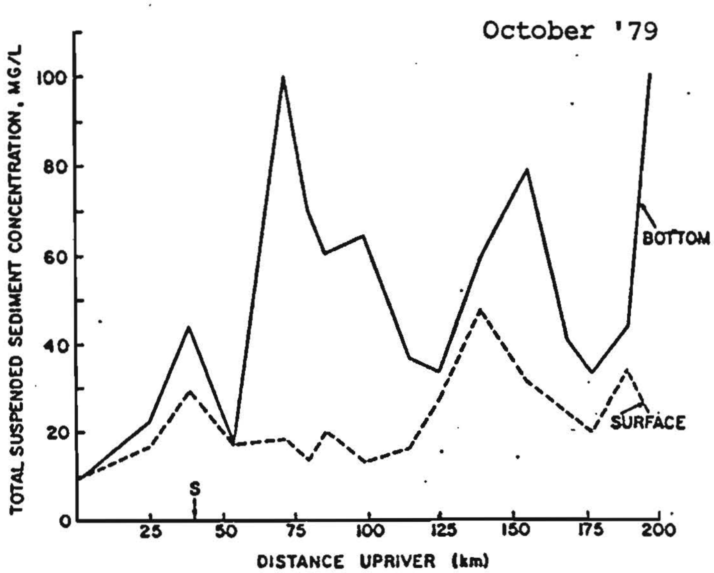
Figure 4





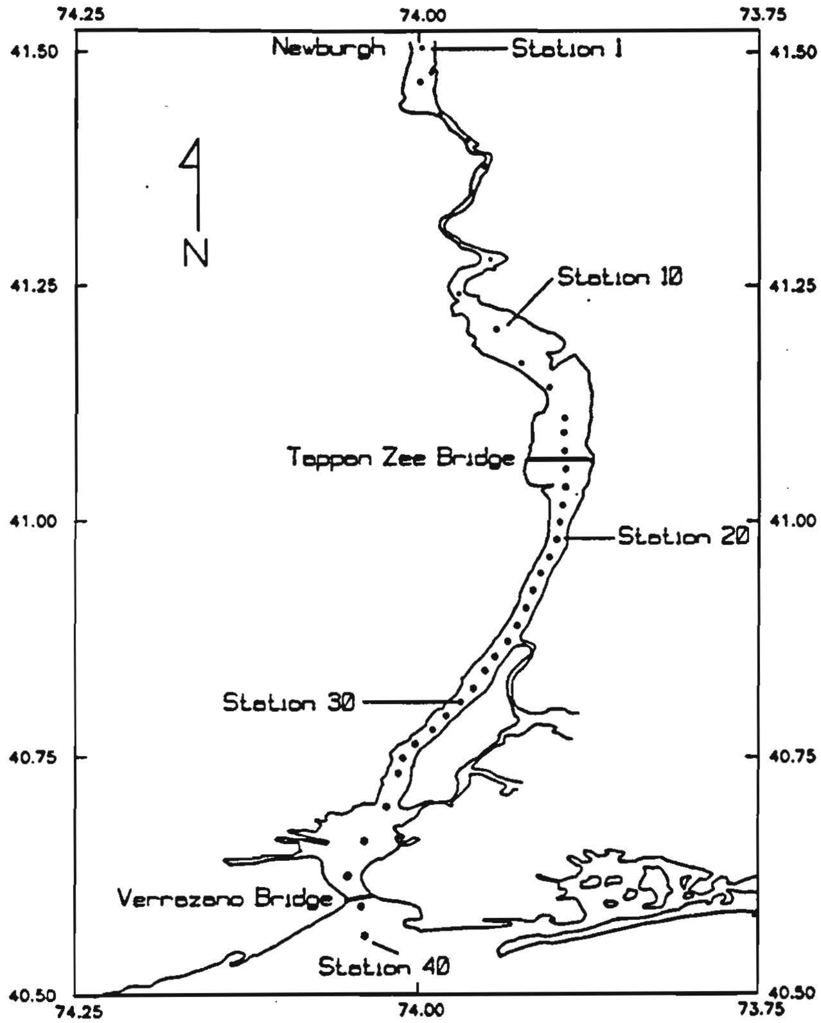






"S" indicates the appearance of sea salt (1-2 ppt)

Figure 5



Station Locations for Hudson River Sampling

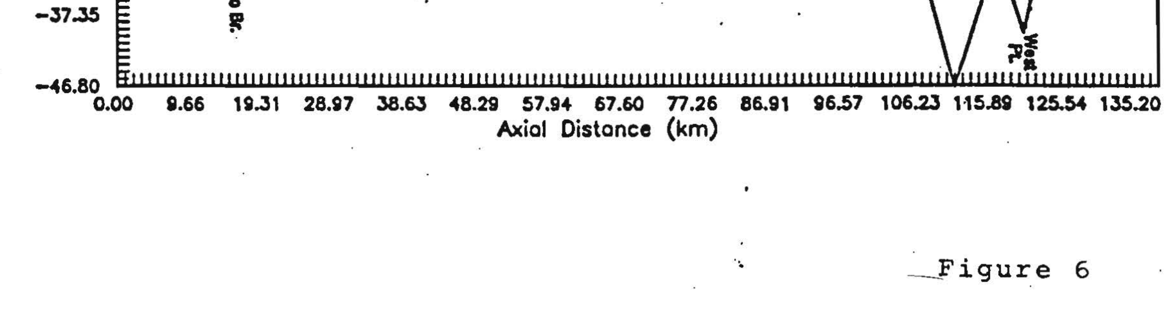
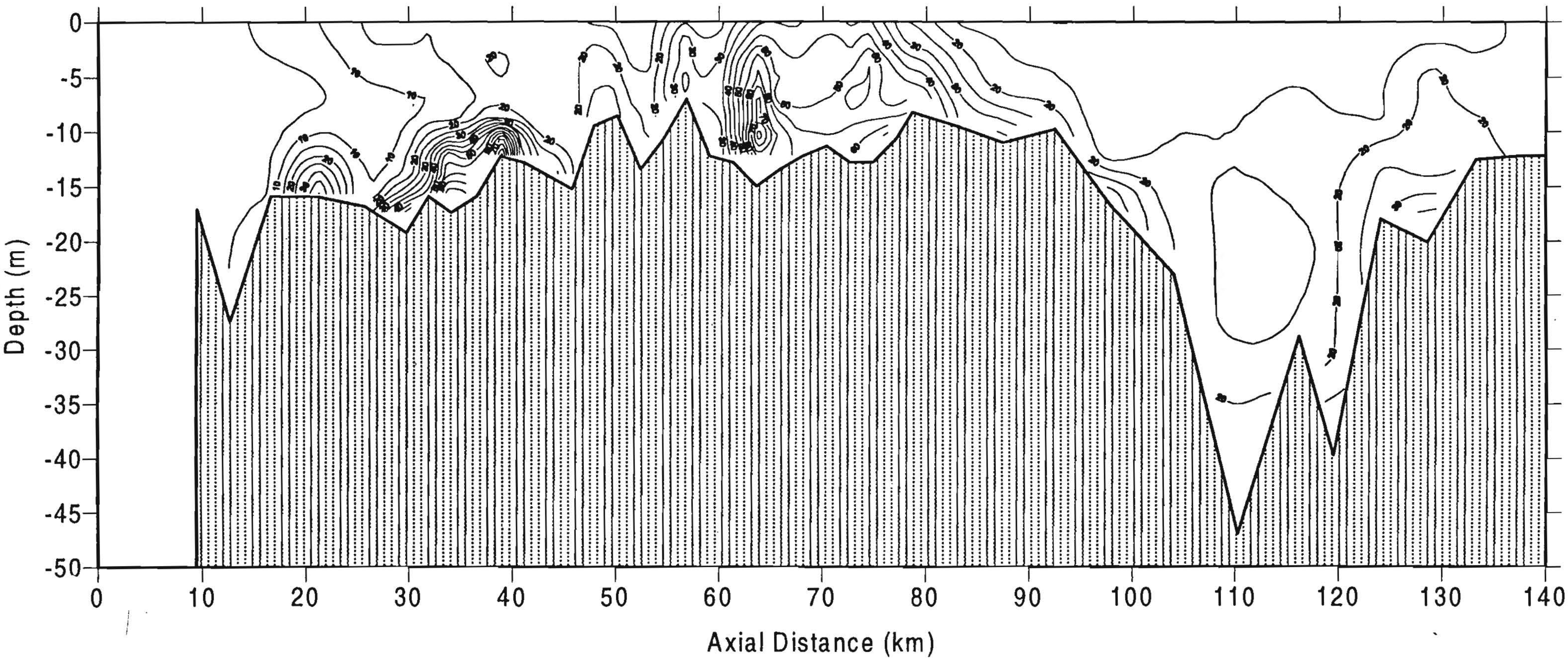


