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SALINITY DISTRIBUTION IN THE
JAMES ESTUARY

by

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Executive Summary

Under the aegis of the Cooperative State Agencies Program, since 1970 the Virginia Institute of Marine Science has been monitoring conditions in the tidal portions of the James, York, and Rappahannock Rivers. The data from the 1970-1980 decade have been presented graphically in data reports. The purpose of this report is to organize and summarize the information on the salinity distributions in the James River.

The source of the salt is the ocean and salinity generally declines with distance from the ocean. Salt is a conservative substance that is not created nor is it destroyed or transformed within the estuary. Rather there is a dynamic balance between the intrusion of saltwater from the ocean, the river flow, which tends to "push" the saltwater downriver, and tides and other phenomena which mix the fresher and saltier water masses.

In this report the salinity distributions observed over the duration of the program have been organized to show the effects of tidal phase and river flow; because freshwater inflow varies seasonally, the salinity profiles also vary seasonally. The upriver limit of saltwater intrusion also is examined, as is the strength of the salinity stratification. These data should prove useful to persons working in the estuary by providing an atlas of "typical" conditions against which observed conditions can be compared.

Introduction

The salinity level in any portion of the James River estuary is not constant, but varies with many factors, including the state and strength of the tide, the quantity of freshwater entering the river, wind conditions, location in the river, and location in the water column. Scientists, engineers, and resource managers are often interested in salinity conditions at a particular location for evaluation of the effects of salinity on desired river uses (e.g., drinking water, irrigation) or on biological organisms (e.g., distribution of oysters, MSX, oyster drills). Since 1971, the Virginia Institute of Marine Science, in cooperation with the State Water Control Board under the Cooperative State Agency (CSA) Program, has monitored salinity at 31 locations in the James River approximately monthly at slack before ebb and slack before flood tides. The purpose of this report is to describe salinity conditions in the James River based on these data and to illustrate and interpret variations in salinity conditions.

I. Factors Affecting Salinity

Tide is one of the most important factors affecting salinity in the James River estuary. Twice daily **flood tides** push high salinity water into the estuary, increasing the salinity at any particular point in the estuary. Twice daily **ebb tides** drain water back out of the estuary, returning salinity to lower values. It is therefore expected that at any particular location in the estuary, salinity would tend to be higher after the flood tide (i.e., at slack before ebb tide) than after the ebb tide (i.e., at slack before flood tide). Except when the moon is directly over the equator, **diurnal inequality** exists in the tides; more extreme high and low tides are followed by less extreme high and low tides, then by another set of more extreme high and low tides.

Other cyclic **astronomical variations** involving alignment of the sun, moon, and earth result in cyclic tidal components. One important component is the **spring/neap tidal cycle.** Spring tide occurs fortnightly, approximately at new and full moons when lunar and solar attractions act together to produce tides and tidal ranges of greatest magnitude. Spring tides push salt water further upriver than the tides at other phases of the spring/neap cycle. Neap tide also occurs fortnightly at the first and third quarters of the moon when lunar and solar attractions are perpendicular to each other. The smallest tidal ranges occur at neap tides; salt water is not pushed as far upriver. It is expected that at any location in the estuary, salinity at slack before ebb tide would be higher at spring tides than at neap tides, and salinity at slack before flood tide would be lower at spring tides than at neap tides.

Density increases with salinity, so fresher water tends to float over saltier water, leading to a **vertically layered system.** The James River is usually a partially mixed estuary in which some vertical mixing occurs between layers creating continuous vertical as well as longitudinal salinity gradients. Usually salinity increases from the surface to the bottom of the water column and from upstream to the river mouth in any depth layer. The relative strengths of freshwater inflows and tides determine the amount of mixing which occurs between the layers. The stronger the tide and the weaker the freshwater inflows, the better the water column mixes.

Just as a stronger flood tide pushes salt water further up-estuary, a large **input of freshwater** from the river tends to counteract tidal forces and pushes salt water down-river. During periods of greater freshwater input, salinity at any particular location would be expected to be lower than at times of lower freshwater input. Freshwater discharge to the river tends to be seasonal, with greatest inputs occurring during the late winter/spring, and the lowest inputs occurring in summer/early fall.

Because of the earth's rotation and resulting Coriolis effect, **lateral differences** in salinity across the estuary would be expected. Since the James River estuary is in the northern hemisphere, at any lateral cross section, salinity would be higher on the right side of the estuary (looking upstream) than on the left side. Irregular river geometry also contributes to lateral variation in salinity, which may, at some locations, mask the effect of earth's rotation.

Wind direction and magnitude also affect salinity distribution. For example, if wind was blowing in the upstream direction, it would force high salinity water from the lower estuary toward the upper estuary, increasing salinity at up-estuary locations. Down-estuary winds would force the fresher water from the upper estuary toward the lower estuary, decreasing salinity there. Wind induces greater mixing between surface and subsurface layers, leading to a less vertically stratified system. The magnitude of these effects would increase with increasing wind magnitude and duration. It is possible for up-estuary winds of long duration to reverse the circulation in an estuary, directing surface flow in an upstream direction, resulting in downstream flow at depth.

Sea level fluctuation also affects salinity in the estuary. The mean tide level in Hampton Roads has an annual cycle with a range of 18 cm (0.6 ft), being lowest in January and highest in September. The water surface in the bay also responds to meteorological events (e.g., tropical storms and "Northeasters"). Higher water level at the mouth of the estuary forces more saline water into the estuary and results in higher salinity.

II. Monitoring Program

In a program sponsored jointly with the State Water Control Board, the Virginia Institute of Marine Science has monitored water quality on the James River since 1971. Thirty-one sampling stations between the river mouth and Richmond have been occupied at various times during this period; sampling stations are shown in Figure 1; years of station occupation are shown in Table 1a. In general, the river has been monitored monthly at slack before flood and/or slack before ebb tides. Sampling during the winter months and at slack before ebb tide has occurred more sporadically than sampling during summer and at slack before flood tide. Table 1b shows, by tide state, the months in each year in which salinity observations were made. A total of 99 sampling runs were made at slack before flood; 43 runs were made at slack before ebb. Table 1c shows the number of surveys made at each station in each month.

Each sampling run began at the river mouth and followed the slack tide upriver toward Richmond according to the schedule in Table 2. A number of sampling runs included the whole length of the tidal river for the purpose of measuring water quality parameters (e.g., dissolved oxygen, nutrients) in the freshwater as well as saline portions of the river. When water quality

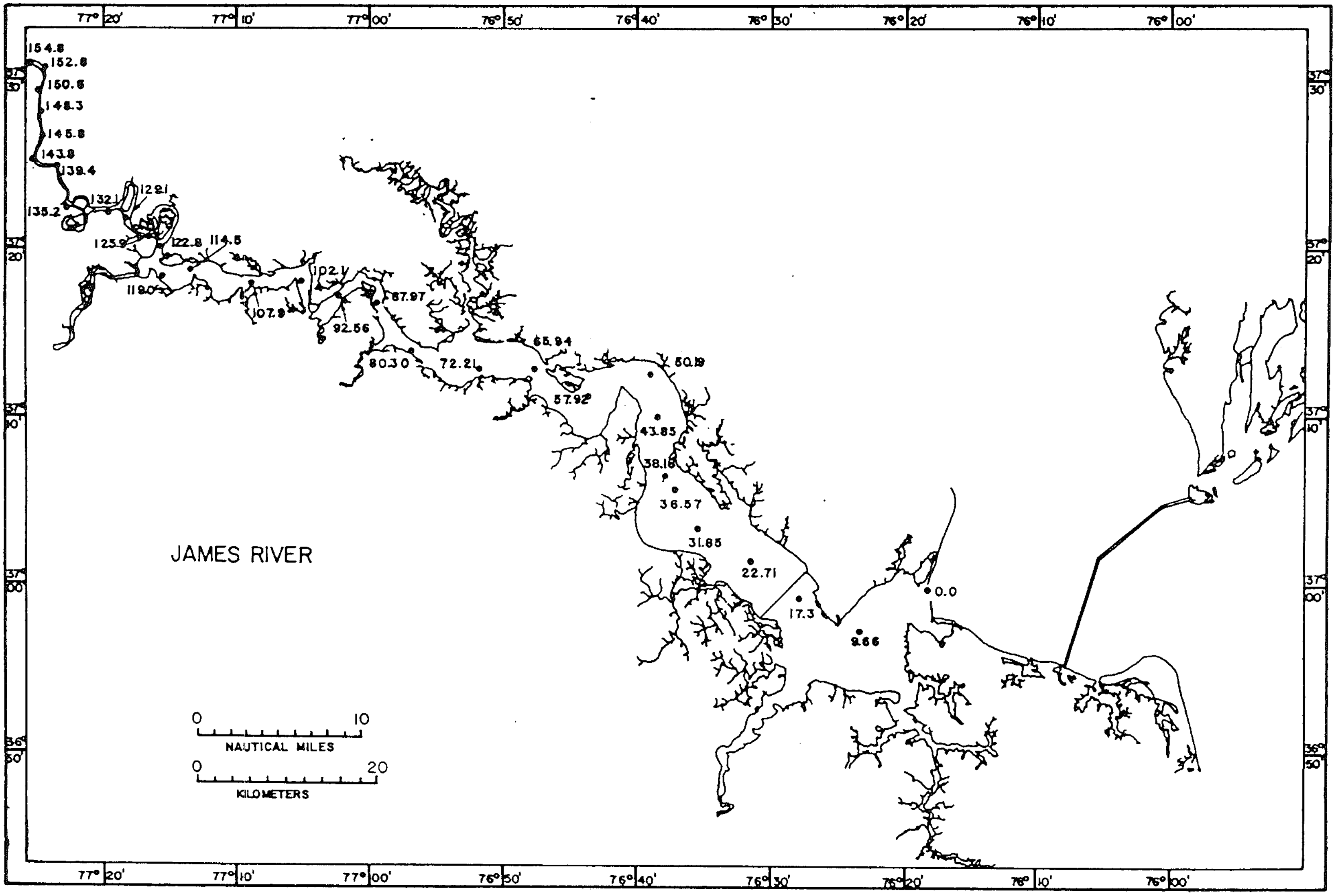


Figure 1. Map of the James River showing the station locations (numbers are km from river mouth).

Table 1a. Schedule of stations sampled during monitoring program.

	Year														
Distance from river mouth (km)	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
0.00	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
9.66	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	XX	XX
17.30	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
22.71	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	XX	XX
31.85	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
36.57	.	.	.	.	.	.	.	.	.	XX	.	XX	XX	.	.
38.18	.	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	XX
43.85	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	XX	XX
50.19	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
57.92	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	XX	XX
65.94	.	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
72.21	.	.	.	.	.	.	.	.	.	XX	XX	XX	XX	.	XX
80.30	XX	XX	XX	XX	.	XX	.	.	XX	XX	XX	XX	XX	XX	XX
87.97	.	.	.	.	.	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
92.56	XX	.	XX	XX	.	XX	XX	.	XX	XX	XX	XX	XX	XX	XX
102.10	.	.	.	.	.	XX	XX	.	XX	XX	XX	XX	XX	XX	.
107.90	XX	.	.	XX	.	XX	XX	XX	.	XX	XX	XX	XX	.	.
114.50	XX	.	.	XX	.	XX	XX	.	.	.	XX	XX	XX	XX	.
119.00	.	.	.	.	.	XX	.	.	.	.	.	XX	XX	XX	.
122.80	XX	.	.	XX	.	XX	.	.	.	.	.	XX	.	XX	.
125.90	XX	.	.	XX	.	XX	.	.	.	.	.	XX	.	XX	.
129.10	.	.	.	.	.	XX	.	.	.	.	.	XX	.	XX	.
132.10	XX	.	.	XX	.	.	.	.	.	.	.	XX	.	XX	.
135.20	.	.	.	.	.	XX	.	.	.	.	.	XX	.	XX	.
139.40	XX	.	.	XX	.	XX	.	.	.	.	.	XX	.	XX	.
143.80	.	.	.	.	.	XX	.	.	.	.	.	XX	.	XX	.
145.80	.	.	.	.	.	.	.	.	.	.	.	XX	.	XX	.
148.30	.	.	.	.	.	.	.	.	.	.	.	XX	.	.	.
150.60	XX	.	.	XX	.	XX	.	.	.	.	.	XX	.	.	.
152.80	.	.	.	.	.	XX	.	.	.	.	.	XX	.	.	.
154.80	.	.	.	.	.	XX	.	.	.	.	.	XX	.	.	.

XX = observations occurred during this year

Table 1b. Schedule of sampling surveys for each month and year by tide phase.

		Month											
Year	Tide	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
71	sbf	.	.	.	.	.	XX	.	.	XX	.	.	.
	sbe	.	.	.	.	.	.	.	.	XX	XX	.	XX
72	sbf	XX	.	XX	XX	XX	.	.	.	XX	XX	XX	.
	sbe	.	.	XX	.	XX	.	.	.	XX	.	.	XX
73	sbf	.	.	.	.	.	.	.	.	.	XX	.	.
	sbe	XX	XX	XX	.	XX	XX	.	.	.	XX	.	.
74	sbf	.	.	.	.	XX	.	XX	XX	XX	XX	XX	.
	sbe	.	XX	.	XX	.	XX	XX	.	.	.	.	XX
75	sbf	.	.	.	XX	.	.	.	.	XX	XX	.	.
	sbe	.	.	.	.	XX	.	.	.	.	.	XX	.
76	sbf	.	.	.	XX	XX	XX	XX	.	.	XX	XX	.
	sbe	.	.	.	.	XX	.	.	.	.	.	XX	.
77	sbf	.	.	.	XX	.	XX	XX	.	XX	.	.	.
	sbe	.	.	.	.	.	.	XX	XX	XX	XX	.	.
78	sbf	.	.	.	XX	.	XX	XX	XX	.	.	.	.
	sbe	.	.	.	XX	XX	.	.	XX	XX	.	.	.
79	sbf	XX	.	XX	XX	XX	XX	XX	XX	XX	XX	XX	.
	sbe	.	.	.	.	.	.	XX	.	XX	.	.	.
80	sbf	.	.	.	.	.	.	.	XX	.	XX	.	.
	sbe	.	.	.	.	.	XX	XX	XX	XX	.	.	.
81	sbf	.	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	.
	sbe	.	XX	.	.	.	.	.	.	.	.	.	.
82	sbf	.	.	XX	XX	XX	XX	XX	XX	XX	XX	XX	.
	sbe	.	.	.	.	.	.	.	.	.	.	.	.
83	sbf	.	.	XX	XX	XX	XX	XX	.	XX	XX	XX	.
	sbe	.	.	.	.	.	.	.	.	.	.	.	.
84	sbf	.	.	.	XX	.	XX	XX	XX	XX	XX	XX	.
	sbe	.	.	.	.	.	.	.	.	.	.	.	.
85	sbf	.	.	.	XX	XX	XX	XX	.	XX	XX	XX	.
	sbe	.	.	.	.	.	.	.	.	.	.	.	.

sbf = slack before flood tide
sbe = slack before ebb tide
XX = observations occurred

Table 1c. Number of surveys at each station for each month.

Distance (km)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.00	1	4	2	9	8	12	13	9	16	13	11	3
9.66	.	.	3	6	5	6	5	6	7	5	5	.
17.30	2	3	4	12	11	13	12	9	16	16	11	3
22.71	.	.	3	5	5	6	3	6	4	4	4	.
31.85	3	3	6	17	12	14	11	11	17	16	10	3
38.18	.	.	3	6	4	5	4	2	6	5	5	.
43.85	.	.	3	6	5	6	4	6	7	4	5	.
50.19	3	3	6	11	11	14	12	11	16	14	11	3
57.92	1	.	4	6	7	8	4	6	7	7	9	.
65.94	2	3	6	11	10	13	11	12	17	12	9	2
72.21	1	2	6	11	7	9	5	8	10	7	8	1
80.30	3	3	6	11	11	14	10	10	16	14	9	3
87.97	3	3	6	11	8	10	10	10	19	12	9	3
92.56	3	3	6	11	10	14	12	11	19	14	9	4
102.10	3	3	6	11	10	11	11	10	19	13	9	3
107.90	3	3	6	12	12	13	12	11	19	14	9	4
114.50	3	3	6	12	12	14	12	11	19	14	9	4
119.00	3	3	6	12	11	13	11	10	18	13	9	4
122.80	3	3	6	12	12	14	12	11	19	14	9	4
125.90	3	3	6	12	12	14	12	11	19	14	9	4
129.10	3	3	6	12	11	13	11	10	19	13	9	4
132.10	3	3	6	12	11	14	11	11	19	14	9	4
135.20	3	3	6	12	11	13	11	10	19	13	9	4
139.40	3	3	6	12	12	14	12	11	19	14	9	4
143.80	3	3	6	12	11	13	11	10	19	13	9	4
145.80	3	3	6	12	11	13	10	10	19	13	9	4
148.30	3	3	6	12	11	13	10	10	19	13	9	4
150.60	3	3	6	12	12	14	12	11	19	14	9	4
152.80	3	3	6	12	12	14	12	11	19	14	9	4
154.80	3	3	6	12	12	14	12	12	19	14	9	4
Total surveys	3	4	7	17	14	14	15	12	20	16	11	5

Note: Table includes salinity values of zero added to complete each survey in which freshwater (bottom salinity <1 ppt) was detected. On some surveys, freshwater was not detected and no zero salinity values were added upstream. In most months, not all stations were visited on each survey. Consequently, the number of surveys for any station may be less than the total number of surveys for that month.

Table 2. Sampling timetable and station location

Distance from river mouth(km)	Time after start(hh:mm)	Latitude(N) (degrees minutes)	Longitude(W) (degrees minutes)
00.00	0:00**	36 59.8	76 18.2
09.66		36 57.3	76 23.5
17.30	1:00	36 59.4	76 27.6
22.71		37 1.6	76 31.3
31.85	1:52	37 3.4	76 35.6
36.57		37 5.7	76 37.2
38.18		37 6.2	76 37.6
43.85		37 9.3	76 38.5
50.19	3:03	37 12.4	76 39.1
57.92		37 11.4	76 43.7
65.94	3:42	37 12.9	76 47.6
72.21		37 13.0	76 51.8
80.30	4:12	37 14.2	76 56.9
87.97	4:27	37 17.1	76 59.4
92.56	4:36	37 17.3	77 2.5
102.1	4:54	37 18.3	77 4.9
107.9	5:06	37 18.1	77 8.8
114.5	5:18	37 19.0	77 13.2
119.0	5:30	37 18.4	77 15.6
122.8	5:36	37 20.2	77 16.3
125.9	5:42	37 21.2	77 17.3
129.1	5:49	37 22.2	77 18.6
132.1	5:54	37 22.8	77 20.4
135.2	6:00	37 22.9	77 22.4
139.4		37 24.6	77 23.7
143.8		37 25.7	77 25.6
145.8		37 26.7	77 25.2
148.3		37 28.1	77 25.3
150.6		37 29.3	77 25.3
152.8		37 30.4	77 25.1
154.8	6:40	37 31.4	77 25.2

** Start at 1:15 hours before predicted slack water at Chesapeake Bay mouth.

measurements were not planned, the sampling runs proceeded upriver just beyond the salt water intrusion, defined as conductivity less than or equal to 0.50 mmho/cm within 1 meter of the bottom. At each sampling station in the saline portion of the river, salinity was measured every 2 meters from surface to bottom. The data are stored permanently on magnetic tape accessible by the VIMS PRIME computer.

Brooks and Fang (1983) presented daily plots of the 1971-1980 temperature, salinity, and dissolved oxygen data. In this report the 1971-1985 salinity data are summarized and some analyses of the data to demonstrate the seasonal patterns, tidal effects, and effect of freshwater input on salinity are presented.

There are several limitations inherent in the data set which are important to note when interpreting the data. It is apparent upon examination of Table 1a that not all stations have been sampled on every sampling run. Some stations were added later in the monitoring program; upstream stations were often sampled only when saltwater intruded particularly far upstream. In order to account for the latter event, on any sampling run in which a bottom salinity less than 1.0 ppt was found but the sampling run did not continue upstream, salinity values of 0.0 ppt were added to the data set for unsampled upstream stations. On sampling runs in which a bottom salinity less than 1.0 ppt was not found, no zeroes were added and the survey was considered incomplete with respect to salinity. Table 1c indicates number of surveys at each station after adding zeroes.

Within each year of the monitoring program, not all months were sampled (Table 1b). A long-term average of salinity for a particular month would therefore be biased toward the years in which that month was sampled and would not truly represent a long-term average condition. In the later years of the program, only slacks before flood tide were sampled (Table 1b). During early years of the program, both slacks were sampled, but not with any regularity. Any comparisons of the slacks should therefore take into account the distribution of the observations through years and months.

Tidal effects (i.e., spring/neap cycle and flood/ebb cycle) occur on a shorter time period than is sampled by this monitoring program. In other words, the flood/ebb cycle encompasses approximately 12 hours, while the spring/neap cycle encompasses approximately 2 weeks, but monitoring occurs generally only once per month. This monitoring program cannot illustrate the variations which occur within each month. Since all monitoring took place at either slack before ebb tide or slack before flood tide, long-term averages for these two states of the tide may be compared. No attempt was made to time the surveys with any particular phases of the spring/neap tidal cycle. The effect of the spring/neap variation on salinity structure can not be evaluated with this data set.

The stations monitored were generally in the center of the river channel; lateral variability in salinity was not investigated in this monitoring program. Similarly, the one-month time step of the monitoring was not short enough to quantify effects of the wind and other meteorological events on salinity.

III. Longitudinal Patterns

A. Seasonal Variations

The most apparent salinity pattern is the gradual decrease of salinity with increasing distance from river mouth. This longitudinal pattern responds slowly to the variation of freshwater inflow except during short periods of extreme high runoff events. Therefore, longitudinal salinity profiles have a distinct seasonal variation following the annual hydrological cycle. Figures 2 through 13 show the means and ranges of vertically-averaged salinities for each month of the year versus distance from river mouth. Means shown for each month and station are the results of averaging over depths and years. The means and ranges of surface and bottom salinities are presented in figures 14 through 25, and 26 through 37 respectively. Measurable salinity was observed in the river reach beyond 100 km from the mouth only during prolonged drought. Therefore the figures in this report display only the section of the James River between 0 and 100 km from the river mouth.

These plots illustrate the effect of freshwater discharge on the longitudinal salinity patterns. The greatest monthly mean freshwater discharge (about 390 m^3s^{-1}) occurred in the early spring, and the smallest (about 120 m^3s^{-1}) occurred in early fall. Therefore salinity was generally highest in late summer to early fall and lowest in the spring. Comparison of April and September mean salinities (Figures 5 and 10) reveals that mean September salinities for stations between 20 and 80 km above the river mouth averaged about 4 ppt higher than those of April.

When examining these plots, it is important to keep in mind that the salinity record for each station is not complete. As shown in Table 1a, not all stations were sampled on each sampling run. Although some points truly represent long-term (10 to 15 year) averages, others represent averages for only a portion of the monitoring period. In some cases, when the number of observations for a particular station during a month was significantly lower than for other stations during that month, the stations with few data were

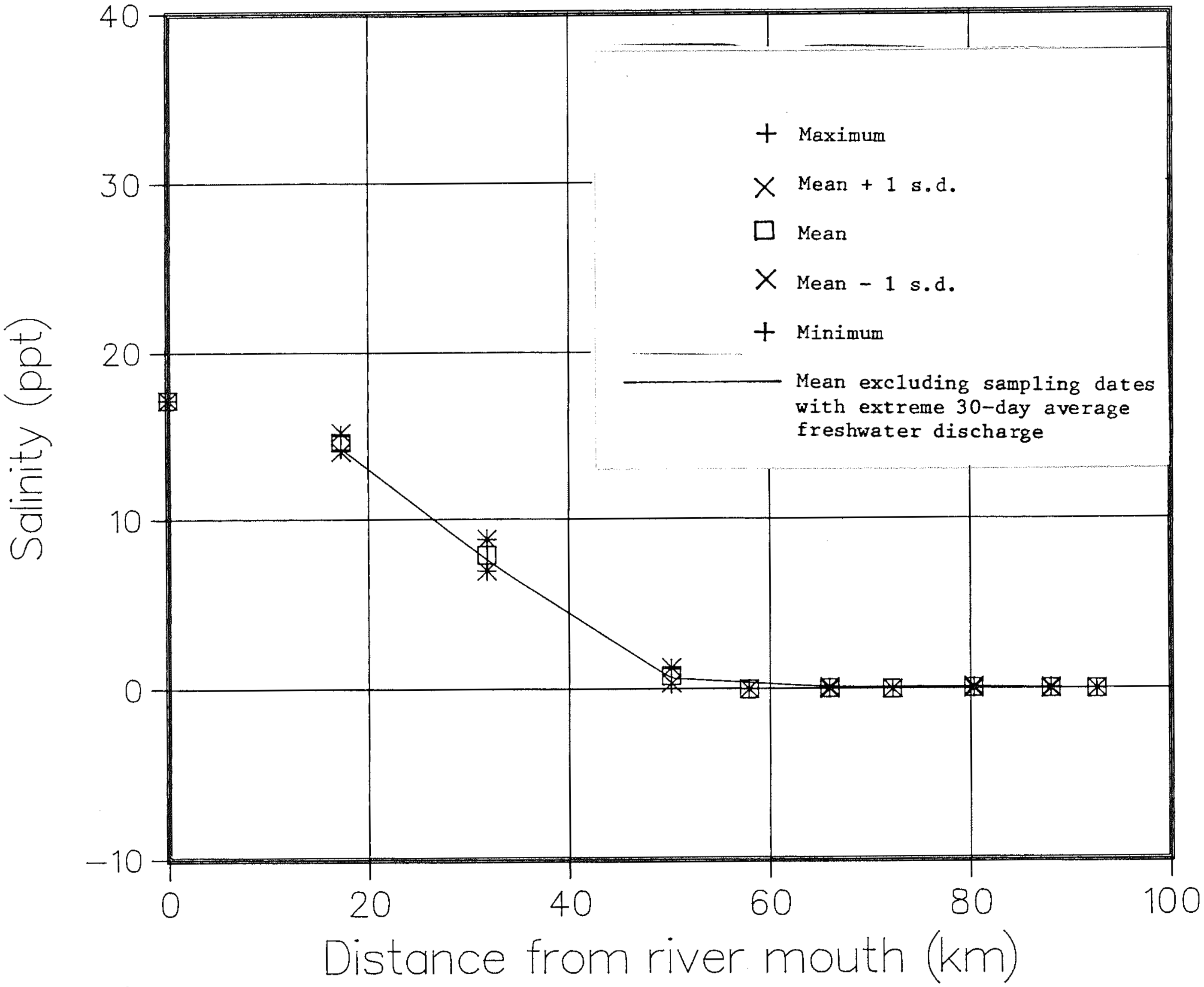


Figure 2. January vertically averaged salinity with distance from river mouth.

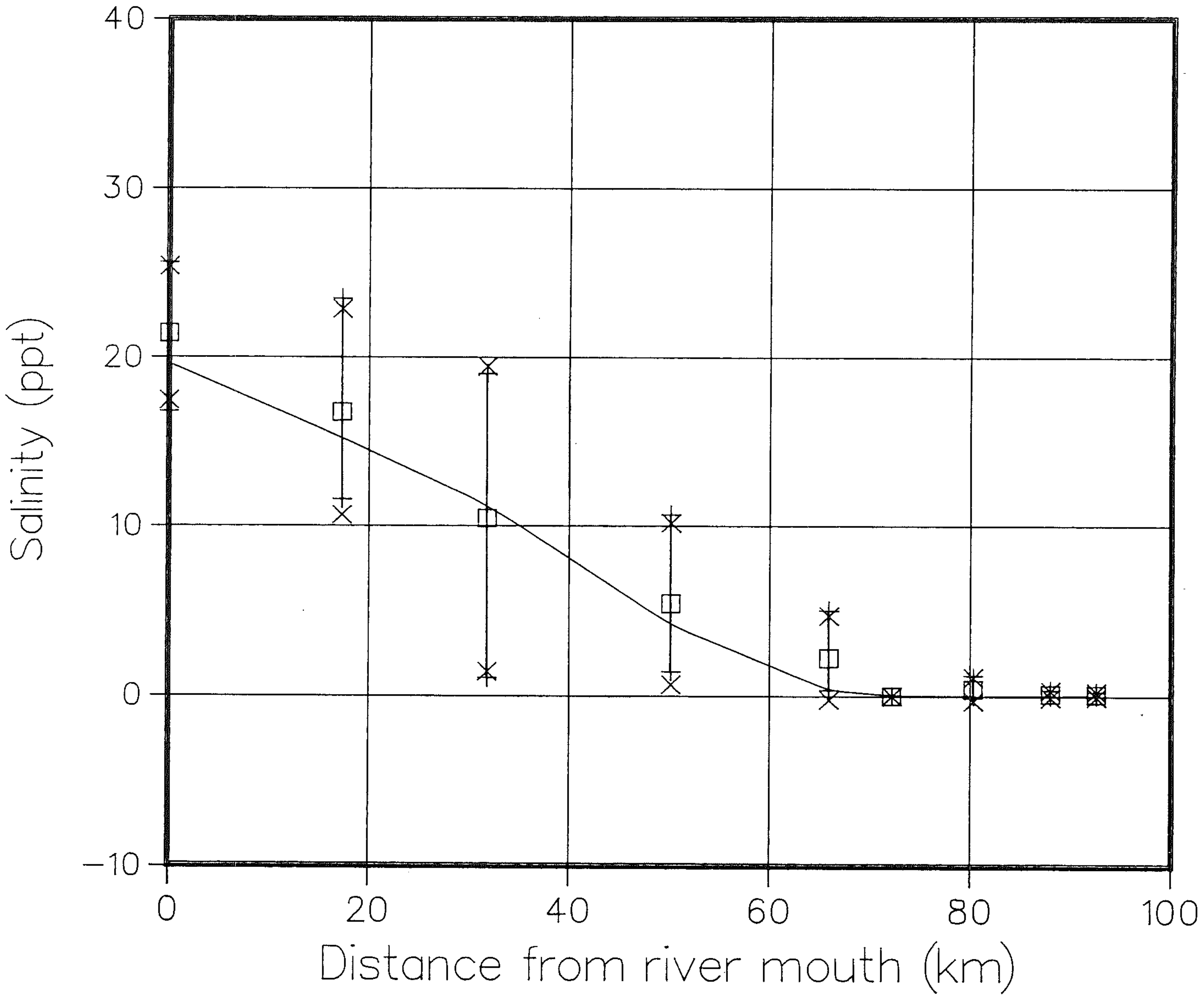


Figure 3. February vertically averaged salinity with distance from river mouth (key as in figure 2).

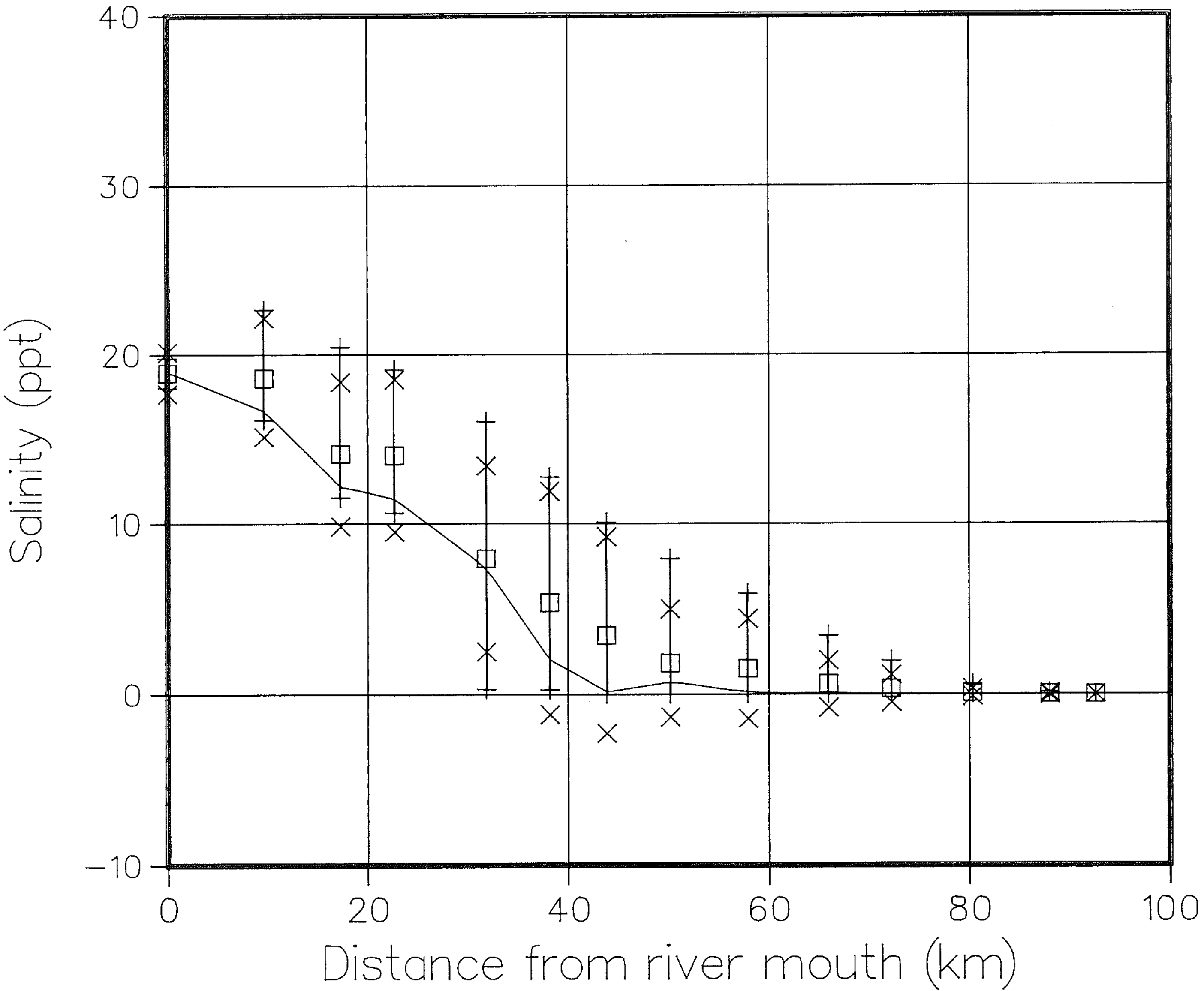


Figure 4. March vertically averaged salinity with distance from river mouth (key as in figure 2).

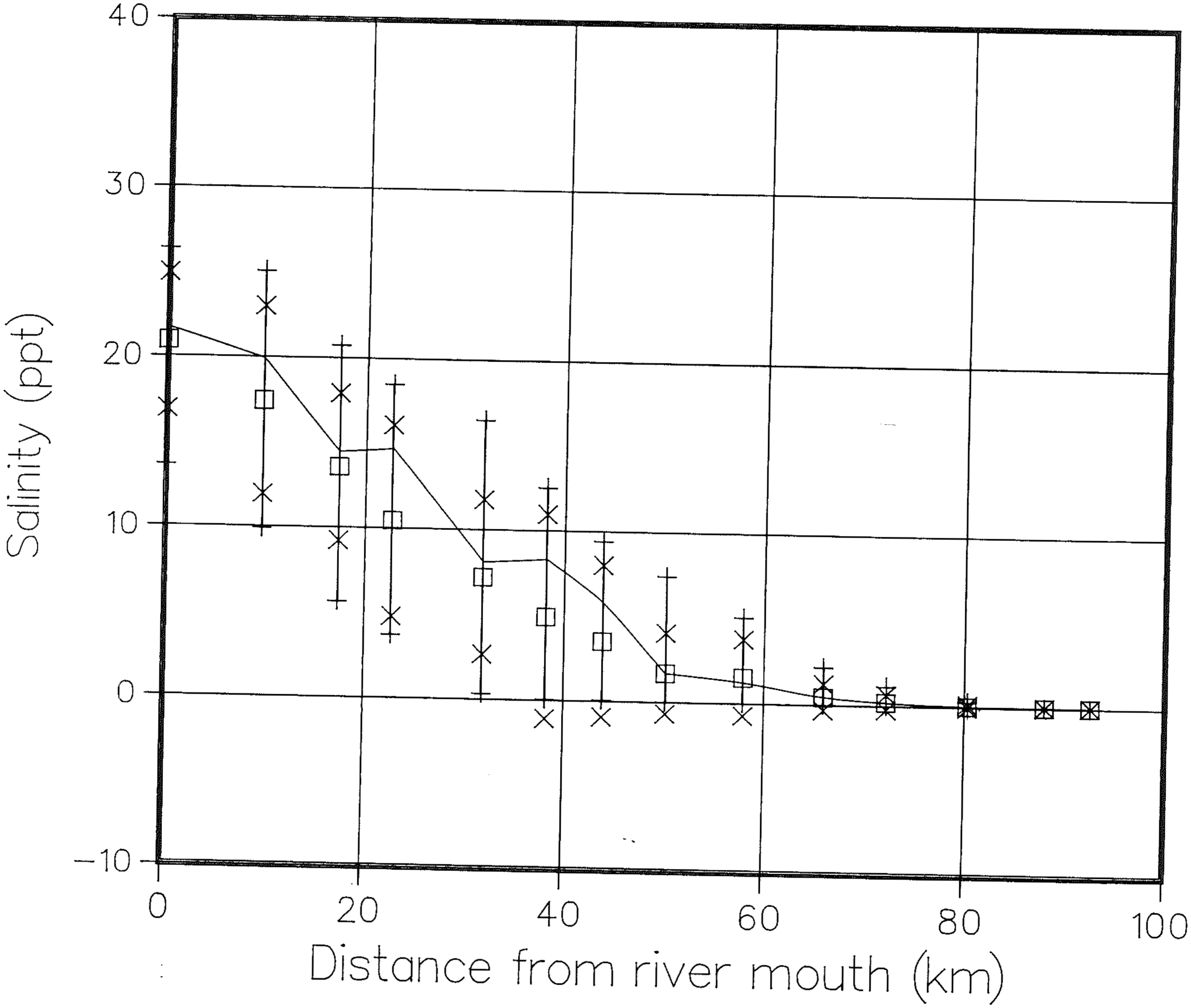


Figure 5. April vertically averaged salinity with distance from river mouth (key as in figure 2).

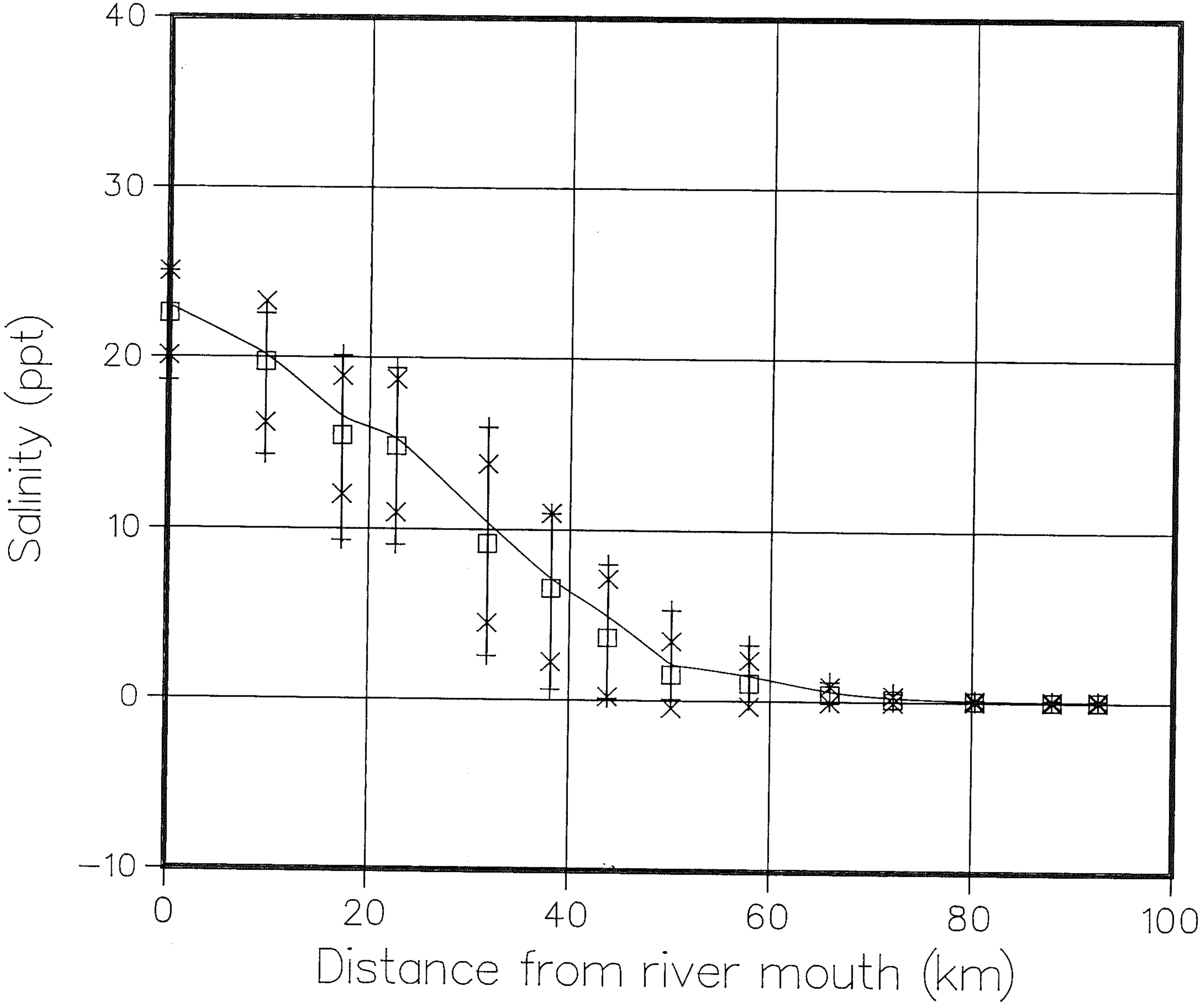


Figure 6. May vertically averaged salinity with distance from river mouth (key as in figure 2).

