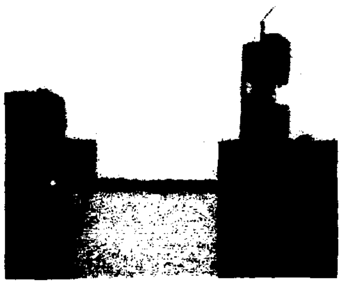

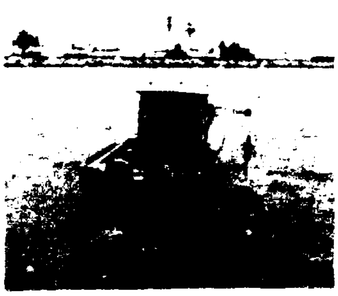

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EFFECTS OF COOPER RIVER REDIVERSION FLOWS ON SHOALING CONDITIONS AT CHARLESTON HARBOR, CHARLESTON, SOUTH CAROLINA

by

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This report summarizes analyses relating to sediment flushing from Charleston Harbor using salinity, suspended sediment, and velocity data from a total of 11 tidal surveys and from long-term monitors. The US Army Corps of Engineers rediversion project was designed to return the Cooper River to inflows of 3,000 cfs or slightly higher, and greatly reduce Charleston Harbor shoaling. Harbor monitoring was conducted before and after rediversion for the purpose of recommending an appropriate rediversion inflow level. Harbor conditions were considered optimum if the harbor was well-flushed and if shoaling conditions were similar to the base condition defined for the project (3,000 cfs). Harbor conditions were found to be optimum between 3,000 and 4,500 cfs, and this flow range was recommended as the weekly average flow from Pinopolis Dam.

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PREFACE

The collection and analysis of field data for the determination of sediment flushing characteristics of the Charleston Harbor after rediversion of the Cooper River were performed for the US Army Engineer District, Charleston.

This analysis study was conducted in the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES) during the period January 1986 to December 1987 under the general supervision of Messrs. Frank A. Herrmann, Jr., Chief, HL; Richard A. Sager, Assistant Chief, HL; William H. McAnally, Jr., Chief, Estuaries Division; and George M. Fisackerly, Chief, Estuarine Processes Branch.

The study was conducted and this report prepared by Mr. Allen M. Teeter, Estuarine Processes Branch. Mr. Walter Pankow, Estuarine Processes Branch, assisted in the preparation of this report. Mr. Howard A. Benson, Estuarine Processes Branch, was the field engineer for the field data collection which preceded this study. Field technicians who collected data included Messrs. David Crouse, Joseph W. Parman, James T. Hilbun, Samuel E. Varnell, Billy G. Moore, John T. Cartwright, Douglas M. White, and John S. Ashley, all with the Estuaries Division. Mrs. Clara Coleman, Estuarine Processes Branch, reduced the data to computer files. Mrs. Marsha C. Gay, Information Technology Laboratory, WES, edited this report.

The Charleston District contact persons were Messrs. Lincoln Blake, Robert Billue, and James Joslin.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
knots (international)	0.5144444	metres per second
miles	1.6093	kilometres

EFFECTS OF COOPER RIVER REDIVERSION FLOWS ON SHOALING CONDITIONS AT CHARLESTON HARBOR, CHARLESTON, SOUTH CAROLINA

PART I: INTRODUCTION

Background

1. Charleston Harbor is formed by the junction of the Ashley, Wando, and Cooper River estuaries, and is a major South Carolina seaport. Figure 1 shows the lower estuary. The Cooper River contributes almost all of the freshwater inflow to the system, and is the largest of the subestuaries, extending about 57 miles* from the harbor entrance to the Pinopolis Dam. Characteristic tide ranges are 4.4 ft neap, 5.3 ft mean, and 6.1 ft spring at the Customs House gage at Charleston. Unless otherwise noted, all tide ranges cited in this report are referenced to the Customs House gage.

2. The Cooper River rediversion project was designed to reduce excessive Charleston Harbor maintenance dredging by restoring an estuarine condition similar to that which existed before the 1942 diversion. Studies of the problem concluded that rediversion of flow away from the Cooper River would be the only practical solution to the problem.

3. Inflows to Charleston Harbor before the 1942 diversion were 261 cfs from the Ashley River, 82 cfs from the Wando River, and 72 cfs from the Cooper River. Diversions of the Santee River via Lake Moultrie and the Pinopolis Dam to the Cooper River increased inflows by 15,000 cfs to a total average of about 15,600 cfs. Inflow was controlled at the Pinopolis hydroelectric plant. The increased inflow caused the character of the harbor to change from vertically well-mixed to a more stratified condition, and increased sediment inflows. After diversion, shoaling in navigation channels of Charleston Harbor jumped from about 110,000 cu yd to over 10 million cubic yards per year and, through improved dredging and disposal methods, stabilized at about 7.5 million cubic yards per year.

4. The US Army Corps of Engineers (USACE) rediversion project was

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* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 4.

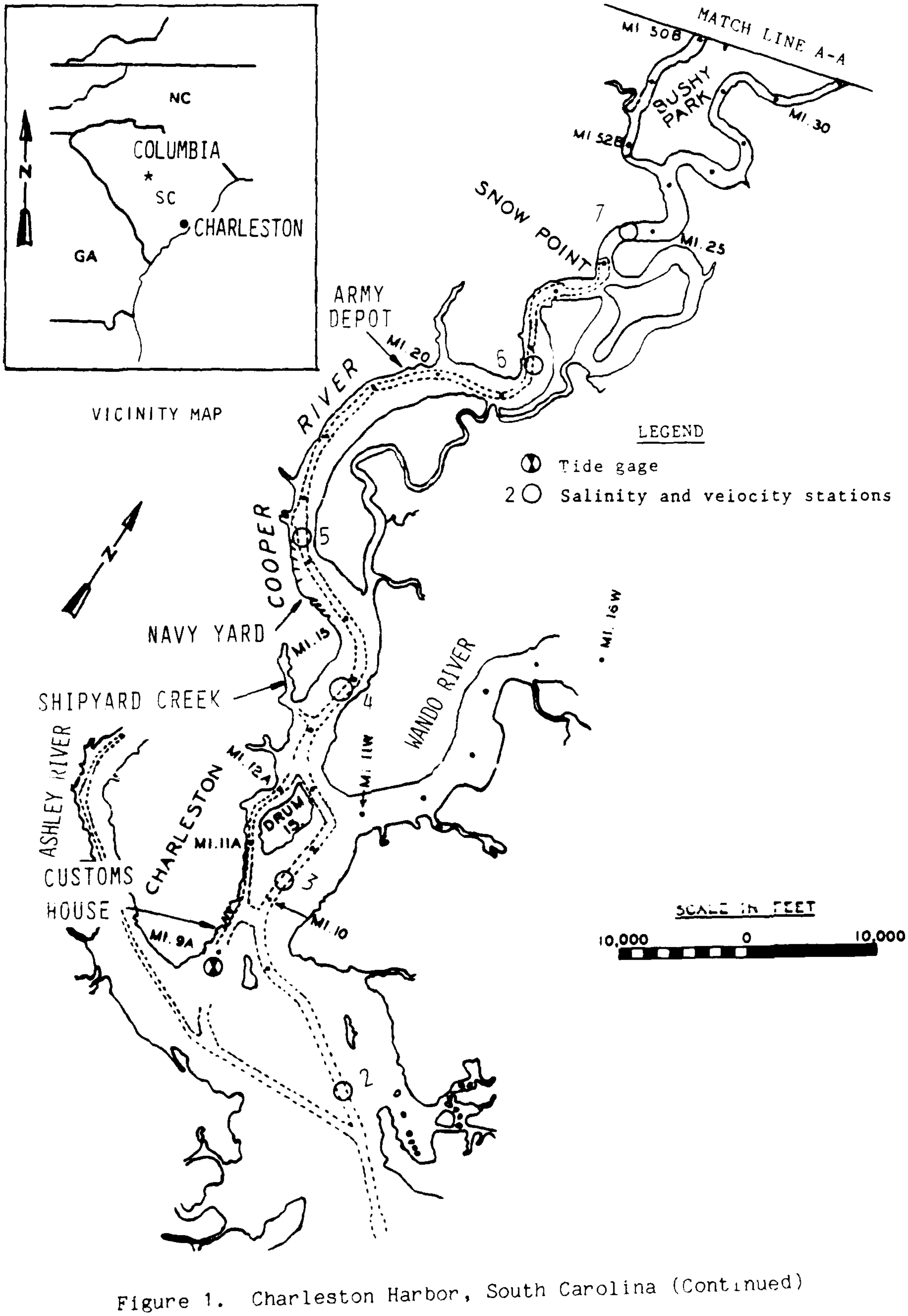

Figure 1. Charleston Harbor, South Carolina (Continued)

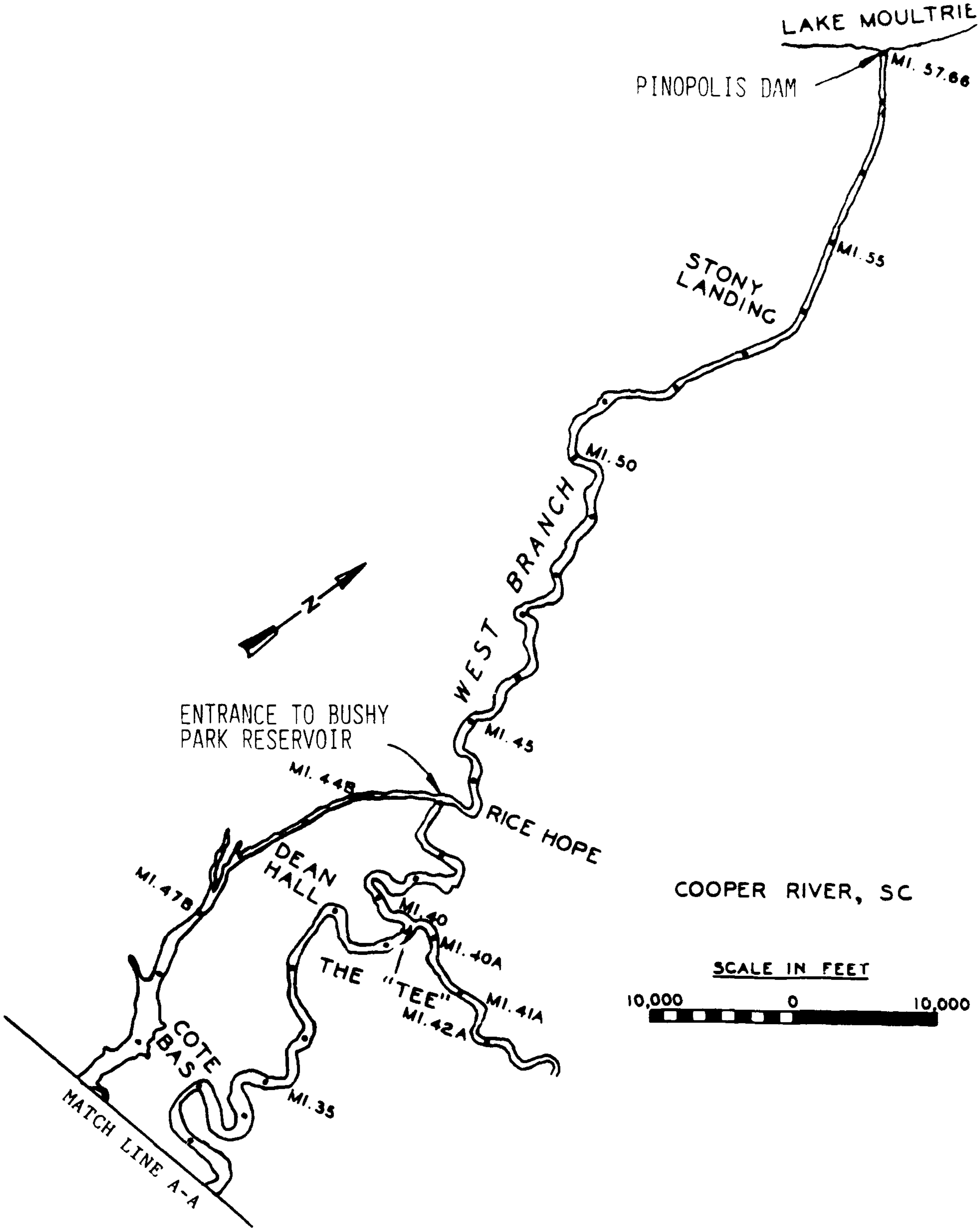

Figure 1. (Concluded)

designed to return the inflow from the Cooper River to 3,000 cfs or slightly higher and thus to return Charleston Harbor to an essentially prediversion shoaling condition. A determination of an appropriate inflow was to be made after project completion. The studies required to make that determination are discussed in this report.

5. The rediversion project has reduced flows and shoaling in the Cooper River estuary. Test flows were established at the initial phase of rediversion in 1985 to allow study of the harbor response to average weekly inflows between 3,000 and 4,500 cfs. Inflows were restricted during 1986 by a water shortage. Another test period was established in 1987 for average weekly inflows slightly higher than 4,500 cfs. Monitoring data were collected during these test inflow periods, and were analyzed herein.

6. Tidal surveys were conducted by the US Army Engineer Waterways Experiment Station's (USAEWES) Harbor Monitoring Study prior to the rediversion in 1979-1982, immediately after rediversion in 1985, and again in 1987. The intensive 13-hr surveys consisted of six stations (numbered 2-7) along the estuary that collected current speed and directions and salinity samples. Figure 1 shows the locations of the sampling stations. Long-term instrument deployments were used in 1987 to monitor the effects of tidal conditions on harbor mixing. Data from the surveys were reduced and plotted, and were presented in a separate report along with a more complete description of the procedures and equipment.* Data were used here to develop correlations and averages to describe flow, salt, and suspended sediment regimes.

Purpose

7. The purpose of this study was to recommend to the US Army Engineer District (USAED), Charleston, an appropriate postrediversion inflow or range of inflows slightly above a weekly average of 3,000 cfs for the Cooper River. The recommendation was based on the observed flushing characteristics of the harbor at various inflows and on expected shoaling conditions. Harbor conditions were considered optimum if the harbor was well-flushed and if

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* H. A. Benson. "Charleston Harbor Monitoring Study," US Army Engineer Waterways Experiment Station, Vicksburg, MS, furnished to Charleston District.

shoaling conditions were similar to the base condition defined for the project. An optimum freshwater inflow was considered to be sufficient to assure desirable harbor flushing, but not so great as to cause detrimental vertical salinity and density stratification. Inflows found to meet these criteria were considered appropriate and consistent with rediversion project requirements.

Scope

8. This report summarizes analyses relating to sediment flushing from the harbor using salinity, suspended sediment, and velocity data from a total of eleven tidal surveys and from long-term monitors. Details are given in Appendices A-C. Salinity and velocity data numbered about 2,500 items for each of the 1985 surveys, and about 760 for each of the 1987 surveys. Two surface and bottom long-term monitors were sampled hourly for several months. Monitoring data were collected and analyzed to evaluate stratification, circulation, and vertical mixing. Salinity and suspended sediment fluxes, flux components, and statistical correlations were also computed. A list of terms is given in Appendix D.

9. Suspended sediment data were more limited in number than salinity and velocity data. Suspended sediment data from a 24-day automatic suspended sediment sampler and from a single survey station collected at and between two surveys in 1985 were used by the study. Suspended sediment data were collected to describe the fortnightly tidal effects and suspended sediment flux characteristics.

10. A desk analysis of harbor shoaling over the inflow range 3,000-4,500 cfs was also performed and presented. An analysis of the sediment source reduction which accompanied rediversion of the Cooper River was made by the US Geological Survey (Patterson 1983) and was used as a basis for the desk study. Reduction of sediment sources was predicted for 3,000- and 4,500-cfs inflows.

PART II: STUDY DESCRIPTION

Rediversion Project Requirements

11. An agreement with the South Carolina Public Service Authority reached before the start of the project set a weekly average of 3,000 cfs as the rediversion inflow level, with 70 hr of allowable zero-flow. However, project documents state that USACE can specify a slightly higher inflow if, after postproject testing, it is found that such inflow will not diminish harbor mixing nor cause stratification and sediment trapping characteristics in the navigation project area. Benefits of the optimum inflow were identified as increased peaking capacity at Pinopolis hydroplant and enhanced water quality at Charleston Harbor.

12. The project established that field tests were to be performed after rediversion for the purpose of establishing an appropriate inflow level. The project established a 3,000-cfs average inflow as the basis for determining nondamaging harbor shoaling conditions.

13. The protection of Bushy Park Reservoir from ocean chloride intrusion after rediversion has also become a local and USACE concern. At the time of the project report (US Senate 1968), no development had taken place in Bushy Park; but by the 1970's, substantial industrial concerns had sited there and were assured by USACE that the freshwater supply would be protected. Further assurances were given as the rediversion project approached completion. LTC B. E. Stalmann, District Engineer, Charleston District,* wrote that "we agree to prevent ocean salinity intrusion from raising chloride levels at the entrance to Durham Canal above the background chloride levels in the adjacent Cooper River." In 1983, a postauthorization report submitted to the Chief of Engineers identified saltwater intrusion at Bushy Park as a possible problem, and proposed project changes if mitigation were required. LTG E. R. Heiberg III, Chief of Engineers,** wrote that "the Corps remains committed to the protection of water quality in Bushy Park Reservoir and will take whatever reasonable steps are necessary." Thus the protection of Bushy Park water

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* Letter, 15 Dec 1982, to Mr. J. Bettis, Commissioner of Public Works, Charleston, SC.

** Letter, 30 Aug 1985, to the Honorable Strom Thurmond, Senator, South Carolina.

quality, while not considered by the rediversion project report, has become an important operational priority for USACE. However, since the protection of Bushy Park Reservoir from ocean chloride intrusion is technically outside of the rediversion project scope, it will not be considered a project requirement for this study.

Inflow Criteria

14. The rediversion project report (entered as a Senate document) defined a weekly average discharge of 3,000 cfs as a "nondamaging" condition for Charleston Harbor shoaling, based on physical hydraulic model tests. "Nondamaging" was not explicitly defined; but the project report states, based on hydraulic model shoaling studies, that "reduction of inflows below 3,000 cfs is not estimated to benefit maintenance" (US Senate 1968, page 28). The USAEWES shoaling study (USAEWES 1957) predicted a difference of 8 percent in shoaling reduction between 3,000- and 0-cfs inflow (59 and 67 percent reductions, respectively) for 100 percent shoaling potential tests. Therefore, the intent of the project report appears to be that small differences in shoaling reduction are considered nondamaging and allowable to benefit hydropower peaking operations and water quality conditions.

15. The criteria used in this study were that sediment sources and flushing must be similar to the project base 3,000-cfs shoaling condition (within about 8 percent of expected shoaling reduction) for harbor conditions to be optimum and hence nondamaging. The project report predicted that a reduction of the weekly average inflow to the Cooper River to 3,000 cfs would reduce the maintenance dredging rate to 3 million cubic yards per year.

Field Study Approach and Chronology

16. The USAEWES hydraulic model studies indicated a breakpoint at which a small reduction in freshwater inflow resulted in a dramatic increase in harbor mixing (USAEWES 1957). The breakpoint at which this would occur was not determined exactly but was between 2,500- and 5,000-cfs inflow in the model. The improvement in harbor mixing was found to be an important factor in shoaling reduction. Thus, mixing conditions were an important consideration for the evaluation of rediversion inflows.

17. A series of five field surveys was planned and performed immediately following rediversion to observe harbor conditions as the inflow was stepped down from 4,500 cfs in 500-cfs increments to 3,000 cfs. Inflows were stepped down toward 3,000 cfs rather than up from 3,000 cfs to avoid water quality problems at the Bushy Park Reservoir. Inflow levels were maintained 4-6 weeks prior to surveys to allow the estuary system to adjust and reach equilibrium with the reduced inflow.

18. Flow testing began on 24 March 1985 when inflow was reduced to a 4,500-cfs weekly average. That inflow was maintained for 7 weeks until a problem at the new rediversion project hydropower dam caused the rediversion to be rescinded. After a nontesting period, the tests were restarted in September at a 4,000-cfs weekly average inflow, then 3,500 cfs in October, 3,000 cfs in November, and 4,500 cfs in December. Details of the initial flow testing are given in Appendix A.

19. The preliminary results from the initial inflow testing showed that it was difficult to differentiate inflow effects from postrediversion surveys. Scatter in the survey results appeared greater than the effect of freshwater inflow, implying that conditions other than freshwater inflow were controlling harbor conditions. Therefore, it was planned to test inflows slightly higher than 4,500-cfs weekly average. During water year 1986, below-normal volumes of water were available for release into the Cooper River and no testing was performed.

20. Preliminary results also prompted a study of shoaling at 3,000- and 4,500-cfs inflows. A sediment budget approach similar to that used by Patterson (1983) was employed. Details are presented in Appendix C.

21. In the spring and summer of 1987, additional inflow testing was performed. The details of that testing are described in Appendix B. The approach to these surveys was similar to that of the previous tests, except that long-term monitors were installed in the estuary to sense surface and bottom conductivities over several months. The long-term monitors allowed a more complete analysis of estuarine variability over the period April-August 1987. Weekly average inflows were varied from a base level of about 4,500 cfs to 5,000-5,600 cfs.

Results Obtained

22. General salinity distribution and flow predominance results

presented in Appendices A and B indicated that rediversion increased harbor salinities and the extent of salinity intrusion over that observed during the 1979-1980 surveys. The null zone for net tidal-averaged circulation was moved upstream away from the developed portion of the estuary.

23. Results from the 1985 harbor testing surveys further indicated that conditions other than inflow were more influential to harbor stratification in the range of inflows from about 3,000- to 4,900-cfs weekly average. The important conditions were not specifically identified by the 1985 surveys. Harbor mixing was generally greatly improved over the prerediversion surveys. Before rediversion the harbor had been in the partly mixed to salt wedge regime proceeding upstream in the harbor. The rediversion had changed the harbor to the well to partly mixed regime.

24. Results from the 1987 surveys and monitoring identified the strong effect tide range had on vertical salinity stratification and mixing. Tide ranges below normal produced sharply higher salinity stratification. Average salinity stratification was found to increase with weekly average inflow increase from 4,500 to 5,000-5,600 cfs (5,250-cfs average).

25. The study to predict differences in shoaling between weekly average inflows of 3,000 and 4,500 cfs concluded that contributions by direct sediment inflow and plant production would amount to 160,000 cu yd annually, and that the overall difference in dredged volumes would be 200,000 cu yd annually. The assumption was made that harbor flushing conditions would be equivalent in the 3,000- to 4,500-cfs weekly average inflow range. Details are presented in Appendix C.

Supplemental Salinity Stratification Data

26. Short-duration low-inflow tests were performed prior to rediversion by the Santee Cooper power company in 1971 and 1978. Follow-up hydraulic model studies of Charleston Harbor were conducted at USAEWES and reported by Bobb and Simmons (1966), Benson (1976), and Benson (1977). These studies were sources of supplemental information on salinity stratification.

27. During the 1978 prototype low-inflow test, weekly inflows averaged 3,000 cfs with 2 days zero inflow (South Carolina Water Resources Commission 1979). A salinity stratification parameter $\delta S/\bar{S}o$ was calculated as the

top-to-bottom difference divided by the average salinity.* Prototype stratification averaged 0.19 (range 0.04-0.43) on 1-3 December 1978 during three 5.6- to 6.0-ft tides. Only high slack-water surface and bottom salinity samples were taken and therefore calculated stratifications were qualitative. Inflow had been reduced to 3,000-cfs weekly average on 11 November 1978.

28. Some additional high slack-water stratification data from another field study were reported by Benson (1977). Stratification averaged 0.37 (range 0.14-0.90) on 13 November 1971 with a 5.4-ft tide range and 3,000-cfs continuous inflow for the previous 9 days.

29. Salinity stratification data are not available from the original hydraulic model study (USAEWES 1957). Subsequent model studies collected high and low slack-water salinities at the surface and bottom, allowing a fair estimate of stratification to be made. For a 3,000-cfs continuous inflow and 5.2-ft tide range, average stratification for river miles 8-26 (four stations) was 0.34 (range 0.10-0.52) (Bobb and Simmons 1966). For a 3,000-cfs weekly average inflow with 60 hr of 1,000-cfs inflow and 5.2-ft tide range, average stratification for river miles 8-26 was 0.25 (range 0.07-0.50) (Bobb and Simmons 1966). For another model study that used a continuous 3,500-cfs inflow and 6.0-ft tide range, the average stratification for 10 stations for river miles 8-26 was 0.18 (range 0.04-0.39) (Benson 1976).

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* For convenience, symbols and abbreviations are listed in the Notation (Appendix E).

Important Sediment Flushing Conditions

30. Estuaries such as Charleston Harbor are among the most complex hydrodynamic mixing zones occurring in nature. Four principal processes related to sediment flushing are vertical mixing, tidal hydraulics, sediment dynamics, and vertical circulation. A description of important shoaling conditions is presented in the following paragraphs as background for further discussion of results. More details on process description are given in Appendix A. Appendix C gives a more complete description of previous sediment studies.

31. The earliest hydraulic model study (USAEWES 1957) found that more than 99 percent of the shoaling increase that began in the 1940's was due to the diversion, brought on by the following conditions:

- a. A net tidal-averaged vertical circulation superimposed on the tidal flow that produced strong flood-dominated flows near the bed, and prevented the estuary from disgorging its sediment load to the sea.
- b. Increased colloids and dissolved material available to shoal the harbor, both from suspended load in the river and from erosion of the upper channel (assumed to have equal magnitudes).

The study concluded that the improved sediment flushing from the harbor after rediversion would reduce shoaling further than merely the reductions associated with sediment inflows.

32. Three hydrodynamic sediment traps were created by the diversion, and were largely responsible for increased retention of shoaling material and buildup of unconsolidated mud throughout the estuary:

- a. Vertical salinity stratification increased dramatically, suppressed turbulent mixing, and trapped sediments near the bed.
- b. Net tidal-averaged vertical circulation affected near-bed tidal flow patterns and pumped near-bed suspended sediments into developed areas of the estuary.
- c. Once concentrated and deposited, sediments were trapped in unconsolidated mud and isolated to a large extent from transport by turbulent tidal flows.

33. The major effects of rediversion on shoaling conditions for 3,000- to 4,500-cfs weekly average inflows were as follows:

a. Reduce vertical salinity stratification, improving vertical mixing, preventing sediments from being trapped near the bed, and improving sediment flushing from the harbor.

b. Move the null-zone area of vertical circulation upstream, altering near-bed tidal flows, and reducing suspended sediment accumulation and unconsolidated mud formation in project and facility areas. The null zone of vertical circulation is where near-bed net tidal-averaged velocities are neither landward nor seaward, and is often an area of rapid shoaling.

c. Reduce sediment and nutrient loadings to the harbor.

34. Salinity stratification was used as the primary indicator of harbor mixing conditions for the study for the rediversion range of inflows. As described in Appendix A, salinity stratification was the most reliable and important indicator of harbor flushing. Stratification causes buoyancy effects in the flow that decrease turbulence and near-bed velocities. Decreased vertical mixing produces higher near-bed concentrations of suspended material. Decreased near-bed velocities allow greater deposition of sediments. Stratification is coupled through its effect on vertical mixing to vertical circulation. Additional discussion of estuarine processes can be found in Appendix A.

Variability of Harbor Stratification

35. Stratification was found to be highly variable in space and time. Results for the 11 USAEWES field surveys are shown in Table 1. Average stratifications for river miles 8-26 varied from 0.15 to 1.12 for all the surveys, and 0.15 to 0.63 for those surveys with less than 5,000-cfs weekly average inflow. Stratification generally increased upstream. The lower harbor connects to the other subestuaries, which have very little freshwater inflow and are more well mixed than the Cooper River estuary.

36. Supplemental salinity stratification data from field and hydraulic model slack-water samplings are summarized in Table 2.

37. Estuarine conditions for the last four of the 1985 surveys were unusual with respect to the extent and fluctuation in the extent of salinity intrusion into the upper reaches of the estuary (paragraph 8 of Appendix A). Tide ranges for most surveys were below average and variable. Tide ranges for the 1987 boat surveys were very low.

38. Stratification was also found to be variable during long-term monitoring. For example, for the 4,500-cfs weekly average inflow level, average

stratification was 0.20 and the standard deviation was 0.11 at Army Depot (Figure 1). For the 5,000- to 5,600-cfs weekly average inflow level, average stratification was 0.32 and the standard deviation was 0.12 at Army Depot.

39. Stratification was found by the 1987 survey to decrease markedly with increased tide range, and hence tidal mixing. Figure 2 shows the relationship found between stratification and tide range for boat survey data and trend lines for long-term monitors in the vicinity of the Army Depot station. Long-term monitor trend lines were found by regression analysis of daily average stratification and tide range, and corrected to the channel (Appendix B). The 4,500-cfs inflow level was sampled for 66 tidal cycles (34 days) and the 5,250-cfs inflow level was sampled for 93 tidal cycles (48 days) at this station. Correlation coefficients between stratification and tide range were 0.75-0.85. The standard deviations for the residuals between the data and trend lines were about 0.06, about half as great as for the raw data. Variation from the trend lines could not be accounted for by variations in daily inflow.

40. Figure 2 also shows the results from boat surveys and supplemental data for the vicinity of Army Depot. The general trend was for increasing stratification with decreased tide range, with the possible exception of the highest prerediversion inflows tested. Figure 2 shows that at the 23,700- to 24,700-cfs inflow, stratification was insensitive to tide range. This could suggest that the vicinity of the Army Depot was inflow dominated at the 23,700- and 24,700-cfs inflow surveys, although there was a considerable difference in the average estuarine stratifications for these surveys according to Table 1. Scatter in the data could also be responsible.

Effects of Inflow on Harbor Stratification

41. The range of weekly average inflows from 3,000 to 4,500 cfs had no discernible effect on harbor stratification. There was considerable scatter in survey stratification results in this inflow range. However, no trend in stratification versus inflow level could be identified for this inflow range even though a number of survey data points are available. Figure 2 shows that the seven boat survey data points available for the vicinity of Army Depot for 3,090- to 5,010-cfs weekly average inflow were grouped around the 4,500-cfs long-term monitor trend line.

42. Inflows slightly above 4,500 cfs increased harbor stratification

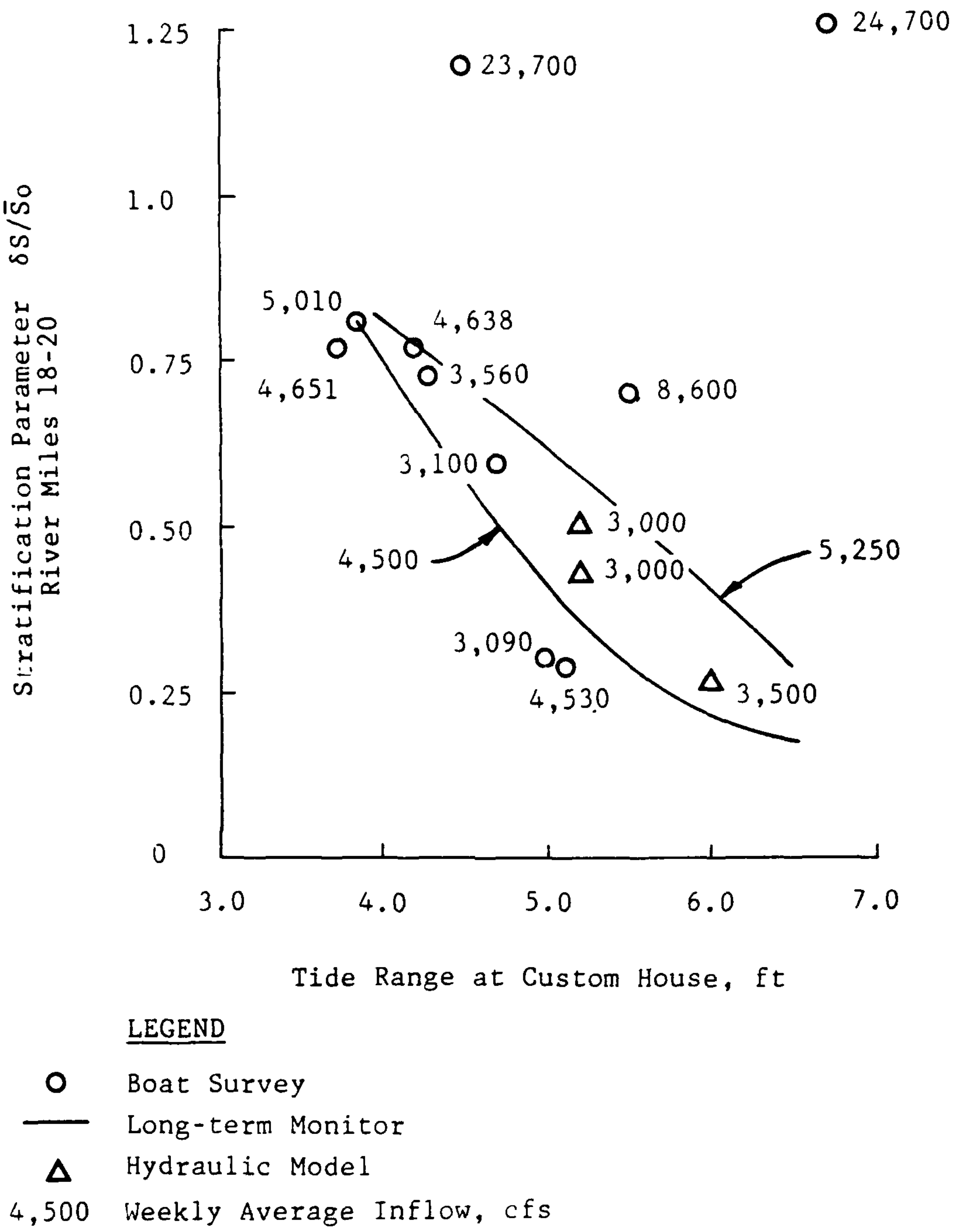

Figure 2. Variability of salinity stratification with tide range in the vicinity of Army Depot

according to the 1987 long-term monitoring data. The effect was more pronounced at the upstream long-term monitoring station.