Figure 6

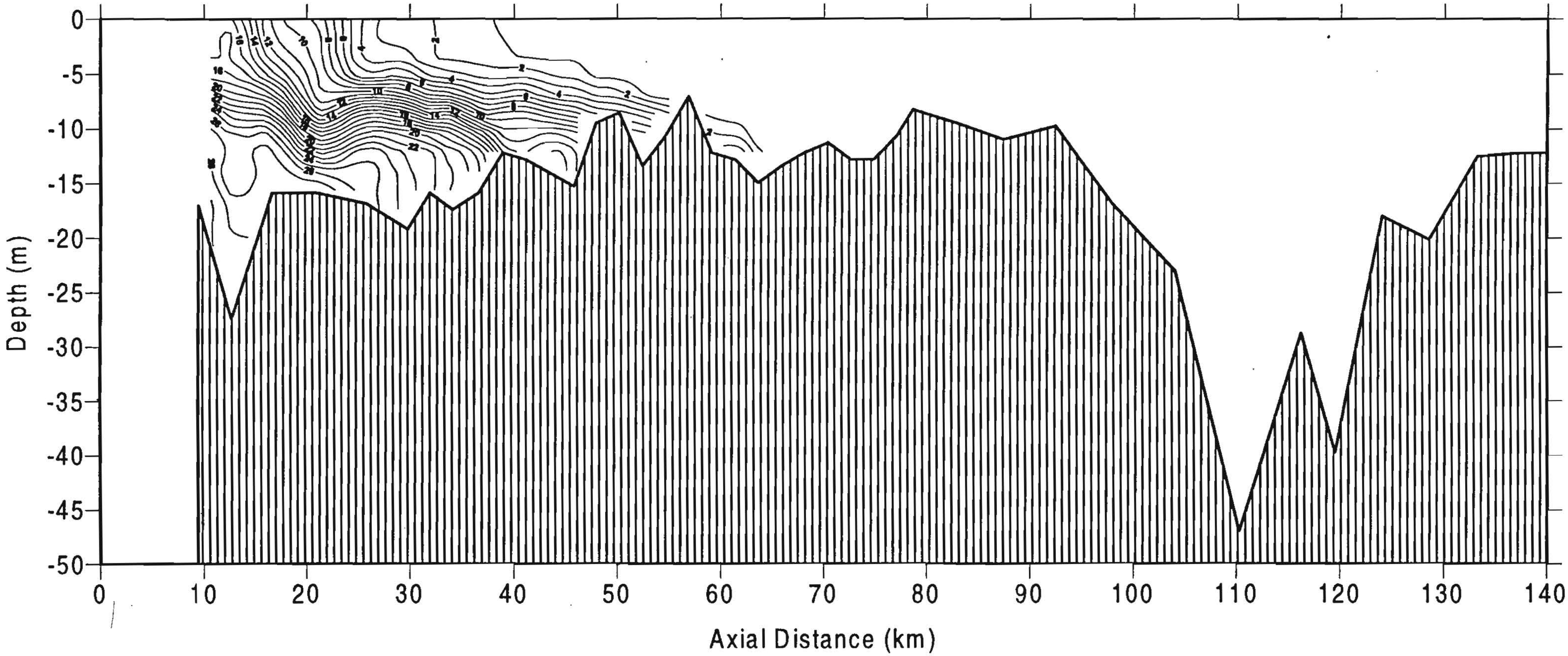
Suspended Sediment Concentration (mg/l), May 1994



* the interval used for contouring: 5 units (i.e. mg/l)

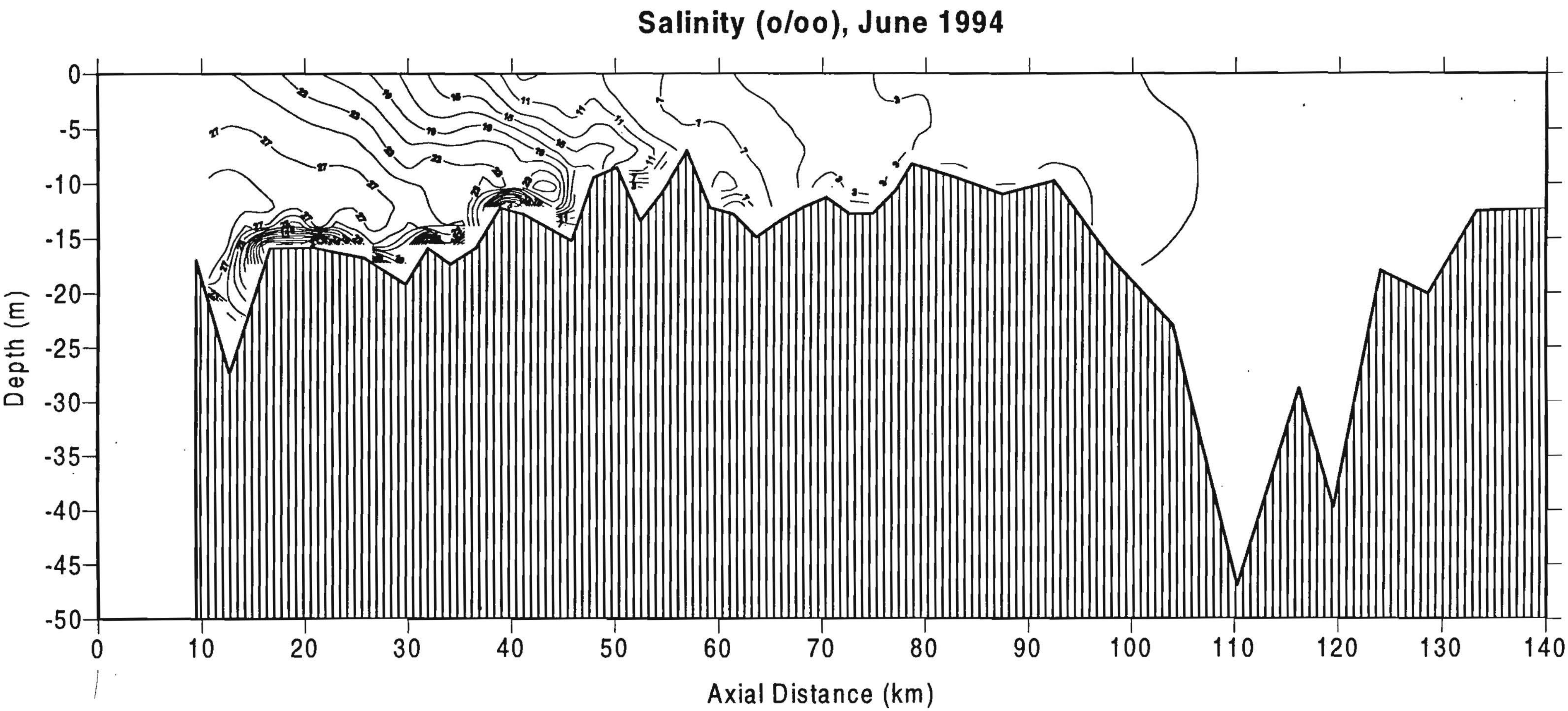
Figure 7

Salinity (o/oo), May 1994



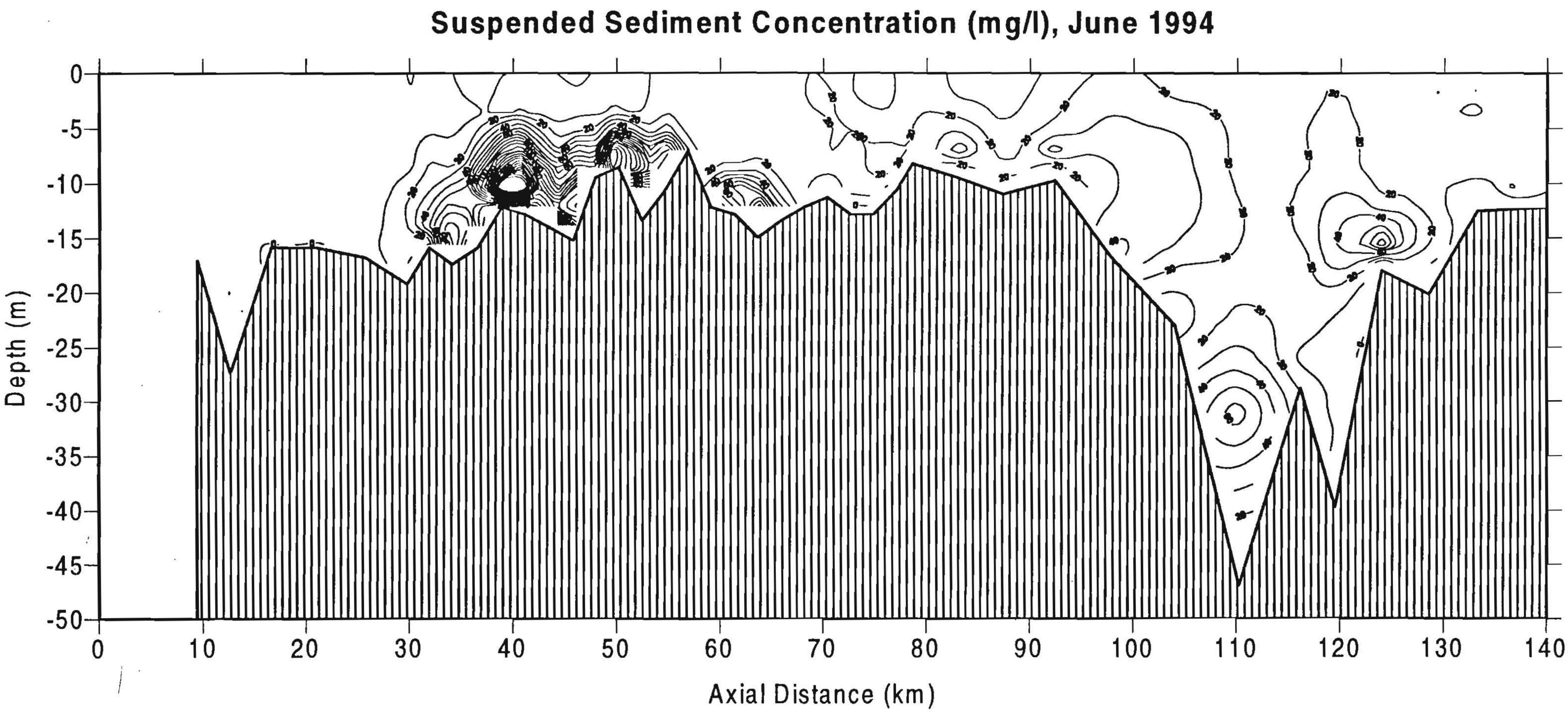
* the interval used for contouring: 1 unit (i.e. o/oo)

