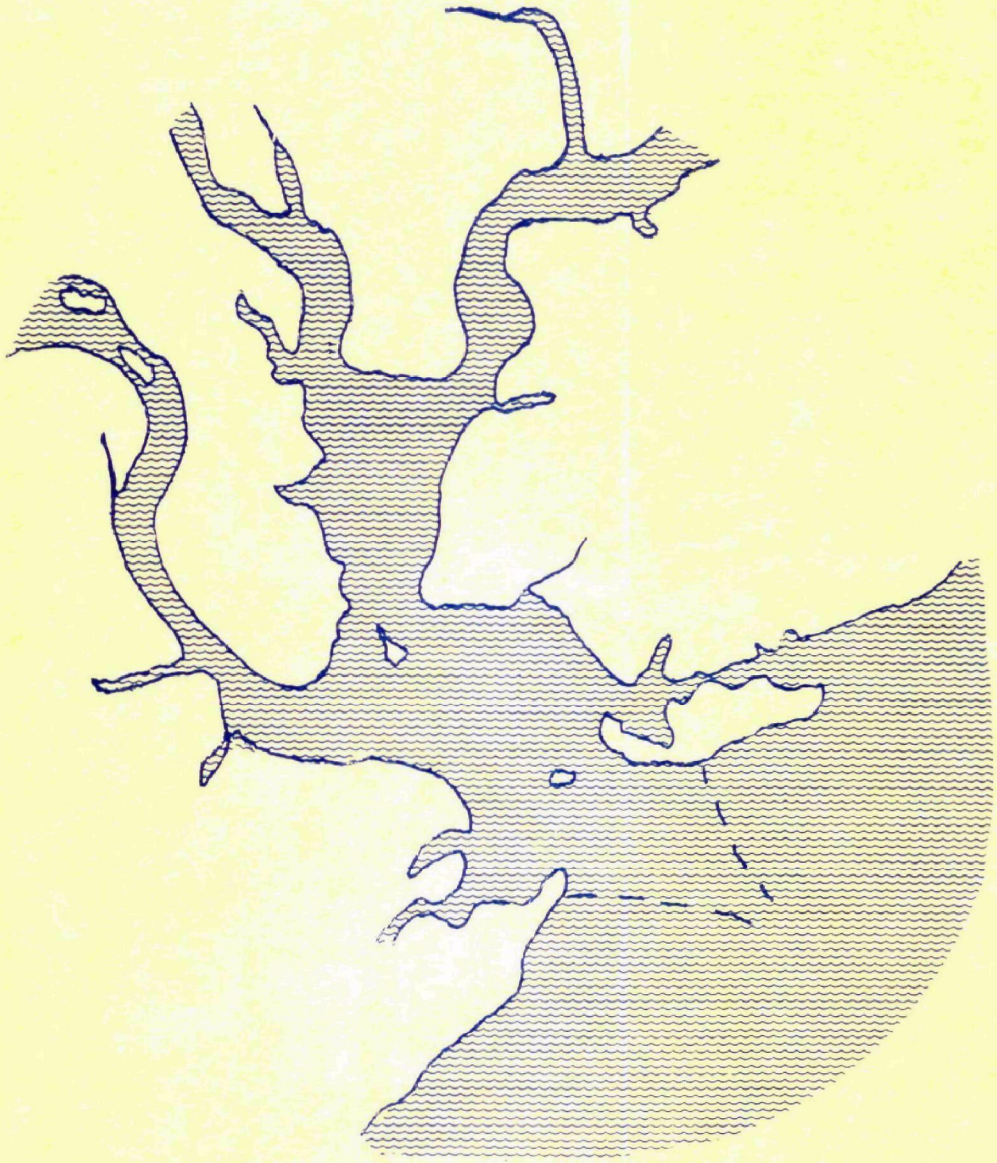
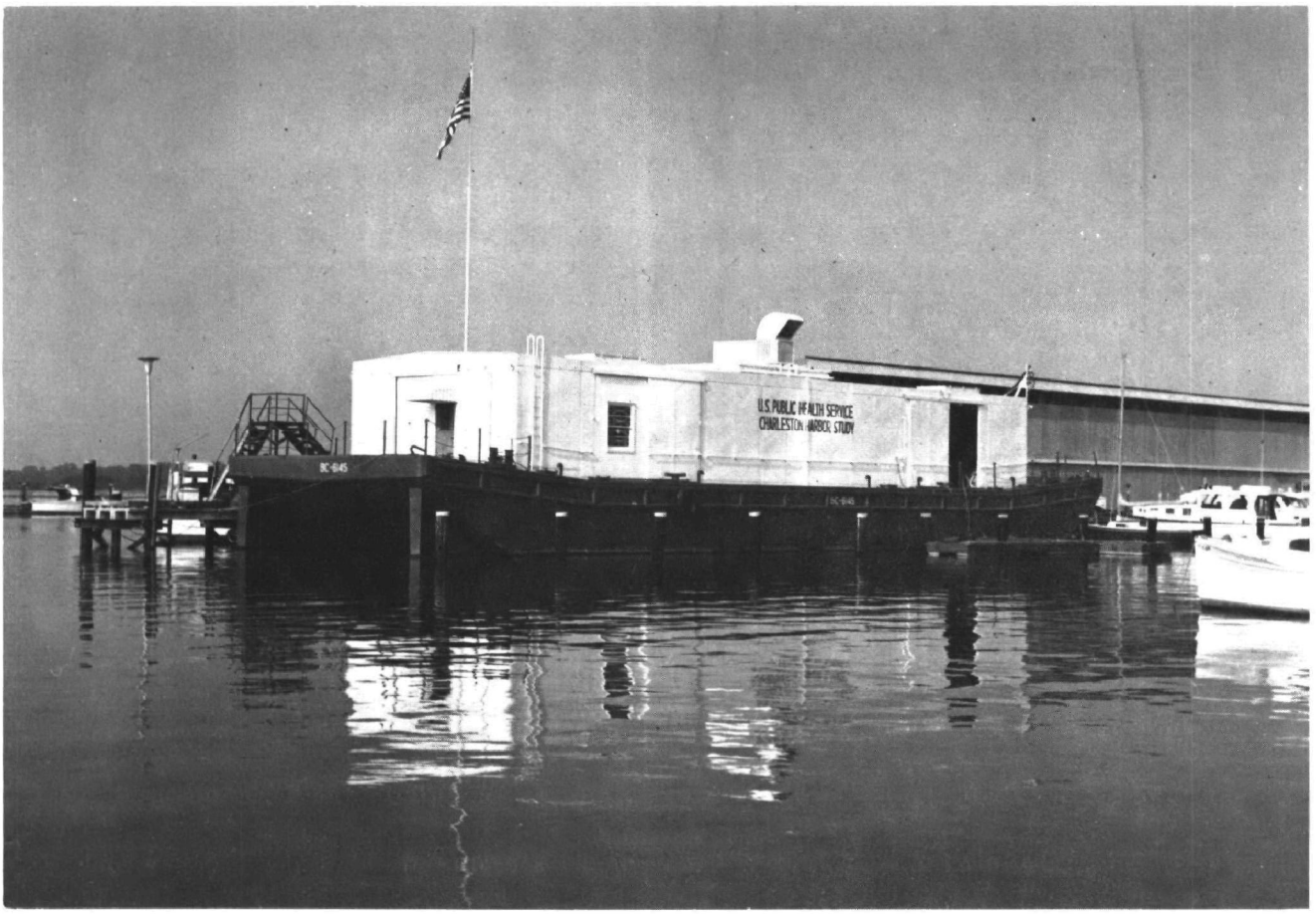
CHARLESTON HARBOR WATER QUALITY STUDY



FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

A REPORT ON THE WATER QUALITY OF CHARLESTON HARBOR AND THE EFFECTS THEREON OF THE PROPOSED COOPER RIVER REDIVERSION



UNITED STATES DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
Southeast Water Laboratory
Charleston Harbor-Cooper River Project
Charleston, South Carolina
June 1966

TABLE OF CONTENTS

	Page No.
INTRODUCTION	1
Authority	3
Purpose and Scope of Study	4
Acknowledgements	4
SUMMARY	5
CONCLUSIONS	11
Present Conditions	11
Future Conditions	12
DESCRIPTION OF STUDY AREA	15
DESCRIPTION OF STUDY	19
Specific Objectives	19
Study Methods	19
RESULTS OF STUDY	37
Present Water Quality	37
Relationship of Present Water Quality to Environmental Changes	52
PREDICTION OF FUTURE WATER QUALITY	79
Coliform Concentrations	80
Sludge Beds	81
Toxic Materials	81
Nutrient Buildup	82
Dissolved Oxygen	82
BIBLIOGRAPHY	84
APPENDICES	A-1
A Summary of Routine Survey Data	A-1
B Summary of Intensive Survey Data	B-1
C Summary of Chloride-Discharge Analysis Data	C-1

LIST OF TABLES

Table No.	Title	Page No.
1	Hydro Plant Discharges-Pinopolis Dam.....	18
2	Water Quality Parameters Measured.....	21-22
3	Laboratory Analytical Procedures.....	23-25
4	Intensive Sampling Program.....	27
5	Special Studies.....	29-31
6	Source of Organic Material in Benthic Deposits..	44
7	Laboratory Investigation of Oxygen Utilization by Benthic Deposits.....	45
8	Benthic Biota.....	49
9	Phytoplankton Concentrations.....	50
10	Cumulative Knots of Wind by Direction.....	53
11	Major Waste Discharges.....	55-56
12	Cumulative Solar Radiation.....	58
13	Solar Radiation and D.O. Variance.....	60
14	Analysis of Model Dye Studies.....	70
15	Overall Response of D.O. Percent Saturation to River Discharge.....	73
16	Analysis of D.O. Response to River Discharge and Correction for Tide Range.....	74

Appendices

A-1	Results from Routine Monitoring.....	A-2-5
B-1	Mean Values of Percent Saturation of Dissolved Oxygen.....	B-2
B-2	Mean Values of Water Temperature.....	B-3
B-3	Mean Values of Chlorides.....	B-4
B-4	Mean Values of Total Coliforms.....	B-5
B-5	Mean Values of Fecal Coliforms.....	B-6
B-6	Surface to Bottom Chloride Ratios.....	B-7
B-7	Mean Values of 5-Day BOD.....	B-8
B-8	Mean Values of Ammonia.....	B-9
B-9	Mean Values of Nitrates.....	B-10
B-10	Mean Values of Organic Nitrogen.....	B-11
B-11	Mean Values of Total Phosphates.....	B-12
B-12	Summary of pH Data.....	B-13
B-13	Summary of Turbidity, Total Solids and Volatile Solids.....	B-14
C-1	Overall Response of Chloride Concentration to River Discharge.....	C-2
C-2	Analysis of Chloride Response to Tide Ranges....	C-3
C-3	Slack Tide Salinity Measurements.....	C-4
C-4	Salinity Profile Study.....	C-5
C-5	Analysis of Chloride Data for Upper and Lower Harbor Areas.....	C-6

LIST OF FIGURES

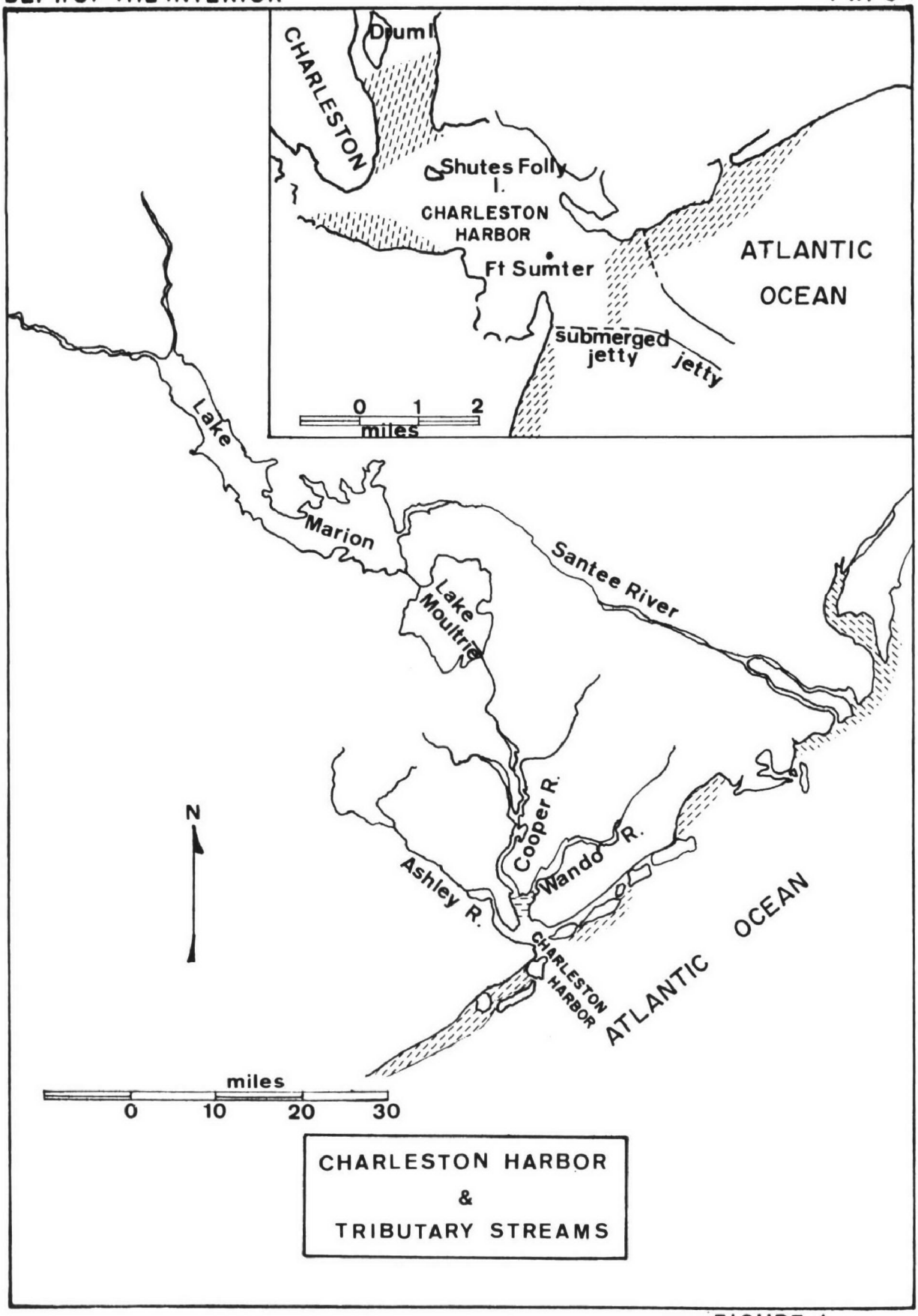
Figure No.	Title	Following Page No.
1	Charleston Harbor and Tributary Streams.....	1
2	Charleston Harbor Sampling Locations.....	Rear of Report
3	Mean Values of Percent Saturation of Dissolved Oxygen, Study D.....	38
4	Mean Values of Water Temperatures, Study D.....	38
5	Mean Values of Chlorides, Study D.....	38
6	Mean Values of Total Coliforms, Study D.....	38
7	Mean Values of Fecal Coliforms, Study D.....	38
8	Sediment Sampling Stations, Charleston Harbor..	44
9	Sediment Sampling Stations, Upper Cooper River.	44
10	Biological Sampling Stations, Charleston Harbor.....	48
11	Charleston Harbor, Mean Dissolved Oxygen Percent Saturation.....	60
12	Charleston Harbor, Mean Chloride Values.....	61
13	Response of Chloride Concentration to River Discharge, Lower Harbor.....	67
14	Response of Chloride Concentration to River Discharge, Upper Harbor.....	67
15	Response of Dissolved Oxygen Percent Saturation to River Discharge.....	77
Appendix		
C-1	Typical Response Spectra, Chlorides to River Discharge.....	C-6

INTRODUCTION

Charleston Harbor is one of the finest natural harbors on the Atlantic Coast. It is one of the most important economic assets of the State of South Carolina serving both commercial and military navigation. Since the completion of the Santee-Cooper hydroelectric complex in 1942, maintenance of the ship channels has become an extremely costly burden for the United States Government as a result of increased rates of sediment deposition. The annual expenditure of funds for dredging is now approximately 2.5 million dollars and is expected to increase unless the sedimentation problem is controlled. Historical records show that the amount of material removed annually from the ship channels and berthing facilities has increased from 120,000 cubic yards prior to 1942 to over 7,000,000 cubic yards in 1961. Figure 1 shows a map of the harbor area and tributary drainage basins.

The cause of this sedimentation problem has been attributed to the Santee-Cooper project and the resulting change in the physical nature of the tributary watersheds. Prior to the completion of the Santee-Cooper project, the harbor had three tributary streams, the Ashley, the Cooper and the Wando. All were coastal streams with a combined average flow estimated at less than 200 cfs. Completion of the Santee-Cooper project resulted in the diversion of the Santee River from the piedmont into the Cooper River Basin. Both the average flow and sediment load delivered to the harbor were increased. The average annual regulated

DEPT. OF THE INTERIOR FWPCA



CHARLESTON HARBOR
&
TRIBUTARY STREAMS

FIGURE 1

flow in Cooper increased from about 6000 cfs when Santee-Cooper started operation in 1942 to over 18,000 cfs in 1965. The increase in flow changed the nature of the estuary from a vertically-mixed type to a salt-wedge stratified type. This change created an ideal environment for deposition and entrapment of sediments in the harbor. The average flow rate of the Ashley and Wando Rivers remained unchanged and is considered to be negligible.

The solution to the sedimentation problem appears to be elimination of the primary source of sediment and reduction of inflow into the harbor to a level low enough to dispel the salinity stratification. The U.S. Army Corps of Engineers has proposed a rediversion of 80 per cent of the flow of the Cooper River back into the old Santee River channel as a means of achieving this goal. One of the more important ramifications of this proposed project is the effect of the rediversion on the water quality in Charleston Harbor.

At the present time the majority of political entities and industries within the Charleston metropolitan area discharge substantially untreated wastes into the harbor. The large quantities of fresh water inflow coupled with the tidal prism volume of approximately 350,000 acre-feet have enabled the harbor to assimilate these wastes with only moderate indications of pollution. Fish kills have occurred in the Ashley River and were primarily caused by toxic industrial wastes. High coliform concentrations from the

domestic wastes have been observed and a reduction of dissolved oxygen to levels near 50 percent saturation (less than 3 mg/1) is common in the late summer. The effect of the proposed reduction of fresh water inflow on the quality of water in the harbor is of primary concern to the planning agencies.