43. The composite trend of the effect of inflow on salinity stratification in the vicinity of Army Depot was plotted in Figure 3 using available data from the 5.0- to 5.5-ft tide range grouped around the average tide range.

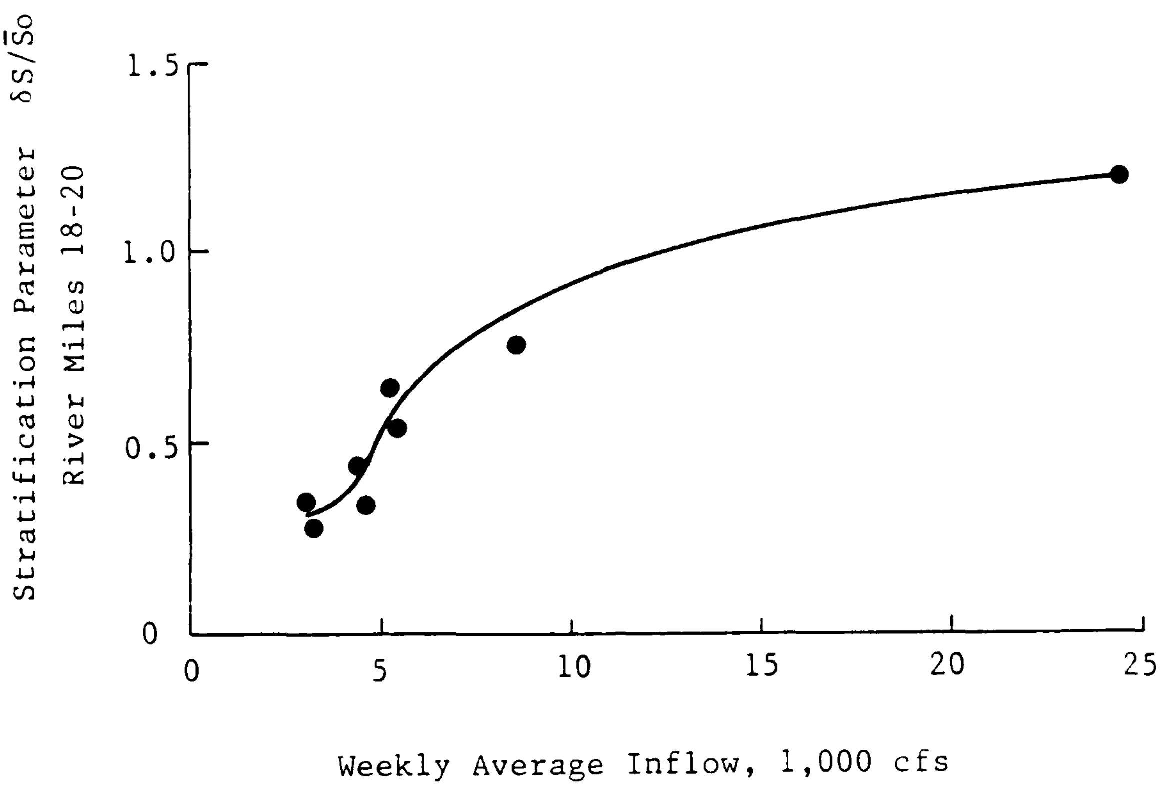

Figure 3. Inflow effects on salinity stratification in the vicinity of Army Depot for 5.0- to 5.5-ft tide range

Figure 3 includes USAEWES boat survey and long-term monitor data, and the 1971 prototype low-inflow test data point. All available data for the vicinity of the Army Depot were included in Figure 3, specifically the following:

Approximate Inflow, cfs	Data Sources
3,000	USAEWES survey 10/25/85, supplemental data 11/13/71
4,500	USAEWES survey 4/16/85, 1987 long-term trend lines at 5.0- and 5.5-ft tide ranges
5,250	Long-term trend lines at 5.0- and 5.5-ft tide ranges
8,600	USAEWES survey 7/15/82
25,000	USAEWES surveys 12/5/79 and 5/7/80 (interpolated)

A sharp increase in stratification regime is shown to occur between the 4,500- and 5,250-cfs weekly average inflows, indicating a deterioration in harbor mixing in this inflow range.

Maximum Daily Inflows

44. The effects of maximum daily inflow levels on harbor conditions

were not specifically tested during harbor monitoring studies. The maximum daily inflow range experienced during the 1987 monitoring period was not important to harbor conditions, while 2-day and longer total inflows did have an effect on harbor stratification.

45. Daily and 2-day total inflows were compared to stratification fluctuations from the tide range/stratification trend line. The 2-day total inflows showed a weak correlation (about 0.35) to stratification fluctuations, while the daily inflows showed almost no correlation (<0.0).

46. Maximum inflow limits specified as a series of total inflows for 1-4 days would protect harbor stratification conditions based on observed conditions presented in Appendix B. The rediversion project report (US Senate 1968) had planned for an allowable 70-hr zero-flow period. Previous hydraulic model tests showed that a 4-day weekly inflow schedule had no adverse effect on harbor conditions (Bobb and Simmons 1966), so that 31,500-cfs total inflow (4,500-cfs weekly average) for 4 days should not adversely affect harbor conditions. Maximum consecutive total daily inflows for 1-4 days were about 9,500, 16,850, 22,000, and 27,000 cfs, respectively, for the 4,500-cfs weekly average period in April 1987. Weekly zero-flow periods were 2 days or less in April 1987.

Shoaling Reduction at 3,000- to 4,500-cfs Inflow

47. Appendix C presents an analysis of shoaling in the range of 3,000- to 4,500-cfs weekly average inflows, which is summarized here. Rediversion shoaling reduction will result from improvements in harbor flushing and sediment inflow conditions. Less than half of the prediversion shoaling material could be accounted for by upstream and harbor sources, which were assumed to be reduced in proportion to the inflow. The unknown sediment source could be made up largely from sediments of ocean origin. Reduction of the unknown source was assumed to be related to the flushing efficiency of the harbor, and therefore equal for both 3,000- and 4,500-cfs inflows.

48. The prediction method used a sediment budget approach. The effect of rediversion inflows on each sediment source component was estimated and summed to an overall reduction for 3,000- and 4,500-cfs inflows. Entrance channel shoaling was estimated to be reduced in proportion to the harbor shoaling reductions.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

49. This study concluded that harbor sediment flushing conditions were variable but similar in the range from 3,000- to 4,500-cfs weekly average inflows. Field tests in Charleston Harbor showed that a 4,500-cfs weekly average freshwater inflow produced the vertical mixing conditions that had been expected after the rediversion of all but 3,000 cfs of the Cooper River. Vertical salinity stratification was found to be slightly better (less stratified) during 4,500-cfs field tests than predicted by 3,000-cfs hydraulic model tests (Figure 2). Weekly average inflows between 3,000 and 4,500 cfs did not show further decreases in vertical salinity stratification, while inflows slightly higher produced more stratified harbor conditions (Figure 3).

50. Within the 3,000- to 4,500-cfs inflow range, shoaling reductions are expected to be within about 4 percent and hence nondamaging with respect to rediversion project expectations. The harbor maintenance dredging requirements for this range of inflows is expected to be about 200,000 cu yd annually.

51. It is recommended that the weekly average flow from Pinopolis be set in the range of 3,000-4,500 cfs to obtain expected shoaling reduction benefits. That recommendation is based on an analysis of harbor monitoring field data and harbor shoaling conditions. *Higher weekly average inflows would inhibit sediment flushing and could be damaging to harbor shoaling conditions.*

52. Inflows established by the rediversion will vary day-to-day to maintain a weekly average. Maximum consecutive total daily inflows for 1, 2, 3, and 4 days are recommended to be 10,000, 17,000, 24,000, and 31,500 cfs, respectively, slightly greater than the observed maximum total inflows for April 1987. Consecutive total daily inflow is the sum of average daily inflows taken over a certain number of consecutive days. Higher total inflows for 1-4 days would require testing to ensure that they would not adversely affect harbor conditions.

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Table 1

Charleston Harbor Salinity Stratification for USAEWES Surveys, Average for River Miles 8-26

Survey Date	Inflow cfs*	Tide Range ft**	$\delta S/\bar{S}o$	
			Mean†	Range
5 Dec 1979	24,700	6.7	0.65	0.12-1.27
7 May 1980	23,700	4.5	1.12	0.41-2.22
15 Jul 1982	8,600	5.5	0.56	0.21-1.16
16 Apr 1985	4,530	5.1	0.15	0.06-0.28
4 Oct 1985	3,560	4.3	0.57	0.17-1.11
25 Oct 1985	3,090	5.0	0.27	0.09-0.45
23 Nov 1985	3,100	4.8	0.58	0.14-1.08
19 Dec 1985	4,900	4.3	0.56	0.23-1.10
6 May 1987	4,651	3.7	0.62	0.36-0.79
3 Jun 1987	4,147	3.8	0.63	0.21-0.96
1 Jul 1987	4,638	4.2	0.57	0.21-1.10

* Average of the week prior to the survey.
** Referenced to the Customs House gage.
† Using hourly or half-hourly samples over a tidal cycle.

Table 2

Supplemental Salinity Stratification Data for River Miles 8-26

Inflow cfs*	Tide Range ft**	$\delta S/\bar{S}o$		Source
		Mean	Range	
High-Water Field Samples Taken 1-3 Dec 1978				
3,000	5.6-6.0	0.19	0.04-0.43	South Carolina Water Resources Commission 1979
High-Water Field Samples Taken 13 Nov 1971				
3,000	5.4	0.37	0.14-0.90	Benson 1977
High and Low Slack-Water Model Data				
3,000	5.2	0.34	0.10-0.52	Bobb and Simmons 1966
3,000	5.2	0.25	0.07-0.50	Bobb and Simmons 1966
3,500	6.0	0.18	0.04-0.39	Benson 1976

* Average of the week prior to the survey.
** Referenced to the Customs House gage.

APPENDIX A: ANALYSIS OF 1985 HARBOR MONITORING DATA

Purpose

1. The purpose of this appendix is to present results of prerediversion and 1985 postrediversion field surveys with respect to the flushing characteristics of Charleston Harbor. The purpose of the overall study is given in the main body of this report.

Scope

2. This appendix presents analyses relating to sediment flushing from the harbor using salinity and velocity data from five surveys made after rediversion in 1985, at about 3,000- to 5,000-cfs weekly average inflow, and three surveys made before rediversion (1979-1982) for comparison. The intensive 13-hr surveys consisted of six stations along the estuary where current speed and directions and salinity samples from five depths were collected every half hour. Figure A1 shows the locations of the sampling stations. Sta 2-7 were located and sampled at channel center lines. Data from the surveys were reduced to computer files and plotted. Data were used to develop correlations and averages to describe flow and salt regimes.

3. Suspended sediment data, not previously reported, are also presented here. Data were collected from a 24-day automatic suspended sediment sampler between the fourth and fifth surveys. These data were collected to describe the fortnightly tidal effects on suspended sediment concentrations. Suspended sediment data were also collected at sta 2 during the fourth and fifth surveys. These data were used to calculate suspended sediment stratification and flux components.

Survey Conditions

4. Surveys were arranged into three groups for analysis and comparison. The first group consisted of the three prerediversion surveys, lettered A-C. The remaining surveys were performed after rediversion. The second group was the single survey taken 16 April 1985, designated survey 1. The third group was the fall 1985 surveys, numbered 2-5. Results from survey 1,

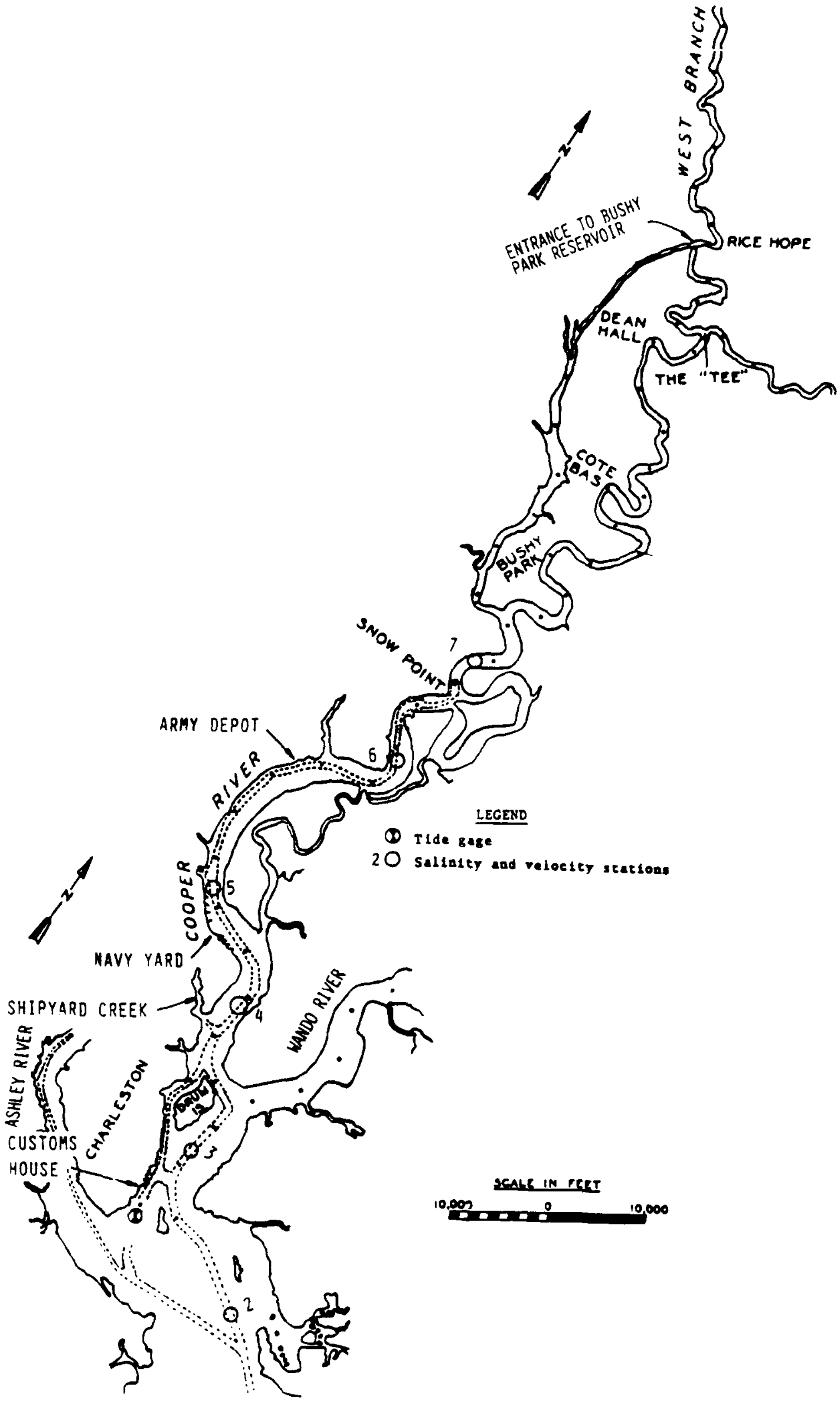


Figure A1. Location of tide, salinity, and velocity stations discussed later, were different enough from the other postrediversion surveys to warrant a separate grouping. Conditions other than inflow were apparently responsible.

5. Table A1 summarizes tidal and freshwater inflow conditions for the surveys. A weekly average was used to characterize freshwater inflow for the purpose of identifying harbor effects. Previous hydraulic model studies found that changes in inflow shorter than about a week had little effect on harbor conditions (Bobb and Simmons 1966),* although salinity conditions in the upper estuary could be affected by such changes (Benson and Boland 1977).

6. Rainfall can act as a direct freshwater inflow to the estuary and wind can affect circulation and mixing. Both are important to the interpretation of survey results. The following is a summary of conditions that occurred during and before each of the surveys, rainfall as reported by the National Weather Service at Charleston, and winds as observed on the survey boats:

Survey	Rainfall and Wind Conditions
A	No rain fell the day of the 5 Dec 1979 survey, nor during the week preceding the survey. Survey winds were south 8-10 knots.
B	No rain fell the day of the 7 May 1980 survey, nor during the week preceding the survey. Survey winds were northwest 8-10 knots then southwest 12-15 knots.
C	The day of the 15 Jul 1982 survey, 1.99 in. of rain fell. In addition, 1.4 in. of rain fell during the week preceding the survey. Survey winds were southeast 5-8 knots then became calm.
1	The day of the 16 Apr 1985 survey, 0.01 in. of rain fell. In addition, 0.36 in. of rain fell during the week preceding the survey. Survey winds were southwest 8-10 knots.
2	No rain fell the day of the 4 Oct 1985 survey, nor during the preceding week. At the Charleston Airport, however, 1.59 in. of rain fell during the week preceding the survey. Survey winds were west 5-8 knots then south 10-12 knots.
3	No rain fell the day of the 25 Oct 1985 survey, and only 0.08 in. of rain fell during the preceding week. Survey winds were north 5-10 knots.

(Continued)

* References cited in this appendix appear at the end of the main body of the report.

Survey	Rainfall and Wind Conditions
4	No rain fell the day of the 23 Nov 1985 survey, but 1.57 in. of rain fell the preceding day and 0.36 in. of rain fell 2 days prior to that (3.15 in. were recorded at the Charleston Airport). These rainfalls were associated with Hurricane Kate, which also produced high winds in the area. Survey winds were north 8-10 knots.
5	No rain fell the day of the 19 Dec 1985 survey, but 0.77 in. of rain fell during the preceding week. Survey winds were north-northwest 8-12 knots.

7. During the spring-neap suspended sediment collection, a storm occurred on the 12th and 13th of December. This storm dropped 0.77 in. of rain and was accompanied by very high winds.

8. Conditions in the upper estuary during the 1985 surveys displayed variability, reflecting to a certain extent circulation and mixing in the harbor. During the spring 1985 survey (survey 1) average water and conductance levels in the upper estuary were lower than for the fall 1985 surveys (2-5). Figures A2 and A3 show plots of daily average water levels inside the Bushy Park Reservoir at the DuPont intake US Geological Survey (USGS) station, and daily average surface specific conductances at Pimlico (river mile 47) for the spring and fall surveys, respectively. Figure A4 shows daily surface maximum conductances at the DuPont intake station for all of water year 1986 (beginning 1 October 1985) including the fall survey period.

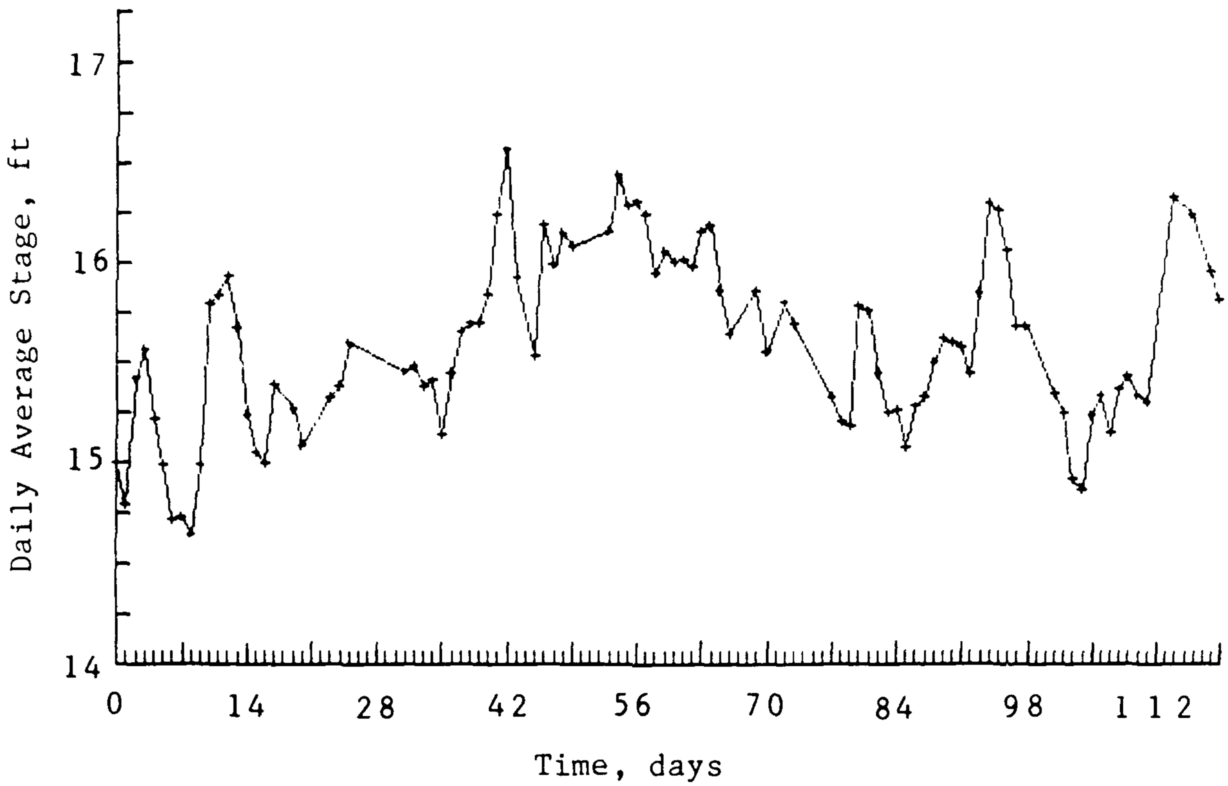
Process Description

9. Rediversion project studies indicated that the effectiveness of the inflow reduction in reducing shoaling was due not only to the reduction of sediment supply but also to the increased capacity of the harbor to flush sediments seaward. Thus, the flushing capacity of the harbor is the main technical issue for this appendix.

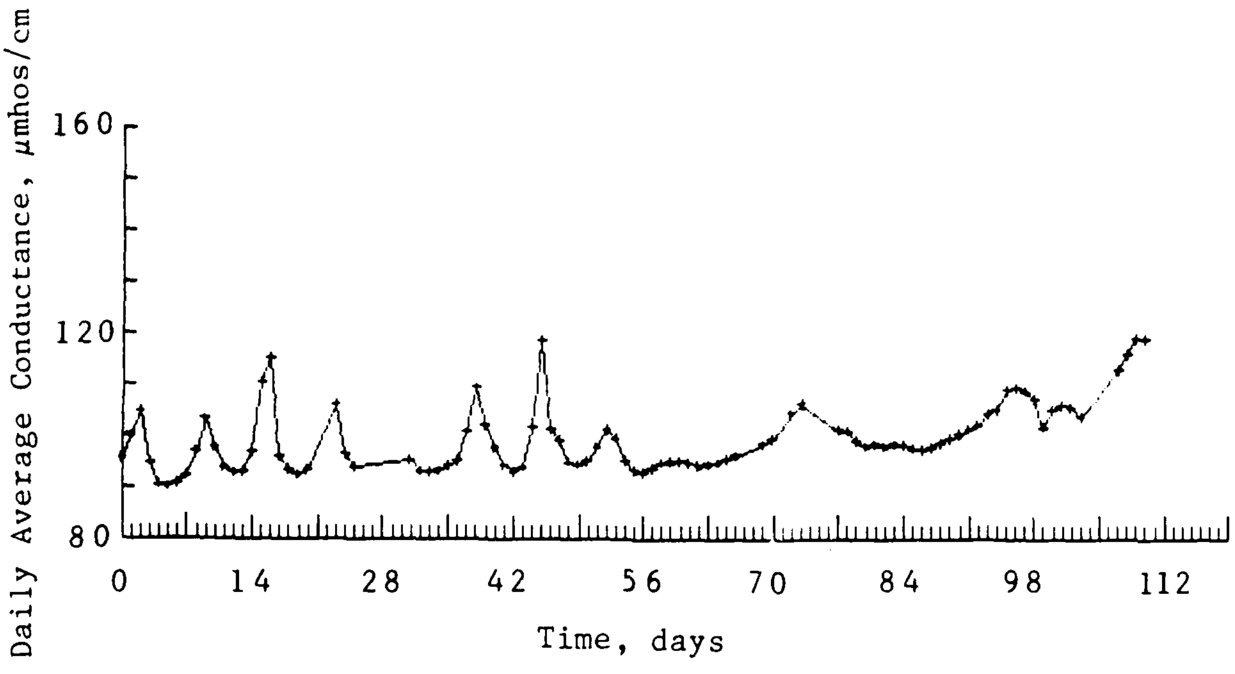
10. This section briefly reviews general sediment flushing processes in estuaries and results from hydraulic model sediment studies of Charleston Harbor. A conceptual model of sediment flushing in estuaries is presented to describe general processes and process interrelationships. Sediment flushing parameters used in this study are introduced in this section, and defined in more detail in the next section on analytical procedures.

Sediment flushing in estuaries

11. Sediment flushing is the ability or property of an estuary to

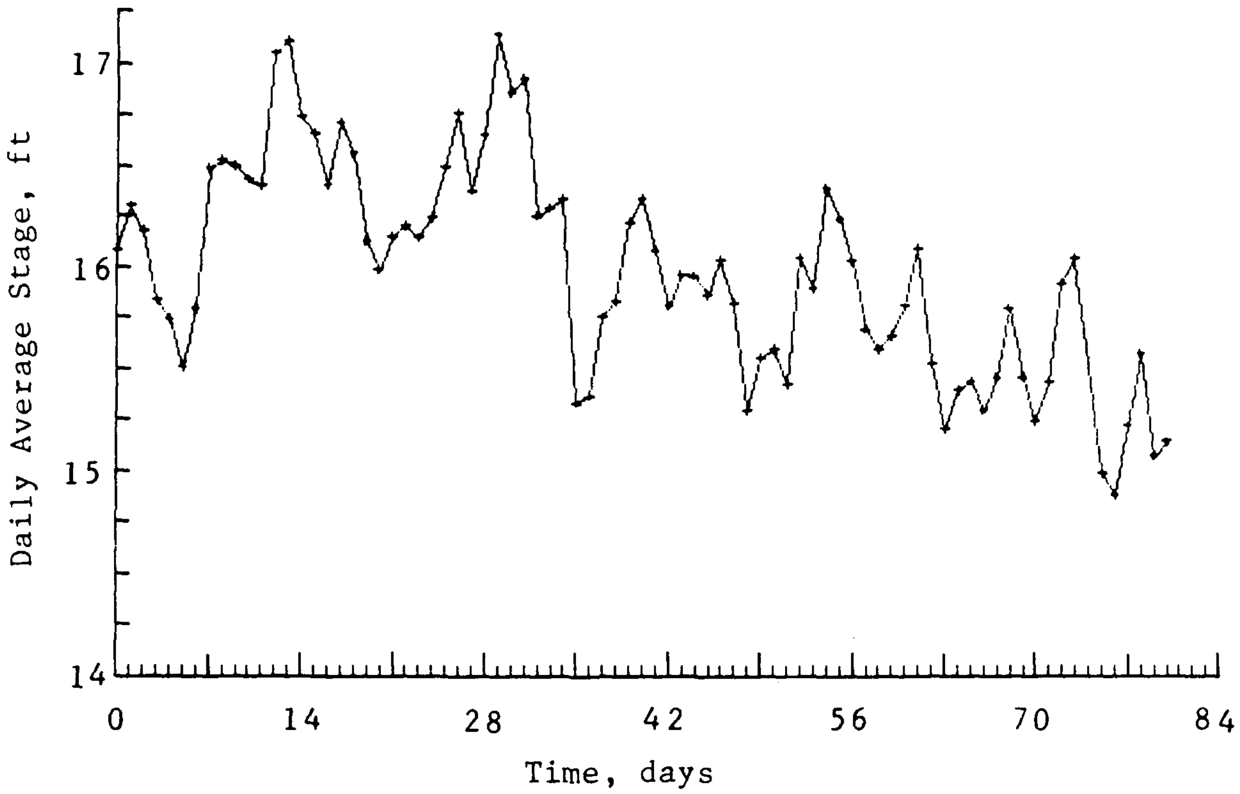


a. DuPont intake station

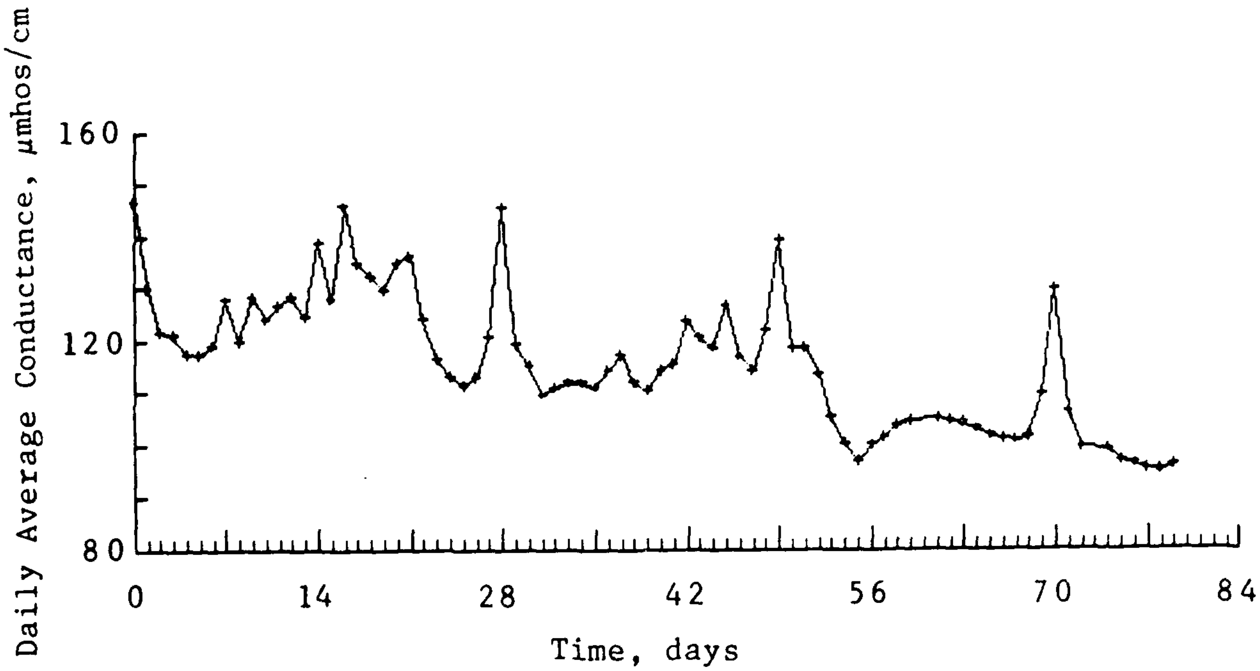


b. Pimlico station

Figure A2. Daily average stage at the DuPont intake station inside Bushy Park (top), and daily average conductances at the Pimlico station (river mile 47, bottom) starting 24 March 1985 (spring survey 1 taken day 23)



a. DuPont intake station



b. Pimlico station

Figure A3. Daily average stage at the DuPont intake station inside Bushy Park (top), and daily average conductances at the Pimlico station (river mile 47, bottom) starting 1 October 1985 (fall surveys 2-5 taken on days 3, 24, 53, and 79, respectively)

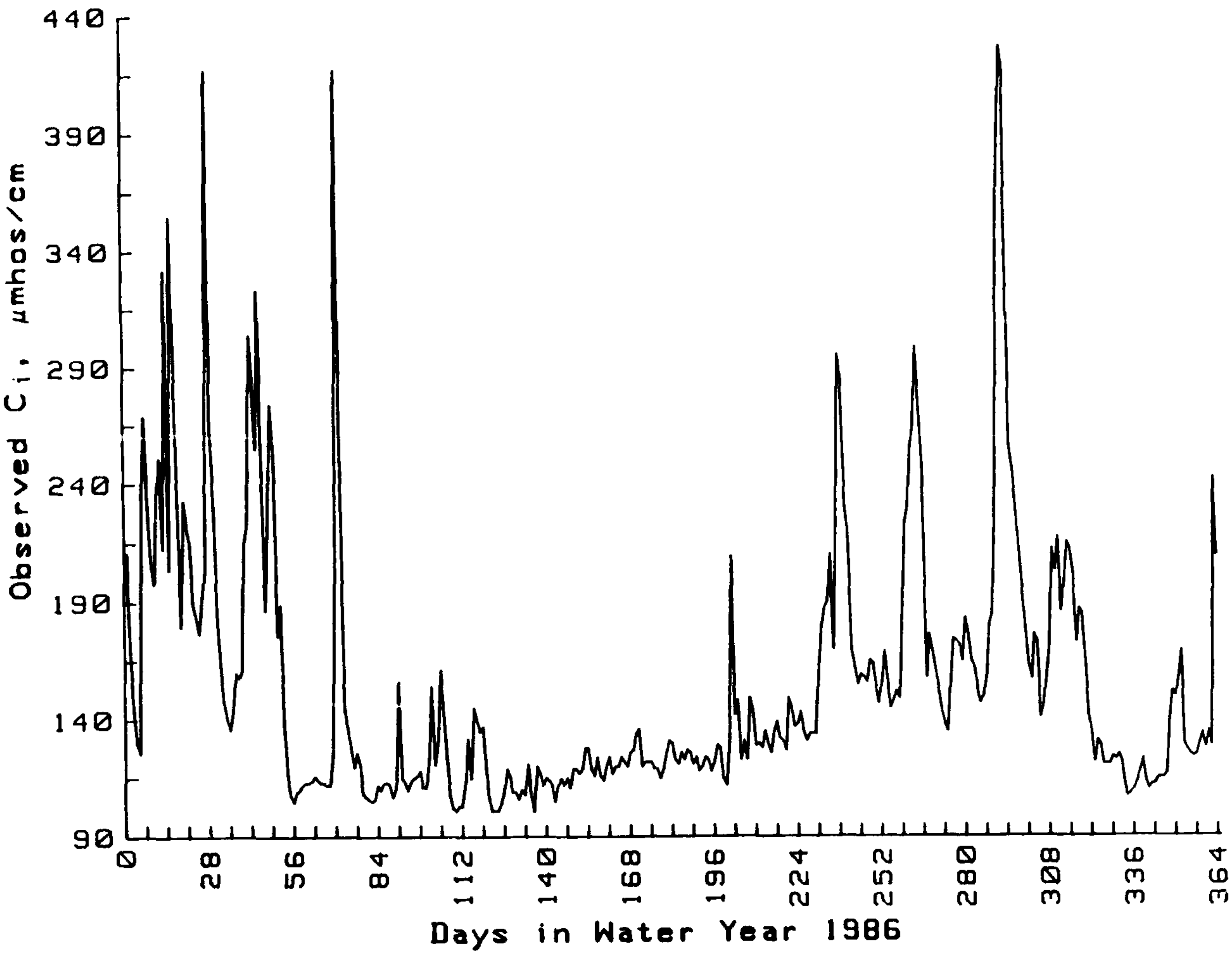


Figure A4. Daily surface maximum conductances at the DuPont intake station inside Bushy Park starting 1 October 1985 (fall surveys 2-5 taken on days 3, 24, 53, and 79, respectively)

transport sediments seaward, carrying them permanently out of the system. Sediment flushing is inversely proportional to shoaling at a given sediment inflow. It is well-established that estuaries generally retain and/or accumulate sediments with varying degrees of efficiency. However, the present state of understanding of the pathways and budgets of sediments in estuaries is generally rather limited (Uncles, Elliott, and Weston 1985).