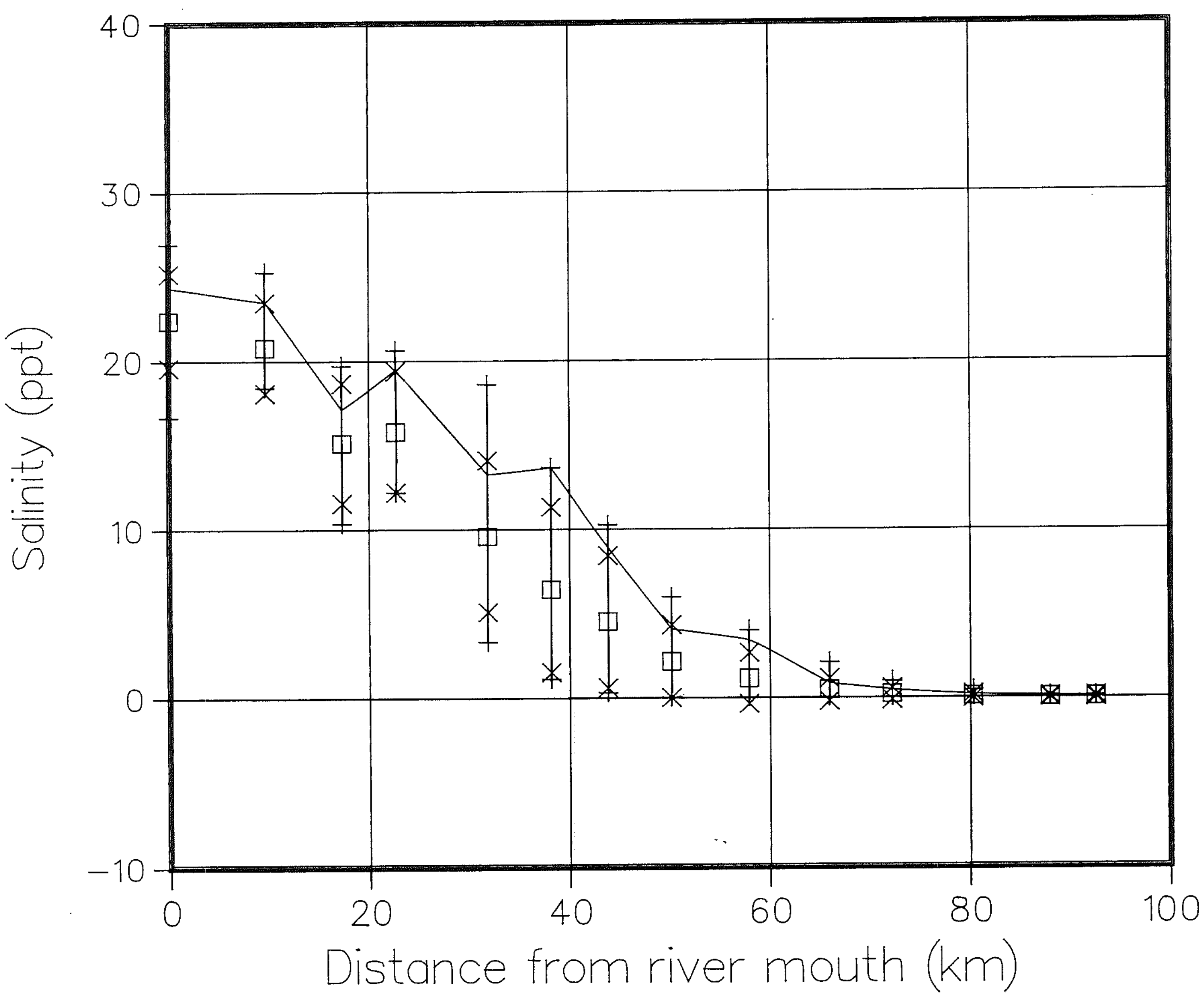


Figure 7. June vertically averaged salinity with distance from river mouth (key as in figure 2).

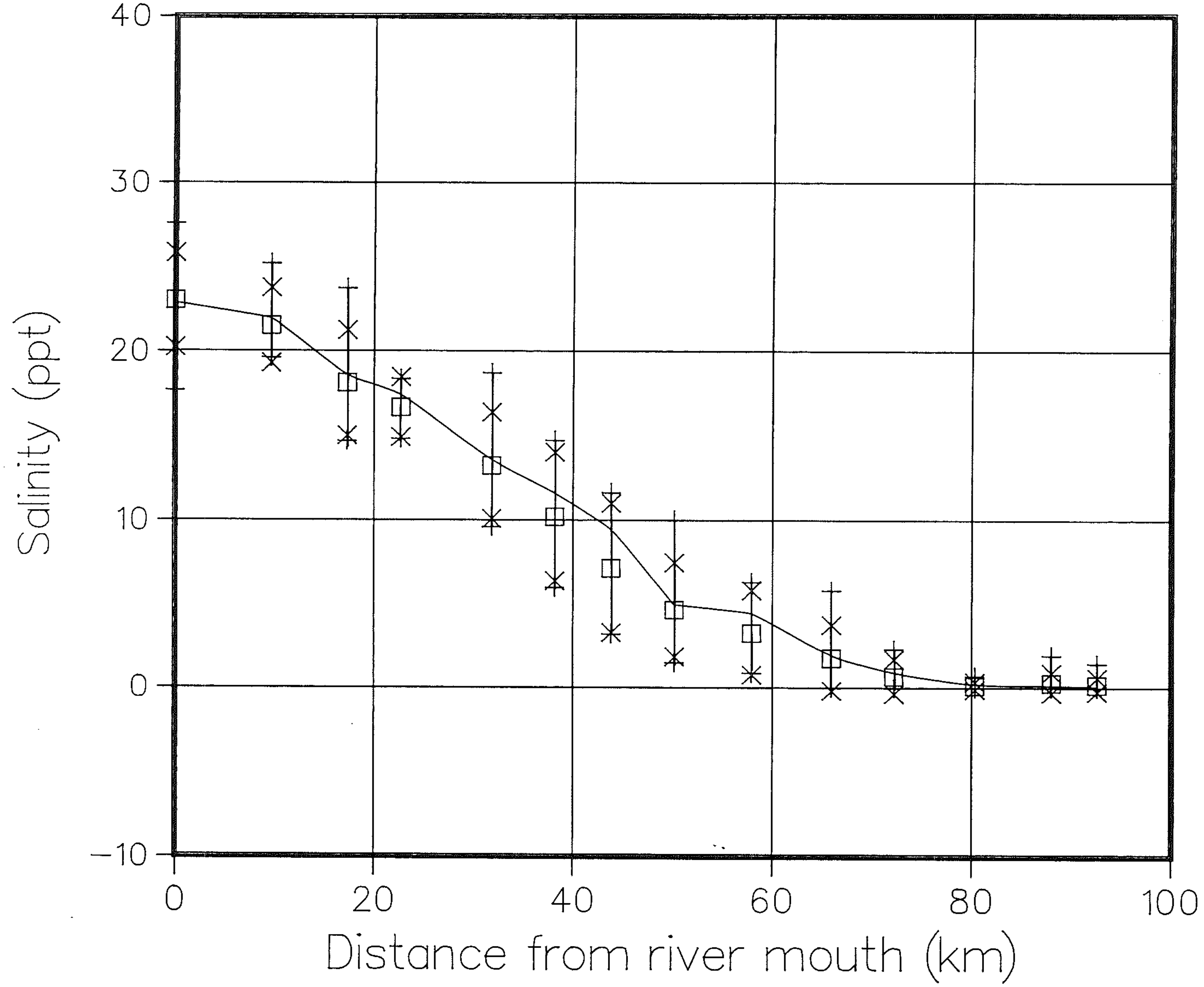


Figure 8. July vertically averaged salinity with distance from river mouth (key as in figure 2).

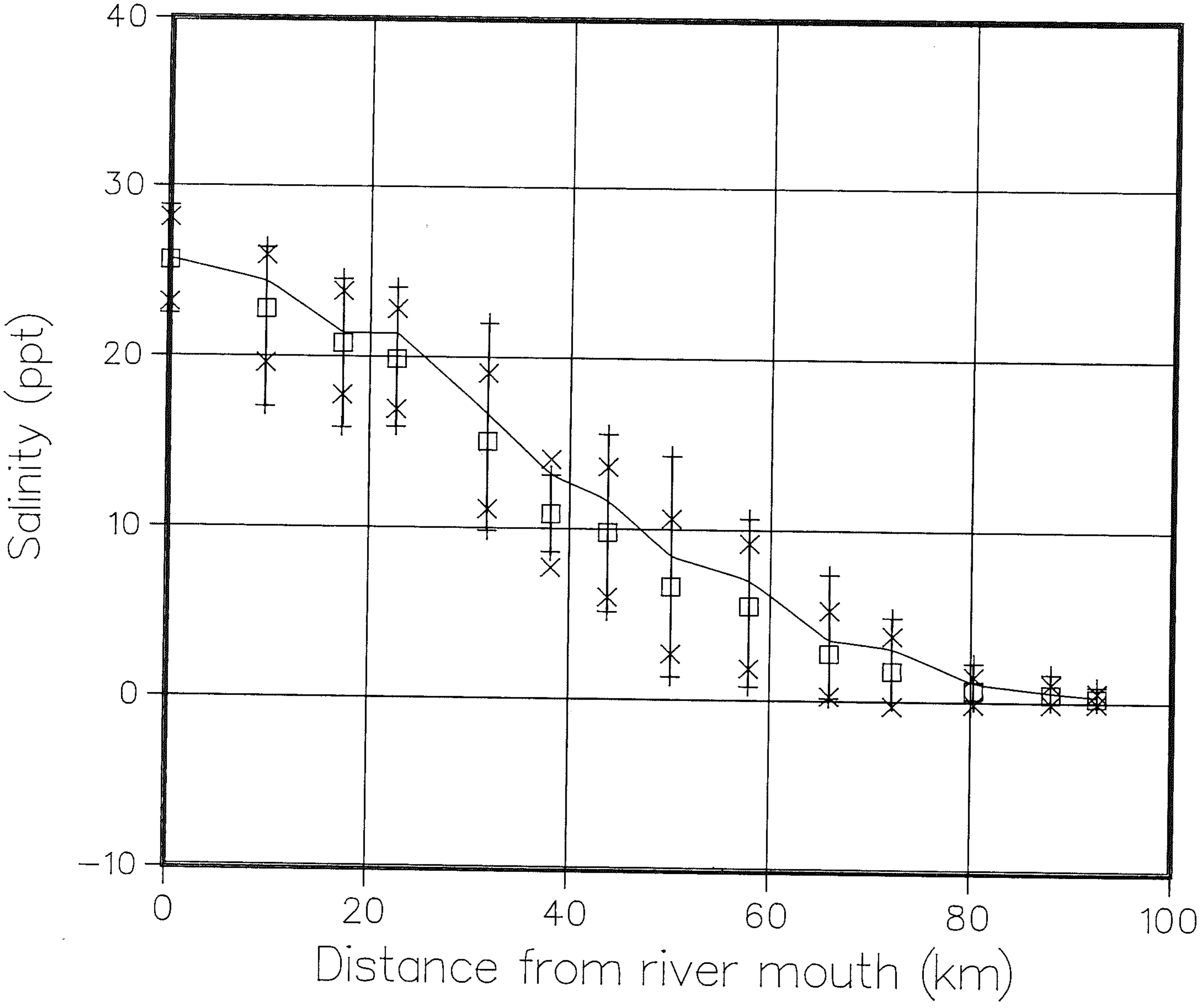


Figure 9. August vertically averaged salinity with distance from river mouth(key as in figure 2).

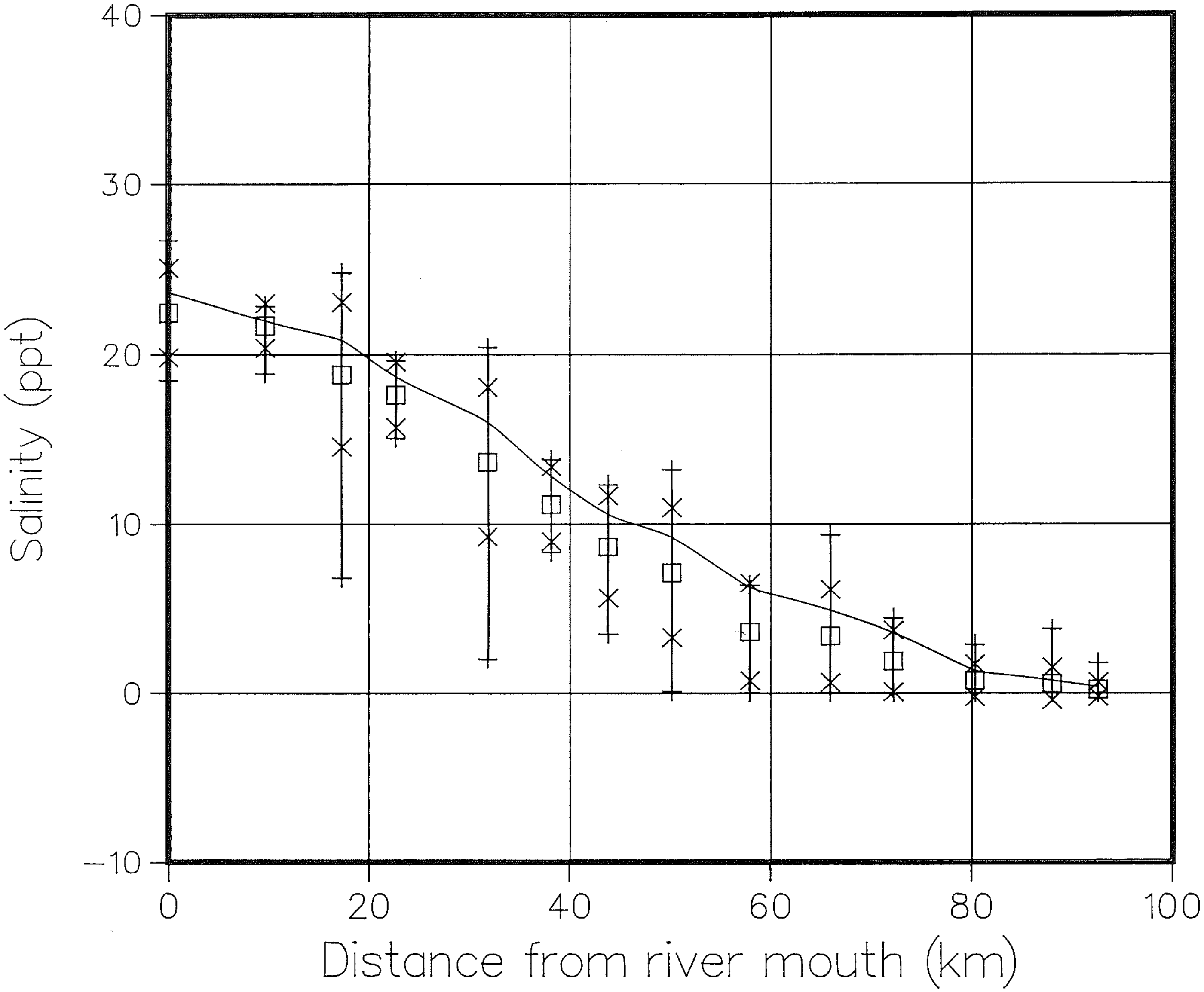


Figure 10. September vertically averaged salinity with distance from river mouth(key as in figure 2).

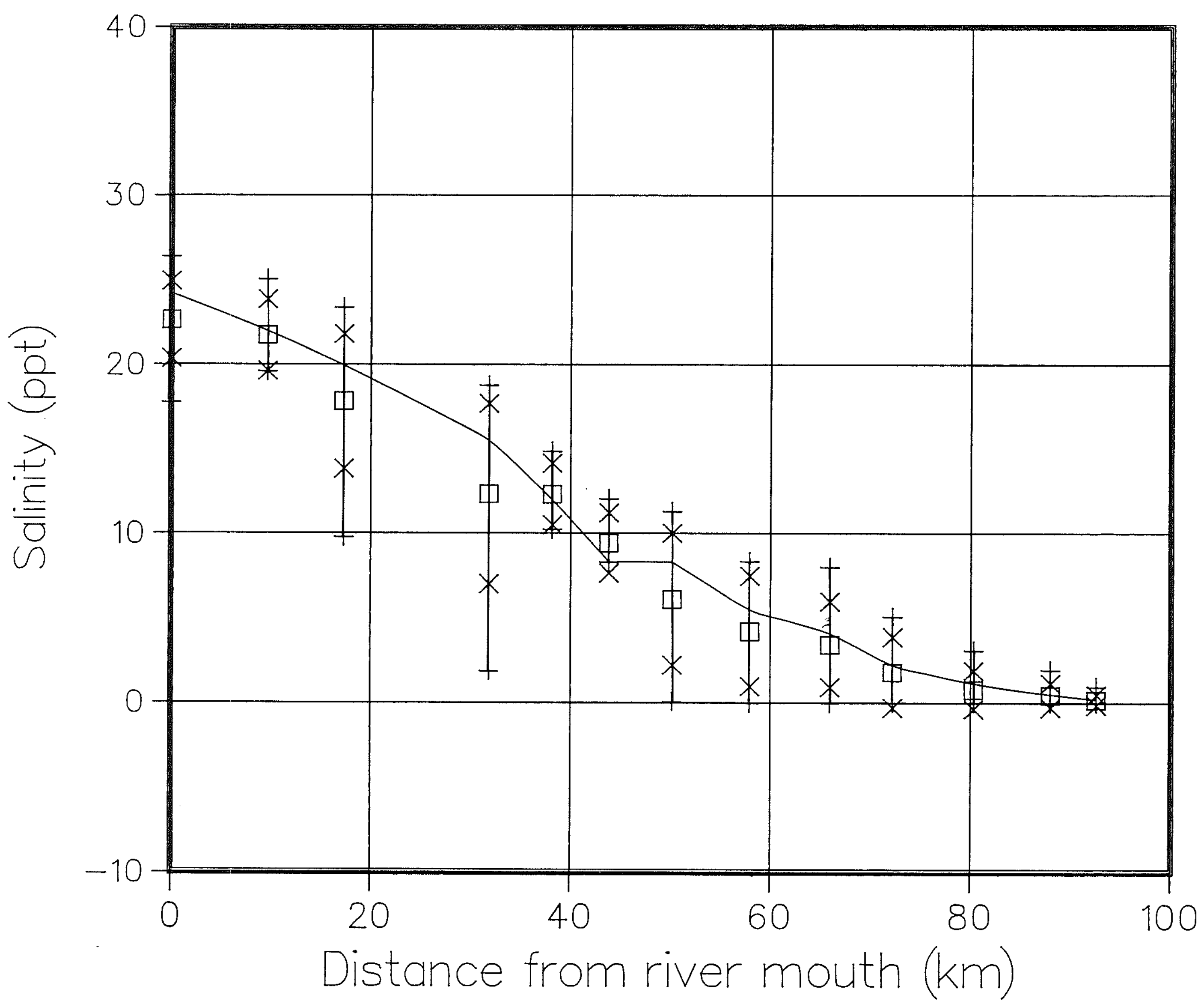


Figure 11. October vertically averaged salinity with distance from river mouth (key as in figure 2).

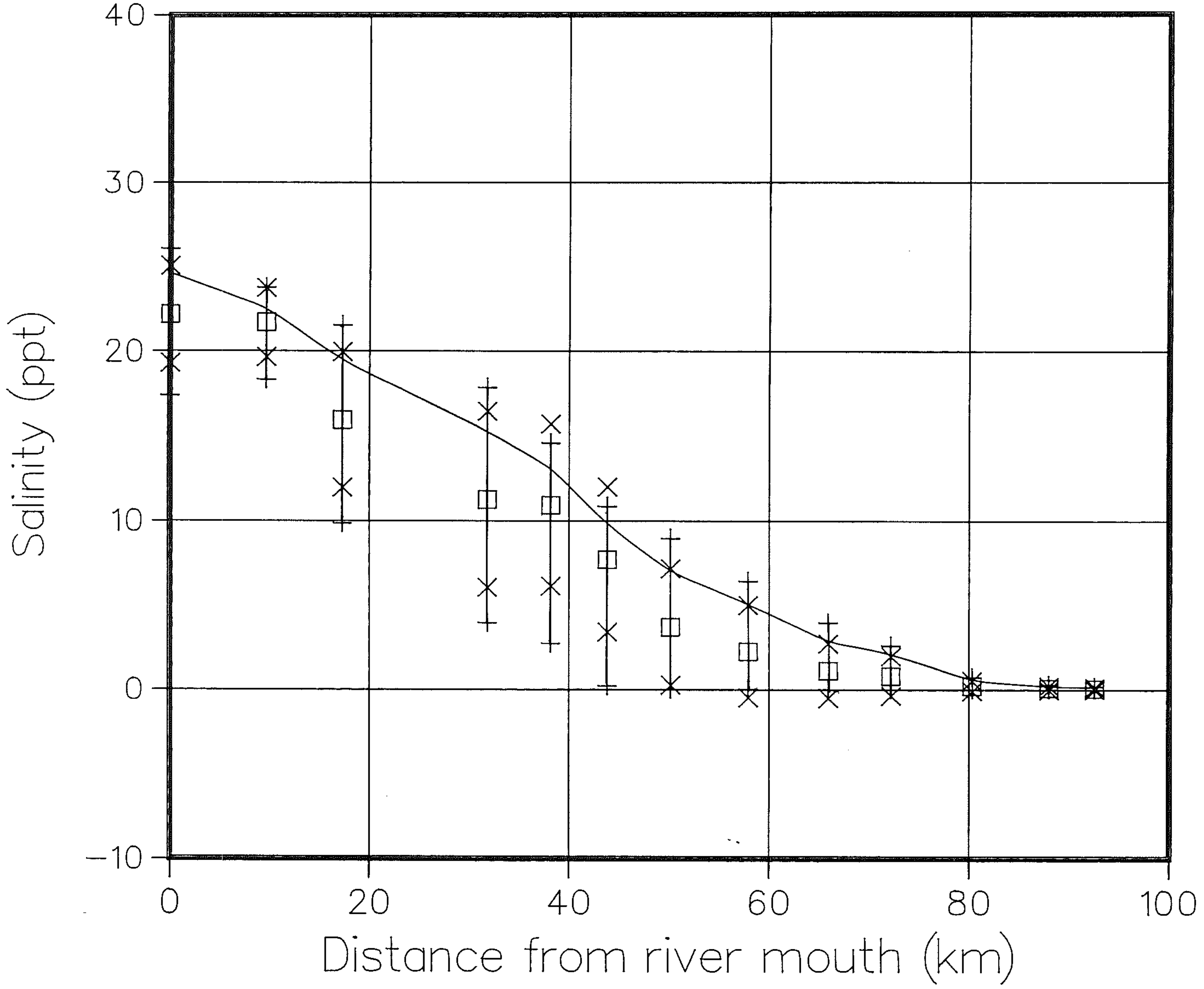


Figure 12. November vertically averaged salinity with distance from river mouth (key as in figure 2).

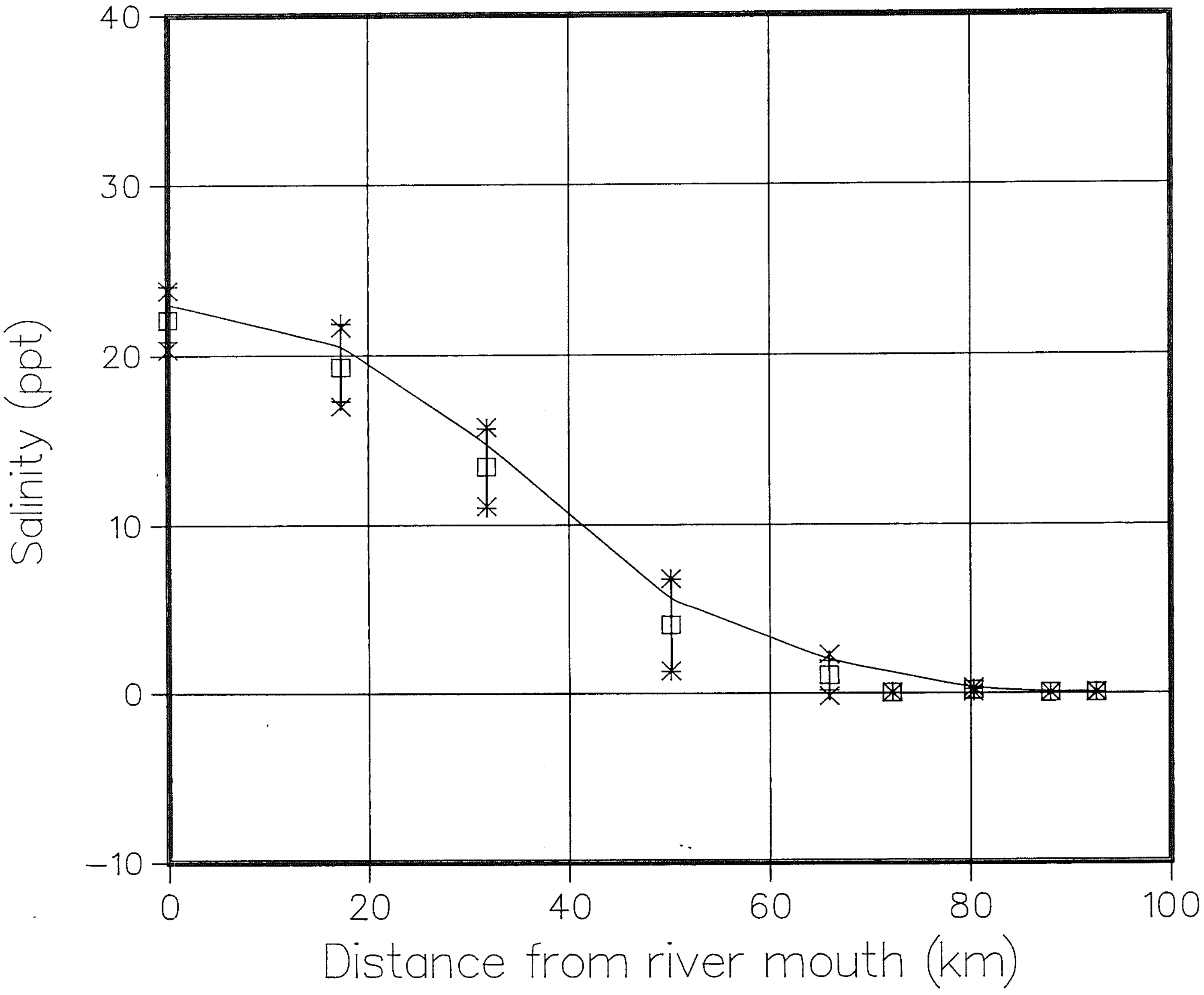


Figure 13. December vertically averaged salinity with distance from river mouth (key as in figure 2).

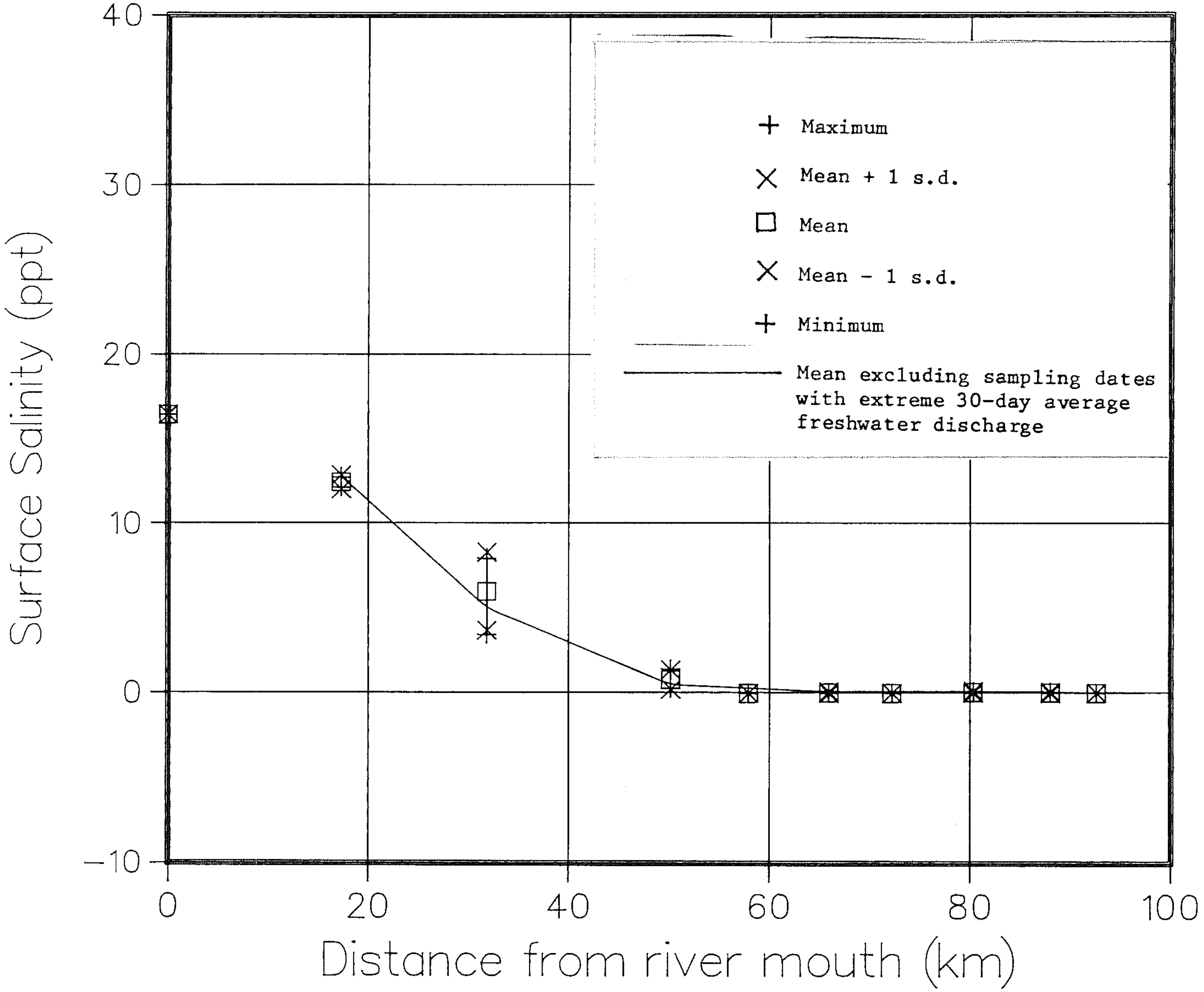


Figure 14. January surface salinity with distance from river mouth.

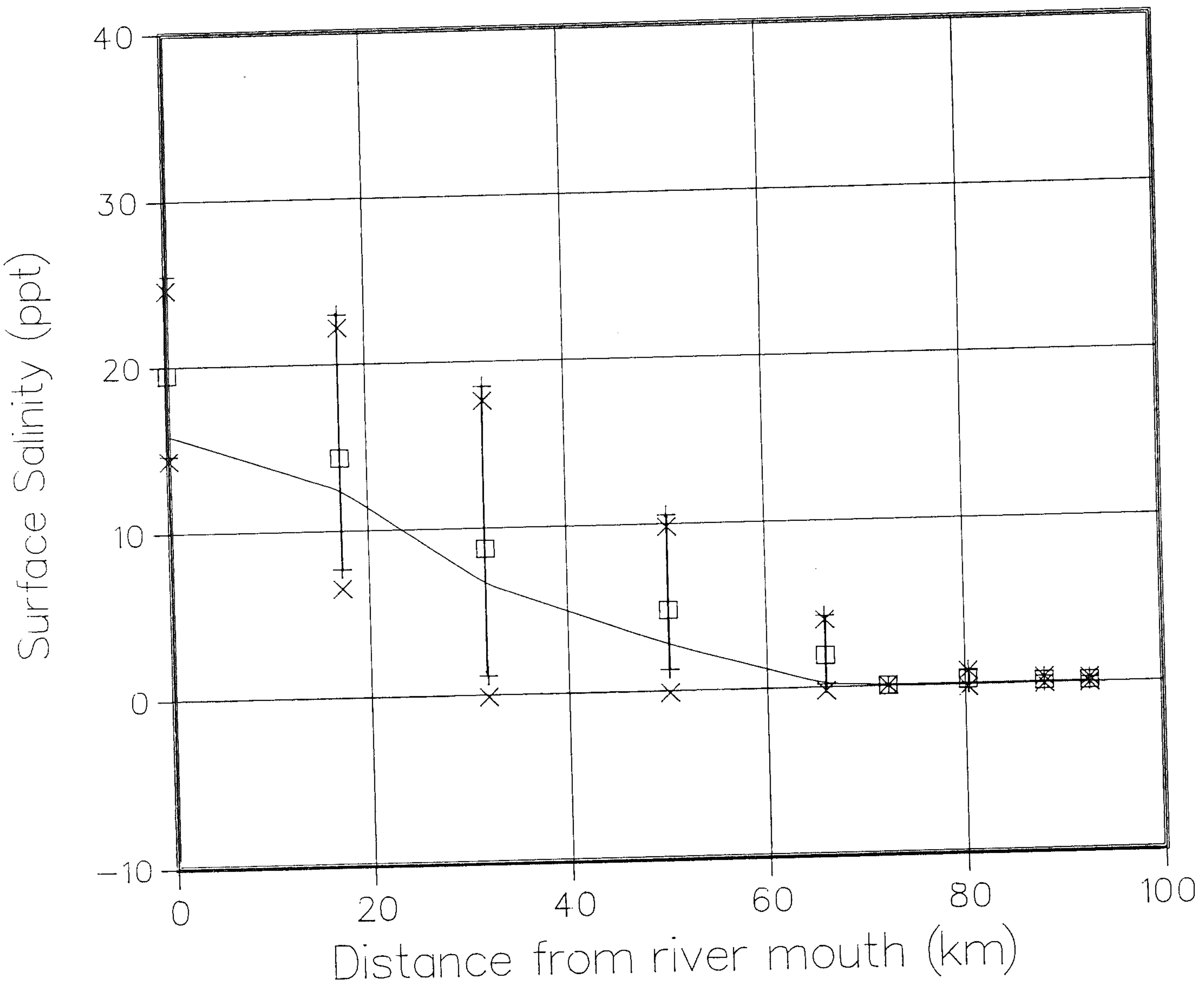


Figure 15. February surface salinity with distance from river mouth (key as in figure 14).

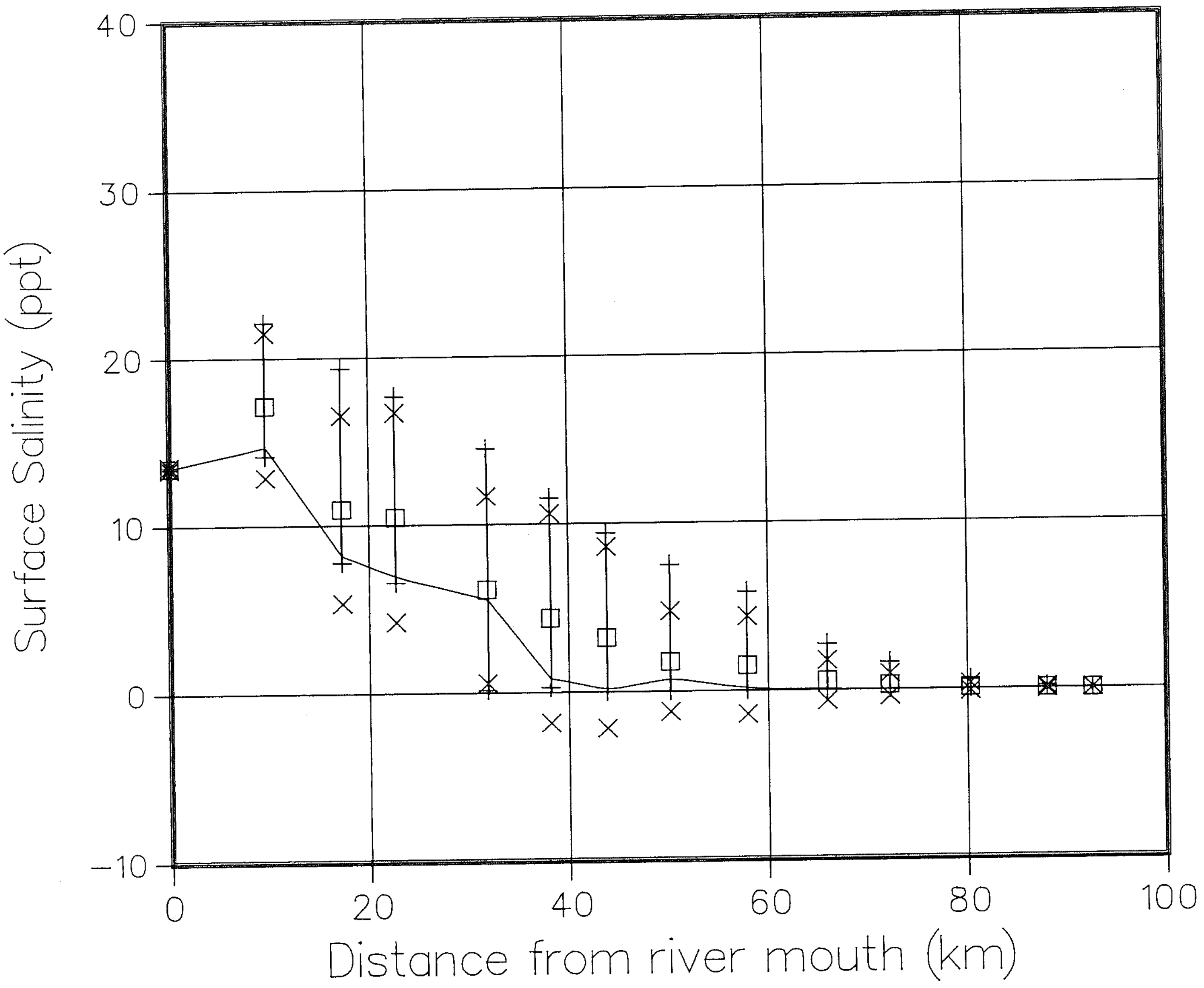


Figure 16. March surface salinity with distance from river mouth (key as in figure 14).

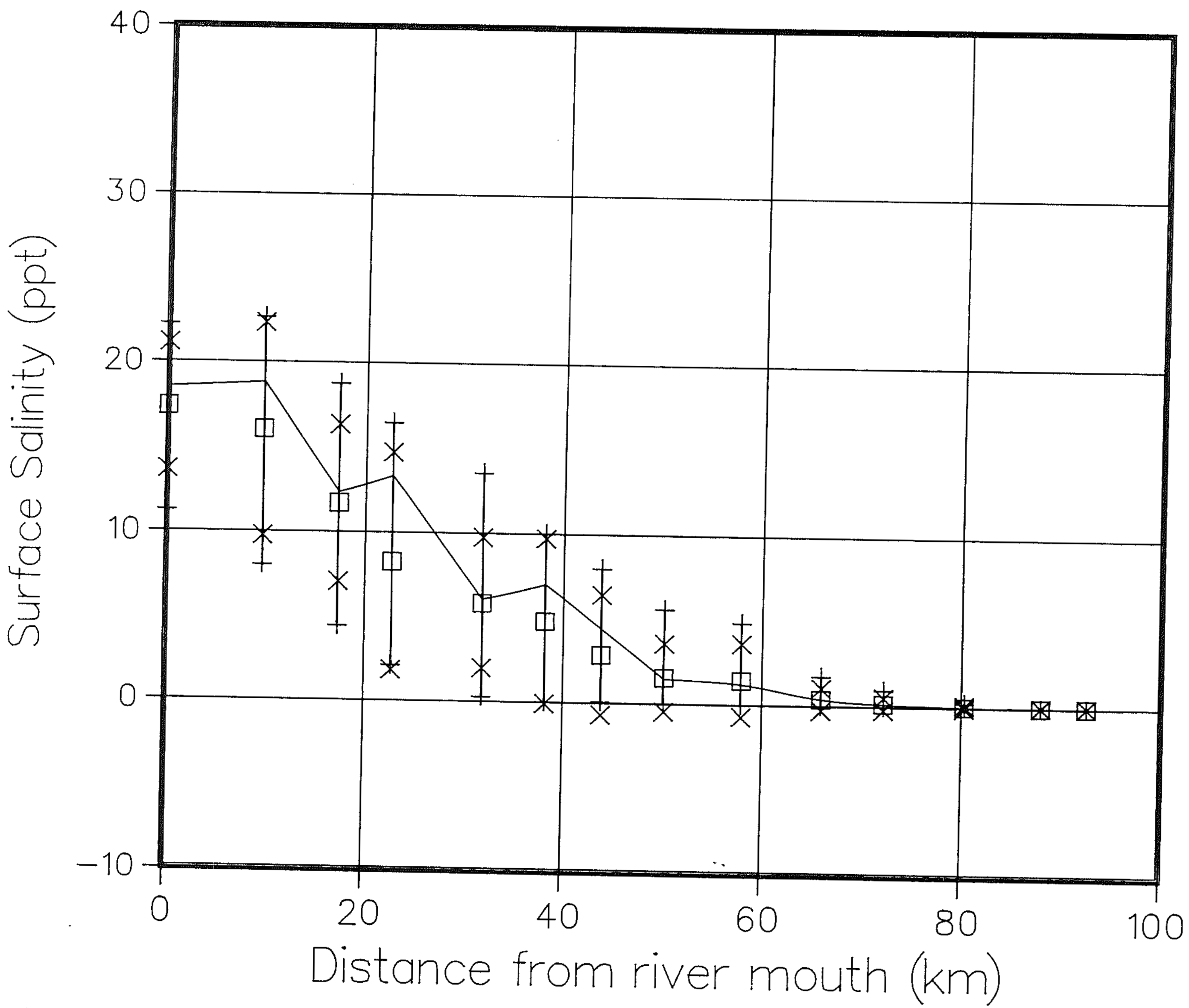


Figure 17. April surface salinity with distance from river mouth (key as in figure 14).

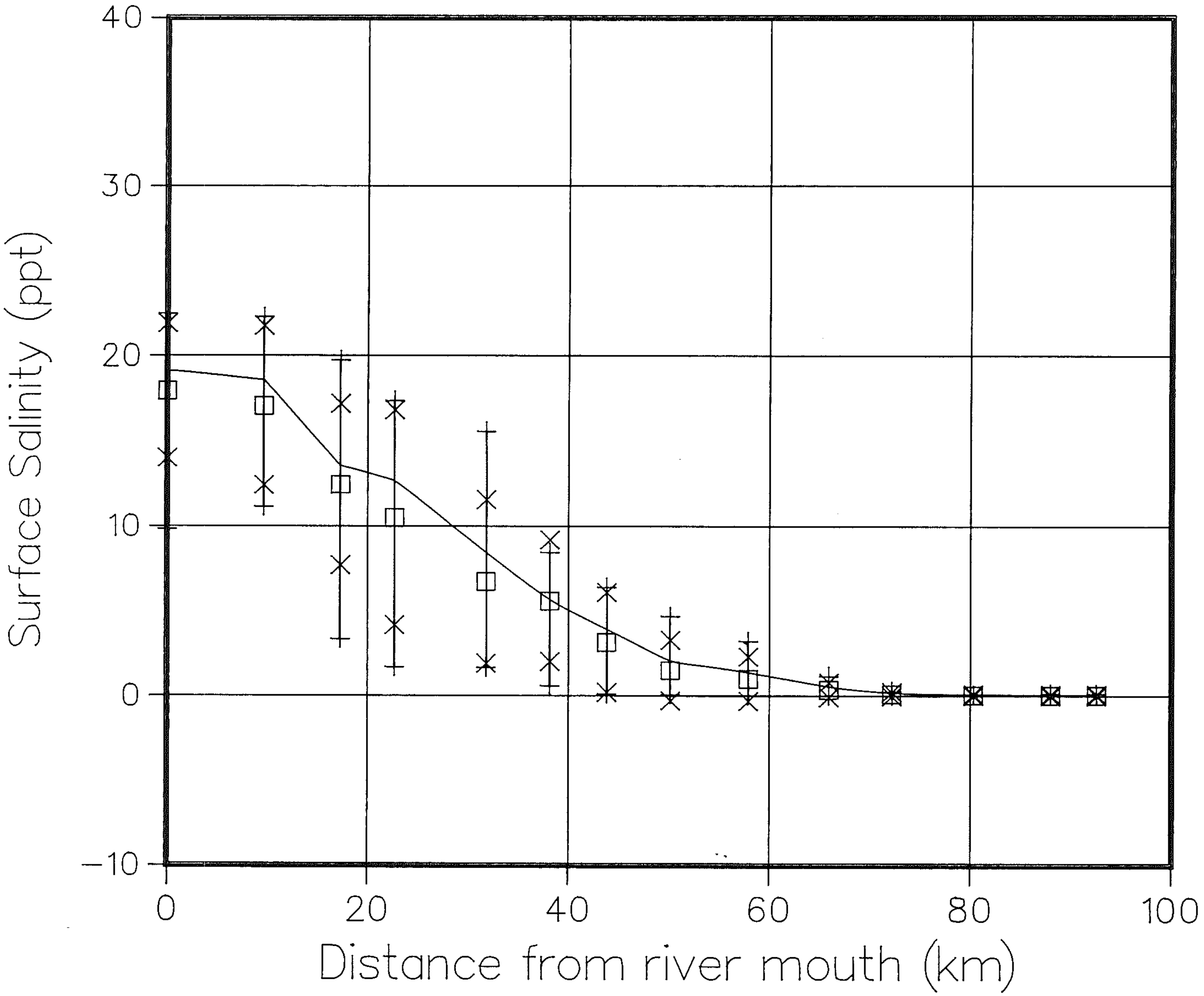


Figure 18. May surface salinity with distance from river mouth (key as in figure 14).