AUTHORITY

The Charleston Harbor study was initiated at the request of the U. S. Army Corps of Engineers by a letter dated May 15, 1963. The letter from the Chief of Engineers to the Secretary of Health, Education, and Welfare stated:

> The purpose of the coordinated study of pollution and waste assimilative capacity of the harbor waters from the Corps of Engineers' view is to determine the net effect thereon of changes in fresh water inflow from the upstream drainage area. However, since data are not available on the current waste loadings and assimilation, the scope of the study must include evaluation of conditions without changes which may result from future Corps of Engineers' improvements. Please regard this letter as a request for cooperation and coordination of the Public Health Service in the prosecution of the Charleston Harbor investigation.

The study was performed by personnel of the Division of Water Supply and Pollution Control, Public Health Service, U. S. Department of Health, Education, and Welfare.[1/] Authority for the study is outlined in the Federal Water Pollution Control Act as amended (33 U. S. C. 466 c[b]).

1/As of May 10, 1966, this agency became the Federal Water Pollution Control Administration, U. S. Department of the Interior.

PURPOSE AND SCOPE OF STUDY

The purpose of the study was to investigate the effects of the proposed Cooper River rediversion on the water quality in Charleston Harbor.

The scope of the study was to determine the existing water quality as measured by various bacteriological, biological, chemical and physical parameters; an investigation of the effects of interactions of these parameters on environmental changes; and a prediction of the response of the water quality to the proposed reduction of fresh water inflow. The area of study included the lower reaches of the Ashley, Cooper, and Wando Rivers, the harbor area between these tributaries, and the harbor entrance. Figure 2, the foldout at the rear of the report, shows the study area and the primary water sampling stations.

ACKNOWLEDGMENTS

A number of government and private organizations and individuals provided useful assistance during the study. Acknowledgment is gratefully extended to the following for their help: Harbor Pollution Committee of the Greater Charleston Chamber of Commerce, U. S. Army Corps of Engineers, City of Charleston, Charleston Development Board, U. S. Navy, U. S. Coast Guard, West Virginia Pulp and Paper Company, South Carolina State Pollution Control Authority, South Carolina Commercial Fisheries, Bears Bluff Laboratories, U. S. Army Transportation Depot, Medical College of South Carolina, Charleston Evening Post and News Courier, and other industries and individuals.

SUMMARY

In 1942 the Santee River above Charleston, South Carolina, was diverted into the Cooper River, the primary source of fresh water for Charleston Harbor. This diversion increased the average fresh water flow into the harbor almost one hundredfold, and the result was that a highly stratified, salt-wedge estuary developed.

Since 1942 the amount of municipal and industrial waste discharged into the harbor or its tributaries has increased substantially as a result of economic growth in the Charleston area. These increased wastes discharges have caused an increasing degradation of water quality.

When the U. S. Army Corps of Engineers proposed in 1963 that most of the flow of the Cooper River be rediverted back into the old Santee River channel, there was increased concern about future water quality within the harbor and its tributaries. It was feared that a radical change in estuary type might develop as a result of fresh water inflow reduction, and that this change might aggravate the already polluted conditions.

In order to define the existing water quality conditions more thoroughly and to determine the effects of reduced river inflow, together with any consequent change in estuary type, on the waste assimilative mechanisms in the harbor, the Public Health Service initiated its Charleston Harbor Study. A statistical study approach was selected, using techniques of spectral analysis to interrelate existing water quality parameters with environmental influences and to

project those interrelationships to future conditions. With this approach it was not necessary to consider individual waste loads or extensive cause-and-effect relationships as in systems analysis. Only the average measured effects of these causative factors on existing water quality in the harbor were needed to arrive at conclusions pertaining to the overall effects of reduced river discharge and projected changes in municipal waste treatment on the future water quality. Because of the absence of significant seasonal changes in municipal and industrial waste discharged to the Charleston area, it was assumed that the harbor received a constant waste discharge during the period of study. This assumption made it possible to evaluate the relative effects of environmental changes without an accurate knowledge of the total entering waste load.

Initial investigations showed that there was a paucity of data on water quality patterns in the harbor. Consequently, it was necessary to gather sufficient information to establish a present water quality base and to develop a clear understanding of the predominant forces affecting the complex interactions in the harbor.

A water quality base was developed from an intensive environmental sampling program. The results of this program showed the harbor to be moderately polluted with dissolved oxygen depletions in the range of 50 percent of saturation during the late summer and average concentrations of total coliform organisms in excess of 1000 organisms per 100 ml, i.e., frequently reaching 30,000 organisms per ml. However, the total nitrogen and phosphorus concentrations and 5-day BOD data in

the order of 1 mg/l were not consistent with the low dissolved oxygen and high coliform measurements. This dichotomy led to a series of special studies to determine the fate of wastes discharged to the harbor system.

Because study data indicated that there was a lack of organic material in aqueous phase in relation to the amount of untreated wastes discharged, the initial series of special studies was devoted to an examination of the bottom sediments. Laboratory analyses showed that the sediments contained large amounts of organic carbon and organic nitrogen, suggesting that organic materials were precipitated with the natural colloidal silt. A series of laboratory studies of the oxygen uptake by the sediments further indicated the organic nature of these sediments.

The dissolved oxygen data from the intensive surveys also demonstrated very clearly the oxygen demand of the sludge. The estuary was highly stratified during most of the intensive surveys as shown by surface to bottom chloride ratios which averaged 0.57. The D.O. percent saturation data showed mean dissolved oxygen in the bottom layers that decreased from 77 percent in the outermost stations in the harbor to 52 percent near the waste outfalls in the upper harbor and river tributaries. In the surface layers an increasing dissolved oxygen percent saturation profile was shown that progressed from 64 percent near the innermost stations to 82 percent seaward.

Measurements of other water quality parameters demonstrated that the stratified system could assimilate the existing waste discharges

with only moderate quality degradation. Although the waters were not of suitable quality for water contact sports as indicated by the coliform concentrations, noxious pollution conditions did not exist.

It was determined that the projected low flows of 3000 cfs of fresh water in the Cooper River would change the hydraulic character of the harbor from a stratified estuary to a vertically mixed estuary. Additional evidence of the hydraulic effects of the proposed flow reduction was obtained from a series of dye studies in the hydraulic model of Charleston Harbor. The dye studies indicated that wastes discharged into the lower reaches of the Cooper and Ashley Rivers (upper harbor) would tend to remain there for a longer period of time. Conversely, the removal of wastes from the lower harbor would be accelerated by the effects of tidal action on the projected unstratified conditions.

Thus the proposed rediversion of the flow from the Santee-Cooper Reservoirs into the old Santee channel would be beneficial to the water quality in lower portions of Charleston Harbor but detrimental to water quality in the upper portions. After rediversion and the resultant change of the harbor to a vertically mixed estuary, the major source of oxygen for waste stabilization throughout the estuary would no longer be the more dense oceanic inflow but would be surface reaeration; and the amount of oxygen available for stabilization of existing bottom deposits would be reduced. In the lower harbor, this decrease in oxygen availability would be offset by an accelerated hydraulic removal of wastes and a decreased inflow of wastes from the

upper harbor. However, in the vicinity of the paper plant on the Cooper River and in the industrial complex on the Ashley River, the waste materials would be more concentrated and would remain in these reaches for longer periods of time. The end result would be a much greater degradation of water quality in both upper harbor areas. In the Cooper River, from about a mile above to about three miles below the West Virginia Pulp and Paper Company waste outfall, the D.O. depletion would become severe. The sludge demands combined with the suspended load would probably overtax the oxygen resources in this reach to a point where periods of complete speticity can be expected, especially during the late summer and early fall. In the Ashley River the toxic materials discharged from the industrial complex would be dispersed and diluted at a much slower rate than at present and would create a hazard for fish and other aquatic organisms.

Existing municipal waste disposal practices will be greatly modified before the proposed diversion scheme can be initiated. In 1963, the South Carolina legislature passed a law making it illegal for any person or political entity to discharge untreated sewage into tidal waters in Charleston County. It is thus anticipated that municipal treatment plants in the harbor area will be constructed soon. A minimum of primary treatment, properly operated, will remove essentially all settleable solids and will reduce BOD loads up to 40 percent. If outfall lines from proposed treatment plants are properly located to disperse the effluent, i.e., in areas of the harbor where a high degree

of mixing is expected to occur, and if the effluents are adequately chlorinated, there may be no buildup of nutrients from municipal sources in the harbor and the bacterial pollution will be essentially eliminated. However, improper treatment plant operations and/or improperly located outfalls could lead to areas of high nutrient concentrations and creation of a potential for nuisance plankton growth. A need for a higher degree of treatment may result.

Pollution in Charleston Harbor will not be adequately controlled until the industries are subjected to the same regulatory procedures as those in effect for municipalities. Elimination of toxic waste discharges by plants on the Ashley River will be necessary to maintain the waters of the Ashley River as a suitable fish habitat. Wastes from the West Virginia Pulp and Paper Company are the major cause of the oxygen-consuming sludge beds in the lower reaches of the Cooper River. Worse conditions of dissolved oxygen depletion in the Cooper can be expected with proposed reduction of freshwater inflow unless adequate waste treatment practices are adopted by the paper plant.

While the proposed rediversion of the Cooper River would decrease the capacity of certain areas of the harbor to assimilate wastes, it would not be the cause of a pollution problem. This problem already exists because the cities and industries are using the harbor as a repository for untreated waste products. Only through the control of these waste products can the quality of the waters in Charleston Harbor be improved for the enhancement of all beneficial uses.

CONCLUSIONS

PRESENT CONDITIONS

1. Under the existing fresh water flow conditions, Charleston Harbor is a stratified or salt-wedge type estuary with two well-defined density layers.
2. The present practice of discharging untreated domestic and industrial wastes into the harbor has resulted in moderate pollution throughout the system, as evidenced by (a) dissolved oxygen depletion to less than 50 percent saturation, (b) by high concentrations of fecal and total coliform organisms with total counts above 1000 organisms per 100 ml, frequently as high as 30,000 organisms per 100 ml, and (c) by extensive sludge bed deposits.
3. The reduction of dissolved oxygen to 52 percent saturation in the harbor is predominantly caused by the chemical and biochemical stabilization of the organic materials in the sludge-silt deposits as shown by low BOD values in the water averaging one mg/l and the high oxygen uptake rates of the sediments ranging from one to five milligrams of oxygen per day per gram of dry sediment.
4. The major source of dissolved oxygen for stabilizing waste products is from the large volumes of oceanic inflow in the salt wedge. The tidal prism volume is approximately 350,000 acre-feet.
5. The most critical areas from the pollution standpoint are the lower reaches of the Ashley and Cooper Rivers, which receive untreated industrial wastes as well as raw municipal sewage. The wastes discharged into the Ashley River principally by chemical and fertilizer industries contain organophosphorus compounds,

heavy metals, and phenols, all of which create a potentially toxic aquatic environment. The West Virginia Pulp and Paper Company is the major source of industrial wastes discharged into the Cooper River. The paper mill wastes contain fibers, suspended solids and dissolved organic material, all of which contribute materially to the depletion of dissolved oxygen.

FUTURE CONDITIONS

1. Reduction of flow in the Cooper River to an average of 3000 cfs as proposed by the Corps of Engineers would change the estuary from a salt-wedge type to a vertically mixed type. The ratio of surface to bottom chlorides would approach 1.0 and vertical mixing would be unrestricted throughout the harbor.
2. The change in estuary type would result in more rapid mixing and flushing of materials from the lower or seaward portions of the harbor. Based on model dye studies, mean residence time in the lower harbor would decrease from seven to two tidal cycles with a river flow decrease from 30,500 to 3500 cfs (Table 14). However, the lower reaches of the tributary rivers in the upper harbor would have poorer mixing characteristics and would retain materials for a longer period of time resulting in a reduced assimilative capacity. Mean residence time in the upper harbor would increase from 5.4 to 30 tidal cycles for the above reductions in flow (Table 14). The net effect of these changes would be an improvement in water quality in the lower harbor but a deterioration in water quality in the upper harbor. The most troublesome area would be the lower part of the Cooper River, where septic conditions

would probably exist during summer and early fall months unless a substantial reduction is made in industrial waste loads entering this reach of the river.

3. Construction and proper operation of at least primary sewage treatment facilities (with chlorination of effluent) by all political entities discharging municipal wastes to the Charleston Harbor system as required by South Carolina law would reduce average bacterial pollution in most areas to levels below the limits deemed safe for water contact sports by the State of South Carolina (1000 total coliform organisms/100 ml). Untreated wastes from storm drains, however, would cause bacterial pollution in localized areas.
4. The outfall of the proposed City of Charleston primary sewage treatment plant is being located near the Battery. If this outfall discharges into the Ashley River it could produce such high concentrations of polluting materials in the river that a higher degree of treatment might be required to avoid severe damage to water quality, particularly with respect to the buildup of nutrients sufficient to stimulate heavy algal growth. Location of the outfall in a more open area of the harbor where more thorough mixing and consequent flushout is prevalent should preclude the possibility of nutrient buildup.
5. The dissolved oxygen depleting effects of the sludge-silt deposits will continue for an indeterminate future period regardless of the waste treatment programs adopted. The severity of this problem will depend on such factors as waste disposal practices and amount of dredging for channel maintenance.

6. The proposed reduction in fresh water inflow from the Cooper River would not cause a pollution problem. A condition of pollution already exists due to the reliance on waste dilution instead of treatment.

7. To restore the water quality of Charleston Harbor, the most immediate need is for at least primary treatment by industry as well as by municipalities. Provision for expansion to secondary treatment should be planned; an even higher degree of treatment may be required of troublesome wastes or of wastes discharged into critical areas.

DESCRIPTION OF STUDY AREA

The City of Charleston on the southeast coast of South Carolina was built on the peninsula between the Ashley and Cooper Rivers, and its harbor has been a center of commerce since early colonial days. Existing ground elevation throughout the city is extremely low, varying between 5 and 15 feet above mean sea level. North of the city is the unincorporated area of North Charleston which contains most of the industry in the Charleston area. To the west, across the Ashley River, are modern residential subdivisions and attendant shopping centers. Eastward from the city, across the upper reaches of the harbor, are the communities of Mount Pleasant and Sullivan's Island.

The population of Charleston County, which encompasses most of the study area, was 220,000 in 1960; this includes 76,925 in the city of Charleston. The city itself cannot expand much on the original peninsula because it is confined by either water or political boundaries. However, some of the area west of the Ashley has been annexed, and any further expansion will probably be due to further annexation in this area. It has been estimated by Hazen and Sawyer, consulting engineers, that the 1970 city population will be approximately 115,000 and the county population will grow to 240,000.

The military occupies a prominent role in the economic base of the Charleston area. The Charleston Navy yard on the Cooper River serves as a home for destroyer, mine sweeper and submarine fleets and has one of the larger shipyards in the Southeast. In addition the Navy has an ammunition depot upstream from the

Navy yard, the Army Transportation Corps has a supply and storage depot also on the Cooper River, and the Charleston Air Force Base near the upper Ashley River maintains both transport and defense squadrons.

Industrial development in the Charleston area is helping to diversify the economic base. West Virginia Pulp and Paper Company and Virginia-Carolina Chemical Corporation are the two largest manufacturing industries. There are other smaller businesses as well as light industry such as Manhattan Shirt Company, Lockheed-Georgia Corporation, and Avco Lycoming which will begin operations late in 1966. The industrial development of Charleston County is projected to grow in the future because of the large quantities of land and fresh water available and because of transportation facilities, especially in the Port of Charleston.

Charleston Harbor has an area of approximately 14 square miles with depths generally ranging between 10 and 25 feet at mean low tide. Navigation channels are maintained to a depth of 35 feet. Hydraulic characteristics of the harbor are predominantly controlled by tides and fresh water inflow modified by some minor wind effects. The tidal prism is estimated at 350,000 acre-feet and the average fresh water inflow is between 18,000 and 20,000 cfs based on 1964-1965 records.

Of the three major tributary rivers, the Ashley, the Cooper and the Wando, the Cooper is the predominant source of inflow. The Ashley, a coastal river, meanders along the west side of the city, draining an area of about 350 square miles. The flow

in the Ashley River has not been measured since it is affected by tides its entire length. Based on salinity measurements made during the study, the inflow of the Ashley is negligible in comparison to the tidal exchange. The Wando River is similar to the Ashley, with a drainage area of 115 square miles. This tributary, which is tidal for its entire length, enters the east side of the harbor in a joint confluence with the Cooper River. The fresh water inflow from the Wando is also considered a negligible contribution to the system.

The Cooper River is the most important of the three. It was originally a coastal river with a drainage basin of 720 square miles and an estimated average flow of about 200 cfs. Diversion of the Santee system into the upper Cooper added an additional drainage area of 14,700 square miles and increased the average flows to more than 15,000 cfs. The regulated discharges in the Cooper for the past six years are shown in Table 1.

All three tributary streams are important to navigation. The lower reach of the Ashley River is part of the Intracoastal Waterway: on the east bank of the Ashley just above the waterway is the Charleston Municipal Marina. The Wando River has a major shipyard facility approximately 12 miles upstream from the harbor. And on the west bank of the Cooper River extending upstream for about 10 miles from the confluence with the harbor, there are the major commercial terminals and the Navy facilities.

TABLE 1

HYDRO PLANT DISCHARGES - PINOPOLIS DAM
1960 - 1965
MONTHLY AVERAGES
(in cfs)

	1960	1961	1962	1963	1964	1965
January	25,142	15,677	24,428	12,926	22,944	25,949
February	26,319	15,355	25,953	17,101	24,994	25,469
March	26,979	24,914	26,238	23,641	26,831	27,410
April	23,820	25,909	26,992	16,027	27,282	25,206
May	19,825	24,983	13,835	9,041	18,319	15,271
June	10,973	10,775	14,392	12,596	13,069	19,824
July	9,771	19,479	13,238	14,401	14,194	18,978
August	13,402	13,880	9,653	10,923	20,429	17,588
September	16,106	17,187	6,381	5,016	23,426	11,401
October	10,240	8,993	6,419	6,674	25,758	11,218
November	9,180	6,699	8,700	7,368	24,892	10,556
December	10,457	14,666	15,177	13,461	22,657	13,425
	202,214	198,517	191,406	149,175	264,795	222,295
Monthly Avg. Flow	16,851	16,543	15,950	12,476	22,066	18,524

DESCRIPTION OF STUDY

SPECIFIC OBJECTIVES

In accordance with the specific request for information by the U. S. Army Corps of Engineers, a study program was planned to obtain necessary data. This program had three specific objectives. The first was to collect sufficient environmental data on the physical, chemical, biological and hydraulic characteristics of the harbor in order to establish a study datum. The second was to develop a model of the estuarine system which would describe the interactions of measured characteristics with the fresh water inflow and tidal forces. The third objective was to predict the water quality patterns that would exist under the proposed modifications of streamflow regulation and foreseeable development of the Charleston area.