12. Sediment particulates and colloids carried by freshwater inflows change upon contact with saline water as interparticle aggregations, and hence settling, increase. Significant amounts of sediment, both coarse and fine, can enter estuaries from seaward and accumulate. Generally, estuaries tend to be depositional and fill over time.

13. A dominant feature of suspended sediment in estuaries is an area of

maximum concentration known as the turbidity maximum. This zone is often an area of rapid sediment accumulation. The zone of maximum suspended sediment concentration is usually located longitudinally at the location of 1-5 ppt salinity average, or at the inflection point of the longitudinal salinity gradient (Fischer 1972). This zone often coincides with the null zone of vertical circulation, where the upstream gravity current is balanced by seaward riverflow, and tidal-averaged near-bed flows are minimal.

14. Recent measurements of suspended sediment flux in partly mixed estuaries, summarized by Dyer (1987), indicated the importance of the tidal pumping to sediment flux and to the maintenance of the zone of maximum suspended sediment concentration. Tidal pumping occurs as phase differences between suspended concentrations and velocities cause a preferred direction for transport. Tidal pumping often operates in the direction of near-bed vertical circulation, and cycles sediment material into the turbidity maximum. However, tidal pumping does not depend directly on vertical circulation. Vertical circulation has been found by recent studies to be of secondary importance to suspended sediment transport in partly mixed estuaries. Older conceptual models generally assumed that vertical circulation maintained turbidity maximums and was responsible for suspended sediment transport. Tidal pumping is defined in more detail in the section on analytical procedures.

15. Seaward of the null zone, flood flows near the bed are generally greater than ebb flows and contribute to tidal pumping. Flux measurements by Uncles, Elliott, and Weston (1985) in the partly mixed Tamar River estuary showed that during spring tides, upstream tidal pumping was the most important flux component. Teeter (1987) found that in the well-mixed Acushnet River estuary, tidal pumping was the dominant mode of transport for suspended sediments, and responsible for supplying the depositional zone and maintaining the zone of maximum suspended sediment concentration.

Hydraulic model findings

16. Hydraulic model studies examined the effects of rediversion on shoaling. Model tests indicated that at between 2,500 and 5,000 cfs the harbor abruptly became well-mixed and sediment flushing improved. Model shoaling studies found that an 80 percent reduction of flow (and sediment source strength) from 15,600 to 3,000 cfs reduced shoaling by 92 percent exclusive of entrance shoaling. The effectiveness of the flow reduction in reducing model shoaling was due not only to the reduction of sediment supply

but also to the increased capacity of the harbor to flush sediments seaward.

17. The earliest model study (USAEWES 1957) concluded that more than 99 percent of the shoaling increase in the 1940's was due to the diversion, brought on by the following factors:

- a. A density flow superimposed on the tidal flow that produced strong flood-dominated flows near the bed, preventing the estuary from disgorging its load to the sea.
- b. Increased colloids and dissolved material available to shoal the harbor, both from suspended load in the river and from erosion of the upper channel (assumed to have equal magnitudes).

Rediversion model tests performed at 2,500- and 5,000-cfs inflow implied that about 3,000 cfs was the maximum tolerable to harbor stratification, but the report cautioned that no single flow was best for the entire harbor.

Conceptual model of sediment flushing

18. The following paragraphs describe a conceptual model of sediment flushing. The conceptual model is an aid to the understanding and evaluation of the sediment flushing parameters developed from the field data. The conceptual model conveys the essential elements of a very complex system.

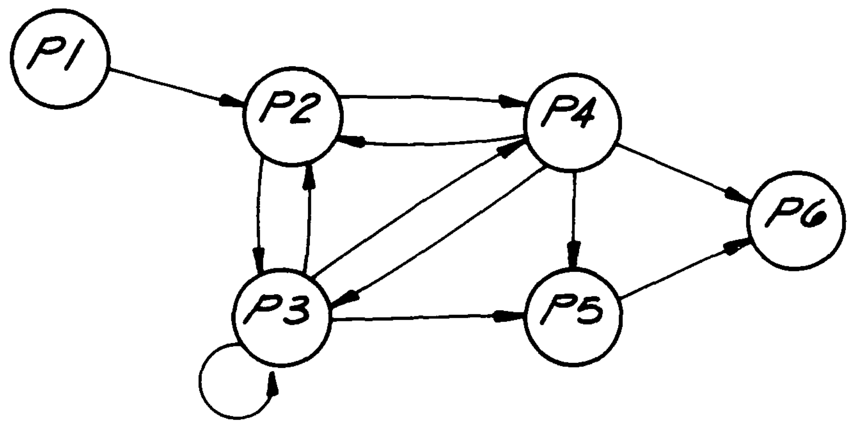
19. Important physical processes or activities contributing to sediment flushing were assembled and organized to describe estuarine processes interaction. Complex classes of processes or activities were grouped into a few general ones for the sake of simplicity. The following six general processes were identified that relate freshwater inflow to sediment flushing: freshwater inflow, vertical mixing, tidal hydraulics, sediment dynamics, vertical circulation, and tidal pumping.

20. A directed graph of the six processes or activities showing how they interact is presented in Figure A5. Terms used in Figure A5 to describe related field parameters are defined in the following section. In the directed graph, the six general processes are linked by directional coupling or influences. These couplings indicate influence and the direction of influence, not the flow of materials. Only the most important couplings were included in the conceptual model. Several pairs of processes have couplings in both directions between them. Individual processes and interaction are discussed in the next paragraphs. Tidal pumping was described previously in this section and will be further defined in the next section.

21. Freshwater inflow. By the definition of an estuary as an area where fresh and salt waters intermingle, freshwater inflow is an external

Symbol	Activity or Process	Related Observed Field Parameters*
P1	Freshwater inflow	Weekly average freshwater inflow Uf
P2	Vertical circulation	<Uov> , predominance, (<Uov> + Uf)/Uf
P3	Vertical mixing	$\delta S/\bar{S}o$, $\delta C/\bar{C}o$, Kz/Kzo
P4	Tidal hydraulics	U, Ui
P5	Sediment dynamics	C
P6	Tidal pumping	$\overline{UiCi}$, $\overline{UivCiv}$

* These parameters are defined in the Notation, Appendix E.



Process	Coupled Processes	Description of Couple
P1	P2	Horizontal buoyancy flux (+ gravity current)
P2	P3	Generation of vertical density gradient
	P4	Contribution to instantaneous velocity
P3	P2	Vertical buoyancy flux (- gravity current)
	P3	Reduction of vertical density gradient
	P4	Transmission of shear stress and velocity profile
	P5	Vertical sediment flux
P4	P2	Stoke's drift component
	P3	Shear stress generation
	P5	Shear stress at the bed
	P6	Instantaneous flow distribution
P5	P6	Sediment concentration distribution

Figure A5. Directed graph of processes influencing suspended sediment transport and flushing in partially mixed estuaries estuarine condition. The volume and density of freshwater inflows produce cross-sectionally averaged seaward flow and gravitational circulation seaward at the surface and upstream near the bed. In the system under consideration, freshwater inflow is largely controlled by releases at the Pinopolis Dam.

22. Vertical mixing. Vertical mixing involves the turbulent transport of momentum, energy, and mass (salinity and suspended sediments for this discussion), and decreases vertical gradients of these properties. Vertical mixing is controlled by the stabilizing effects of vertical salinity stratification and by turbulence generated by the tidal flow. Vertical mixing is damped by buoyancy effects in estuaries. Since vertical mixing controls transmission of shear stresses in the flow, velocity gradients increase and near-bed velocities decrease in more stratified flows (Anwar 1983). Vertical mixing is responsible for vertical buoyancy flux in estuaries and interacts with circulation (Linden and Simpson 1986). Conceptually, vertical mixing and circulation are inversely proportional (Bowden and Hamilton 1975). Circulation generates vertical gradients in the flow and hence decreases vertical mixing. Vertical mixing along with sediment settling properties controls the vertical distribution or stratification of suspended sediments, and thereby influences the position of suspended sediments in the flow. Similarly, vertical mixing redisperses eroded or entrained sediments into the water column.

23. Tidal hydraulics. Tidal hydraulics is defined as instantaneous flows and water level fluctuations. Tidal flows generate hydraulic shear stresses that produce vertical mixing and control several sediment dynamic processes. Instantaneous tidal flows, especially important near the bed, generally interact with suspended sediment fields to produce the dominant sediment flux component, tidal pumping. Tidal flows also produce tidal-averaged flow components that contribute to vertical circulation and mass transport. The nature of tidal propagation in estuaries often produces a tidal-averaged component opposite from the gravity current. This tidal-average component is usually referred to as Stokes drift, and is more completely described in the next section.

24. Vertical circulation. Vertical circulation is driven by salt-induced density effects produced by freshwater inflow and by geometry-induced tidal effects. Vertical circulations exist as time- or tidal-averaged flows and are superimposed onto tidal flows, making important contributions to tidal flow magnitudes, especially near the bed. The gravity current is usually the

dominant component of vertical circulation overall, and is proportional to the horizontal gradients of salinity and inversely proportional to the vertical mixing. Channel constrictions and branches and secondary circulation caused by channel curvature can also produce local tidal-averaged components in any direction. Vertical circulation produces vertical density gradients in the flow, and is important to salt flux over most of the length of estuaries.

25. Sediment dynamics. Sediment dynamics includes settling, deposition, consolidation, and erosion. Erosion and deposition are controlled by hydraulic shear stresses. Near-bed suspended sediment concentrations also control deposition. In the simple conceptual model presented here, sediment dynamics does not influence other processes. However, the components of sediment dynamics influence one another. For instance, settling influences deposition and consolidation influences erosion.

Important sediment flushing parameters

26. Many of the field processes described in the previous section are difficult to gage. Field parameters such as those shown in Figure A5 were developed from the field measurements to characterize certain aspects of all processes for this study. Those field parameters will be further defined in the next section.

27. In the main report, the key parameter used to judge sediment flushing conditions was salinity stratification, which is linked to vertical mixing. From the previous discussion it can be seen that vertical mixing is a very important process to sediment flushing. In addition, vertical mixing times are much shorter than vertical circulation times, meaning that sediment particles are mixed many times between surface and bottom waters in the time required for tidal-average flows to circulate them through and flush them from the estuary. An equally important consideration in evaluating sediment flushing parameters is the reliability of the field measurements, as will be discussed in the section on discussion of results.

Analytical Procedures

28. The following paragraphs describe the various analyses used to evaluate the sediment flushing characteristics of the harbor. Parameters were used to describe the important sediment flushing processes described in the previous part. In some cases, more than one parameter was used to describe

each process in an attempt to avoid certain weaknesses or assumptions inherent to all such parameters. In addition, correlations and correlation coefficients were calculated to determine the effects of freshwater inflow on sediment flushing from Charleston Harbor. Estuarine dynamics are complex, and even extensive, synoptic data sets can be difficult to interpret.

Vertical circulation

29. Flow predominance was one of several parameters developed from the field data used to characterize vertical circulation. Flow predominance is the fraction of the total flow over a tidal cycle that is in the ebb or seaward direction. Flow predominances were calculated as the seaward flow divided by the total flow at each station depth. Bottom flow predominances were used as an indication of upstream vertical circulation, the 0.5 bottom value indicating the null point where the flow at all depths was evenly balanced between seaward and landward during the measured tidal cycle. A value of 1.0 would indicate that the flow at that point was seaward throughout the tidal cycle, whereas a value of 0.0 would indicate upstream flow throughout the tidal cycle.

30. How well the predominance parameter represents vertical circulation depends on the presence of other estuarine dynamics. Subtidal motions and/or tidal asymmetries can cause depth-averaged tidal-mean currents to be different from the velocity associated with the average freshwater flow and vertical circulation, complicating data interpretation. For instance, if the daily mean water level is increasing, depth-averaged tidal-mean flows could be upstream. Predominances calculated from data taken at such a time would be too low, whereas those calculated from data taken one or more tidal cycles later might be too high with respect to vertical circulation.

31. Another circulation description was developed that removes the effects of depth averaged tidal-mean flows. Velocity data were first decomposed into components using a method similar to that of Lewis and Lewis (1983). For example at some time* t and station depth z :

$$U(z,t) = \bar{U}o + Uov(z) + Ui'(t) + Uiv'(z,t) \qquad \text{(A1)}$$

* For convenience, symbols and abbreviations are listed in the Notation (Appendix E).

where

$\bar{U}o$ = depth-averaged tidal-mean velocity

$Uov(z)$ = vertical deviation of the tidal-mean velocity from the depth mean

$Ui'(t)$ = instantaneous deviation of the depth mean from the tidal mean

$Uiv'(z,t)$ = vertical deviation of the instantaneous velocity from the depth mean

Then a parameter describing steady vertical shear at a station, $\langle Uov \rangle$, can be calculated as the root mean square (rms) of a station's $Uov(z)$. The depth average of $Uov(z)$ at a station is zero. $\langle Uov \rangle$ can be visualized as seaward at the surface and upstream at the bottom. Since $\langle Uov \rangle$ is separated from $\bar{U}o$, it can be combined with Uf, the weekly average cross-sectional mean freshwater velocity, to obtain circulation parameters ($\langle Uov \rangle - Uf$ at the bottom and $\langle Uov \rangle + Uf$ at the surface), which are independent from the fluctuations in Uo mentioned earlier.

32. Stokes velocities were computed from the data. Stokes velocity arises from the mass transport by tide or other wave propagation, and is related to the Lagrangian component not measurable at a fixed point. Stokes velocity was considered as a steady component and calculated as

$$Us(z) = \int \frac{\overline{U\ dt\ dU}}{dx} = \bar{U}so + Usv(z) \qquad \text{(A2)}$$

The Stokes velocity component was used in addition to other steady components to more accurately represent steady transport velocity components.

33. Tidal-mean currents at depth were also calculated during velocity decomposition processes. These parameters have the same shortcomings as predominance and, in addition, are dimensional.

34. All circulation parameters rely on point measurements of velocity. Such measurements can have errors introduced by boat motions, especially when sampling in deep, relatively open waters such as Charleston Harbor. Station location is another factor in the interpretation of circulation data. Previous hydraulic model studies (USAEWES 1957) collected circulation data at points across a channel section. Those measurements indicated that circulation can change in magnitude and even in direction with relatively small changes in horizontal location across the channel sections at Charleston Harbor.

Circulation/stratification

35. The method developed by Hansen and Rattray (1966) was used to analyze circulation and stratification. Their classification scheme is based on a theoretical analysis of estuarine salt balance. By plotting estuarine or estuarine area data in coordinates of circulation and stratification, the estuary "type" can be identified. Therefore, any change in circulation or stratification causes a change in the estuary type and could be a useful indicator of the importance and/or direction of the change.

36. The circulation parameter used in the analysis is the tidal-mean velocity at the surface normalized by the cross-sectional average freshwater velocity. In the notation developed here, a characteristic nondimensional tidal average velocity was formed by dividing the surface circulation parameter $\langle Uov \rangle + Uf$ by Uf . Thus:

$$\text{Nondimensional circulation parameter} = \frac{\langle Uov \rangle + Uf}{Uf} \qquad \text{(A3)}$$

A stratification parameter was calculated as the bottom-to-surface mean salinity difference δS divided by the depth-averaged tidal-mean salinity $\bar{S}o$

$$\text{Stratification parameter} = \frac{\delta S}{\bar{S}o} \qquad \text{(A4)}$$

Hansen and Rattray's salt balance analysis includes both river-induced and density-induced advection and horizontal diffusion. The upstream salt flux is taken as an advective component induced by vertical circulation and a diffusive component driven by horizontal diffusion. The fraction of total upstream salt flux driven by diffusion is designated v . If both circulation and stratification parameters can be measured, then v can be discerned using a circulation/stratification diagram.

Vertical mixing

37. In certain hydrodynamic systems, vertical mixing can be determined by observing passive tracers or with extremely sensitive measurement devices. Unfortunately, estuaries do not lend themselves to such measurement techniques, and vertical mixing must be inferred from other measurements. Salinity stratification, which was described in the last section, is one such parameter. In this section, another indirect measure of vertical mixing is described.

38. Buoyancy effects generally reduce vertical mixing in estuaries.

Richardson numbers gage the effect of buoyancy in a shear flow. Richardson numbers Ri were calculated and used to compute the ratio of vertical diffusivity to the vertical diffusivity of a homogeneous flow. Richardson numbers were calculated from instantaneous profiles of velocity and salinity using a quadratic function fit to determine spatial derivatives

$$Ri = \frac{g}{\rho} \frac{d\rho/dz}{(dU/dz)^2} \tag{A5}$$

where

g = acceleration of gravity

ρ = density (computed from salinity)

z = vertical distance up from the bed

The problem with estimating Ri in tidal flows is that velocity profiles are often nonlogarithmic and sometimes velocity gradients have negative signs.

39. The well-known Munk and Anderson (1948) expression was used to estimate the Richardson number effect on vertical eddy diffusivity Kz . The ratio of Kz to the homogeneous case Kzo was calculated using Ri :

$$\frac{Kz}{Kzo} = (1 + 3.33Ri)^{-3/2} \tag{A6}$$

This ratio has a range from 0 to 1, with 1 representing no effect of stratification on vertical mixing. The ratio was depth- and time-averaged at each station.

40. The weakness of the Kz/Kzo parameter for the present purposes is that it does not gage the effective or absolute value of the vertical eddy diffusivity, and therefore does not reflect the feedback between stratification and slopes of velocity profiles.

Correlation coefficients

41. The correlation coefficient is a measure of the linear relationship between two parameters. If the correlation coefficient is positive, then the two parameters vary directly. If the correlation coefficient is negative, then the two parameters vary inversely. Correlation coefficients of ±1 indicate perfect correlation, and 0 indicates no correlation.

42. Statistical correlation coefficients were determined for a matrix of twelve parameters: (a) river mile, (b) Kz/Kzo , (c) stratification δS , (d) stratification parameter, (e) predominance at the bottom, (f) Ui ,

(g) $\langle Uov \rangle$, (h) $\langle Uov \rangle - Uf$, (i) $\langle Uov \rangle / Ui$, (j) $Ui(\langle Uov \rangle - Uf)/\langle Uov \rangle$, (k) Uf , and (l) $(\langle Uov \rangle + Uf)/Uf$.

<u>Salinity flux components</u>

43. Synoptic measurements of salinities and currents taken over a tidal cycle can be decomposed into salinity flux components, each representing a different transport mode. The tidal average or residual transport is determined for each flux component allowing the importance of these transport modes to be assessed. The method used was similar to that presented by Lewis and Lewis (1983). Transport modes include circulation, tidal pumping, and depth-mean transport discussed in the previous section.

44. Salinity flux components, time- and/or space-averaged products of salinity, and velocity components were determined. These statistical properties are called correlations, and their values are related to the magnitudes of individual salinity and velocity components. Salinities S were first decomposed, for example, at some time t and depth z :

$$S(z,t) = \bar{S}o + Sov(z) + Si'(t) + Siv'(z,t) \qquad \text{(A7)}$$

where the salinity components were defined as for velocity. Salinity flux components were then calculated using velocity and salinity components, and the six important correlations used to represent net salt flux over a tidal cycle and flow depth h :

$$\text{Flux of } S = h\left(\bar{U}o\bar{S}o + \bar{U}s\bar{S}o + \overline{UiSi} + \overline{UovSov} + \overline{UsvSov} + \overline{UivSiv}\right) \qquad \text{(A8)}$$

where $\bar{U}o\bar{S}o$ and $\bar{U}s\bar{S}o$ were computed as the products of the depth- and time-averaged values, and the other correlations were time- and depth-averaged instantaneous products. $\bar{U}o\bar{S}o$ and $\bar{U}s\bar{S}o$ represent salt transport by depth-mean residual flows. $\overline{UiSi}$ is the correlation between depth-mean velocity and salinity fluctuations. $\overline{UovSov}$ and $\overline{UsvSov}$ represent transport by steady vertical shear. $\overline{UivSiv}$ is the transport from correlations between velocity and depth fluctuations. The first three components are depth mean, and the last three arise from vertical effects and circulation.

<u>Suspended sediment flux components</u>

45. Synoptic measurements of suspended sediment concentrations and currents taken over a tidal cycle can be decomposed into suspended sediment

flux components, each representing a different transport mode. The tidal average or residual transport is determined for each flux component, allowing the importance of these transport modes to be assessed.

46. Suspended sediment flux components were calculated by a method analogous to the salinity flux components described in the previous section. Suspended sediment flux components were calculated using velocity and suspended sediment C data, and the six important correlations used to represent net suspended sediment flux over a tidal cycle and flow depth h :

$$\text{Flux of } C = h\left(\bar{U}o\bar{C}o + \bar{U}s\bar{C}o + \overline{UiCi} + \overline{UovCov} + \overline{UsvCov} + \overline{UivCiv}\right) \qquad \text{(A9)}$$

where $\bar{U}o\bar{C}o$ and $\bar{U}s\bar{C}o$ were computed as the products of the depth- and time-averaged values, and the other correlations were time- and depth-averaged instantaneous products. $\bar{U}o\bar{C}o$ represents suspended sediment transport by depth-mean residual values. $\overline{UiCi}$ is the correlation between depth-mean velocity and sediment concentration fluctuations. $\overline{UovCov}$ is the transport associated with steady vertical shear and concentration deviations, and is produced by vertical circulation. $\overline{UivCiv}$ *represents transport by correla-*lations between fluctuations in velocity and concentration depth deviations. $\overline{UiCi}$ and $\overline{UivCiv}$ comprise tidal pumping. The first three components are depth mean, and the last three arise from vertical effects and circulation.

Suspended sediment
<u>spring-neap variability</u>

47. As described earlier in this appendix, suspended sediment fluxes can vary in magnitude and even direction during a spring-to-neap tidal sequence. This variation is caused by changes in the resuspension of sediments by tidal currents, circulation, and vertical mixing that accompany changes in tidal range and currents.

48. A 24-day automatic sampler was used to describe the spring-neap cycle of suspended solids in the lower estuary, which was then compared to spring-neap tidal variations. A strong meteorologic event was also documented by these data. The sampler was deployed at sta 2, drew a subsample at 0.75 depth every 6.2 hr, and composited four subsamples together into one sample representing a tidal day of 24.8 hr.

Results

49. Table A1 shows date, freshwater inflows, tide ranges, and daily mean tide level for the surveys. Table A1 also contains a key to the plots used to present results. Surveys were divided into three groups: the prerediversion surveys (A-C), the spring postrediversion survey (1), and the fall postrediversion surveys (2-5). Rediversion first started in March 1985, ran for about 2 months, and then was delayed until September 1985. Spring conditions in the harbor for survey 1, apart from freshwater inflow, were different enough from other surveys to warrant separating the spring from fall surveys. Data from the six center-line stations, surface, middepth, and bottom were used for analyses.

Circulation

50. Flow predominances at the bottom were plotted against channel mile distance. Figures A6-A8 show the results for the three survey groups. Flow was upstream at the bottom where predominances were less than 0.5, and seaward above 0.5.

51. The bottom circulation parameter, $\langle U_{ov} \rangle - U_f$, was described earlier as the vertical variation in the depth-mean flow offset by the freshwater velocity. This circulation parameter is in units of feet per second. $\langle U_{ov} \rangle - U_f$ was positive if the tidal-mean flow was upstream at the bottom and negative if seaward. Figures A9-A11 show the bottom circulation parameter plotted against river mile for the three survey groups.

Circulation/stratification

52. The nondimensional circulation parameter, defined by $\langle U_{ov} \rangle + U_f$ and normalized by U_f, was plotted against the stratification parameter on Hansen and Rattray's circulation/stratification diagrams (Hansen and Rattray 1966). Figures A12-A14 show results for the three survey groups. Figure A15 shows how other estuaries have classified on this diagram. A well-mixed estuary with little circulation should plot in the lower left of the diagram, while a salt wedge estuary should plot at the top of the diagram above $\delta S/\bar{S}_o = 1$. The vertically well-mixed condition was considered as less than $\delta S/\bar{S}_o = 0.1$ by Hansen and Rattray (1966). See Figure A15 for a further explanation of the diagram. The values of ν are the diffusive fraction of salt flux. For example, at $\nu = 0.2$, the diffusive portion of the salt flux is 20 percent and the remaining 80 percent is advective flux (circulation and