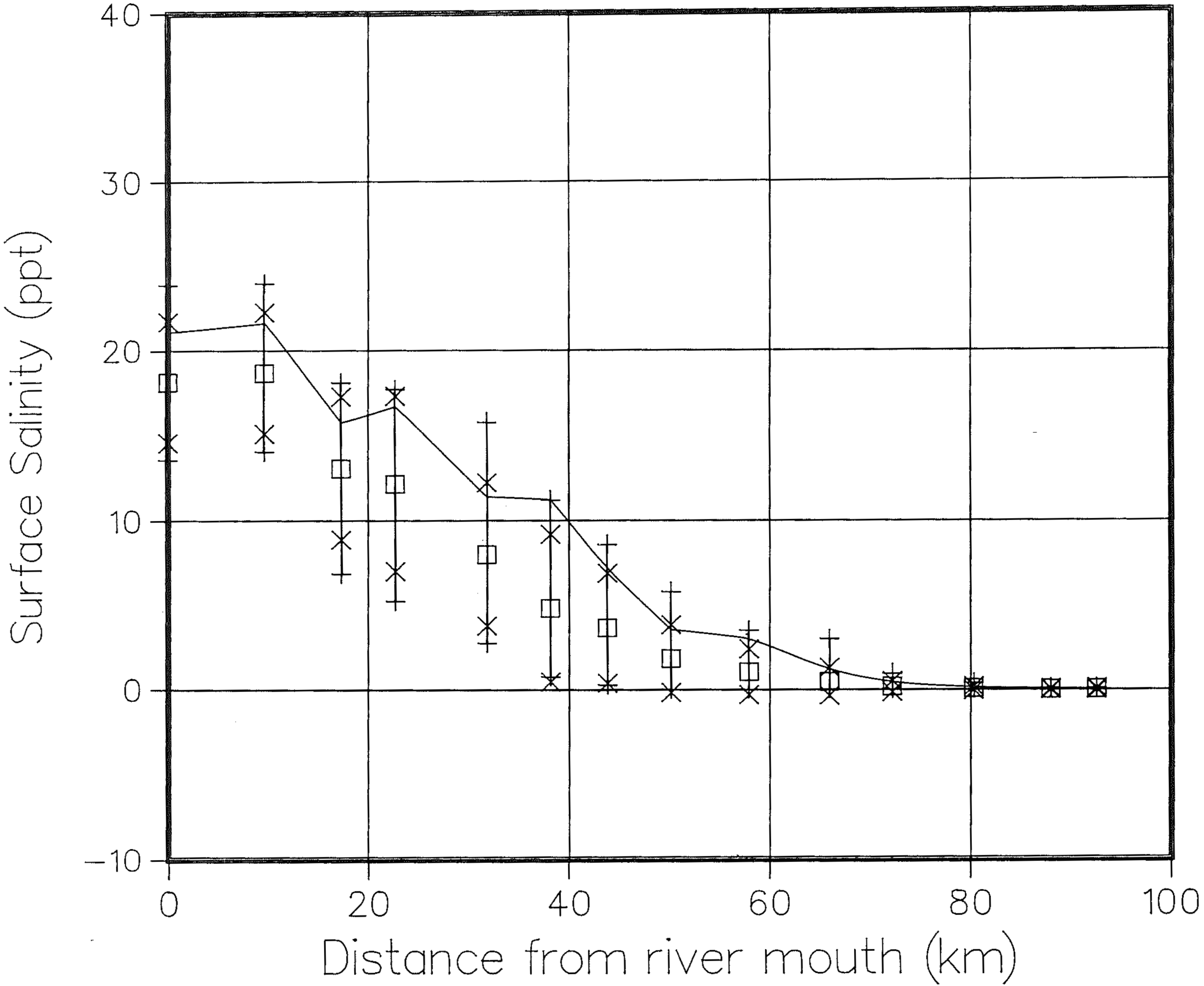


Figure 19. June surface salinity with distance from river mouth (key as in figure 14).

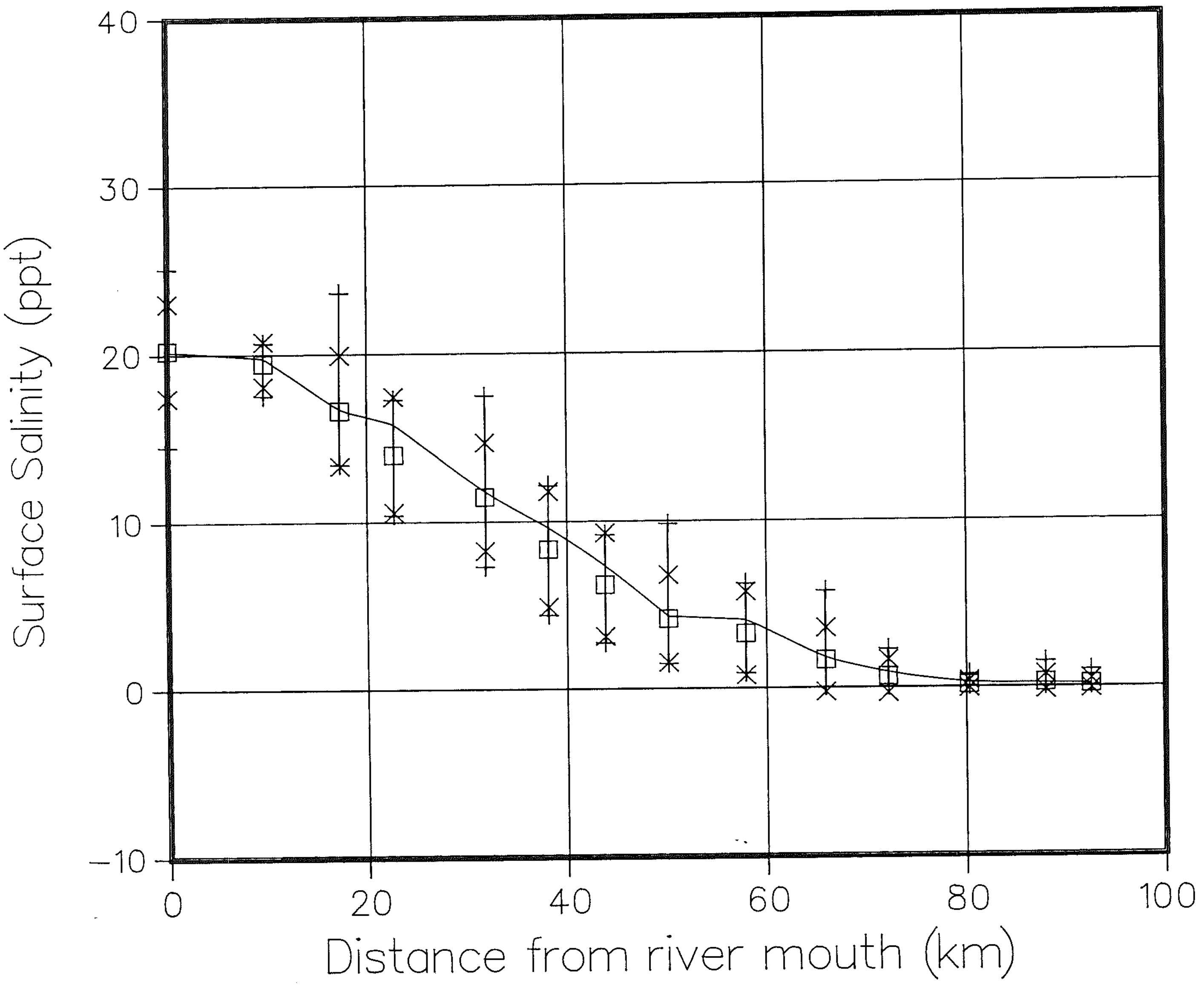


Figure 20. July surface salinity with distance from river mouth (key as in figure 14).

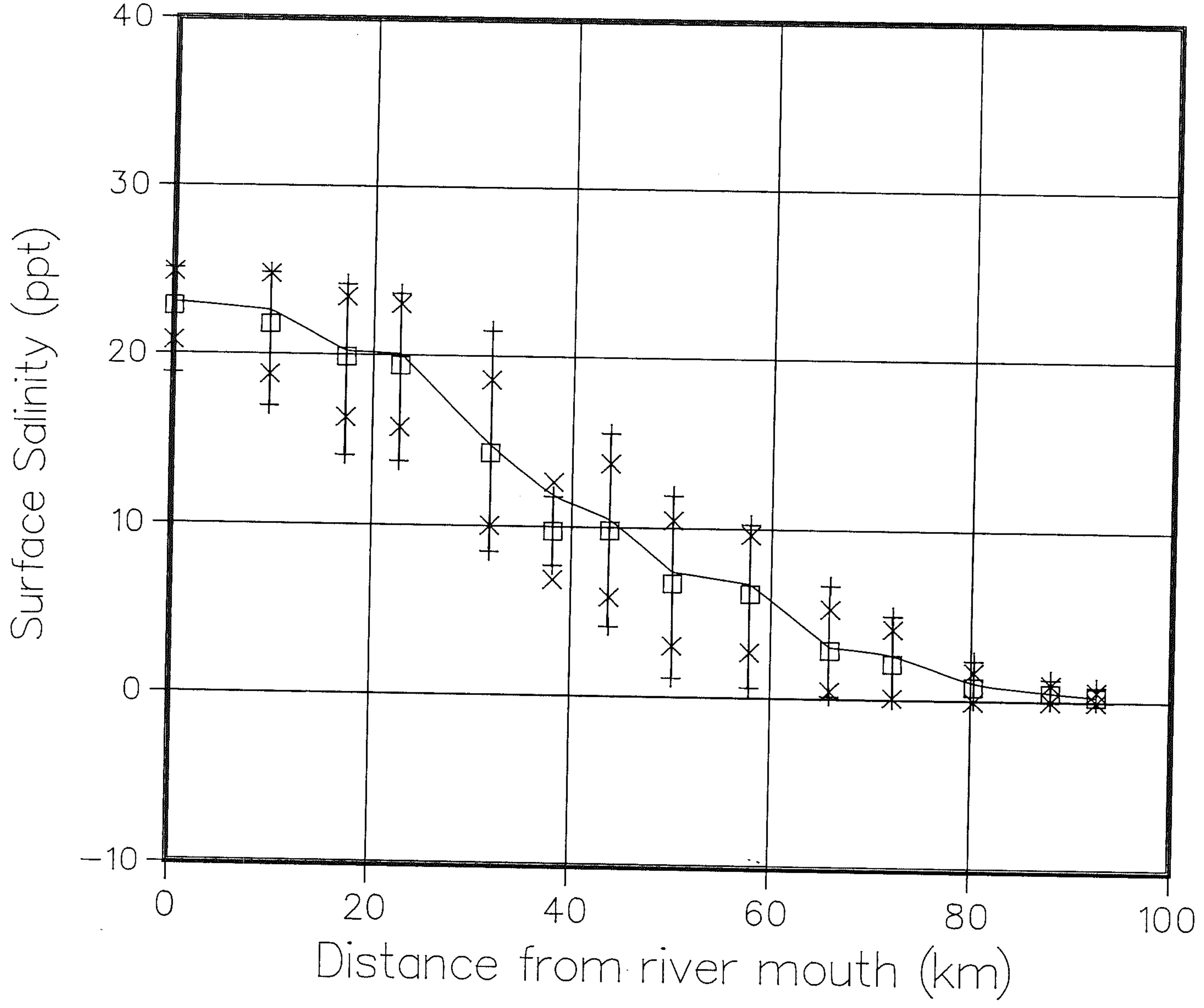


Figure 21. August surface salinity with distance from river mouth (key as in figure 14).

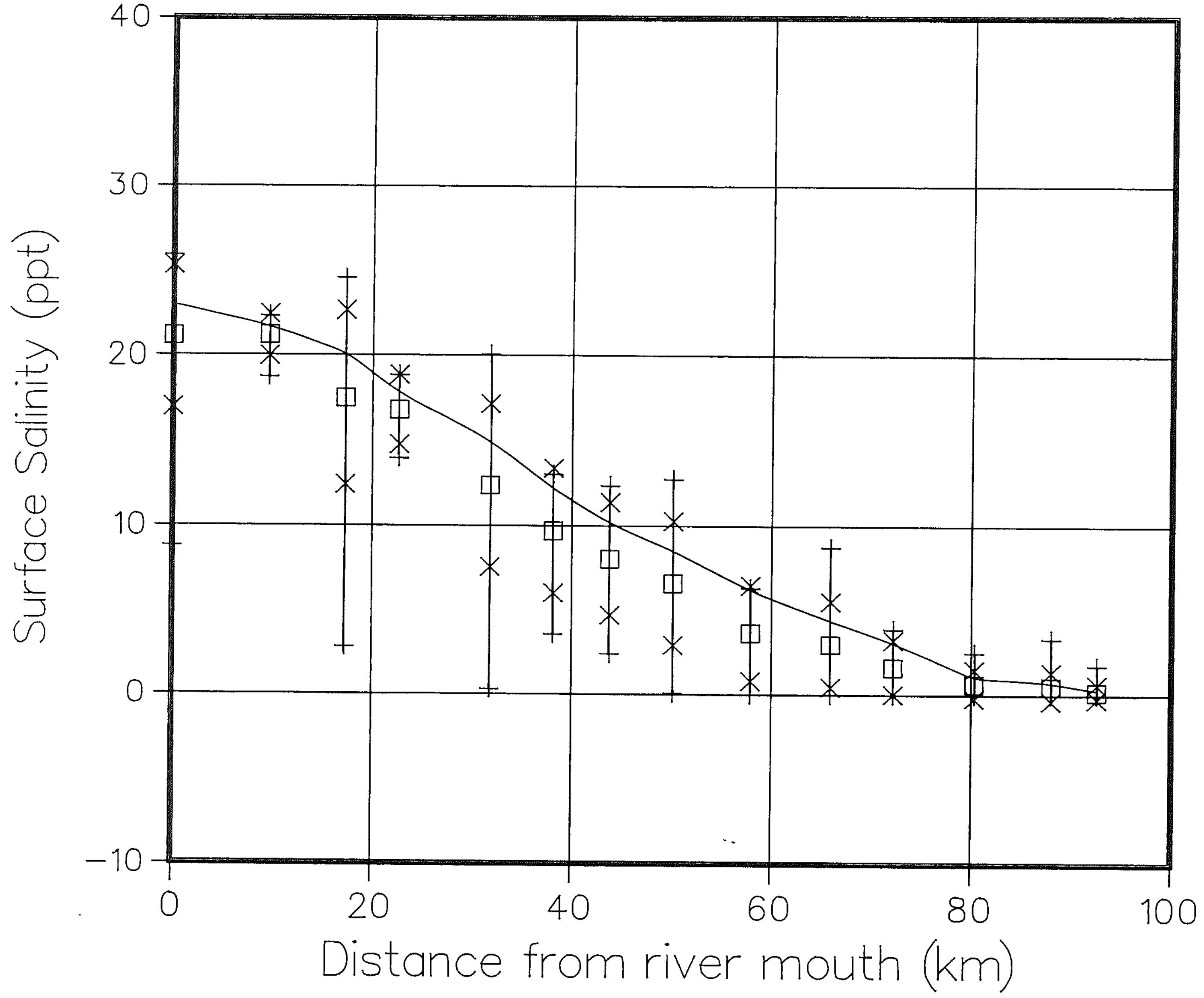


Figure 22. September surface salinity with distance from river mouth (key as in figure 14).

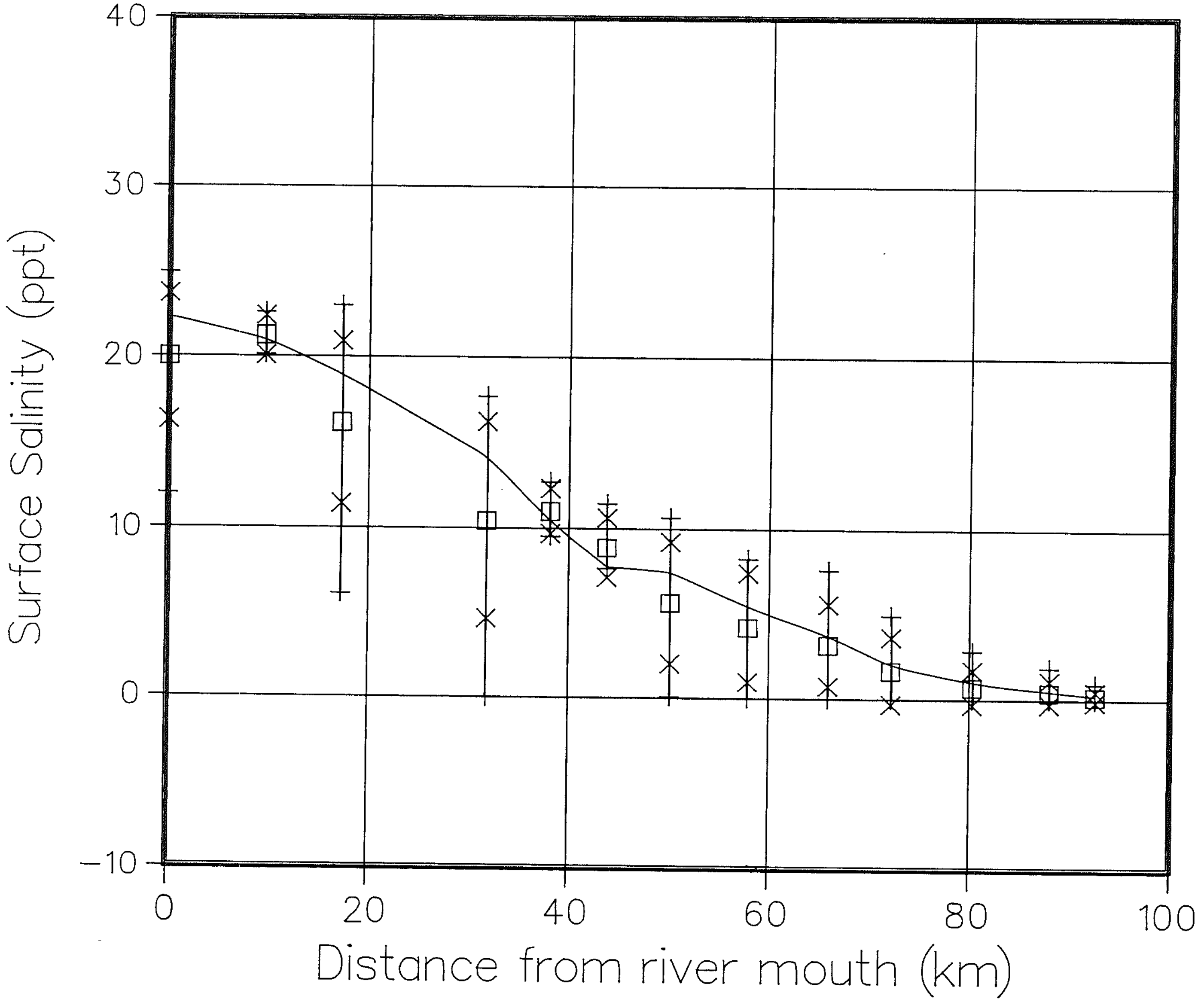


Figure 23. October surface salinity with distance from river mouth (key as in figure 14).

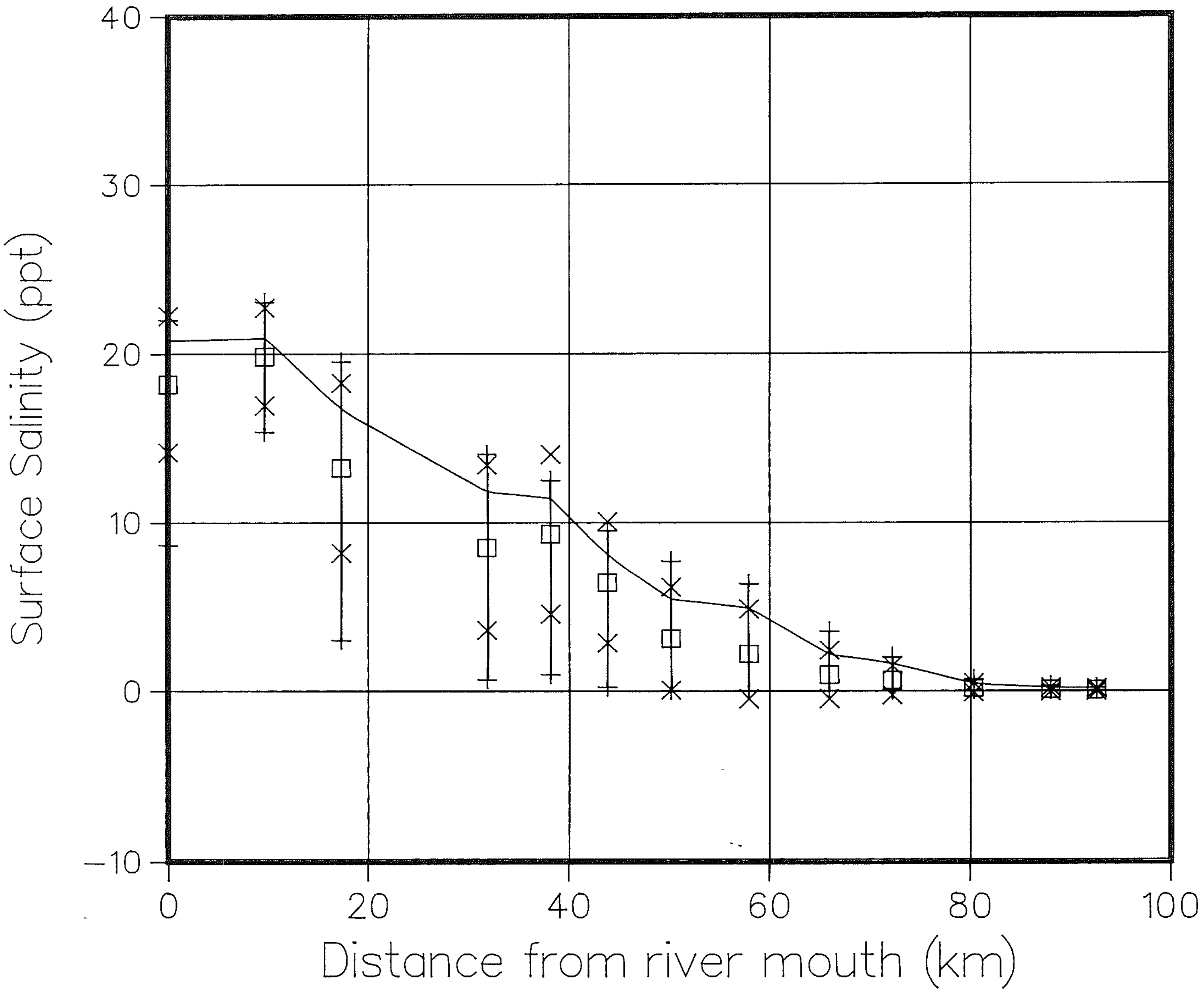


Figure 24. November surface salinity with distance from river mouth (key as in figure 14).

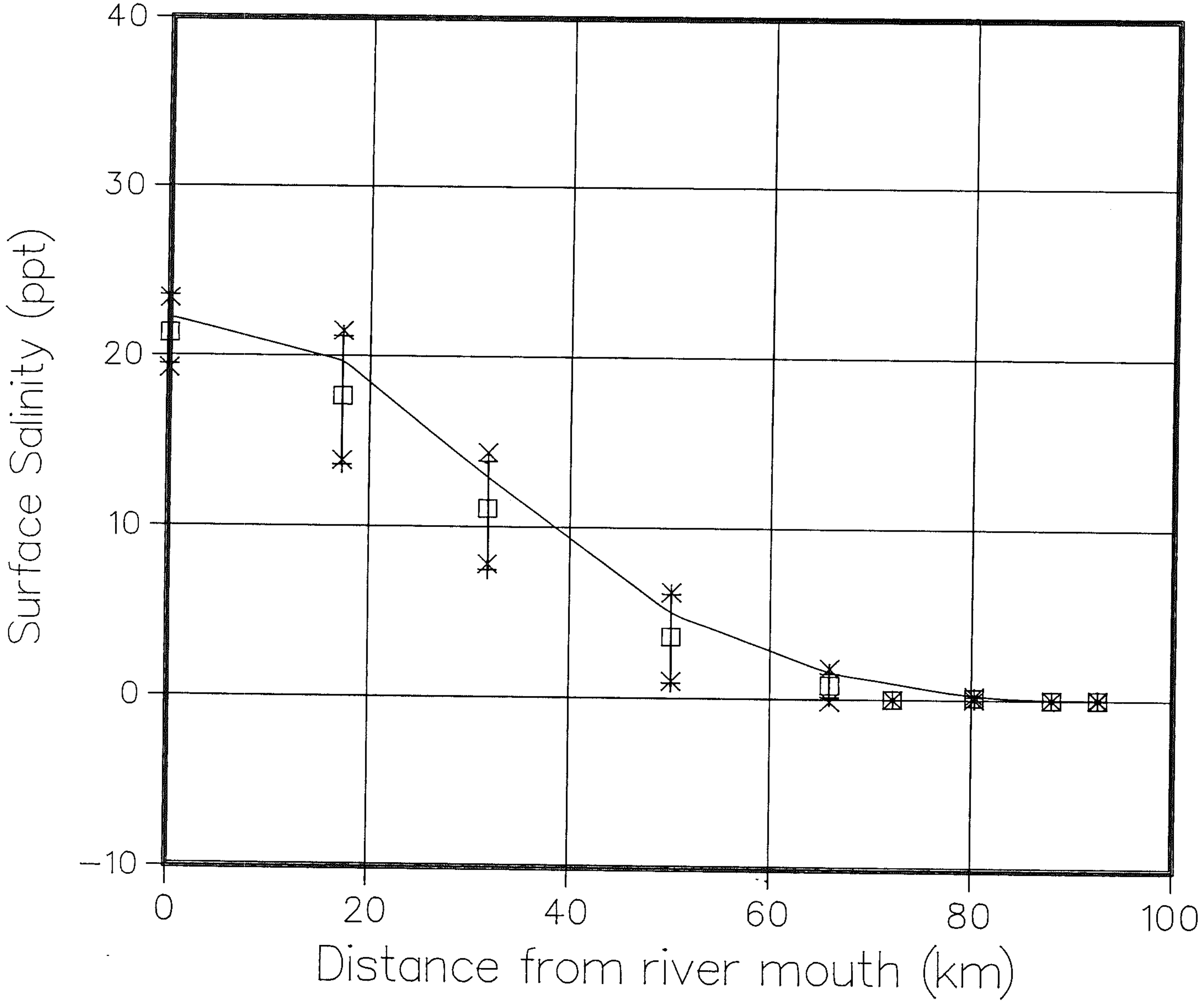


Figure 25. December surface salinity with distance from river mouth (key as in figure 14).

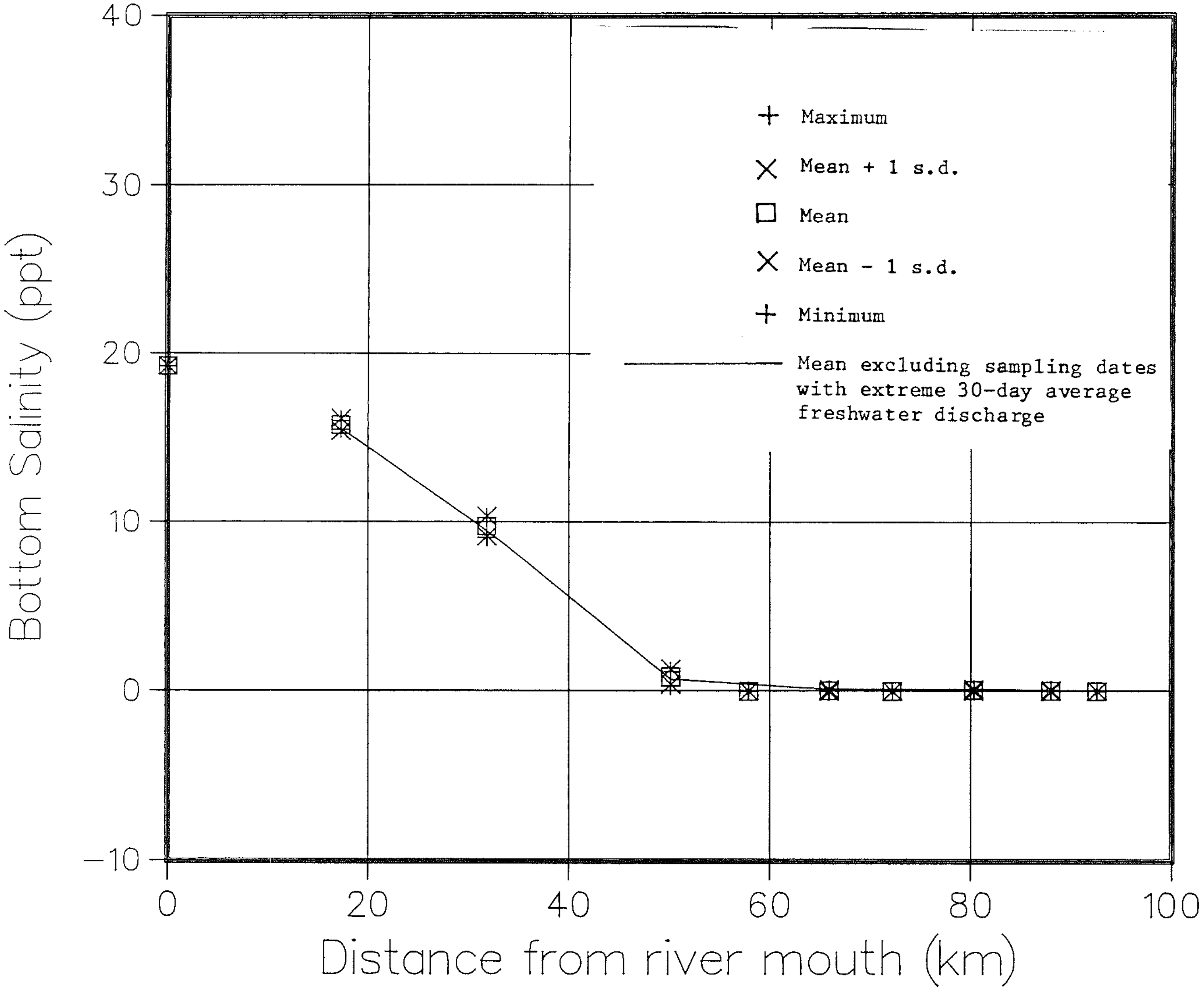


Figure 26. January bottom salinity with distance from river mouth.

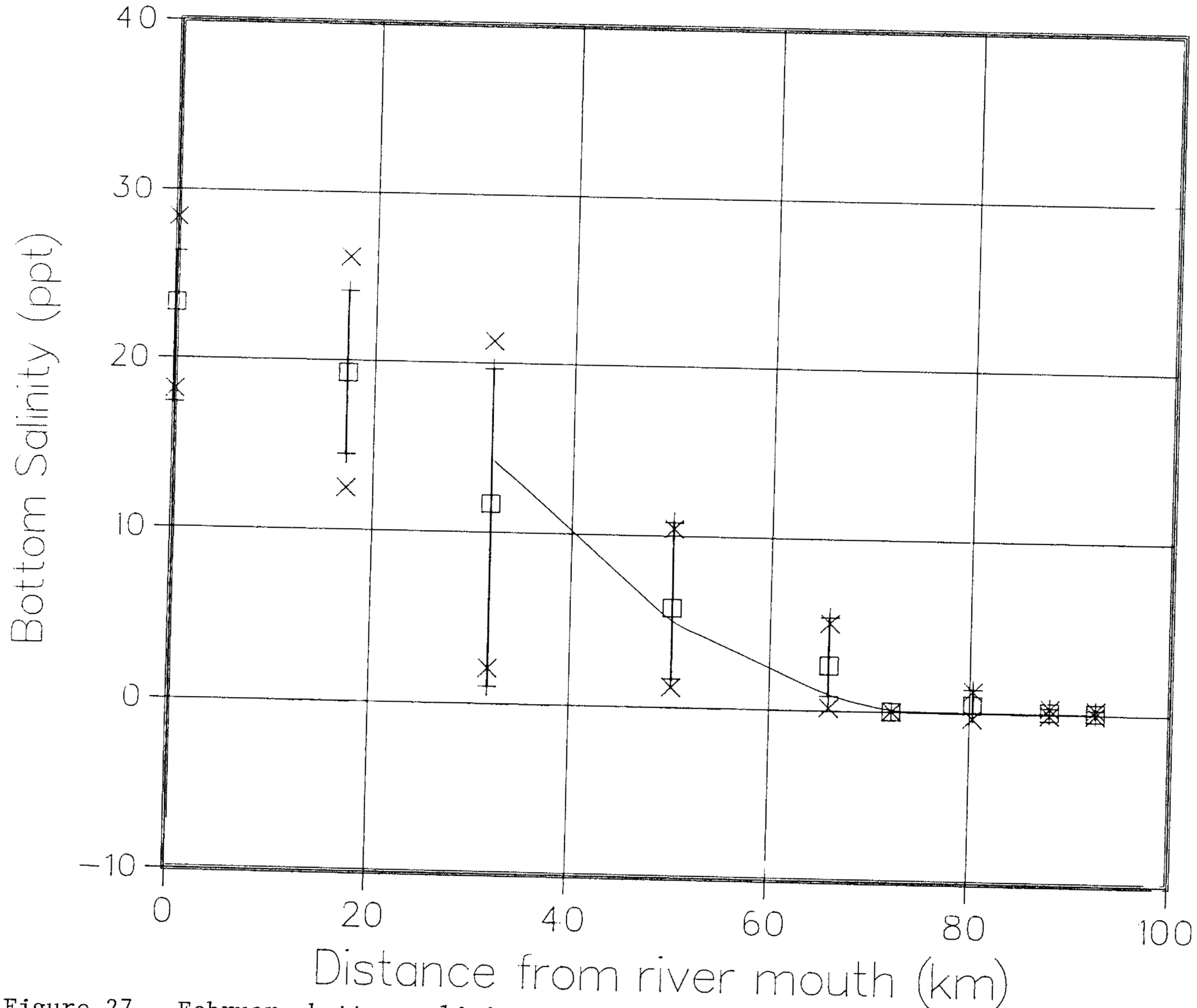


Figure 27. February bottom salinity with distance from river mouth (key as in figure 26).

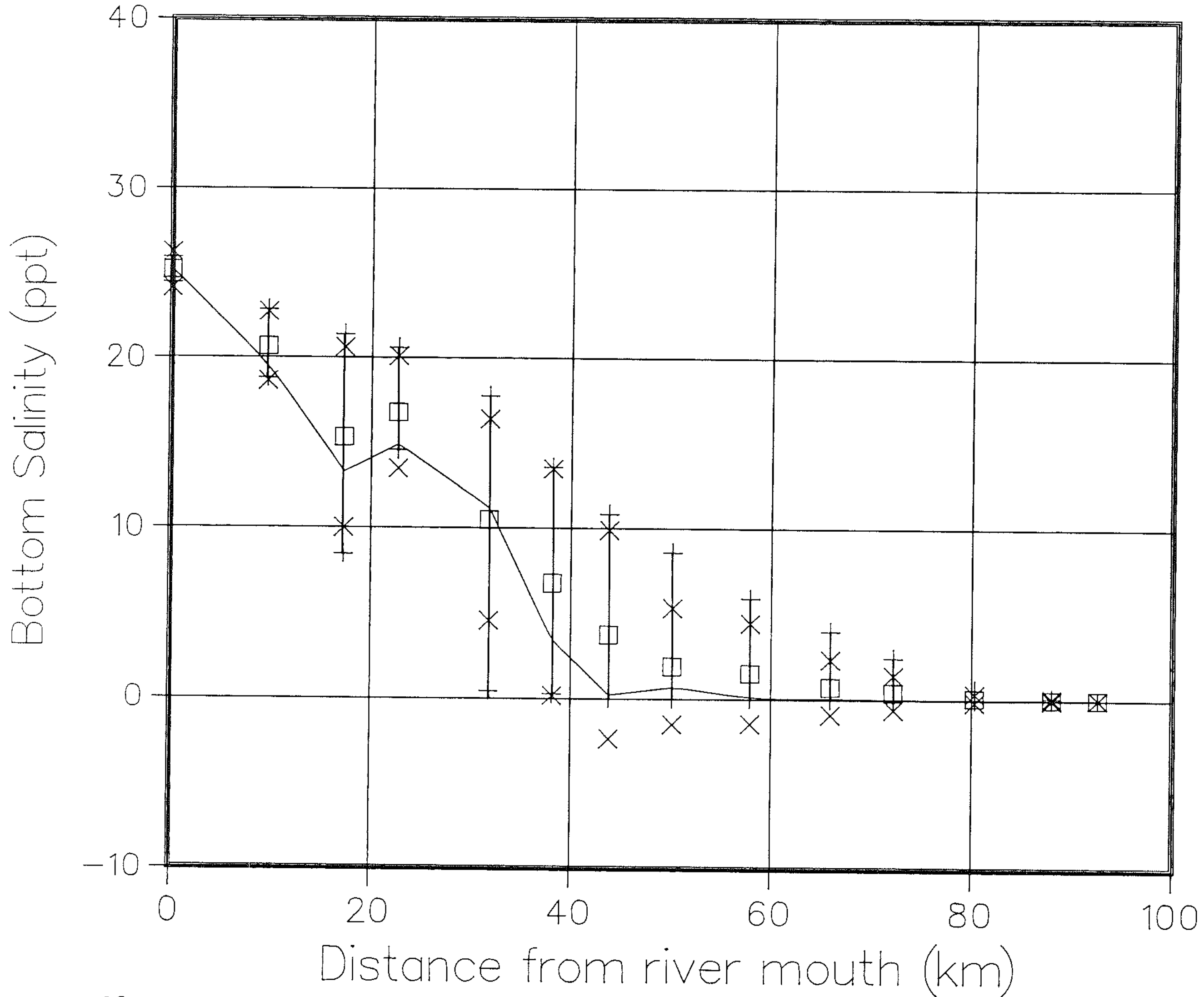


Figure 28. March bottom salinity with distance from river mouth (key as in figure 26).

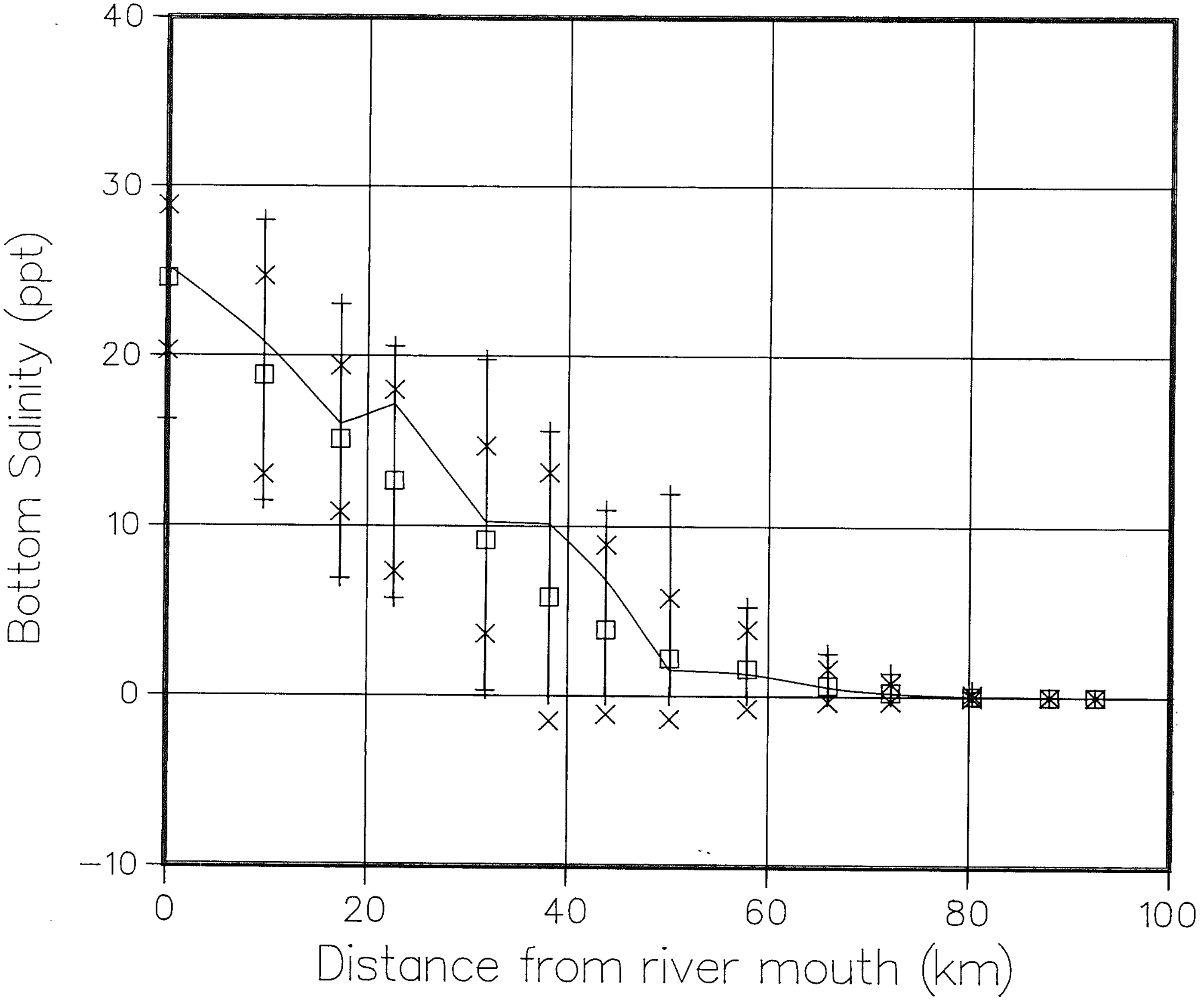


Figure 29. April bottom salinity with distance from river mouth (key as in figure 26).