STUDY METHODS

Field and Laboratory Methods

The Charleston Harbor Study was designed for a multiphased approach to the analysis of a complex estuarine system.

Initiation of the Charleston Harbor Study involved a unique solution to the problem of obtaining laboratory facilities. The deckhouse of a large warehouse barge was remodeled to contain a complete laboratory and office space for project staff. Utilization of the floating installation facilitated the conduct of the study by eliminating problems of sample handling, sample boat mooring,

and access to the study area.

A preliminary reconnaissance was made to locate sampling stations, to determine significant water quality parameters, to enable laboratory personnel to check existing analytical procedures, and to make modifications where necessary. Table 2 shows the water quality parameters initially tested, the ones measured during the intensive studies, and comments on the few which were discontinued. Table 3 lists the laboratory analytical procedures used and the modifications that were made to adapt them for estuarine samples of varying salinity.

Two types of sampling programs were utilized. One was a routine weekly program, and the other was an intensive program of sampling each station on a four-hour frequency for a five-day period. The routine program was used to monitor the harbor for sudden changes in quality patterns, and the intensive program was used to develop data which could be statistically analyzed to show the quality patterns and reflect the effects of the system dynamics.

Ten sampling stations were selected to develop a water quality base for the harbor. Criteria for choosing these stations were: (1) the station had to be in an area that would be affected by the proposed diversion (within the tidal range); (2) the station had to be accessible during all tide conditions; (3) samples collected from these stations could not be influenced unduly by external factors such as nearby waste discharges; and (4) all stations (Figure 2) had to be located within an area that could be

TABLE 2

WATER QUALITY PARAMETERS MEASURED

Item No.	Parameters Initially Measured	Used During Intensive Phase?	Remarks
1	Dissolved oxygen (D.O.)	Yes	Determined on all samples collected.
2	Biochemical oxygen demand (BOD)	Reduced frequency	Surveys AA and AB;[1/] determinations on all samples collected; surveys B, C, D and E, reduced to stations 1, 3, 4, 8, 9 and 13 (surface and bottom) on 8-hour frequency. Test discontinued due to low values observed in samples and laboratory personnel schedule.
3	Chemical oxygen demand (COD)	Discontinued	Values of less than 100 mg/l in salt water are not accurate and are meaningless.
4	Chloride (Cl)	Reduced frequency	Determined on cycle 1, 2 and 3 of Survey B. Conductivity measured on all other samples collected and converted to chloride equivalence.
5.	Conductance	Yes	(See remarks under chloride above)
6	pH	Reduced frequency	Determined on all samples collected during Surveys AA, AB and E. Reduced due to consistently neutral pH values.
7	Turbidity	Reduced	Determined on all samples collected during Surveys AA and AB. Laboratory personnel schedule prohibited turbidity determinations for Surveys B, C, D and E.

1/Survey identification in Table 5

Table 2 (Continued)

8	Total suspended solids and volatile suspended solids	Reduced frequency	Determined on all samples collected during surveys AA and AB. Laboratory personnel schedule prohibited solids determinations for surveys B, C, D and E.
9	Ammonia nitrogen	Yes	Determinations on all samples collected.
10	Nitrite nitrogen	Discontinued	No measurable nitrite present in Charleston Harbor.
11	Nitrate nitrogen	Yes	Determined on all samples collected.
12	Organic nitrogen	Reduced frequency	
13	Ortho and total phosphates	Reduced frequency	Ortho Phosphates discontinued due to laboratory personnel schedule. Total phosphates determined for all samples collected during Surveys AA, AB, B, C, D, and some of E (cycles 1, 5, 10, 15, 20, 25 and 30). Laboratory schedule forced reduction for Survey E.
14	Total coliforms and fecal coliforms	Reduced frequency	Surveys AA and AB, bacteriological examination made on all samples collected at Stations 1, 3, 4, 8, 9 and 10 (Surface and Bottom): Surveys B, C, D and E, bacteriological examinations made on all samples collected at Stations 1, 3, 4, 8, 9 and 13 (Surface and Bottom).

TABLE 3

LABORATORY ANALYTICAL PROCEDURES

Parameter	Test Initially Used	Modifications of Test	Reference
1. Dissolved Oxygen	Winkler Alsterberg azide modification	Floc settled only one time, 300 ml sample automatically titrated with 0.038 N sodium thiosulfate	Standard Methods for the Examination of Water and Wastewater, 11th Ed., 1960.
2. Biochemical Oxygen Demand	Dilution Method	None	Standard Methods, 11th Ed.
3. Chemical Oxygen Demand	Dichromate reflux method with mercuric sulfate modification	None	1) Standard Methods, 11th Ed. 2) Dobbs, R.A., Williams, R.T., "Elimination of Chloride Interference in the Chemical Oxygen Demand Test," Analytical Chemistry, 35, 1064-7, (1963). 3) Chemical Analytical Procedures, Raritan Bay Project.
4. Chloride	Mercuric Nitrate method	0.2000N NaCl standard and 0.2000N $Hg(NO_3)_2$ used. Sample automatically titrated with or without indicator.	Standard Methods, 10th Ed.
5. Conductance	Conductivity Cell method	Resistance in ohms measured on Industrial Instruments, Inc., Model RC-8 conductivity bridge at temperatures less than 30°C. Data converted to specific conductance at 25°C with a temperature specific conductance table prepared by Chas. Harbor Project.	Standard Methods, 11th Ed.
6. pH	Glass Electrode method	Fisher 13-639-90 combination electrodes	Standard Methods, 11th Ed.

TABLE 3 - cont'd

Parameter	Test Initially Used	Modifications of Test	Reference
7. Turbidity	Jackson Candle method	None	Standard Methods, 11th Ed.
8. Total Suspended Solids and Volatile Suspended solids	Gooch Crucible method	Reeve angle glass fiber filter, 934 AH, size 2.4 cm employed	Standard Methods, 11th Ed.
9. Ammonia Nitrogen	PreFloc and direct Nesslerization	2 ml zinc sulfate and 5 ml of sodium hydroxide solution added to 200 ml sample	Standard Methods, 11th Ed.
10. Nitrite Nitrogen	PreFloc and sulfuric acid-naphthylamine hydrochloride method	2 ml zinc sulfate and 5 ml of sodium hydroxide to 200 ml sample for PreFloc treatment. pH adjust. made with 10% HCl solution	Standard Methods, 11th Ed.
11. Nitrate Nitrogen	Modified Brucine method	Reagent blank is not boiled	1) Standard Methods, 11th Ed. 2) Jenkins, D., and Medsker, L.L., "Brucine Method for Determination of Nitrate in Ocean, Estuarine, and Fresh Waters," Analytical Chemistry, 36, 610-12, (1964). 3) Finger, J.H., "Nitrate Determination in Saline and Estuarine Waters: Comparison of Hydrozine Reduction and Brucine Modification Methods," Laboratory Investigation No.3, Tech. Adv. & Inves. Section, TSB, Robt. A. Taft Sani. Eng. Center, Cinn., Ohio.

TABLE 3 - cont'd

Parameter	Test Initially Used	Modifications of Test	Reference
12. Organic Nitrogen	Micro Kjeldahl digestion with mercuric sulfate catalyst-Nesslerization method	None	1) Standard Methods, 11th Ed. 2) Kabat, E.A., and Maver, M.M., Experimental Immunochemistry. C.C. Thomas Publ., 2nd Print. (1953).
13. Ortho and Total Phosphate	Stannous chloride method	Technique Improvements	Standard Methods, 11th Ed.
14. Total Coliform	Membrane filter method with M-Endo Broth procedure	None	1) Standard Methods, 11th Ed. 2) "Recent Developments in Water Microbiology", short course conducted by Water Supply and Pollution Control training Program, PHS, Robt. A. Taft Sanitary Eng. Center, Cinn., Ohio.
15. Fecal Coliform	Membrane filter method with M-FC Broth procedure	None	(Same as #14 above)

sampled in a time period less than one-half the tidal frequency. It should be noted that sampling station number 10 was replaced by station 13 after the first and second intensive surveys because of the influence of the paper mill wastes. Since the harbor was stratified during much of the sampling period, samples were collected at the surface and at a depth of 20 to 25 feet at each of the ten stations.

The program development was devoted to formulating procedures for a fast, efficient method for collecting samples. The submersible pump technique which supplied a constant sampling source was adopted for collecting all samples.

A total of six intensive surveys covering a large range of both tidal conditions and river inflows was conducted during the study. These surveys are summarized in Table 4. While the laboratory was operated on a 24-hour basis to minimize the delay between collection and analysis for dissolved oxygen, BOD, and coliform organisms, all of the samples collected during each intensive survey could not be analyzed immediately. Portions of each sample collected were preserved for nutrient analyses performed in the periods between and after completion of intensive surveys.

Results from preliminary analyses of data collected during the early intensive surveys and from routine monitoring indicated that several areas required special investigation. To obtain a better understanding of the water quality environment, a series

TABLE 4

INTENSIVE SAMPLING PROGRAM

Intensive Survey Designation	Dates Survey Conducted	No. of Parameters Measured	Total Number of Samples Collected	Average Cooper River Discharges (cfs)	Mean Tidal Range (ft.)
*AA	March 3 through March 7, 1965	13	600	27,588	5.22
*AB	March 23 through March 27, 1965	13	600	27,749	4.08
B	June 21 through June 25, 1965	10	600	26,290	4.09
C	July 19 through July 23, 1965	9	600	19,295	4.11
D	August 16 through August 20, 1965	9	600	16,235	4.42
E	Sept. 20 through Sept. 24, 1965	9	600	13,486	5.76

* Surveys AA and AB represent the first and last 5 day periods of a 30 day intensive survey conducted during the month of March.

of special laboratory and field studies were initiated to develop information on certain segments of the system interactions. These studies are described in Table 5.

Quality control was a prime consideration for all aspects of the Charleston Harbor Study. Specific sampling techniques were developed for the project and careful supervision was maintained over all sampling operations. Chemists either conducted or closely supervised each phase of the laboratory operations from initial sample handling to the reporting of the data. A system of cross-checking was maintained throughout the study to eliminate any errors (a record of all laboratory determinations and calculations was kept on bench cards). The final data output from the laboratory was a double-checked sheet made ready for preliminary analysis.

Data Analysis

The data analysis scheme was primarily designed to interpret the results of the intensive surveys. Data evolved from such a high frequency sampling program are much more reliable for describing the dynamic characteristics of an estuarine environment than are random grab samples. The constant change of circulation patterns in the system caused by the predominant natural forces of wind, tide and river inflow created a statistical distribution of any measured water quality parameter with a large variance. High frequency time series measurements were necessary to describe this distribution adequately.

TABLE 5

SPECIAL STUDIES

Title of Study	Purpose	Description
Organic Carbon-Organic Nitrogen Ratios of Sediments	To identify the nature and source of sediment deposits in Charleston Harbor.	Sediments collected from 61 stations in the harbor and tributary rivers were analyzed for organic carbon and organic nitrogen content. Data produced from this investigation characterized the sediment deposits as to organic or inorganic and permitted a differentiation of sources of organic material in the sludge deposits as to industrial or domestic origin.
Flocculation Phenomena	To confirm the importance of the interfacial flocculation phenomena in forming the sediment deposits and to determine the effect of reduced colloidal materials from the Cooper River on sludge deposit formations.	Various proportions of river water and sea water were mixed in the laboratory and the rate of change of suspended solid concentration was measured. Only preliminary tests were conducted due to a lack of manpower for completing the study.
Salinity Profile	To substantiate the degree of salinity stratification at the main sampling stations and to describe the longitudinal slack water salinity profile.	Vertical salinity profiles were measured at 3 feet intervals at each sampling station during high and low water slack tides. Longitudinal slack water profiles were measured along the channel centerlines at the surface and at a depth of 25 feet.
Dye Dispersion	To obtain information on the movement and mixing characteristics of the water masses in the harbor to verify the hydraulic model data.	Two dye releases were made in the harbor, one in the entrance jetties and the other in the Ashley River. In both cases all traces of the dye disappeared shortly after the release, providing a negligible amount of information for model verification.

TABLE 5 - cont'd

Title of Study	Purpose	Description
Hydraulic Model Verification	To determine(1) if the hydraulic model of Charleston Harbor would reproduce the salinity distributions observed in the prototype during the intensive surveys and(2) if the model could be used as a tool for future low inflow predictions of salinity distribution.	Salinity measurements were made in the hydraulic model using the same fresh water inflow hydrographs and the same sampling schedule utilized during the last four intensive prototype surveys. The model data were compared statistically with the prototype data to ascertain the degree of similitude.
Sample Preservation	To determine the effects of preservation of nutrient samples on the accuracy of the analytical results.	A series of samples of known nutrient concentrations were preserved and then analyzed at a given frequency to determine the effectiveness of the preservation technique. Preservation effects were checked for ammonia nitrogen, nitrate nitrogen, total nitrogen and total phosphate determinations.
Free Carbon Dioxide	To determine if gas bubbles observed at the water surface were carbon dioxide and to investigate the carbonate-carbon dioxide balance in estuarine waters.	Water samples collected under mineral oil were analyzed for free carbon dioxide concentration using a Natelson Microgasometer.
Organic Carbon	To measure the amount of organic carbon in solution in the harbor water, to confirm whether the results obtained from BOD and COD tests are reasonable or are in error.	Samples collected at regular stations in the harbor were analyzed with a Beckman Carbonaceous Analyzer.

TABLE 5 - cont'd

Title of Study	Purpose	Description
Oxygen Uptake by Sediments	To measure quantitatively in the laboratory the oxygen utilized in stabilizing the organic materials in sediments collected from harbor stations.	Sediment samples collected with a Peterson dredge were brought into the laboratory and placed in five gallon carboys filled with fresh seawater. Oxygen consumption with respect to time was measured in both mixed and non-mixed situations to establish the range of potential dissolved oxygen depletion by the sediments. In addition, moisture content, percent volatile solids, organic carbon, and organic nitrogen determinations were made on the sediment samples.
In situ Benthic Respiration measurements	To measure quantitatively the oxygen consumption with respect to time at the water-sediment interface and to develop relationships between organic content of sediment deposits, the laboratory oxygen uptake studies and in situ oxygen utilization.	An experimental benthic respiration chamber was constructed to make in situ measurements. This semicircular chamber was lowered over the side of a boat until it rested firmly on the bottom. Measurements of dissolved oxygen were made periodically to determine the depletion.

A scheme of data analysis was used by which the data were initially interpreted using fundamental statistical principles of data handling and analysis. While this approach introduces an element of complexity in the calculations not usually present in the analysis of field survey data, it does provide a sound means for determining the observed degree of variation in results, thus providing a reliable starting point for evaluation of the results.

The data obtained for each parameter in each intensive survey were treated similarly in the basic statistical computations. The first step in the analysis was the computation of the descriptive statistics of each record obtained. The statistics computed were the mean, $\bar{x}$: the variance, s^2; the standard deviation, s; the skewness, L; and the kurtosis, K.

To provide a common mathematical basis for evaluation of observed frequency distributions, the coefficients of the Pearson theoretical frequency distribution were also calculated for each record. This distribution was selected because it is a general analytic representation of a wide variety of possible observed distributions. The Pearson frequency distribution is discussed further in the Technical Appendix.[1/]

The observed frequency distribution for each record was also plotted for ranges of one standard deviation from the mean.

1/The Technical Appendix referred to is a separate document containing a detailed discussion on field operations, analytical procedures, special studies, data analysis, and also containing the bulk of basic data.

Each parameter was next subjected to an analysis of variance based on two crossed classifications with replication. The analysis was made between surveys and stations using first all surveys and stations, and then pairs and other submultiples of surveys and stations for the entire body of data available for each parameter.

Significance at the five per cent and one per cent fiducial levels was examined.

Analysis of variance on each record was performed to answer these questions:

(1) Was there a significant change in the statistics of each water quality parameter between surveys at the same stations? That is, did each of the six surveys represent sampling of a different physical environment, or might two or more of the surveys have been used as representing the same environment? A lack of significance in the F-ratio between surveys would indicate that the surveys being considered could be regarded as one survey, and that the data obtained were all samples of the same physical environment.

(2) Was there a significant change in the statistics of each water quality parameter between stations for each survey? That is, were the stations chosen sufficiently far apart that the observed changes in parameters between the stations represent changes in the environment between them, or may some of the stations be grouped together in the data analysis? A lack of significance in the F-ratio between stations would indicate that the station records concerned are actually measurements of the same environment and may be treated as such.

(3) Were the statistics of differences between the same parameters at different stations the same for all surveys or sequential pairs of surveys? For example, was the change in chlorides between stations 1 and 2 the same for survey B as for survey C? A lack of significance in the F-ratio for station-survey interaction would indicate that the relationships between stations were similar for the surveys concerned.

(4) For the environmental factors (river discharge, tide height, air temperature, solar radiation, etc.), which factors showed significant changes between surveys? A lack of significance in the F-ratio between surveys would indicate that the environmental factor analyzed did not change and could be regarded as having similar effects during each survey.

The results of the analysis of variance were used as a basis for selecting pairs of environmental and water quality parameters on which harmonic covariant or spectral analysis was run.

The first step of the spectral analysis of the intensive survey data was the computation of the individual power spectrum of each record. This power spectrum analysis is essentially the sorting of the total variance of the record into its component frequencies resulting in a delineation of those parts of the variance that recur at constant time intervals as well as the part that is random in character. For example, the analysis of a continuous chloride record of an estuarine sampling station would show a sinusoidal fluctuation about the mean. Spectral analysis would show a predominant variance recurring at approximately

a 12-hour frequency coinciding with the tide frequency. If the record were sufficiently long, gradual chloride variations in the sea water would be shown by the occurrence of a variance component at a long term frequency. Thus the spectral analysis would give much more insight into the probable environmental factors affecting the chloride concentrations.

The second step of the spectral analysis was the computation of the cross-spectra which is a comparison of pairs of individual power spectra or a covariant harmonic analysis of two time-series records. The cross-spectral computations provide a measure of correlation or coherence of the two records; they show the temporal relationship between respective maxima or minima of the two records; and they give a quantitative estimate of the amount of variation in one record that is associated with a similar variation in the second record. The cross-spectral computations are a statistical manipulation of two time-series records in which it is assumed that one of the records is of a causative factor and the other a record of the resulting condition. For example, in the cross-spectral analysis of a river discharge record and a salinity record at a point in the harbor, the river discharge would be regarded as a causative factor and the salinity as a resulting condition; this does not imply that river discharge is assumed to be the only causative factor in the system. The results of the computation are an empirical evaluation of how closely changes in river discharge are related to changes in salinity. These computations do not explain what is

happening in the environment, but the results are a sound and detailed analysis of the data and provide a firm foundation for deduction of mechanisms governing the system.