Figure 8



* the interval used for contouring: 2 units (i.e. o/oo)

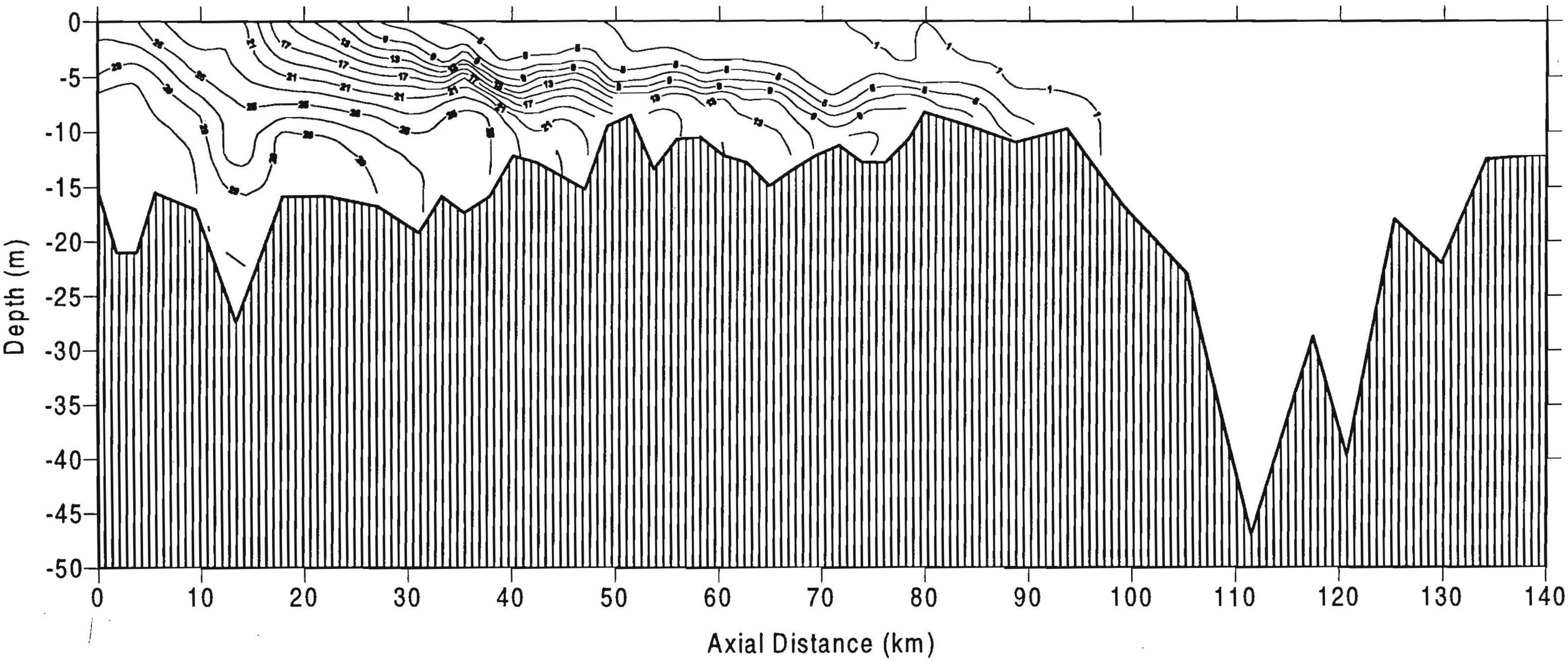
Figure 9



* the interval used for contouring: 10 units (i.e. mg/l)

Figure 10

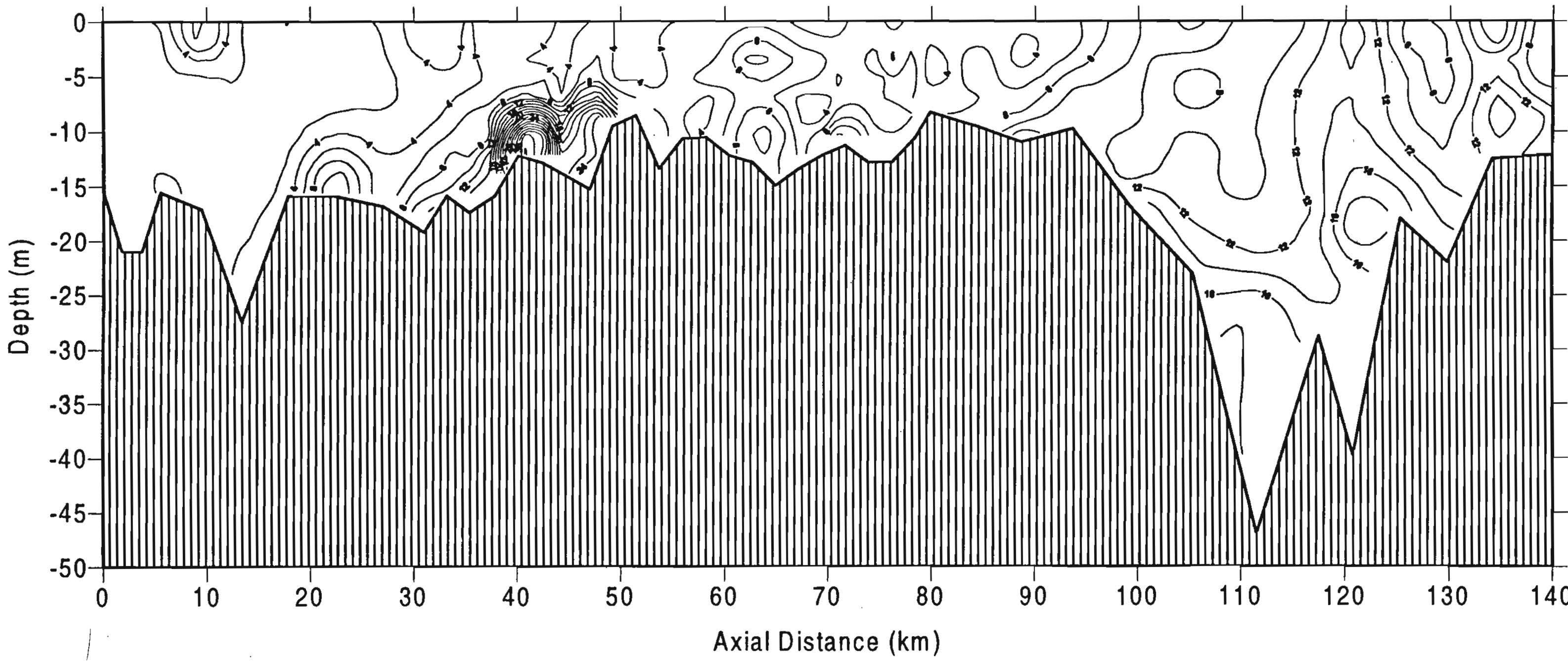
Salinity (o/oo), August 1994



* the interval used for contouring: 2 units (i.e. o/oo)

Figure 11

Suspended Sediment Concentration (mg/l), August 1994



* the interval used for contouring: 2 units (i.e. mg/l)