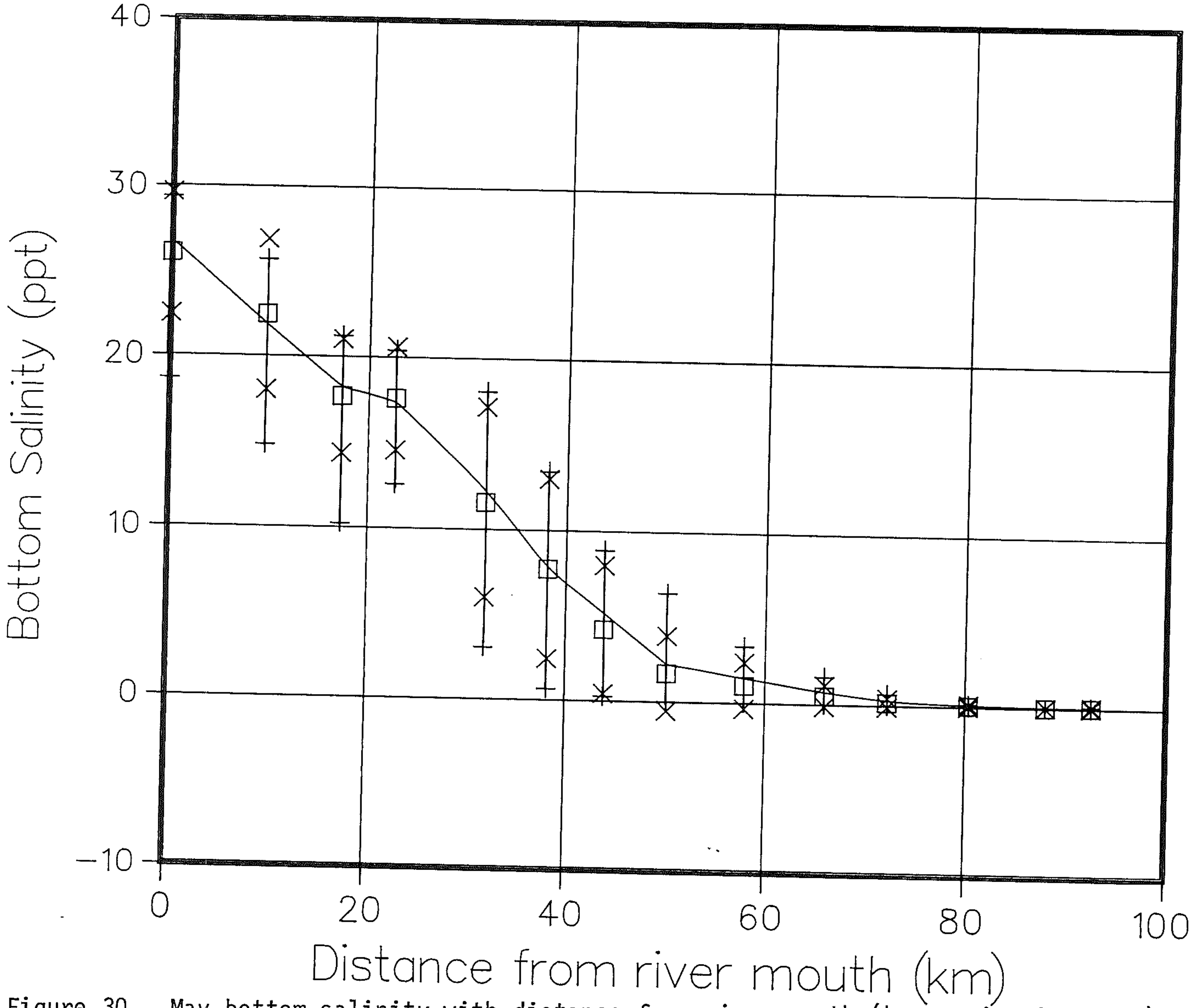


Figure 30. May bottom salinity with distance from river mouth (key as in figure 26).

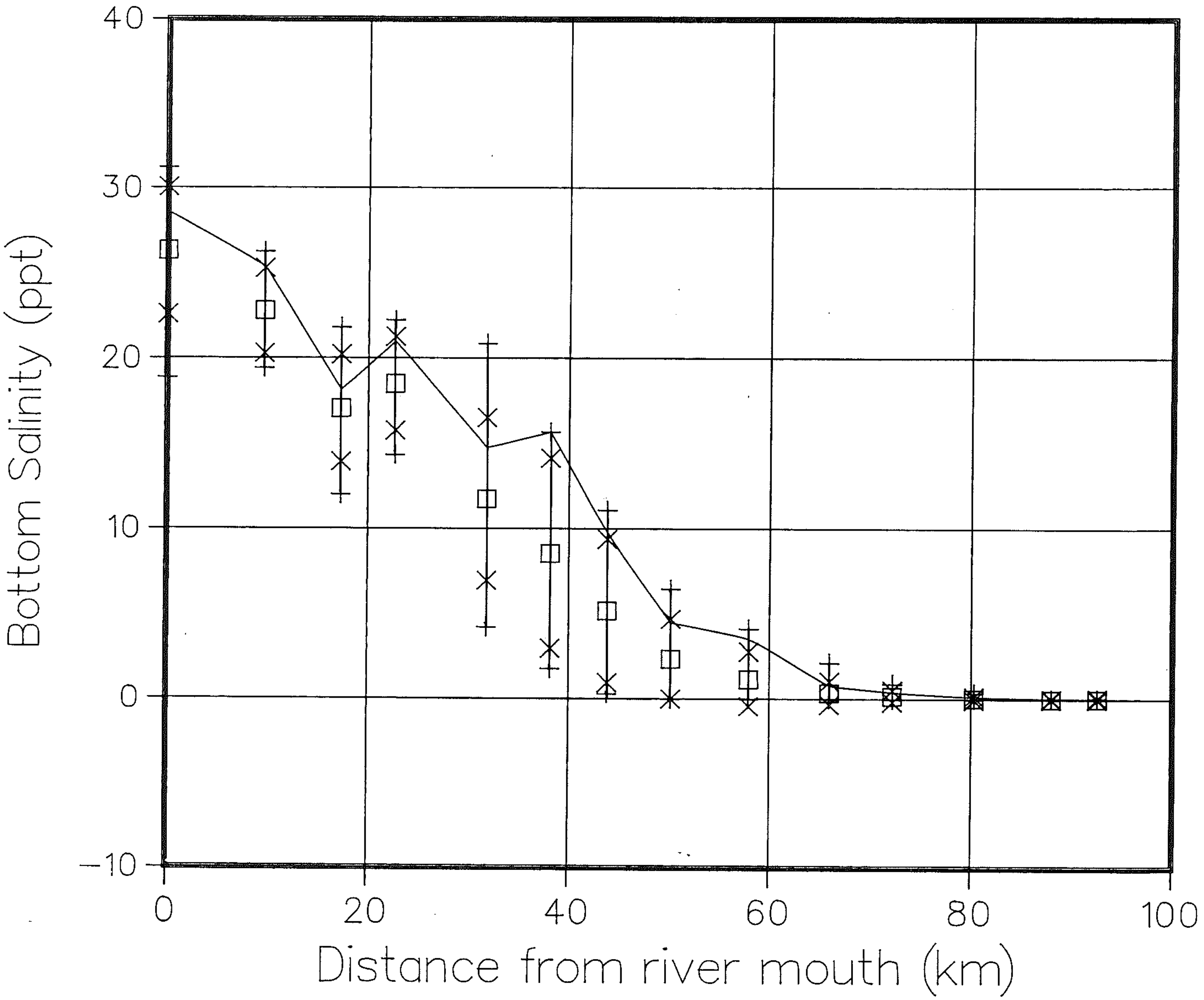


Figure 31. June bottom salinity with distance from river mouth (key as in figure 26).

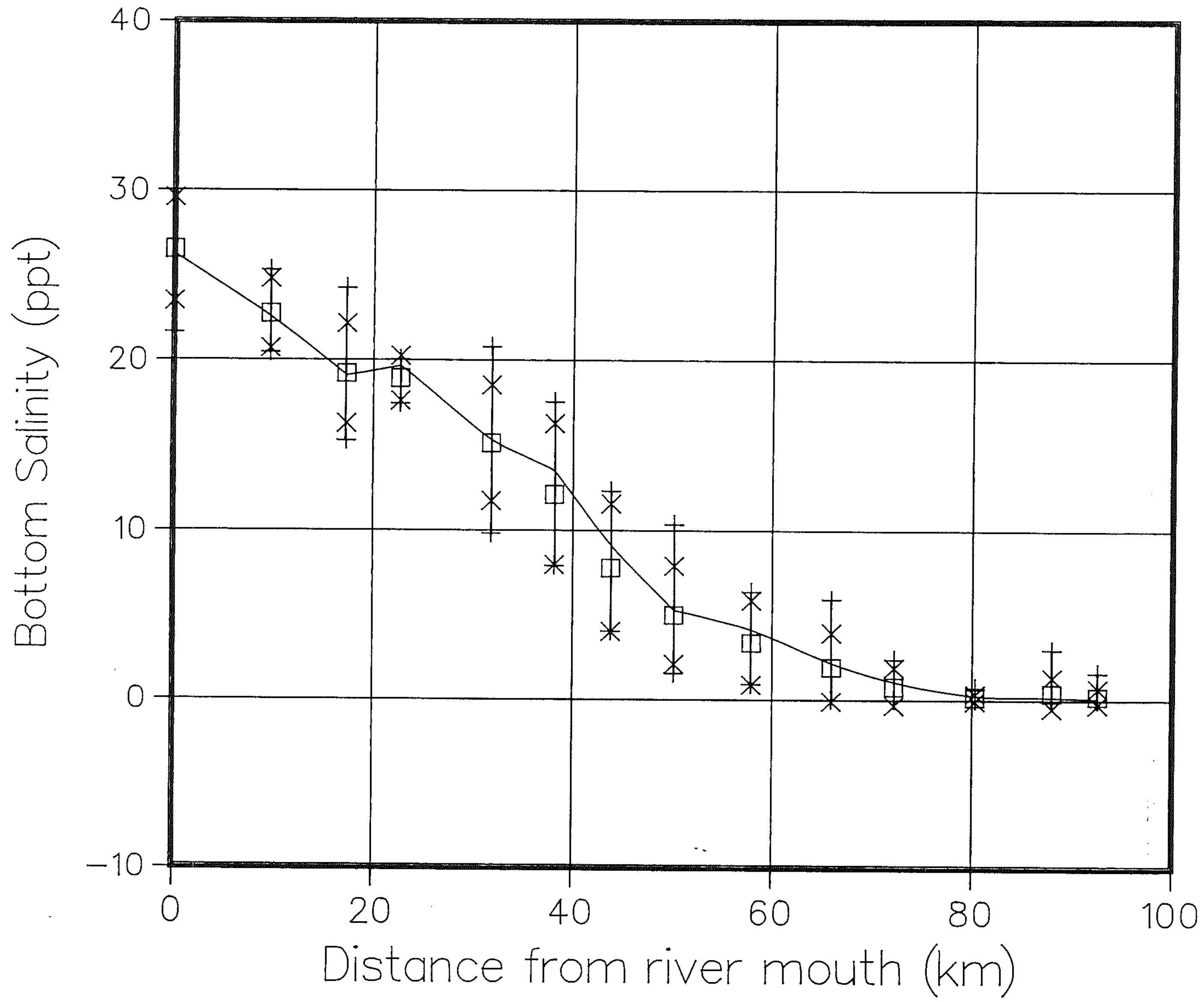


Figure 32. July bottom salinity with distance from river mouth (key as in figure 26).

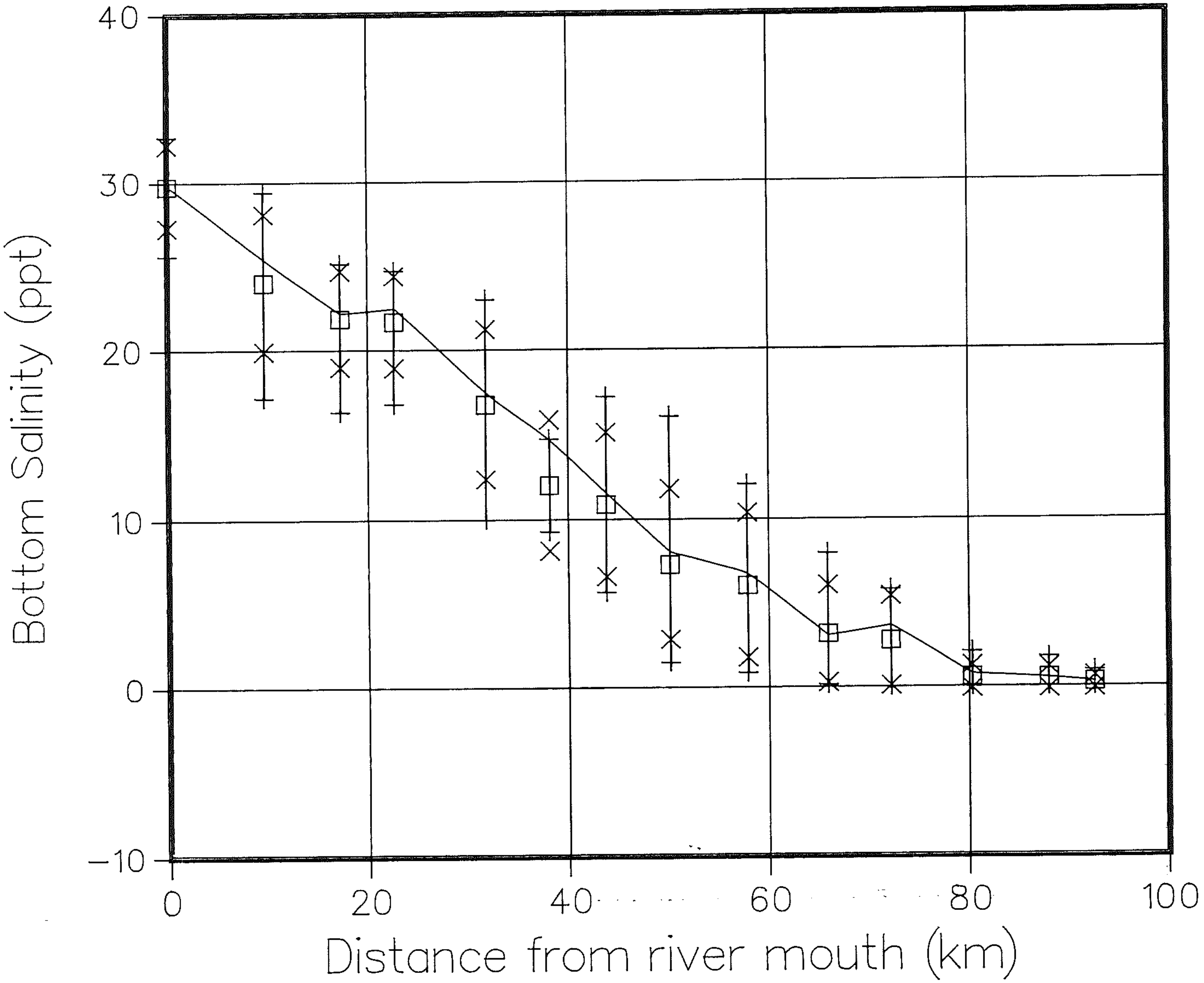


Figure 33. August bottom salinity with distance from river mouth (key as in figure 26).

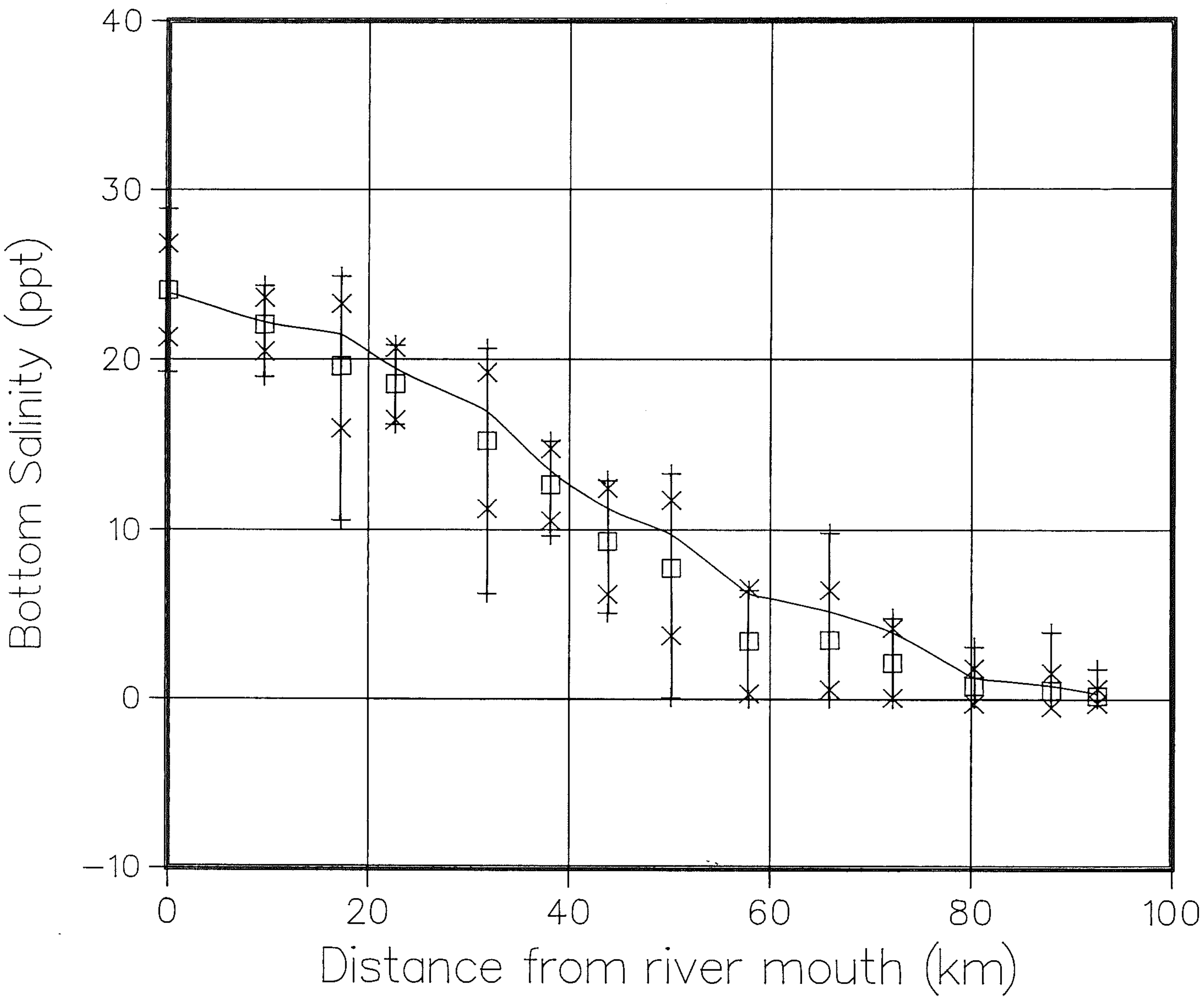


Figure 34. September bottom salinity with distance from river mouth (key as in figure 26).

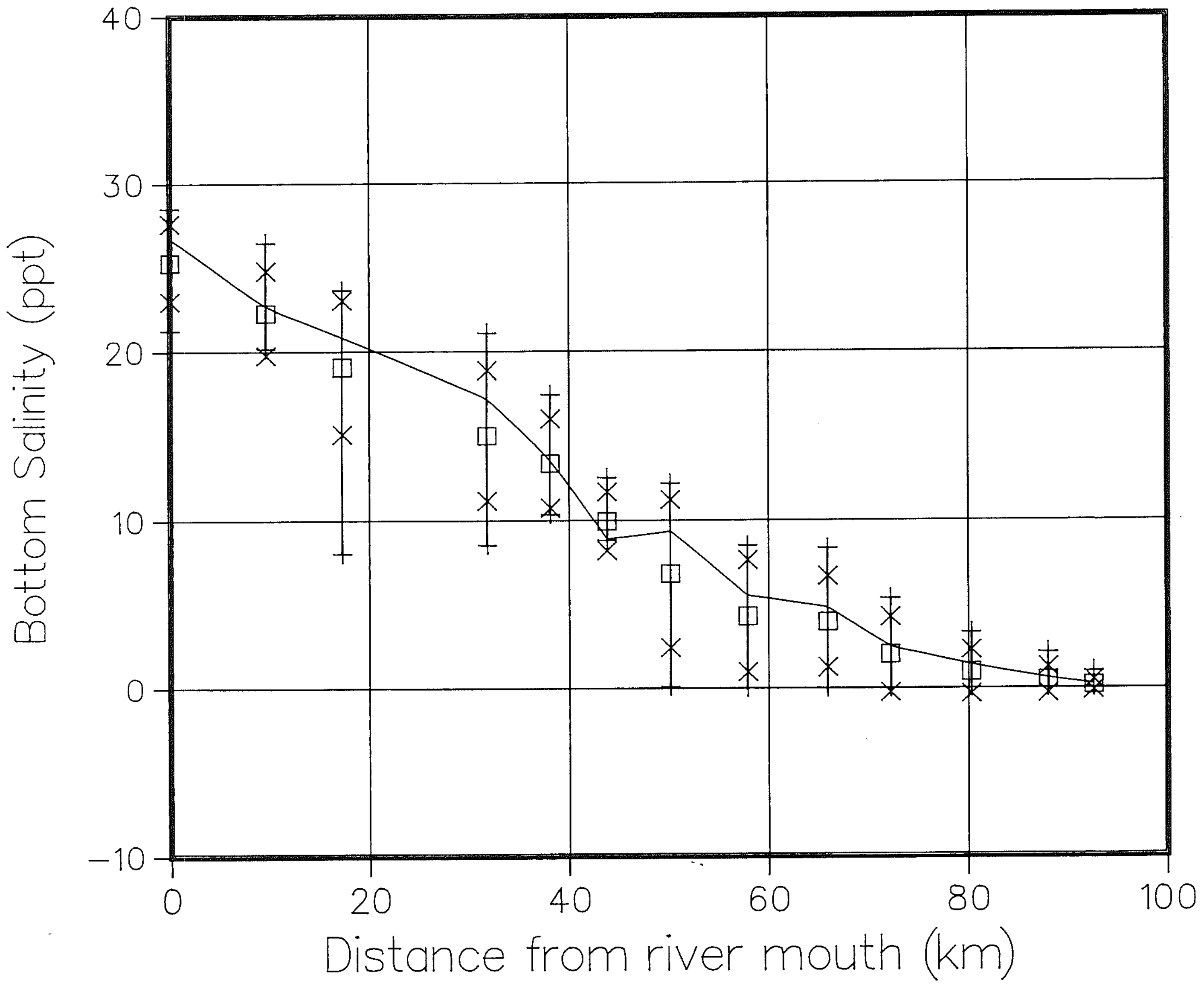


Figure 35. October bottom salinity with distance from river mouth (key as in figure 26).

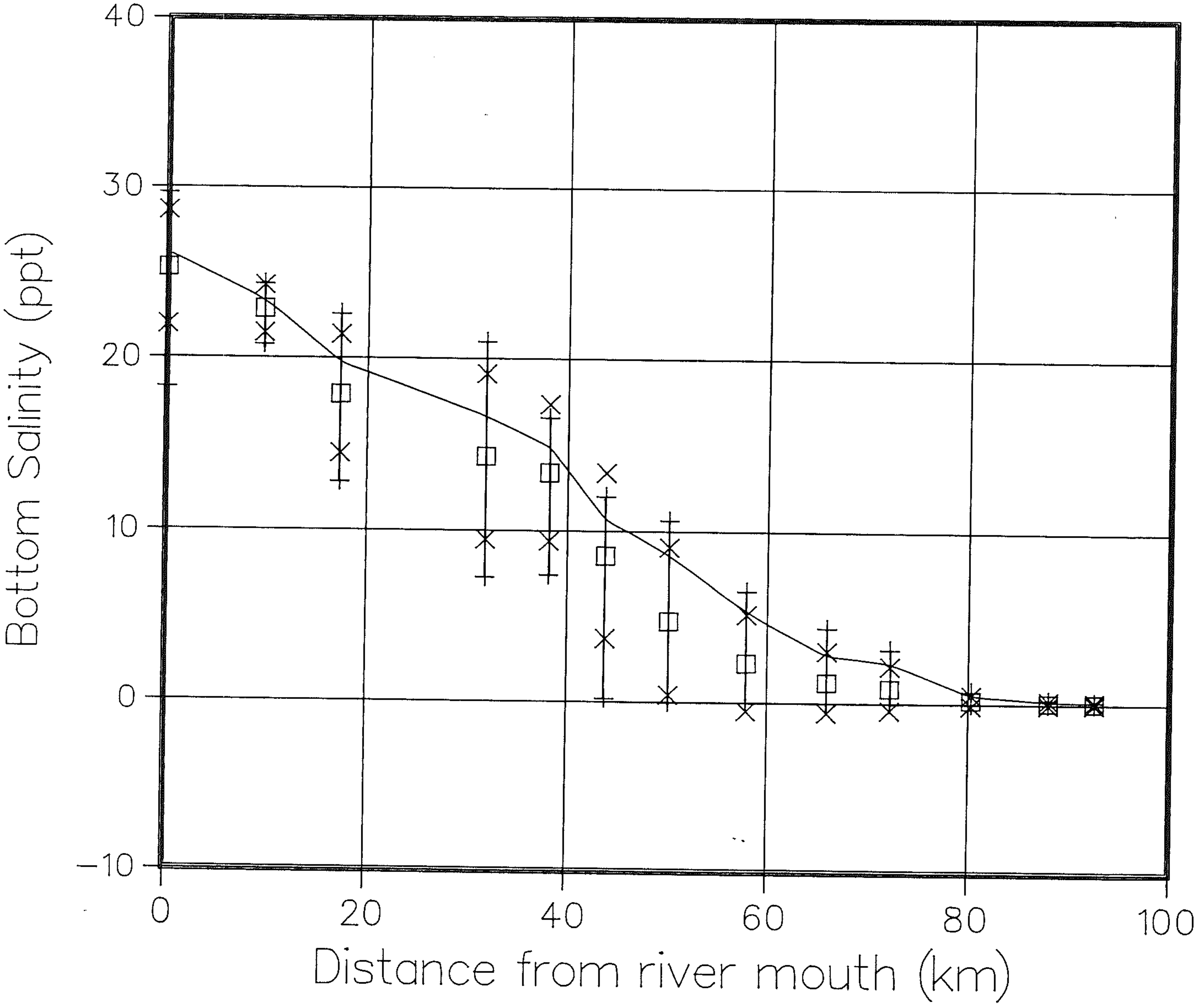


Figure 36. November bottom salinity with distance from river mouth (key as in figure 26).

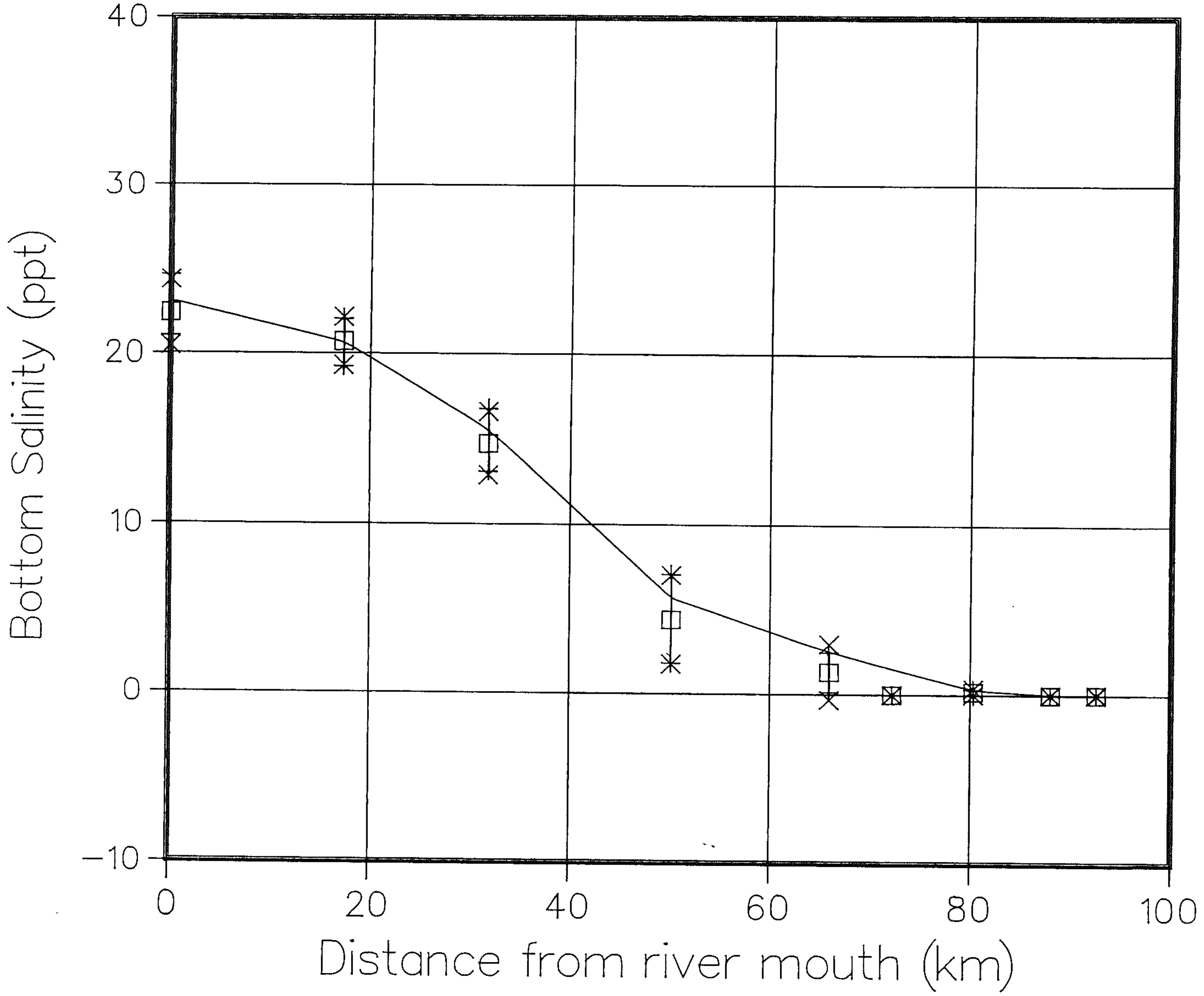


Figure 37. December bottom salinity with distance from river mouth (key as in figure 26).

not plotted (e.g., 36.57 km in all months, and 22.71 km in October and November). The number of surveys for each station and month on which Figures 2 through 37 are based is shown in Table 1c.

Table 1b shows that the number of surveys per month was not uniform; fewer surveys were conducted in winter months. The monthly mean salinity presented in figures 2 through 37 may significantly differ from the long-term mean if the number of surveys is small for that month. For example, the March plots are actually based on just 6 years of data (1972, 1973, 1979, 1981, 1982, 1983). Mean freshwater discharges for March in these years were 325, 592, 632, 103, 441, and 466 $m^3 s^{-1}$ respectively (USGS Richmond and Kanawha Canal gages). The long-term (1925-1967) median March freshwater discharge was 357 $m^3 s^{-1}$. The importance of freshwater discharge in determining salinity is apparent in Figure 38, which shows depth-averaged salinity for March delineated by year. During March 1981, an abnormally dry month, very high salinities were observed at all stations, and the upstream extent of saltwater was greater (80 km) than for other years' data (<40 km). The mean is a statistic greatly affected by outlying observations, such as those of March 1981. If the 1981 data were removed from Figure 38, the mean salinity for each station would be greatly reduced, and would be more representative of typical March salinities, since the discharge rates for those years remaining were closer to the long-term median discharge rate for March.

An attempt was made to construct the seasonal pattern of longitudinal salinity distribution under normal hydrological conditions. Each slackwater survey was assumed to represent the condition under a given freshwater discharge, which is the average discharge for the 30 days immediately

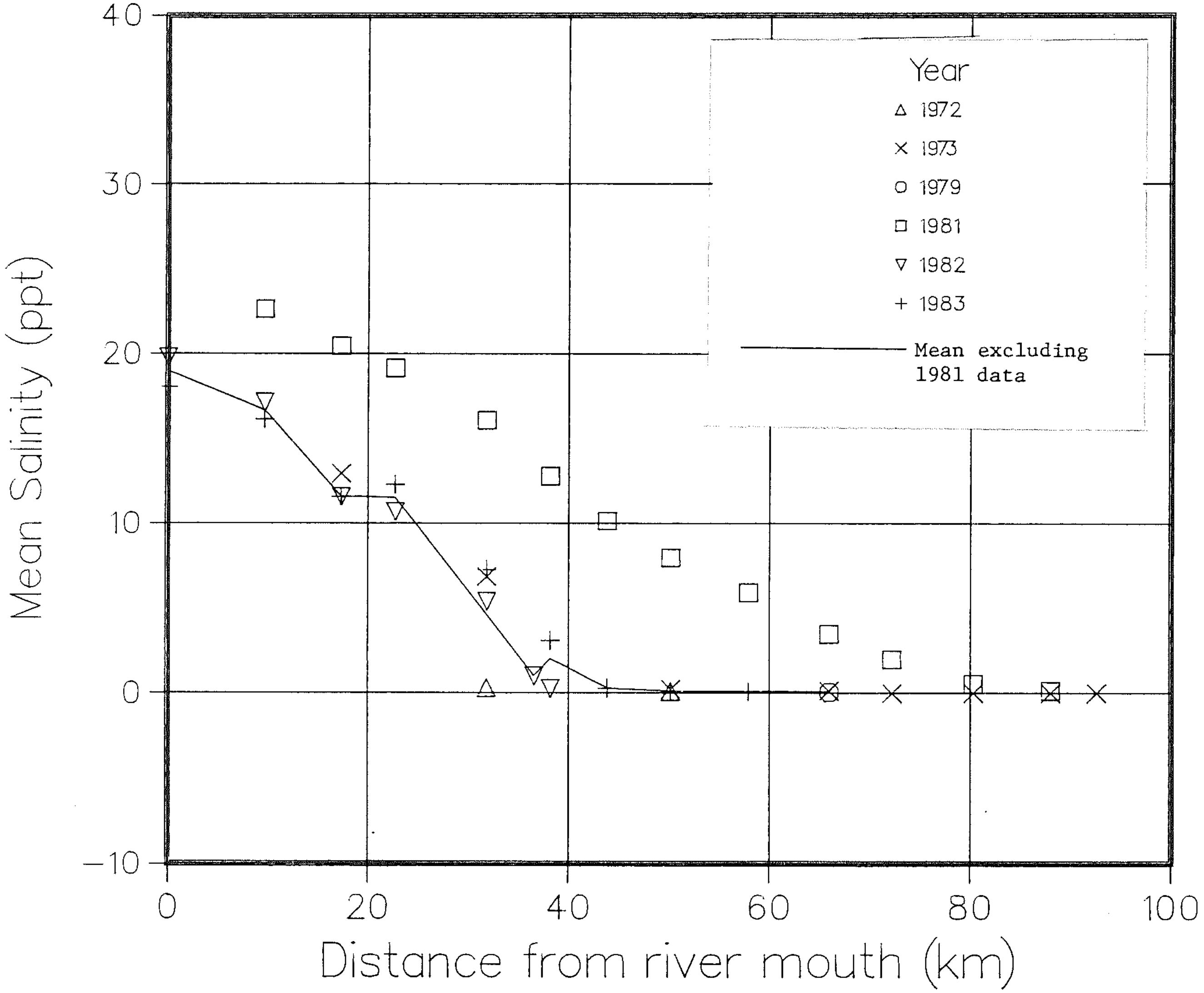


Figure 38. March vertically averaged salinity with distance from river mouth by year.

preceding the survey date. The black bars in Figure 39 represent the means of the 30-day averaged discharges for all surveys conducted in the given months of the year. For comparison, the long-term monthly mean and median discharges are also presented in Figure 39. It is seen that except for the month of February, the surveys were conducted under an average discharge much higher than long-term median flow for the month. This occurred partly by chance, but also, for those surveys in April-July which occurred toward the beginning of the month, most of the 30 days for which discharge was averaged would be in the previous month, which was characterized by higher discharge. The 30-day averaged discharge for each survey was compared with long-term median of the average flow for the month, and those surveys with discharge falling in the range from 50 percent to 150 percent of the median flow were identified. Table 3 lists the surveys so identified and deemed appropriate for calculation of normal salinity pattern. Salinity distribution under median flow conditions was constructed for each month by averaging the data from the surveys identified as appropriate. The resulting average salinity patterns are included in Figures 2 to 37. The means of 30-day average freshwater discharges for those identified surveys are also presented in Figure 39; they were quite close to the long-term monthly median flow.

Maximum monthly surface (within 1 meter of the water surface) and bottom (within 1 meter of the bottom of the water column) salinities for each sampling station are tabulated in Table 4. For any particular station, salinity maxima were generally greatest at the bottom of the water column (e.g., 5.66 ppt at the surface and 11.92 ppt at the bottom at 50.19 km in April) and greatest in the dry summer and fall (e.g., 20.67 to 22.98 ppt at the bottom at 31.85 km in June through October, and 10.29 to 19.69 ppt in

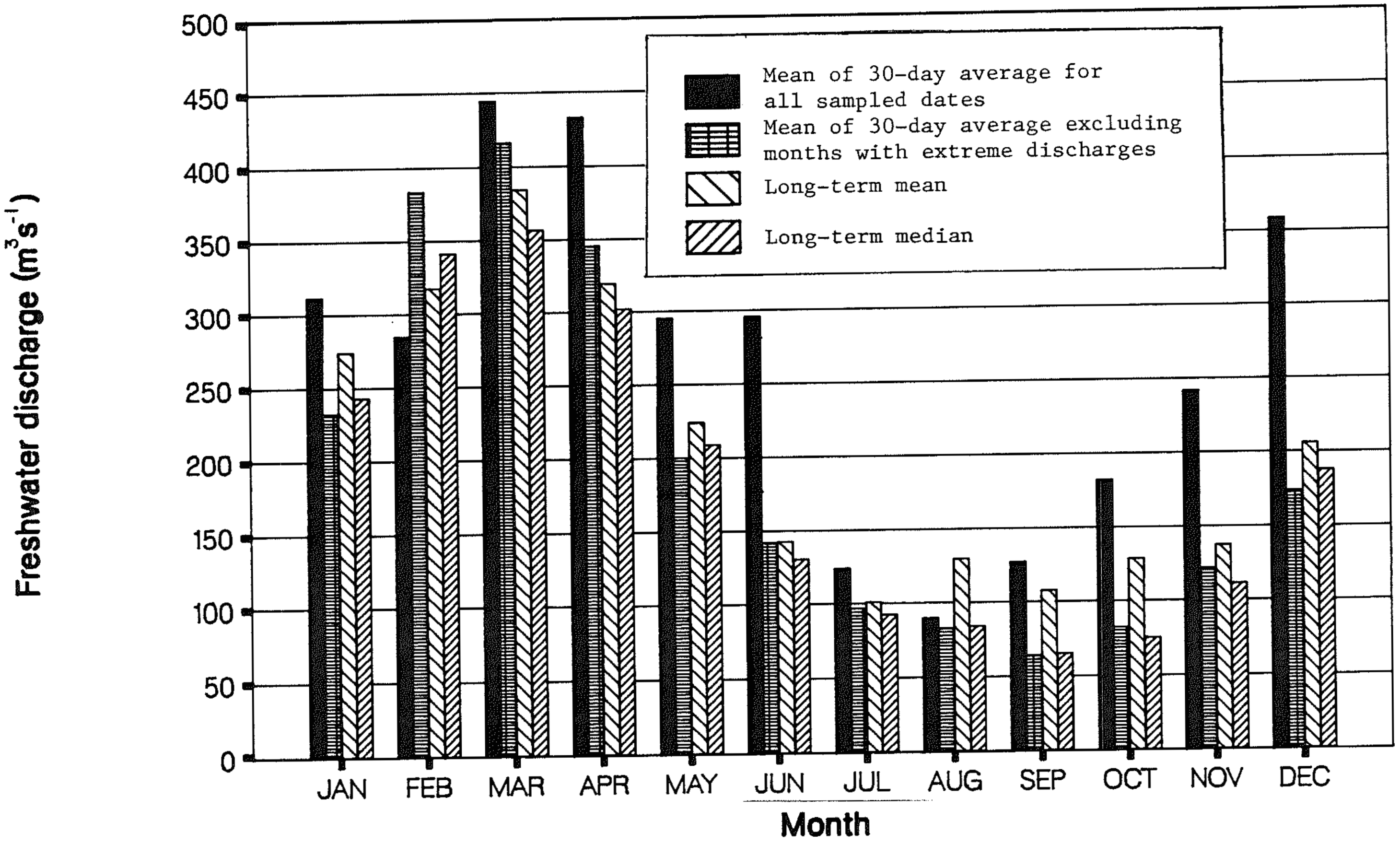


Figure 39. Seasonal variation in freshwater discharge over the long term and over the monitoring period.

Table 3. Surveys chosen for calculation of normal salinity pattern based on comparison of 30-day average discharge and long-term median monthly discharge.

	Month											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	.	.	.	.	.	.	.	.	X	.	.	X
1972	X	.	X	X	X	.	.	.	X	.	.	.
1973	.	.	X	.	.	.	.	.	.	X	.	.
1974	.	X	.	X	X	.	X	X	.	X	X	X
1975	.	.	.	.	.	.	.	.	.	.	.	.
1976	.	.	.	X	X	X	X	.	.	.	X	.
1977	.	.	.	X	.	X	X	.	X	X	.	.
1978	.	.	.	X	.	X	X	X	X	.	.	.
1979	X	.	.	X	X	.	X	X	X	.	.	.
1980	.	.	.	.	.	X	X	X	X	X	.	.
1981	.	.	.	.	X	.	X	X	X	X	X	.
1982	.	.	X	X	X	.	.	X	X	X	X	.
1983	.	.	X	.	.	.	.	.	X	.	X	.
1984	.	.	.	.	.	.	X	.	.	X	X	.
1985	.	.	.	X	X	X	X	.	.	.	.	.

Table 4. Maximum monthly surface and bottom salinities for each station.