The pairs of parameters chosen for analysis in later sections of this report were considered those most significant for determining water quality conditions in the harbor.

RESULTS OF STUDY

PRESENT WATER QUALITY

While the general character of wastes entering the Charleston Harbor system is easily established from the nature of the dominant waste sources, the specific effects of the combination of effluents on water quality and the significant sanitary parameters showing these effects had to be determined from field investigations and laboratory analyses.

Initially a broad spectrum of chemical and biochemical determinations was run at a large number of sampling stations in the harbor and in the Cooper and Ashley Rivers. As the sampling program progressed, 10 locations (Figure 2) were chosen as being typical of conditions in various parts of the system. Each of these locations was sampled just beneath the surface and at 20 or 25 foot depths. The determination of present water quality and predictions of future water quality are based on observations obtained from these locations unless otherwise stated.

Routine Surveys

The results of the routine monitoring program are useful in illustrating seasonal changes. These results are summarized in Appendix Table A-1. In general, there was a definite worsening of dissolved oxygen values and coliform numbers from the beginning of summer through early fall. At those times, temperatures were highest and river discharges were lowest.

Some parameters remained fairly constant from season to season. The 5-day BOD values remained low throughout the year in the order of 1 mg/l. Nutrient concentrations, characterized by phosphate and nitrogen compounds (Table 3) also remained at low values, e.g., ammonia, 0.2 - 0.8 mg/l; nitrate, <0.1 - 0.2 mg/l; total phosphate, 0.02 - 0.1 mg/l.

Intensive Surveys

The results of the intensive survey program permitted a more detailed examination of conditions for the 5-day periods of each intensive survey. The mean values for D.O. (per cent saturation), temperature, chlorides, total coliforms, and fecal coliforms are presented in Figures 3 through 7, respectively, for survey D (August). The mean values from 30 samples for all surveys are presented in Appendix Tables B-1 through B-5, respectively. The mean ratios of surface to bottom chlorides at each station are presented for all surveys in Appendix Table B-6.

Examination of the D.O. results for these six surveys, particularly those in Figure 3, show that there was a progressive decrease of D.O. per cent saturation from the mouth of the harbor (Station 1) into the Cooper and Ashley Rivers. This decrease was particularly pronounced in the Cooper River (Stations 1, 5, 7, 8, 13, 10). Dissolved oxygen concentrations lower than 50 per cent saturation (2.7 mg/l) were found in the Cooper River during surveys D and E (August and September).

Analyses of variance run on combinations of surface and bottom stations showed that there were significant differences

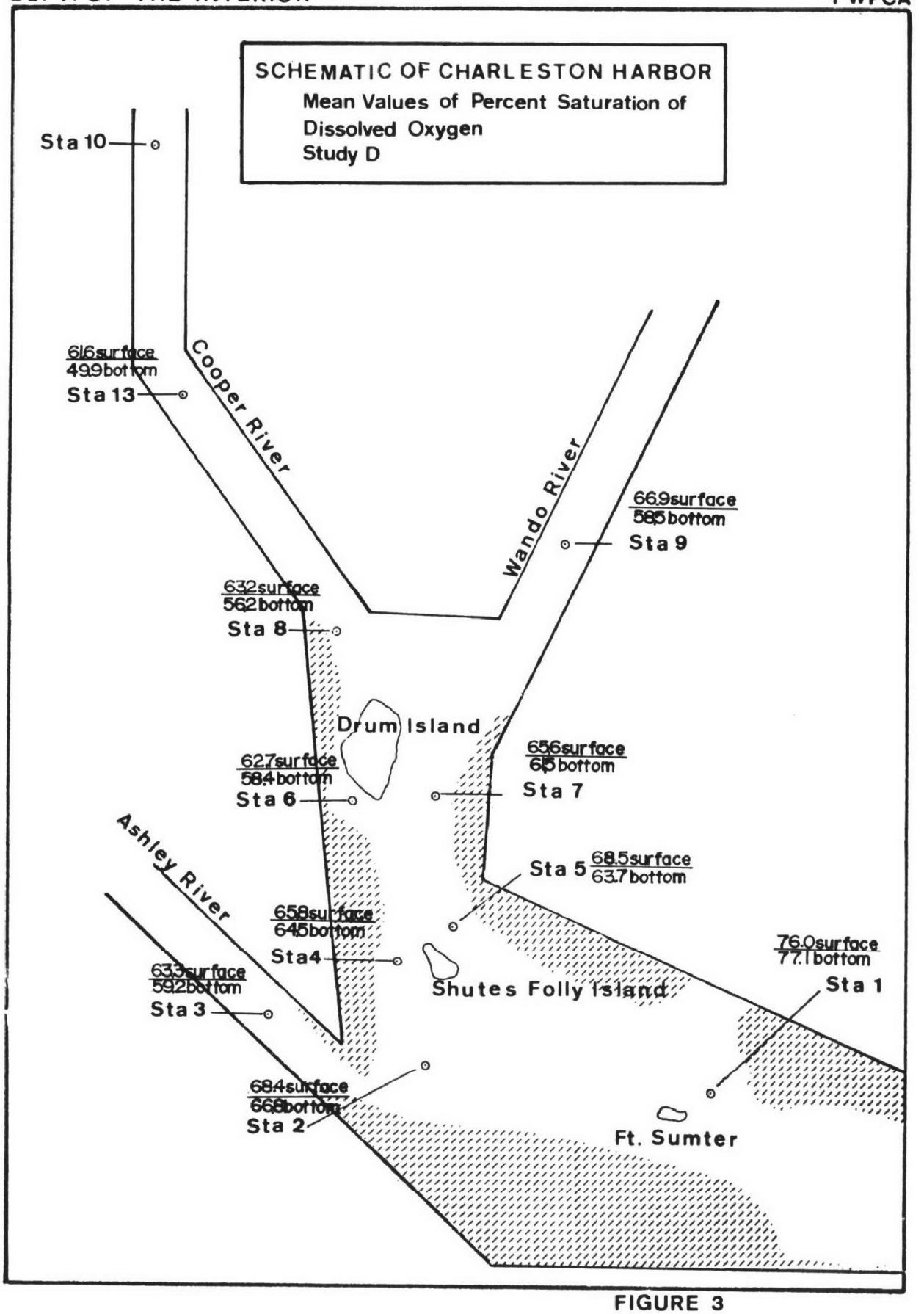

SCHEMATIC OF CHARLESTON HARBOR
Mean Values of Percent Saturation of Dissolved Oxygen
Study D
Sta 10
616surface
499bottom
Sta 13
Cooper River
Wando River
669surface
585bottom
Sta 9
632surface
562bottom
Sta 8
Drum Island
627surface
584bottom
Sta 6
656surface
65bottom
Sta 7
Ashley River
Sta 5 685surface
637bottom
658surface
645bottom
Sta4
760surface
771bottom
Sta 1
633surface
592bottom
Sta 3
Shutes Folly Island
684surface
668bottom
Sta 2
Ft. Sumter

FIGURE 3

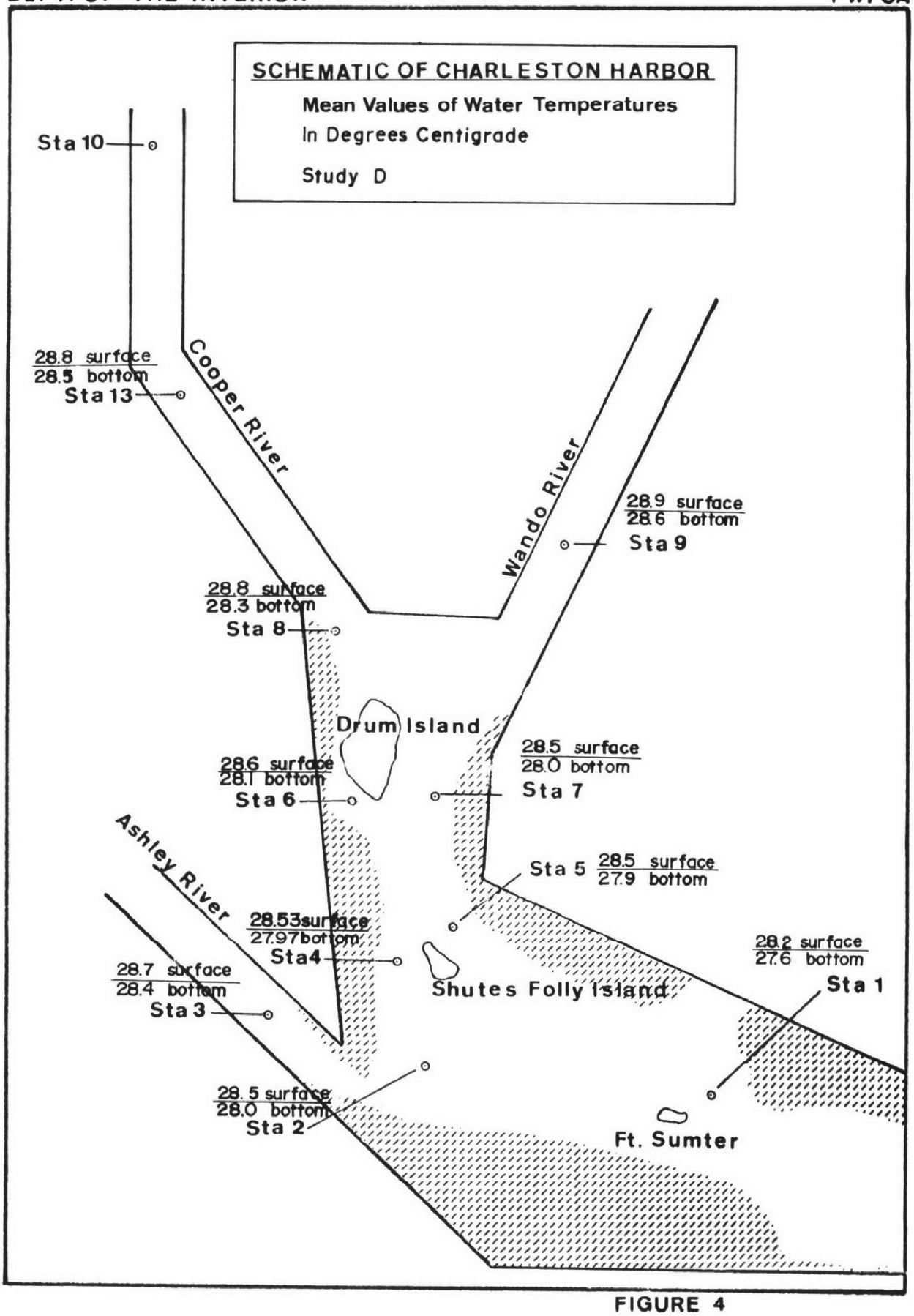

SCHEMATIC OF CHARLESTON HARBOR
Mean Values of Water Temperatures
In Degrees Centigrade
Study D
Sta 10
28.8 surface
28.5 bottom
Sta 13
Cooper River
Wando River
28.9 surface
28.6 bottom
Sta 9
28.8 surface
28.3 bottom
Sta 8
Drum Island
28.6 surface
28.1 bottom
Sta 6
28.5 surface
28.0 bottom
Sta 7
Ashley River
Sta 5 28.5 surface
27.9 bottom
28.53surface
27.97bottom
Sta4
28.2 surface
27.6 bottom
Sta 1
28.7 surface
28.4 bottom
Sta 3
Shutes Folly Island
28.5 surface
28.0 bottom
Sta 2
Ft. Sumter

FIGURE 4

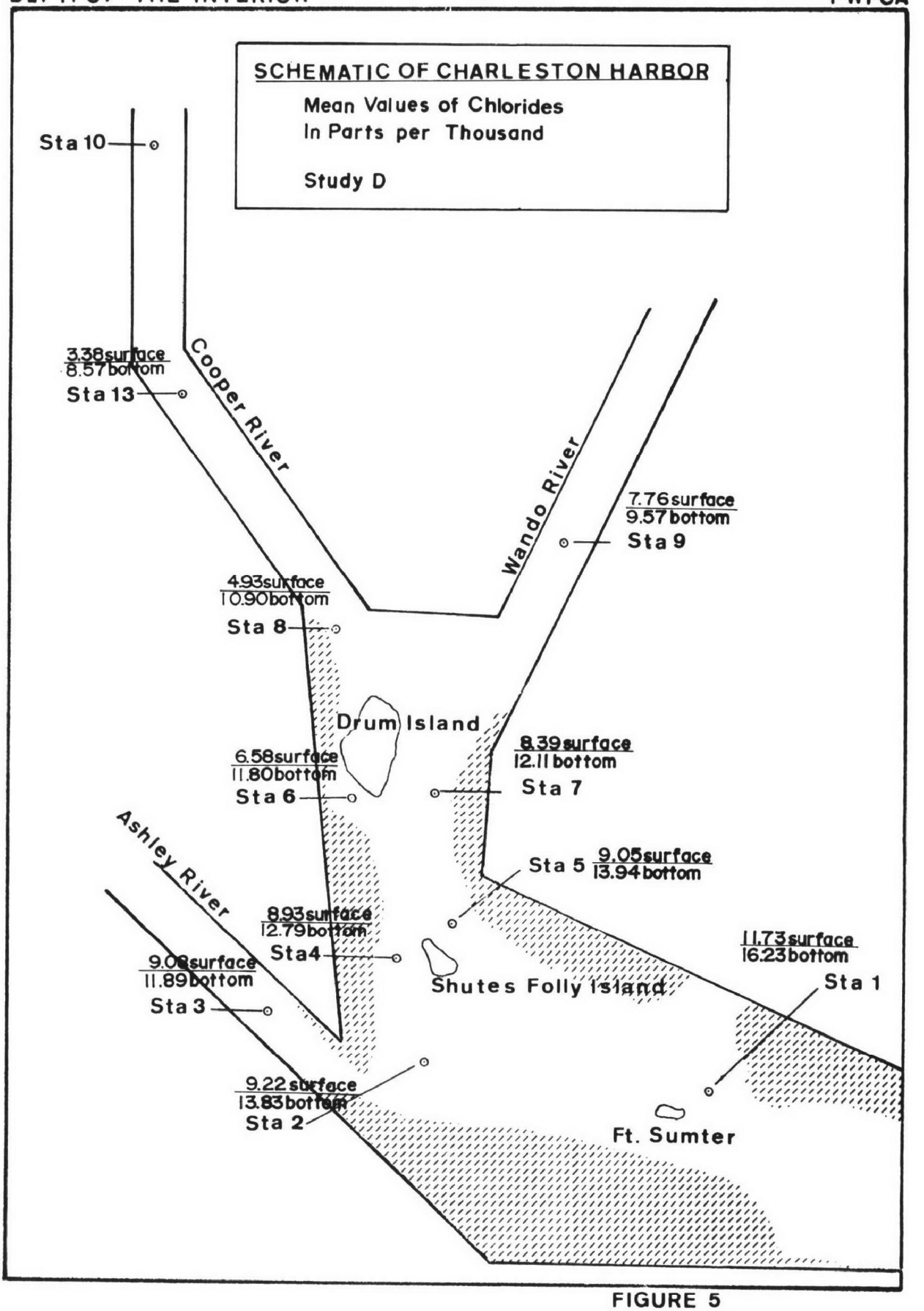

SCHEMATIC OF CHARLESTON HARBOR
Mean Values of Chlorides
In Parts per Thousand
Study D
Sta 10
3.38 surface
8.57 bottom
Sta 13
Cooper River
Wando River
7.76 surface
9.57 bottom
Sta 9
4.93 surface
10.90 bottom
Sta 8
Drum Island
6.58 surface
11.80 bottom
Sta 6
8.39 surface
12.11 bottom
Sta 7
Ashley River
Sta 5
9.05 surface
13.94 bottom
8.93 surface
12.79 bottom
Sta 4
11.73 surface
16.23 bottom
Sta 1
9.08 surface
11.89 bottom
Sta 3
Shutes Folly Island
9.22 surface
13.83 bottom
Sta 2
Ft. Sumter

FIGURE 5

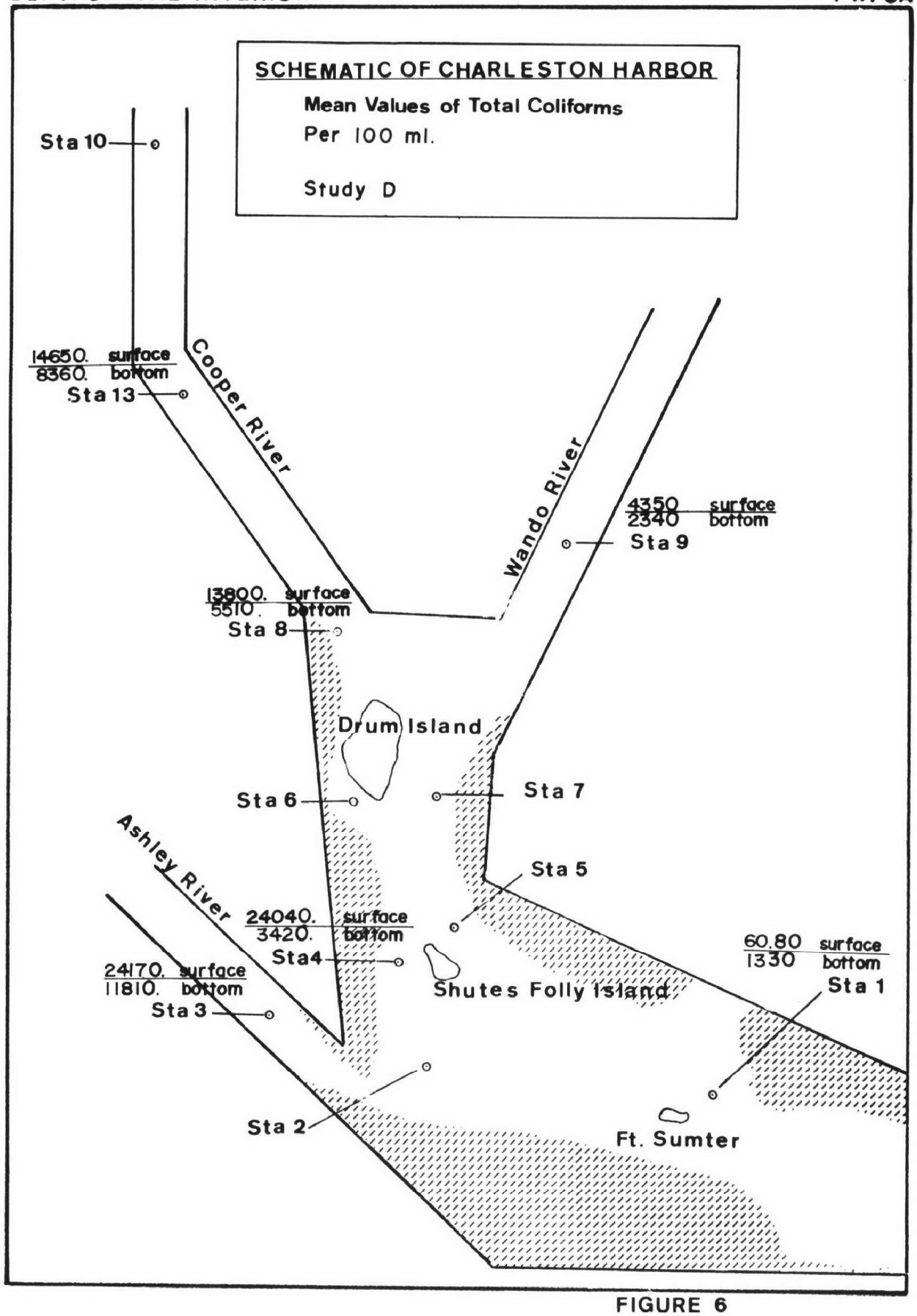

SCHEMATIC OF CHARLESTON HARBOR
Mean Values of Total Coliforms
Per 100 ml.
Study D
Sta 10
14650. surface
8360. bottom
Sta 13
Cooper River
Wando River
4350 surface
2340 bottom
Sta 9
13800. surface
5510. bottom
Sta 8
Drum Island
Sta 6
Sta 7
Ashley River
Sta 5
24040. surface
3420. bottom
Sta4
60.80 surface
1330 bottom
Sta 1
24170. surface
11810. bottom
Sta 3
Shutes Folly Island
Sta 2
Ft. Sumter