Figure 12

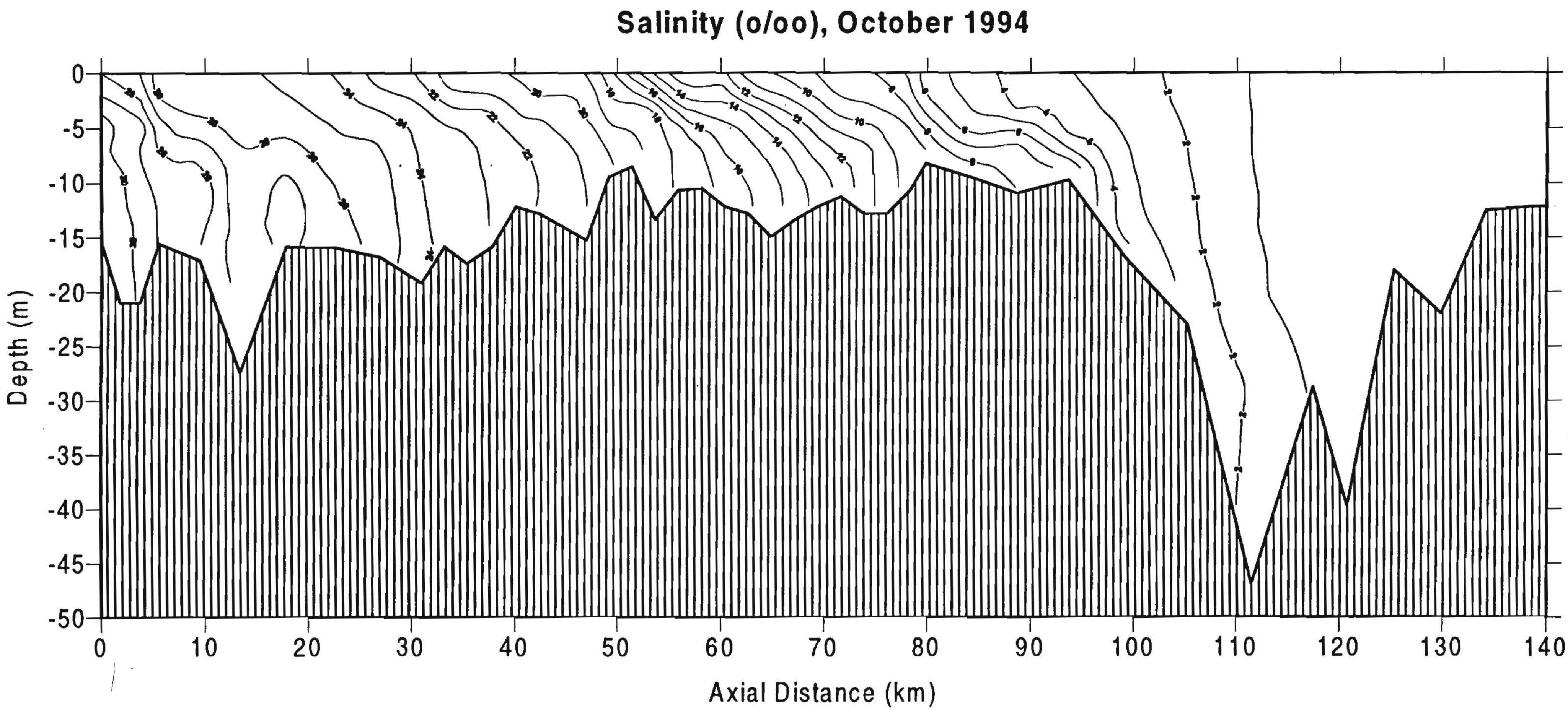


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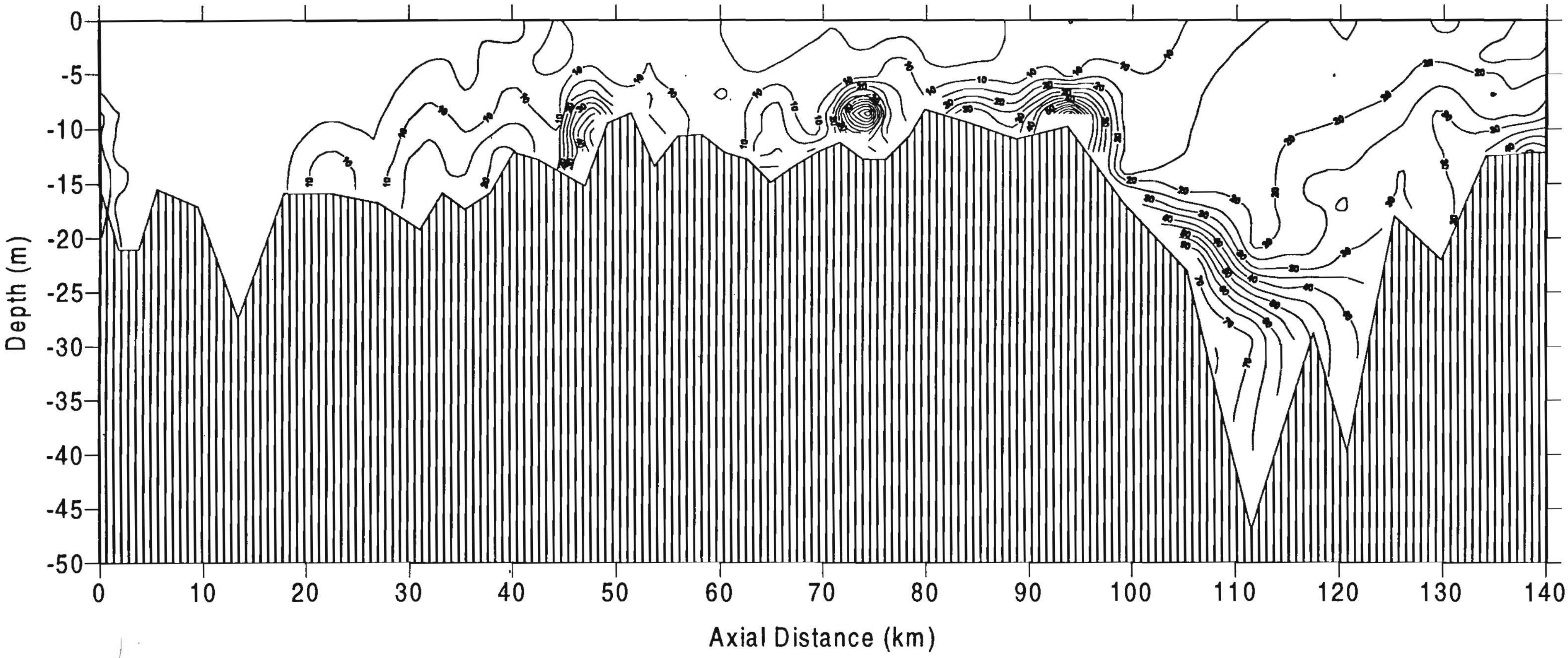
Figure 13

Suspended Sediment Concentration (mg/l), October 1994



* the interval used for contouring: 5 units (i.e. mg/l)