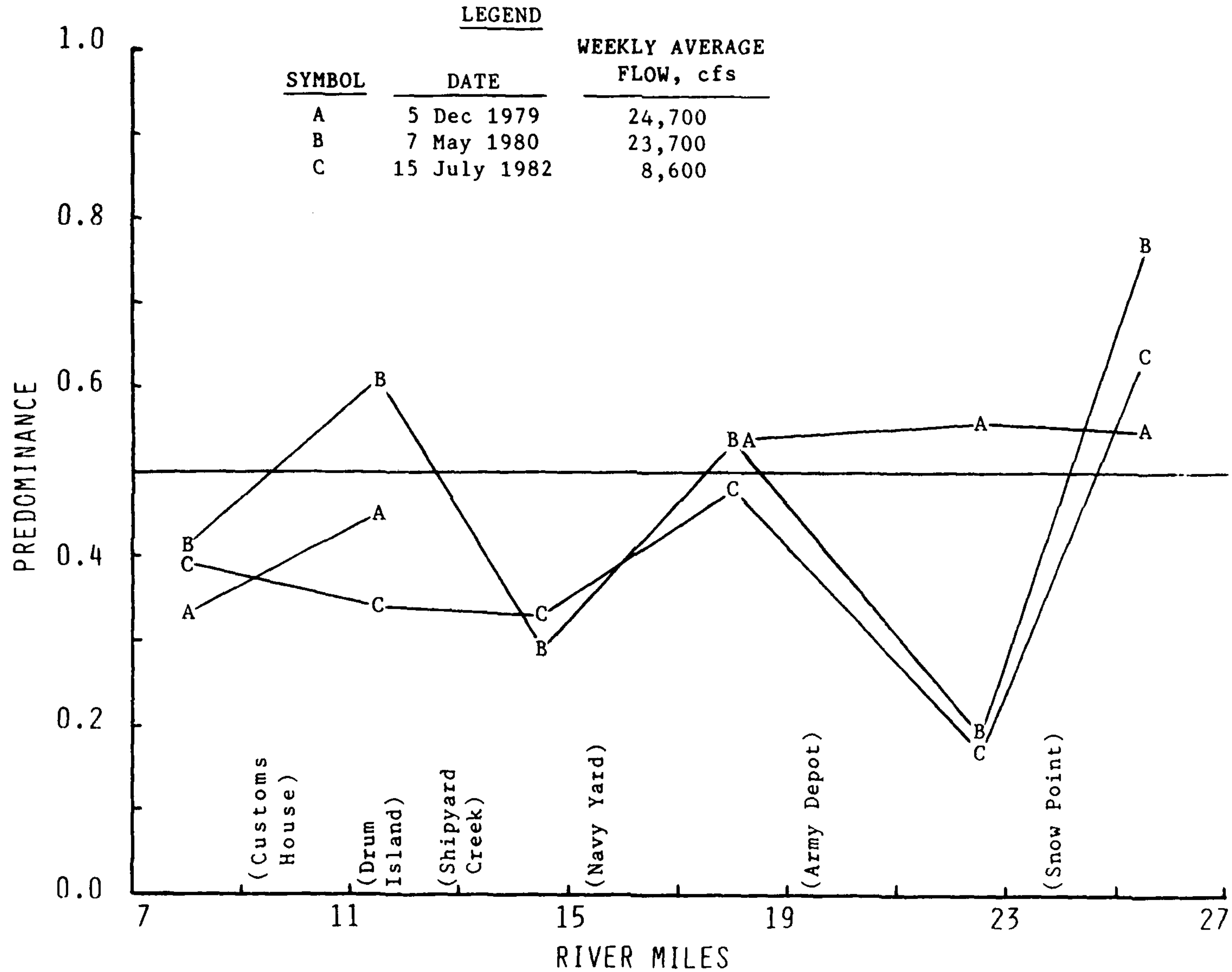


Figure A6. Bottom flow predominance for prerediversion surveys

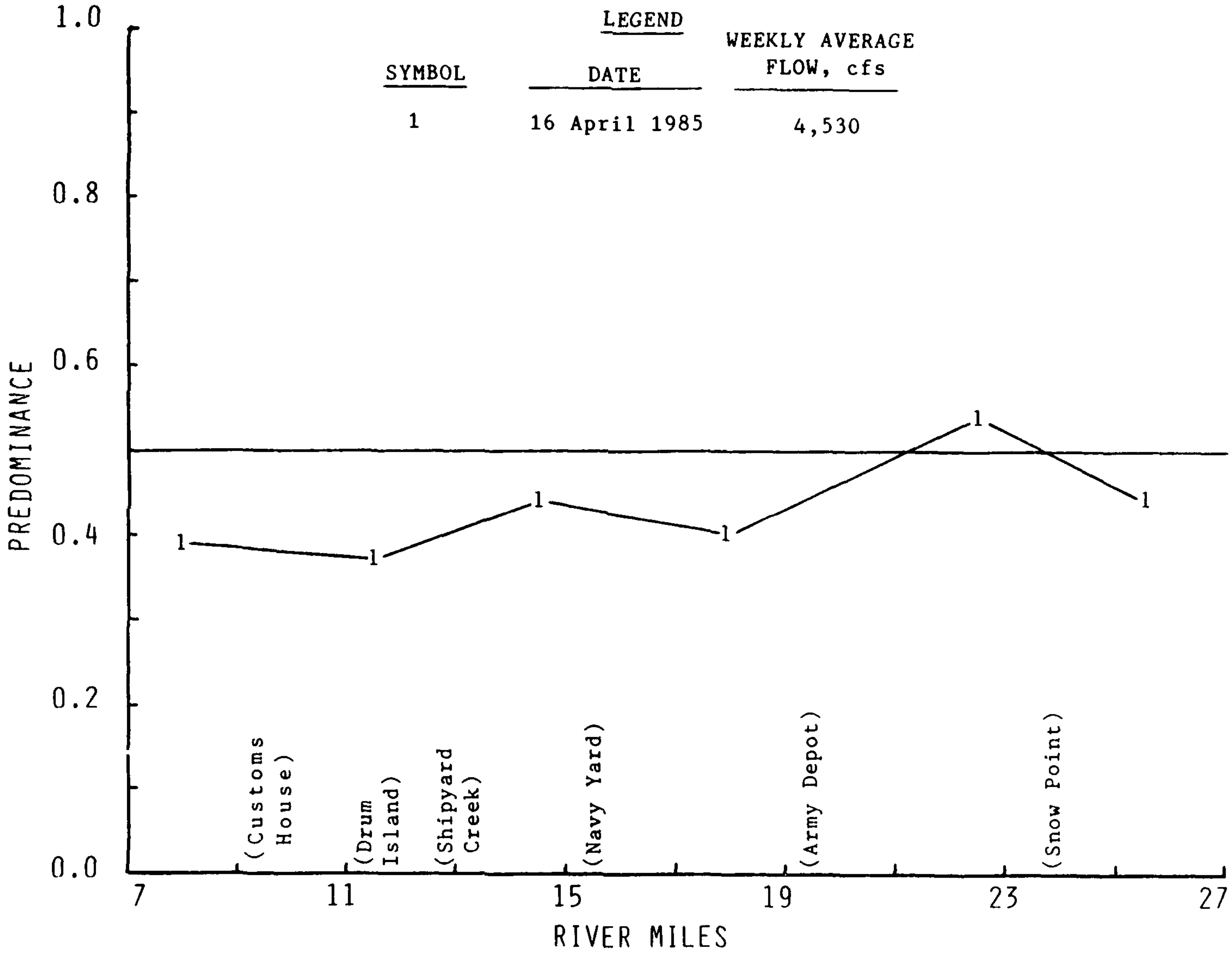


Figure A7. Bottom flow predominance for the 16 April 1985 survey

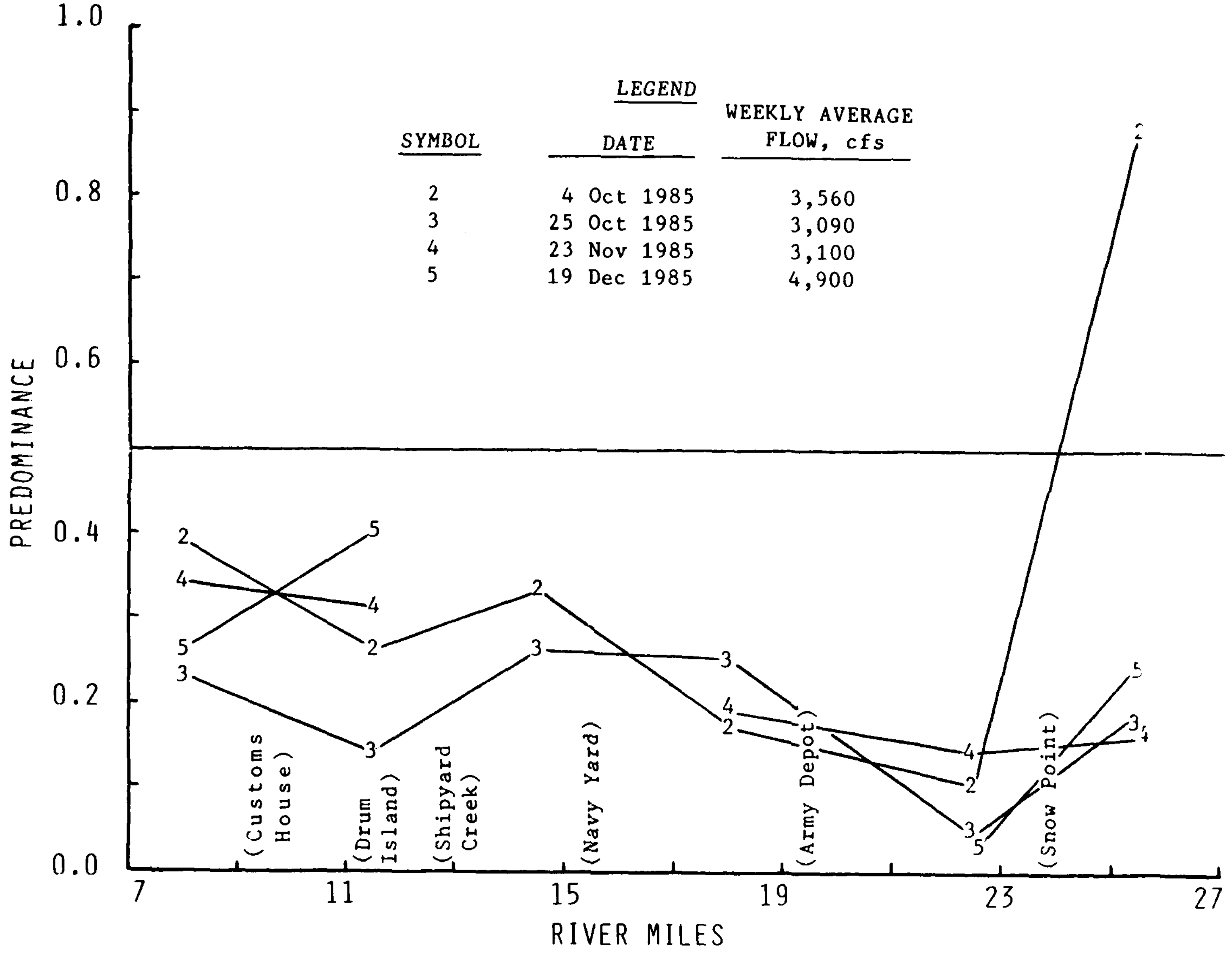


Figure A8. Bottom flow predominance for fall 1985 surveys

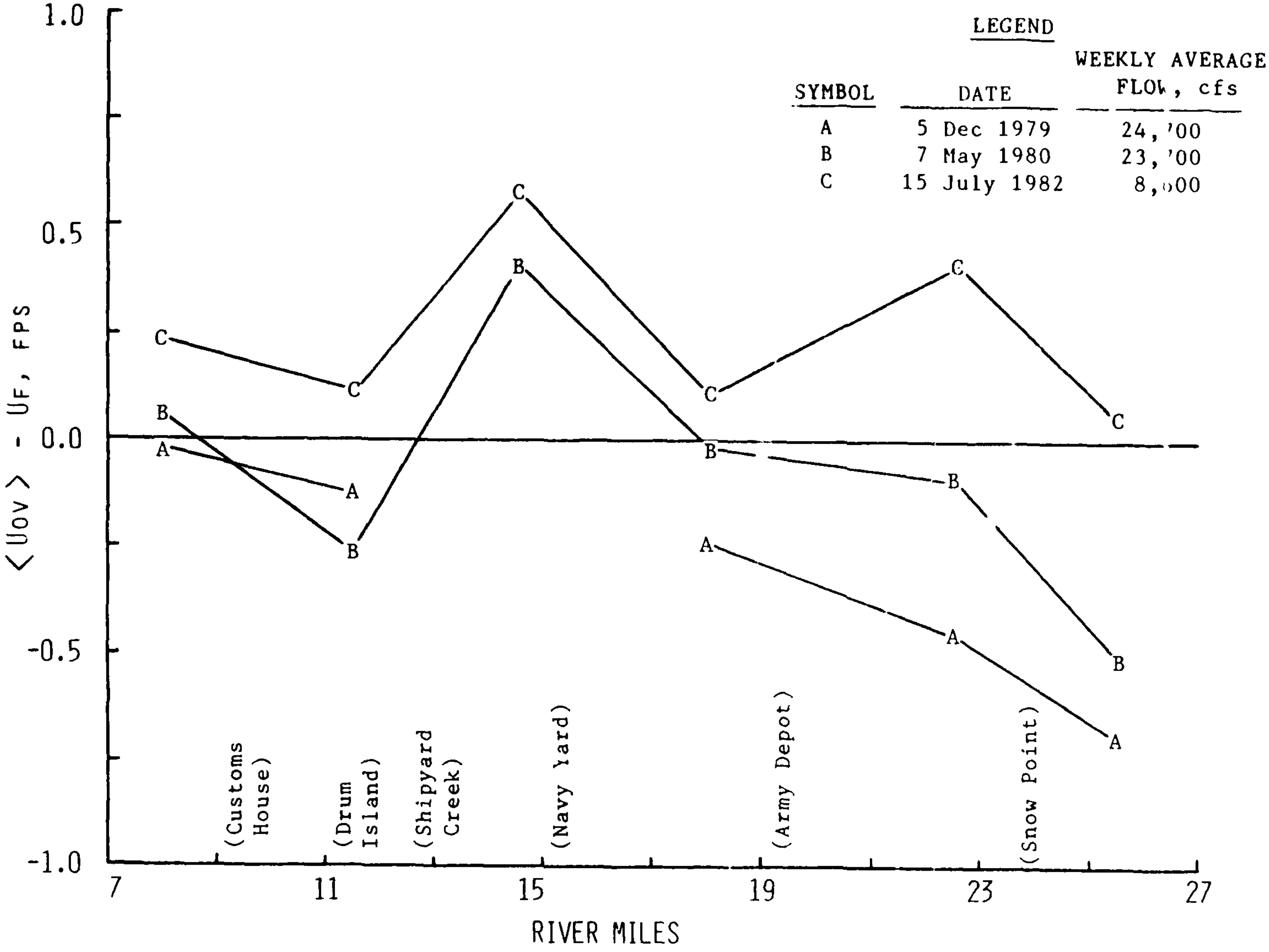


Figure A9. Bottom tidal-averaged circulation parameter for prediversion surveys

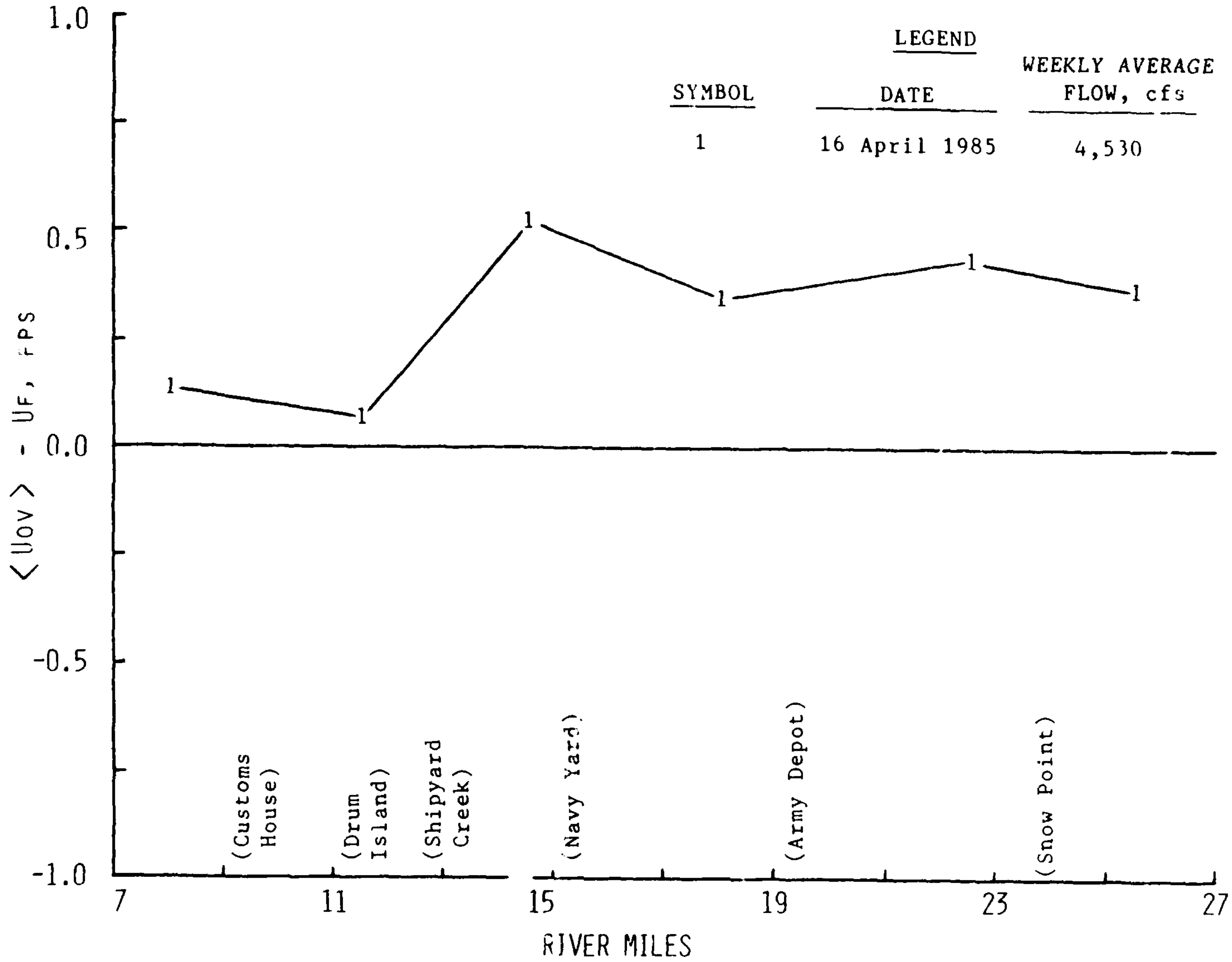


Figure A10. Bottom tidal-averaged circulation parameter for 16 April 1985 survey

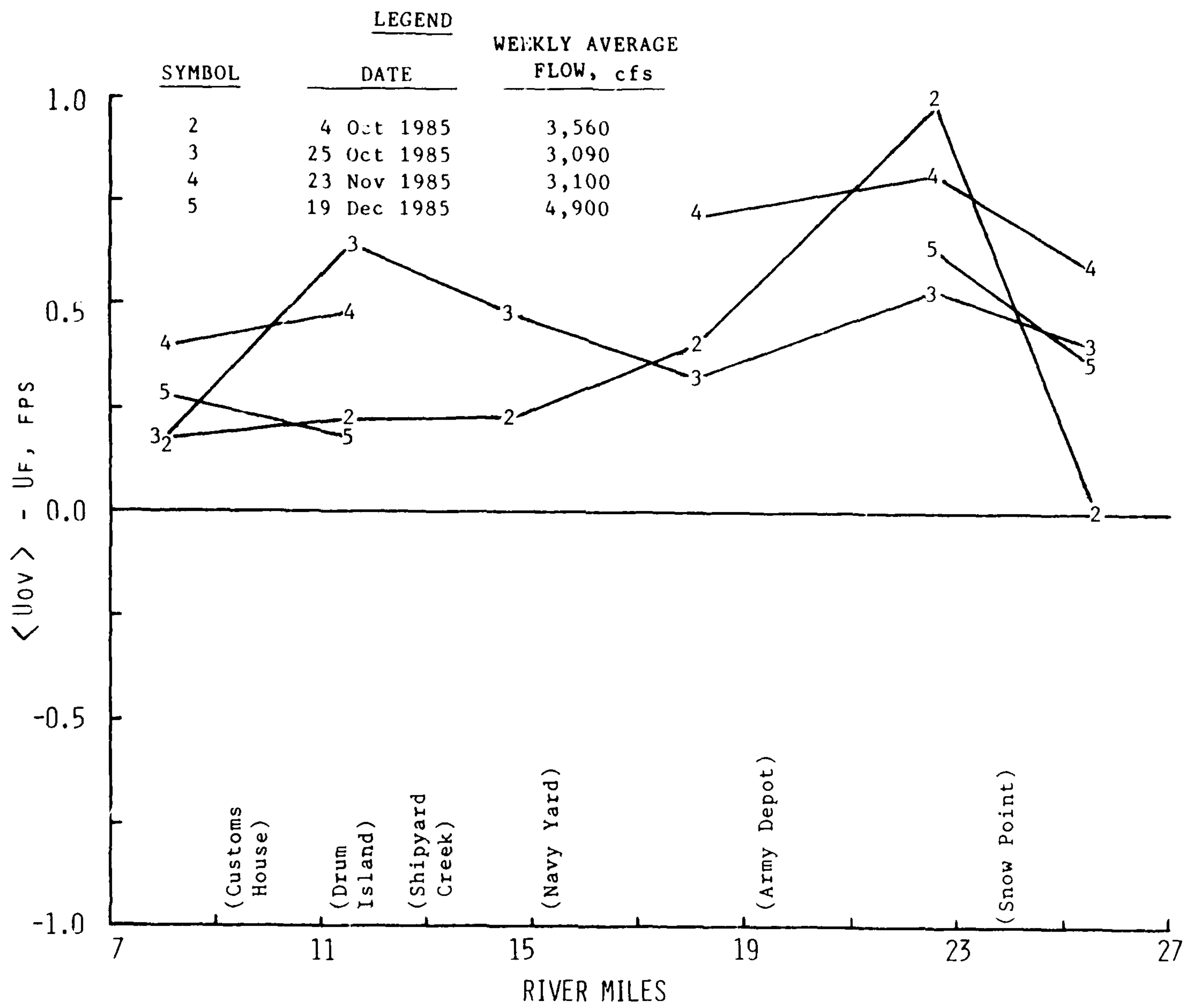
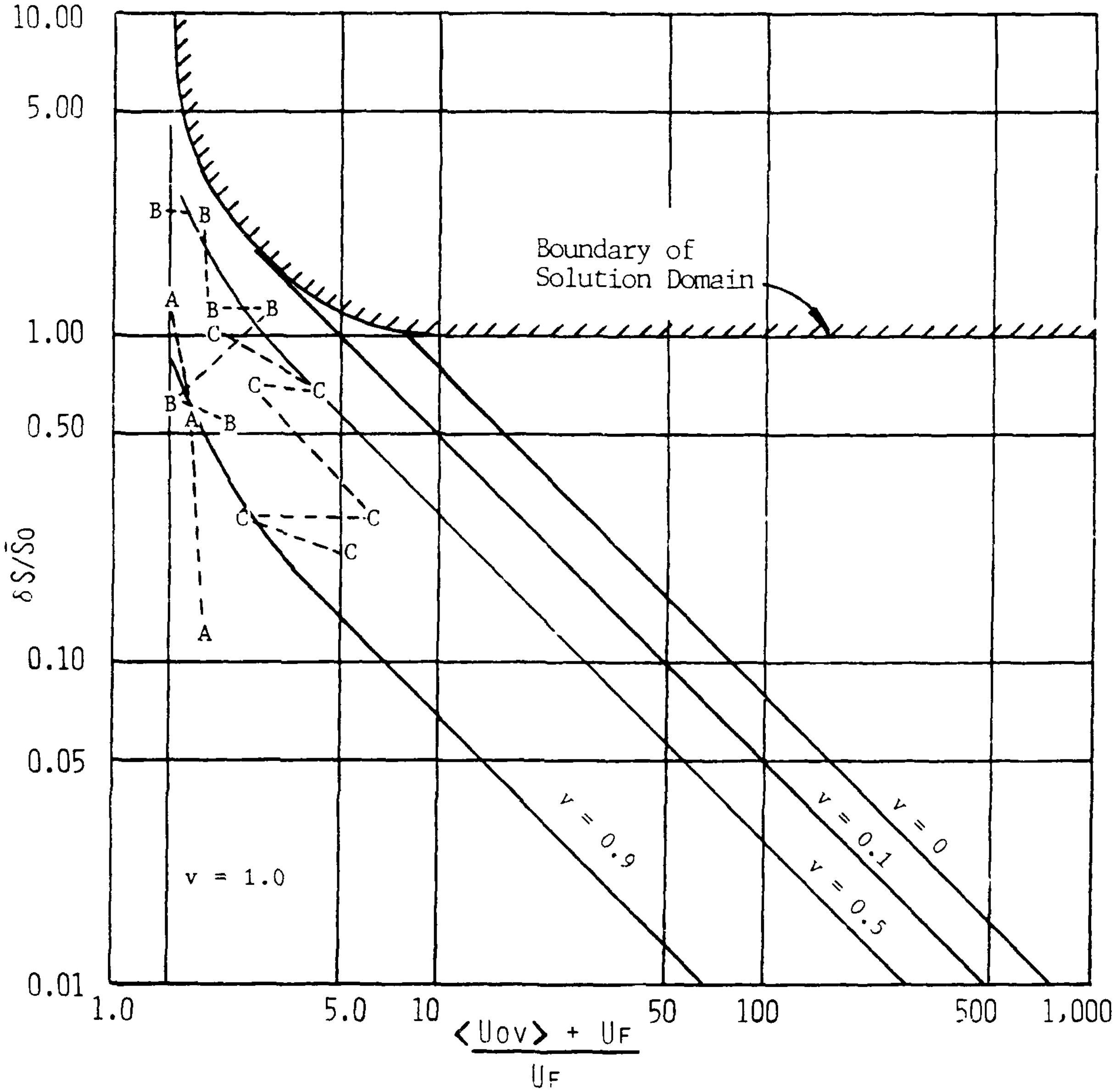


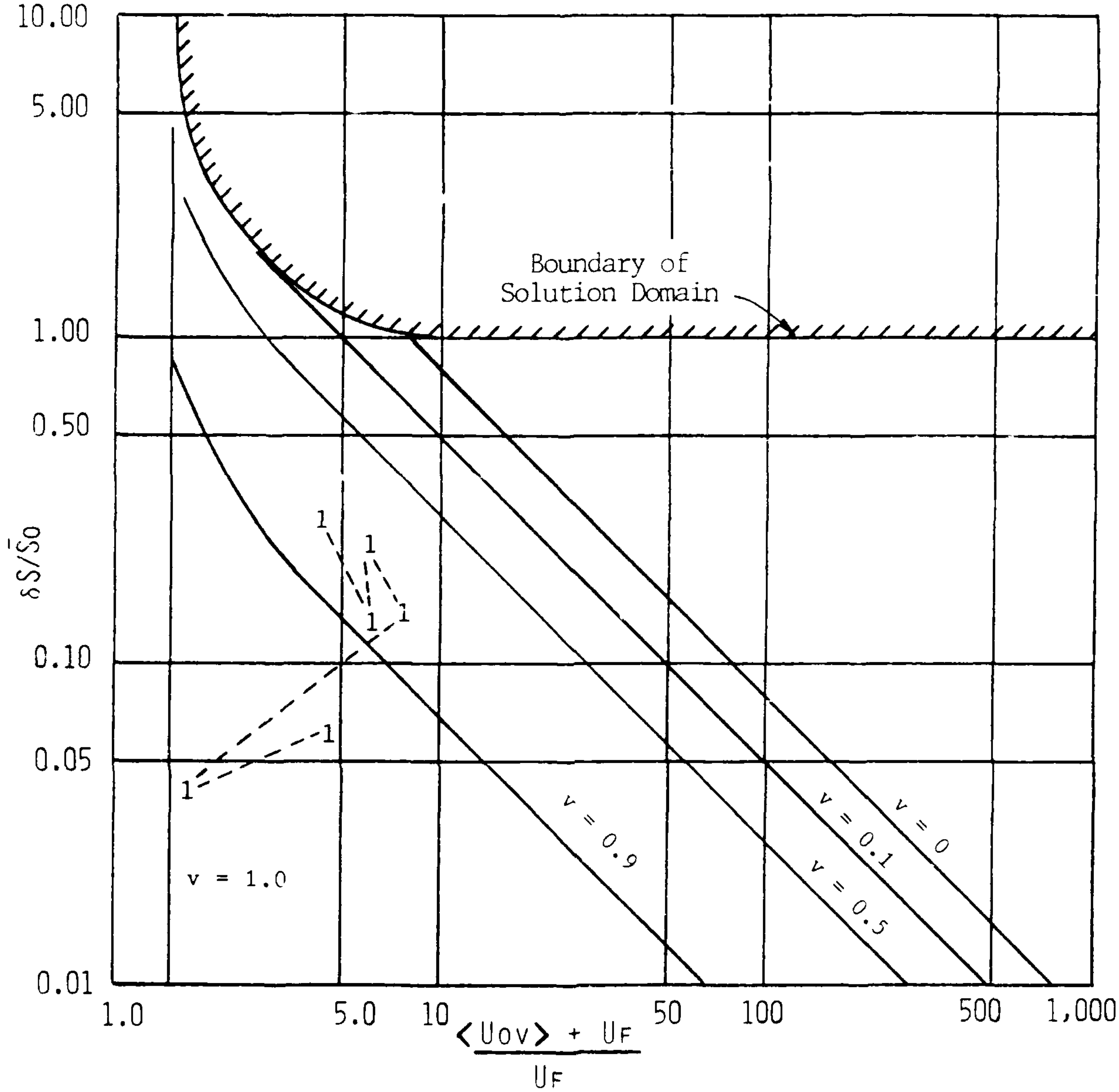
Figure A11. Bottom tidal-averaged circulation parameter for fall 1985 surveys



LEGEND

SYMBOL	DATE	WEEKLY AVERAGE FLOW, cfs
A	5 Dec 1979	24,700
B	7 May 1980	23,700
C	15 July 1982	8,600

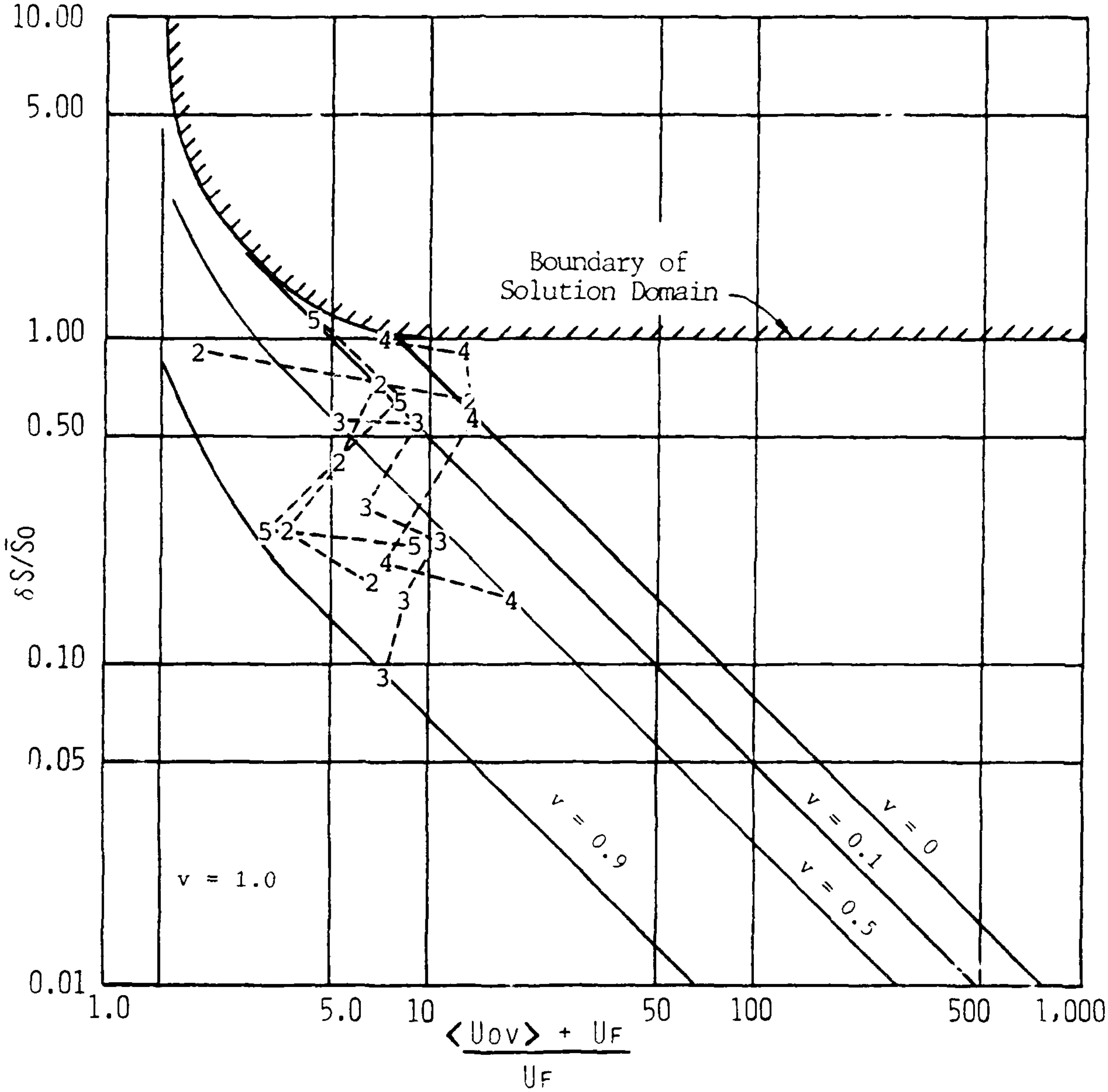
Figure A12. Circulation/stratification characterization of prerediversion surveys



LEGFND

SYMBOL	DATE	WEEKLY AVERAGE FLOW, cfs
1	16 April 1985	4,530

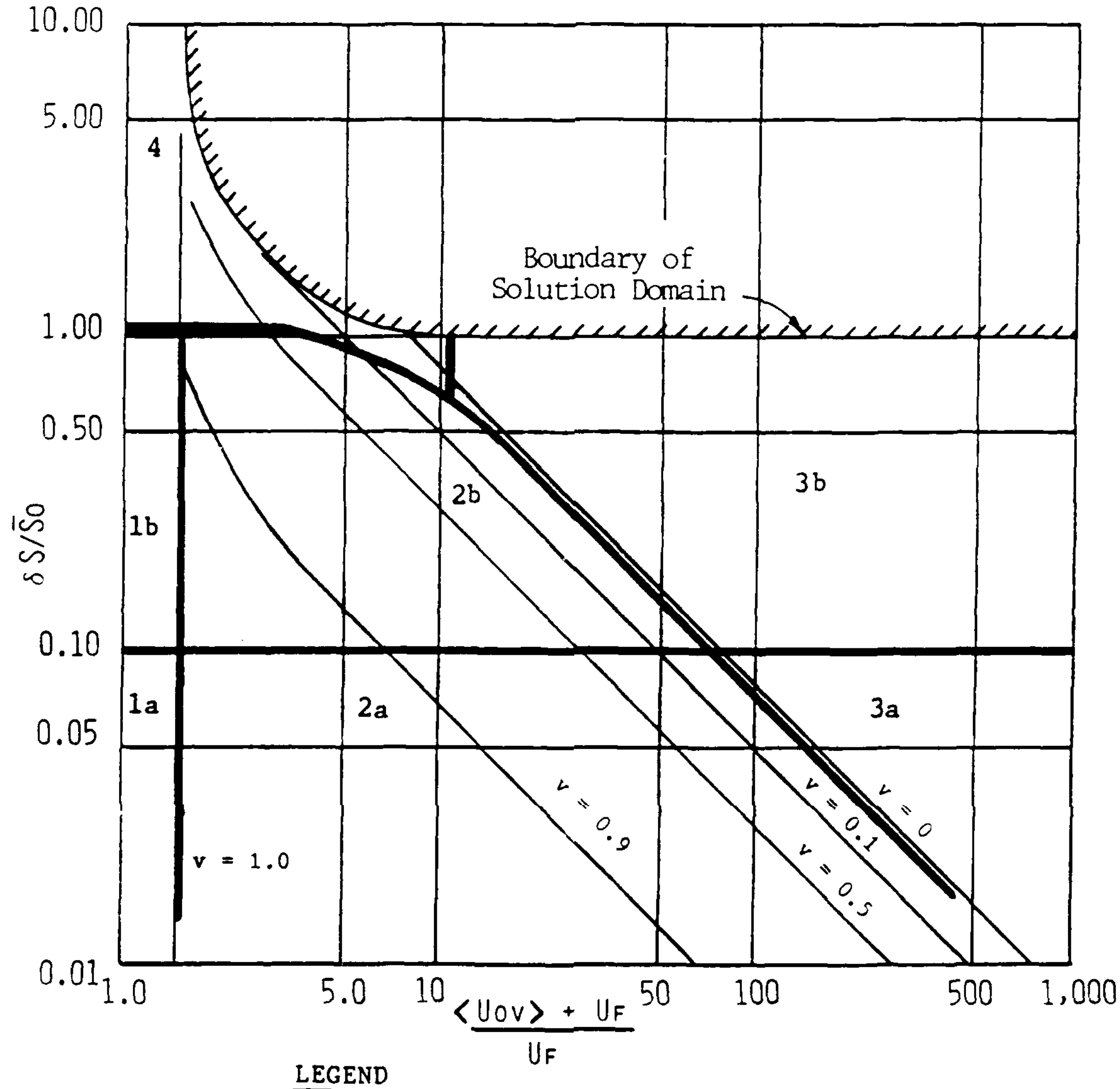
Figure A13. Circulation/stratification characterization of 16 April 1985 survey



LEGEND

SYMBOL	DATE	WEEKLY AVERAGE FLOW, cfs
2	4 Oct 1985	3,560
3	25 Oct 1985	3,090
4	23 Nov 1985	3,100
5	19 Dec 1985	4,900

Figure A14. Circulation/stratification characterization of fall 1985 surveys



LEGEND

REGION	DESCRIPTION
1a	Net flow seaward at all depths, well-mixed
1b	Net flow seaward at all depths, partially mixed
2a	Net flow reverses at depth, well-mixed
2b	Net flow reverses at depth, partially mixed
3a	Fjord-type estuaries, well-mixed
3b	Fjord-type estuaries, partially mixed
4	Salt wedge-type estuaries

Figure A15. Estuarine classification using circulation and stratification parameters (after Hansen and Rattray 1966) freshwater flow). The diffusive part of the salt flux comes from horizontal diffusion, while the advective part comes from the gravity current. For a given stratification parameter, a decrease in v is associated with an increase in circulation.