FIGURE 6

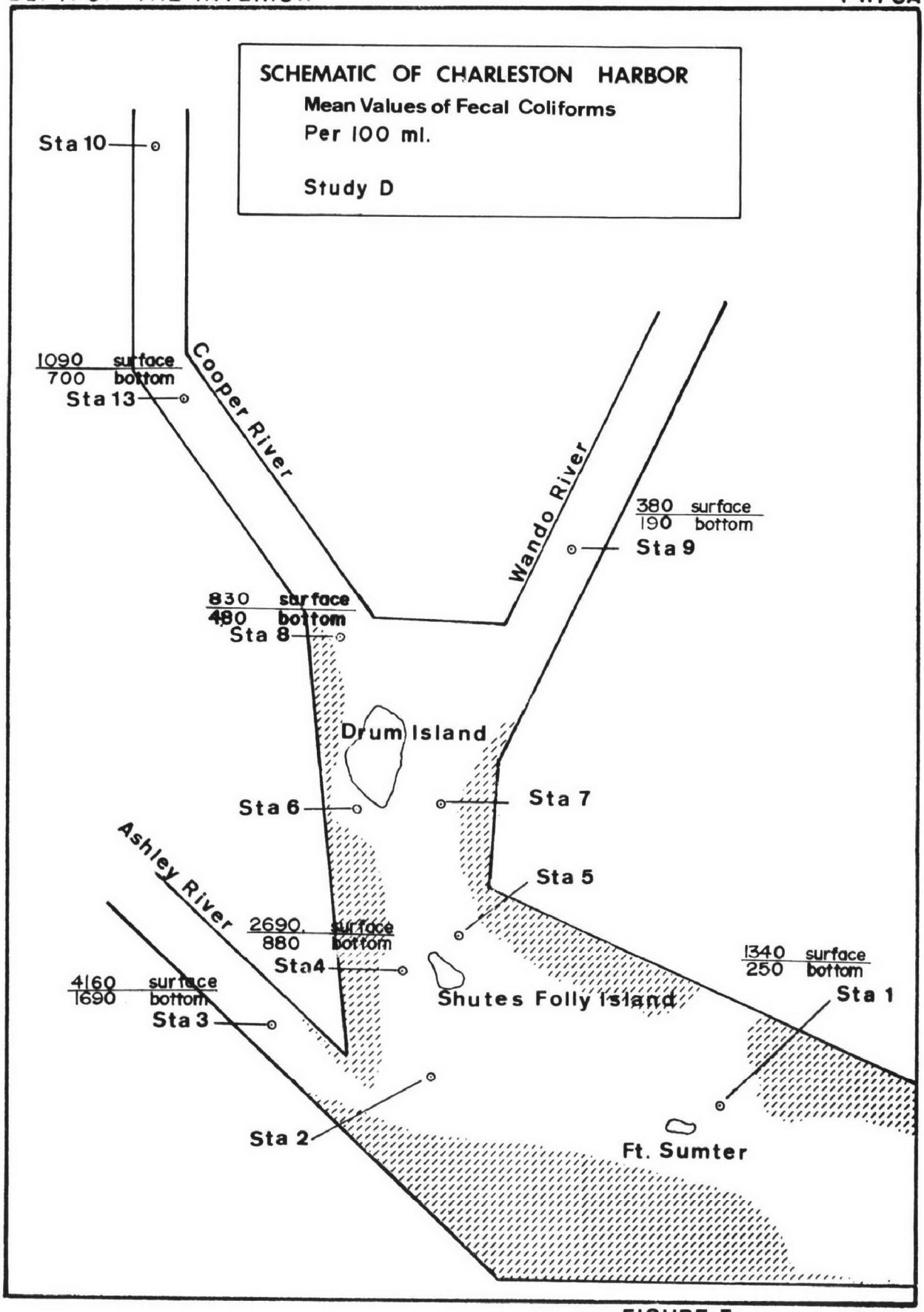

SCHEMATIC OF CHARLESTON HARBOR
Mean Values of Fecal Coliforms
Per 100 ml.
Study D
Sta 10
1090 surface
700 bottom
Sta 13
Cooper River
Wando River
380 surface
190 bottom
Sta 9
830 surface
480 bottom
Sta 8
Drum Island
Sta 6
Sta 7
Ashley River
Sta 5
2690 surface
880 bottom
Sta4
1340 surface
250 bottom
4160 surface
1690 bottom
Sta 3
Shutes Folly Island
Sta 1
Sta 2
Ft. Sumter

FIGURE 7

in the distributions of data obtained at nearly all sampling stations. These results showed that the surface and bottom stations represented regimes operating independently of each other; that is, the D.O. percent saturation near the bottom at a particular station is controlled by a different combination of environmental factors than is that near the surface.

The differences between surface and bottom chloride concentrations found during these surveys can be correlated with differences between surface and bottom D.O. concentrations. Chloride concentrations of about 19 gm/liter may be regarded as representing undiluted oceanic water, while lower concentrations represent dilution of this water with fresh water or waste effluent inflows.

The results in Appendix Table B-6 show that there were significant differences between surface and bottom chloride concentrations at all stations for most of the intensive survey program. Survey AB exhibited the lowest ratios, running from 0.21 to 0.52 for all stations in the harbor. Only far up the Cooper River at station 10 were higher ratios observed up to 0.89 and 0.76. While no quantitative means for relating the degree of stratification to estuarine type have been developed, ratios of this magnitude indicated a strong stratification during survey AB.

The progress of chloride ratio magnitude toward a value of one for surveys B, C, D, E showed a gradual transition toward a vertically homogeneous regime during the study period. In the Ashley River during survey E there was vertical homogeneity for all practical purposes (mean chloride ratios of 0.933 and 0.918 at stations 2 and 3).

The relationship of the chloride ratios between surveys AA and AB was striking (Appendix Table B-6), especially since river discharges and other environmental factors were similar during these two surveys. Low chloride values throughout the system during survey AA suggested that the estuary may have been in a period of transition from a partially mixed or vertically homogeneous system to a strongly stratified system, or that there may have been an abnormal decrease in oceanic salinity offshore. Since river discharges in the Cooper River were high for several months before studies began (above 22,000 cfs), it seems likely that any transition would have been completed. A major disturbance of the immediate off-shore oceanic salinity is therefore a more reasonable explanation for the observed data.

The chloride results point to the existence of a well-known type of estuarine circulation pattern in which there is an extremely large inflow of ocean water along the bottom of the system and a correspondingly large outflow along the surface. There is some mixing of oceanic water into the upper layer and a corresponding influx of ocean water to maintain a state of dynamic equilibrium of densities throughout the system. Downward mixing of surface water, composed of river discharge and sea water, into the bottom layers is quite restricted in this type of system.

The amount of ocean water flowing into the system in such an estuarine circulation pattern is directly proportional to the river discharge, but may be an order of magnitude greater because of the loss of ocean water into the surface layers. The influx of ocean water in such a regime is a major source of new water within the system.

Examination of the D.O. results within the framework of the chloride results and an analysis of D.O. variance showed some important characteristics of waste assimilation and oxygen utilization within the harbor. With restricted circulation between surface and bottom water, the oxygen used for waste stabilization in the bottom layers must be supplied primarily from the inflowing ocean water rather than from surface reaeration or from the river discharge which stays in the surface layer.

The 5-day BOD data obtained during these surveys are presented in Appendix Table B-7. They show the same general picture that the results of routine monitoring show. As mentioned previously, the values were low, well within the range normally attributed to background conditions, i.e., an unpolluted system. Surface and bottom samples showed similar results for all surveys and stations except for Station 10 during survey AA. Long term BOD analyses of samples obtained at several locations confirmed these results.

Chemical oxygen demand determinations made on harbor samples had values so low that the interference from chloride was of the same magnitude as the COD. All measures of the amount of oxygen-consuming load entering the harbor were far too low to account for the degree of oxygen depletion observed.

The total coliform and fecal coliform data (Appendix B-4 and B-5) show an increase in numbers of organisms within the harbor during the summer and early fall months. While total coliform concentrations were lower at Station 1 (which is at the harbor mouth) concentrations were generally proportionately

higher in the Ashley River, the lower part of the Cooper River, and near the Battery than they were in other locations. At Station 4, for example, there were 16,380 organisms per 100 ml at the surface in Survey AB and 26,870 in Survey C. Total coliform results included the fecal coliform group and encompassed coliform organisms contributed by land runoff and warm-blooded animals in general, as well as contributions from human wastes. The fecal coliform results were regarded as representing the direct contribution from waste of human origin.

These results show that during warmer weather and with lower river discharges, concentrations of both groups of coliform organisms were far above the upper limits recommended for swimming and other water contact sports in South Carolina (1000 total coliform organisms per 100 ml).

No excessive algal growth was observed during the period of study. Measured nutrient concentrations are shown in Appendix Tables B-8 through B-11. Phosphate concentrations were slightly higher in the Ashley River than elsewhere, probably due to industrial waste discharges in the upper part of the Ashley River.

During the summer months, several fish kills occurred in the Ashley River. Some of the mortality was traced to the discharge of toxic waste material from an industry. Concurrently, levels of free carbon dioxide were high enough (up to 84 mg/l) with the existing D.O. values to cause mortality in some species of fresh water fish. No lethal standards for the marine species concerned have been established. Extracts of sludges from the

vicinity of industrial waste discharges in the Ashley were toxic to shrimp and menhaden in dilute concentrations. Results indicated that the presence of sludge deposits in the Ashley River affected aquatic life adversely either directly or indirectly. The neutral ranges of pH data for surveys AA, AB, and E are summarized in Appendix Table B-12. Turbidity and total and volatile solids data appear in Appendix Table B-13.

Sediment Studies

Additional measurements were made to determine the mechanism leading to loss of oxygen in the harbor system. About 60 samples of sediments from the harbor and its contiguous streams were analyzed for volatile solids, organic carbon, and for organic nitrogen. A summary of the results of these tests is shown in Table 6 and the sampling stations are shown in Figures 8 and 9. Laboratory measurements of oxygen uptake by the sediments were made on samples taken at the same locations, using both constantly stirred and unstirred samples. These results are summarized in Table 7.

These data show that there were extensive deposits of organic material throughout the harbor and that these deposits could consume oxygen at a rapid rate. Sediments in the harbor system contained as much as 13 per cent organic carbon, indicating that such sediments were composed of about 30 to 40 per cent organic matter. Sediments with this much organic material, or even less, can be regarded as organic sludges and would be expected to have a high rate of oxygen consumption. The oxygen uptake studies (Table 7) showed that this was the case, and that oxygen uptake

TABLE 6

SOURCE OF ORGANIC MATERIALS IN BENTHIC DEPOSITS

Area	No. of Samples	% Organic Carbon			% Organic Nitrogen			Mean Ratio (C/N)	Remarks
		High	Low	Mean	High	Low	Mean		
1) Upper Cooper R. No Wastes Discharged	6	0.05	0.02	0.032	0.003	0.002	0.0027	11.95	Natural Organic Material.
2) Industrial Wastes near Paper Mill, Cooper River	9	13.84	2.25	5.26	0.398	0.088	0.237	22.42	Untreated waste products from semi-neutral sulfate mill.
3) Paper Mill and Domestic Wastes, Cooper River	6	5.87	2.34	3.79	0.418	0.177	0.267	14.38	Raw domestic wastes combined with substantially untreated paper mill wastes.
4) Domestic Wastes in Harbor	9	4.45	2.40	3.54	0.338	0.234	0.302	11.84	Untreated domestic wastes.
5) Industrial and Domestic Wastes, Ashley River	3	5.00	2.13	3.15	0.131	0.118	0.124	25.73	Untreated chemical and fertilizer industries and domestic wastes.
6) Outer Harbor	9	1.26	0.13	0.55	0.099	0.013	0.050	10.77	No tributary waste discharges.