Figure 14

beginning of Ebb

Suspended Sediment Concentration (mg/l), December 1994

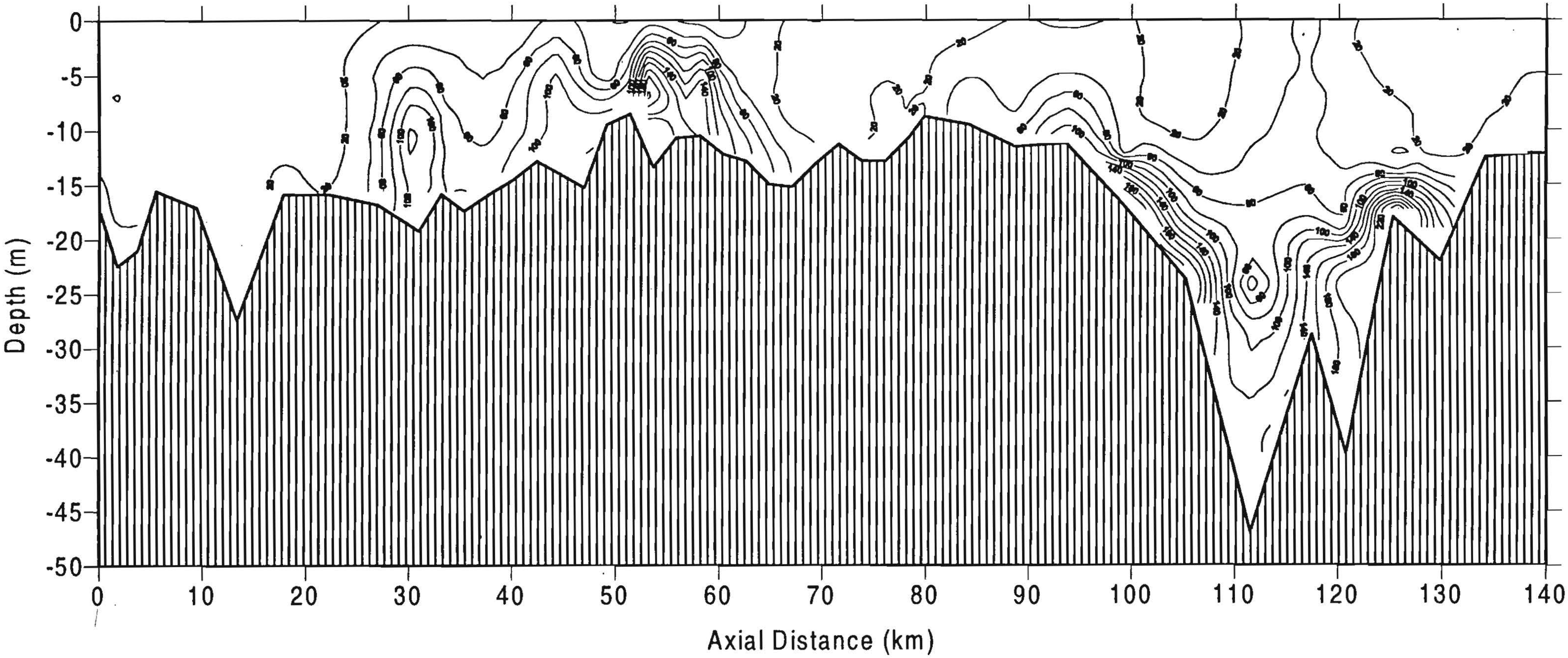


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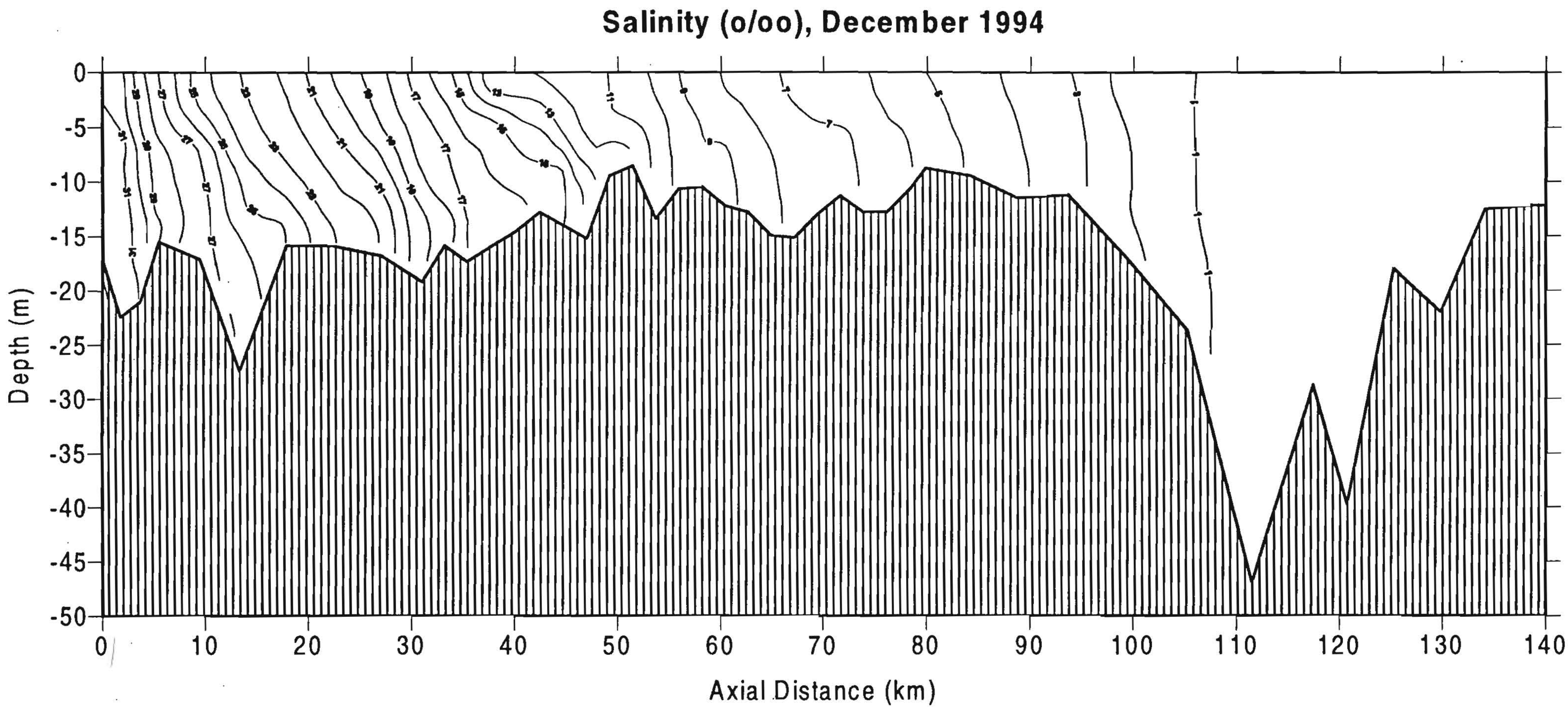
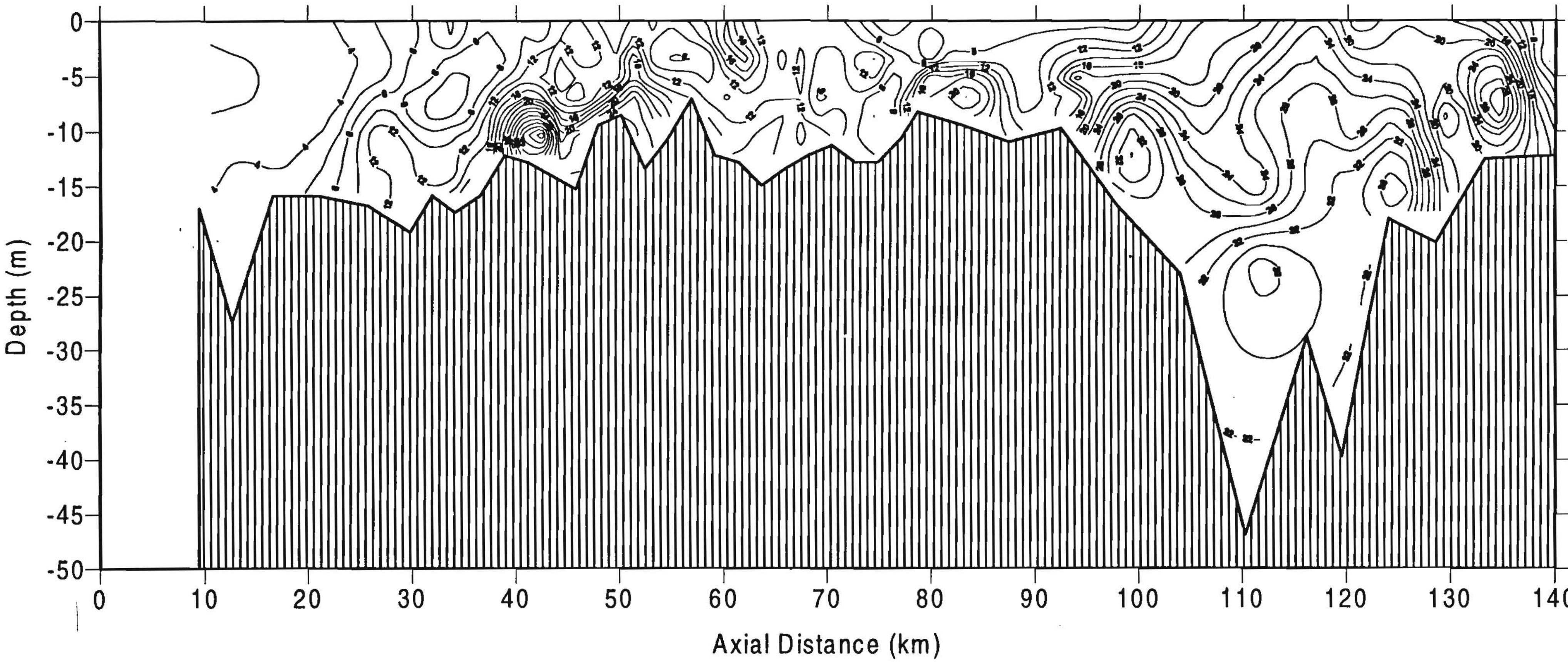
Figure 15



* the interval used for contouring: 1 unit (i.e. o/oo)