DIST. (km)	DEPTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.00	Surface	16.43	25.46	13.54	22.24	22.47	23.90	25.07	25.10	25.91	24.94	22.02	23.54
	Bottom	19.24	26.35	25.93	30.00	29.36	31.19	30.01	32.68	28.87	28.52	29.66	24.61
9.66	Surface	.	.	22.12	22.65	22.27	24.00	20.70	24.85	22.31	22.57	23.07	.
	Bottom	.	.	22.85	27.98	25.68	26.24	25.34	29.38	24.34	26.50	24.31	.
17.30	Surface	12.71	23.04	19.38	18.76	19.76	18.12	23.64	24.20	24.56	23.01	19.56	21.15
	Bottom	16.06	24.13	21.40	23.04	21.18	21.82	24.27	25.14	24.89	23.68	22.58	22.06
22.71	Surface	.	.	17.71	16.49	17.39	17.72	17.31	23.67	18.88	18.33	18.24	.
	Bottom	.	.	20.62	20.59	20.38	22.22	20.04	24.71	20.86	19.98	21.22	.
31.85	Surface	7.94	18.51	14.56	13.59	15.60	15.78	17.52	21.51	20.09	17.71	14.07	13.88
	Bottom	10.29	19.67	17.77	19.80	18.04	20.85	20.80	22.98	20.67	21.10	20.99	16.81
36.57	Surface	.	.	0.75	.	0.55	10.22	.	17.81	12.23	.	.	.
	Bottom	.	.	1.62	.	14.45	13.97	.	23.40	13.47	.	.	.
38.18	Surface	.	.	11.57	10.05	8.45	11.23	12.15	11.79	13.01	12.75	12.48	.
	Bottom	.	.	13.57	15.60	13.45	15.69	17.59	14.77	15.26	17.44	16.59	.
43.85	Surface	.	.	9.44	8.02	6.38	8.59	9.18	15.54	12.33	11.47	9.50	.
	Bottom	.	.	10.85	10.97	8.87	11.08	12.32	17.25	12.95	12.52	12.03	.
50.19	Surface	1.43	10.51	7.50	5.66	4.68	5.82	9.82	11.93	12.72	10.69	7.70	6.14
	Bottom	1.15	10.78	8.62	11.92	6.39	6.46	10.38	16.09	13.35	12.19	10.64	7.07
57.92	Surface	0.00	.	5.85	4.90	3.21	3.49	6.21	10.29	6.31	8.27	6.33	.
	Bottom	0.00	.	5.95	5.30	3.33	4.12	6.39	12.05	6.44	8.49	6.54	.
65.94	Surface	0.07	4.26	2.71	1.77	1.15	2.97	5.75	6.72	8.73	7.62	3.51	1.52
	Bottom	0.09	5.42	4.03	2.54	1.62	2.14	5.95	7.97	9.82	8.33	4.40	2.48
72.21	Surface	0.00	0.00	1.61	0.99	0.26	0.93	2.24	4.96	3.88	4.96	1.97	0.00
	Bottom	0.00	0.00	2.47	1.41	0.67	0.91	2.42	5.81	4.79	5.35	3.17	0.00
80.30	Surface	0.12	0.86	0.53	0.28	0.10	0.37	0.71	2.36	2.49	2.86	0.63	0.19
	Bottom	0.13	1.38	0.61	0.36	0.16	0.39	0.73	2.07	3.07	3.30	0.75	0.34
87.97	Surface	0.08	0.34	0.14	0.03	0.14	0.09	1.47	1.29	3.35	1.90	0.28	0.00
	Bottom	0.08	0.35	0.14	0.03	0.00	0.08	3.00	1.75	3.95	2.12	0.29	0.00
92.56	Surface	0.00	0.26	0.00	0.00	0.13	0.10	0.96	0.87	1.73	0.95	0.17	0.05
	Bottom	0.00	0.26	0.00	0.00	0.10	0.10	1.61	0.94	1.78	0.98	0.17	0.03
102.10	Surface	0.00	0.17	0.00	0.00	0.00	0.01	0.65	0.36	0.76	0.43	0.13	0.00
	Bottom	0.00	0.17	0.00	0.00	0.00	0.01	0.82	0.36	0.75	0.46	0.14	0.00
107.90	Surface	0.00	0.16	0.00	0.00	0.16	0.10	0.28	0.31	0.31	0.37	0.15	0.06
	Bottom	0.00	0.16	0.00	0.00	0.18	0.10	1.48	0.31	0.16	0.37	0.15	0.04

Table 4, continued.

DIST. (km)	DEPTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
114.50	Surface	0.00	0.16	0.00	0.00	0.04	0.10	2.61	0.10	0.25	0.34	0.11	0.00
	Bottom	0.00	0.16	0.00	0.00	0.04	0.10	0.46	0.10	0.08	0.21	0.10	0.00
119.00	Surface	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.00	0.00	0.27	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.00	0.00	0.15	0.00	0.00
122.80	Surface	0.00	0.00	0.00	0.00	0.04	0.10	0.09	0.10	0.08	0.27	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.04	0.10	0.09	0.10	0.08	0.21	0.00	0.00
125.90	Surface	0.00	0.00	0.00	0.00	0.04	0.10	0.09	0.10	0.07	0.33	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.04	0.10	0.09	0.10	0.07	0.27	0.00	0.00
129.10	Surface	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.00	0.13	0.33	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.00	0.13	0.21	0.00	0.00
132.10	Surface	0.00	0.00	0.00	0.00	0.00	0.10	0.09	0.09	0.13	0.33	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.10	0.09	0.08	0.13	0.21	0.00	0.00
135.20	Surface	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.00	0.13	0.28	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.00	0.13	0.16	0.00	0.00
139.40	Surface	0.00	0.00	0.00	0.00	0.04	0.10	0.10	0.09	0.13	0.22	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.04	0.10	0.10	0.09	0.13	0.16	0.00	0.00
143.80	Surface	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.00	0.14	0.29	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.00	0.14	0.16	0.00	0.00
145.80	Surface	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.22	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.16	0.00	0.00
148.30	Surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.22	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.16	0.00	0.00
150.60	Surface	0.00	0.00	0.00	0.00	0.03	0.10	0.09	0.08	0.08	0.22	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.04	0.10	0.08	0.08	0.08	0.16	0.00	0.00
152.80	Surface	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.08	0.22	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.08	0.00	0.00	0.00
154.80	Surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.09	0.16	0.00	0.00
	Bottom	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00

DIST. = Distance from river mouth (km); . = no observations

Note: The maximum values for October all occurred in the 1982 survey. Since in 1981 (a drier year), there was no saltwater found as far upstream as in 1982, the apparent 1982 salinity must be due to something other than salinity (e.g., high concentration of ions in an industrial discharge).

December to March at 31.85 km). Maxima decreased with distance upstream. The maximum bottom salinity at the mouth was 32.68 ppt and occurred in August 1980; the maximum surface salinity there was 25.91 ppt in September 1977. The maximum salinities at 31.85 km (the vicinity of Wreck Shoal) were 22.98 ppt at the bottom and 21.51 ppt at the surface in August 1980. The furthest upstream intrusion of saltwater (when saltwater is defined as > 0.5 ppt salinity) during the monitoring period was 102 km, with both surface and bottom salinities greater than 0.7 ppt in September 1980. (Examination of nearby salinity data in July 1977 (Table 5) reveals that salinity values of 1.48 and 2.61 ppt at 107.9 and 114.5 km appear to be anomalous--perhaps laboratory or reporting errors.)

B. Tidal Variations

The variation of longitudinal salinity pattern with the state of tide is very difficult to discern with the data set. The dominant tidal components have time scales of 12 hours (flood/ebb cycle) and 14 days (spring/neap cycle), while the sampling interval of slackwater surveys was of order of one month. The effect of state of tide is generally masked by other factors such as freshwater discharge and meteorological events.

Within the salinity data set being studied, there were two days on which consecutive slack before ebb and slack before flood tides were sampled, permitting examination of the effects of tide on salinity while minimizing the effects of seasonal patterns. One of the sampling days, August 22, 1980, occurred approximately 3.5 days after neap tide. The other sampling day, August 27, 1980, occurred approximately 1 day after spring tide. Freshwater discharges for the months preceding each of these sampling

Table 5. Salinity at selected stations on July 28, 1977.

	Salinity at (km from river mouth):				
Depth (m)	87.97	92.56	102.1	107.9	114.5
1.0	1.47	0.96	0.65	0.28	2.61*
2.0					
3.0					
4.0				0.23	
5.0					0.23
6.0	1.40		0.52		
7.0					
8.0				1.48*	
9.0					0.46
10.0	3.00	1.84	0.82		
11.0					
12.0					
13.0					
14.0					
15.0					
16.0					
17.0					
18.0		1.61			

(last value in each column is bottom salinity--within 1 meter of bottom of water column)

* apparently anomalous data, perhaps due to laboratory or collection error, or due to high conductivity of local discharge

dates were relatively constant (30-day mean discharge for August 22 was 62 m^3s^{-1}, standard deviation 12 m^3s^{-1}; for August 27, 30-day mean discharge was 58 m^3s^{-1}, standard deviation 10 m^3s^{-1}).

The intra-tidal variation (flood/ebb cycle) is evident in longitudinal plots of depth-averaged salinity for August 22 and 27, 1980 (Figures 40 and 41); salinity at slack before ebb was generally higher than salinity at slack before flood. This pattern was also generally true for the entire data set; Figure 42 is a plot of depth- and time-averaged salinity for those stations with a complete (1971-1985) record.

Comparison of spring and neap tides is possible using the August 22 and 27, 1980 data, with the August 22 data representing neap tide and August 27 data representing spring tide. Examination of figures 40 and 41 reveals that there was less intra-tidal difference between salinities at any particular station on August 22 than on August 27; mean salinity on August 22 was 14.93 ppt at slack before flood and 15.09 ppt at slack before ebb; mean salinity on August 27 was 10.44 ppt at slack before flood and 12.81 ppt at slack before ebb.

Tidal excursion is the longitudinal distance a parcel of water travels during the flood or ebb tide. A measure of tidal excursion is the longitudinal distance between the locations of same-salinity water at consecutive slacks; on figures 40 and 41 this measure would be the horizontal distance between curves. This is not an exact measure because some mixing occurs as the parcel of water travels upstream or downstream. Depending on whether longitudinal or vertical mixing dominates, a parcel of surface water moving **upstream** during **flood** tide could mix with fresher water coming downstream or with saltier water from deeper layers. In the former

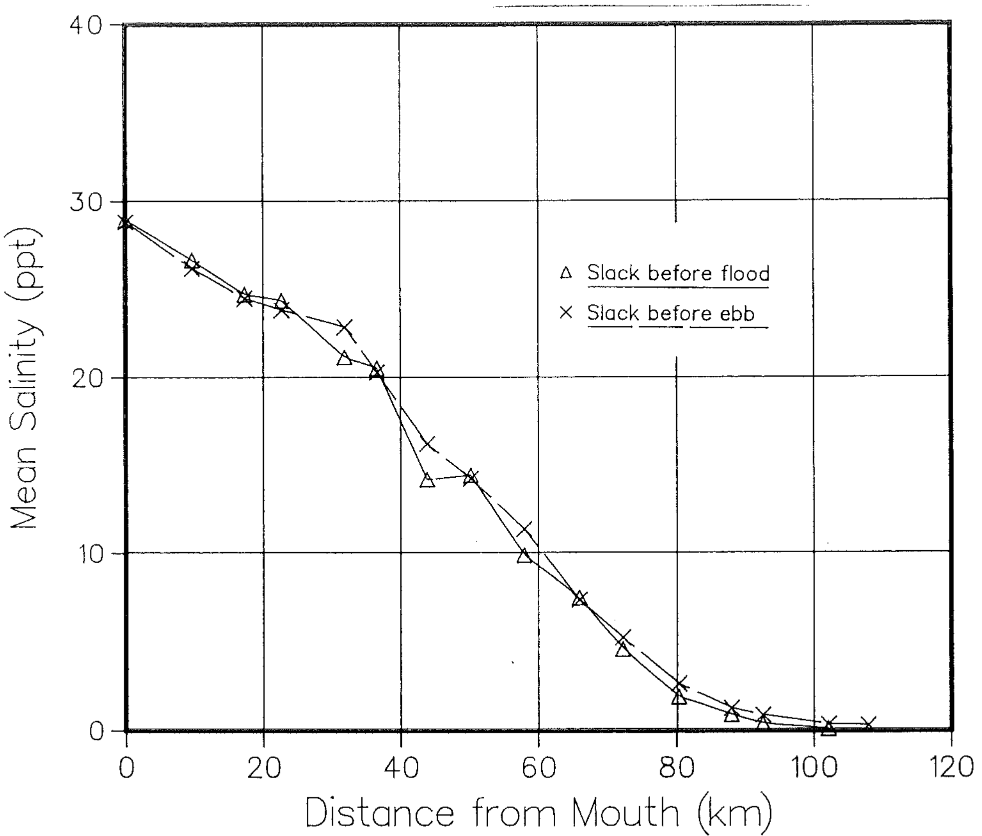


Figure 40. August 22, 1980 vertically averaged salinity with distance from river mouth by phase of tidal cycle.

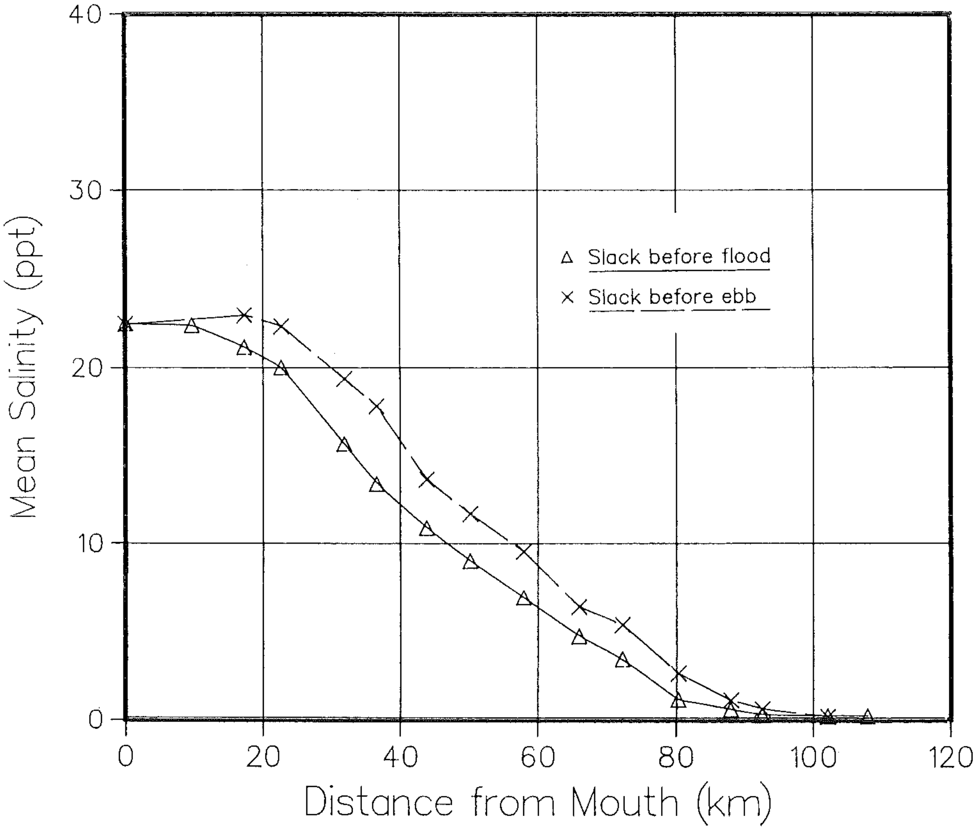


Figure 41. August 27, 1980 vertically averaged salinity with distance from river mouth by phase of tidal cycle.

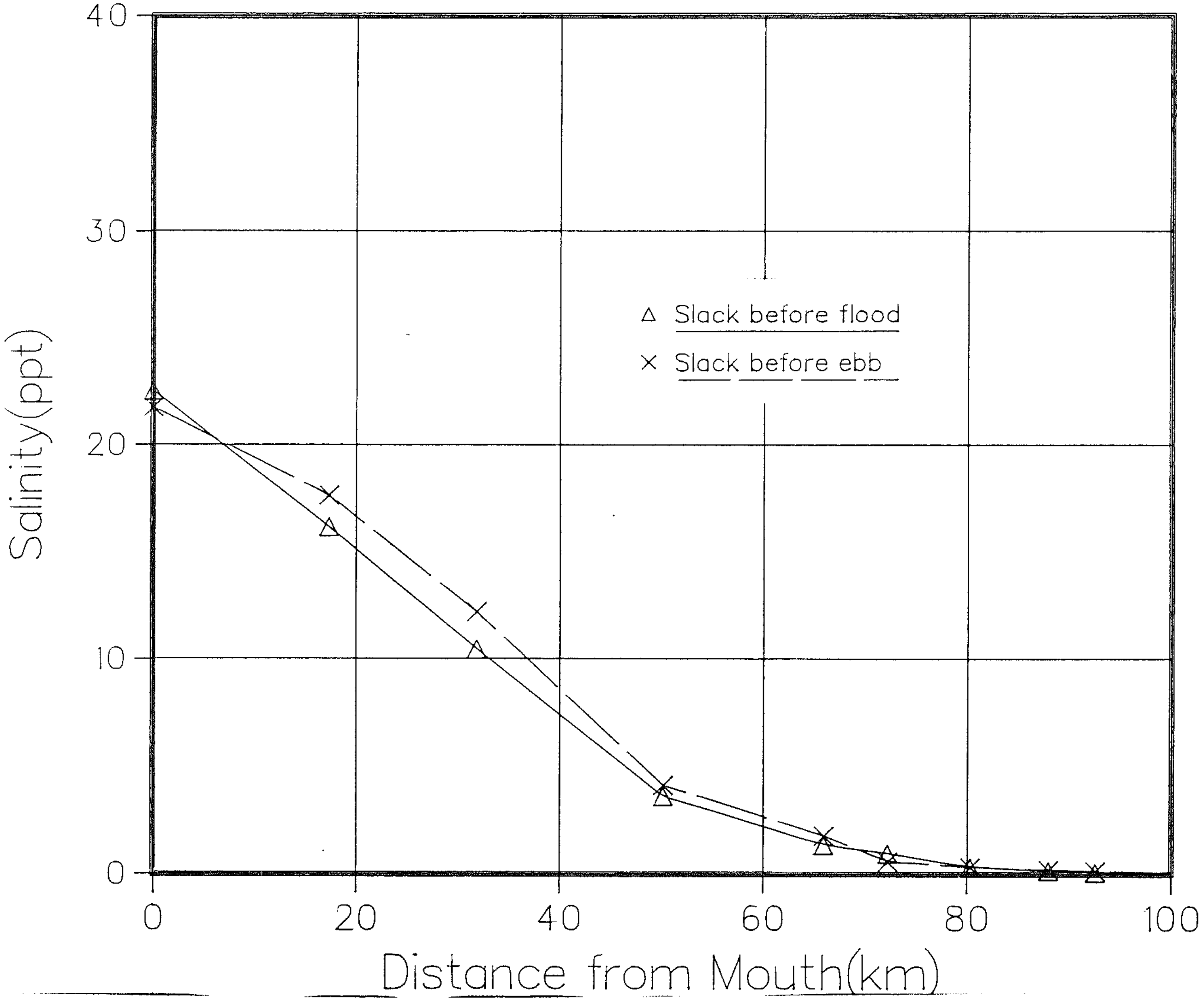


Figure 42. Vertically averaged salinity with distance from river mouth by phase of tidal cycle for those stations monitored from 1971-1985.

case, the distance between same-salinity waters would be shorter than the actual tidal excursion distance; in the latter case the distance between same-salinity waters would be longer than the actual tidal excursion distance. A parcel of water moving **downstream** with the **ebb** tide would mix with saltier water whether longitudinal or vertical mixing dominates; the distance between parcels of same-salinity surface water would therefore be shorter than the tidal excursion distance.

On August 27, 1980 the **flood** tidal excursion was sampled (i.e., slack before flood was sampled before slack before ebb). On August 22, 1980, the **ebb** tidal excursion was sampled (i.e., slack before ebb was sampled before slack before flood). The distance between same-salinity surface waters on August 27 could be either longer or shorter than the actual tidal excursion distance, depending on mixing; the distance between same-salinity surface waters on August 22 should be shorter than the actual tidal excursion distance. Figures 43 and 44 are longitudinal plots of surface salinity for the two sampling days. By assuming that salinity changed linearly with distance between observed salinities, distances between same-salinity surface water at the different slacks were calculated for every 0.5 ppt interval for each of the two dates (i.e., the horizontal distances between the curves on figures 43 and 44 were calculated). The mean distance between same-salinity surface water between 2.0 and 20.0 ppt (between approximately 20 and 80 km from the river mouth) on August 22 was 2.5 km; on August 27, the mean distance was 7.5 km. Since the August 22 calculation is a measure of **ebb** tidal excursion, the actual tidal excursion on this date was probably somewhat greater than 2.5 km. Since tidal excursion should be proportional to tidal range, and the predicted tidal range ratio at Mulberry Point (about 39 km) for August 22 and 27 was 0.64 m/0.98 m = 0.65, but measured tidal

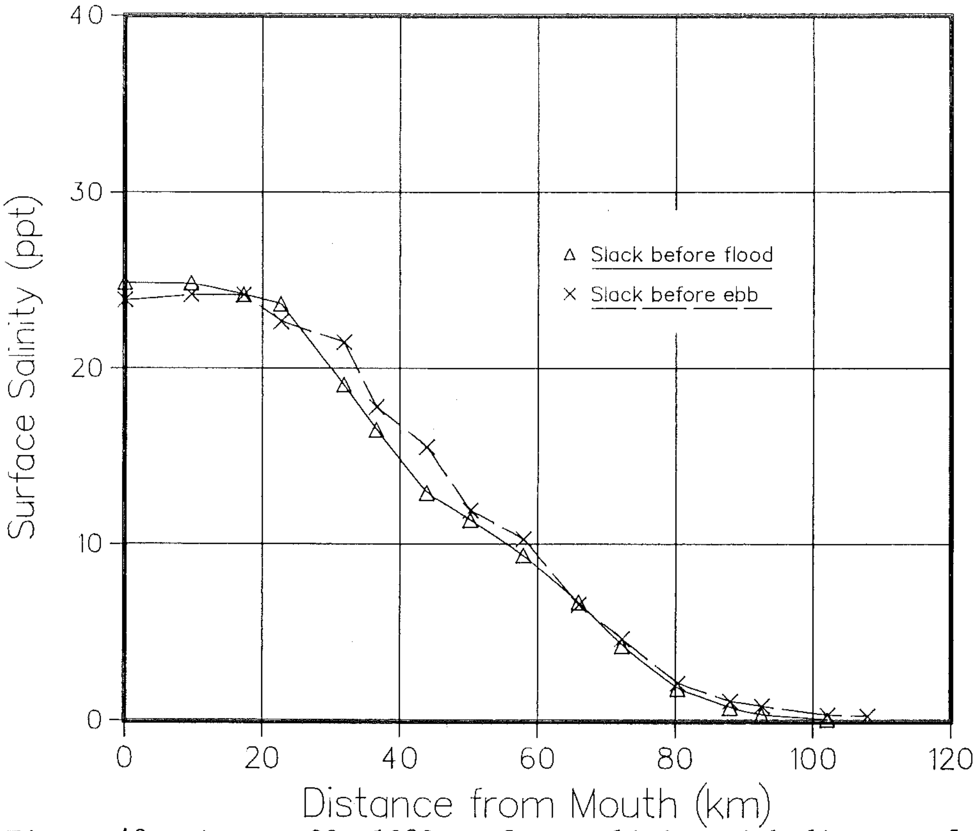


Figure 43. August 22, 1980 surface salinity with distance from river mouth by phase of tidal cycle.

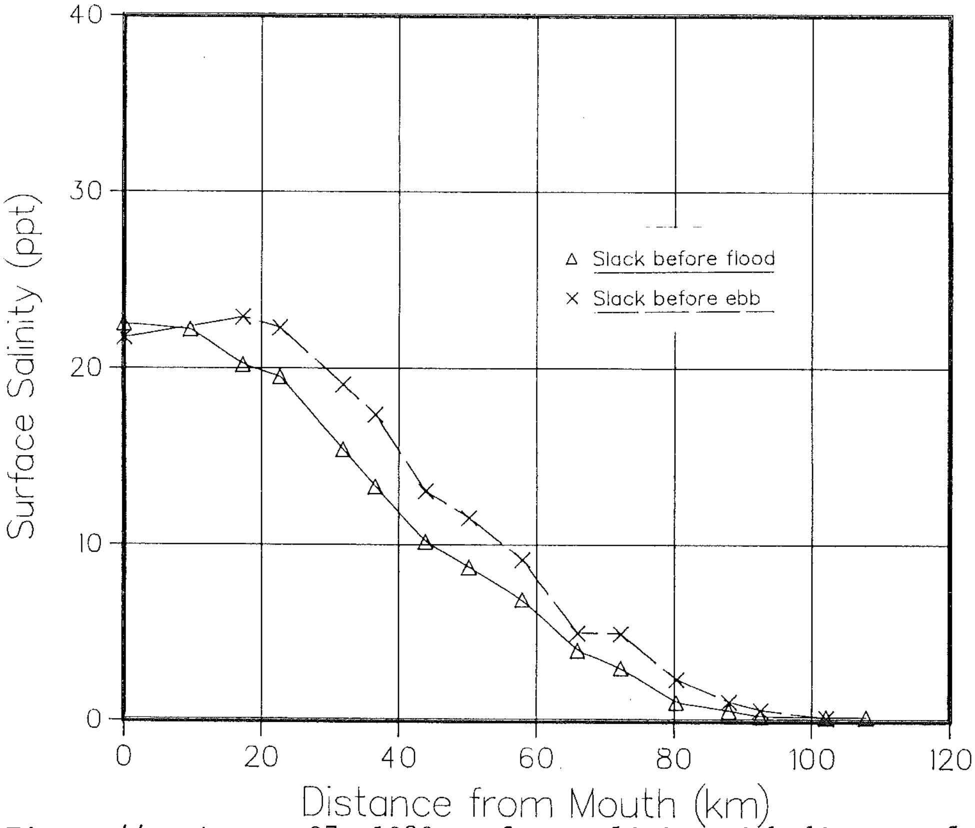


Figure 44. August 27, 1980 surface salinity with distance from river mouth by phase of tidal cycle.

excursion ratios were 2.5 km/7.5 km = 0.33, it is suspected that the actual flood tidal excursion was somewhat smaller than 7.5 km.

C. Limit of saltwater intrusion

Figures 2 through 37 show that, under average conditions, only the lowest quarter to the lower half of the tidal river (160 km long from river mouth to Richmond) had measurable salinity. The limit of saltwater intrusion is a feature of longitudinal salinity pattern which is of particular practical interest. Not only does it affect the distribution of living resources in a tidal river, it also plays a role in decisions on freshwater utilization. The limit of saltwater intrusion may be defined as the location upriver of which salinity is less than 0.2 to 1.0 ppt, depending on the purpose of the definer. The limit of salt water intrusion was calculated for each sampling cruise which sampled both salt and freshwater portions of the river. Surface and bottom salinities were examined separately. Boundaries between "salt" and "fresh" water at 1.0 ppt and 0.5 ppt were examined. To calculate the upstream extent of saltwater intrusion for a particular sampling cruise, the two stations with salinities just greater than and just less than the defined boundary (1.0 or 0.5 ppt) were found, and the distance at which the defined boundary would occur, given a linear salinity gradient between the two stations, was calculated. Monthly mean distances from the river mouth to the upstream extent of bottom and surface saltwater intrusion (when defined as 1.0 and 0.5 ppt), along with ranges and standard deviations, are shown in Tables 6 through 9. During this monitoring period, the overall average of the limit of saltwater intrusion (i.e., bottom salinity = 0.5 ppt) was 75 (± 17) km from the river mouth at slack before ebb tide, and 66 (± 18) km at slack before flood tide.

Table 6. Saltwater intrusion distance for bottom salt/fresh boundary = 1.0 ppt

Month	Tide	Mean Distance	Minimum Distance	Maximum Distance	Std Dev	Number of Observations
Jan	Slack before flood	50.4	48.8	52.1	2.4	2
Feb	Slack before ebb	60.1	31.8	83.1	26.0	3
Mar	Slack before flood	53.1	37.3	78.6	22.3	3
	Slack before ebb	48.5	48.5	48.5	.	1
Apr	Slack before flood	46.7	30.7	75.4	13.5	9
	Slack before ebb	59.8	59.8	59.8	.	1
May	Slack before flood	52.8	37.7	70.0	11.7	8
	Slack before ebb	55.4	49.0	68.1	11.0	3
Jun	Slack before flood	52.9	41.2	64.0	7.8	10
	Slack before ebb	61.8	57.6	69.8	6.9	3
Jul	Slack before flood	69.7	55.8	84.2	11.0	7
	Slack before ebb	73.1	63.0	99.9	17.9	4
Aug	Slack before flood	72.0	55.8	87.9	12.0	9
	Slack before ebb	91.1	89.5	92.2	1.4	3
Sep	Slack before flood	68.8	47.4	98.4	16.9	10
	Slack before ebb	83.9	72.8	99.8	9.2	7
Oct	Slack before flood	75.2	48.2	92.5	17.8	8
	Slack before ebb	67.5	49.1	79.2	16.1	3
Nov	Slack before flood	64.7	43.2	79.4	16.0	6
	Slack before ebb	49.4	49.4	49.4	.	1
Dec	Slack before ebb	69.5	58.0	75.9	9.9	3

(Distances in km from river mouth)

Table 7. Saltwater intrusion distance for bottom salt/fresh boundary = 0.5 ppt

Month	Tide	Mean Distance	Minimum Distance	Maximum Distance	Std Dev	Number of Observations
Jan	Slack before flood	59.1	49.8	68.3	13.1	2
Feb	Slack before ebb	86.9	86.9	86.9	.	1
Mar	Slack before flood	54.6	37.9	82.1	24.0	3
	Slack before ebb	49.6	49.6	49.6	.	1
Apr	Slack before flood	49.4	31.5	79.2	15.4	8
	Slack before ebb	63.6	63.6	63.6	.	1
May	Slack before flood	55.3	40.4	74.9	13.0	8
	Slack before ebb	58.6	49.9	74.9	14.1	3
Jun	Slack before flood	55.3	43.1	65.6	8.3	10
	Slack before ebb	66.5	62.5	74.4	6.8	3
Jul	Slack before flood	77.9	60.9	87.3	10.5	5
	Slack before ebb	84.3	65.6	114.2	26.2	3
Aug	Slack before flood	78.5	61.7	91.9	11.7	8
	Slack before ebb	97.4	95.2	99.5	3.0	2
Sep	Slack before flood	72.0	48.9	100.8	17.3	10
	Slack before ebb	85.8	77.3	96.9	7.8	5
Oct	Slack before flood	79.1	49.3	101.4	20.0	8
	Slack before ebb	63.7	49.8	77.7	19.7	2
Nov	Slack before flood	67.5	43.6	84.5	17.9	6
Dec	Slack before ebb	73.4	62.7	79.2	9.3	3

(Distances in km from river mouth)

Table 8. Saltwater intrusion distance for surface salt/fresh boundary= 1.0 ppt

Month	Tide	Mean Distance	Minimum Distance	Maximum Distance	Std Dev	Number of Observations
Jan	Slack before flood	47.7	46.2	49.2	2.2	2
Feb	Slack before ebb	70.2	60.6	79.7	13.5	2
Mar	Slack before flood	50.8	35.8	76.8	22.6	3
	Slack before ebb	47.3	47.3	47.3	.	1
Apr	Slack before flood	49.7	28.3	72.1	14.9	9
	Slack before ebb	56.4	56.4	56.4	.	1
May	Slack before flood	51.8	34.7	67.0	12.7	8
	Slack before ebb	53.8	47.3	65.2	9.9	3
Jun	Slack before flood	51.1	37.4	71.2	10.3	10
	Slack before ebb	56.3	50.1	65.7	8.3	3
Jul	Slack before flood	67.9	55.1	83.6	10.8	7
	Slack before ebb	70.0	61.2	92.2	14.9	4
Aug	Slack before flood	69.9	52.3	86.4	11.7	10
	Slack before ebb	89.9	88.9	90.4	.9	3
Sep	Slack before flood	65.9	27.8	92.2	19.2	10
	Slack before ebb	84.7	77.1	99.7	8.9	6
Oct	Slack before flood	68.9	30.8	92.3	20.5	11
	Slack before ebb	62.4	38.0	78.1	21.4	3
Nov	Slack before flood	56.6	29.7	78.1	19.9	7
	Slack before ebb	49.0	48.4	49.5	.8	2
Dec	Slack before ebb	65.0	49.9	73.5	13.1	3

(Distances in km from river mouth))

Table 9. Saltwater intrusion distance for surface salt/fresh boundary = 0.5 ppt

Month	Tide	Mean Distance	Minimum Distance	Maximum Distance	Std Dev	Number of Observations
Jan	Slack before flood	54.6	49.0	60.2	7.9	2
Feb	Slack before ebb	74.7	63.7	85.6	15.5	2
Mar	Slack before flood	53.6	37.4	80.9	23.8	3
	Slack before ebb	49.2	49.2	49.2	.	1
Apr	Slack before flood	51.5	30.8	77.8	14.7	8
	Slack before ebb	62.4	62.4	62.4	.	1
May	Slack before flood	55.1	37.4	70.4	13.3	8
	Slack before ebb	57.7	49.0	70.4	11.3	3
Jun	Slack before flood	55.5	41.1	78.4	11.4	10
	Slack before ebb	63.6	58.8	71.5	6.9	3
Jul	Slack before flood	75.0	60.5	87.1	10.6	6
	Slack before ebb	76.8	64.7	104.4	18.8	4
Aug	Slack before flood	75.9	60.4	91.0	12.1	9
	Slack before ebb	97.3	95.2	99.5	3.1	2
Sep	Slack before flood	70.9	30.7	100.7	21.3	9
	Slack before ebb	84.8	74.2	96.9	8.6	5
Oct	Slack before flood	73.4	31.3	100.8	22.2	11
	Slack before ebb	60.8	45.1	76.5	22.2	2
Nov	Slack before flood	61.9	40.2	83.1	19.1	7
	Slack before ebb	49.7	49.7	49.7	.	1
Dec	Slack before ebb	71.0	58.5	77.7	10.8	3

(Distances in km from river mouth)

The upstream extent of saltwater intrusion for water at the bottom of the water column is further upstream than that for water at the top of the water column.

The effect of freshwater discharge on the limit of saltwater intrusion is quite apparent. As seen in Tables 6 through 9, the upstream extent of saltwater intrusion was greatest during July through October when freshwater discharge was generally lowest, and was least in March through May when freshwater discharge was generally greatest. The monthly mean distances of saltwater intrusion at slackwater before flood are presented in Figures 45a to 45d. The limits of saltwater intrusion at slack tide before ebb are not depicted because the data set is much smaller. Also shown in the figures are the mean distances excluding those observations made when 30-day averaged freshwater discharges were either higher than 150 percent or lower than 50 percent of the long-term monthly median. These figures show a distinct annual cycle in saltwater intrusion distance which correlates negatively with the hydrological cycle of freshwater discharge.

IV. Vertical Stratification

The saline portion of the James River is a partially-mixed estuary. There is some degree of vertical mixing between freshwater and saltwater, however, the mixing is not complete. Stratification exists most of the time (i.e., salinity at a given station generally increases from surface to bottom). Freshwater inflow tends to enhance stratification; tidal mixing works to erase vertical inhomogeneity. Meteorological events may enhance or weaken stratification. The vertical diffusion coefficient in the James

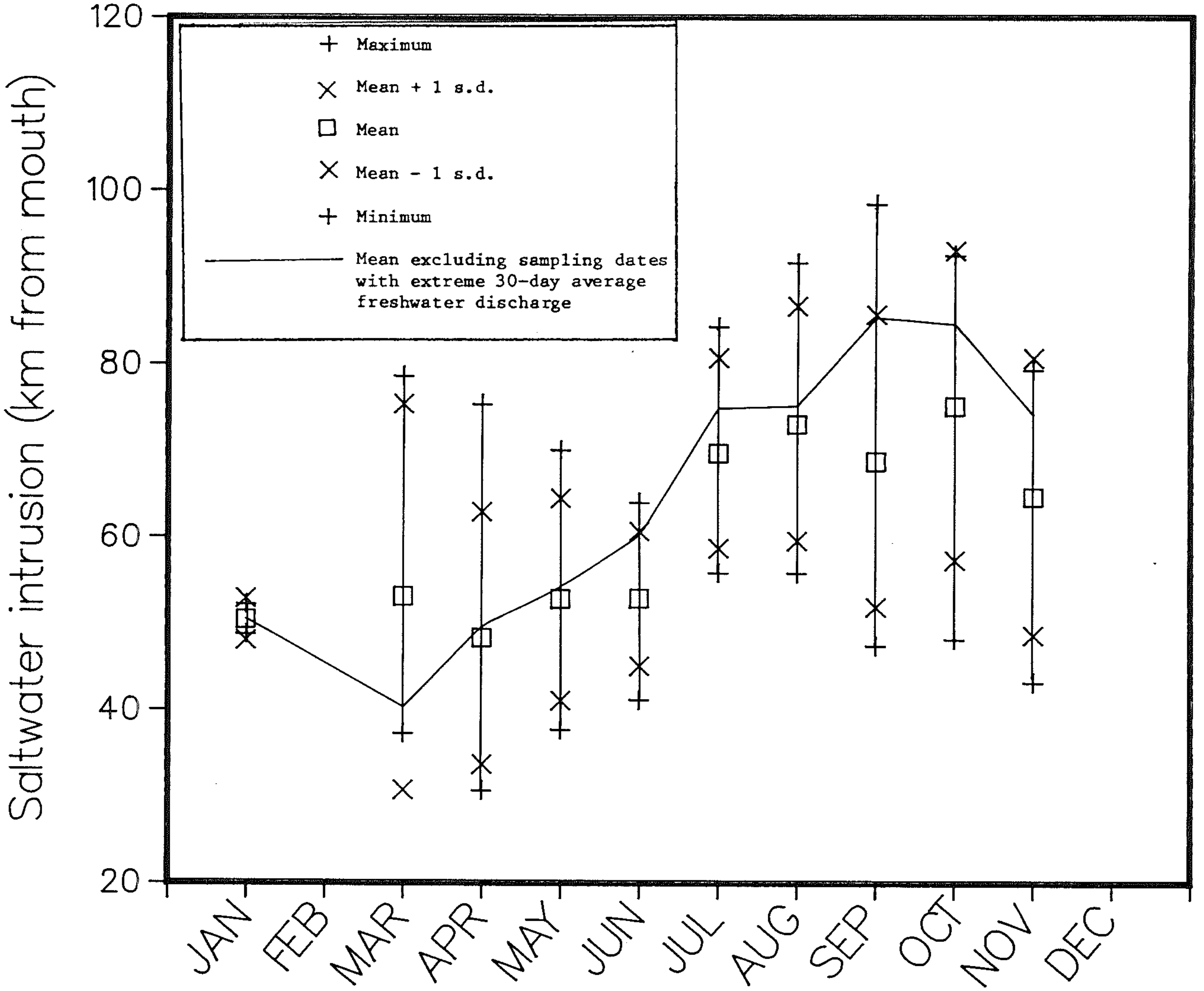


Figure 45a. Seasonal variation in distance of saltwater intrusion at slack before flood tide for bottom fresh/salt boundary = 1.0 ppt.

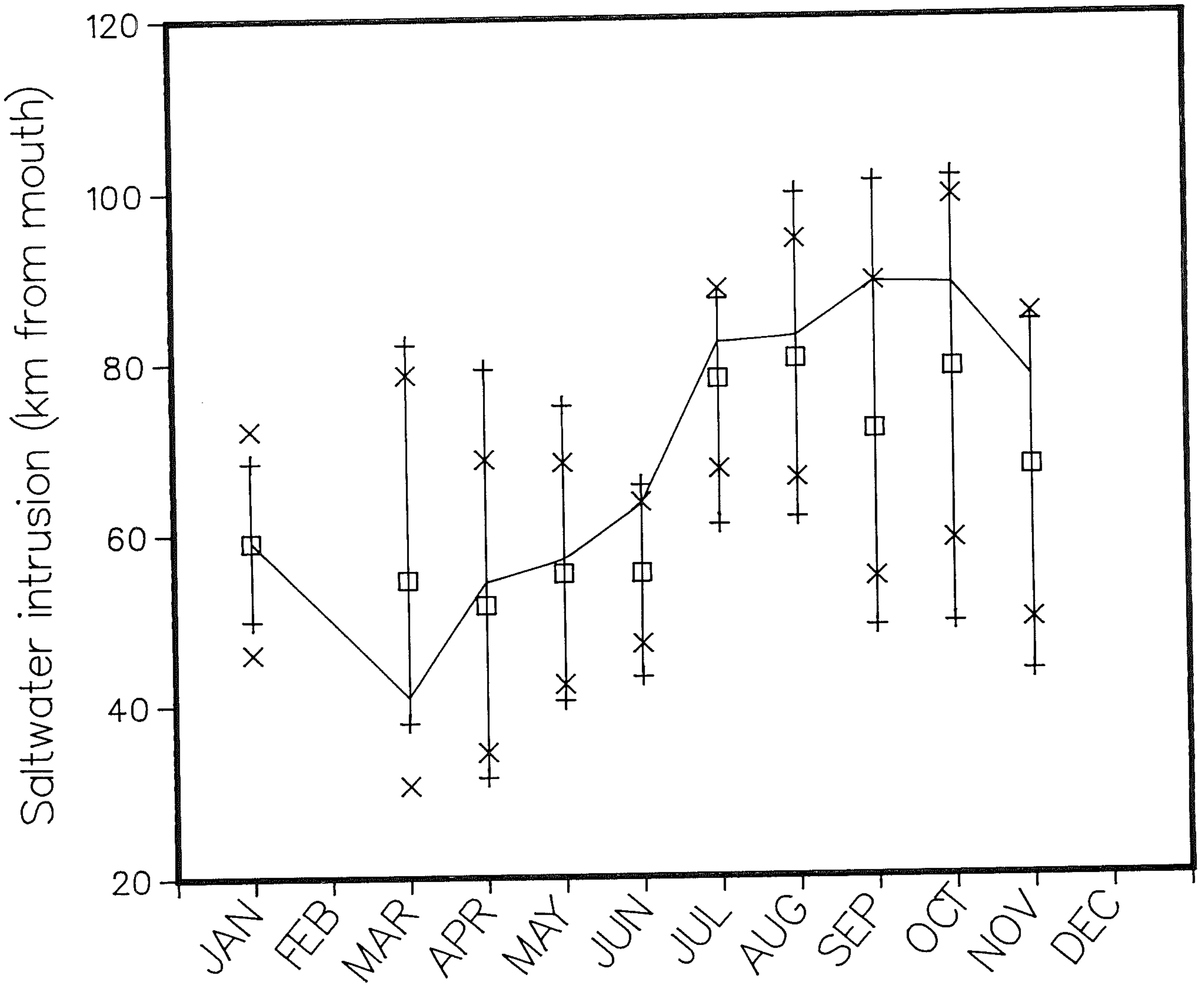


Figure 45b. Seasonal variation in distance of saltwater intrusion at slack before flood tide for bottom fresh/salt boundary = 0.5 ppt (key as in figure 45a).