SEDIMENT SAMPLING STATIONS CHARLESTON HARBOR

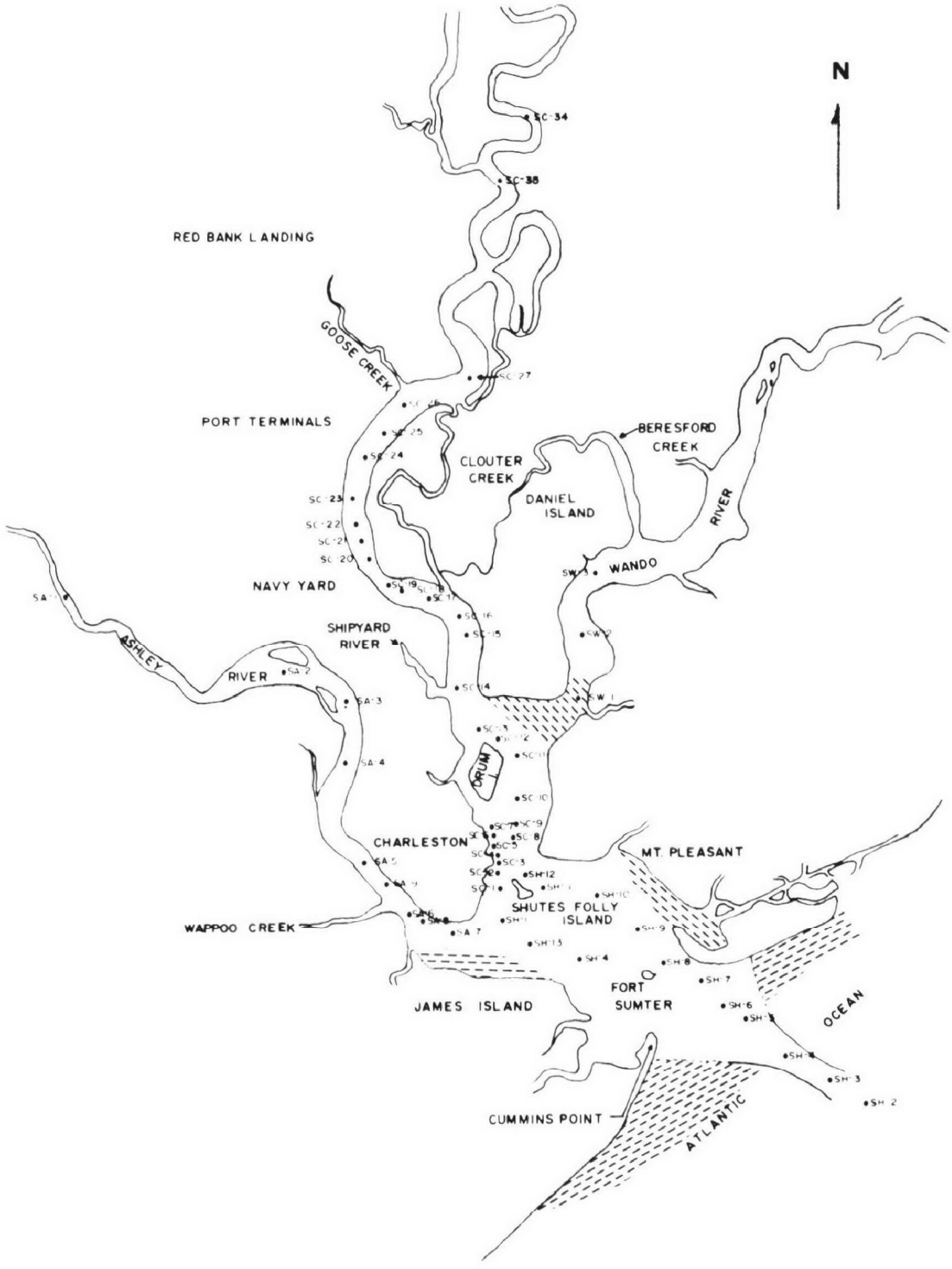


FIGURE 8

SEDIMENT SAMPLING STATIONS UPPER COOPER RIVER

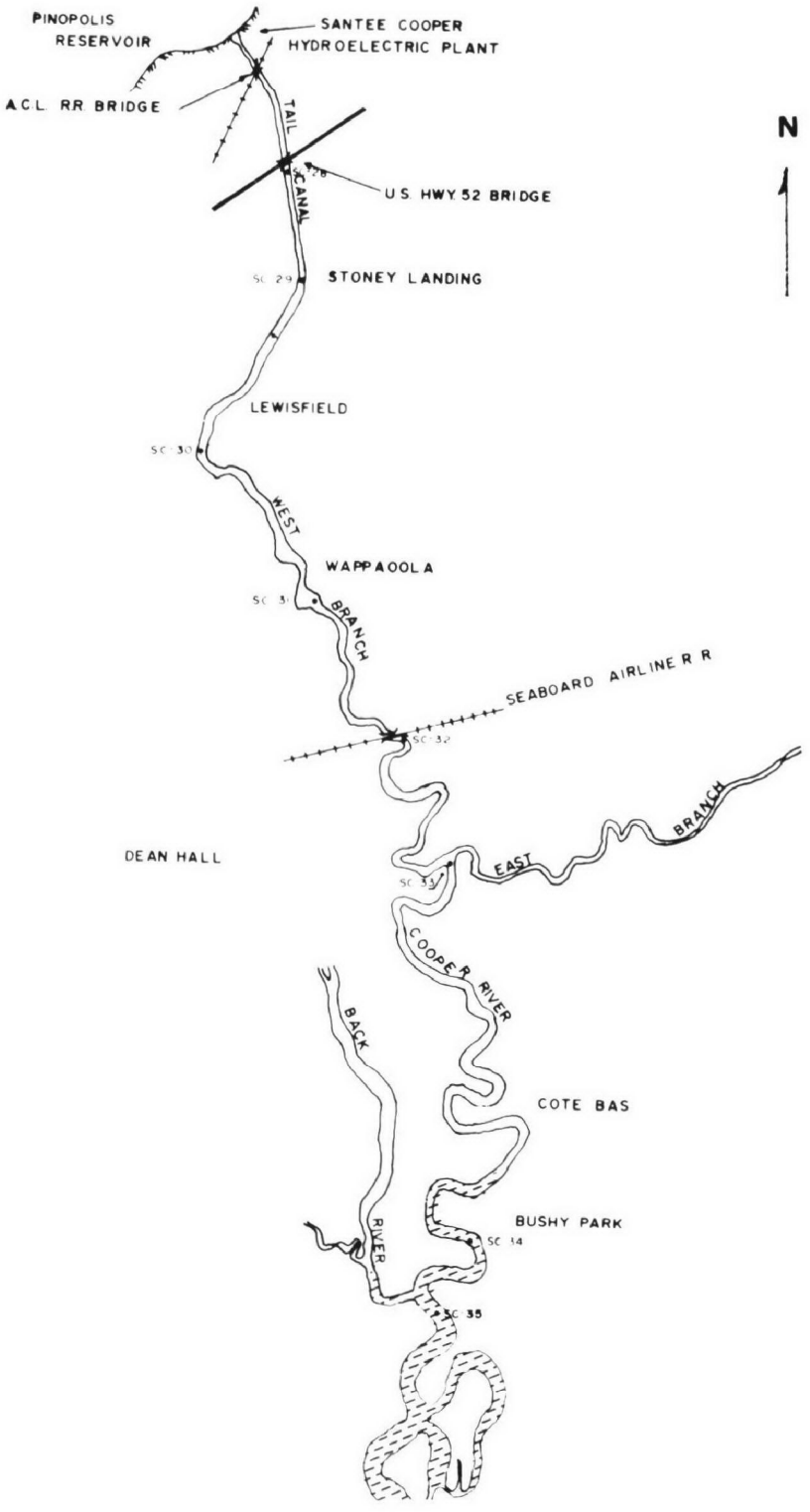


FIGURE 9

TABLE 7

LABORATORY INVESTIGATION OF OXYGEN UTILIZATION BY BENTHIC DEPOSITS

Area	No. of Samples	Test Type	Oxygen Utilization at End of Period mg O_2 util./gm Sed.dry wt. mean 1 day	mean 5 day	Sediment Characteristics: Mean % Moisture	Mean % Vol. Solids (dry wt)	Mean % Org. C.	Mean % Org. N	Mean Org.C-Org.N Ratio	Mean Theoretical O_2 Demand mg.O_2/gm dry wt. 1/
Upper Cooper R., No Wastes Discharged	6	mix	0.15	0.51						
		non-mix	0.07	0.26	22.4	0.95	0.15	0.009	17.8	4.4
Ind. Wastes near Paper Mill, Cooper River	9	mix	4.42	8.84						
		non-mix	2.12	4.97	59.8	10.03	7.08	0.134	64.8	195.1
Paper Mill and Domestic Wastes, Cooper River	6	mix	4.34	6.63						
		non-mix	0.78	2.24	63.9	8.45	3.03	0.142	23.1	87.4
Domestic Wastes in Harbor	8	mix	4.53	7.20						
		non-mix	1.00	2.55	71.0	11.07	3.06	0.203	15.6	91.1
Ind. & Domestic Wastes-Ashley R.	3	mix	5.57	8.44						
		non-mix	0.97	2.54	73.3	11.52	4.16	0.172	26.2	119.0
Outer Harbor	9	mix	0.58	1.17						
		non-mix	0.28	0.74	34.5	2.90	0.71	0.046	15.4	21.0

1/ Computed from equation Theoretical Oxygen Demand = 2.67 (organic carbon) + 4.57 (organic nitrogen) which was developed in "Effects of Polluting Discharges on the Thames Estuary," Water Pollution Research Technical Paper No. 11; Dept. of Scientific and Industrial Research, Her Majesty's Stationery Office, London, England, 1964.

rates of 2 to 5 mg per day per gram of dry sediment were common. There were large differences between results from the stirred and unstirred samples; this is the result of the greater exposure of nutrient surface area in the stirred samples. Oxygen uptakes from stirred sediments as high as five times those from unstirred sediments were observed.

The mechanism of oxygen consumption from the water, as suggested by these results, is that sediments are agitated as bottom water velocities increase following slack water (tidal velocities of one to two knots are common in this system); oxygen is consumed from the water in stabilizing these sediments in suspension. As velocities decrease toward the next slack, the sediments settle to the bottom. Pumped samples taken at depths near the bottom showed that there was an aquatic zone in some cases several feet thick which contained a thick suspension of solids.

The ratios of organic carbon to organic nitrogen in the sediments can be used to differentiate between types of waste materials comprising the organic fraction of the sediments. Industrial wastes of non-human origin have very high ratios, generally running between 15 and 40. Human wastes, such as primarily compose domestic and municipal sewage, have ratios much lower than this, generally between 10 and 15.

Sediment survey data showed that deposited wastes in the Cooper River and above the Grace Memorial Bridge were primarily industrial, as were those in the upper reaches of the Ashley River. Around the Battery and in the lower reaches of the Ashley River there was a zone

of sludge deposits from municipal sewage sources, while farther out in the harbor there were beds of mixed composition.

The sludge deposits were the principal cause of the low D.O. values observed during the intensive survey program. The combination of high temperature and low river discharge in the summer and early fall brought about the worst conditions because of a decrease of available oxygen in the water combined with an acceleration of the biochemical processes utilizing the oxygen. The theoretical oxygen demand (TOD) shown in Table 7 demonstrates the theoretical potential for oxygen consumption by the sediments.

Biological Studies

An examination of benthic biota and plankton populations was made during survey E (September) by a team of aquatic biologists. The results of their study are described below.

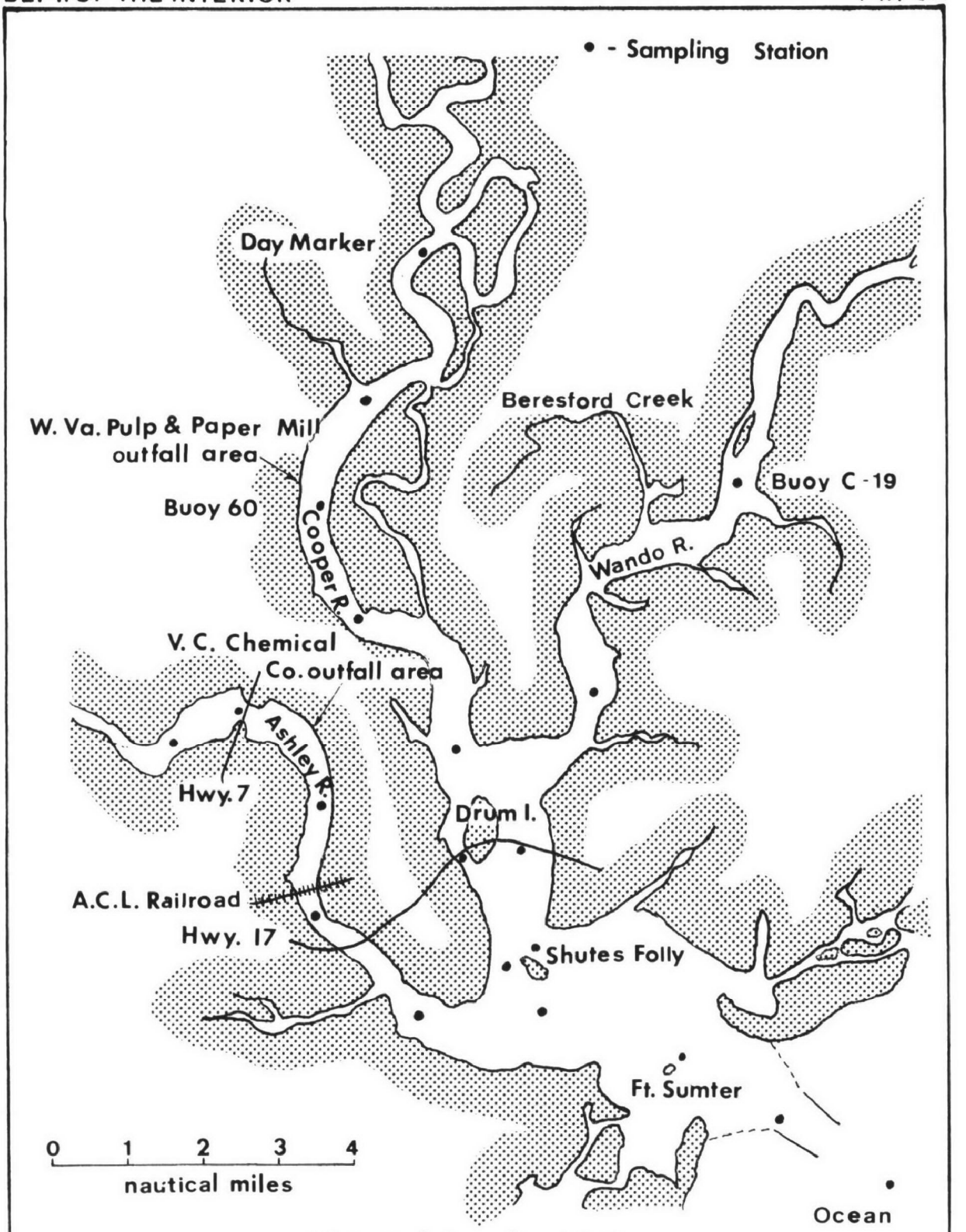
Samples of phytoplankton and bottom-associated animals were collected from the Charleston Harbor estuary during September 20-24, 1965. These were preserved and shipped to the Technical Advisory and Investigations Activities laboratory at Cincinnati for analysis. Additional samples of estuarine muds were obtained to determine the occurrence and distribution of organophosphate pesticides and the effects of such muds on selected aquatic organisms. Analyses to delineate the presence and distribution of merphos (tributyl trithiophosphate) were conducted by personnel of the Robert A. Taft Sanitary Engineering Center at Cincinnati, Ohio. Bioassays to determine the effects of such muds on snails, shrimp, and fish were implemented by Dr. G. Robert Lunz, Director, Bears Bluff Laboratory, Division of Commercial Fisheries, South Carolina

Wildlife Resources Department. Mud samples for a series of five bioassays were collected on several dates between September 30 to November 12, 1965. Figure 10 shows the biological sampling stations in the harbor. Tables 8 and 9 list the results of the biological analyses for bottom organisms and plankton.

Samples of bottom-associated life, collected during September 20-24, 1965, revealed adverse conditions for benthos in several reaches of the Charleston Harbor estuary:

(1) In the lower reaches of the Ashley River, pollution was evident from the vicinity of the Virginia-Carolina Chemical Company downstream to the mouth of the river. Mid-channel benthic environments of these reaches lacked bottom-associated organisms. Deposits in the channel near the outfalls of the Virginia-Carolina Chemical Company were comprised of dark-colored muds and oily substances that emitted odors similar to those of petroleum. Bioassays conducted with such deposits on certain snails, shrimps, and fish demonstrated that certain constituents of these muds were toxic to the organisms tested. Bottom deposits in downstream reaches to the mouth of the river consisted of black muds and organic matter, and produced foul odors like those of domestic sewage.

(2) The lower reaches of the Cooper River contained significant discharges of waste from upstream sources. Pollution was evident in the Cooper River in reaches immediately upstream and downstream from the vicinity of the West Virginia Pulp and Paper Company. Sludge deposits were abundant, and bottom associated organisms were



Biological Sampling Stations
Charleston Harbor
9/20-24/65

FIGURE 10

TABLE 8

BENTHIC BIOTA

Station Location	Station Number	Number of Organisms[1] Polychaete Worms	Snails	Oysters	Clams	Barnacles	Mussels	Crabs	Anemones	Shrimp	Total Kinds	Total Numbers
				OCEAN AREA								
Seaward From Harbor Jetties	O-1	5 (2)*	2	-	-	-	-	-	-	13 (3)	6	20
Harbor Jetties	O-2	29 (2)	-	-	-	-	-	18	-	41 (3)	6	88
				HARBOR AREA								
Near Ft. Sumter	H-1	5 (2)	-	-	2	-	-	-	-	5 (3)	6	12
South From Shutes Folly Island Near Junction Buoy 32	H-2	14 (4)	-	-	-	-	-	-	-	-	4	14
West of Shutes Folly Island	H-4	90 (5)	-	-	-	-	-	-	-	-	5	90
North of Shutes Folly Island	H-5	3 (2)	-	-	-	-	-	-	-	-	2	3
West of Drum Island	H-6	13 (4)	-	-	-	-	-	-	-	-	4	13
East of Drum Island	H-7	6 (2)	-	-	-	-	-	-	-	-	2	6
				ASHLEY RIVER								
Mouth of Ashley River	A-1	-	-	-	-	-	-	-	-	-	0	0
Between U. S. Hwy. 17 & A.C.L. Railroad Bridges	A-2	-	-	-	-	-	-	-	-	-	0	0
Between State Hwy. 7 & A.C.L. Railroad Bridges	A-3	-	-	-	-	-	-	-	-	-	0	0
At State Hwy. 7 Bridge	A-4	13 (2)	-	3	-	-	-	2	-	-	4	18
One Mile Upstream From State Hwy. 7 Bridge	A-5	13 (2)	-	3	-	16	2	18	-	3 (2)	8	54
				COOPER RIVER								
Mouth of Cooper River	C-1	30 (5)	-	-	-	16	-	-	34	-	7	80
Near Buoy 52 at U. S. Navy Pier J	C-2**	2 (1)	-	-	-	-	-	-	-	-	1	2
Downstream From W. Virginia Pulp and Paper Mill Outfall	C-3	-	-	-	-	-	-	-	-	-	0	0
Near Goose Creek Confluence	C-4	-	-	-	-	-	-	-	-	-	0	0
Day Marker Buoy	C-5	3 (2)	-	-	-	-	-	-	-	-	2	3
				WANDO RIVER								
Mouth of Wando River	W-1	8 (3)	-	-	-	-	-	-	-	3 (1)	4	11
Near Buoy C-19	W-2	8 (3)	-	-	-	-	-	-	-	2 (1)	4	10

* Numbers in parentheses denote number of kinds of polychaete worms and shrimp.

** This station was recently dredged for silt removal.

[1] Number and kinds of organisms per square foot sampled at Charleston Harbor and lower reaches of tributary rivers, September 20-24, 1965.

TABLE 9

PHYTOPLANKTON CONCENTRATIONS

Phytoplankton (number per milliliter and ppm wet weight)

Charleston Harbor and Tributary Rivers

September 20-24, 1965

Station Number	Number per milliliter		Amount as ppm	
	Surface	Bottom	Surface	Bottom
Ocean Area				
O-1	1,200	100	3.3	2.2
Harbor Area				
H-1	225	650	0.6	2.0
H-2	1,200	-*	2.8	-
H-6	1,050	1,750	5.8	6.7
H-7	3,050	2,750	12.9	8.3
Ashley River				
A-1	1,050	330	3.0	1.0
A-2	2,700	3,800	8.2	12.0
A-4	2,200	5,150	6.8	18.0
Cooper River				
C-1	1,000	4,450	4.2	4.1
C-3	2,950	-	7.7	-
C-5	200	-	0.5	-
Wando River				
W-1	1,800	3,400	5.9	11.1
W-2	1,250	550	5.1	1.9

* Not sampled.

not found in these reaches. Marine worms were found in benthic environments both upstream and downstream from these grossly polluted reaches. Partial recovery was indicated near the mouth of the Cooper River where oysters and seven other kinds of animals were found; however, certain clean-water associated forms such as shrimps and crabs were absent.

(3) The Wando River was not discernibly polluted. Benthic reaches of this river were composed of hard clays mixed with scraps of shells and vegetation, and provided conditions suitable for three kinds of clean-water associated shrimp.

(4) Moderately polluted areas were apparent in the main harbor from the mouths of the Ashley, Cooper, and Wando Rivers seaward to near Fort Sumter. Benthic environments in these reaches supported only marine worms. Bottom deposits were either black mud or black muds mixed with bits of shells, clay, or sand. Deposits consisting only of black mud were found in the reach south of Shutes Folly Island near the mouth of the Cooper River, and in the reach west of Shutes Folly Island; these muds emitted foul odors comparable to those associated with deposits in the lowermost reaches of the Ashley River, i.e., petroleum.

Benthic environments near Fort Sumter and seaward were not perceptibly polluted. Such environments were suitable for clean-water associated shrimp, and clams or crabs. Phytoplankton tended to be more abundant than 3.5 ppm in reaches inland from Shutes Folly Island, and was less than 3.5 ppm seaward from Shutes Folly

Island. This distribution of phytoplankton was apparently associated with estuarine enrichment induced by waste discharges.

RELATIONSHIP OF PRESENT WATER QUALITY TO ENVIRONMENTAL CHANGES

Water quality at any particular time depends not only upon the amount and character of wastes entering a system but also upon whatever environmental factors dominate the regime. Dissolved oxygen and coliform organisms are the principal water quality parameters of concern in Charleston Harbor.

The major environmental factors affecting any estuarine D.O. system are:

(1) Waste load

(2) Temperature

(3) Solar radiation

(4) Tide

(5) River discharge

Minor factors such as rainfall and wind speed and direction may also be important in specific instances.

In the present case neither rainfall nor wind vector (measured at the Charleston Weather Station) were sufficiently dominant or consistent to cause more than slight variations in the data. Table 10 presents the total cumulative knots of wind by direction for each survey. Winds were mostly light and variable, though there were occasional gusts of high winds in all surveys. Total inches of rainfall for each survey are shown in Table 10.