Vertical mixing

53. Stratification parameters were plotted by river mile and presented in Figures A16-A18 for the three survey groups. Relative vertical diffusivities Kz/Kzo were plotted by river mile and presented in Figures A19-A21 for the three survey groups.

Correlations

54. Some statistically important correlations between various parameters were found to have some possible physical meaning. The parameters correlated and the correlation coefficient included the following:

a. <Uov> - Uf to Uf at -0.77 .

b. Predominance to <Uov> - Uf at -0.71 .

c. Stratification parameter to Uf at 0.66 .

d. Surface circulation parameter to Uf at -0.61 .

Data from all eight surveys were used in the statistical analysis.

Salinity flux components

55. Tabulations of salt flux components, tidal-average flow velocities, and flow predominances are given in Tables A2-A9 for surveys A-C and 1-5. Each table is divided into three parts. Part A includes tidal- and depth-mean estuarine characteristics. Negative velocities are seaward. <Sov> is the root mean square of the tidal means at depth, and is about half of the stratification δS . Part B of the tables lists the six important salt flux correlations and a total for each station (paragraph A44). Totals represent depth-mean salt flux over a tidal cycle, and would theoretically be zero if the estuary were at a steady state and the station were representative of the cross section. The total fluxes shown in Part B may be slightly different from the numerical totals of the six correlations listed because they include six other generally minor correlations. Part C of the tables shows tidal-mean transport velocities Uo(z) + Uso(z) and salinities So(z) at depth and flow predominances. Lagrangian predominances include Stokes velocity. Depth indices 1, 2, and 3 represent surface, middepth, and bottom, respectively.

Suspended sediment flux components

56. Suspended sediment data were available only for sta 2, surveys 4

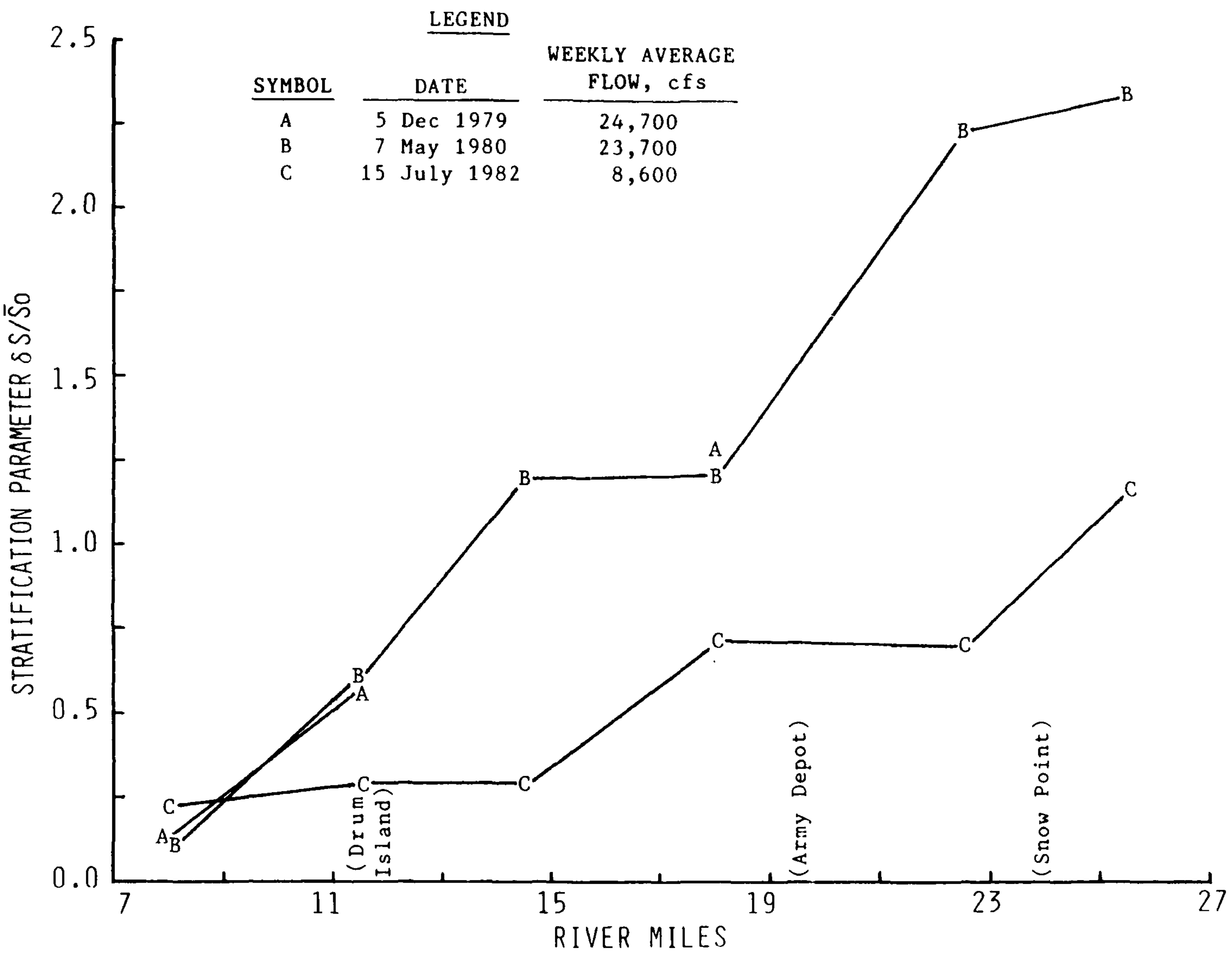


Figure A16. Stratification parameter for prediversion surveys

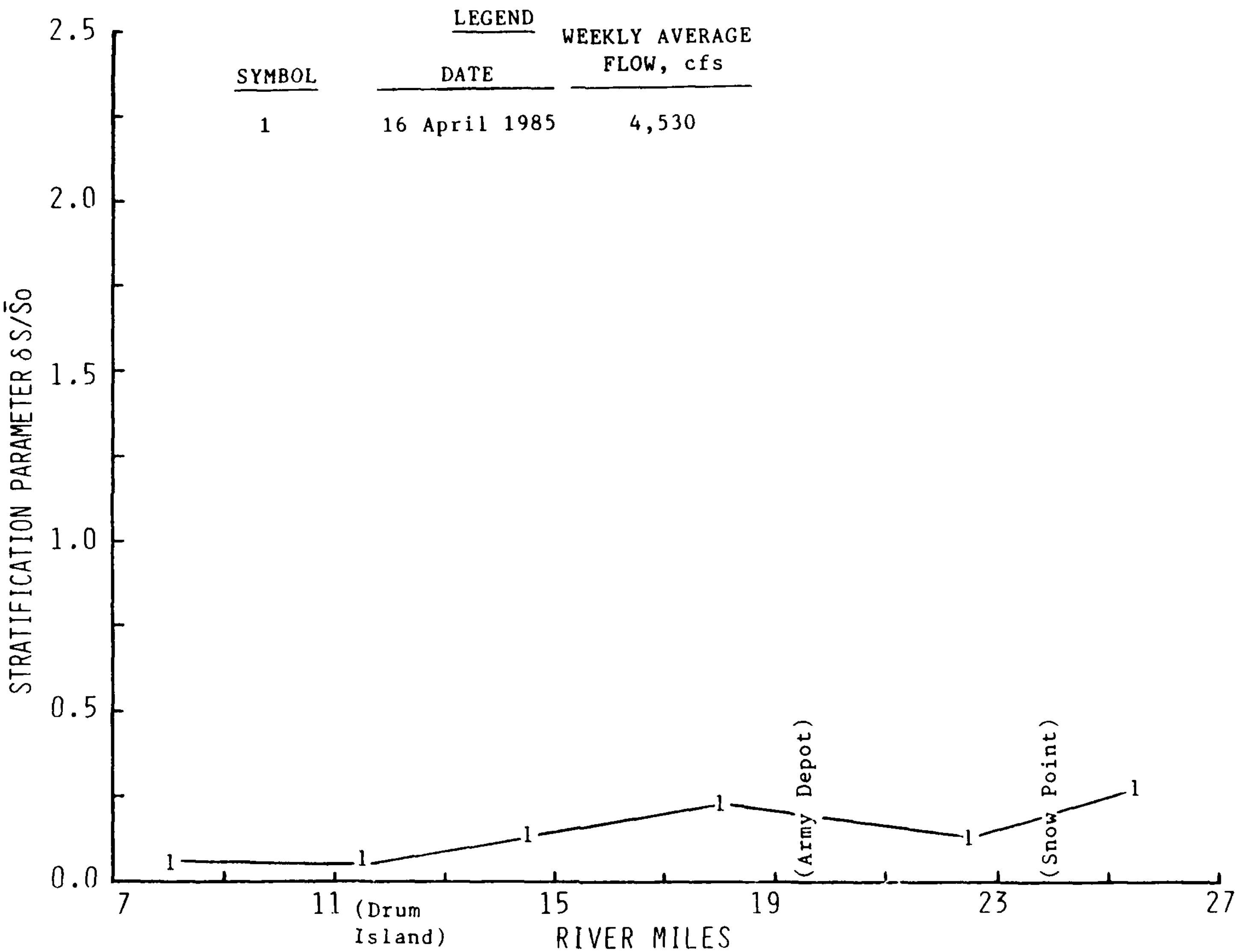


Figure A17. Stratification parameter for the 16 April 1985 survey

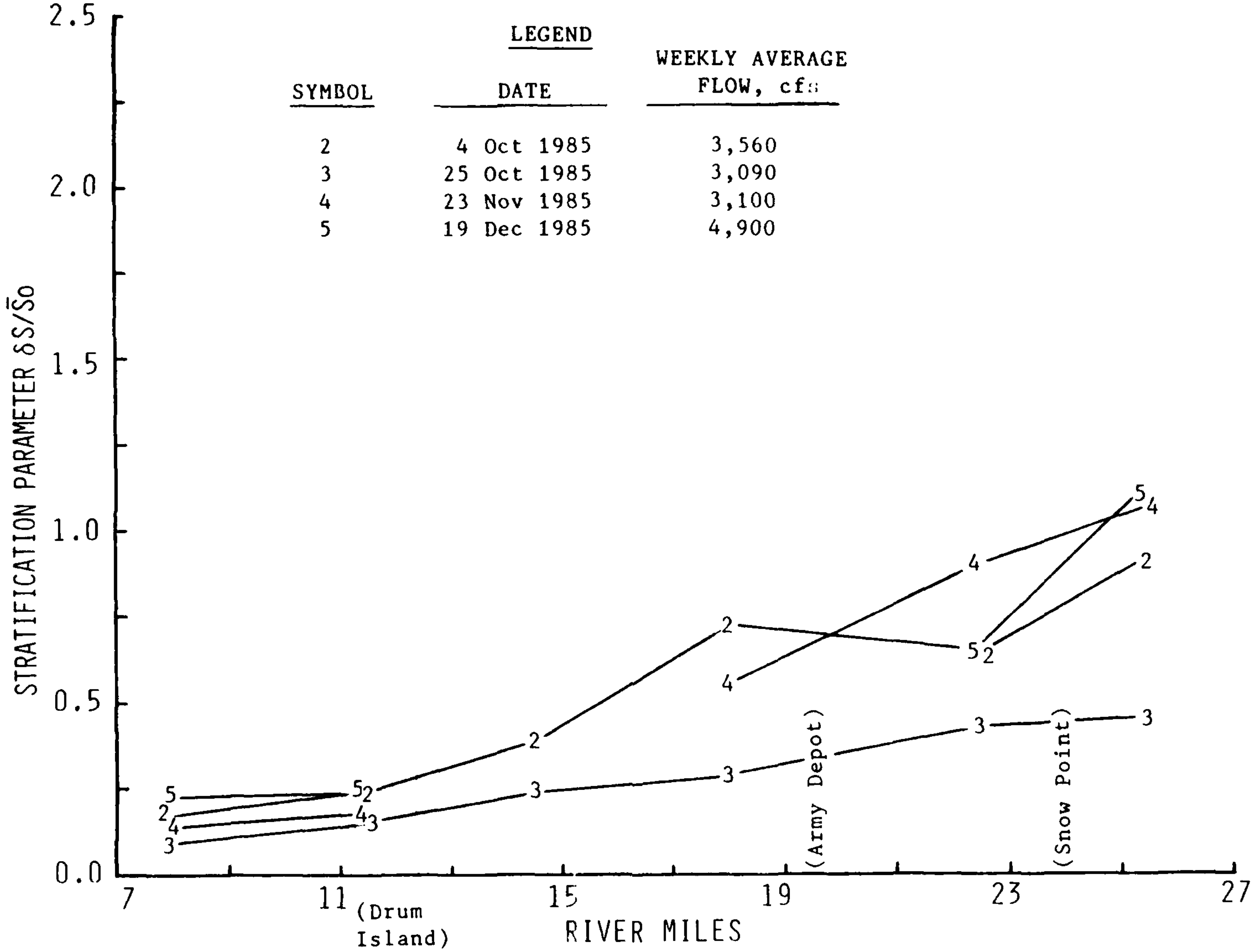


Figure A18. Stratification parameter for fall 1985 surveys

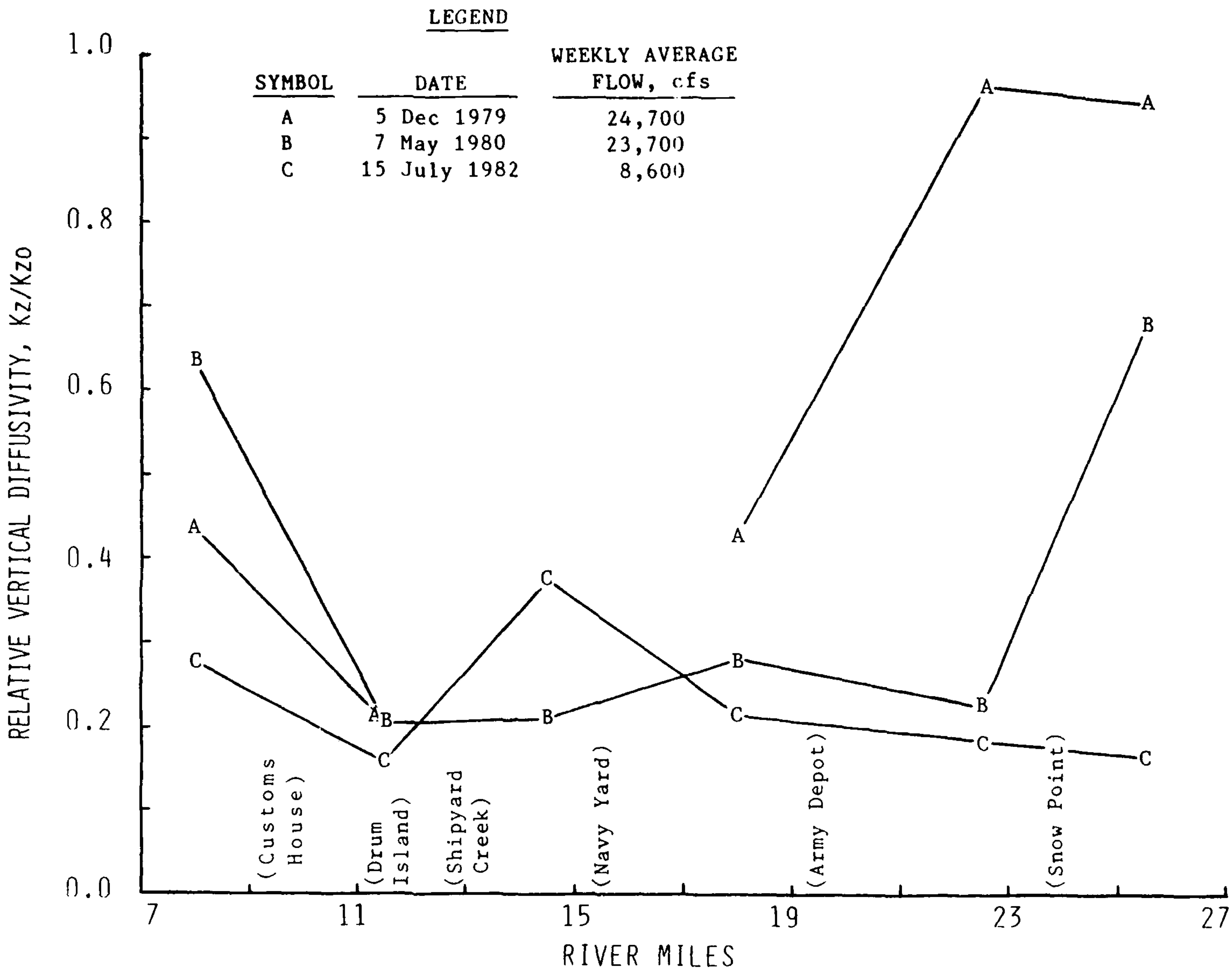


Figure A19. Vertical mixing parameter Kz/Kzo for prediversion surveys

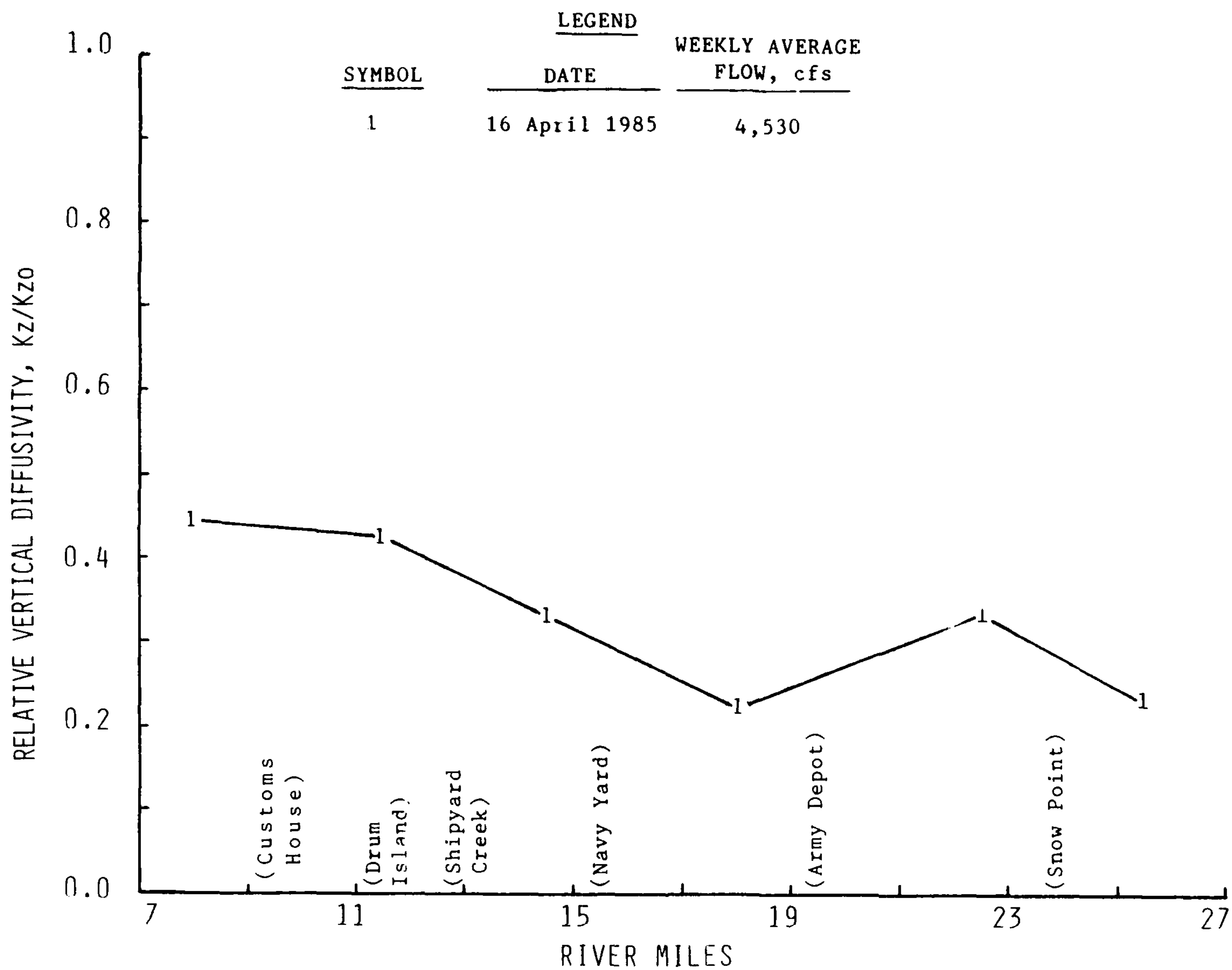


Figure A20. Vertical mixing parameter Kz/Kzo for 16 April 1985 survey

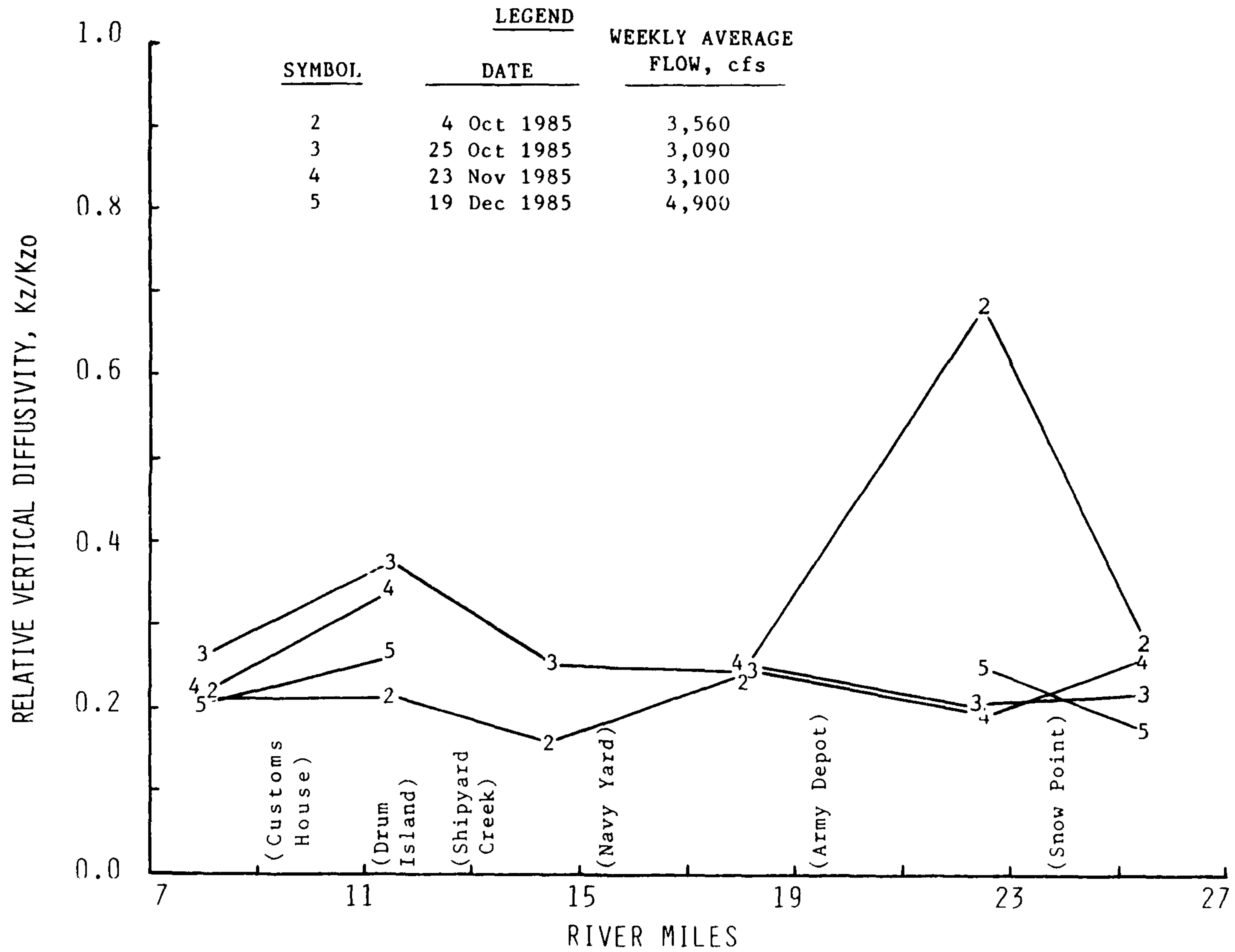


Figure A21. Vertical mixing parameter Kz/Kzo for fal: 1985 survey and 5. Suspended sediment flux components are given in Tables A10 and A11 for surveys 4 and 5, respectively. Each table is divided into three parts. Part A lists the principal estuarine characteristics. Part B lists the six important flux components and totals for sta 2 (paragraph A46). Part C lists flux components at depth. Indices are as for salinity flux tables.

57. Suspended sediment data were available at hour intervals, rather than the half-hourly interval used for salinities. The use of hourly data did not appear to affect results greatly as indicated by comparing values of $\bar{U}o$, $\bar{S}o$, and other characteristics from Tables A8 and A9 with the results in Tables A10 and A11.

Suspended sediment spring-neap variability

58. A plot of the composite total suspended solids for 25 days starting 24 November 1985 is shown in Figure A22, and a plot of the tides over the same time interval is shown in Figure A23. A storm occurred on 12 and 13 December 1985, and is located at days 17 and 18 on Figures A22 and A23.

Discussion of Results

Prerediversion conditions

59. Background surveys A and B showed the lower harbor was in the partially mixed category while the upper harbor was in the salt wedge category. The data points within each survey, when plotted in Figure A12, fell from bottom to top in a downstream to upstream order. The stratification parameter increased upstream in the harbor to over 1.0 (Figure A16). Under prerediversion flow conditions, vertical salinity and/or density stratifications reached large values, reducing vertical mixing of sediments in the harbor. Sediments would be expected to be trapped in the lower layer of the flow and be retained in the harbor for long time periods, if not permanently. Circulation as indicated by predominance and <Uov> - Uf parameters was spatially irregular, had multiple bottom null current areas, and cellular patterns during prerediversion surveys (Figures A6 and A9). Cellular circulation patterns are undesirable as they tend to increase sediment trapping and serve as seed areas for shoaling material. The location of the null zone using the salinity criteria described in the section on process description and Tables A2 and A3 was within the upper harbor, roughly river miles 18-26. Under spring tide conditions

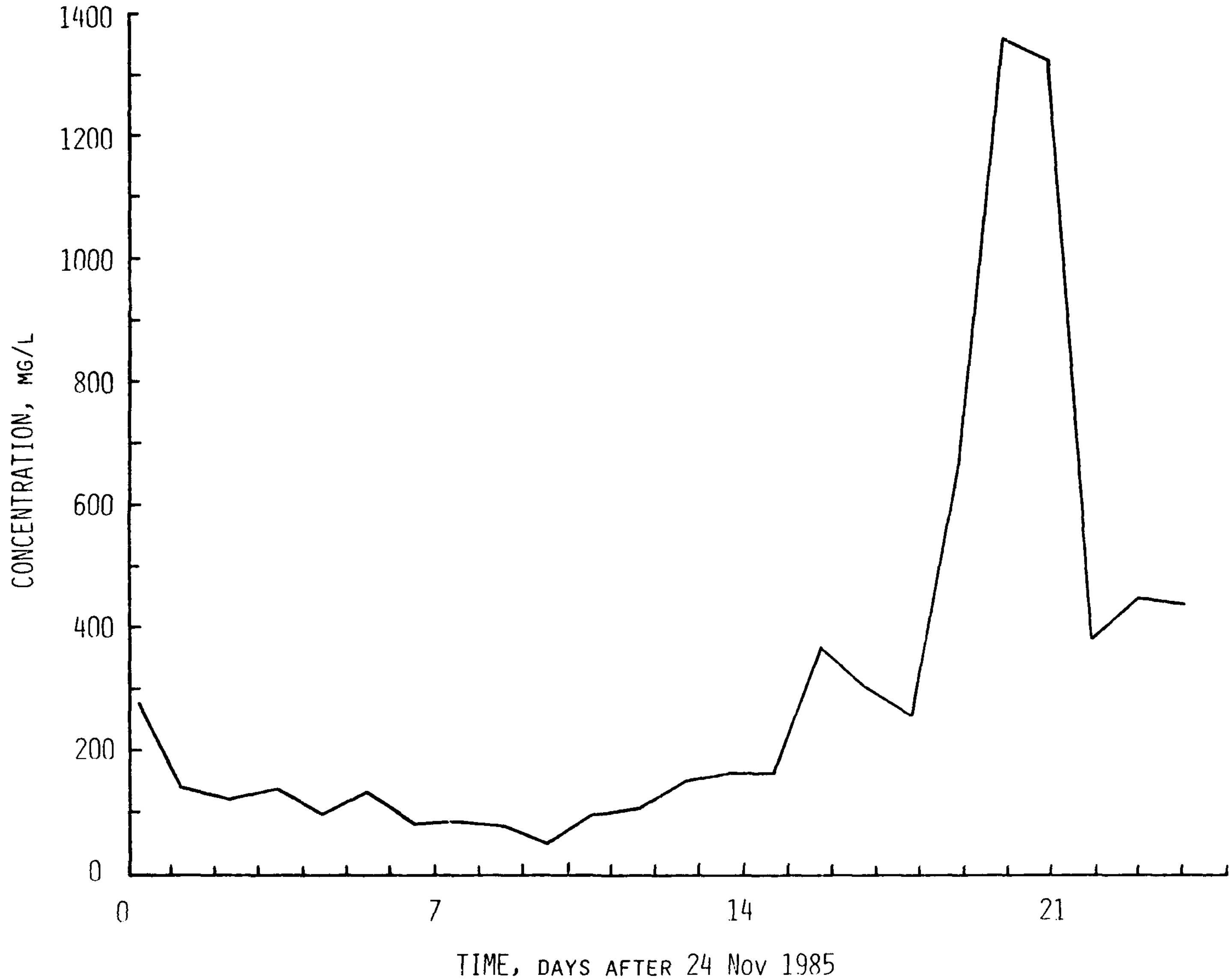


Figure A22. Daily tidal-averaged suspended sediment concentration at sta 2, 0.75 depth (see Figure A23 for tidal conditions)

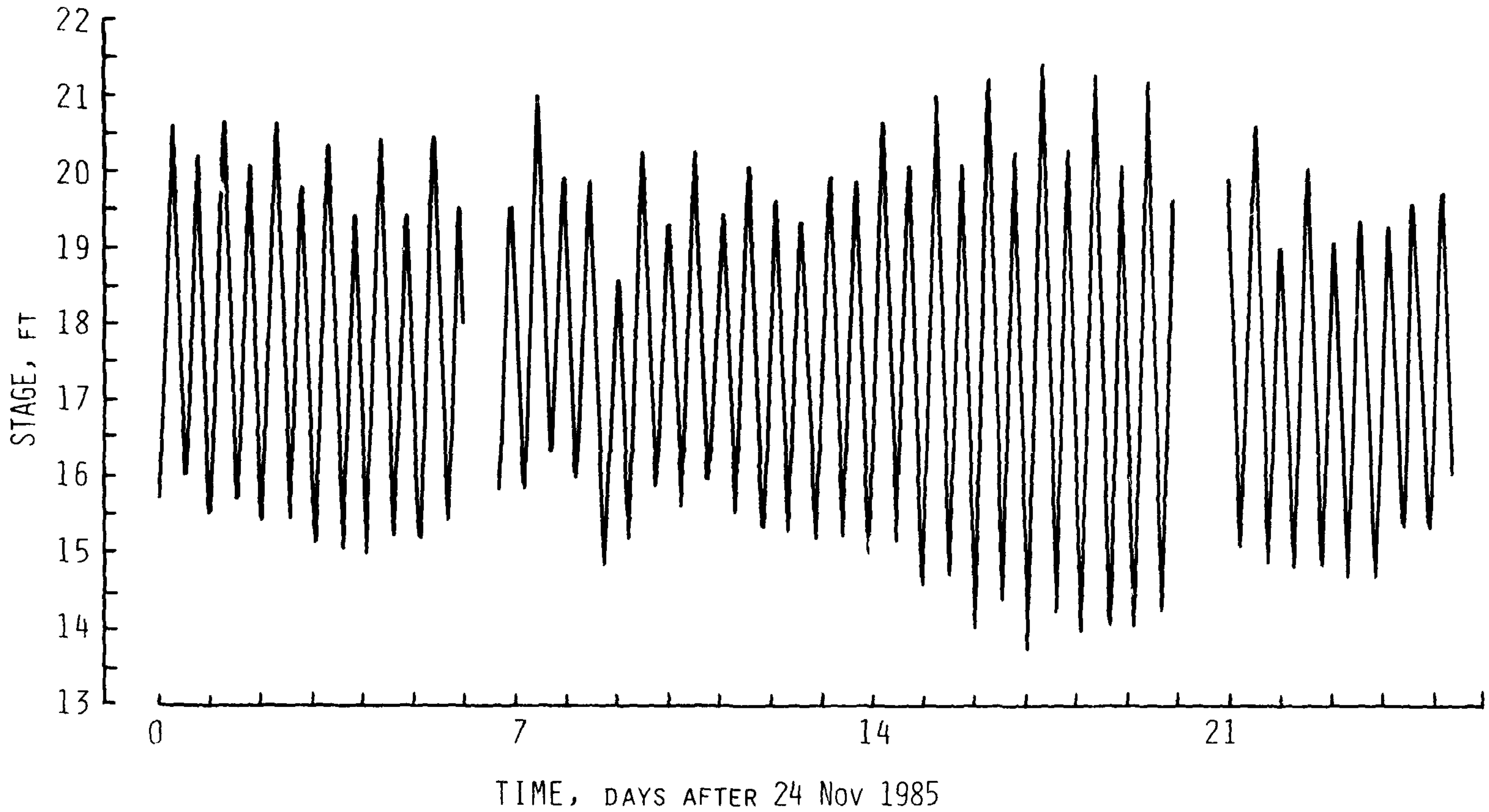


Figure A23. Tides at Customs House for the period of suspended sediment collection

(Survey A, the only survey conducted under spring tide conditions, Table A1), the salinity zone was more diffusive dominated (Figure A12).