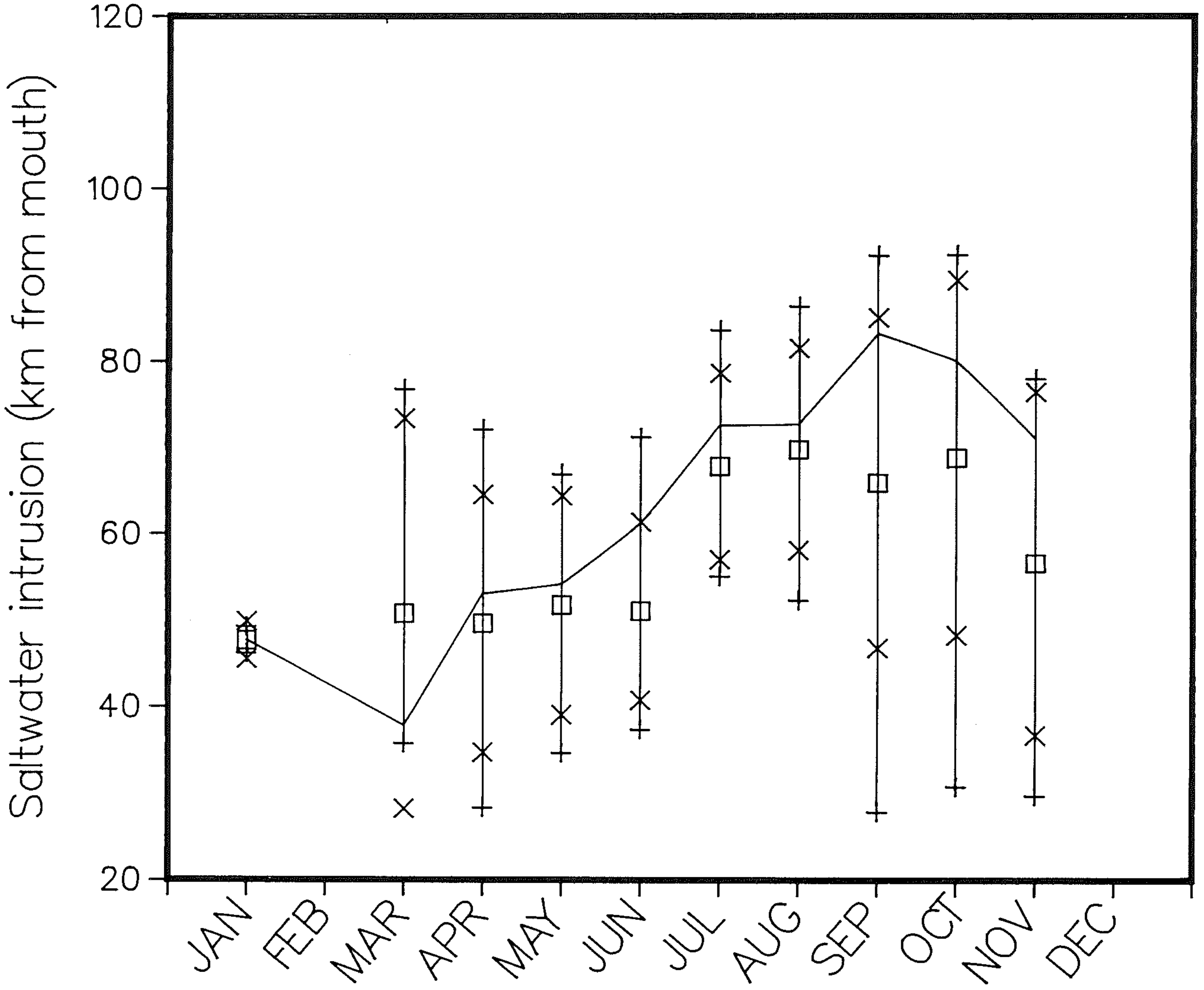


Figure 45c. Seasonal variation in distance of saltwater intrusion at slack before flood tide for surface fresh/salt boundary = 1.0 ppt (key as in figure 45a).

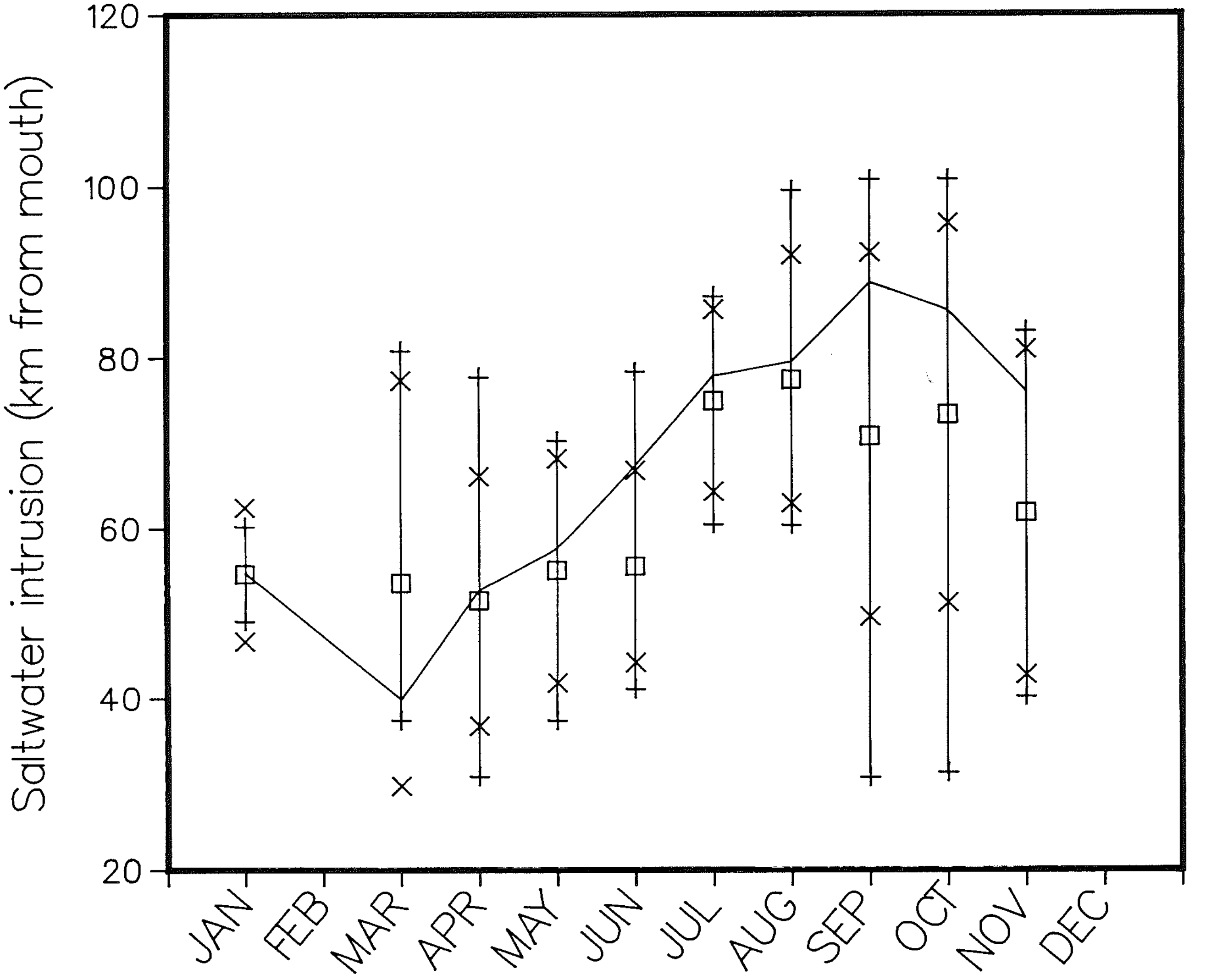


Figure 45d. Seasonal variation in distance of saltwater intrusion at slack before flood tide for surface fresh/salt boundary = 0.5 ppt (key as in figure 45a).

estuary averages about 5 cm^2/sec, which provides mixing for a 10 m water column in a time scale of two to three days. Therefore the vertical salinity structure in the James River could vary from day to day (i.e., more variable than the longitudinal pattern).

One method of quantifying vertical stratification is by the overall average vertical salinity gradient (i.e., the surface to bottom salinity difference divided by depth). For August 22, 1980 (neap tide condition), the average salinity gradient at slack before flood was 0.22 ppt/meter; at slack before ebb the average gradient was 0.18 ppt/meter (Figure 46). For August 27, 1980 (spring tide condition), the average gradient was 0.06 ppt/meter at slack before flood and 0.07 ppt/meter at slack before ebb. Salinity gradients did not appear to vary significantly over the flood/ebb cycle, but did vary over the spring/neap cycle. This observation is consistent with Haas' (1977) observations that vertical homogeneity in salinity was associated with spring tides, and stratification was associated with other phases of the spring/neap cycle in the York River estuary.

Figures 47 to 58 present the average vertical gradients for each month of the year as a function of the distance along the river. It appears that the gradient was generally highest in the middle reach of the estuary and decreased with distance both upstream and downstream. The overall vertical salinity gradients for each station with a complete record over the monitoring period were plotted in figure 59. The stratification was strongest in the region between 20 to 40 km from the river mouth. This suggests that the two-layered estuarine circulation was strongest in this reach of the estuary.

Freshwater discharge is also expected to affect the vertical salinity

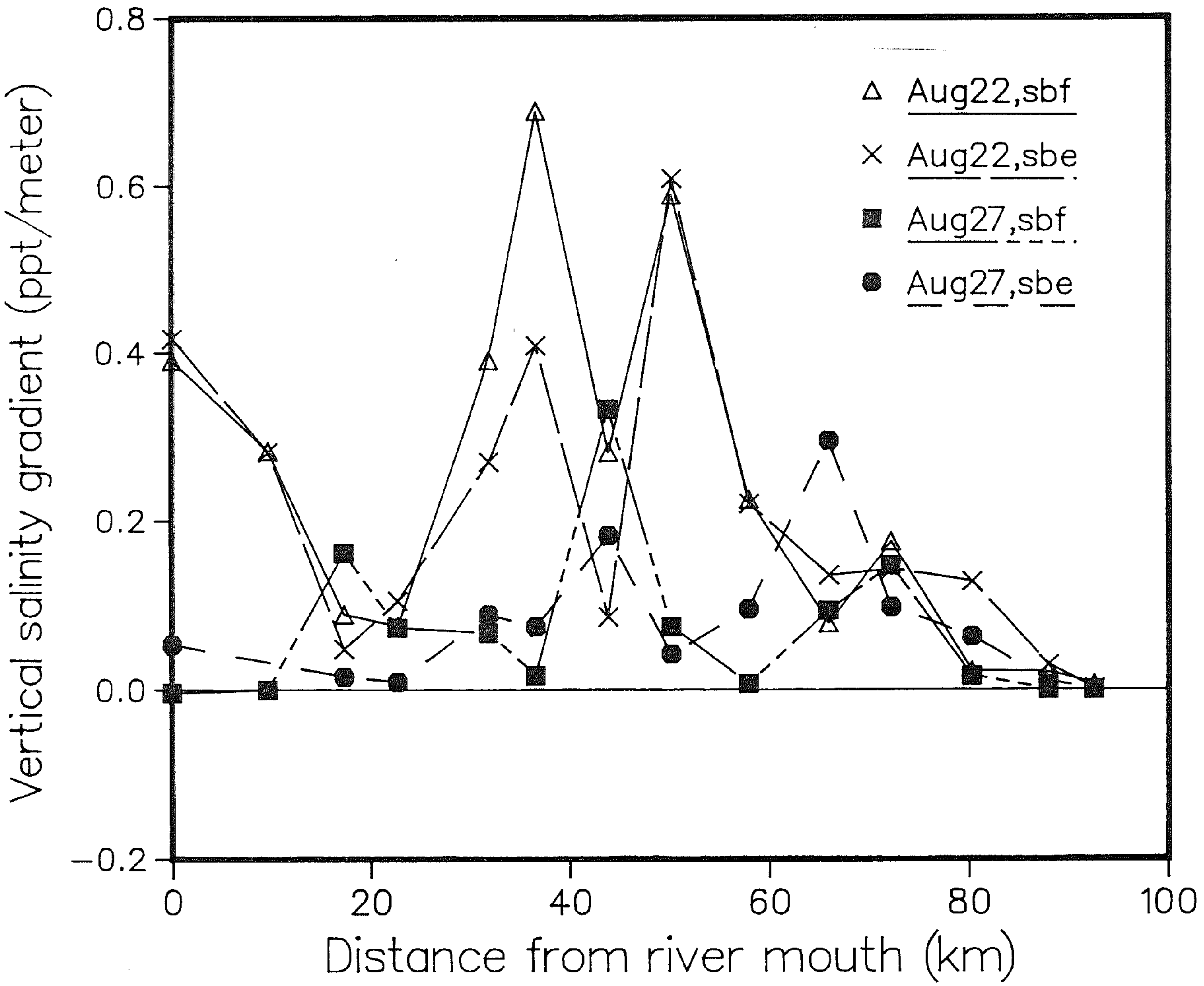


Figure 46. August 22 & 27, 1980 vertical salinity gradient with distance from river mouth by phase of tidal cycle.

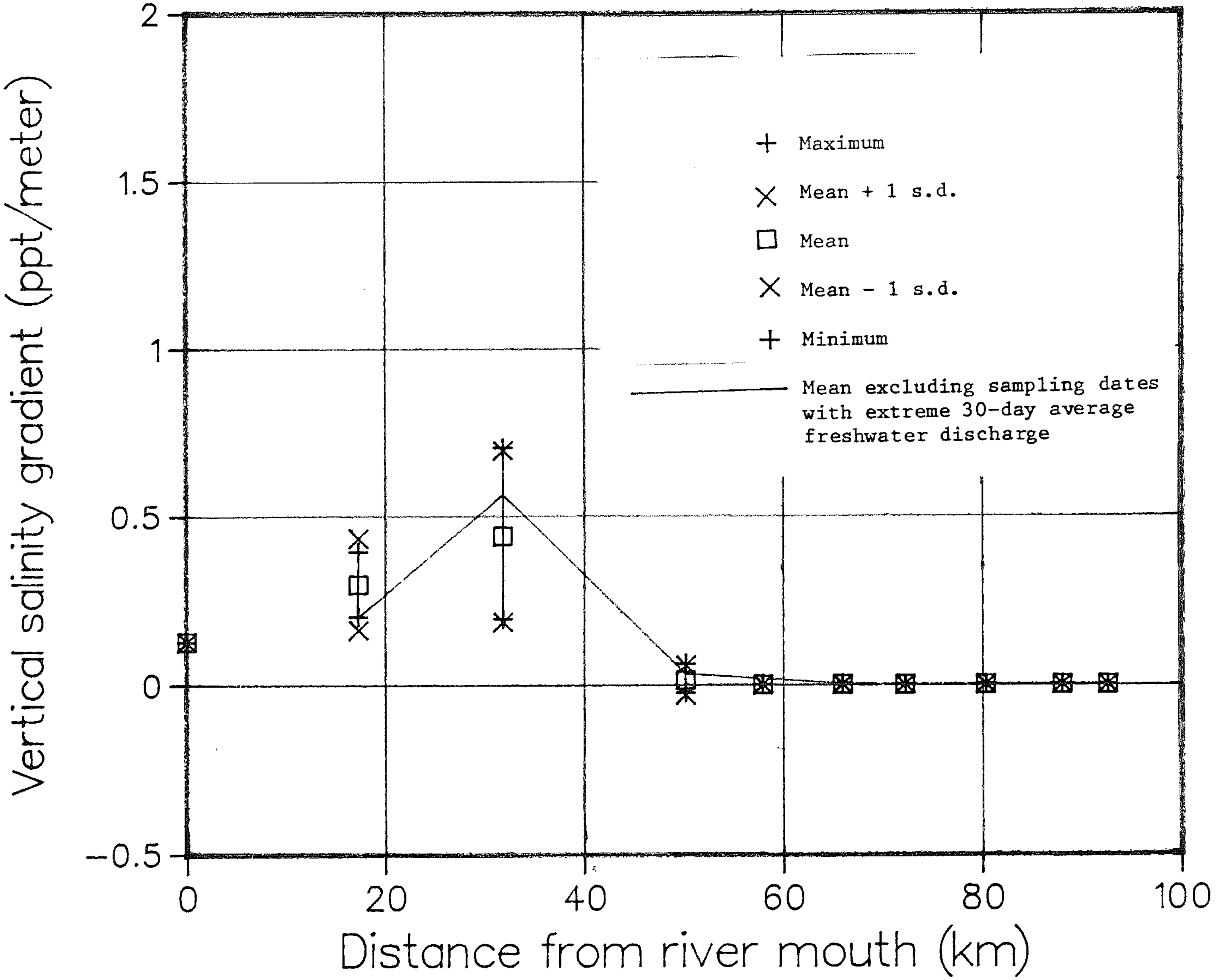


Figure 47. January vertical salinity gradient with distance from river mouth.

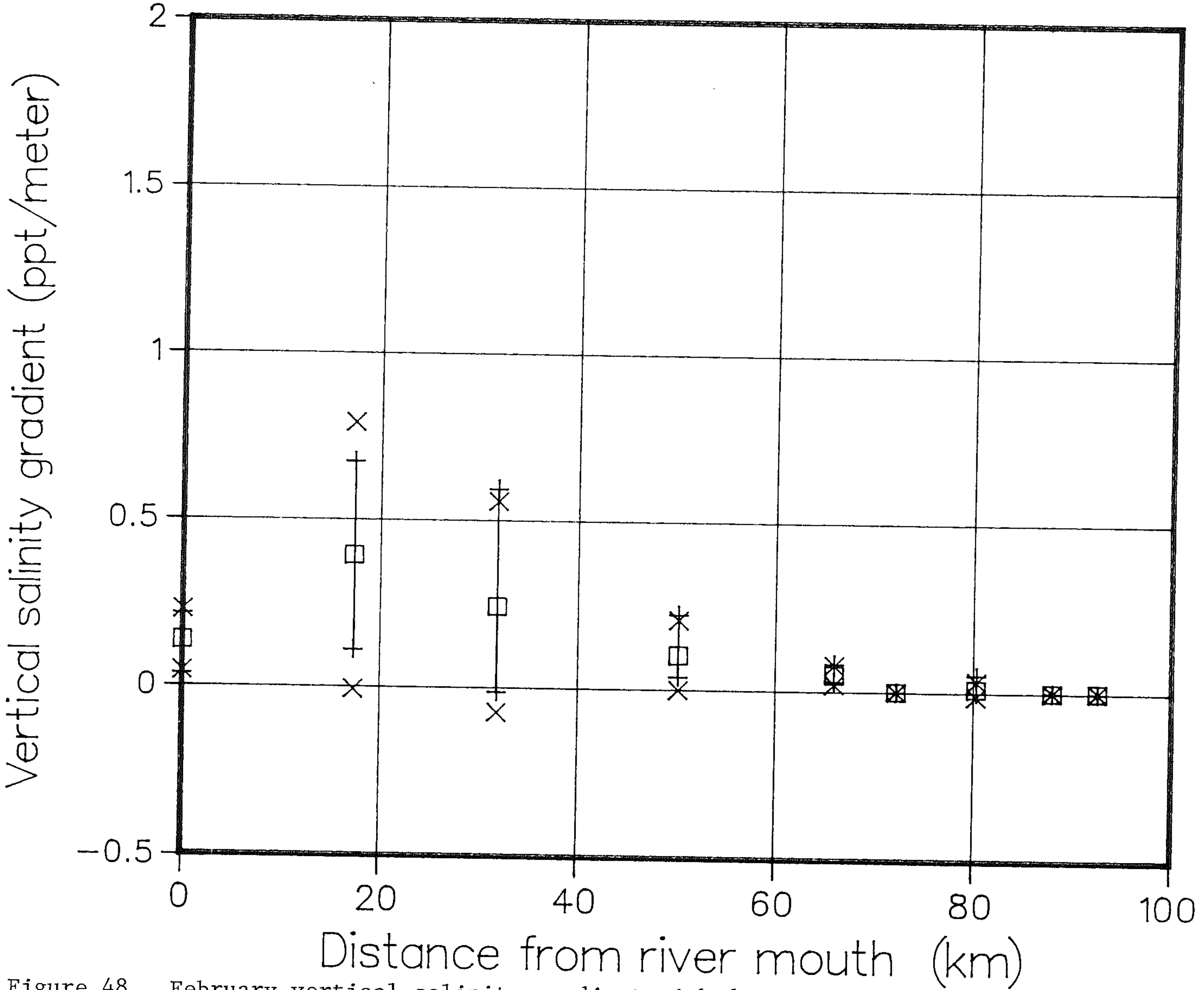


Figure 48. February vertical salinity gradient with distance from river mouth (key as in figure 47).

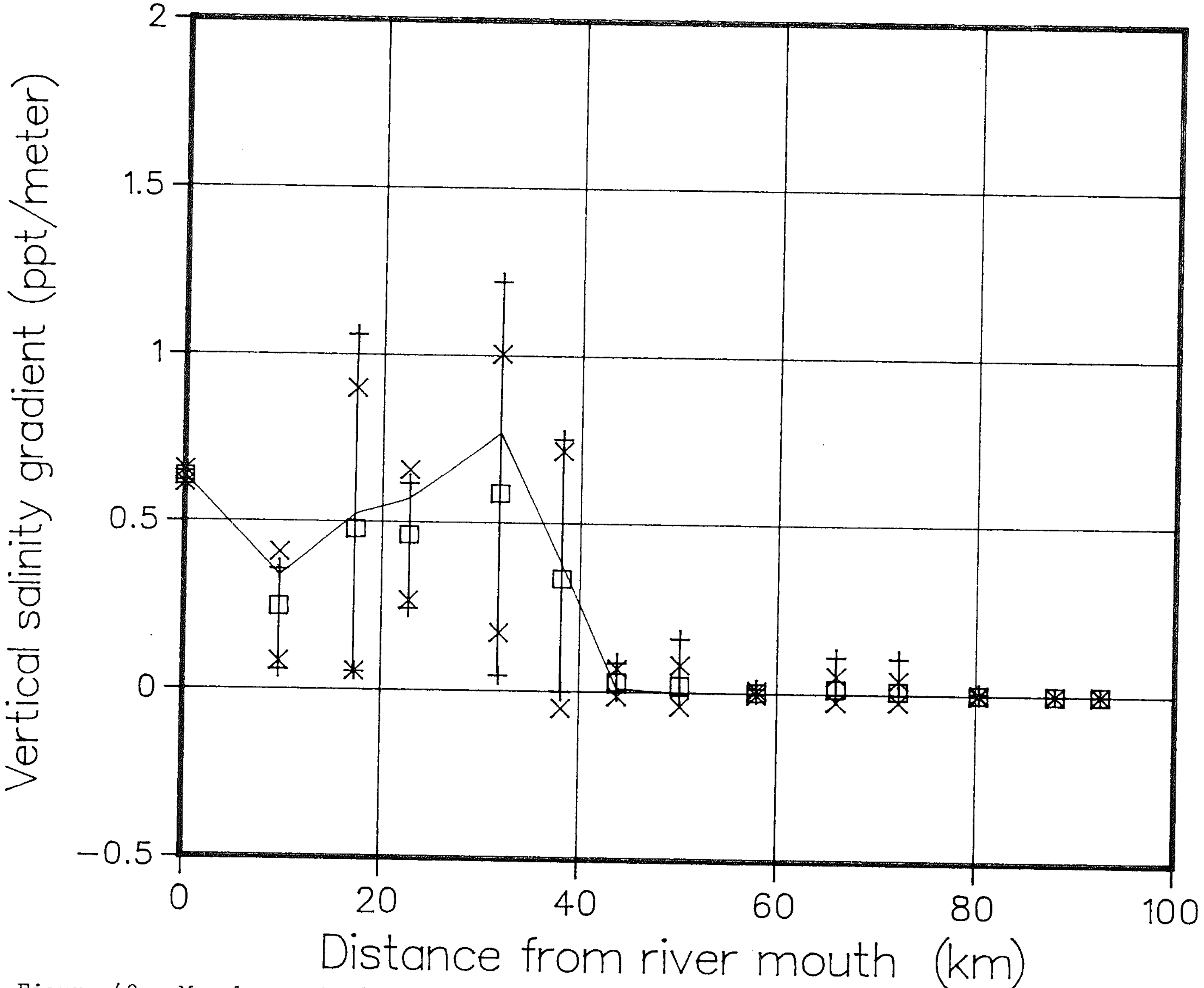


Figure 49. March vertical salinity gradient with distance from river mouth (key as in figure 47).

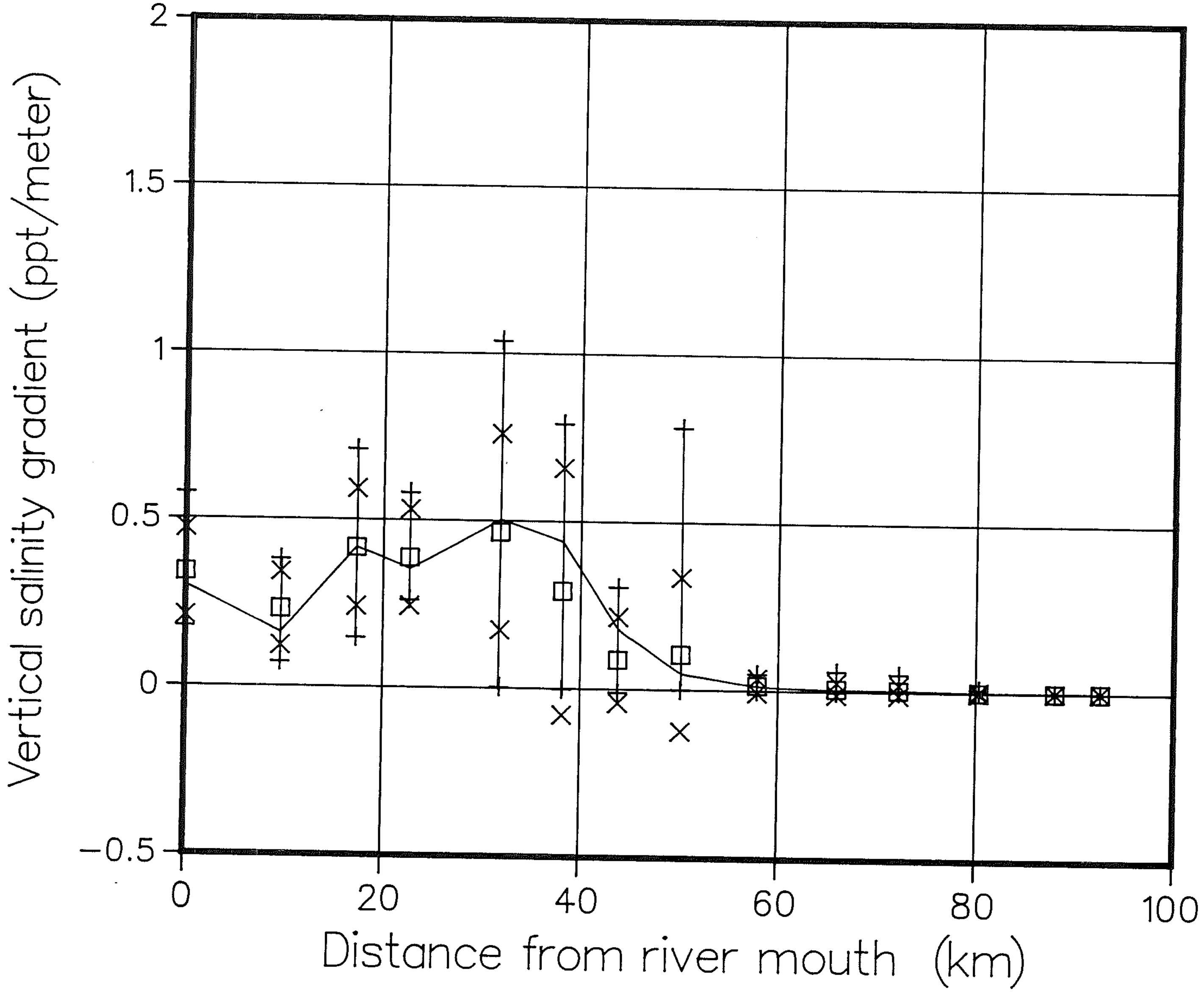


Figure 50. April vertical salinity gradient with distance from river mouth (key as in figure 47).

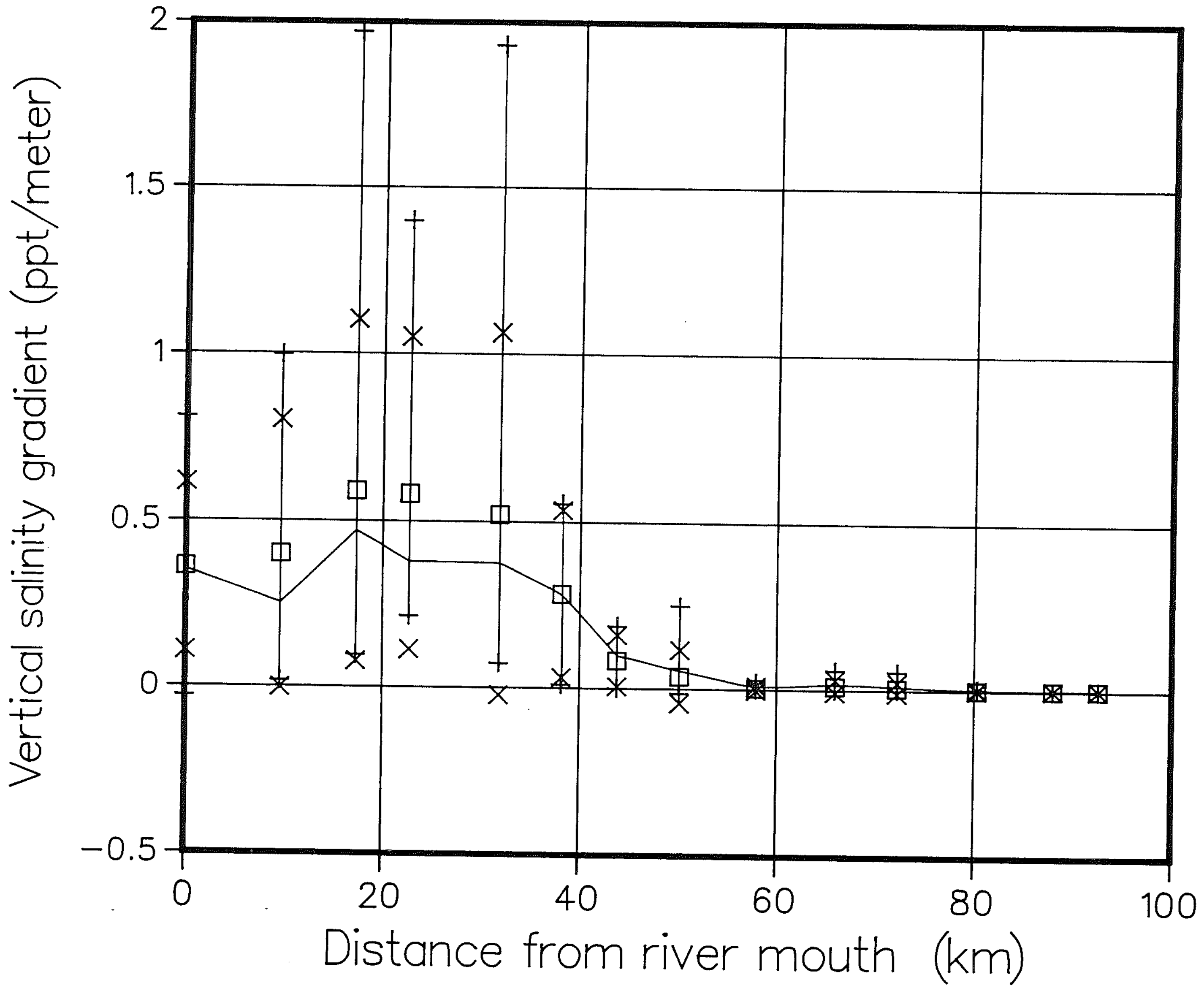


Figure 51. May vertical salinity gradient with distance from river mouth(key as in figure 47).

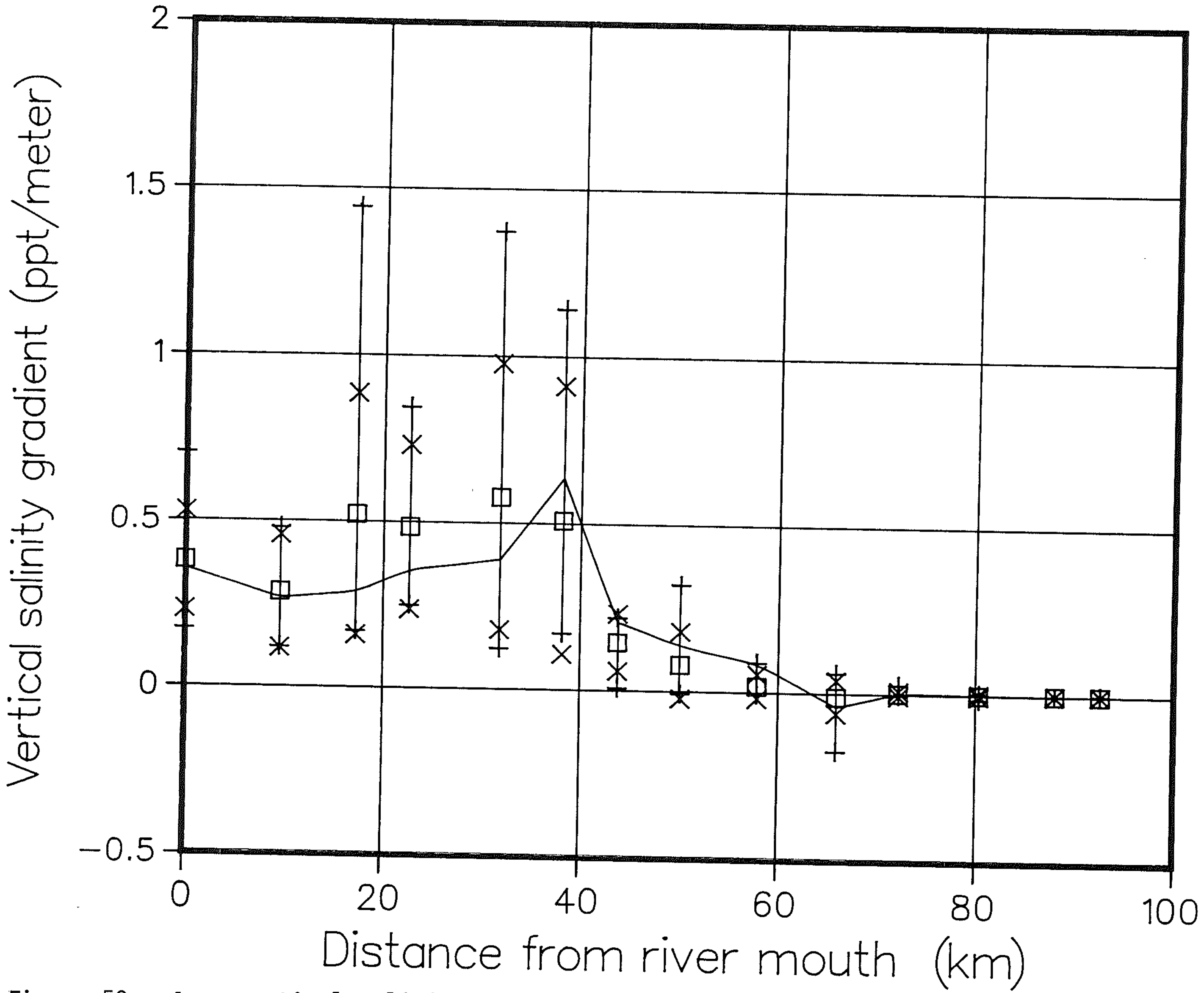


Figure 52. June vertical salinity gradient with distance from river mouth (key as in figure 47).

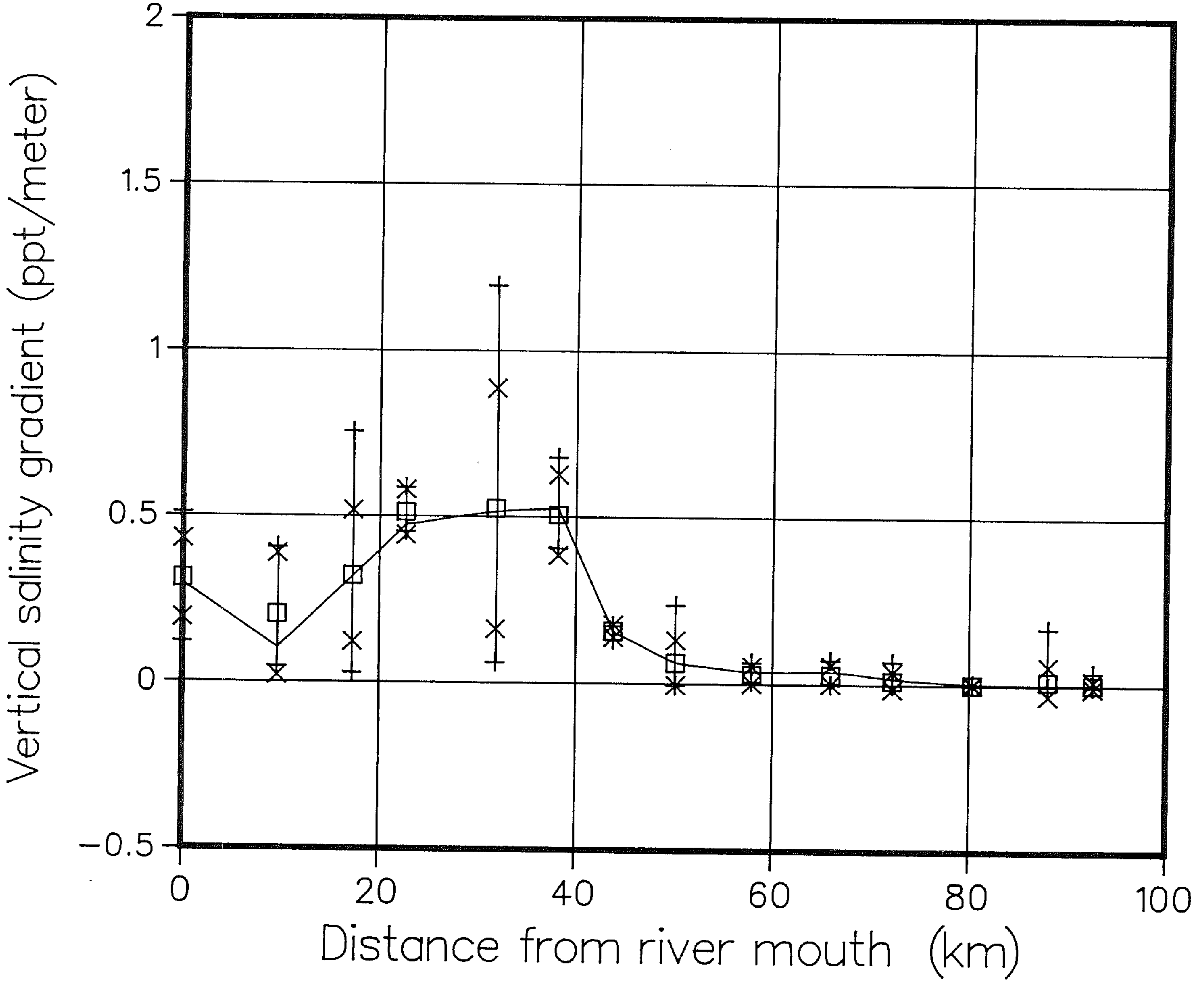


Figure 53. July vertical salinity gradient with distance from river mouth (key as in figure 47).

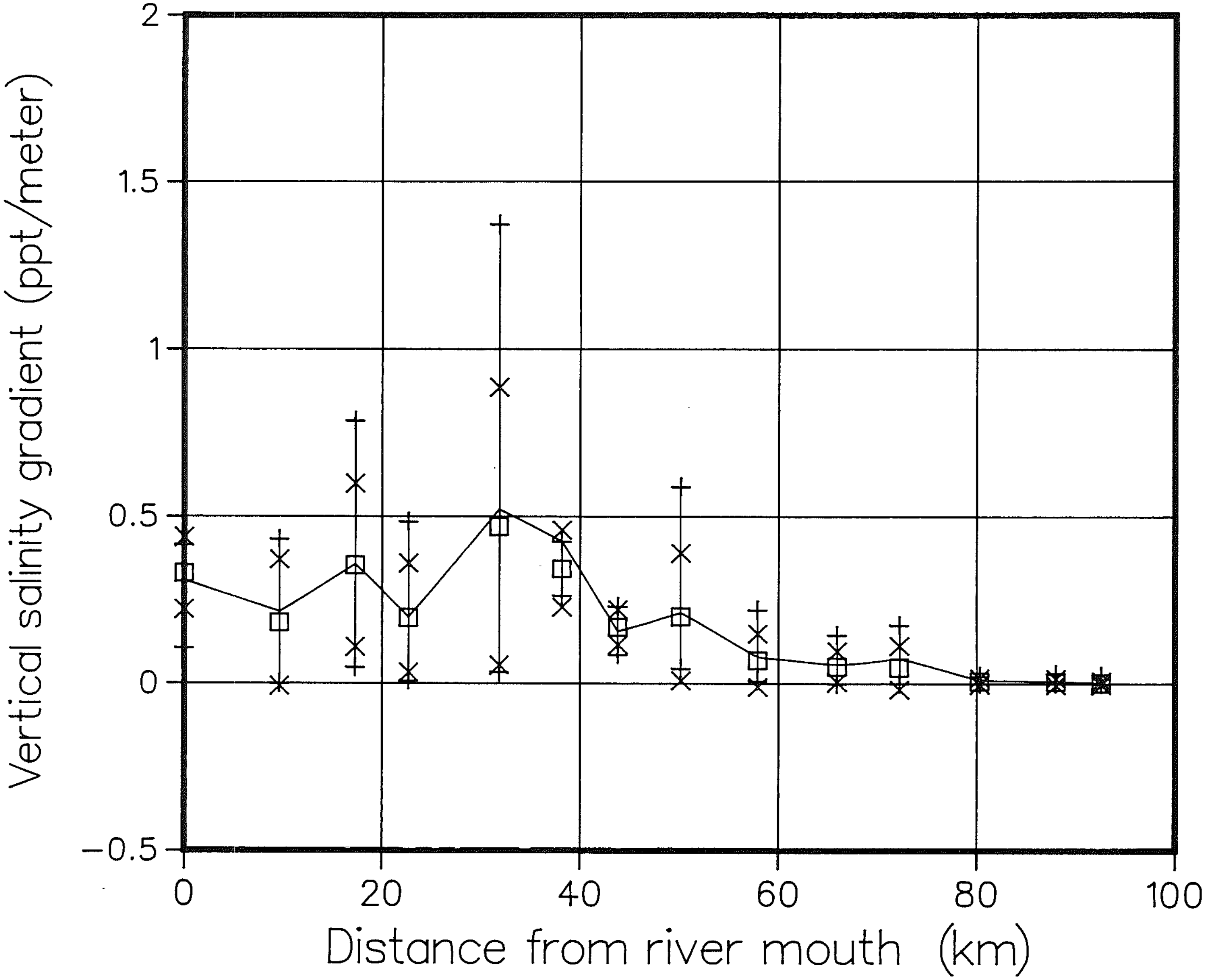


Figure 54. August vertical salinity gradient with distance from river mouth (key as in figure 47).