TABLE 10

CUMULATIVE KNOTS OF WIND BY DIRECTION 1/

Direction in Degrees	Survey AA	AB	B	C	D	E
0	5	15	--	29	38	35
10	9	--	--	22	--	15
20	--	--	--	26	5	--
30	--	2	--	16	--	12
40	--	--	--	12	--	9
50	15	--	--	60	18	8
60	9	12	6	--	--	3
70	--	10	4	--	--	--
80	--	8	--	17	--	--
90	--	33	--	4	--	19
100	--	32	--	100	--	6
110	--	22	--	--	5	8
120	3	22	--	--	2	18
130	--	--	--	--	7	12
140	--	10	5	--	9	10
150	7	21	--	--	4	26
160	13	16	--	12	--	--
170	--	8	12	--	4	--
180	6	9	42	15	6	--
190	--	--	12	10	13	--
200	5	21	25	1	8	4
210	--	12	--	--	9	--
220	--	11	14	--	--	--
230	--	6	--	--	24	--
240	15	--	7	10	23	--
250	--	--	25	--	--	--
260	--	15	--	6	--	--
270	66	--	--	--	--	--
280	26	--	--	2	--	--
290	16	--	--	--	--	--
300	16	--	--	4	--	--
310	7	--	--	--	4	--
320	7	--	--	--	--	--
330	--	--	--	--	--	--
340	11	--	--	1	--	3
350	9	19	7	--	--	--
Total inches of rainfall	.83	1.26	.38	.52	1.32	.72

1/ For each intensive survey, wind velocity in knots and direction in degrees were recorded on the same four hour frequency used for sampling other parameters. The velocities for each direction for each survey were added to give a cumulative knots of wind by survey.

Waste Loads

Industries that discharged significant amounts of wastes to the Charleston Harbor system operated primarily on continuous process schedules on a year-round basis. Almost all wastes were discharged directly from process sewers into the rivers and harbor. Municipal sewage was also discharged untreated from widely distributed pumping stations and gravity sewers. Because there was no significant seasonal variation in waste discharges, it was assumed that Charleston Harbor received a constant waste discharge during the period of study. Such an assumption permitted the evaluation of the relative effects of environmental changes without requiring an accurate knowledge of the total entering waste load. Table 11 lists the major waste discharges.

Temperature

The annual variation in temperature in Charleston Harbor is about 8 to 30°C. An increase in temperature reduces D.O. saturation concentrations and increases the rates of biochemical processes. The use of D.O. data in terms of percent saturation accounts for much of the effect of temperature changes on the D.O. data. In some estuaries, temperature differences between surface and bottom can affect stratification to a marked degree. The data of Appendix Table B-2 show that there was no significant difference between surface and bottom temperatures for any of the surveys. Stratification in Charleston Harbor was, therefore, not thermally dominated.

TABLE 11

MAJOR WASTE DISCHARGES

Source	Type of Waste	Treatment Facilities	Discharge Location	Estimated Load lbs. 5-day BOD/day	Remarks
City of Charleston	Municipal Sewage	None	14 outfalls to lower Ashley and Cooper Rivers and to Harbor	13,500	State law prohibits the discharge of untreated sewage into Charleston Harbor by any person or political entity after July 1, 1970.
Mt. Pleasant	Municipal Sewage	None	Shem Creek & Harbor	500	See Above
No.Charleston Consolidated Public Service District	Industrial and Municipal Sewage	None	14 outfalls to Ashley and Cooper Rivers in upper harbor.	7,000	See Above
St. Andrews Public Service District	Municipal Sewage	1)Septic Tanks or oxidation ponds for some subdivisions, and 2)raw discharges	15 outfalls to Ashley and Stono Rivers	No data available (NDA)	District services approximately 2000 individual dwellings.
Hanahan Public Service District	Municipal Sewage	Primary	Goose Creek near Cooper River	1,100	Not in Charleston County.
Charleston Air Force Base	Municipal and some Industrial Sewage	Primary	Ashley River	NDA	---
Bird & Son, Inc. (roofing and Siding)	Industrial	None	Ashley River	NDA	Soap and dyes are major components. Wastes have high pH.

TABLE 11 - cont'd

Source	Type of Waste	Treatment Facilities	Discharge Location	Estimated Load lbs. 5-day BOD/day	Remarks
Koppers Co., Inc. (treated wood products)	Industrial	Raw material recovery unit	Ashley River immediately above WOKE radio tower	NDA	Two waste streams. Wastes contain metals and phenols.
So.Carolina Electric and Gas Company	Cooling Water	None	Ashley River	NDA	Cooling water from steam generators.
Planters Fertilizer Co. (sulfuric acid & fertilizer)	Industrial	None	Ashley River	NDA	Two waste streams with high metal concentrations.
Va.-Carolina Chemical Co. (organic and inorganic phosphorus chemicals)	Industrial	None	Ashley River ½ mile below State Hwy. 7 bridge	NDA	Three waste streams containing organic and inorganic phosphorus products, sulfuric acid and metals.
W. Virginia Pulp and Paper Company	Industrial	Some in-plant treatment	Cooper River immediately below Port Terminal	69,200	In-plant modifications in Aug. 1965 resulted in 47% reduction of BOD load discharged to Cooper River. BOD load shown is average for the period Aug.1965 to April 1966.
American Agricultural Chemical Co.	Cooling Water	None	Ashley River	NDA	No significant wastes discharged.

Solar Radiation

Solar energy affects water temperature and also furnishes the energy necessary for the photosynthetic production of oxygen by algae. The effect of solar energy on temperature was included in overall temperature changes for which allowance has been made in the D.O. regime. The response of D.O. in the harbor to photosynthetic oxygen production was obtained from examination of the solar radiation and D.O. records for the intensive surveys (Table 12 and Appendix Table B-1). The response of D.O. to solar radiation was shown to be negligible in this study by the reasoning developed below.

Table 12 presents values for the cumulative solar radiation on each day of each survey. There were differences in solar radiation from day to day, and the total energy inputs for each survey showed significant variation. The actual quantitative effect of solar radiation on D.O. was obtained from the results of cross-spectral analysis of the solar radiation and D.O. records. A very strong diurnal response (expressed as units of percent saturation per gram-calorie per square centimeter per minute) of D.O. to solar radiation was regarded as caused by photosynthetic oxygen production and oxygen utilization by the algal population. There may have also been longer period responses of D.O. to sunlight caused by a pronounced secular trend in solar radiation over the period of record. A strong semidiurnal (tidal) component may have also appeared as water of different algal populations was advected past the sampling station. The net effect of all these responses on the D.O. variance was examined by use of the overall response (total response of the record) results of D.O. to solar radiation.

TABLE 12

CUMULATIVE SOLAR RADIATION in gm.cal per cm^2 per day

	Survey					
Day	AA	AB	B	C	D	E
1st	456	288	648	432	544	475
2nd	432	480	768	240	494	403
3rd	676	264	744	636	240	403
4th	336	264	698	636	452	276
5th	504	264	768	552	504	288
Total	2424	1560	3626	2494	2234	1845

Stations 1 and 3 for surveys D and E were used for the radiation and D.O. relation analysis since these stations represented areas of extremes in nutrient concentrations and the surveys represented the months of August and September, the hottest and driest periods. The data of Table 12 was used with the overall response to calculate the fraction of D.O. variance which was related to solar radiation variance. Table 13 contains the results of this calculation. The effect of solar radiation contributed up to 10 per cent of the D.O. variance at these two stations. This proportion is sufficiently small to be considered negligible in influencing the D.O. regime of the harbor system. Solar radiation is not considered therefore a major environmental factor affecting the water quality of Charleston Harbor.

Tide and River Discharges

The degree of interaction between tide and river discharge in Charleston Harbor was illustrated by the variable degree of stratification observed during the intensive survey program. The combination of river discharge and tide was the controlling factor in the chloride distribution and the degree of stratification. Figure 11 shows the changes in D.O. percent saturation from the harbor mouth up the Cooper River for each of the six intensive surveys. The abscissa is drawn on a scale proportional to river miles between stations. At higher river discharges, D.O. levels remained fairly high and uniform; as river discharges declined the D.O. began to drop, particularly in the reach above the Grace

TABLE 13

SOLAR RADIATION AND D.O. VARIANCE

		Total D.O. Variance (per cent saturation)^2	D.O. Variance Response to Solar Radiation	
			(per cent saturation)^2	Per Cent of Total Variance
Survey D				
Station 1	Surface	85.3	8.0	9.4
	Bottom	69.8	6.2	8.9
Station 3	Surface	52.3	3.9	7.5
	Bottom	20.0	2.0	10.0
Survey E				
Station 1	Surface	179.0	13.0	7.3
	Bottom	207.0	15.5	7.5
Station 3	Surface	104.0	7.6	7.3
	Bottom	55.9	2.0	3.6

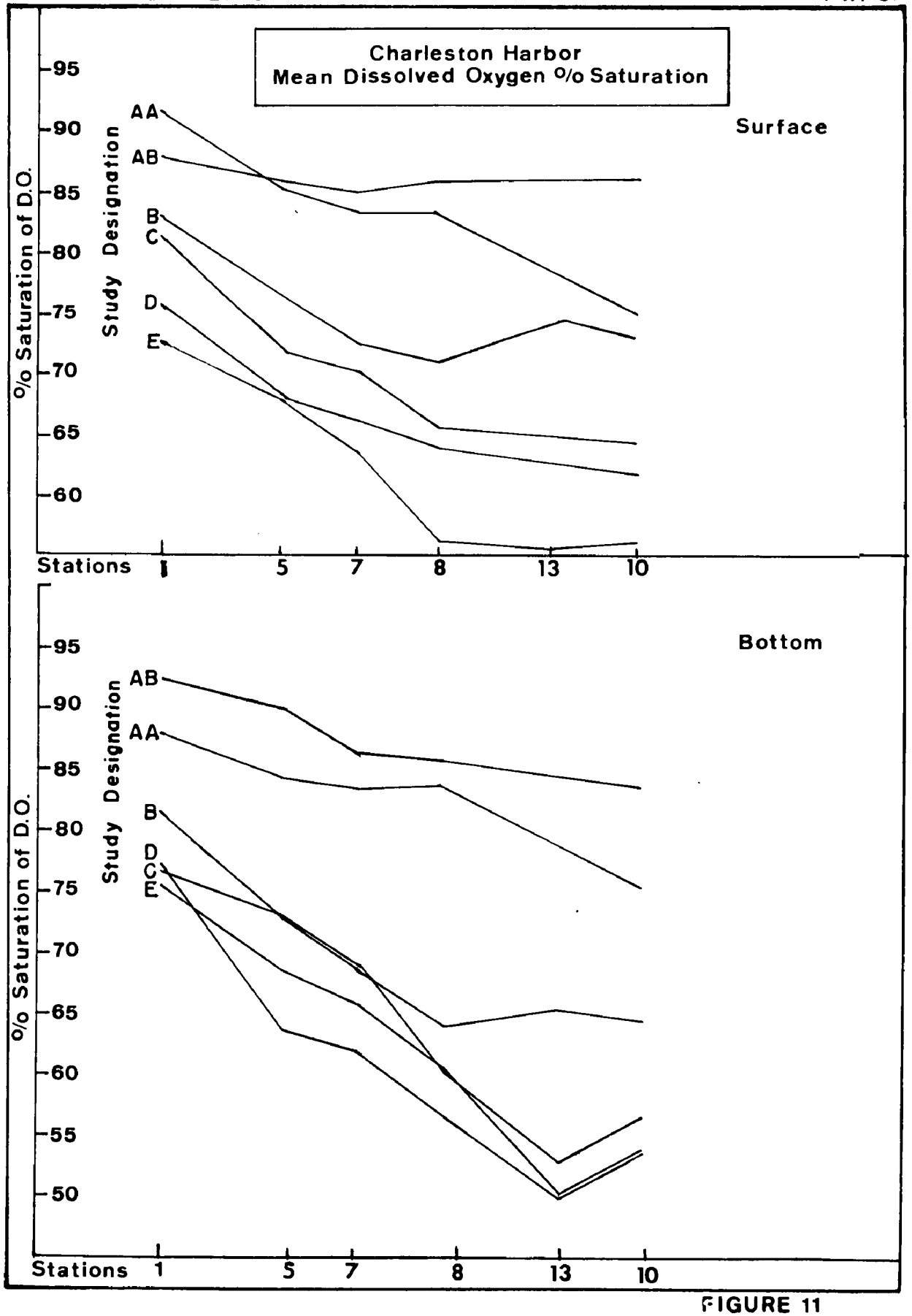

Charleston Harbor
Mean Dissolved Oxygen % Saturation
Surface
Bottom
% Saturation of D.O.
Study Designation
AA
AB
B
C
D
E
95
90
85
80
75
70
65
60
55
50
Stations
1
5
7
8
13
10

FIGURE 11

Memorial Bridge. The corresponding graphs for chloride changes (Figure 12) shows similar trends, although the drops in chloride concentrations were more pronounced than were those for D.O.

To develop a quantitative appreciation of the effect of tide and river discharge on circulation and stratification in the Charleston Harbor system, it was necessary to use some of the more sophisticated techniques of systems analysis, namely the results of cross-spectral analysis of the river discharge, chloride, and D.O. records.

Relationships between River Discharge and Chlorides. Relationships between river between river discharge and chloride concentrations were derived from the results of six intensive surveys, salinity profiles at all sampling stations at HWS and LWS (high water slack and low water slack tides), and a series of four same-slack runs made also at HWS and LWS. The last two bodies of data are important because they show conditions at discharges as low as 7700 cubic feet per second, which was far lower than the minimum that occurred during the intensive sampling program.

The response spectra of chlorides to river discharge showed the amounts of variance in the chloride record which could be attributed to river discharge (Appendix Figure C-1 shows typical response spectra). The effects of river discharge on the tide at the sampling stations was reflected in the semidiurnal tidal component of the chloride response spectra. This type of analysis was carried out for all stations in all surveys.

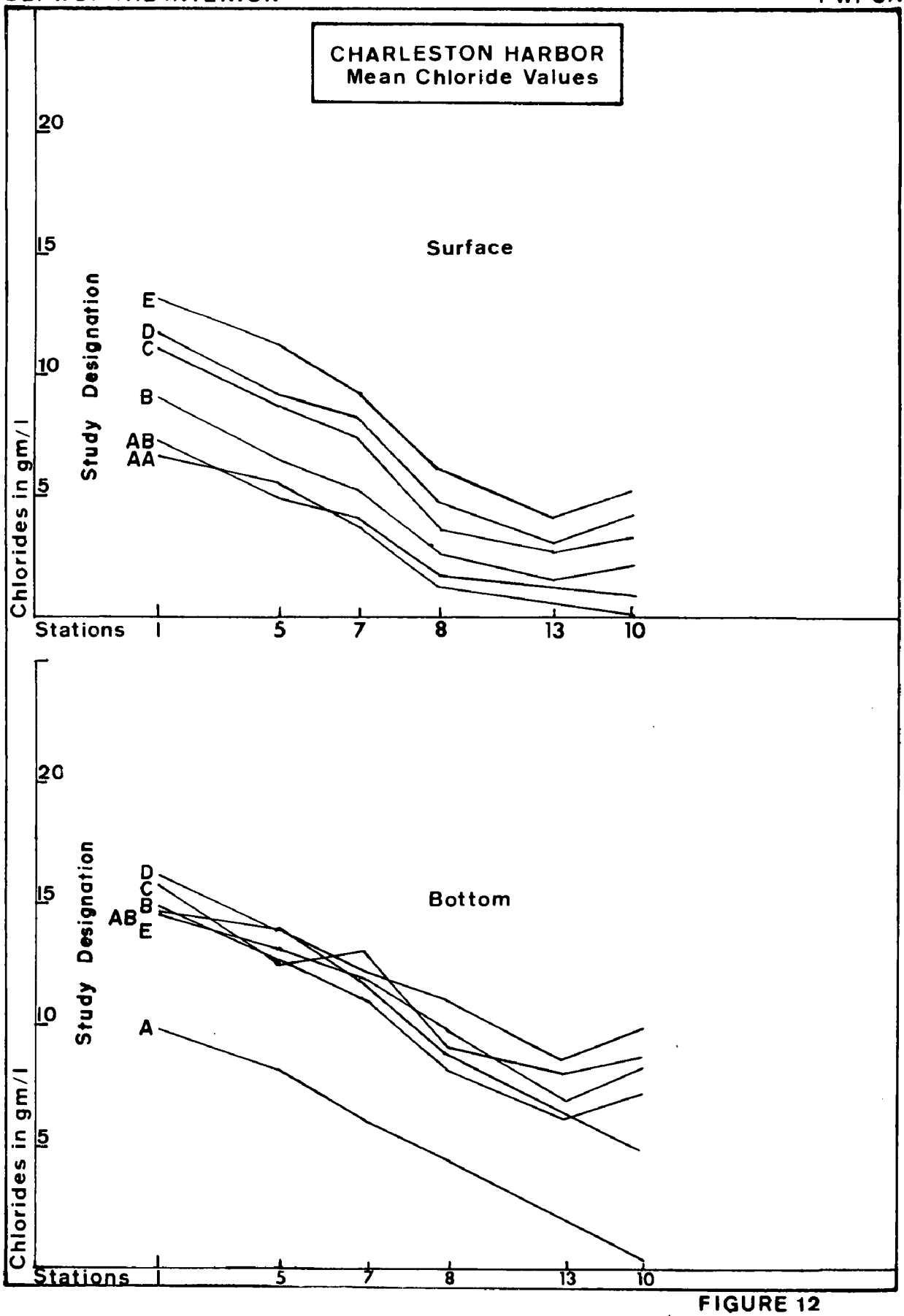

CHARLESTON HARBOR
Mean Chloride Values
Surface
Chlorides in gm/l
Study Designation
E
D
C
B
AB
AA
Stations
1
5
7
8
13
10
Bottom
Chlorides in gm/l
Study Designation
D
C
B
AB
E
A
Stations
5
7
8
13
10

FIGURE 12

Although surveys AA and AB were subject to nearly the same river discharge, there was during survey AA a spring tide with a range of 5.2 feet, and during survey AB there was an equinoctial neap tide of 3.5 feet range. Data from these surveys afforded an opportunity to examine the effects of differences in the range of tidal heights on the chloride distribution.

At Station 1 (harbor mouth) during survey AA, the major response of chloride concentration to river discharge was semidiurnal (tidal), with the bottom response about double the surface response. During survey AB the major response was long-period in frequency and the semidiurnal responses were quite small.

During survey AA there were significant semidiurnal responses on the surface at stations 2, 4, 5, and 7. Other stations during this survey exhibited a negligible effect of river discharge on chlorides in the surface layer. During survey AB, only stations 1 and 2 exhibited any response of chlorides to river discharge on the surface.

The response of the bottom stations during survey AA showed a strong and fairly uniform semidiurnal response and a varying amount of long-period response at all stations except 9 and 10 (in the Wando River and far up the Cooper River). In survey AB the major bottom station response was long-period and responses of tidal period were suppressed for all stations except 8 and 9.