Postrediversion conditions

60. The spring postrediversion survey (survey 1) showed a marked improvement in stratification (Figure A17 compared to Figure A16), and generally the fraction of advective salt flux was reduced (Figure A13 compared to Figure A12). The estuary was in the well-mixed regime in the lower harbor to the partly mixed regime in the upper harbor. The locations of 0.5 bottom flow predominance and null zone moved upstream above the upper harbor. Bottom predominance and circulation parameters for the spring survey were more uniform along the lower harbor (Figures A7 and A10). This survey was performed at about an average tide range so that normal spring tide conditions would result in even better vertical mixing.

61. The fall surveys (surveys 2-5) were not consistent with the spring survey nor with the expected effect of reducing freshwater inflow. Fall survey data show increased circulation, as indicated by both predominance (Figure A8) and $\langle U_{ov} \rangle - U_f$ (Figure A11) parameters. Bottom predominances generally decreased upstream, and $\langle U_{ov} \rangle - U_f$ generally increased landward, indicating that the estuarine bottom null area was landward of the survey ranges. This pattern of bottom predominance and $\langle U_{ov} \rangle - U_f$ does not fit conceptual models of circulation, in which these parameters would have the opposite trends upstream toward the null zone. This pattern is not easily explained. Stratification parameters and advective salt flux fractions $(1 - \nu)$ were also greater than observed during the spring survey (Figure A14 compared to Figure A13). One fall survey data point plotted outside the theoretical range of the diagram in Figure A14, and was most likely a measurement error. There was no clear correlation between various parameters and the levels of freshwater inflows.

62. Conditions responsible for the fall survey estuarine response appear to be rainfall and subtidal fluctuations, and not the freshwater inflows from Pinopolis. The rainfall total for October through December was 9.08 in. (11.28 in. at the Charleston Airport). A particularly important condition during the fall surveys was the fluctuation in the daily mean water levels, which occurs typically at this time of the year in response to sequential weather frontal passages. Average daily mean water levels were also above normal. Longshore winds caused harbor setups and setdowns, and

this pumping action appears to have been rectified to an increased estuarine circulation component.

63. Salinity intrusions into the upper estuary, which were relatively frequent during the fall flow testing, were another symptom or manifestation of subtidal effects on circulation. Variation in daily average conductances at Pimlico (river mile 47) for the periods of the spring and fall surveys are shown in Figures A2 and A3. Daily maximum conductances at DuPont intake in the entrance canal to Bushy Park Reservoir are shown in Figure A4 for the period of the fall surveys.

Vertical circulation

64. The effects of freshwater inflows on circulation are difficult to identify from the data. Survey 1 showed a modest decrease in circulation as indicated by changes in predominance and $\langle Uov \rangle - Uf$, while other postrediversion surveys showed an increase in circulation over prediversion surveys.

65. Taking all data together, circulation was negatively correlated to Uf and hence to inflow. A plot of all $\langle Uov \rangle - Uf$ versus Uf data is shown in Figure A24.

66. If inflow and circulation were actually negatively correlated, reducing the inflow would increase circulation. This possibility can be demonstrated by studying the circulation/stratification diagram such as Figure A15. For example, a fixed fraction of advective salt flux v and decreasing stratification (increasing vertical mixing) would drive greater circulation. However, it would seem reasonable that decreased inflow and increased vertical mixing would increase v, as it did for survey 1 (Figure A13). Examination of the fall postrediversion survey data as a group does not show a good correlation, either positive or negative, between freshwater flow and circulation. Increased circulation during the fall surveys could have been caused by other conditions stimulating circulation dynamics (Figure A24).

67. The consistent upstream decrease in bottom predominance during the fall surveys (Figure A8) is contrary to conceptual models of estuarine circulation. One explanation is that sampling station locations changed slightly during the prediversion surveys, and between the spring and fall surveys, and that the change of locations was sufficient to bias the measured bottom predominance. Therefore, the effect of inflow on circulation may not have been gaged and may have been masked by local circulation effects.

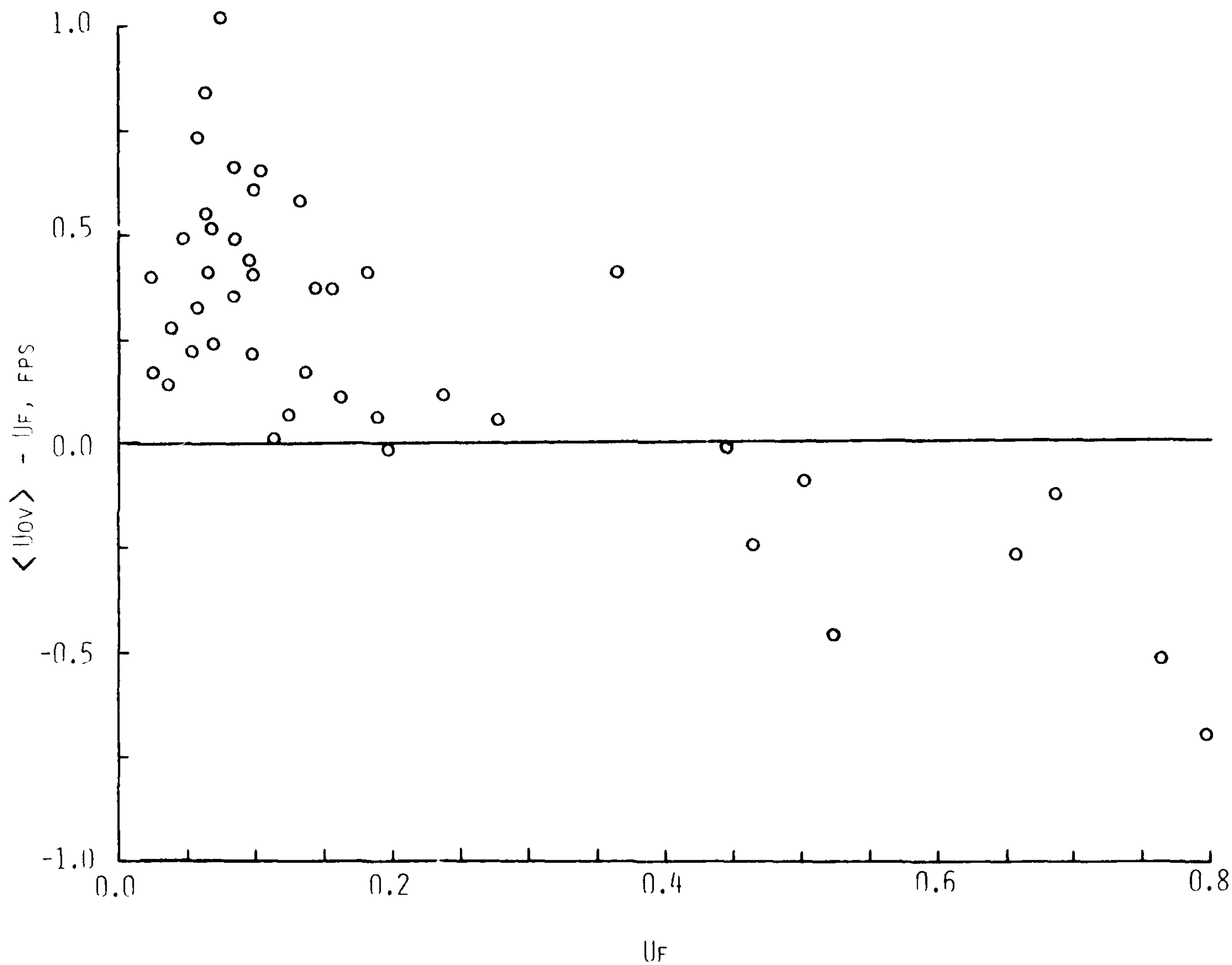


Figure A24. Bottom circulation parameter <Uov> - Uf plotted against freshwater velocity Uf for all eight surveys

Vertical mixing

68. Effective vertical mixing according to the salinity stratification parameter was greatly reduced for the fall survey compared to the prediversion surveys (Figure A18 compared to Figure A16). The fall surveys showed a more modest decrease. The fall survey stratifications were poorly correlated to freshwater inflow.

69. Relative vertical mixing according to the Kz/Kzo parameter results were highly variable within tidal cycle surveys, due to abrupt changes in vertical mixing and measurement problems. Average values of Ri , influenced by some very large individual values, were meaningless. All velocity gradient data less than or equal to zero were excluded from the analysis. Given that intratidal variability, average survey results (Figures A19-A21) were remarkably consistent, even between postdiversion and prediversion surveys. The effective mixing will depend on the tide range and hence on the magnitude of the depth-averaged flow, as well as on velocity distribution and stratification. The constancy of the Kz/Kzo parameter could mean that a constant fraction of tidal energy dissipation went into vertical mixing.

Salt fluxes

70. Salt fluxes in the estuary were highly variable and did not reflect steady-state conditions very well. A preponderance of station total salinity fluxes were upstream. This result may have come from using only midchannel stations for the flux computations. The circulation components ($\overline{UovSov}$, $\overline{UsvSov}$, and $\overline{UivSiv}$) were usually larger than the depth-mean components ($\overline{Uo}\overline{So}$, $\overline{Us}\overline{So}$, and $\overline{UiSi}$) and in the upstream direction (positive). The upstream trend in the total fluxes could have come from greater vertical circulation in the deep channels than outside of the channels, and could have been balanced by seaward total fluxes in the shallows.

71. The tidal- and depth-averaged flows Uo were not well-correlated to the freshwater velocities Uf , but were generally seaward. The exception was sta 2, which always had an upstream Uo . Data from middepth at sta 2 (river mile 8) showed persistent large upstream time means Uzo and low predominances.

Suspended sediment fluxes

72. Suspended solids concentrations correlated well with tide range. Concentrations were roughly 250-350 mg/ℓ during spring tides and only about 50 mg/ℓ during the neap (Figures A22 and A23). A storm occurred on days 17

and 18 of the deployment, and suspended solids concentrations jumped to about 1,350 mg/ℓ for 2 days before slowly subsiding. Spring tides will transport much greater quantities of suspended material than will neap tides, and therefore spring tide periods will be critical to sediment flushing from the harbor.

73. The largest suspended sediment flux components were associated with tidal pumping ($\overline{UiCi}$ and $\overline{UivCiv}$) (Tables A10 and A11). The vertical deviations $\overline{UivCiv}$ were particularly large. The results suggest that tidal pumping is the most important transport mode under rediversion flow conditions, consistent with other recent studies (Dyer 1987; Uncles, Elliott, and Weston 1985).

Validity of sediment flushing parameters

74. Of the parameters calculated from the field data, it appears that salinity stratification was the most representative of sediment flushing conditions with respect to both its theoretical importance and measurement reliability (paragraphs A18 to A27). Salinity stratification was not strongly dependent on the sampling location across the channel as were the predominance, $\langle Uov \rangle + Uf$, and $\langle Uov \rangle - Uf$ circulation parameters. Salinity stratification was not affected by inconsistencies in the data as was the Kz/Kzo parameter. Thus, the salinity stratification parameter was the best indicator developed by this study to gage sediment flushing conditions.

Summary and Conclusions

75. Over the range of flows from about 3,000 to 4,900 cfs, mixing and circulation parameters were so strongly affected by other factors (e.g., tide range, subtidal fluctuations, wind, rainfall) that the dependence on freshwater flow was obscured. The cause of this variability was not determined. The fall postrediversion survey periods were unusual with respect to the extent of salinity intrusion in the estuary, and therefore may not be representative of typical conditions.

76. Sequential frontal passages, such as those usually experienced in the fall (October-December), produce increased circulation, stratification, and salinity intrusion in the Cooper River, and will periodically limit sediment flushing.

77. Salinity stratification was found to be the most reliable indicator of sediment flushing because of reliable measurement techniques and procedures

and because it is strongly coupled to the vertical mixing process.

78. Spring tides and storm events will be peak times of sediment transport. Postrediversion surveys were performed at below-average tide ranges, ensuring that the harbor mixing will normally be greater than observed at times of maximum fortnightly sediment transport. The dominant sediment flux component after rediversion was tidal pumping.

Table A1

Summary of Survey Conditions

Date	Inflow cfs*	Custom House Tide Range, ft	Daily Mean Tide Level, ft**	Plot Symbol
5 Dec 1979	24,700	6.7	0.2	A
7 May 1980	23,700	4.5	-0.2	B
15 Jul 1982	8,600	5.5	0.4	C
16 Apr 1985	4,530	5.1	-0.4	1
4 Oct 1985	3,560	4.3	0.0	2
24 Oct 1985	3,090	5.0	0.6	3
23 Nov 1985	3,100	4.8	0.2	4
19 Dec 1985	4,900	4.3	-0.5	5

* Average based on previous week's release from Pinopolis Dam.

** Average related to short-term record (surveys A,B,C) or to yearly average (surveys 1,2,3,4,5).

Table A2

Survey A, 5 December 1979

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{U}o$ fps	$\overline{U}s$ fps	$\langle \overline{U}i \rangle$ rms	$\overline{S}o$ ppt	$\langle \overline{S}i \rangle$ rms	$\langle \overline{U}ov \rangle$ rms	$\langle \overline{U}sv \rangle$ rms	$\langle \overline{S}ov \rangle$ rms
2	8.0	0.29	0.01	1.52	25.7	4.1	0.18	0.05	1.57
3	11.5	-0.14	0.06	1.76	17.8	4.7	0.56	0.05	4.04
5	18.0	-0.35	-0.06	1.65	2.6	2.0	0.22	0.03	1.41
6	22.5	-0.18	-0.00	1.17	0.0	0.0	0.07	0.00	0.00
7	25.5	-0.21	0.03	1.25	0.0	0.0	0.10	0.02	0.00

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{U}o\overline{S}o$	$\overline{U}s\overline{S}o$	$\overline{U}i\overline{S}i$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	7.39	0.36	-1.26	0.28	-0.07	9.95	16.65
3	11.5	38	-2.49	1.00	-1.59	2.24	-0.19	8.71	7.68
5	28.0	43	-0.92	-0.17	0.39	0.28	0.05	-0.03	-0.40
6	22.5	37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	25.5	45	0.00	0.00	0.00	0.00	0.00	0.00	0.00

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	So(z) ppt	$\langle UivSiv(z) \rangle$ fps-ppt
2	8.0	1	0.12	0.49	0.47	23.4	19.27
		2	0.46	0.35	0.36	26.9	-2.98
		3	0.33	0.31	0.33	26.6	13.56
3	11.5	1	-0.78	0.69	0.65	12.7	22.70
		2	0.08	0.49	0.48	18.0	2.04
		3	0.45	0.17	0.17	22.6	1.38
5	18.0	1	-0.73	0.68	0.70	1.3	0.13
		2	-0.39	0.59	0.61	2.0	-0.64
		3	-0.12	0.54	0.55	4.6	0.42
6	22.5	1	-0.18	0.58	0.57	0.0	0.00
		2	-0.27	0.61	0.61	0.0	0.00
		3	-0.10	0.56	0.56	0.0	0.00
7	25.5	1	-0.27	0.62	0.59	0.0	0.00
		2	-0.22	0.60	0.59	0.0	0.00
		3	-0.08	0.55	0.55	0.0	0.00

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A3

Survey B, 7 May 1980

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{U}o$ fps	$\overline{U}s$ fps	$\langle \overline{U}i \rangle$ rms	$\overline{S}o$ ppt	$\langle \overline{S}i \rangle$ rms	$\langle \overline{U}ov \rangle$ rms	$\langle \overline{U}sv \rangle$ rms	$\langle \overline{S}ov \rangle$ rms
2	8.0	0.07	-0.00	0.96	23.8	3.2	0.25	0.04	3.87
3	11.5	-0.61	0.16	1.31	17.5	2.4	0.39	0.09	4.27
4	14.5	-0.47	-0.06	1.40	13.4	2.2	0.94	0.21	6.75
5	18.0	-0.52	-0.04	1.40	5.9	2.6	0.62	0.20	3.14
6	22.5	-0.40	0.01	0.73	4.9	1.0	0.59	0.17	4.89
7	25.5	-0.87	0.19	1.47	0.6	0.9	0.43	0.17	0.79

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	1.56	-0.03	-0.54	0.43	-0.07	-1.97	-0.62
3	11.5	38	-10.75	2.74	-0.71	1.65	-0.37	10.40	2.96
4	14.5	46	-6.31	-0.75	1.13	4.95	0.28	10.32	9.63
5	18.0	43	-3.07	-0.24	0.79	1.15	0.10	3.45	2.18
6	22.5	37	-1.97	0.02	-0.42	1.89	-0.03	4.39	3.89
7	25.5	45	-0.56	0.12	0.35	0.15	-0.01	0.56	0.61

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	So(z) ppt	$\langle UivSiv(z) \rangle$ fps-ppt
2	8.0	1	-0.22	0.62	0.59	19.8	-4.13
		2	0.30	0.35	0.38	22.7	-3.78
		3	0.11	0.41	0.43	29.0	2.01
3	11.5	1	-0.84	0.81	0.71	12.3	11.34
		2	-0.43	0.69	0.61	17.5	3.56
		3	-0.11	0.61	0.58	22.7	16.31
4	14.5	1	-1.65	0.91	0.91	4.8	-4.06
		2	-0.18	0.54	0.55	14.5	22.16
		3	0.24	0.29	0.31	20.8	12.86
5	18.0	1	-1.18	0.84	0.84	2.9	2.75
		2	-0.45	0.63	0.64	4.8	3.02
		3	-0.06	0.54	0.54	10.0	4.58
6	22.5	1	-0.86	0.84	0.83	0.6	6.52
		2	-0.46	0.80	0.77	2.7	3.94
		3	0.13	0.19	0.22	11.5	2.72
7	25.5	1	-0.91	0.81	0.72	0.1	-0.05
		2	-0.76	0.79	0.71	0.3	0.56
		3	-0.37	0.77	0.66	1.5	1.17

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A4

Survey C, 15 July 1982

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle\overline{U}i\rangle$ rms	$\overline{So}$ ppt	$\langle\overline{S}i\rangle$ rms	$\langle\overline{U}ov\rangle$ rms	$\langle\overline{U}sv\rangle$ rms	$\langle\overline{S}ov\rangle$ rms
2	8.0	0.16	-0.09	1.74	27.6	2.7	0.30	0.07	2.40
3	11.5	-0.11	0.01	1.51	22.2	2.3	0.35	0.03	2.54
4	14.5	-0.41	-0.22	1.70	21.1	2.0	0.71	0.10	3.08
5	18.0	-0.09	-0.00	1.28	15.3	2.0	0.27	0.01	4.45
6	22.5	-0.35	-0.01	0.92	11.3	2.2	0.59	0.01	3.20
7	25.5	-0.51	0.03	1.04	5.5	3.3	0.33	0.04	2.62

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	4.34	-2.61	1.22	0.46	0.06	3.03	6.51
3	11.5	38	-2.43	0.32	-0.99	0.88	-0.00	7.18	4.95
4	14.5	46	-8.69	-4.59	0.58	2.07	0.22	4.71	-5.71
5	18.0	43	-1.41	-0.00	0.90	0.83	0.02	13.78	14.12
6	22.5	37	-3.93	-0.13	-0.00	1.87	0.04	-0.75	-2.91
7	25.5	45	-2.77	0.15	0.53	0.82	0.07	5.47	4.27

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	So(z) ppt	$\langle UivSiv(z)\rangle$ fps-ppt
2	8.0	1	-0.32	0.56	0.58	24.5	2.49
		2	0.33	0.37	0.43	27.9	3.90
		3	0.18	0.39	0.41	30.4	2.70
3	11.5	1	-0.50	0.65	0.63	19.2	10.81
		2	-0.13	0.53	0.54	22.0	0.96
		3	0.34	0.34	0.33	25.4	9.75
4	14.5	1	-1.71	0.84	0.86	16.8	7.08
		2	-0.37	0.53	0.58	23.6	2.25
		3	0.19	0.33	0.40	23.0	4.79
5	18.0	1	-0.47	0.65	0.64	10.1	3.68
		2	0.16	0.45	0.45	14.9	13.15
		3	0.03	0.48	0.47	21.0	24.51
6	22.5	1	-1.17	0.93	0.93	7.0	5.05
		2	-0.16	0.59	0.58	12.1	-1.39
		3	0.25	0.17	0.19	14.8	-5.91
7	25.5	1	-0.98	0.90	0.89	2.4	8.03
		2	-0.32	0.66	0.63	5.3	3.99
		3	-0.14	0.64	0.60	8.8	4.39

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A5

Survey 1, 16 April 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle\overline{Ui}\rangle$ rms	$\overline{So}$ ppt	$\langle\overline{Si}\rangle$ rms	$\langle\overline{Uov}\rangle$ rms	$\langle\overline{Usv}\rangle$ rms	$\langle\overline{Sov}\rangle$ rms
2	8.0	0.21	-0.04	1.43	28.7	1.3	0.17	0.01	0.76
3	11.5	-0.02	0.02	1.39	25.5	1.1	0.19	0.01	0.74
4	14.5	-0.27	-0.09	1.62	22.7	1.2	0.39	0.02	1.32
5	18.0	-0.11	-0.01	1.43	20.2	1.2	0.22	0.01	1.93
6	22.5	-0.45	-0.01	1.11	16.4	1.7	0.33	0.02	0.90
7	25.5	-0.14	0.07	1.34	13.1	2.8	0.31	0.05	1.47

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	6.02	-1.11	0.06	0.11	0.00	-0.80	4.29
3	11.5	38	-0.41	0.47	0.38	0.13	-0.01	-1.61	-1.05
4	14.5	46	-6.09	-1.96	0.63	0.51	0.02	5.97	-0.92
5	18.0	43	-2.21	-0.27	0.14	0.43	0.02	4.03	2.13
6	22.5	37	-7.32	-0.20	-0.19	0.30	0.02	1.71	-5.69
7	25.5	45	-1.85	0.86	-0.83	0.43	0.06	4.32	2.98

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	So(z) ppt	$\langle UivSiv(z)\rangle$ fps-ppt
2	8.0	1	-0.04	0.50	0.51	27.7	2.64
		2	0.38	0.36	0.38	29.3	-0.56
		3	0.17	0.39	0.41	29.3	-4.47
3	11.5	1	-0.24	0.58	0.57	24.5	0.45
		2	0.06	0.48	0.48	26.2	-1.27
		3	0.18	0.37	0.37	25.9	-4.01
4	14.5	1	-0.91	0.71	0.71	20.9	7.37
		2	-0.21	0.54	0.56	23.4	1.56
		3	0.05	0.44	0.48	23.9	8.96
5	18.0	1	-0.43	0.62	0.62	17.6	3.66
		2	-0.06	0.52	0.52	20.7	0.70
		3	0.13	0.40	0.40	22.2	7.72
6	22.5	1	-0.92	0.83	0.83	15.2	4.33
		2	-0.39	0.69	0.69	16.8	-0.23
		3	-0.06	0.54	0.54	17.3	1.03
7	25.5	1	-0.58	0.72	0.71	11.2	6.21
		2	0.15	0.49	0.45	13.2	3.60
		3	0.20	0.44	0.41	14.8	3.14

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A6

Survey 2, 4 October 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle \overline{Ui} \rangle$ rms	$\overline{So}$ ppt	$\langle \overline{Si} \rangle$ rms	$\langle \overline{Uov} \rangle$ rms	$\langle \overline{Usv} \rangle$ rms	$\langle \overline{Sov} \rangle$ rms
2	8.0	0.15	-0.04	1.23	30.4	1.7	0.19	0.03	2.19
3	11.5	0.02	-0.05	1.03	26.8	1.2	0.31	0.02	2.88
4	14.5	-0.27	-0.01	0.51	21.5	6.6	0.27	0.01	4.00
5	18.0	0.12	0.10	1.07	18.1	2.6	0.47	0.05	5.72
6	22.5	-0.16	-0.14	1.54	13.7	2.1	1.09	0.08	4.29
7	25.5	-0.24	-0.08	0.72	9.0	3.2	0.12	0.09	4.20

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	4.66	-1.17	0.53	0.33	-0.04	6.57	10.88
3	11.5	38	0.50	-1.37	0.03	0.87	0.02	4.01	4.07
4	14.5	46	-5.86	-0.32	-0.12	1.02	0.03	10.09	4.83
5	18.0	43	2.17	1.78	0.54	2.50	-0.24	5.21	11.97
6	22.5	37	-2.16	-1.92	-2.14	4.39	0.34	-36.35	-37.85
7	25.5	45	-2.19	-0.68	0.63	0.34	0.38	-5.49	-7.02

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances		So(z) ppt	$\langle UivSiv(z) \rangle$ fps-ppt
				Flow	Lagrangian		
2	8.0	1	-0.10	0.54	0.54	27.5	10.81
		2	0.29	0.38	0.41	31.1	3.08
		3	0.16	0.39	0.41	32.7	5.81
3	11.5	1	-0.47	0.65	0.66	22.9	8.90
		2	0.14	0.39	0.44	27.8	1.62
		3	0.24	0.26	0.29	29.7	1.51
4	14.5	1	-0.66	0.96	0.96	15.8	12.57
		2	-0.23	0.81	0.82	24.3	1.91
		3	0.02	0.33	0.35	24.3	15.79
5	18.0	1	-0.39	0.71	0.64	10.1	13.29
		2	0.65	0.29	0.26	20.6	3.26
		3	0.39	0.17	0.16	23.4	-0.90
6	22.5	1	-1.95	0.86	0.87	8.3	-24.58
		2	0.34	0.36	0.40	14.0	-3.94
		3	0.71	0.10	0.16	18.8	-80.54
7	25.5	1	-0.52	0.67	0.73	3.3	-12.65
		2	-0.36	0.73	0.73	10.4	0.61
		3	-0.07	0.88	0.82	13.3	-4.44

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A7

Survey 3, 25 October 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle\overline{Ui}\rangle$ rms	$\overline{So}$ ppt	$\langle\overline{Si}\rangle$ rms	$\langle\overline{Uov}\rangle$ rms	$\langle\overline{Usv}\rangle$ rms	$\langle\overline{Sov}\rangle$ rms
2	8.0	0.17	0.10	1.25	32.4	1.5	0.18	0.07	1.29
3	11.5	0.22	0.00	2.15	28.9	1.6	0.74	0.02	1.84
4	14.5	-0.02	-0.09	1.52	24.7	1.6	0.53	0.06	2.56
5	18.0	-0.01	-0.03	1.16	20.7	1.6	0.38	0.02	2.53
6	22.5	-0.09	-0.02	0.85	15.4	1.4	0.61	0.03	2.68
7	25.5	-0.07	0.03	0.95	10.8	2.5	0.50	0.05	2.05

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	5.67	3.14	-0.06	0.23	-0.09	1.89	10.77
3	11.5	38	6.48	0.12	-0.56	1.25	-0.04	4.13	11.38
4	14.5	46	-0.56	-2.20	0.24	1.34	0.15	4.34	3.32
5	18.0	43	-0.17	-0.62	0.42	0.86	0.04	4.38	4.92
6	22.5	37	-1.36	-0.32	-0.17	1.61	0.07	-1.77	-1.94
7	25.5	45	-0.78	0.35	-0.30	1.02	0.07	2.81	3.17

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	So(z) ppt	$\langle$UivSiv(z)$\rangle$ fps-ppt
2	8.0	1	0.13	0.52	0.46	30.7	1.67
		2	0.28	0.41	0.40	32.9	1.41
		3	0.40	0.23	0.22	33.7	2.59
3	11.5	1	-0.79	0.65	0.63	26.6	6.53
		2	0.69	0.31	0.32	29.1	-0.91
		3	0.78	0.14	0.16	31.1	6.77
4	14.5	1	-0.94	0.70	0.72	21.2	3.24
		2	0.22	0.42	0.44	25.7	2.41
		3	0.39	0.26	0.29	27.2	7.38
5	18.0	1	-0.59	0.67	0.68	17.4	5.61
		2	0.26	0.39	0.41	21.2	1.47
		3	0.22	0.25	0.26	23.5	6.05
6	22.5	1	-0.94	0.84	0.85	12.3	1.13
		2	0.00	0.49	0.50	15.1	0.37
		3	0.61	0.04	0.05	18.9	-6.80
7	25.5	1	-0.70	0.83	0.83	8.6	2.52
		2	-0.03	0.55	0.51	10.3	3.22
		3	0.61	0.17	0.16	13.5	2.71

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A8

Survey 4, 23 November 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle \overline{Ui} \rangle$ rms	$\overline{So}$ ppt	$\langle \overline{Si} \rangle$ rms	$\langle \overline{Uov} \rangle$ rms	$\langle \overline{Usv} \rangle$ rms	$\langle \overline{Sov} \rangle$ rms
2	8.0	0.25	-0.04	1.23	28.7	1.4	0.24	0.04	1.71
3	11.5	-0.06	0.01	0.99	24.7	1.1	0.39	0.03	2.23
5	18.0	-0.09	-0.01	1.01	16.6	1.9	0.61	0.01	4.05
6	22.5	-0.14	-0.02	0.85	9.8	0.7	0.73	0.03	3.62
7	25.5	-0.08	0.01	0.94	6.5	1.9	0.52	0.06	2.83

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{So}$	$\overline{Us}\,\overline{So}$	$\overline{Ui}\,\overline{Si}$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	7.24	-1.08	0.32	0.25	-0.05	3.84	10.52
3	11.5	38	-1.60	0.26	-0.11	0.71	-0.05	8.56	7.77
5	18.0	43	-1.48	-0.16	0.71	2.37	0.01	3.09	4.54
6	22.5	37	-1.42	-0.15	0.11	2.39	0.10	-2.54	-1.51
7	25.5	45	-0.51	0.08	0.33	1.47	0.11	6.74	8.21

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances		So(z) ppt	$\langle UivSiv(z) \rangle$ fps-ppt
				Flow	Lagrangian		
2	8.0	1	-0.02	0.51	0.51	26.5	5.04
		2	0.46	0.30	0.34	29.1	0.95
		3	0.20	0.34	0.38	30.6	5.55
3	11.5	1	-0.56	0.68	0.66	21.8	14.28
		2	0.27	0.34	0.35	25.0	10.68
		3	0.12	0.31	0.32	27.3	0.72
5	18.0	1	-0.96	0.85	0.84	10.9	1.67
		2	0.42	0.32	0.33	18.5	0.84
		3	0.24	0.19	0.20	20.2	6.78
6	22.5	1	-1.22	0.89	0.89	5.5	-0.52
		2	0.25	0.37	0.36	9.6	1.68
		3	0.49	0.14	0.14	14.4	-8.79
7	25.5	1	-0.81	0.87	0.87	3.0	1.85
		2	0.07	0.50	0.47	6.6	14.60
		3	0.55	0.16	0.17	10.0	3.77

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A9

Survey 5, 19 December 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\bar{U}o$ fps	$\bar{U}s$ fps	$\langle \bar{U}i \rangle$ rms	$\bar{S}o$ ppt	$\langle \bar{S}i \rangle$ rms	$\langle \bar{U}ov \rangle$ rms	$\langle \bar{U}sv \rangle$ rms	$\langle \bar{S}ov \rangle$ rms
2	8.0	0.14	-0.04	1.28	28.9	1.8	0.31	0.02	2.70
3	11.5	-0.05	0.02	1.09	25.0	1.3	0.30	0.04	2.56
6	22.5	-0.19	-0.03	0.92	14.6	1.2	0.75	0.06	3.98
7	25.5	-0.12	0.02	1.05	9.7	2.3	0.52	0.07	4.41

B. Salinity Flux Components

Sta	River Mile	Depth ft	$\bar{U}o\bar{S}o$	$\bar{U}s\bar{S}o$	$\bar{U}i\bar{S}i$	$\overline{UovSov}$	$\overline{UsvSov}$	$\overline{UivSiv}$	Total
2	8.0	40	4.13	-1.16	0.50	0.78	-0.04	7.48	11.68
3	11.5	38	-1.30	0.41	0.28	0.71	-0.09	1.95	1.97
6	22.5	37	-2.84	-0.51	-0.54	2.88	0.22	-9.65	-10.45
7	25.5	45	-1.19	0.21	-0.17	2.21	0.22	1.96	3.24

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances		So(z) ppt	<UivSiv(z)> fps-ppt
				Flow	Lagrangian		
2	8.0	1	-0.30	0.60	0.60	25.4	8.27
		2	0.28	0.37	0.40	29.4	2.57
		3	0.33	0.26	0.30	32.0	11.60
3	11.5	1	-0.40	0.63	0.61	21.5	6.77
		2	0.19	0.40	0.41	26.1	2.32
		3	0.10	0.40	0.40	27.5	-3.23
6	22.5	1	-1.37	0.89	0.89	9.3	-2.70
		2	0.26	0.37	0.36	15.6	-2.14
		3	0.42	0.03	0.07	18.9	-24.12
7	25.5	1	-0.87	0.87	0.87	4.8	-0.25
		2	0.04	0.52	0.49	8.7	7.36
		3	0.53	0.24	0.23	15.5	-1.21

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A10

Station 2, Survey 4, 23 November 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle \overline{Ui} \rangle$ rms	$\overline{So}$ ppt	$\langle \overline{Si} \rangle$ rms	$\langle \overline{Uov} \rangle$ rms	$\langle \overline{Usv} \rangle$ rms	$\langle \overline{Sov} \rangle$ rms
2	8.0	0.19	0.00	1.24	28.5	1.4	0.22	0.00	1.79

B. Sediment Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{Co}$	$\overline{Us}\,\overline{Co}$	$\overline{UiCi}$	$\overline{UovCov}$	$\overline{UsvCov}$	$\overline{UivCiv}$	Total
2	8.0	40	7.67	0.00	8.85	0.84	0.00	-37.39	-20.03

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	Co(z) ppm	$\langle$UivCiv(z)$\rangle$ fps-ppm
2	8.0	1	-0.08	0.53	0.53	19.0	-15.87
		2	0.46	0.32	0.32	28.8	-21.39
		3	0.18	0.38	0.38	75.8	-74.90

* 1 = near surface, 2 = middepth, and 3 = near bottom.