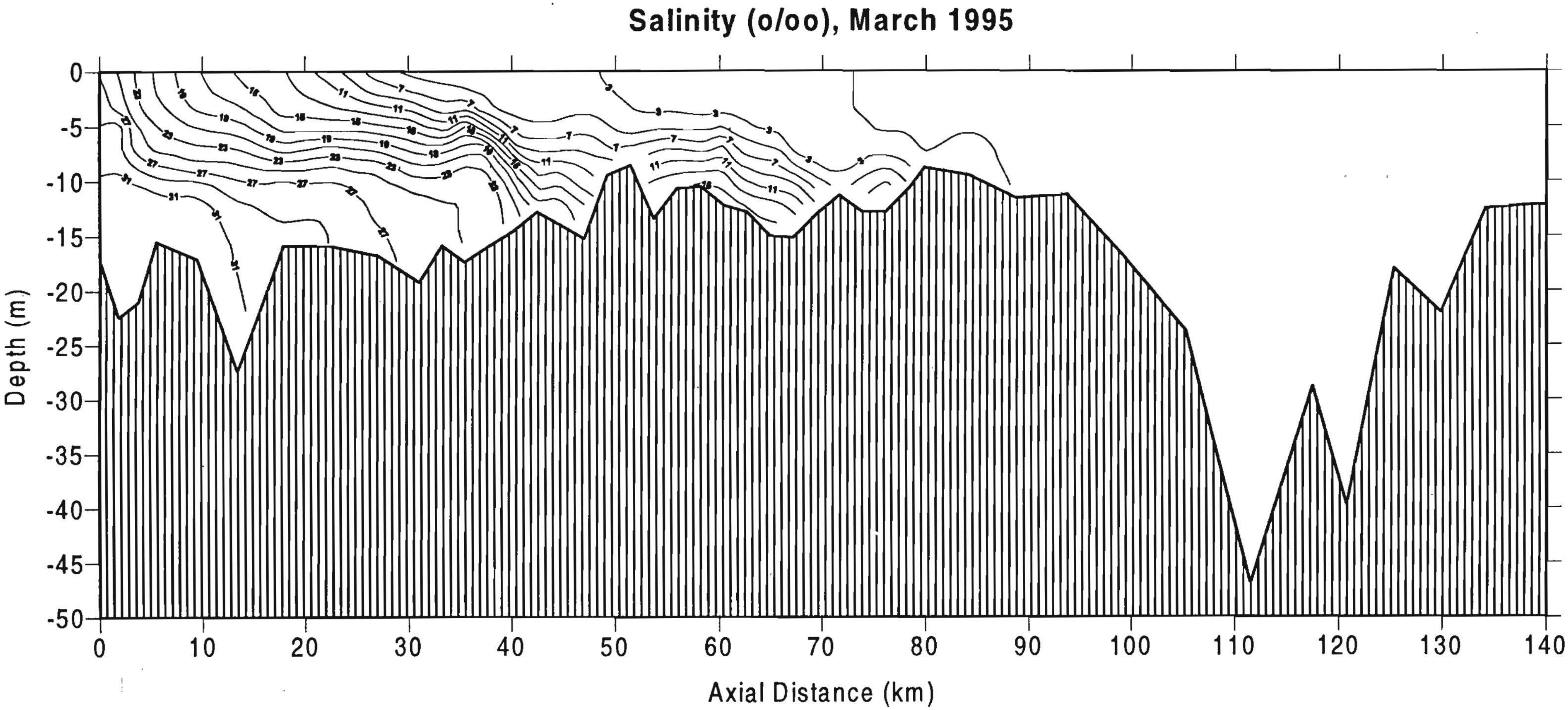
Figure 16

Suspended Sediment Concentration (mg/l), January 1995



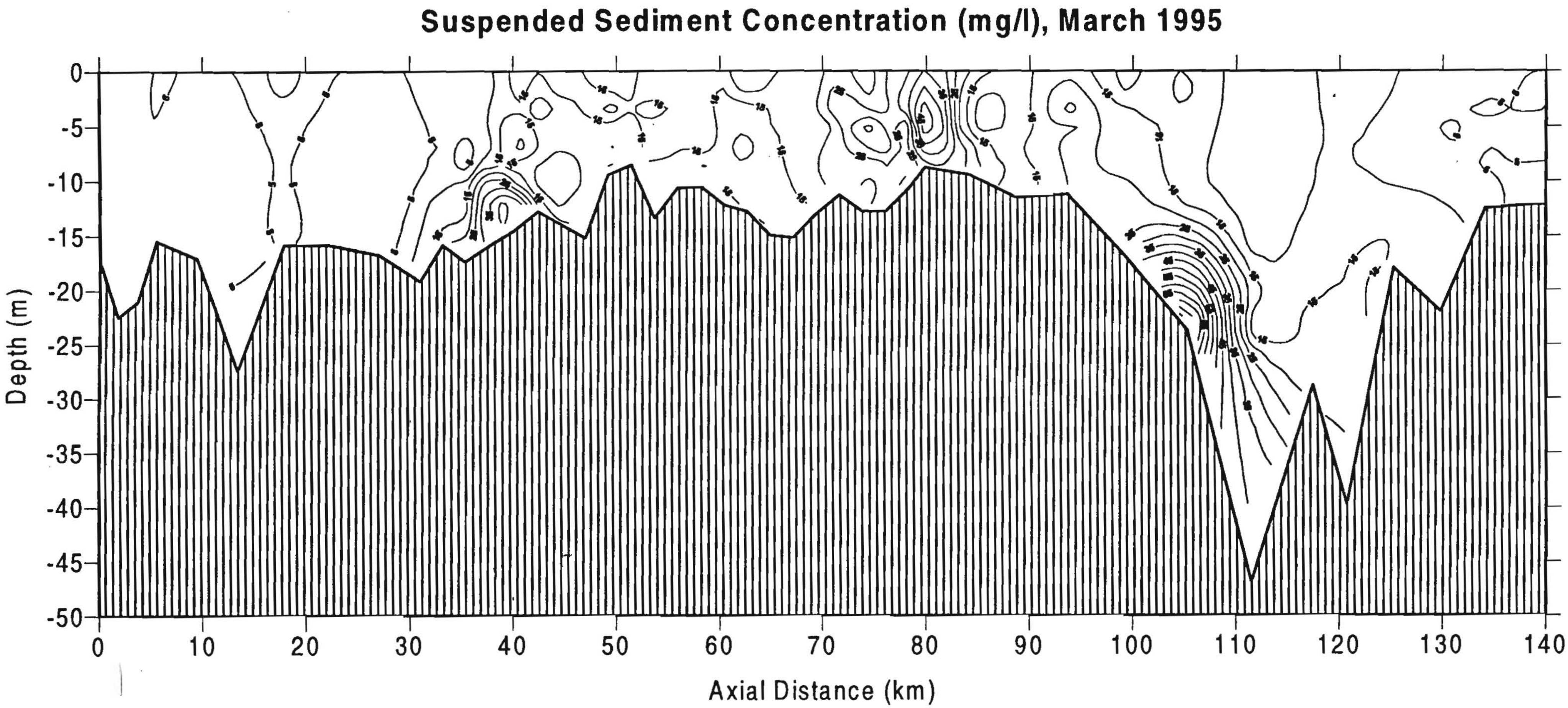
* the interval used for contouring: 2 units (i.e. mg/l)

Figure 18



* the interval used for contouring: 2 units (o/oo)

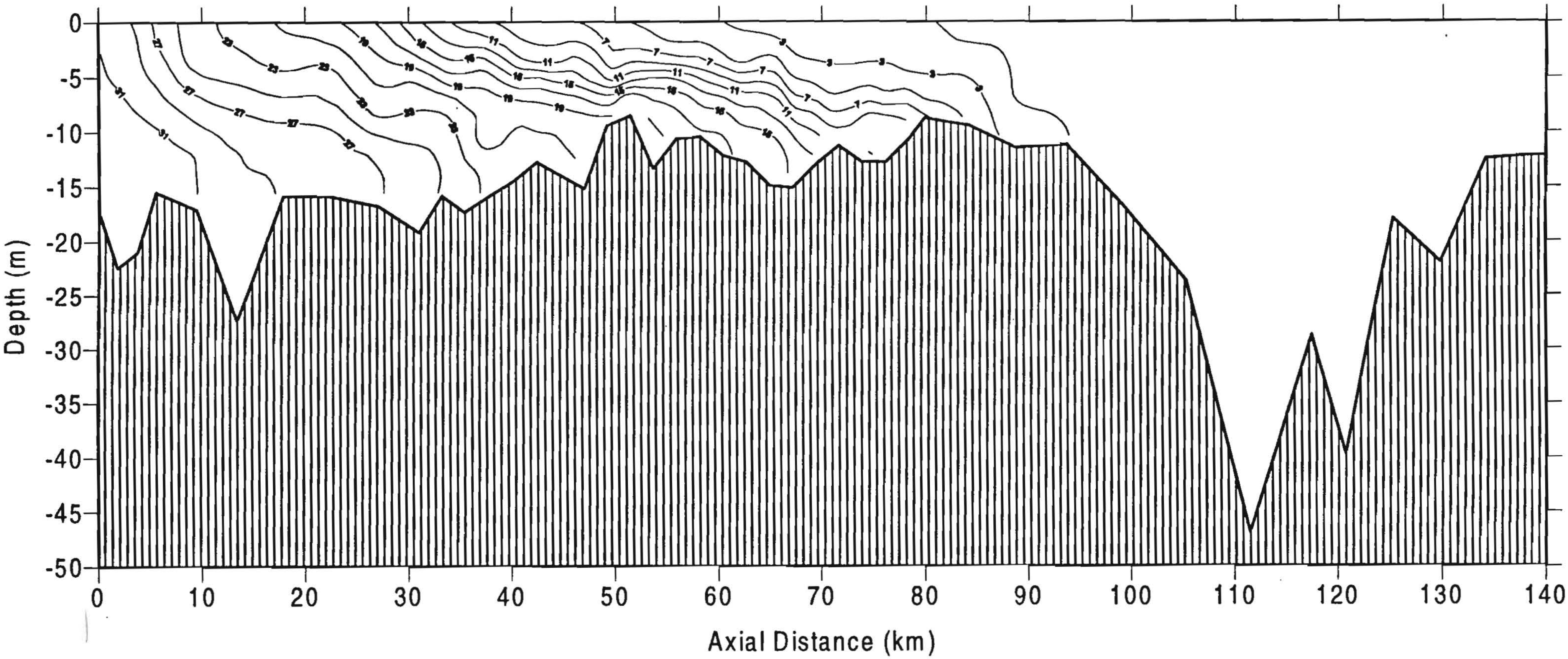
Figure 19



* the interval used for contouring: 5 units (i.e. mg/l)