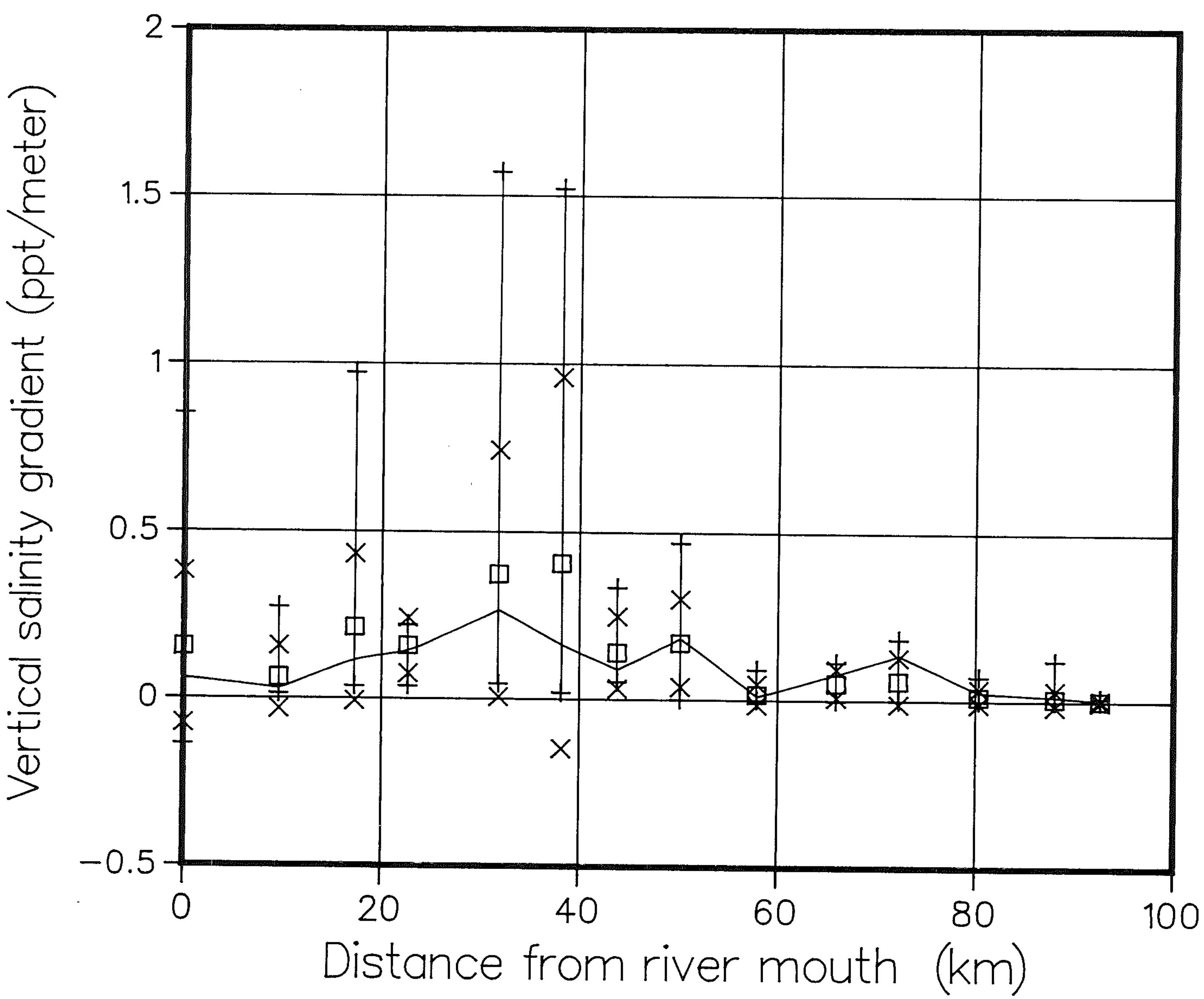


Figure 55. September vertical salinity gradient with distance from river mouth (key as in figure 47).

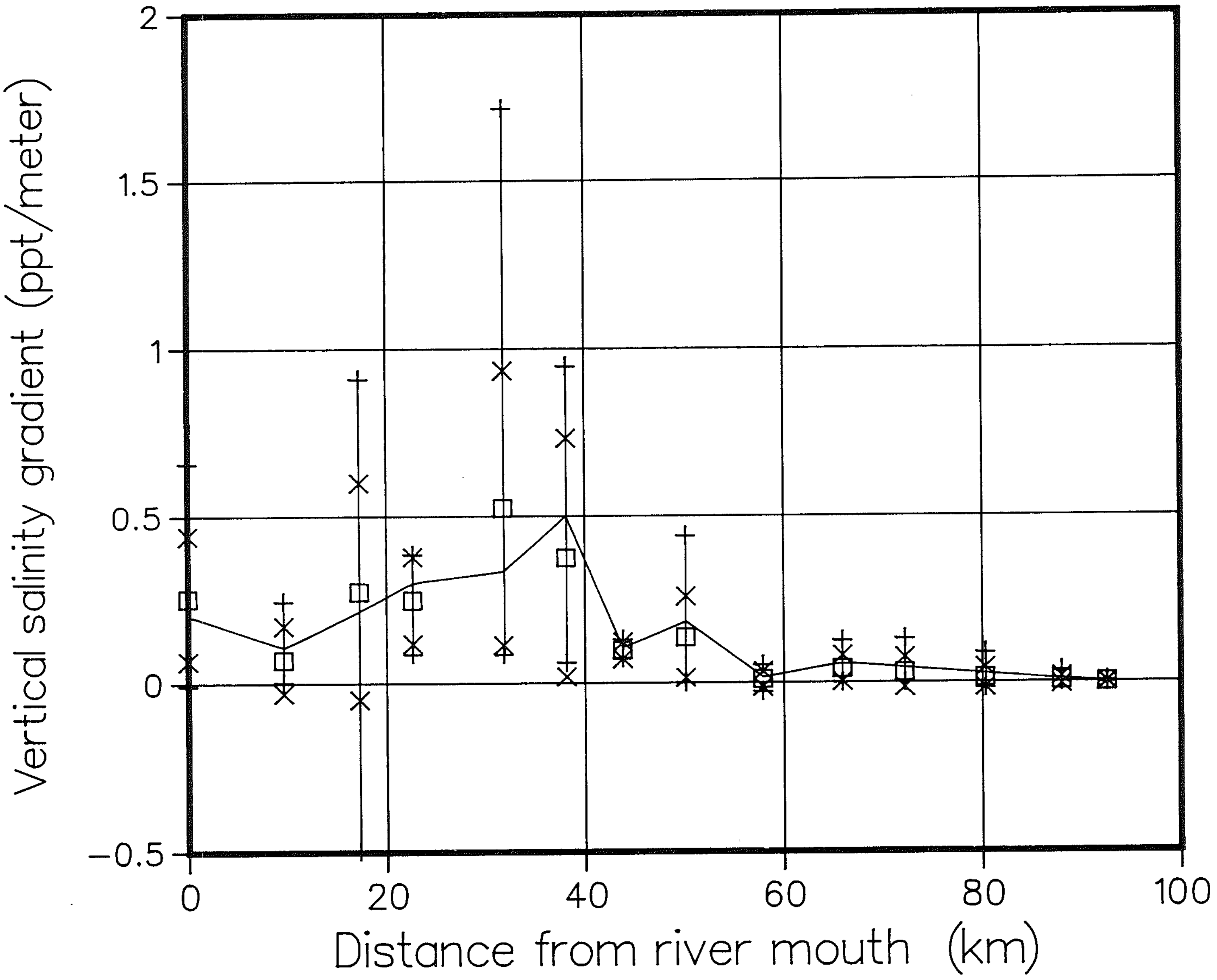


Figure 56. October vertical salinity gradient with distance from river mouth (key as in figure 47).

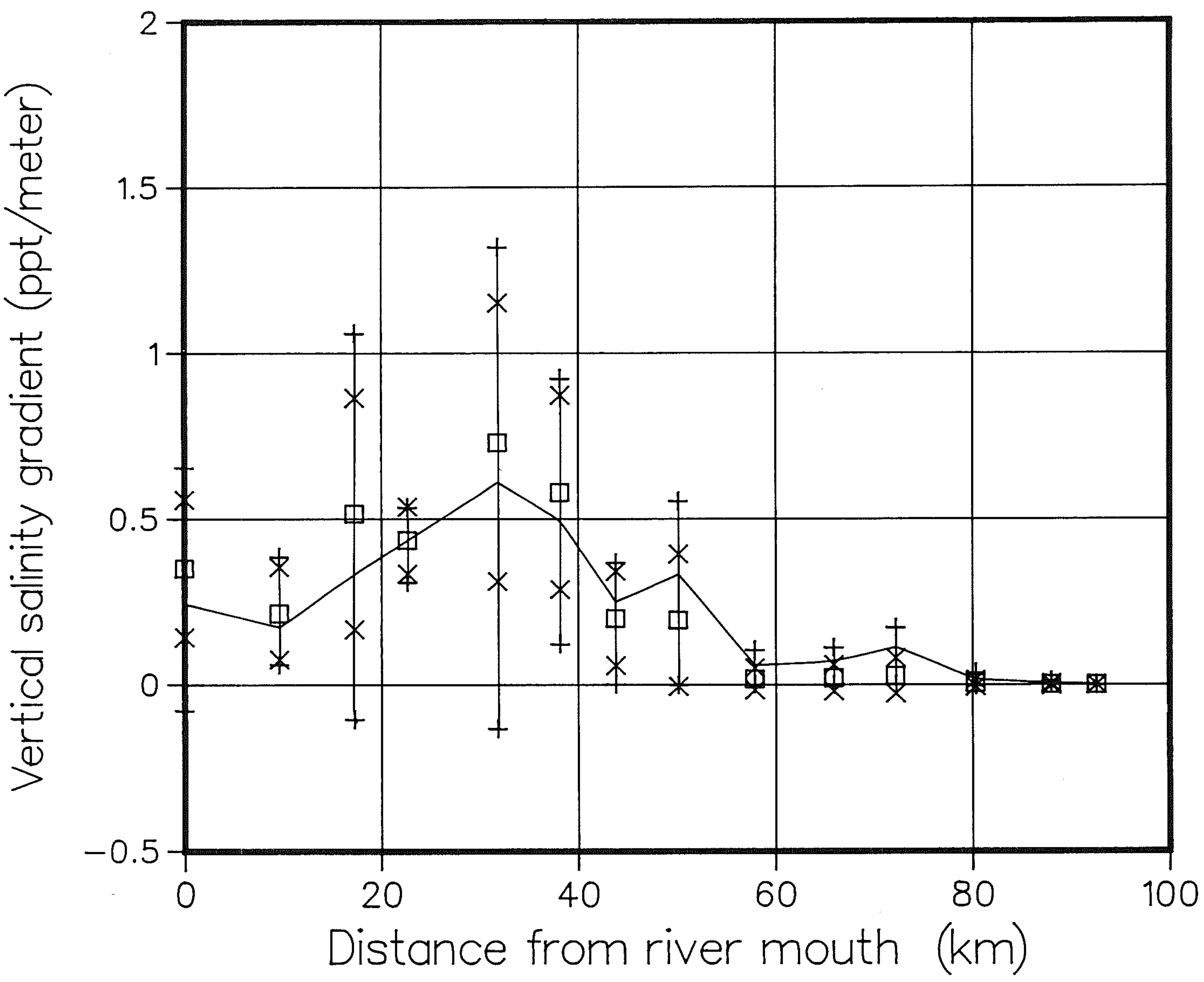


Figure 57. November vertical salinity gradient with distance from river mouth (key as in figure 47).

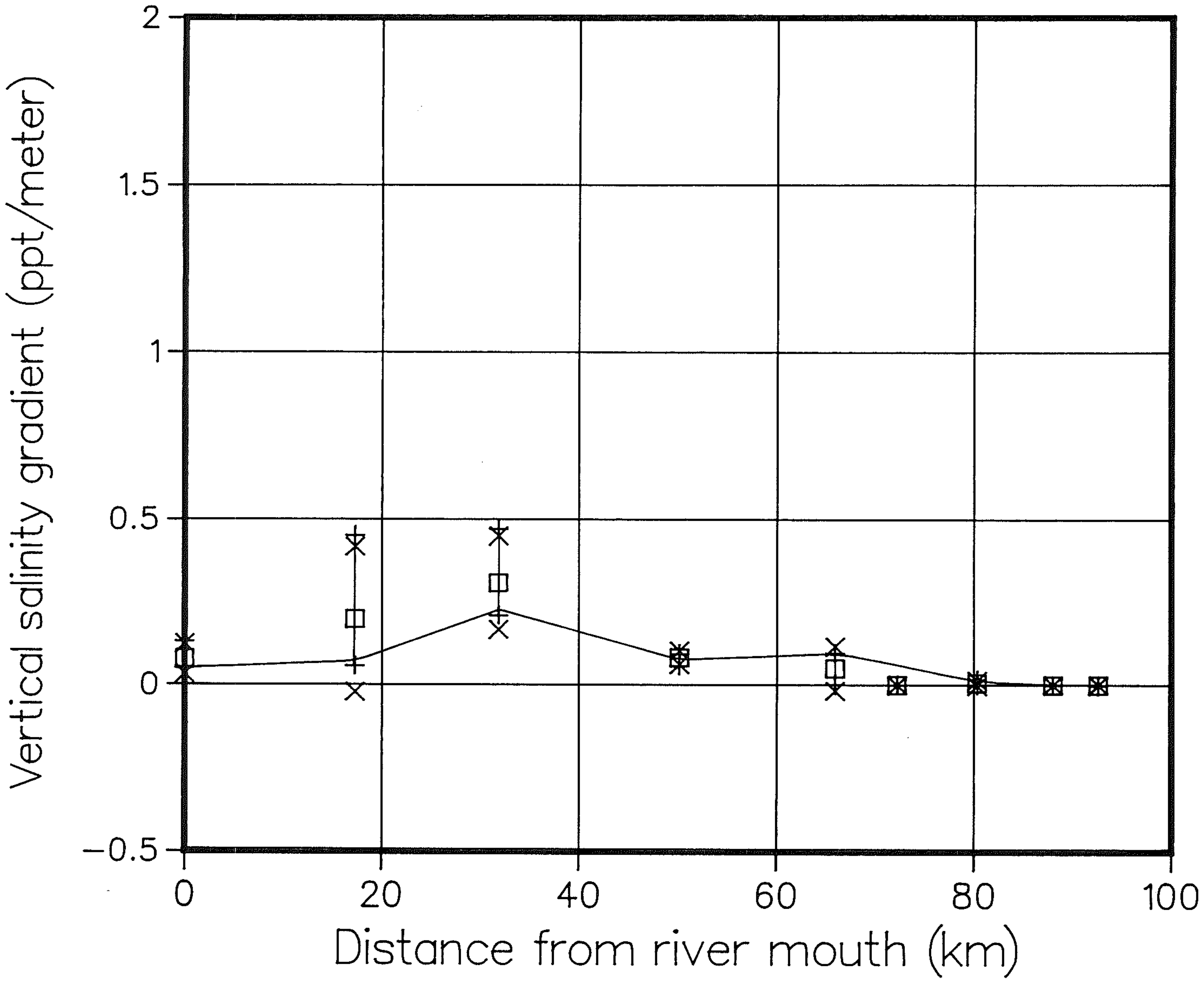


Figure 58. December vertical salinity gradient with distance from river mouth (key as in figure 47).

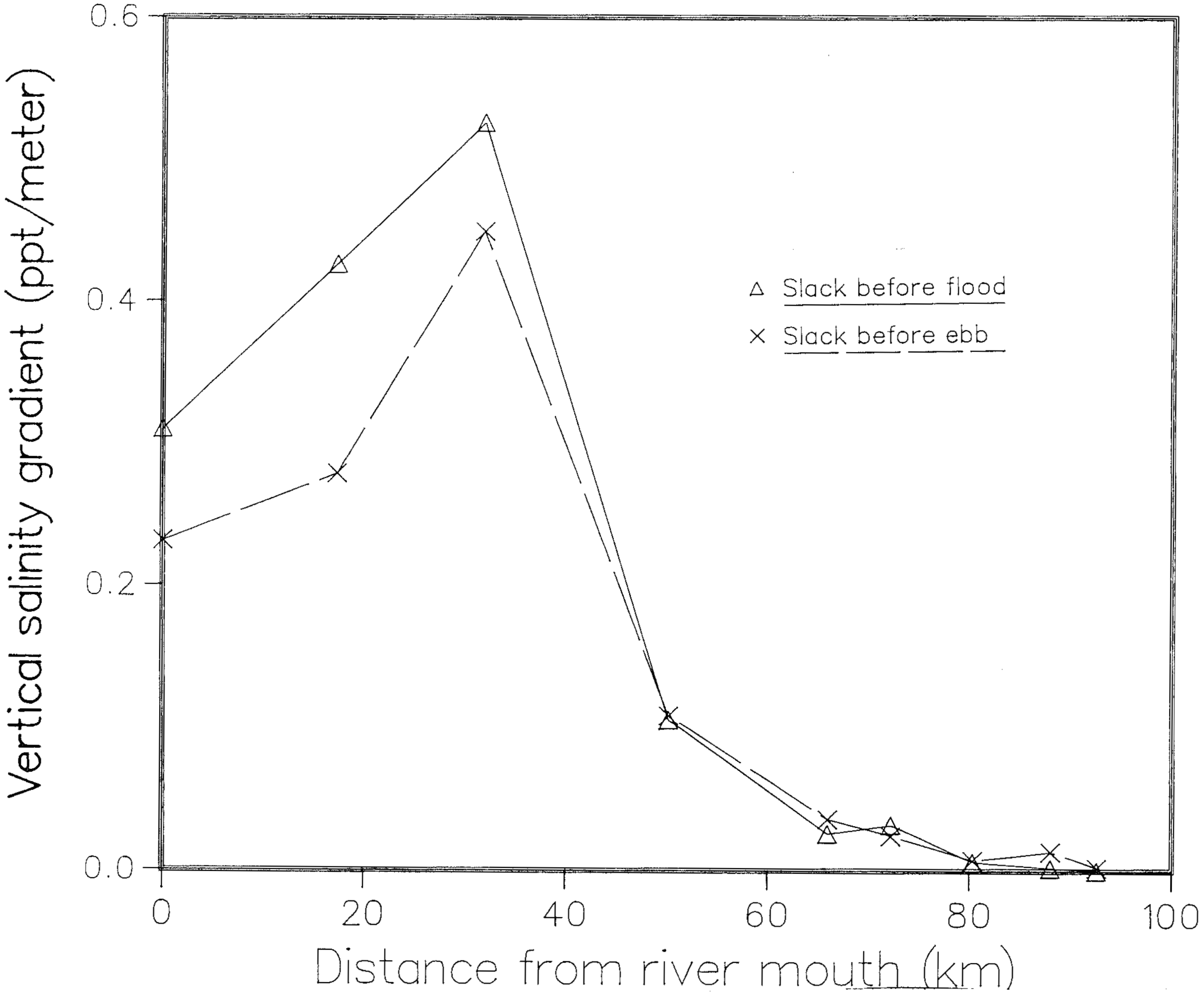
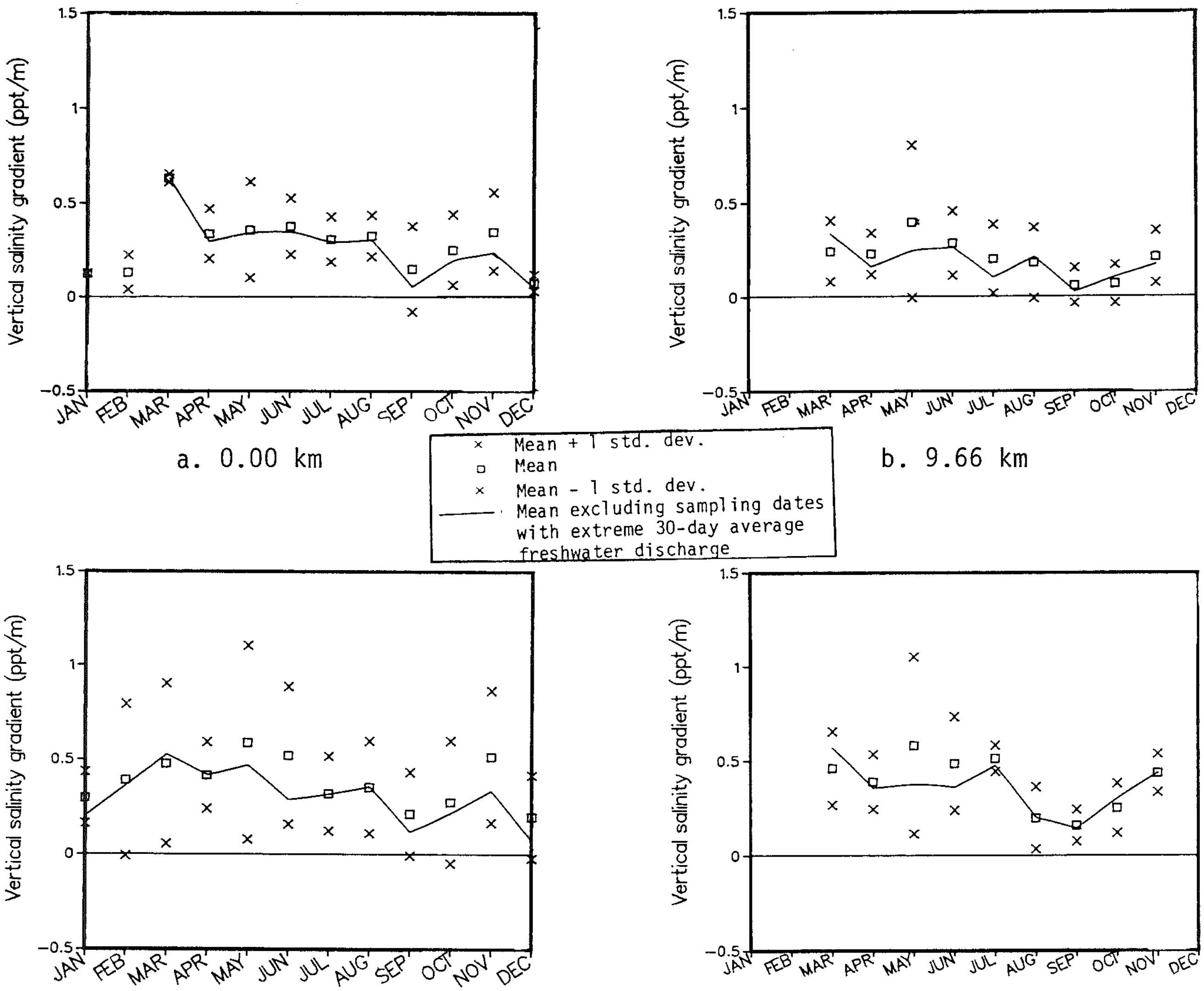


Figure 59. Vertical salinity gradient with distance from river mouth by phase of tidal cycle for stations monitored from 1971-1985.

structure, but a seasonal pattern is not evident in figures 47 to 58. Figures 60a to 60h show the variation in monthly averaged salinity gradients at selected stations. Also presented in the figures are the monthly average gradients excluding those surveys conducted when freshwater discharges were either higher than 150 percent or lower than 50 percent of long-term median of average monthly flows. The salinity gradients were smaller, by varying amounts, in August to October than in March to May in the lower portion of the estuary (Figures 60a to 60f). In the upper estuary (Figures 60g and 60h), salinity gradients were greatest during August to November. This reversed seasonal pattern in the upper estuary was due to greater intrusion of saltwater into this portion of the estuary in drier months.

V. Statistical Regressions on Freshwater Discharge

As discussed in the previous sections, the freshwater discharge is an important factor controlling the salinity level in the James River estuary. Furthermore, the design of the slackwater surveys was such that the data set is more suitable for demonstrating the effect of the seasonally-varying freshwater discharge than that of the short-term tidal variations. The following statistical analyses relate freshwater discharge to those features of salinity distributions which are less affected by other factors. The freshwater discharges used in the analyses are the daily discharges measured in the James River near Richmond, with adjustment for diversion. Although factoring in additional discharges from the Appomattox, Chickahominy and other rivers would have led to a more accurate measure of total freshwater discharge, since the emphasis here was on seasonal trends in discharge which would have been similar for all rivers, the choice of just the Richmond



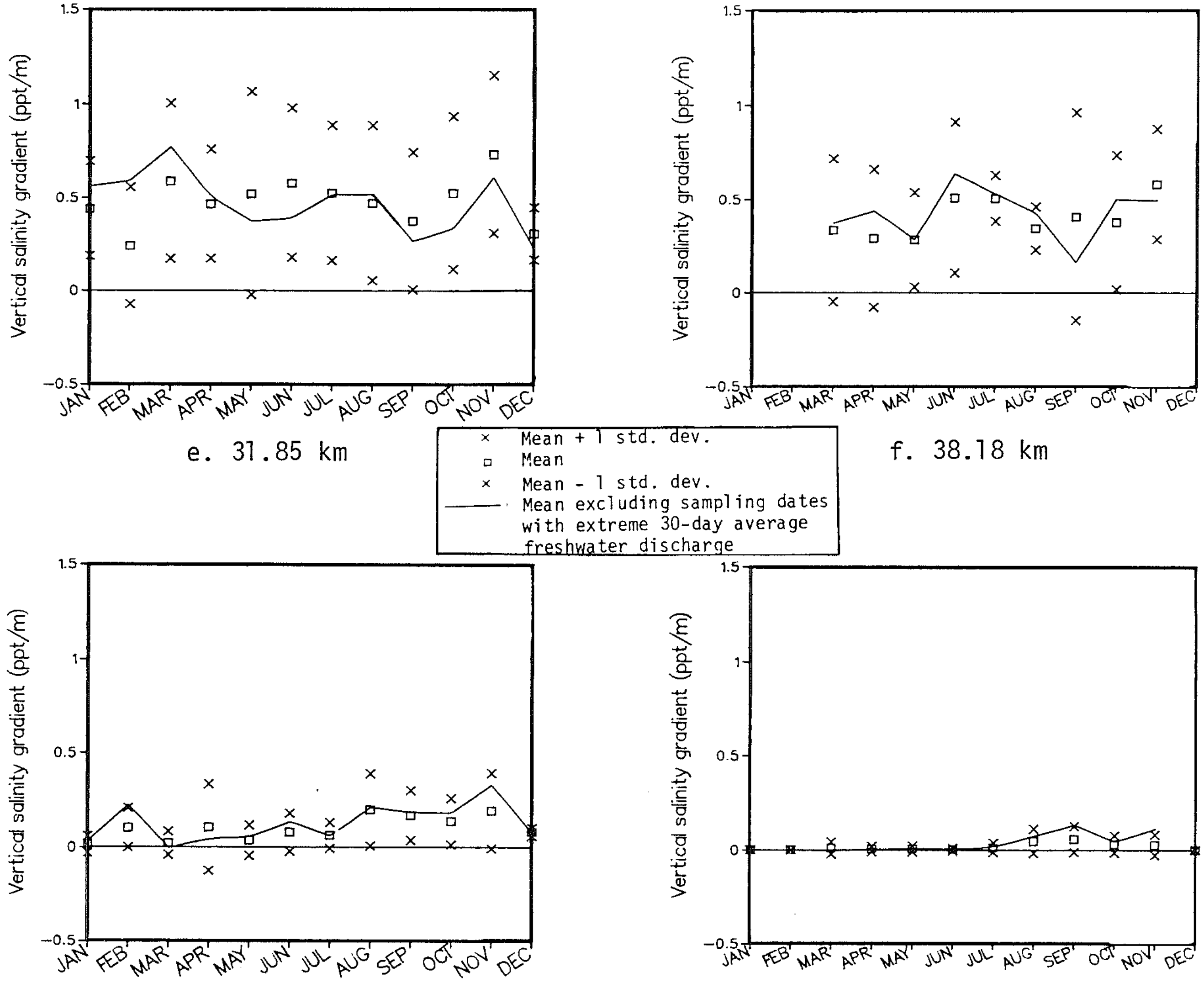
a. 0.00 km

b. 9.66 km

c. 17.3 km

d. 22.71 km

Figure 60. Seasonal variation in vertical salinity gradient.



e. 31.85 km

f. 38.18 km

g. 50.19 km

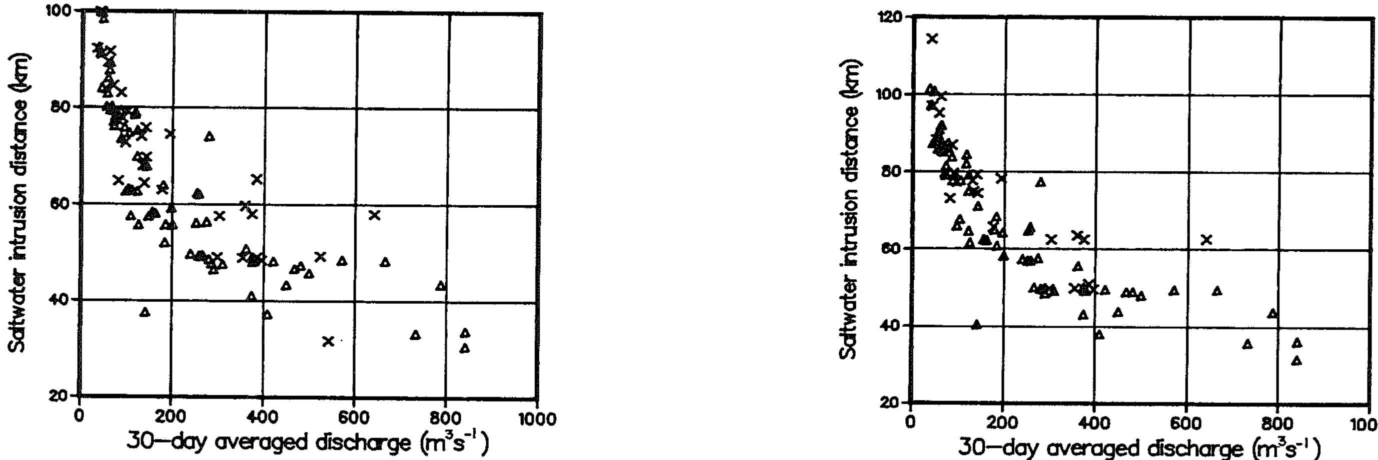
h. 72.21 km

Figure 60, continued. Seasonal variation in vertical salinity gradient.

discharge, which accounts for approximately 67 percent of the James River's total drainage area, seemed justified.

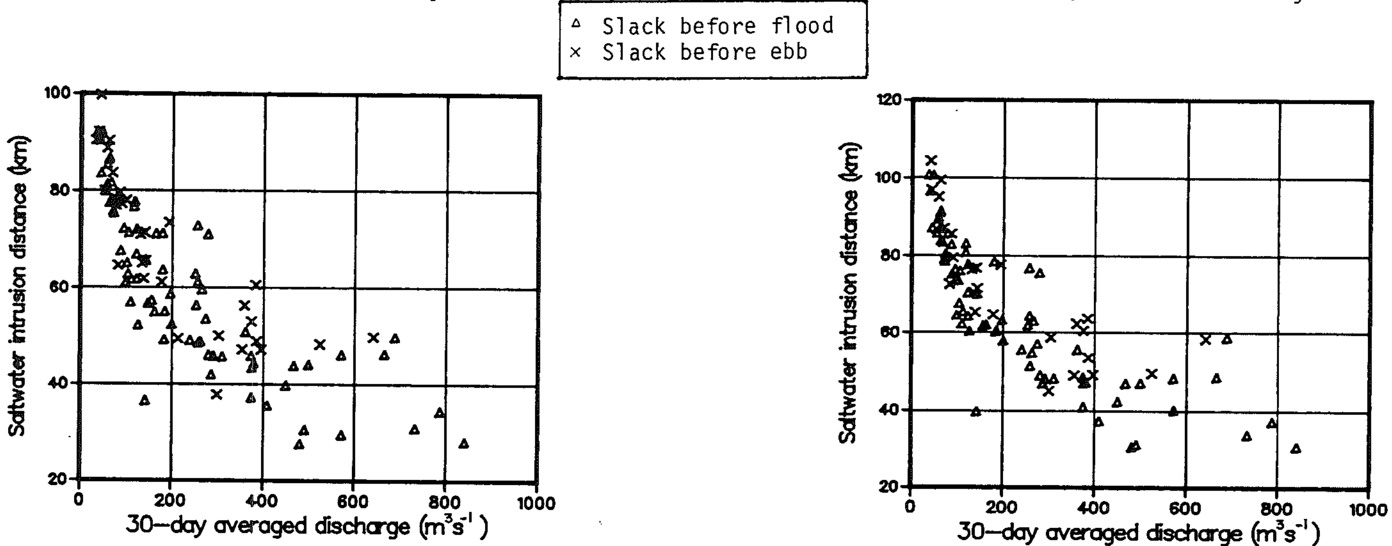
A. Limit of saltwater intrusion

Four sets of saltwater intrusion distances were calculated from field data using linear interpolation between data points (see discussion in Section III). Surface and bottom waters were treated separately with locations of 0.5 ppt and 1.0 ppt salinity defined as intrusion limit. In Figures 61a to 61d, the limit of saltwater intrusion for each sampling date was plotted against the average freshwater discharge for the 30 days preceding and including the sampling date. These plots show a generally negative but nonlinear relationship between the limit of saltwater intrusion and freshwater discharge (i.e., as freshwater discharge increased, the upstream extent of saltwater intrusion decreased). A log transformation of the average freshwater discharge produced a more linear relationship. Figures 62a to 62h show the distance of saltwater intrusion plotted against the log of 30-day average discharge and regression lines. Confidence intervals (95 percent) are also shown. If the regression line was used to predict a **specific** saltwater intrusion distance for a given discharge, one would be 95 percent confident that the saltwater intrusion distance would fall within the **wider** confidence interval shown on the figures. If the regression line was used to predict the **average** saltwater intrusion distance for a given discharge, one would be 95 percent confident that the average saltwater intrusion distance would fall within the **narrow** confidence interval shown on the figures. Table 10 presents the results of least squares linear regressions, which reveal that the regression model explained approximately 80 to 85 percent of the variance in saltwater intrusion



a. bottóm salt/fresh boundary = 1.0 ppt

b. bottom salt/fresh boundary = 0.5 ppt



c. surface salt/fresh boundary = 1.0 ppt

d. surface salt/fresh boundary = 0.5 ppt

Figure 61. Saltwater intrusion distance with 30-day averaged freshwater discharge.

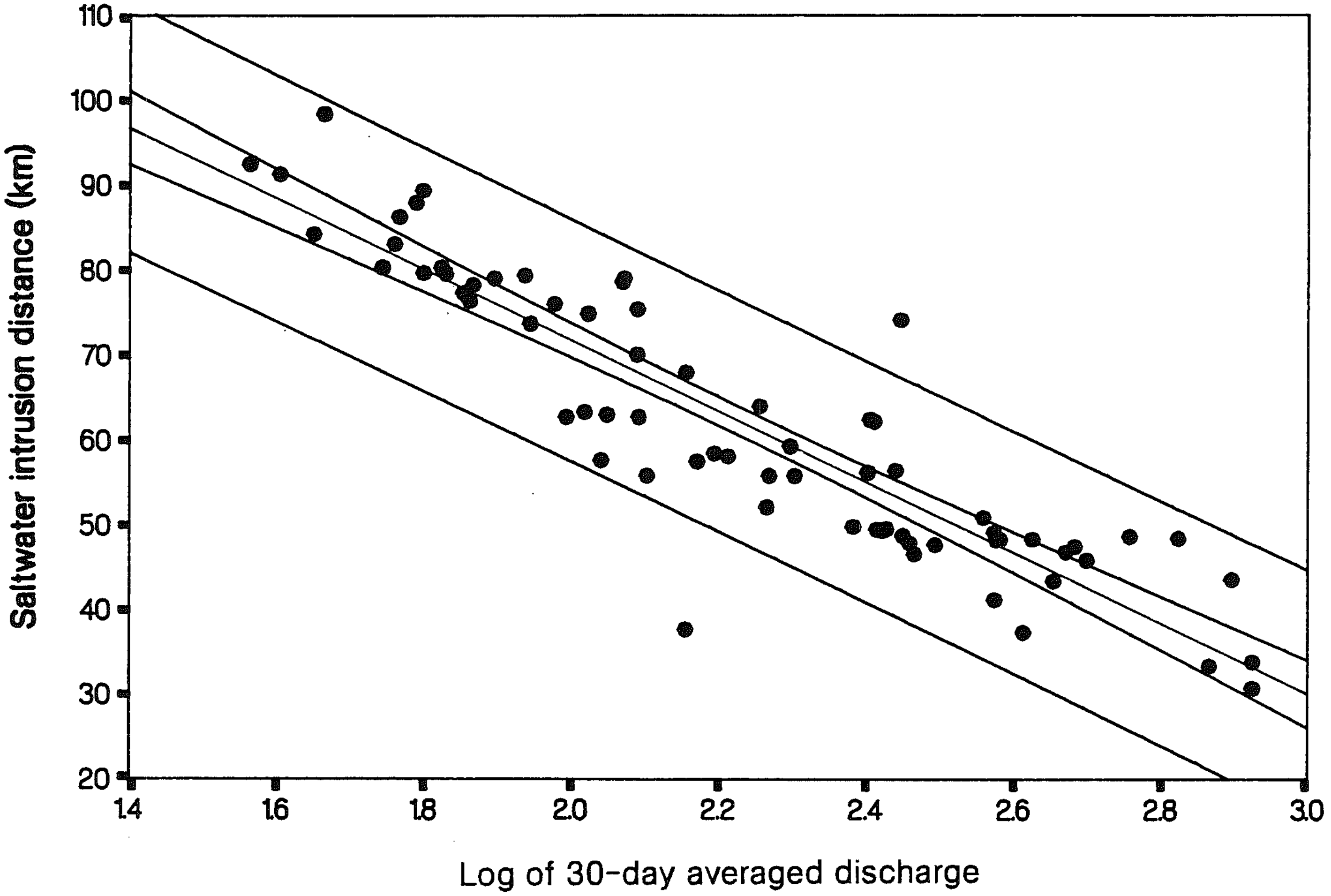


Figure 62a. Regression of saltwater intrusion distance on log of 30-day averaged discharge for bottom salt/fresh boundary = 1.0 ppt at slack before flood tide (95% confidence intervals for mean and specific saltwater intrusion distances).

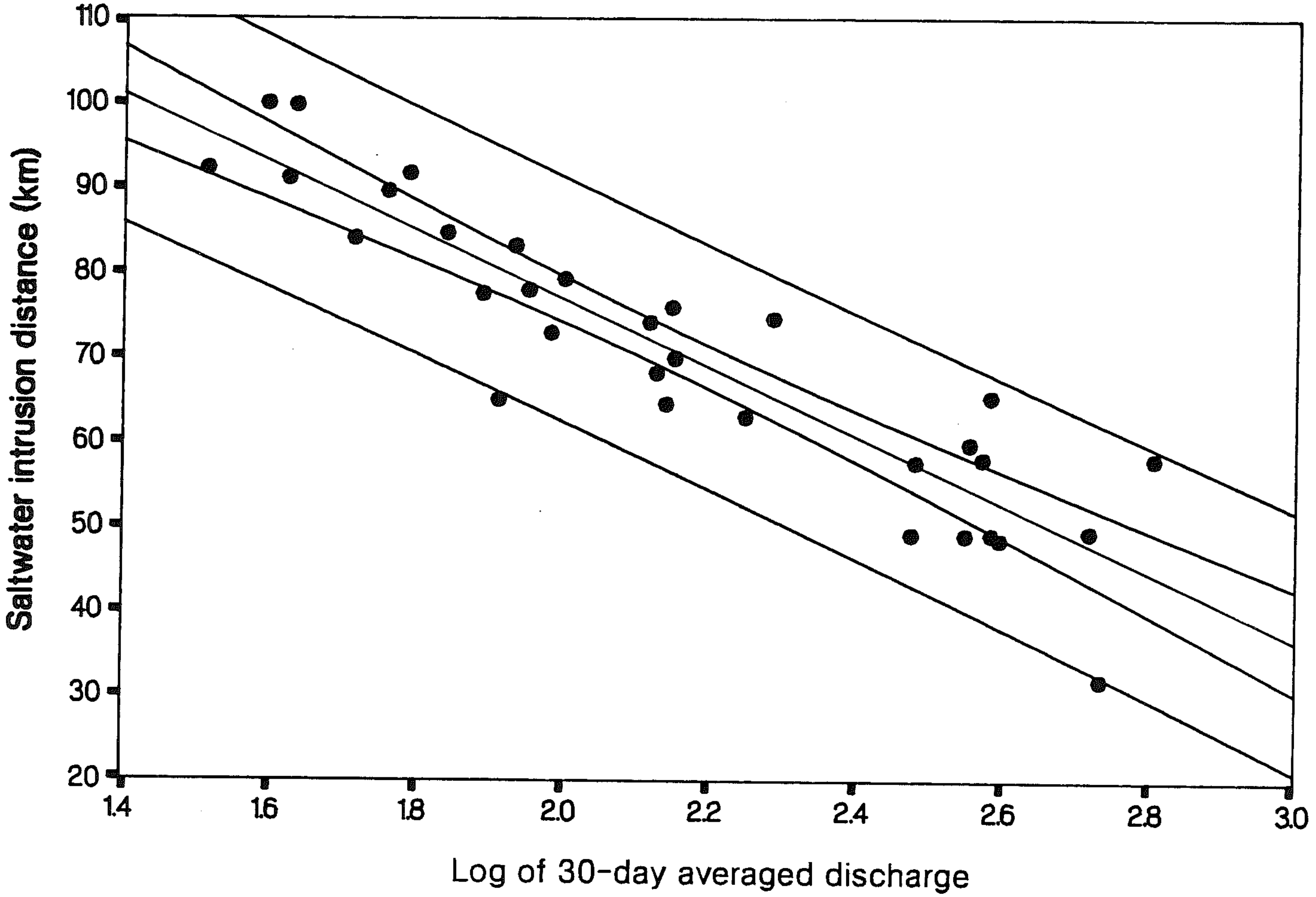


Figure 62b. Regression of saltwater intrusion distance on log of 30-day averaged discharge for bottom salt/fresh boundary = 1.0 ppt at slack before ebb tide (95% confidence intervals for mean and specific saltwater intrusion distances).