Table A11

Station 2, Survey 5, 19 December 1985

A. Principal Estuarine Characteristics

Sta	River Mile	$\overline{Uo}$ fps	$\overline{Us}$ fps	$\langle \overline{Ui} \rangle$ rms	$\overline{So}$ ppt	$\langle \overline{Si} \rangle$ rms	$\langle \overline{Uov} \rangle$ rms	$\langle \overline{Usv} \rangle$ rms	$\langle \overline{Sov} \rangle$ rms
2	8.0	0.08	0.00	1.36	29.0	1.8	0.36	0.00	2.58

B. Sediment Flux Components

Sta	River Mile	Depth ft	$\overline{Uo}\,\overline{Co}$	$\overline{Us}\,\overline{Co}$	$\overline{UiCi}$	$\overline{UovCov}$	$\overline{UsvCov}$	$\overline{UivCiv}$	Total
2	8.0	40	1.67	0.00	5.94	3.01	0.00	-6.10	4.52

C. Fluxes by Depth

Sta	River Mile	Depth Index*	Uo(z) + Uso(z) fps	Predominances Flow	Predominances Lagrangian	Co(z) ppm	<UivCiv(z)> fps-ppm
2	8.0	1	-0.43	0.63	0.63	10.3	-13.93
		2	0.29	0.40	0.40	19.0	-11.39
		3	0.37	0.29	0.29	35.0	7.02

* 1 = near surface, 2 = middepth, and 3 = near bottom.

APPENDIX B: ANALYSIS OF 1987 HARBOR MONITORING DATA

Purpose

1. The purposes of this appendix were to define the effect on Charleston Harbor salinity stratification of weekly average inflows between 4,500 cfs and about 5,500 cfs, and to define relationships between salinity stratification and tides. The overall purpose of the study was to establish a postrediversion inflow level as described in the main body of this report.

Scope

2. During May-July 1987, three boat surveys were performed in Charleston Harbor by the US Army Corps of Engineers to measure currents and collect salinity samples for one tidal cycle. Long-term salinity samples, conductivity, and tide data were obtained at fixed locations in the harbor during April-August 1987. Average weekly freshwater inflows varied from 4,500 to 5,600 cfs. Salinity stratifications were calculated and compared by inflow and tidal conditions.

Field Procedures

3. The plan for the field tests was to regulate the weekly average inflow to 4,500, 5,000, and 5,500 cfs at 4-week intervals with the cooperation of Santee Cooper, operator of the Pinopolis hydropower station. Boat surveys were performed near the end of the test periods, and long-term monitors were operated continuously.

4. The 9 weeks of increased inflow was considered as a single test inflow period. Inflows from Pinopolis Dam were regulated according to plan, but the inflows during the 5,000-cfs period were variable, and slightly high. Boat surveys were performed 6 May, 3 June, and 1 July 1987.

Boat surveys

5. Boat surveys were cooperative efforts between the US Army Engineer Waterways Experiment Station (USAEWES) and the US Army Engineer District, Charleston. USAEWES supplied sampling equipment, a boat, and personnel. The

Charleston District supplied boats and personnel. USAEWES analyzed salinity samples and all recorded data.

6. Three boats were used to sample eight stations at hourly intervals over 13-hr tidal cycles. Samples and current velocities were taken at three depths (surface, middepth, and bottom) near the channel center line. Surface and bottom data were collected 2 ft below the surface and 2 ft above the bottom, respectively. Sampling stations included some stations occupied during the 1985 monitoring surveys and stations at the channel center line adjacent to the long-term monitoring stations to be described later. See Figure B1 for station locations.

Long-term monitors

7. Six conductivity probes and six automatic samplers were used to obtain long-term indications of harbor stratification. The conductivity monitors (probes) were installed by the US Geological Survey (USGS) under contract to the Charleston District at three stations: Customs House, Army Depot, and Mobay Chemical (Figure B1). Probes were installed at upper and lower water column locations off the main channel in about 24 ft of water, mean low water. The vertical separation of the probes was 13-18 ft. Hourly readings were transmitted via satellite to the USGS District Office at Columbia, SC.

8. Automatic water samplers were installed by USAEWES as near to the USGS probe locations as practical to verify readings and to serve as backup. Samplers were operated intermittently, and programmed to composite four subsamples each lunar day (24.84 hr).

Results

9. Data from the boat surveys were used to calculate vertical salinity stratification. The salinity stratification parameter* $\delta S/\bar{S}o$ was defined for consistency with other studies and data sets as

$$\frac{\delta S}{\bar{S}o} = \frac{S_3 - S_1}{\frac{(S_3 + S_1)}{2}} \qquad (B1)$$

* For convenience, symbols and abbreviations are listed in the Notation (Appendix E).

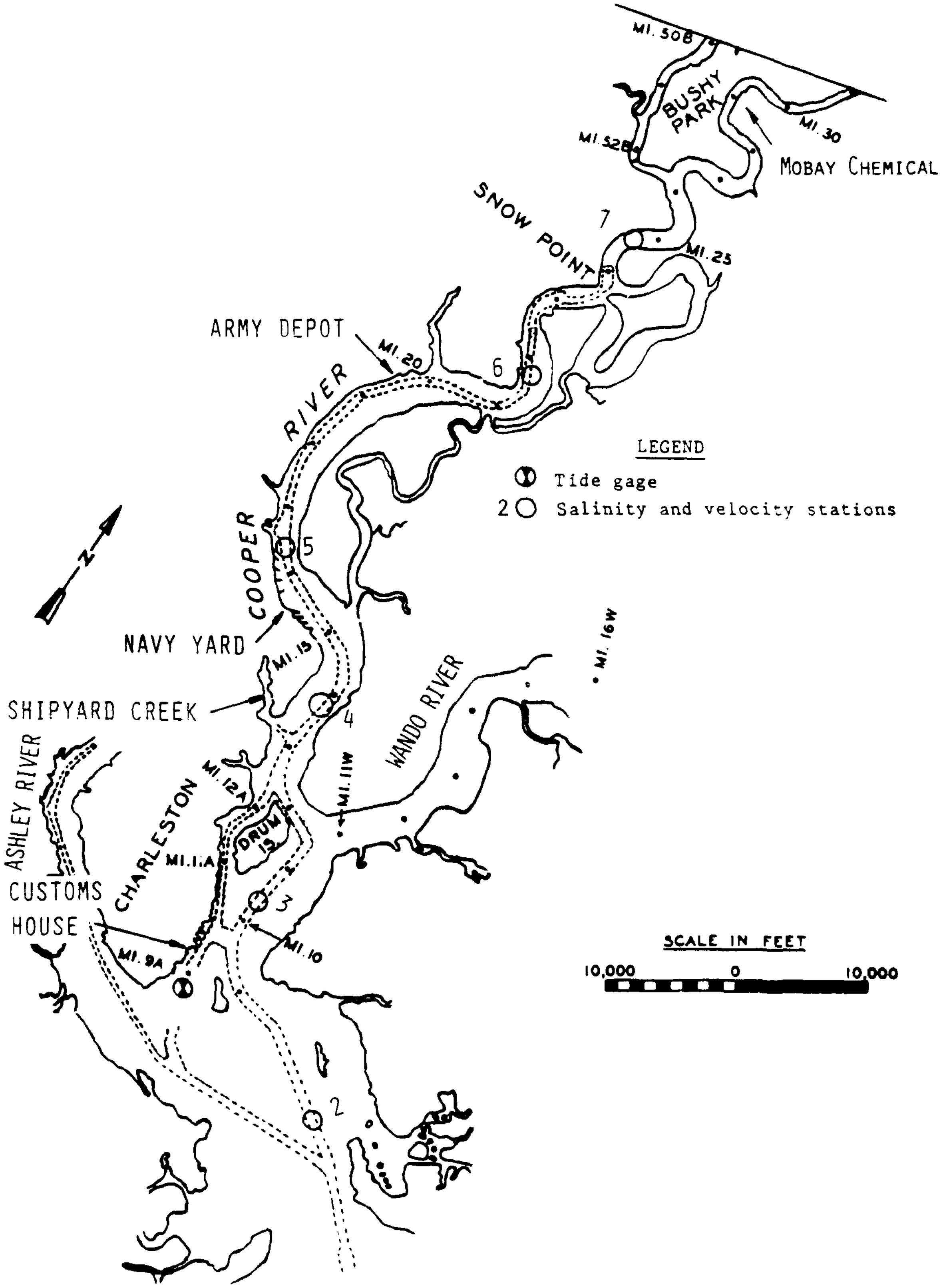


Figure B1. Locations of tide, salinity, and velocity stations where S is salinity, the overbar indicates depth averaging, o indicates depth averaging, and the indices 1 and 3 indicate surface and bottom sampling points, respectively. Conductivities from the USGS monitors were converted to salinities using a standard oceanographic method. Water samples were tested for salinity using a Beckman RS-7 laboratory instrument with an accuracy of ±0.003 ppt. Monitoring data from USGS probes and USAEWES automatic samplers were used to calculate estimates of $\delta S/\bar{S}o$ similar to Equation B1 over that portion of the water column bounded by the probes. Hereafter, the uncorrected USGS $\delta S/\bar{S}o$ values are referred to as apparent $\delta S/\bar{S}o$.

10. Table B1 lists tidally averaged values of $S_3 - S_1$, $\delta S/\bar{S}o$, and $\bar{S}o$ by station for the three boat surveys, and includes survey tidal and inflow conditions. Results for $S_3 - S_1$ and $\bar{S}o$ from boat surveys were compared to apparent USGS monitor values in Table B2. The USGS monitors measured substantially smaller $S_3 - S_1$ values than the boat surveys did, as expected from the smaller vertical separation in the surface and bottom sampling points as compared to boat survey sampling. The ratios between boat survey and USGS monitor values of $S_3 - S_1$ were fairly constant for the three surveys, averaging 1.56 for the Customs House and 1.9 for Army Depot. These ratios were used to correct USGS values of $\delta S/\bar{S}o$. Figure B2 displays conductances from the May boat survey and USGS probes at the Customs House station for comparison.

11. Long-term data from 4,500-cfs weekly average base inflow periods and the 5,000- to 5,600-cfs weekly average test inflow period were compiled for the Customs House and Army Depot monitor stations and analyzed. Much of the data from the USGS monitors, including all USGS data from Mobay Chemical, was spurious or was of insufficient time span, and could not be used. About a week's data were omitted at the transition between the base and test inflow periods.

12. Data coverage and weekly average inflows are shown in Table B3. The base inflow periods were different for the Customs House and Army Depot stations because although test inflow periods for the two stations covered the same days, data sets were slightly different because of missing data during the period. Daily average inflow for the study is given in Table B4. Some USGS probe data from these periods were compared to available USAEWES automatic sampler data and found to be reliable.

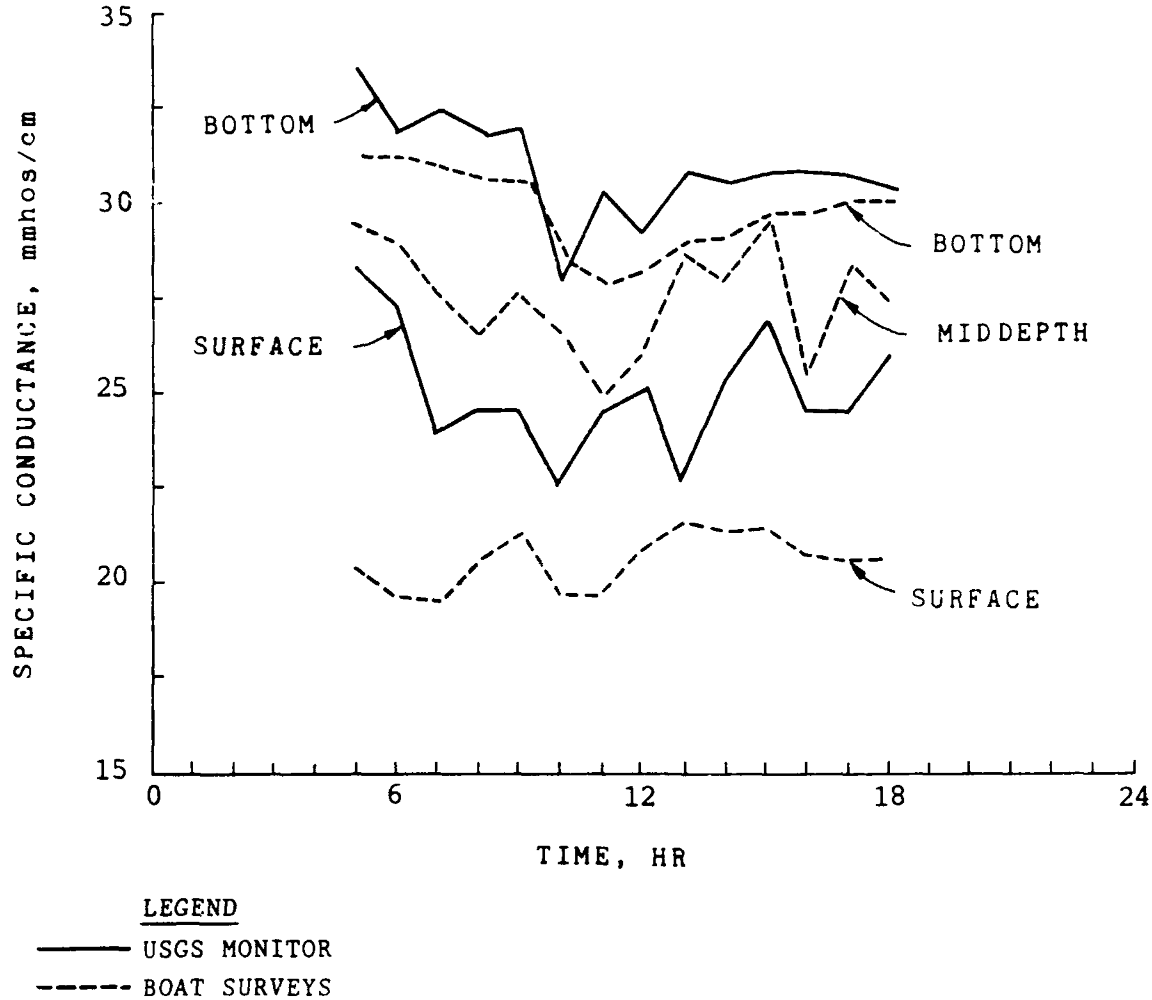
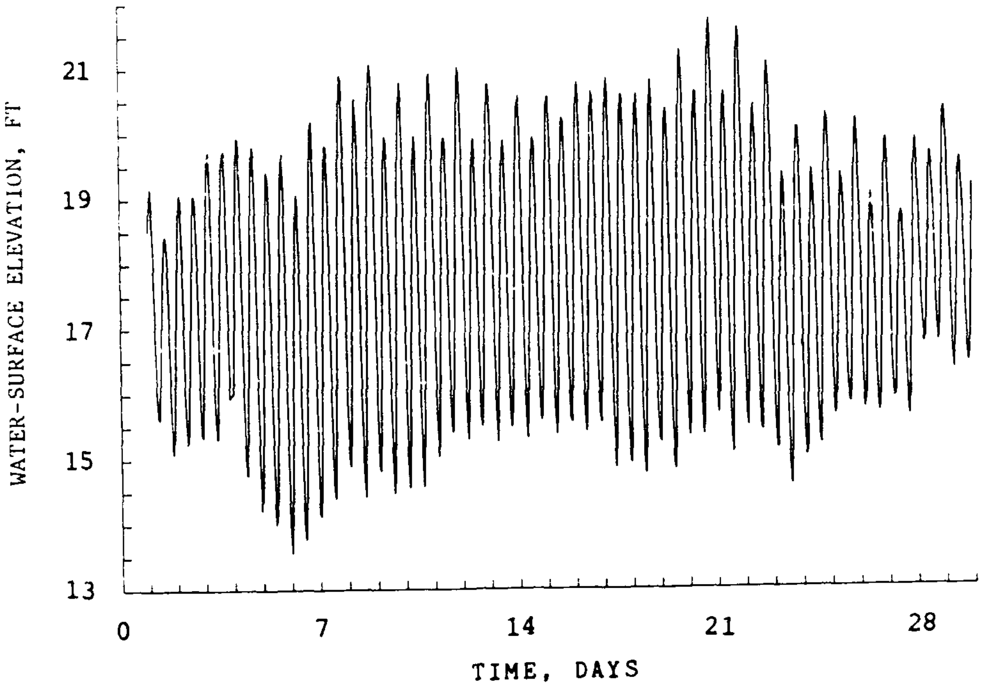


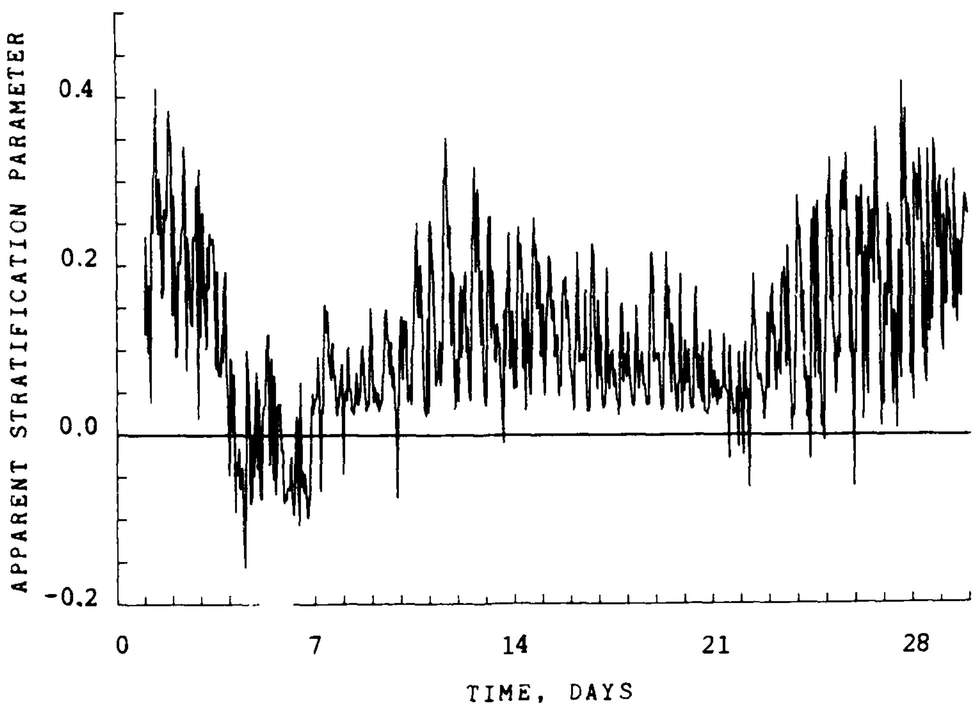
Figure B2. Conductivity data from boat surveys and long-term monitors at the Customs House station, 6 May 1987

13. Figure B3 shows the typical variability in hourly apparent stratification for the base inflow period at the Customs House station along with hourly tidal elevations for the same period. A strong tidal periodicity in stratification was exhibited at both stations, except during very low tide ranges when mixing was suppressed. There were also variations in the stratification parameter with tide range, especially at the Army Depot station.

14. Long-term stratification data were averaged over 24 hr. Daily tide range was characterized as the root mean square (rms) of hourly water level fluctuations about the mean tide level multiplied by 2.82 (to be comparable to conventional tide range measures). Figure B4 shows daily average salinity stratification and tide range corresponding to the hourly data plots in Figure B3. Figure B5 shows an example data plot of daily average salinity

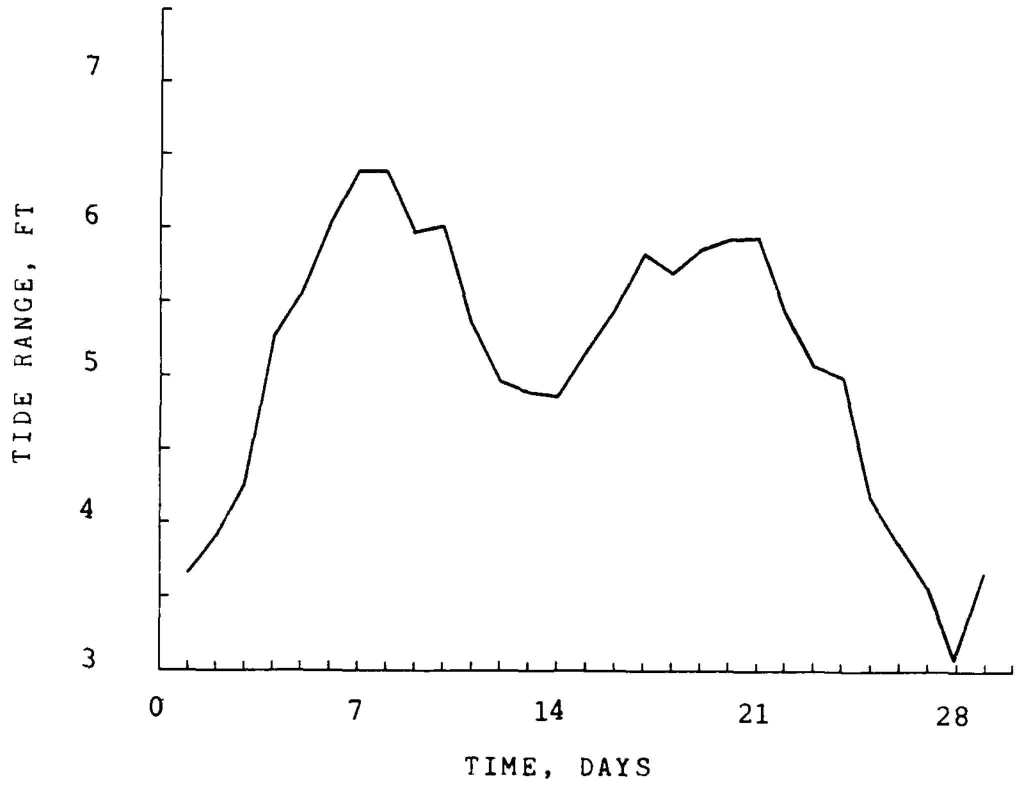


a. Hourly water levels

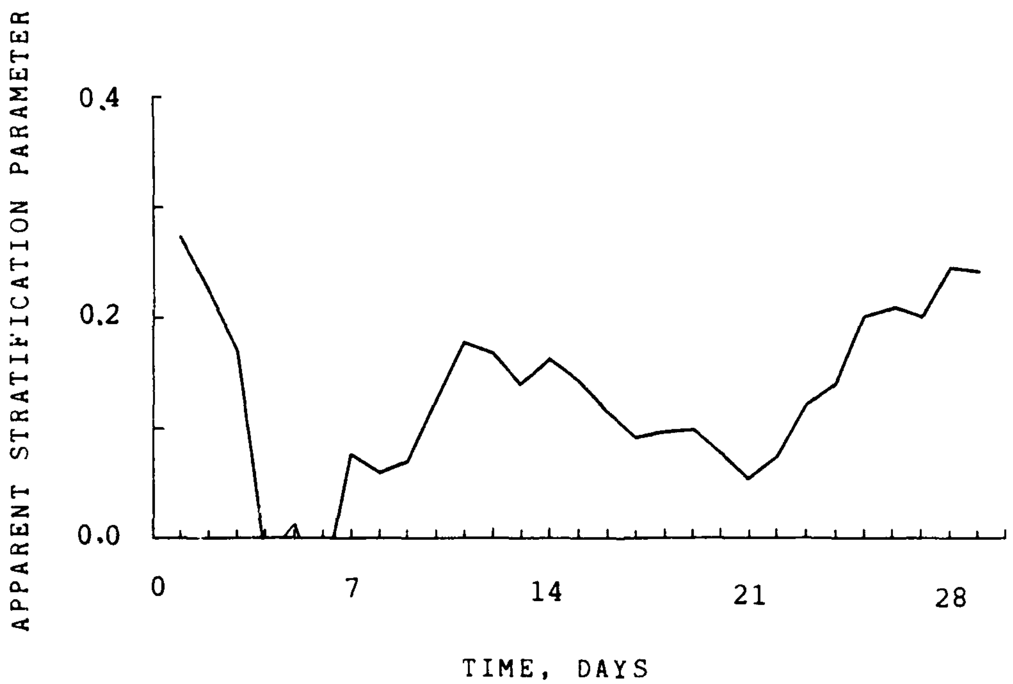


b. Apparent stratification

Figure B3. Hourly water levels and apparent stratification at the Customs House station starting 7 April 1987



a. Tide range



b. Apparent stratification

Figure B4. Daily average tide range and apparent stratification at the Customs House station starting 7 April 1987

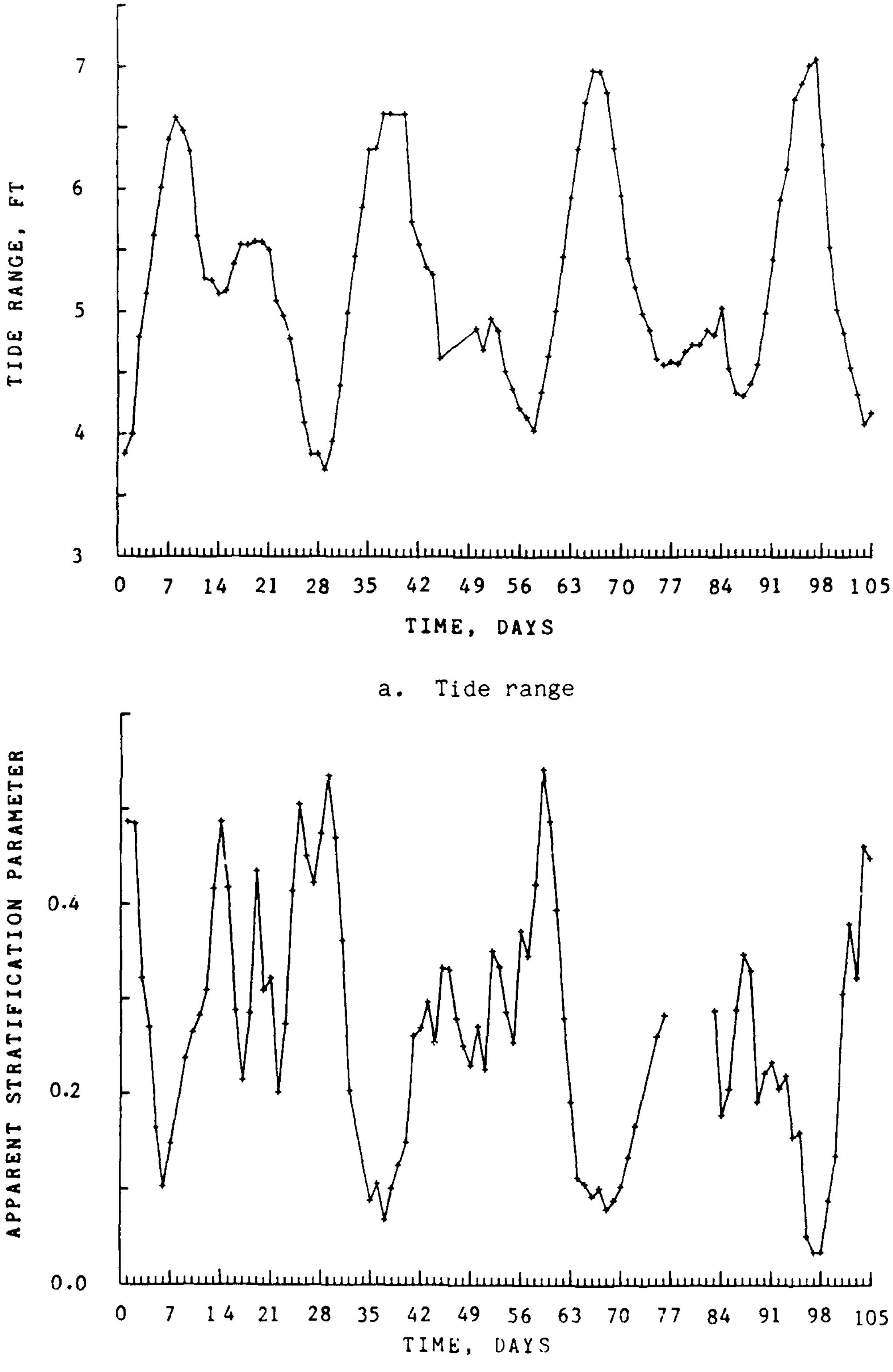


Figure B5. Daily average tide range and apparent stratification at Army Depot starting 6 May 1987 stratification and tide range from the Army Depot station covering a greater number of days.