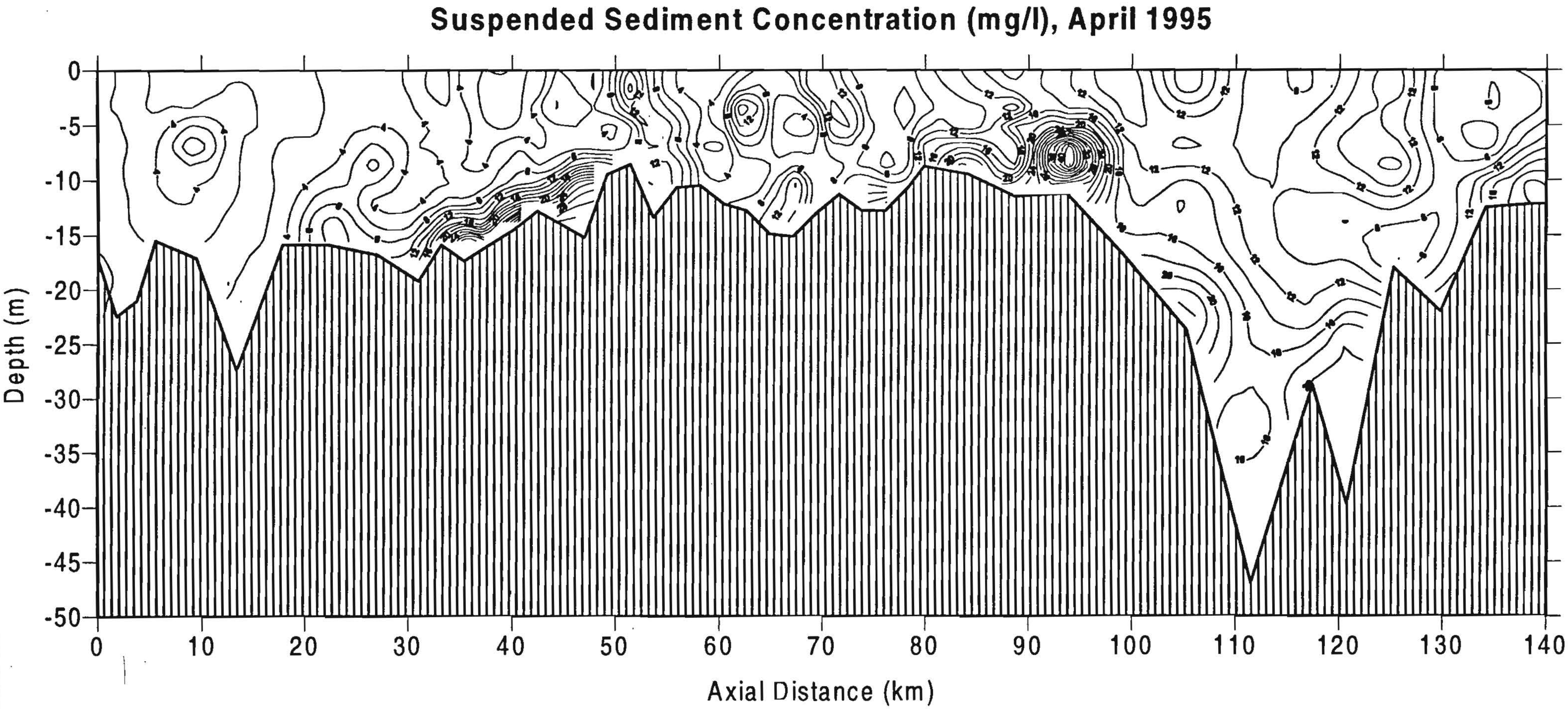
Figure 20

Salinity (o/oo), April 1995



* the interval used for contouring: 2 units (i.e. o/oo)

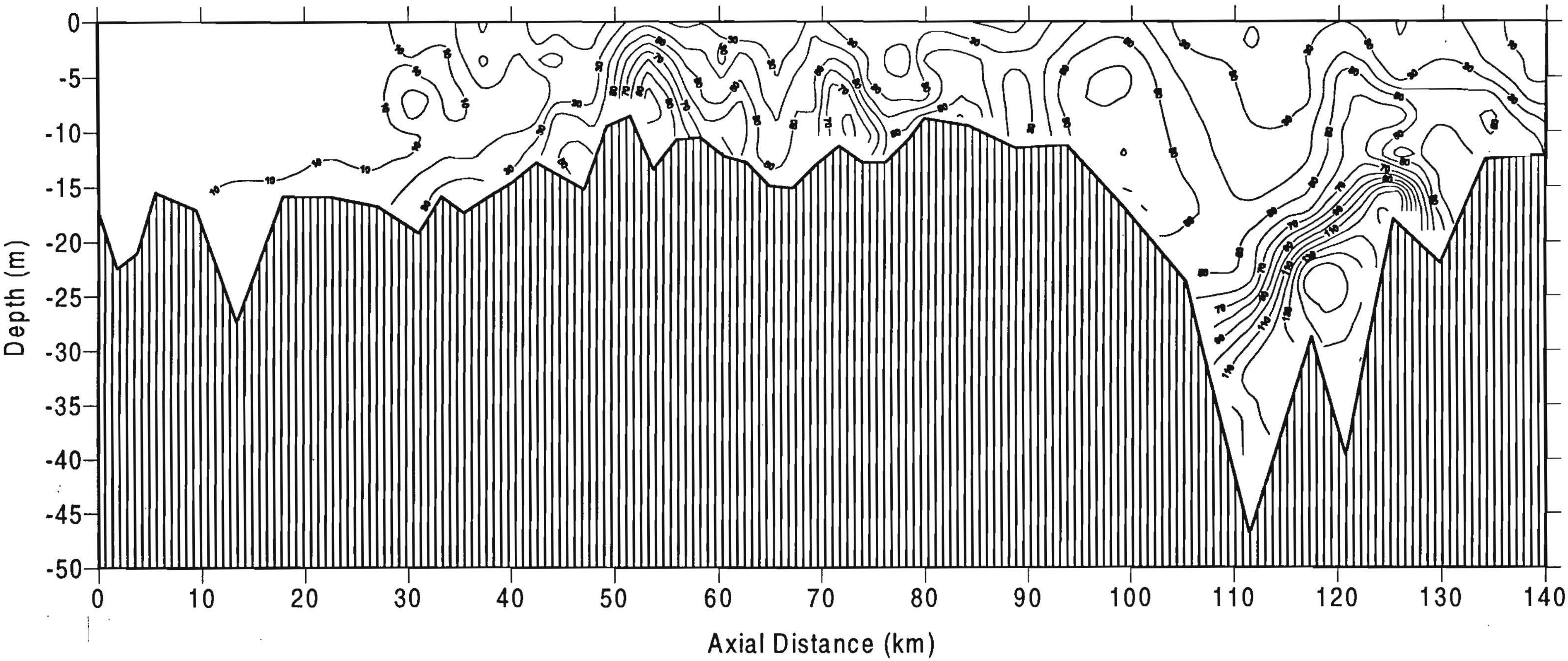
Figure 21



the interval used for contouring: 2 units (i.e. mg/l)

Figure 22

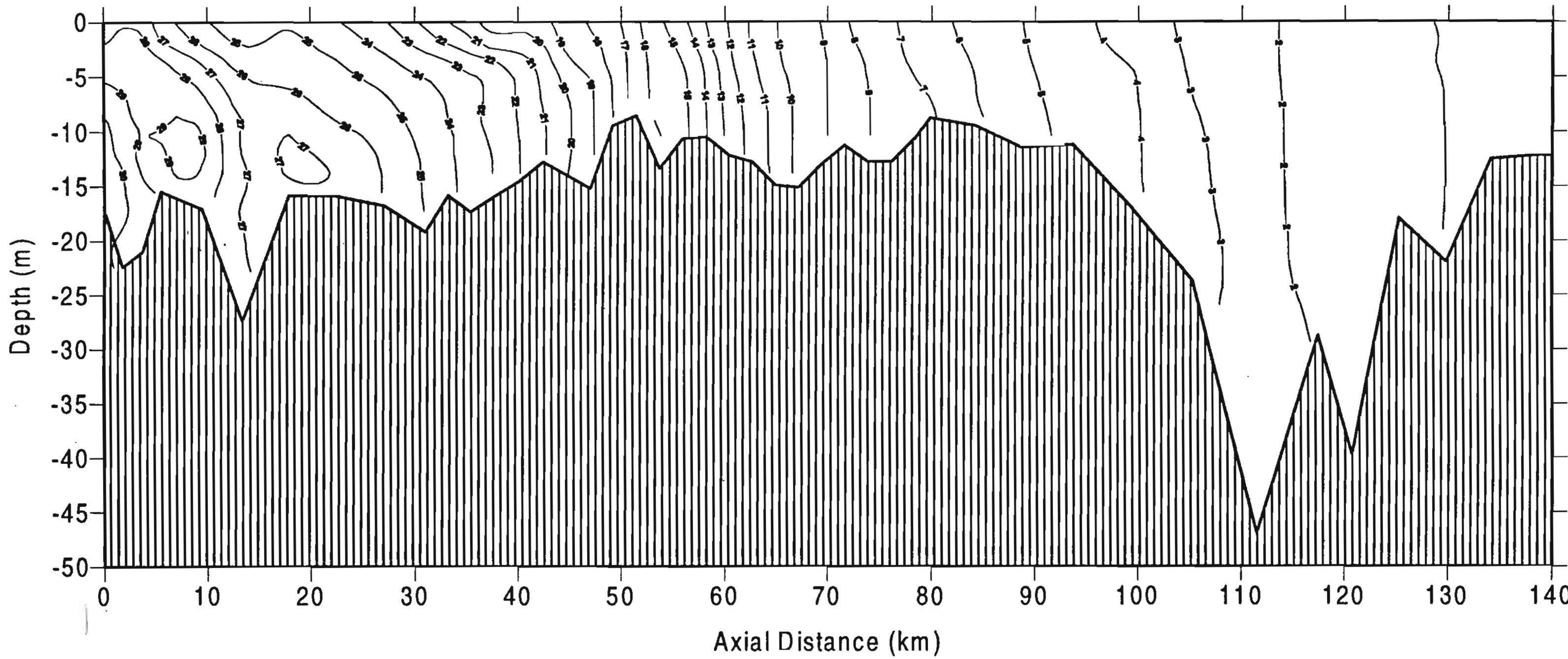
Suspended Sediment Concentration (mg/l), May 1995



* the interval used for contouring: 10 units (i.e. mg/l)