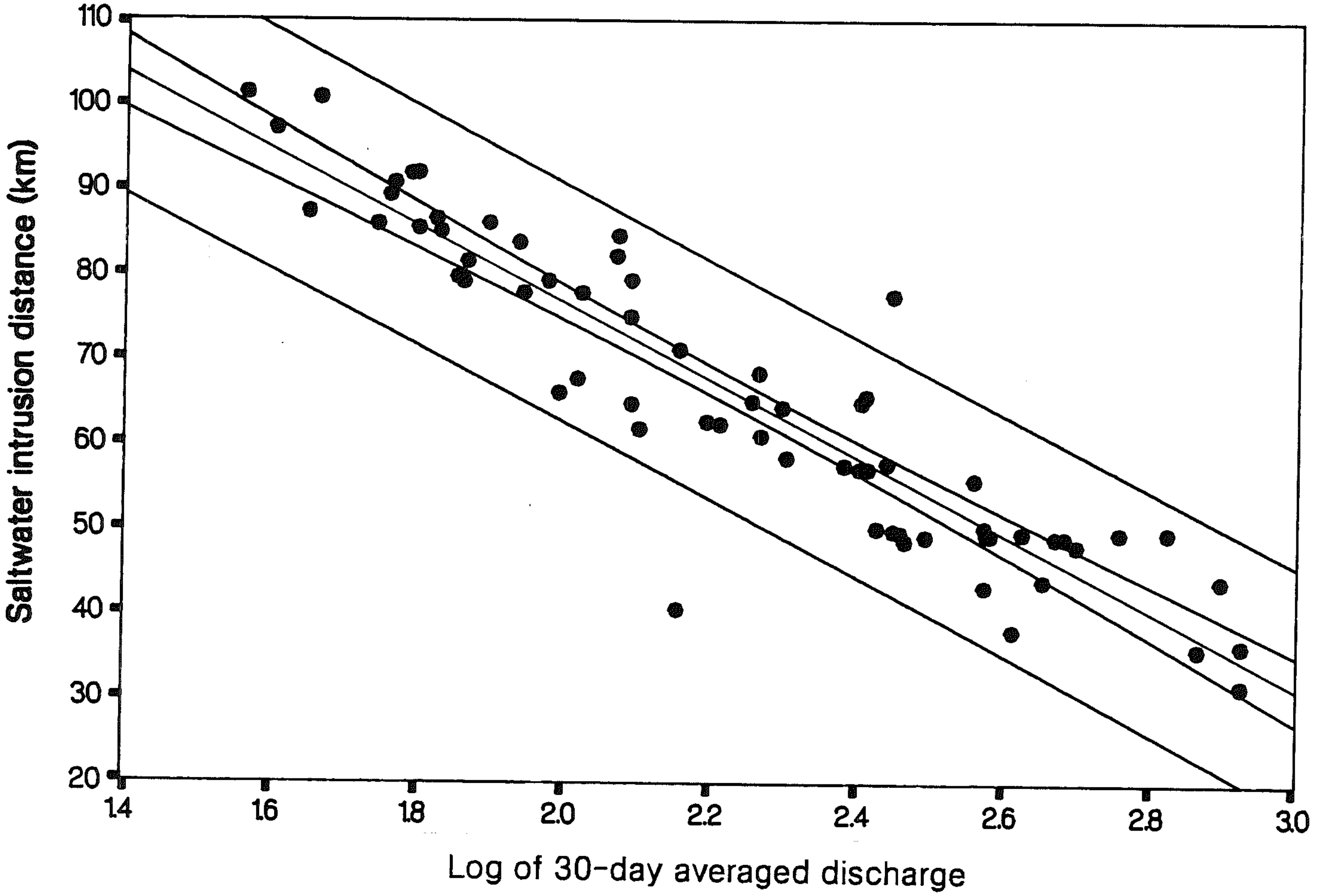


Figure 62c. Regression of saltwater intrusion distance on log of 30-day averaged discharge for bottom salt/fresh boundary = 0.5 ppt at slack before flood tide (95% confidence intervals for mean and specific saltwater intrusion distances).

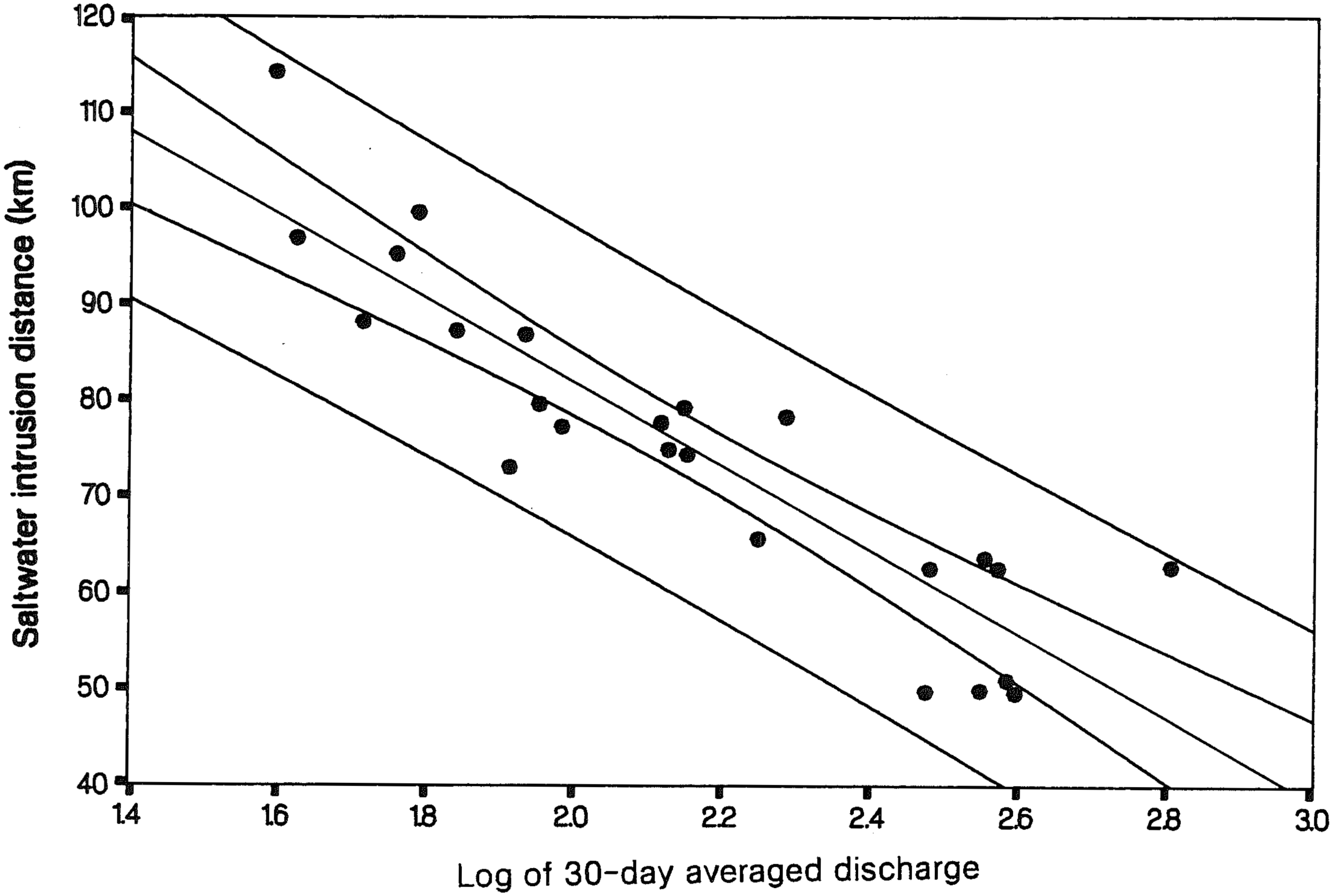


Figure 62d. Regression of saltwater intrusion distance on log of 30-day averaged discharge for bottom salt/fresh boundary = 0.5 ppt at slack before ebb tide (95% confidence intervals for mean and specific saltwater intrusion distances).

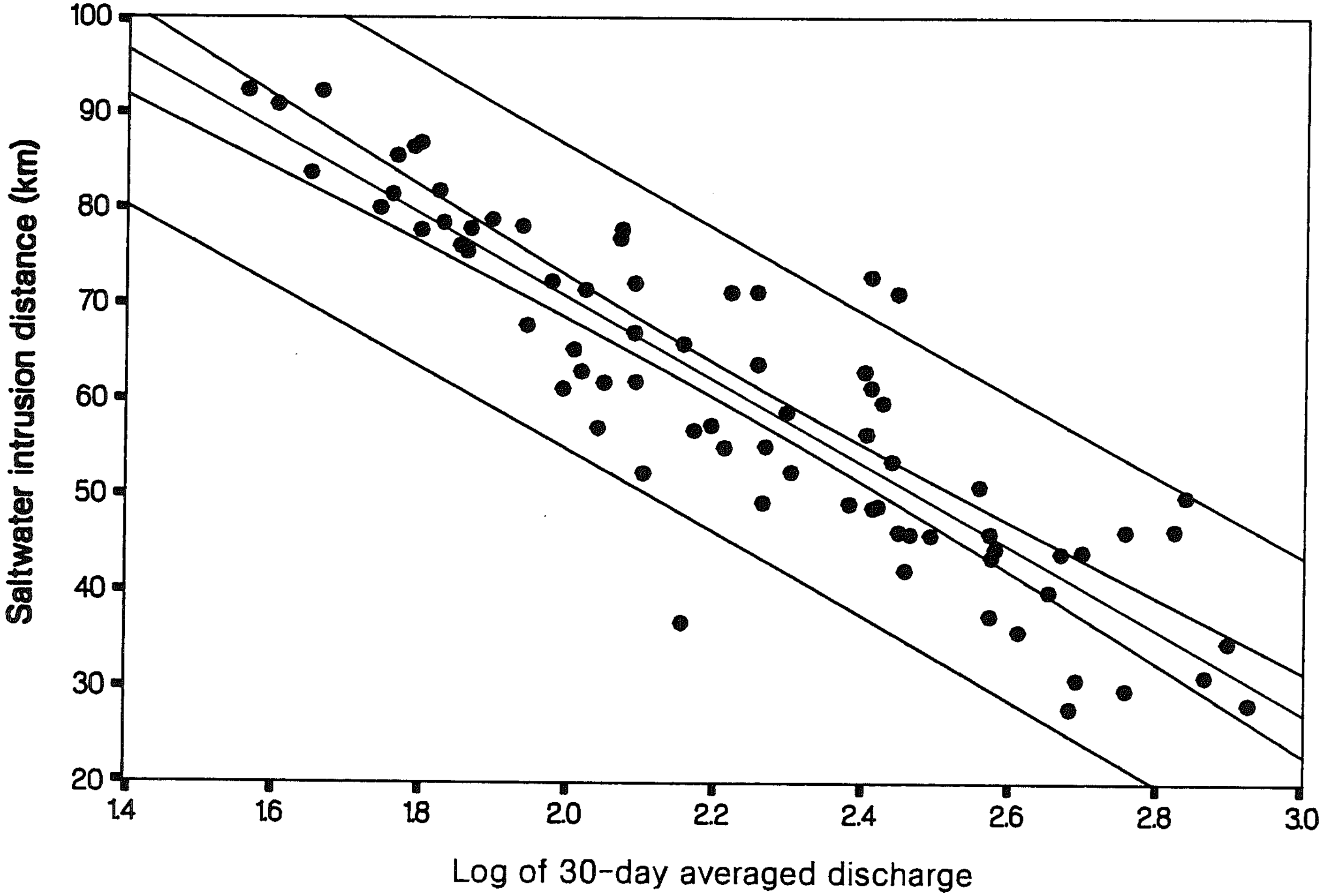


Figure 62e. Regression of saltwater intrusion distance on log of 30-day averaged discharge for surface salt/fresh boundary = 1.0 ppt at slack before flood tide (95% confidence intervals for mean and specific saltwater intrusion distances).

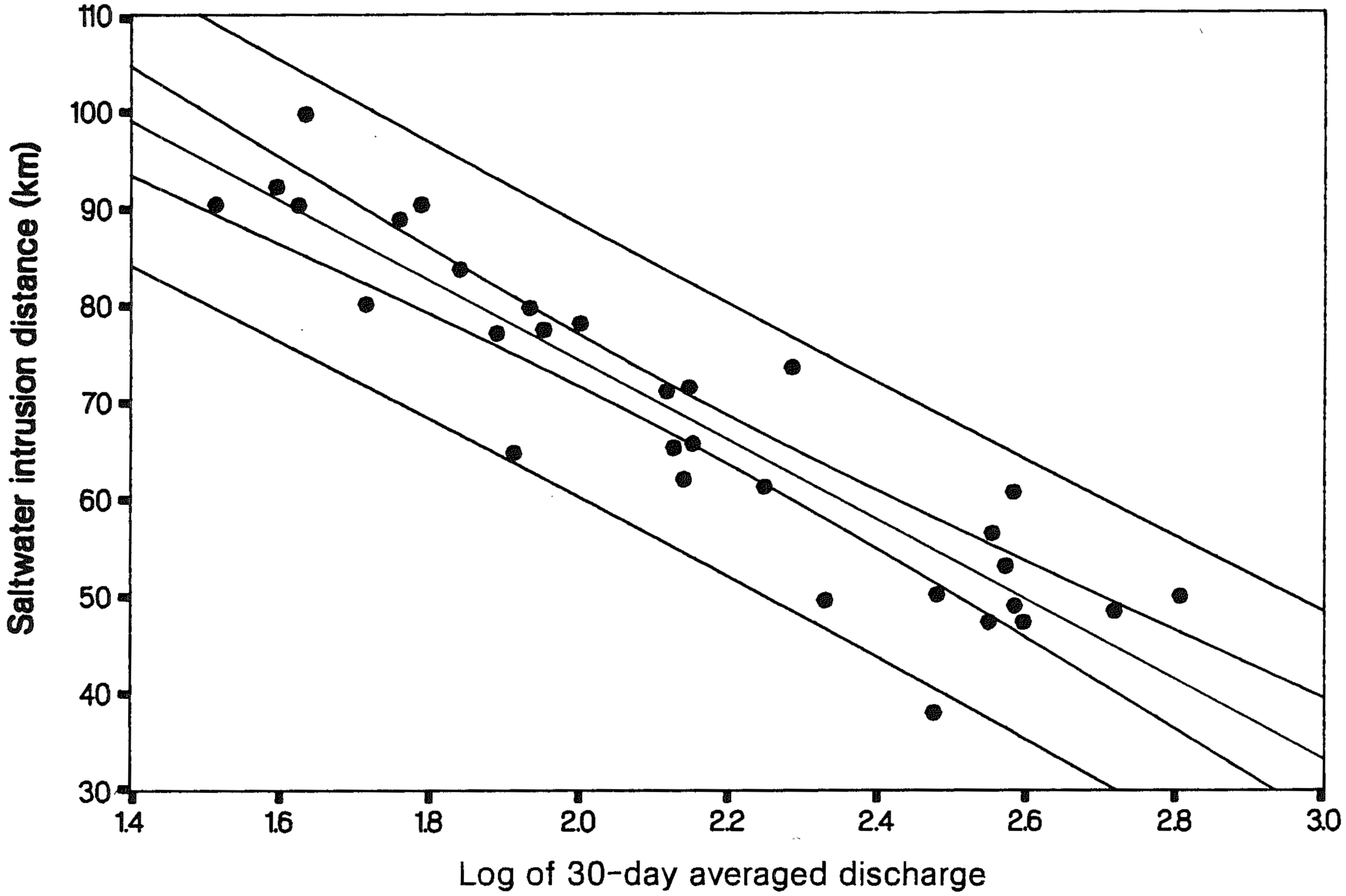


Figure 62f. Regression of saltwater intrusion distance on log of 30-day averaged discharge for surface salt/fresh boundary = 1.0 ppt at slack before ebb tide (95% confidence intervals for mean and specific saltwater intrusion distances).

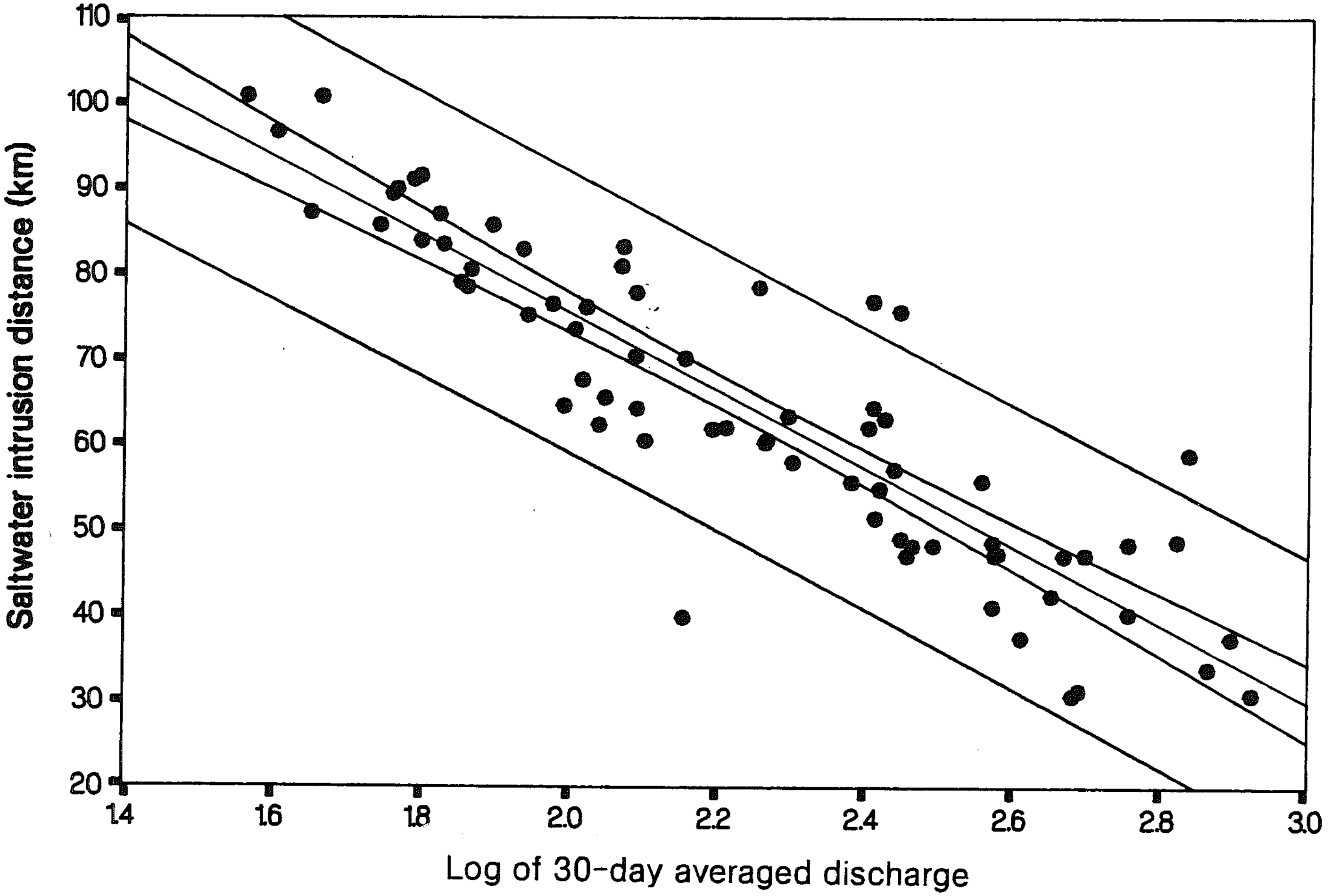


Figure 62g. Regression of saltwater intrusion distance on log of 30-day averaged discharge for surface salt/fresh boundary = 0.5 ppt at slack before flood tide (95% confidence intervals for mean and specific saltwater intrusion distances).

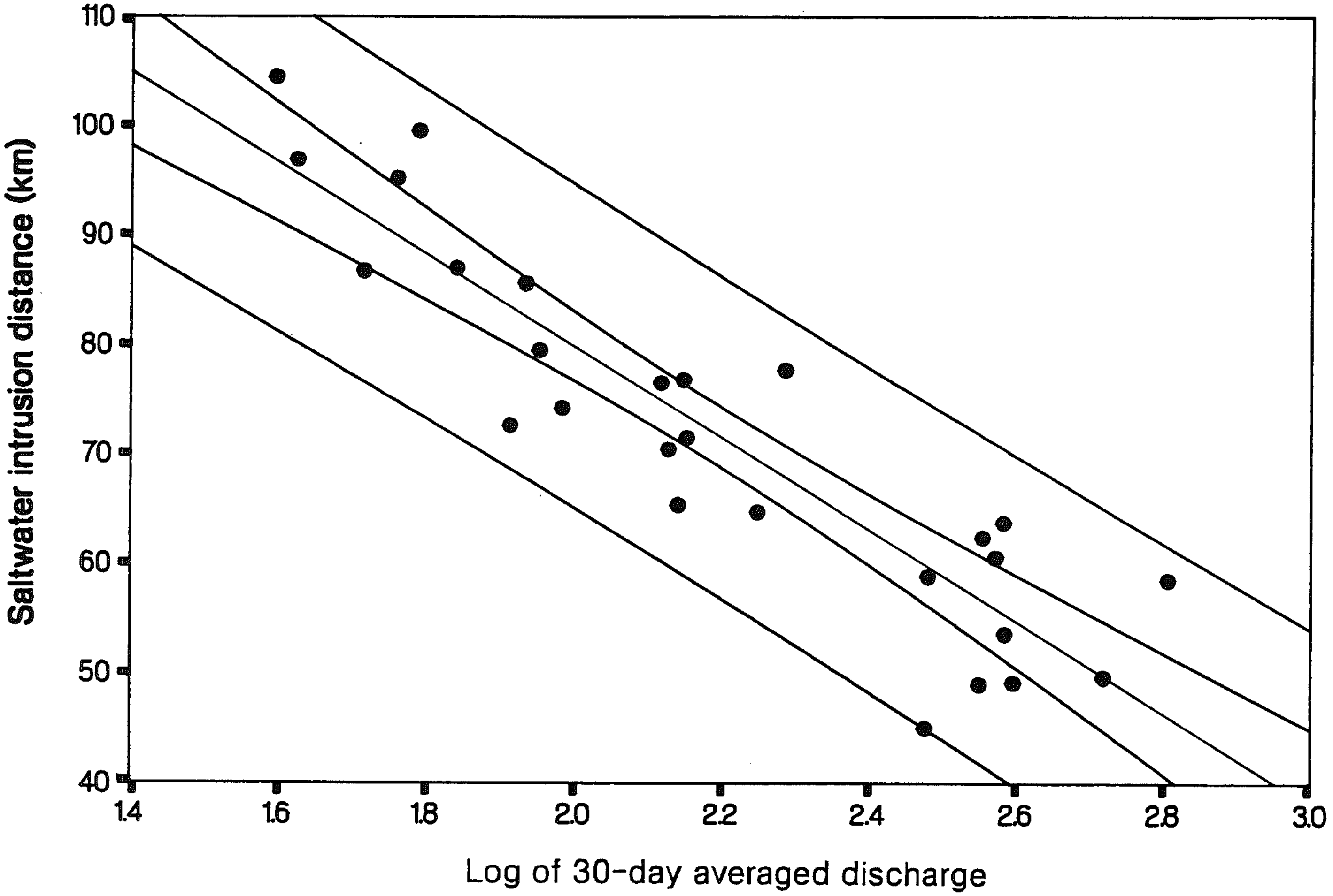


Figure 62h. Regression of saltwater intrusion distance on log of 30-day averaged discharge for surface salt/fresh boundary = 0.5 ppt at slack before ebb tide (95% confidence intervals for mean and specific saltwater intrusion distances).

Table 10. Regression of saltwater intrusion distance on the log of averaged freshwater discharge.

Number of days averaged	Salt/ Fresh Boundary (ppt)	Surface(S) or Bottom(B) Salinity	R-squared	Slope	Y-intercept	Tide State
7	1.0	B	0.73	-37.7	144.2	sbf
7	1.0	B	0.81	-34.6	144.7	sbe
15	1.0	B	0.81	-39.9	150.9	sbf
15	1.0	B	0.83	-38.1	151.9	sbe
15	0.5	B	0.83	-43.0	161.7	sbf
15	0.5	B	0.80	-41.3	163.4	sbe
15	1.0	S	0.78	-41.0	151.9	sbf
15	1.0	S	0.81	-39.4	151.7	sbe
15	0.5	S	0.80	-43.2	161.4	sbf
15	0.5	S	0.81	-40.0	158.4	sbe
27	1.0	B	0.83	-41.5	154.7	sbf
27	1.0	B	0.83	-39.4	155.4	sbe
27	1.0	B	0.82	-41.5	156.2	both
28	1.0	B	0.83	-41.8	155.2	sbf
28	1.0	B	0.83	-39.8	156.1	sbe
28	1.0	B	0.82	-41.8	156.8	both
30	1.0	B	0.82	-41.7	155.1	sbf
30	1.0	B	0.84	-40.3	157.4	sbe
30	0.5	B	0.85	-45.4	167.3	sbf
30	0.5	B	0.81	-43.5	168.9	sbe
30	1.0	S	0.79	-43.3	157.2	sbf
30	1.0	S	0.84	-41.2	156.7	sbe
30	0.5	S	0.80	-45.5	166.5	sbf
30	0.5	S	0.83	-41.8	163.5	sbe

sbf = slack before flood; sbe = slack before ebb
All regressions significant at alpha < 0.001 level.

Note: To use regression equation for prediction of the saltwater intrusion distance, use:

$$L = a + (b * \log Q)$$

where L = saltwater intrusion distance (km from river mouth)
a = y-intercept from table
b = slope from table
logQ = Log of averaged discharge in $m^3 s^{-1}$

R-squared is the proportion of the variation in the saltwater intrusion distance that is explained by the log of averaged freshwater discharge.

distance, suggesting that the log of averaged freshwater discharge is a good predictor of the saltwater intrusion distance. The model with log of 30-day averaged discharge explained slightly more of the variance in saltwater intrusion distance than the model with log of 15-day averaged discharge. The limit of saltwater intrusion at slack before ebb tide was more dependent on discharge than that at slack before flood tide except for the limit of bottom salinity (0.5 ppt) intrusion, for which the distance at slack before flood tide was more dependent on discharge than that at slack before ebb tide. A regression analysis was performed by adding various delay times between the 30-day averaging period and the date of the field survey. The dependence of saltwater intrusion distance on discharge decreased with addition of delay time.

B. Salinity at fixed stations

Salinity at a given location in the estuary usually had a negative relationship with freshwater discharge. Linear regressions were performed to investigate the dependence of salinity at selected stations on the log of averaged discharge. The discharges were averaged over various numbers of days; it was found that the regression models for 28- to 30-day averaged discharge explained more variance in salinity than models for other averaging intervals for all the stations examined. Table 11 presents the results of linear regression of salinity at selected stations on 30-day averaged discharge. Except for the station at the mouth, the R-squared values (alpha level = 0.001) were higher than 0.61, 0.63, and 0.51, respectively for vertically-averaged, surface and bottom salinities. The absolute value of the slope of the regression line was greatest in the middle reach of the estuary; this coincided with the location of the

Table 11. Regression of salinity on the log of 30-day averaged freshwater discharge.

Station	Depth of salinity sampled	R-squared	slope	y-intercept	# of sampling days on which salinity observed
0.0 km	V	.40	-5.10	33.78	99
17.3 km	V	.64	-9.03	39.97	110
22.71 km	V	.61	-8.83	35.44	40
31.85 km	V	.67	-11.48	36.90	121
36.57 km	V	.70	-11.35	35.36	7
38.18 km	V	.64	-11.17	33.34	38
43.85 km	V	.69	-9.77	27.94	43
50.19 km	V	.74	-8.89	23.88	111
65.94 km	V	.63	-5.37	13.52	85
0.0 km	S	.63	-8.36	38.01	99
17.3 km	S	.68	-11.36	40.21	111
22.71 km	S	.74	-13.32	42.74	41
31.85 km	S	.72	-12.19	36.77	122
36.57 km	S	.85	-13.88	39.34	9
38.18 km	S	.67	-10.68	30.90	37
43.85 km	S	.71	-9.62	26.95	45
50.19 km	S	.72	-8.59	22.98	110
65.94 km	S	.63	-5.09	12.73	87
0.0 km	B	.14	-3.63	33.62	97
17.3 km	B	.52	-7.58	35.17	109
22.71 km	B	.52	-7.22	33.97	41
31.85 km	B	.51	-10.17	36.09	121
36.57 km	B	Regression not significant.			7
38.18 km	B	.54	-11.37	35.26	38
43.85 km	B	.70	-10.60	30.32	42
50.19 km	B	.71	-9.56	25.83	109
65.94 km	B	.63	-5.84	14.70	77

V = Vertically averaged salinity
S = Surface salinity
B = Bottom salinity

greatest longitudinal salinity gradient.

The salinity data at station 31.85 km are plotted in figures 63a to 63c against the log of 30-day averaged freshwater discharge. Also shown in the figures are the regression lines and the confidence intervals for predicting the mean and specific salinity. Incorporating time delays between the 30-day averaging period and the sampling date did not improve the relationship between salinity and discharge.

VI. Summary

In this report, we have attempted to describe salinity conditions, and illustrate and interpret variations in salinity conditions, in the James River using the VIMS slackwater survey data of 1971-1985. The salinity conditions were examined in terms of longitudinal distribution, distance of saltwater intrusion and vertical stratification. Factors affecting salinity which were explored were tidal effects and freshwater discharge.

It was found that most of the VIMS slackwater surveys were conducted under average freshwater discharges (i.e., the combined freshwater discharges at Richmond and Kanawha Canal gages averaged over the 30 day period preceeding and including the survey dates) much higher than the long-term median of mean monthly discharges. Since salinity is inversely related to freshwater discharge, a simple averaging of all salinities measured by the VIMS surveys at a particular month of the year would result in low estimates of "typical" salinity for the month. Surveys which were conducted under more typical discharges (i.e., within 50-150 percent of the long-term median of mean monthly discharges) were selected for estimation of "typical" salinities. The "typical" longitudinal salinity patterns show a distinct

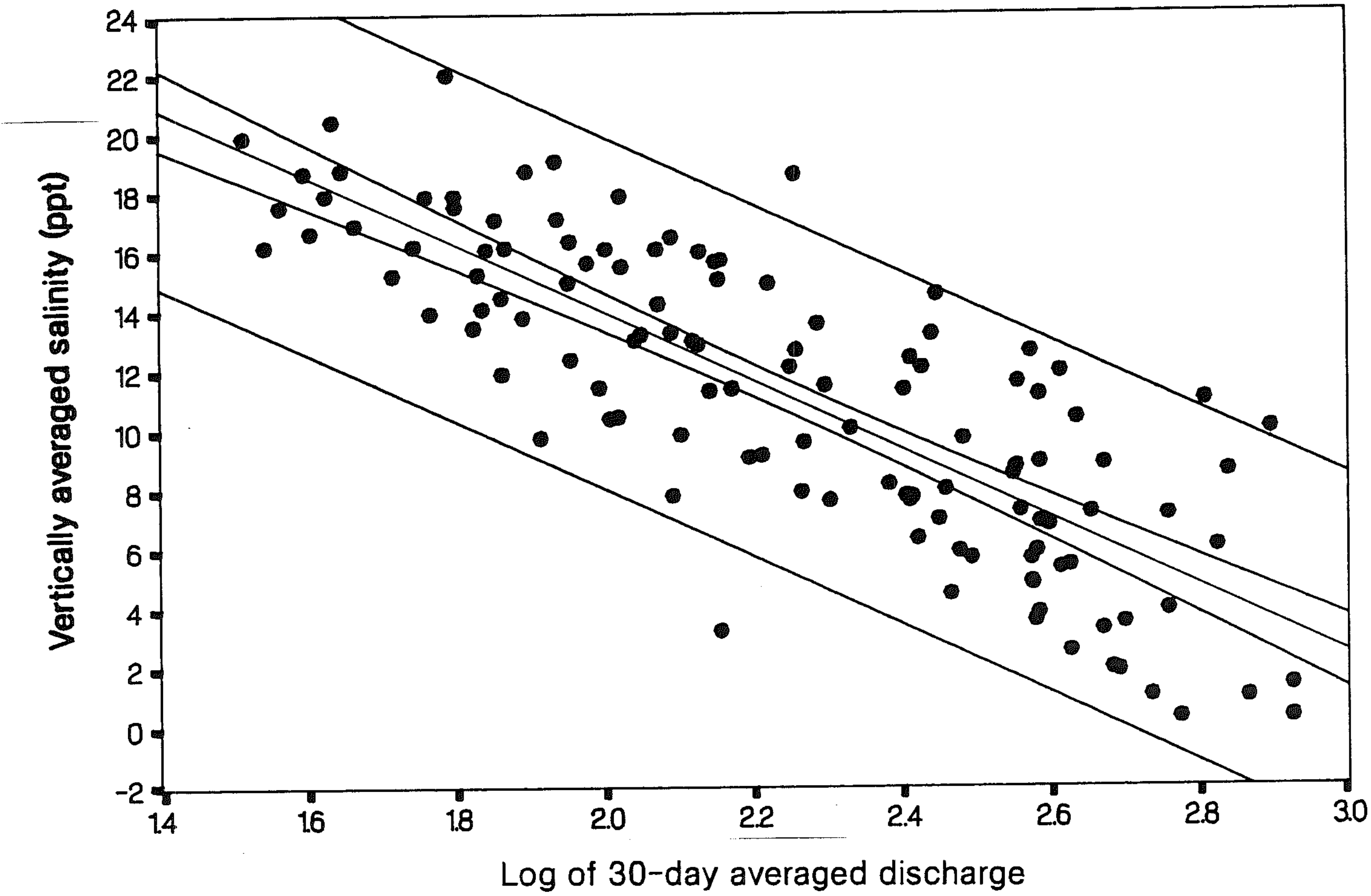


Figure 63a. Regression of vertically averaged salinity at 31.85 km on log of 30-day averaged discharge (95% confidence intervals for mean and specific salinities).

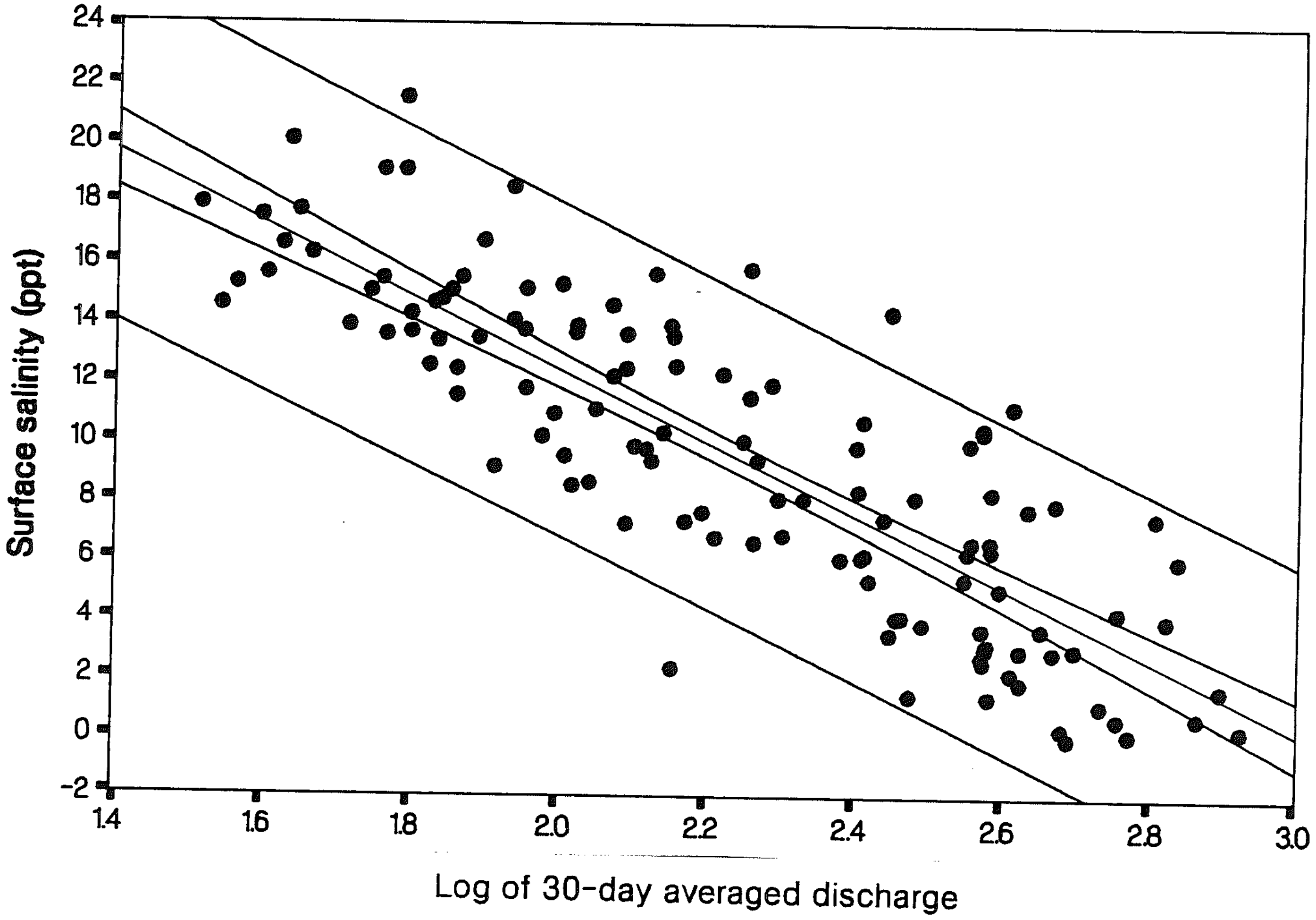


Figure 63b. Regression of surface salinity at 31.85 km on log of 30-day averaged discharge (95% confidence intervals for mean and specific salinities).

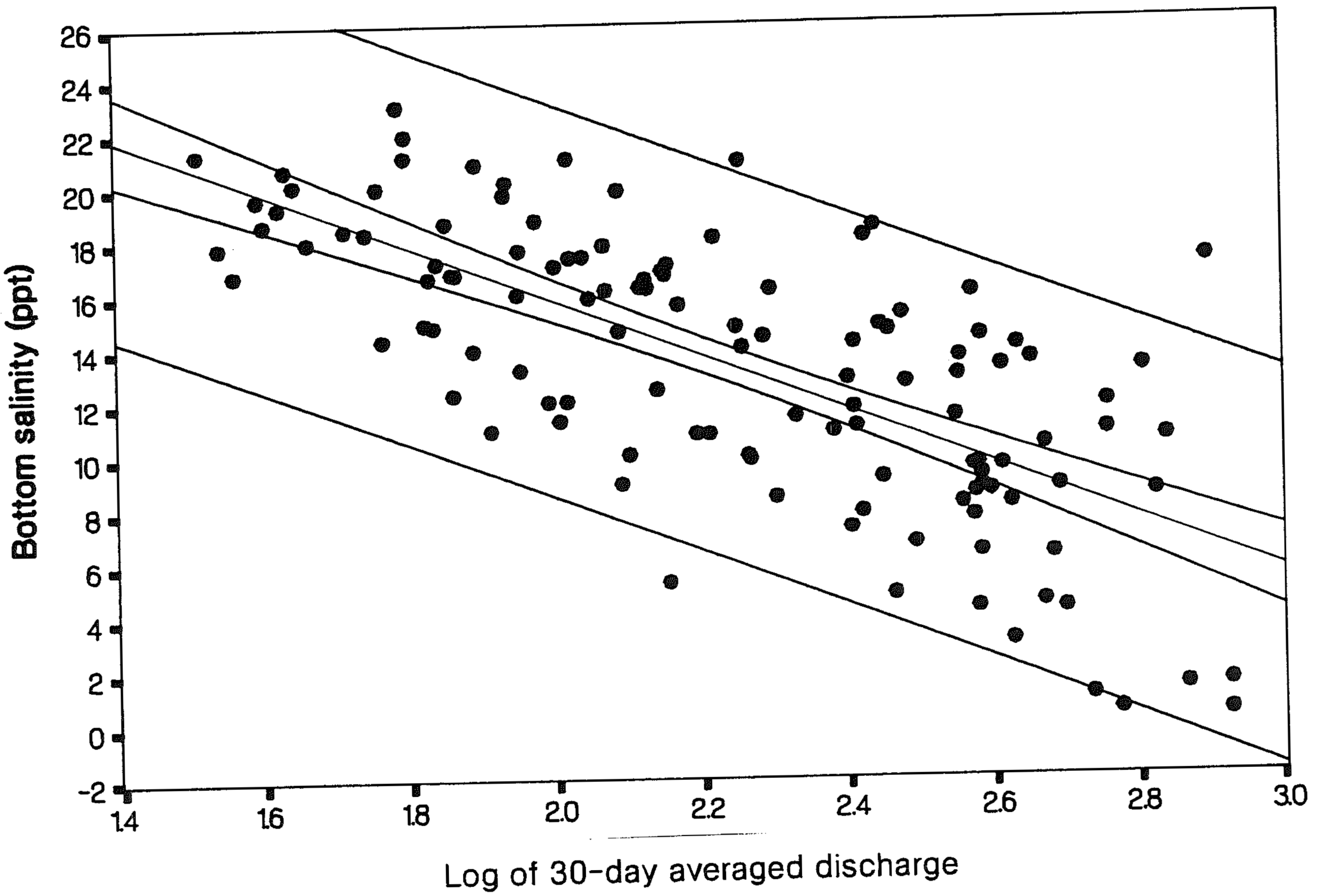


Figure 63c. Regression of bottom salinity at 31.85 km on log of 30-day averaged discharge (95% confidence intervals for mean and specific salinities).

seasonal variation in response to the annual hydrological cycle. Salinities in August averaged 7 ppt higher than those in March.

Tidal variations in salinity were examined with data from the two survey dates which occured in one month, representing spring and neap tides, on which both slack before flood and slack before ebb tides were surveyed. The greatest intratidal variation occurred in the middle reach of the estuary (approximately 20-50 km), where the ranges of variation averaged about 3.2 ppt at spring tide and less than 0.6 ppt at neap tide. Tidal excursion was estimated at less than 7.5 km at spring tide, and greater than 2.5 km at neap tide.

Vertical stratification was greatest (approximately 0.5 ppt/m) in mid-estuary. The vertical salinity gradient was greater at slack before flood than at slack before ebb. In the lower to middle estuary (i.e., 0-50 km), vertical salinity gradients in March-May were greater than in August-October. Due to greater saltwater intrusion distance in the drier months, the vertical salinity gradient in the upper estuary (i.e., > 50 km) was greatest in August-November. The vertical salinity gradient was approximately 0.2 ppt/m at neap tide, and less than 0.1 ppt/m at spring tide for the two survey dates on which both slacks were sampled.

The saltwater intrusion distance was found to be highly dependent on freshwater discharge; specifically, a regression with log of 30-day averaged freshwater discharge explained 80-85 percent of the variation in saltwater intrusion distance. Averaging freshwater discharge over 30 days produced a better estimate of saltwater intrusion distance than averaging over other numbers of days. The limit of saltwater intrusion (defined as 0.5 ppt at the bottom) ranged from approximately 50 km in March-April to approximately 80 km in August-October. The overall average was 75 (± 17) km at slack before ebb tide, and 66 (± 18) km at slack before flood tide.

Salinities at fixed stations were also found to be highly dependent on freshwater discharge. Again, averaging freshwater discharge over 28-30 days produced better estimates of salinity than other averaging intervals. Salinity at stations in the middle reach of the estuary changed more with changes in freshwater discharge than salinity at stations in other parts of the estuary, coinciding with the greatest longitudinal and vertical salinity gradients.

Salinity characterisitics of the James River are important in determining the distribution of many organisms and in determining the possible uses of the river's water. It is hoped that this report will be of some use to scientists, engineers, and managers in their studies of the James River estuary.

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Haas, Leonard W. 1977. The effect of the spring-neap tidal cycle on the vertical salinity structure of the James, York and Rappahannock Rivers, Virginia, U.S.A. Estuarine and Coastal Marine Science 5: 485-496.