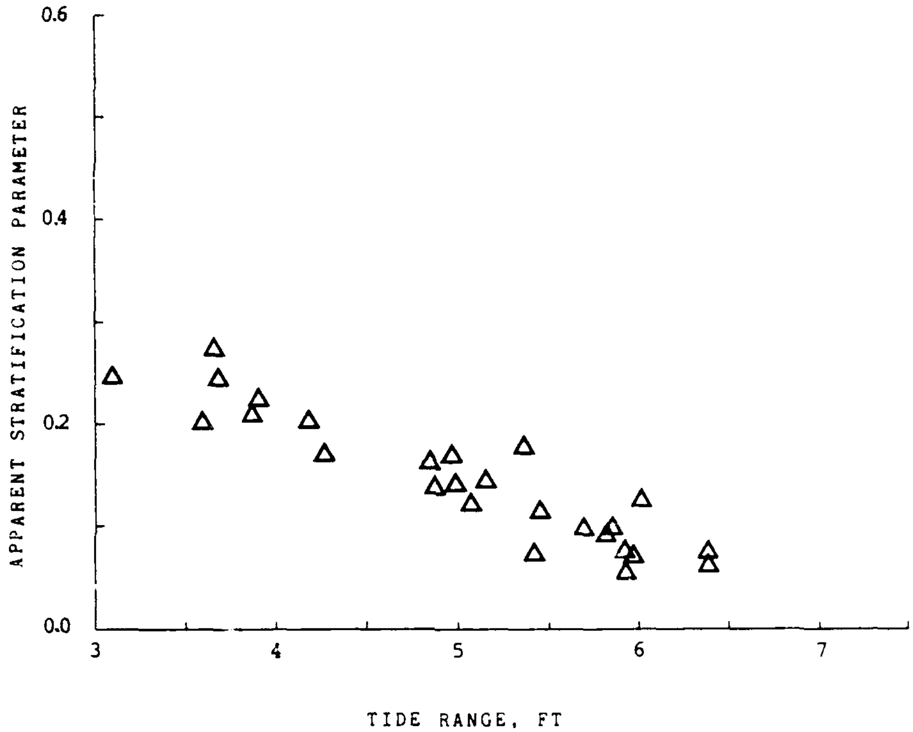
15. Average stratifications increased from base to test inflow periods according to long-term data. The data presented in Figures B6 and B7 were averaged. At Customs House, average apparent stratification increased from 0.1264 to 0.1427, and at Army Depot, apparent stratification increased from 0.2007 to 0.3180. Plots of daily average apparent stratification versus daily tide range for base and test inflows are shown in Figure B6 for the Customs House and Figure B7 for Army Depot.

Discussion

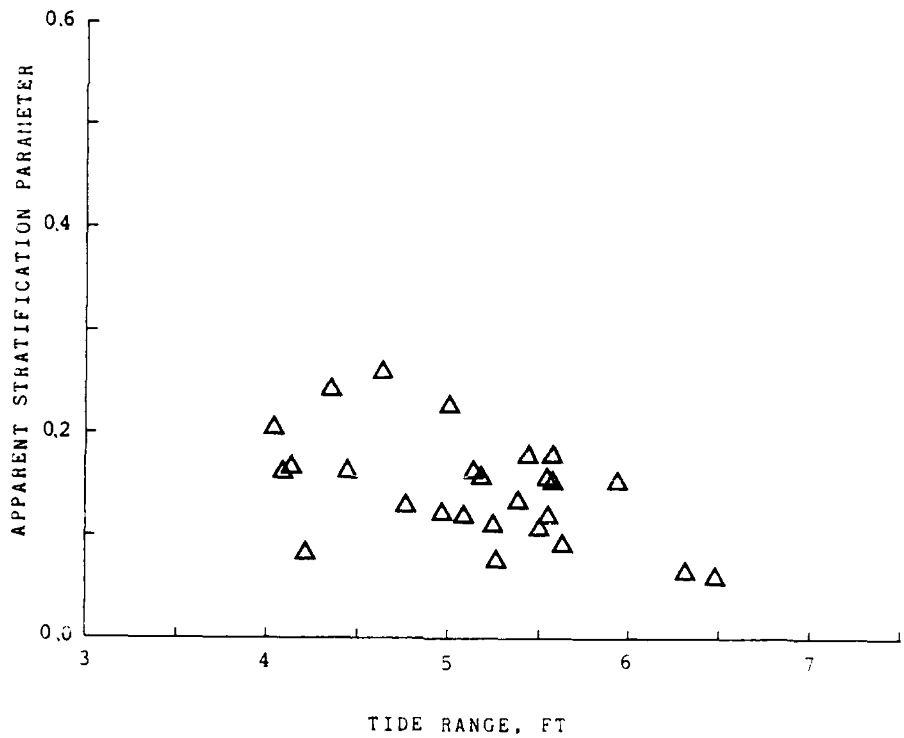
16. Stratifications were found to be relatively high during boat surveys. The boat survey data did not show a consistent effect on stratification from an inflow of slightly greater than 4,500 cfs. Boat surveys were performed over a narrow inflow range of 4,147-4,651 cfs averaged over the preceding week, and at very low, but not identical, tide ranges, as indicated in Table B1. Despite the limitations of the boat survey data, increasing stratification can be seen in Table B1 at the upstream stations between May, June, and July surveys, in agreement with the conclusions from the long-term data. Downstream stations showed an opposite trend, perhaps indicating the dominance of tidal over inflow effects under survey conditions in this area.

17. Stratification in boat survey data was smallest at Customs House and increased steadily upstream to Mobay Chemical, a general trend found in the 1985 harbor surveys (Table B1). Customs House stratifications were less dependent on tide or inflow compared to Army Depot data.

18. Long-term monitoring stations produced good data sets with which to examine stratification variation with inflow and tide range. For the entire range of inflows, daily average stratification decreased markedly with increasing tide range, as seen in Figures B6 and B7. Except during neap tides, stratifications approached zero at times during tidal cycles, as shown in Figure B3, for example. There were occasional negative stratifications recorded at the Customs House station, mostly during periods of very high tidal ranges. Automatic sampler data also displayed negative stratifications (as large as -0.33) during spring tides at the Customs House. Negative stratifications, as seen in Figure B3, may have resulted from strong, local secondary currents,

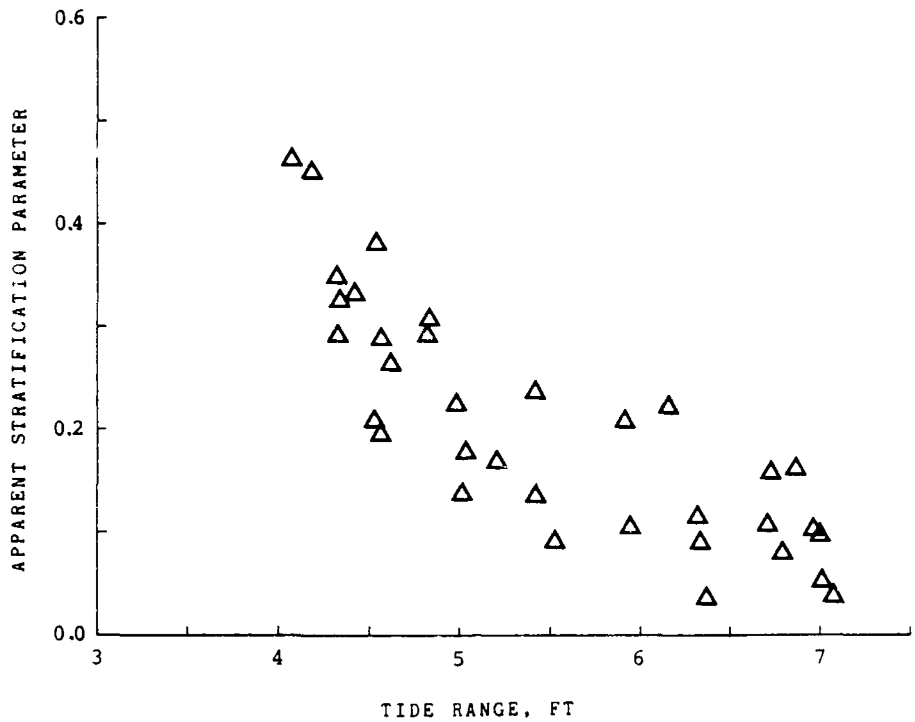


a. Base inflow period

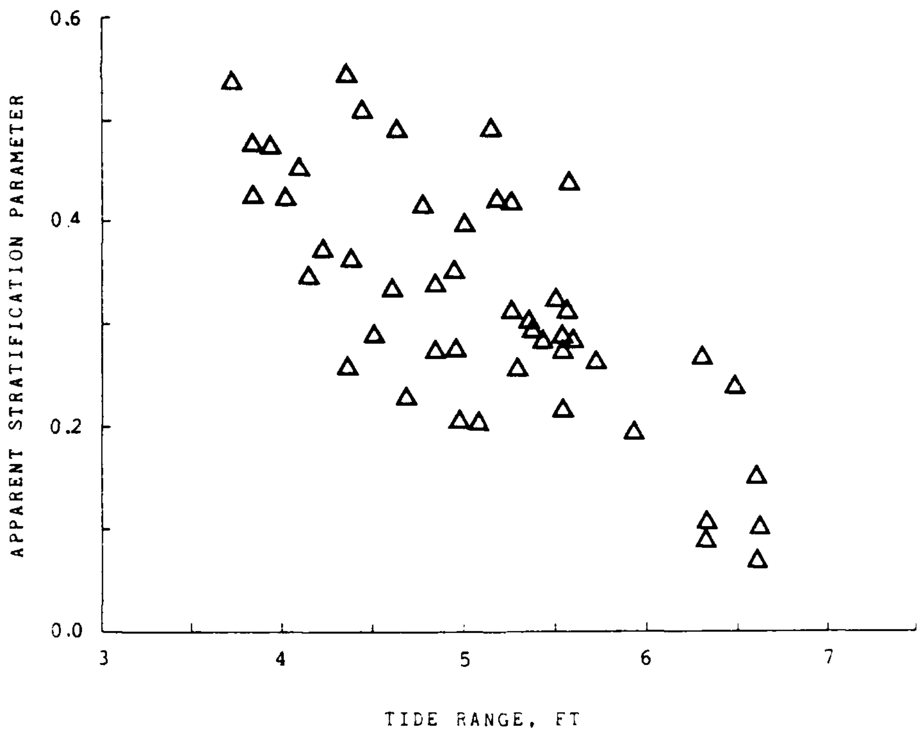


b. Test inflow period

Figure B6. Apparent stratification at Customs House



a. Base inflow period



b. Test inflow period

Figure B7. Apparent stratification at Army Depot and should be interpreted as zero stratification (completely mixed).

19. Stratification varied over tidal cycles. Mixing conditions caused abrupt increases and decreases in stratification, as can be seen by careful inspection of Figure B3. Tidal minimum stratification normally occurred near high water after upstream advection in the direction of decreasing salinities. During slack waters and ebb tidal phases, stratification normally increased.

20. Tide range was the dominant factor in tidal or daily average stratification variability as seen in Figures B4 and B5. A regression analysis was used to define relationships between daily stratification and tide range for base and test inflow periods. Regression analyses showed that stratifications were higher for the same tide range during the test inflow period than during the base period, especially for the Army Depot station. This trend can be seen by comparing Figures B6 and B7.

21. The best indicator of daily average tide range was the rms of hourly water-surface fluctuations from the long-term mean tide level multiplied by 2.82. Daily tide ranges calculated by the rms method had greater correlations to stratification than did daily maximum tide ranges (maximum less minimum water-surface elevations) or daily averages of high-minus-low water elevations.

22. The scatter in the daily stratification versus tide range (Figures B6 and B7) relationship was investigated. Parameters including daily average inflow, inflow lagged up to 2 days, tide range lagged up to 2 days, and daily average water level were tested in regression models and by correlation. The most important parameter found was a lagged inflow calculated as the sum of the two previous days' inflows, which showed a moderate (0.5-0.25) correlation to the residuals between observed values and values calculated by the regression relationship. However, when used in combination with tide range, the lagged inflow parameter improved the regression fit to the data only slightly. Therefore only a small amount of the scatter in the stratification versus tide range data plots was caused by inflow memory of the system and could be accounted for. Other conditions such as wind apparently affected stratification and caused most scatter in the data.

Summary and Conclusion

23. Vertical salinity stratification was determined for a base inflow

of 4,500 cfs and a test inflow of 5,000- to 5,600-cfs weekly average over a range of tidal conditions using boat surveys and long-term monitors in Charleston Harbor. Daily average stratification was greater for the same tidal range for the test inflow, especially at the upper end of the harbor. Since weekly average inflows above 4,500 cfs caused increased stratification, postrediversion weekly average inflow should be set at 4,500 cfs or less to maintain optimum harbor mixing. Salinity stratification was found to vary over tidal cycles and over spring-to-neap tidal sequences.

Table B1

Tidally Averaged Boat Survey Results

Inflow, cfs		Daily Tide Range, ft					
7-day Avg	11-day Avg	Avg	rms	Station*	$S_3 - S_1$ ppt	$\overline{So}$ ppt	$\frac{\delta S}{\overline{So}}$
			6 May 1987				
4,651	4,057	3.20	3.67	CH	9.15	25.22	0.362
				3	9.13	25.28	0.362
				4	14.49	21.25	0.681
				AD	14.64	19.01	0.770
				6	13.45	17.88	0.752
				7	11.95	15.23	0.785
				MC	4.90	5.72	0.857
			3 June 1987				
4,147	4,429	3.45	3.84	CH	5.31	25.47	0.208
				3	6.89	25.14	0.274
				4	10.63	20.58	0.517
				5	13.28	16.63	0.799
				AD	12.87	15.78	0.816
				6	11.34	13.79	0.822
				7	9.44	9.88	0.955
				MC	1.90	1.89	1.005
			1 July 1987				
4,638	4,773	3.76	4.21	CH	5.29	24.76	0.214
				3	5.92	24.47	0.242
				4	10.48	19.65	0.533
				5	11.25	16.59	0.678
				AD	11.61	15.03	0.772
				6	4.60	9.68	0.475
				7	9.09	8.24	1.103
				MC	0.57	0.55	1.036

* CH = Customs House, AD = Army Depot, and MC = Mobay Chemical.

Table B2

Salinity Comparison Between Boat Surveys and Long-Term Monitors

Station	Boat Surveys		Long-Term USGS Monitors	
	$S_3 - S_1$ ppt	$\bar{S}o$ ppt	$S_3 - S_1$ ppt	$\bar{S}o$ ppt
		6 May 1987		
Customs House	9.15	25.22	5.75	26.49
Army Depot	14.64	19.01	7.83	17.65
		3 June 1987		
Customs House	5.31	25.47	--	--
Army Depot	12.87	15.78	7.44	13.77
		3 June 1987		
Customs House	5.31	25.47	--	--
Army Depot	12.87	15.78	7.44	13.77
		1 July 1987		
Customs House	5.29	24.76	3.47	24.47
Army Depot	11.61	15.03	5.56	12.79

Table B3

1987 Monitoring Inflow Periods, Compilation Dates, and Weekly Average Inflows

Data Period	Dates	Weekly* Average Inflow, cfs
Customs House base period covered 8 Apr-6 May	4 Apr-10 Apr	4,671
	11 Apr-17 Apr	4,564
	18 Apr-24 Apr	4,504
	25 Apr- 1 May	4,558
	2 May- 8 May	4,484
Customs House and Army Depot test period covered 15 May-8 July	9 May-15 May	5,000
	16 May-22 May	4,969
	23 May-29 May	4,979
	30 May- 5 Jun	4,975
	6 Jun-12 Jun	5,091
	13 Jun-19 Jun	5,504
	20 Jun-26 Jun	5,488
	27 Jun- 3 Jul	5,644
	4 Jul-10 Jul	5,497
Army Depot base period covered 15 July-19 Aug	11 Jul-17 Jul	4,544
	18 Jul-24 Jul	4,465
	25 Jul-31 Jul	4,521
	1 Aug- 7 Aug	4,527
	8 Aug-14 Aug	4,528
	15 Aug-21 Aug	4,463

* Based on Saturday-Friday inflow week.

Table B4

Daily Average Inflows, cfs, from Pinopolis Dam, 1987

Day	April	May	June	July	August
1	3,220	3,848	5,108	4,974	2,789
2	3,491	0	4,678	8,391	2,301
3	5,263	0	5,406	12,052	4,766
4	1,416	6,255	6,090	3,818	9,183
5	1,338	6,467	9,456	6,056	2,982
6	4,933	2,046	2,208	5,106	2,747
7	6,816	6,075	2,538	4,674	6,929
8	6,083	10,548	6,462	8,073	2,196
9	5,943	1,991	5,408	7,020	2,039
10	6,166	959	6,224	3,730	4,351
11	1,063	8,063	4,275	2,244	4,271
12	0	6,824	8,522	2,086	5,141
13	5,955	7,815	3,056	3,646	5,707
14	5,624	4,453	3,033	4,118	7,993
15	9,520	4,896	6,114	5,047	2,181
16	4,816	3,946	6,206	3,801	2,313
17	4,972	4,546	5,481	10,868	6,732
18	1,135	9,716	5,268	2,068	6,002
19	0	7,129	9,371	4,841	3,353
20	7,698	2,435	4,546	4,009	4,557
21	8,219	2,341	4,690	2,291	6,101
22	6,174	4,667	6,043	4,156	3,371
23	5,048	7,814	4,766	4,354	3,086
24	3,256	7,050	5,252	9,538	2,085
25	0	2,748	4,790	6,391	3,801
26	0	2,079	8,331	3,994	7,090
27	5,388	3,138	3,416	2,676	5,646
28	6,677	4,121	984	2,805	6,299
29	8,135	7,900	4,178	4,661	2,370
30	7,857	2,053	5,515	6,938	2,103
31		2,033		4,186	2,219

APPENDIX C: SHOALING RATES AT 3,000- TO 4,500-CFS INFLOW

Purpose

1. The purpose of this appendix is to present an analysis of the differences in Charleston Harbor shoaling for the range of inflows from 3,000 to 4,500 cfs.

Brief Review of Previous Shoaling Analyses

2. Study of the causes of the Charleston Harbor shoaling began shortly after the diversion of the Santee River's flow into the Cooper River in 1942. A model study at the US Army Engineer Waterways Experiment Station (USAEWES) was authorized in 1947, and complementary studies were carried at the US Army Engineer District (USAED), Charleston, in the late 1940's. By the 1950's, experience with the diversion and investigations into the harbor shoaling had identified the diversion as the major cause of the shoaling problem.

3. Prototype investigations by USAED, Charleston (1954),* showed the suspended material in the Cooper River to be identical to those in the shoal material. Kaolinite was identified as the primary mineral in the fines. Settling tests showed that 75 percent of the particulates settled at less than 0.001 fps. Shoal densities and grain size distributions were measured. By all indications, the shoal material was characteristic of fine-grained, cohesive sediments. During freshet conditions, highly turbid waters were observed to pass from the Lake Moultrie Reservoir into the Cooper River and fill the harbor with a reddish hue. Thin laminations of slick clayey materials, notable by their distinctive color and texture, formed on tidal flats and beaches in several areas.

4. This study concluded that the rivers were the largest initial source, with settling occurring in areas of relative stagnation, trapping material in the flood-dominated bottom levels of the estuary. Material near the bed can move, dependent on its density and viscosity, until it has the opportunity to harden sufficiently.

5. The earliest model study (USAEWES 1957) concluded that more than

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* References cited in this appendix can be found at the end of the main body of the report.

99 percent of the shoaling increase was due to the diversion, brought on by the following factors:

- a. A density flow superimposed on the tidal flow that produced strong flood-dominated flows near the bed, preventing the estuary from disgorging its load to the sea.
- b. Increased colloids and dissolved material available to shoal the harbor, both from suspended load in the river and from erosion of the upper channel (assumed to have equal magnitudes).

Channel deepening from -30 to -35 ft mean low water (mlw) was found to have caused only a minor increase in harbor shoaling. Rediversion model tests performed at 2,500- and 5,000-cfs inflow implied that about 3,000 cfs was the maximum tolerable to harbor stratification, but the report cautioned that no single flow was best for the entire harbor.

6. The latest study of shoaling conditions in Charleston Harbor and the effect of rediversion on shoaling was performed by the US Geological Survey (Patterson 1983). An attempt was made to quantify sediment sources for the system, and balance them against amounts of sediment removed by dredging and storage in deposits. Patterson gathered existing information to estimate rates of sediment inflow, removal, and accumulation. Dredging records, hydrographic surveys, maps, charts, hydrologic data, unpublished files, and knowledgeable individuals were sources of information for this study.

7. Patterson divided the data into approximately 20-year periods to identify trends. The sediment sources identified (and mean annual values for 1966 through 1982) included the following:

- a. Pinopolis discharge (0.8 million cubic yards).
- b. Cooper River scour (0.25 million cubic yards).
- c. Background sources including diatom plankton, marsh vegetation, urban storm runoff, wastewater, and shoreline erosion (0.2, 0.6, 0.15, 0.02, and 0.3 million cubic yards, respectively).
- d. Unknown (ocean and unspecified) sources (3.4 million cubic yards).

The unknown source magnitude was estimated by subtracting the known inputs from the total of the amounts removed and accumulated. This study was able to account for only less than half of the shoaling by known sediment sources. The Pinopolis discharge of suspended sediments (which was estimated using a number of different methods) accounted for only about 15 percent of shoaling volumes.

8. By the early 1960's Charleston Harbor's shoaling rate had stabilized with respect to the diversion. Dredging became more effective in the

early 1950's, and river channel erosion greatly diminished.

9. Sediment sources were projected for 3,000-cfs inflow to predict the effect of rediversion on shoaling rates. A shoaling reduction of 40 to 75 percent was predicted for the Cooper River rediversion, based largely on the unknown component.

Shoaling Processes in Charleston Harbor

10. The 1942 diversion resulted in an increase in freshwater inflow from about 500 to 15,600 cfs, and caused about a 36-fold increase in inner harbor dredging (from 120,000 cu yd per year in 1953 exclusive of bar and jetty channel) as well as substantial increases in other areas (USAEWES 1957). Three hydrodynamic sediment traps were created by the diversion, and were largely responsible for increased retention of shoaling material and buildup of unconsolidated mud throughout the estuary:

- a. Vertical density stratification increased drastically and trapped sediments near the bed.
- b. Net tidal-averaged circulation patterns changed and trapped near-bed suspended sediments in developed areas of the estuary.
- c. Once concentrated and deposited, sediments were trapped in unconsolidated mud and isolated to a large extent from transport by turbulent tidal flows.

The increase in project channel depth that occurred at about the same time as the diversion did not have an important effect on harbor shoaling.

11. The major effects of rediversion on shoaling for both the 4,500- and 3,000-cfs weekly average flows were as follows:

- a. Reduce vertical density stratification, thus improving vertical mixing, preventing sediments from being trapped near the bed, and improving sediment flushing for the harbor.
- b. Move the null area of vertical circulation upstream, thus reducing suspended sediment accumulation and unconsolidated mud formation in project and facility areas.
- c. Reduce sediment and nutrient loadings to the harbor.

Vertical density stratification, which is created by vertical salinity stratification, damps vertical mixing. The null area of vertical circulation is where near-bed net (tidal-averaged) velocities are neither landward nor seaward, and thus is an area of converging net bottom flow. Organic materials contribute to shoaling directly, and foster the coagulation of inorganic sediments.

12. The largest reservoir of potential channel shoaling material is now the vast (20- to 30-million-cubic-yard) blanket of unconsolidated mud that covers the floor of the estuary. This material has densities between 1.22 and about 1.05 g/cu cm, and consistencies between that of mayonnaise and pea soup. Unconsolidated mud has been observed to move within estuaries. It can move longitudinally landward or seaward in response to changing tidal and freshwater inflow conditions, or laterally due to channel slopes or special flow conditions. These sediments are not generally moved with the net estuarine circulation as are suspended sediments. Unconsolidated muds slump or move only with stronger tidal flows near the bed, and tend to accumulate in deeper areas of relative stagnation.

Prediction Method

13. Prediction of the difference in shoaling between 3,000 and 4,500 cfs was made using a method similar to that used by Patterson (1983). A sediment budget was constructed for Charleston Harbor that identified various sediment source components. Data on average annual sediment sources from 1966 through 1982 were used. The effect of rediversion on each component was estimated to make shoaling predictions. Overall shoaling for the Charleston Harbor was considered.

14. The latest Charleston District estimate of the 1965 through 1984 average annual gross dredging for Charleston Harbor (6.19 million cubic yards per year) was used in this analysis, and was somewhat lower than Patterson's value of 7.6 million cubic yards per year. The Charleston District value includes the Naval Ammunition Depot (NAD) channel, shoals 1-6, Customs House and tidewater reaches, Shipyard River, anchorage, and entrance channel dredging. Annual dredging rates and locations of these major shoals are given in Table C1. It does not include Navy and other slips, which amounted to 3.13 million cubic yards per year average for the period 1953 through 1963. The pier-slip contribution to 1965 through 1984 dredging is not known, but is probably lower than the older average. The estimated difference in shoaling rates between 3,000 and 4,500 cfs was not affected by this omission. Runback, the difference between gross dredging volumes and permanent removal, was assumed to be 22 percent.

15. Plant contributions to shoaling by marshes and diatom plankton were

treated separately in this analysis, as they are considered to depend on inflow. The high level of productivity in estuarine and coastal waters has been attributed in part to enrichment by nutrients carried by river waters (Parsons and Takahashi 1973). Additional estuarine biological productivity enhancement comes from the mixing of fresh water (in which phosphorus limits plant growth) with ocean water (in which nitrogen usually limits plant growth), and from the entrainment of deeper, nutrient-rich coastal waters by estuarine flows. Plant production contributions were assumed to come from dissolved and particulate nutrients, largely nitrogenous materials, carried by the inflow.

Expected Shoaling

16. The difference in direct sediment inflow and plant production between 4,500- and 3,000-cfs weekly average flows will amount to about 160,000 cu yd of shoaling material annually (Table C2). Sediment inflow and plant production contributions to shoaling are expected to be proportional to Pinopolis inflow.

17. The unknown sediment source referred to in Table C2 could be made up largely from sediments of ocean origin. Reduction of the unknown source was related to the improved sediment flushing efficiency of the harbor, and therefore inversely proportional to the vertical density stratification observed during flow testing surveys. Scour in the Cooper River is expected to be eliminated for both 3,000- and 4,500-cfs flows.

18. The overall shoaling reduction predicted in Table C2 for 3,000 cfs (74 percent) is slightly greater than the Charleston District overall 1966 estimate (71 percent), and slightly less than the upper limit of Patterson's (1983) predicted range (40-75 percent).

19. The overall difference in dredged volumes between 4,500- and 3,000-cfs weekly average flow will most likely be about 200,000 cu yd annually.

Entrance Channel Shoaling

20. The overall shoaling estimates presented in the preceding paragraphs included the entrance channel. Entrance channel shoaling will be considered separately in this section because of dredging cost concerns for this area and because of the paradoxical nature of shoaling seaward from a

harbor many experts have declared to be an efficient sediment trap.

21. Early studies described Charleston Harbor entrance channel shoaling material as coarse-grained. Patterson (1983) compiled prediversion dredging volumes for the entrance channel. Long-term averages were less than 267,000 cu yd per year. Recently the Charleston District has identified entrance channel shoaling as fine-grained. Average entrance channel dredging was 1.24 million cubic yards per year for 1965 through 1984.

22. Rough calculations of deposition rates from sediment suspensions were made for the entrance channel using reasonable values for settling velocity (0.01 cm/sec), near-bed suspension concentration (200 mg/ℓ), and the frequency of deposition time. The frequency of deposition time was estimated using an assumed critical shear stress for deposition (0.05 Pa) and compiled coastal currents for the area (0.3 to 0.8 knots) as 8 percent (about 30 days per year). To balance the observed shoaling mass (specific weight of shoal material times shoal volume divided by shoal area) with calculated deposition from suspension required unreasonable values for depositional frequency (267 days per year) or for near-bed concentration (1,780 mg/ℓ). Therefore, it is difficult to account for shoaling in the entrance channel by settling from suspension, even when the possibility of reerosion of deposited sediments by storm action is totally ignored. Therefore, even when the possibility of reerosion of deposited sediments by storm action was ignored, only a small part of the shoaling in the entrance channel was attributed to settling from suspension.

23. Entrance channel shoaling increases have probably been caused by near-bed movements of unconsolidated mud. Ebbing tidal flows transported sediments out of the estuary, and they became stranded in the outer entrance channel where tidal flood flows were insufficient to return them.

24. It is reasonable to assume that there will be a considerable reduction in entrance channel shoaling after rediversion and a stabilization period. This was also the opinion of the Committee on Tidal Hydraulics (1966). The shoaling reduction in this area will be of the same order of magnitude as the predicted overall reduction. The unconsolidated mud shoaling source will diminish over the next decade--some of it dredged from channel sites, some flushed seaward from the harbor, and some hardening in place. Suspended sediment flushed seaward is not expected to deposit rapidly enough to increase entrance channel shoaling.

Table C1

Annual Dredging Rates and

Locations of Major Inner Harbor Shoals, 1965-1984*

Shoal/Reach	Annual Gross Yardage 1,000 cu yd	River Mile
Anchorage	767	6.5- 7.7
Tidewater	563	9.1- 9.7
6A	547	9.7-11.1
6B	37	11.4-12.2
6C	263	9.9-10.7
6	115	11.6-12.3
Shipyard River	780	13.0-13.7
5A	406	13.2-14.1
4	170	16.2-17.0
3	37	17.7-18.9
1 and 2	300	18.9-20.4
NAD	828	20.9-23.1
Total	4,813	

* Data supplied by B. Kyzer, USAED, Charleston.

Table C2

Effects of Pinopolis Inflow on Sediment Sources and Shoaling

Volumes for Charleston Harbor

Pinopolis Inflow Weekly Average cfs	Shoaling Volumes,* million cubic yards						Shoaling Reduction percent‡
	Cooper Scour	Sediment Inflow	Plant Production**	Background†	Unknown††	Total	
15,600	0.25‡‡	0.80‡‡	0.80‡‡	0.45‡‡	2.5	4.8	0
3,000	0.0	0.16	0.16	0.45	0.5	1.3	74
4,500	0.0	0.24	0.24	0.45	0.5	1.4	70

* Dredged volumes are expected to be 1.28 times shoaling volumes to account for runback.
** Includes diatom plankton and marsh vegetation. See paragraph 15 in this appendix.
† Urban runoff and shoreline erosion from Patterson (1983).
†† Ocean and other sediment sources. Assumed to be related to estuarine trap efficiency. See paragraph 17 in this appendix.
‡ (1 - total shoaling volume/4.8) × 100.
‡‡ Data from Patterson (1983).

APPENDIX D: DEFINITIONS OF TERMS

Flow predominance	The fraction of the total flow over a tidal cycle in the ebb or seaward direction (usually specified for a specific depth).
Flux	The transport of salt or suspended sediment through a certain area. Calculated as the product of velocities, salinity or suspended sediment concentrations, and cross-sectional or unit areas, and usually summed over a tidal cycle.
Flux components	Statistical correlations calculated by a sequence of time and depth averaging for the purpose of resolving instantaneous and depth deviations in fluxes at a sampling station.
Null zone	The region in an estuary where bottom flow predominance is 0.5, and where tidal-averaged currents are zero. Often occurs at salinity values of 1-5 ppt.
Salinity	Concentration by weight (expressed as parts per thousand or ppt) of inorganic matter (mainly chloride, bromide, sodium, potassium, magnesium, and calcium) in seawater or brackish water (dilute seawater).
Sediment flushing	The effects of estuarine flow and transport processes that transport sediments permanently seaward.
Stokes velocity	A residual flow generated by tide or other long-wave propagation.
Stratification	Vertical salinity and density distributions that stabilize estuarine flows by buoyancy effects, and that inhibit vertical transport of salinity, suspended matter, and momentum.
Tidal average	The average of a function over a tidal cycle. In the case of flows or fluxes, the residual of tidal motion.
Tidal hydraulics	Instantaneous flows and water-surface elevations associated with earth/astronomical gravitational effects.
Tidal pumping	The transport of salt or suspended sediment caused by unequal temporal variability and phasing between concentration and the tidal flow.
Turbidity maximum	The area in estuaries associated with maximum suspended sediment concentration usually near the null zone.
Vertical circulation	Tidal residual flow in the vertical plane characterized in estuaries by upstream flow at the bottom and seaward flow near the surface.
Vertical mixing	The vertical turbulent exchange of salinity and suspended material that is generated by an estuarine flow.

APPENDIX E: NOTATION

Subscripts and indices:

b	Bottom; bed
f	Freshwater
i	Tidal-averaged instantaneous deviation
i'	Instantaneous deviation at time t
o	Indicates a depth average
s	Stokes velocity; surface
v	Vertical deviation
t	Time
z	Depth coordinate
1,2,3	Depth indices for surface, middepth, and bottom, respectively

Parameters:*

C	Suspended sediment concentration
g	Acceleration due to gravity
h	Depth of flow
K	Eddy diffusivity
Ri	Richardson number
S	Salinity
$\bar{S}o$	Average salinity
U	Velocity of tidal flow
Uf	Weekly average freshwater velocity
$\langle Uov \rangle$	Steady vertical shear at a station calculated as the root mean square of $Uov(z)$ components
v	Fraction of total upstream salt flux driven by horizontal diffusion
z	Vertical distance up from the bed
δS	Bottom-to-surface mean salinity difference, $\bar{S}_3 - \bar{S}_1$
ρ	Density (computed from salinity and temperature)

* These parameters are identified with appropriate subscripts and indices and discussed in Appendix A, "Analytical Procedures," and depicted graphically in Figure A5.