Figure 23

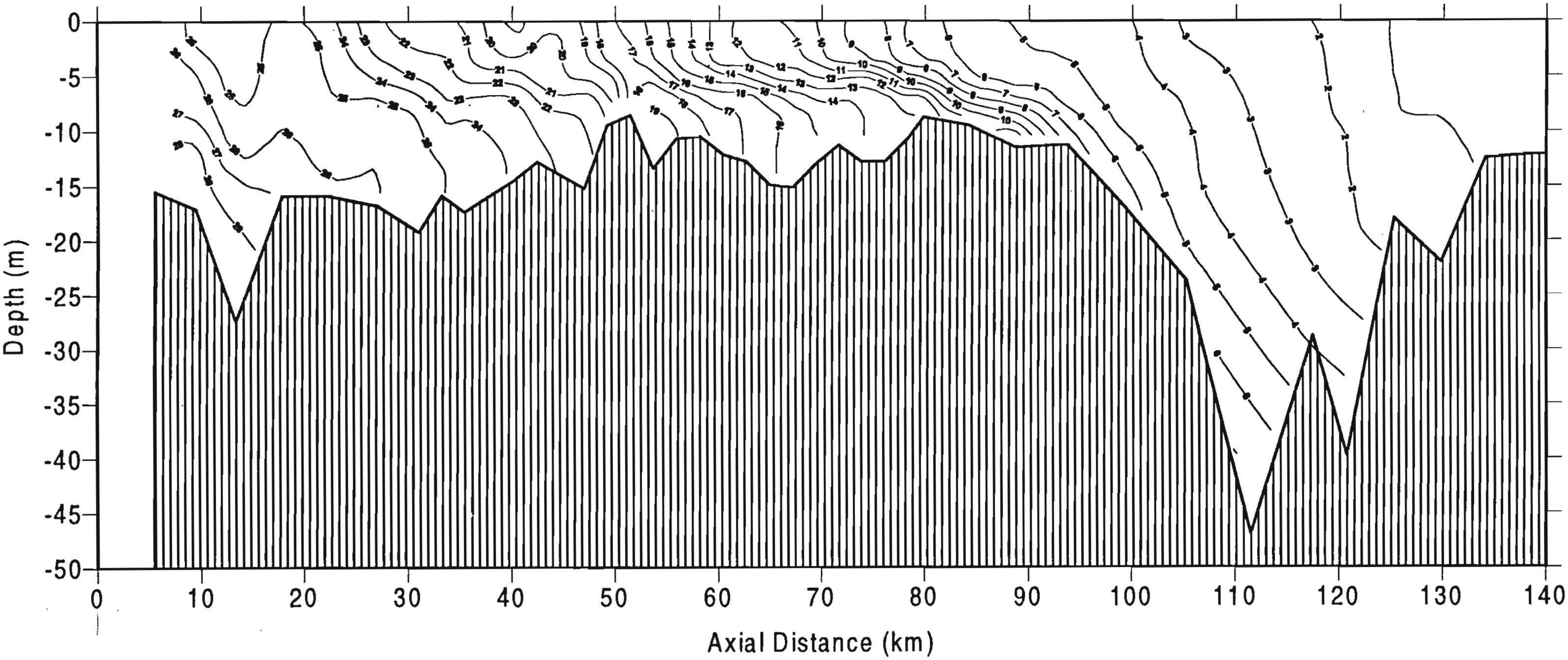
Salinity (o/oo), May 1995



* the interval used for contouring: 1 unit (i.e. o/oo)

Figure 24

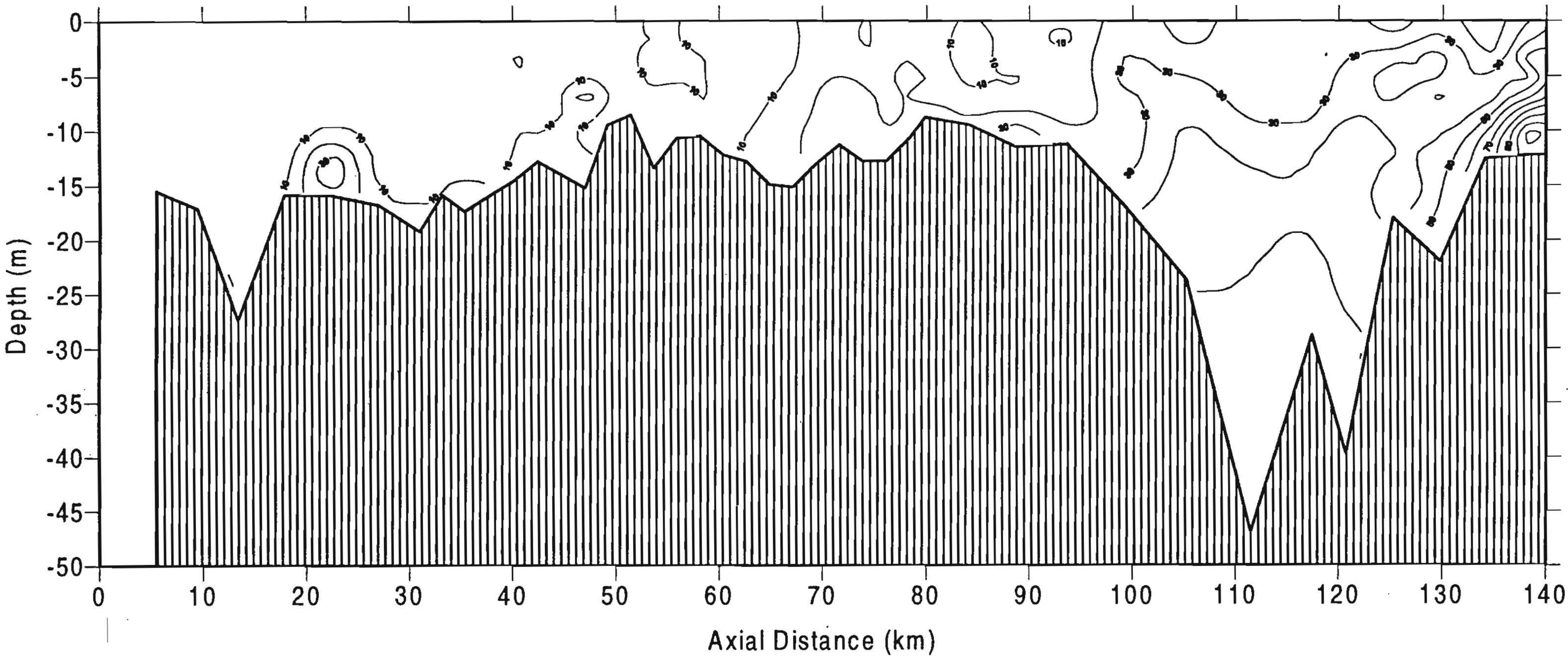
Salinity (o/oo), June 1995



* the interval used for contouring: 1 unit (i.e. o/oo)

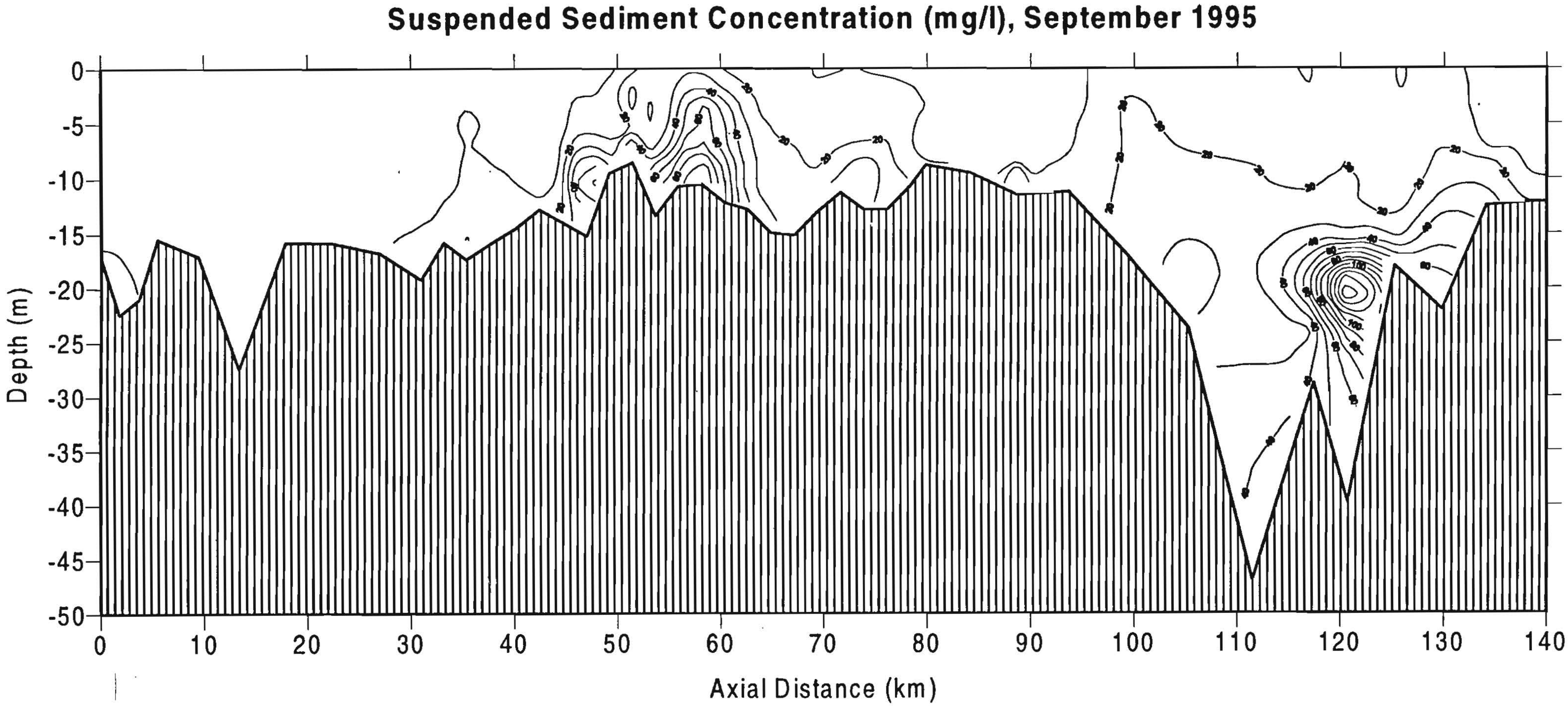
Figure 25

Suspended Sediment Concentration (mg/l), June 1995



* the interval used for contouring: 10 units (i.e. mg/l)

Figure 26



* the interval used for contouring: 10 units (i.e. mg/l)

Figure 28