This analysis demonstrated that a difference in tidal range had a definite effect on chloride distribution and that this effect

was small in the surface layers (except near the harbor mouth) but quite pronounced in the bottom layer.

From the cross-spectral analysis, a coefficient for the overall response of chlorides to river discharge was computed. This coefficient indicates the magnitude of the effect of river discharge on chloride concentration and is expressed in units of gm/l/cfs. Appendix Table C-1 contains the overall response coefficients calculated for each station and survey together with the mean values of these coefficients for each survey. These coefficients include the effect of variations of all periods.

Comparison of the results from surveys AA and AB showed that the means of surface and bottom responses of chloride concentrations to river discharge were about equal for both surveys, 1.29 for AA and 1.35 for AB. On the surface the overall response was slightly higher for the spring tide condition, and on the bottom the response was slightly lower for the spring tide condition. Mean surface to bottom response ratios of 0.555 and 0.46 respectively showed that the estuary was well stratified during both surveys. The mean for the two surveys was 0.51. These values compared well with the measured mean chloride ratios for these surveys of 0.57 (Appendix Table B-6).

At <u>high</u> river discharges with the estuary strongly stratified the average overall response of chlorides in the estuary was dependent upon the state of the tide. During spring tide conditions there was an increase in response in the surface layer which was related to more intense mixing at the interface created by

higher shearing velocities. At the same time there would have been a stronger intrusion of ocean water along the bottom which meant less variation and consequently less response in the bottom layer.

The response spectra for the other four surveys showed generally strong semidiurnal responses with the responses at each station becoming relatively stronger on the surface as the river discharge decreased. Concurrently the overall response of chlorides to river discharge decreased for surveys B, C, and D, and then increased during survey E (made during spring tide conditions). These results reflected a decrease in the strength of the stratification with reduced river discharge and a consequent increased mixing between surface and bottom. The mean ratios of chlorides as shown in Appendix Table B-6 show the same type of progression.

Surveys D and E show mean overall response ratios of 0.834 and 0.872, respectively, indicating that the surface and bottom layers reacted nearly the same to river discharge for both surveys.

The striking differences in overall response between surveys D and E required some examination. Appendix Table C-2 shows the mean tide height range for each survey together with an analysis of the mean overall responses. The tidal height range difference between surveys D and E was about the same as that between surveys AA and AB. The surface and bottom responses for surveys AA and AB were quite different from those during surveys D and E. However, the difference in surface response between both pairs of surveys was practically identical, showing that the surface layer was being

affected similarly by some constant difference between the surveys comprising each pair. The only similarity in environmental factors was the change in tidal range.

One additional result is important; between surveys D and E the change in bottom response was the same as the change in surface response, 0.062 on the surface and 0.067 on the bottom. This comparison shows that the surface and bottom overall responses for surveys D and E were very nearly the same and that the changes of overall response with change in tide height were the same in both surface and bottom records. The net result of this comparison of chloride responses was to demonstrate that the surface and bottom layers in surveys D and E behaved so nearly alike that for all practical purposes the chloride distribution is acting as if estuary stratification was vertically consistent.

The cross-spectral analysis further demonstrated that below discharges of about 16,000 cfs, the Charleston Harbor system, considered as a single unit behaved in its chloride distribution as if it were vertically unstratified. For analyzing the chloride-river discharge relationship at flowrates below the range observed during the intensive survey program, the chloride response factors used were the average of those found during surveys D and E (0.834 and 0.872, respectively) because conditions close to vertical mixing were observed during these surveys. This would correspond to a tide range of 5.0 feet, which is near the mean tide range of 5.2 feet for the primary reference tide in Charleston Harbor.

The preceding discussion has been based on considerations involving all of the stations sampled. Since each station was carefully selected to represent a significant region of the entire system, these results should be a valid representation of the workings of the entire system.

Individual parts of the harbor did, however, respond differently to changes in river discharge. Appendix Table C-3 presents the results of slack tide runs made during high water slack and slow water slack conditions. The values presented are ratios of surface to bottom chloride obtained at the indicated river miles (mile zero at the end of the jetties for the Cooper River). There was an abrupt drop in the ratio between miles 11 and 12 of the Cooper River. Station 7 is at mile 11.6 and station 5 is at mile 10.0. The corresponding results of the special salinity profile studies (Appendix Table C-4) show a similar picture. Figures 11 and 12 show corresponding results in the mean values of chloride and D.O. percent saturation. From the consistency of these results there appeared to be a basic difference in the water quality and hydraulic characteristics of the harbor below the Grace Memorial Bridge and in that part from the bridge on up the Cooper and Wando Rivers. Because of this difference in characteristics it was possible to consider stations 1, 2, 3, 4, and 5 as the "lower harbor" and stations 6, 7, 8, 9, and 10 or 13 as the "upper harbor".

The ratios of surface to bottom values of: (1) mean chlorides (intensive surveys), (2) overall chloride response to river discharge,

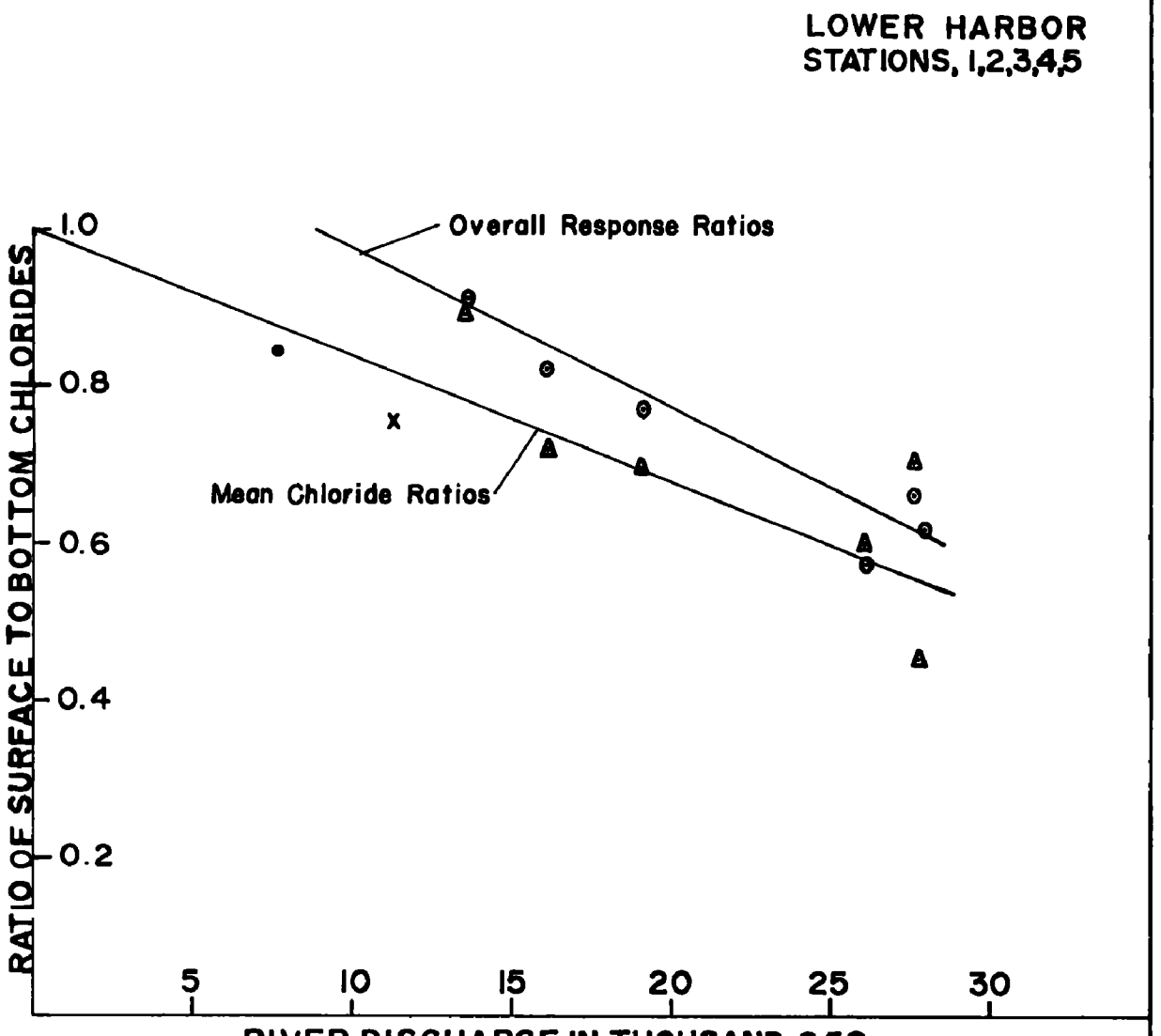
and (3) corresponding values from the slack tide and salinity profile studies are presented in Appendix Table C-5, and are pictured in Figures 13 and 14. The relationship of chloride ratios to river discharge is ambiguous because the intensive survey data, in both overall response and mean chloride ratios, suggest a curvilinear relationship intersecting a ratio of 1.0 at about 10,000 cfs. Both the slack tide and salinity profile results, however, gave observed ratios of less than 1.0 for much lower flows than occurred during the intensive surveys. Response coefficients could not be computed from these results.

Slack tide values obtained during survey E compared with the slack tide and salinity profile results showed that there was no bias in the mean to be expected from a reasonably large sampling (33 samples) of HWS and LWS conditions.

The results in Appendix Table C-5 also show that the differences between overall responses for surveys D and E were all close to the value of 0.067 calculated for the entire harbor. In the upper harbor the difference in response in the surface layer was slightly less than that in the bottom layer, suggesting that progress toward vertical homogeneity was not as far advanced as in the lower harbor.

The difference in overall response between surveys AA and AB (high river discharge) for the upper harbor and the lower harbor are strikingly diverse. In the lower harbor there was a large increase in response with an increase in tide range in both the surface and bottom layers. This indicated that mixing

RESPONSE OF CHLORIDE CONCENTRATION TO RIVER DISCHARGE



Data From Intensive Studies

⊙ Mean Ratios Of Surface To Bottom Responses Of Cl^- To River Discharge

△ Mean Ratios Of Surface To Bottom Cl^- Measurements

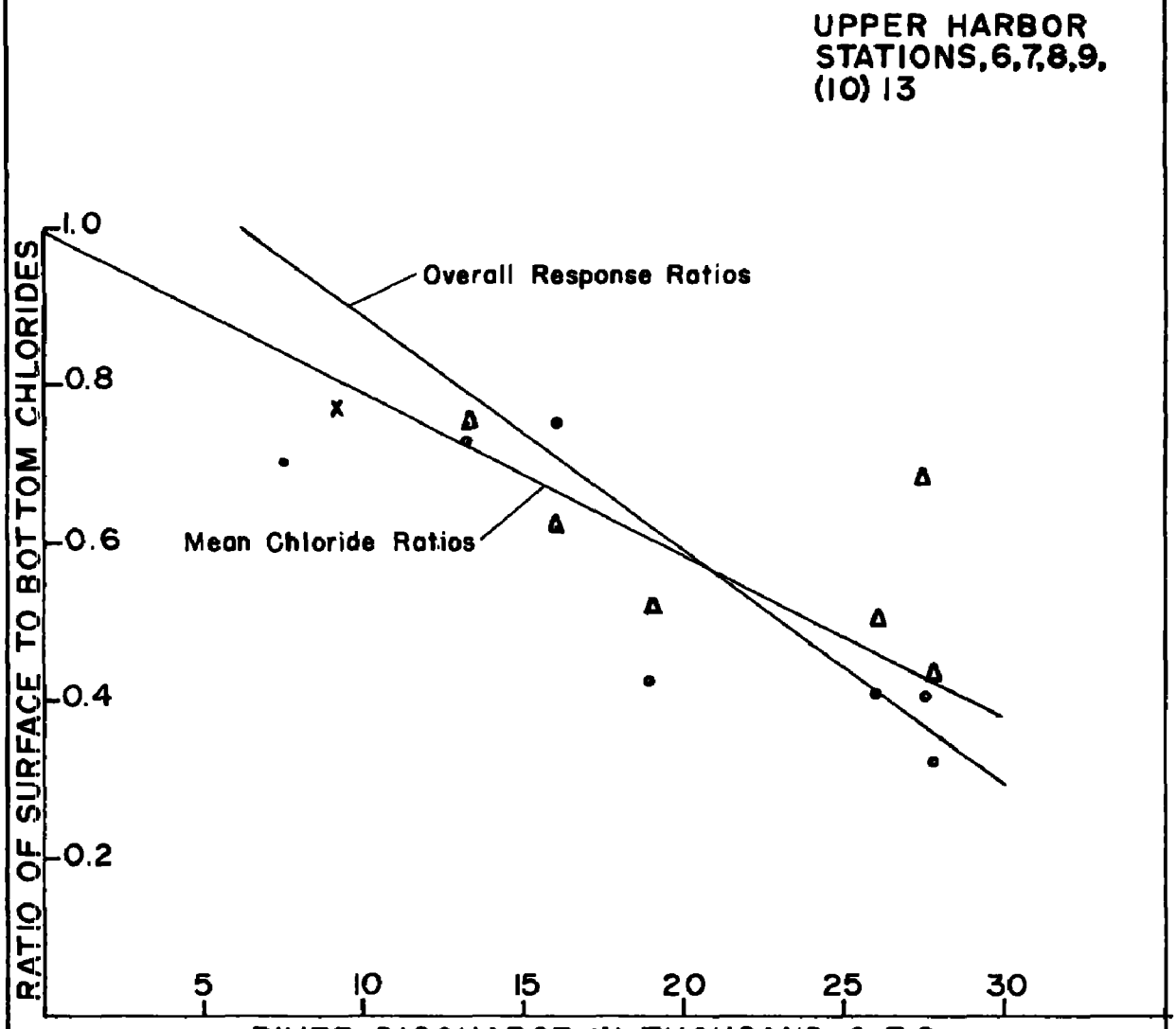
Data From Special Studies

● Ratios From Slack Tide Runs.

X Ratios From Salinity Profiles

FIGURE 13

RESPONSE OF CHLORIDE CONCENTRATION TO RIVER DISCHARGE



Data from intensive studies.

Mean ratios of surface to bottom responses of Cl^- to river discharge.

Δ Mean ratio of surface to bottom Cl^- measurements.

Data from special studies.

• Ratios from slack tide runs.

X Ratios from salinity profiles.

FIGURE 14

between the bottom layer and the surface layer increased with an increase in tidal range for this portion of the harbor. In the upper harbor this situation was reversed, i.e., a small decrease in response occurred in the surface layers and a much larger decrease occurred near the bottom.

These results show that at high discharges the characteristics of mixing and stratification were quite strongly dominated by channel geometry. At lower discharges this is not as strong a factor as demonstrated by the similarity of responses in the upper and lower harbors for surveys D and E.

The straight lines sketched in Figures 13 and 14 illustrate extreme conditions for achieving vertical homogeneity in the harbor systems in the mean of samples taken and in the overall responses. The relationships between the two lines show that each system responds as if it were unstratified at a much higher discharge than that at which vertical homogeneity occurs. In the lower harbor the surface and bottom responses should become the same by the time a discharge of about 9,000 cfs is reached, while in the upper harbor this should occur at about 6,000 cfs.

Relationships between River Discharge and Dissolved Oxygen. The change in the character of the stratification as shown in the analysis of chloride data was closely related to the changes in D.O. with river discharge. At higher flows, with the entire harbor strongly stratified, there was restricted mixing between surface and bottom layers, so that the major source of D.O. available for stabilizing wastes was from the constant input of new ocean water along the bottom of the harbor.

Natural reaeration of the surface layers was not, in this situation, a significant contribution toward waste stabilization, since the major oxygen demand in the harbor came from the sludge deposits on the bottom of the harbor.

As stratification begins to break down, however, reaerated water from the surface will be mixed downward where it can help stabilize the sludge deposits. In a vertically homogeneous system, surface reaeration may be the major source of oxygen available for stabilizing wastes.

One additional consideration related to river discharge is the effect of the fresh water inflow on flushing in the harbor. A series of dye tests was conducted in the Charleston Harbor hydraulic model to investigate this phenomenon. Although verification tests using chloride data developed from the Project's intensive surveys showed some discrepancies between model and prototype, particularly for low river discharges, the model data were by far the best means of evaluating the flushing characteristics.

Analyses of dye concentration data resulting from both instantaneous and continuous releases in the tributary rivers were made to determine the mean time of travel or the mean residence time of the dye particles in the segments between sampling stations. The method of analysis used involved the determination of the time-frequency distribution of the dye particles at each sampling station and the computation of the mean time of travel from the release point. The relation of flushing time to river discharge is shown in Table 14.

TABLE 14

ANALYSIS OF MODEL DYE STUDIES

MEAN TRAVEL AND RESIDENCE TIMES IN TIDAL CYCLES FOR GIVEN COOPER RIVER FLOW

River Mile* Station	Mean Travel Time	Mean Residence Time	Mean Travel Time	Mean Residence Time	Mean Travel Time	Mean Residence Time	Remarks
Cooper River	30,500 cfs		15,500 cfs		3500 cfs		
Upper Harbor							
Mile 37	0	0	0	0	0	0	Release Point.
		1.1		3.0		14.8	
Mile 22	1.1		3.0		14.8		Above Goose Crk.
		2.9		5.8		8.3	
Mile 14	4.0		8.8		23.1		St.8, Fig. 2
		1.4		4.1		7.9	
Lower Harbor							
Mile 10	5.4		12.9		31.0		St. 5, Fig. 2
		6.8		6.1		2.0	
Mile 4	12.2		19.0		33.0		Two miles seaward at Ft. Sumter.
Ashley River	30.500 cfs		15,500 cfs		3500 cfs		
Upper Harbor							
Mile 7	0	0	0	0	0	0	Release Point.
		2.2		2.4		4.9	
Mile 6	2.2		2.4		4.9		Hwy. 17 Bridge
		0.2		2.6		6.5	over Ashley.
Lower Harbor							
Mile 4	2.4		5.0		11.4		Btw.So.tip of Chas.
		3.6		4.6		3.2	and Jas. Isl.
Mile 2	6.0		9.6		14.6		Two miles inland from Ft. Sumter.

* Mile zero for the Cooper River at the end of the jetties (river miles follow the channel). Mile zero for Ashley River at junction of Ashley and Cooper Rivers.

At high flows the residence time between stations was short in the upper sections of both the Cooper and Ashley Rivers but long in the lower harbor.

In the problem areas of both rivers, i.e., between mile 22 and 14 on the Cooper River and between mile 6 and 4 on the Ashley River, the proposed flow reduction to 3000 cfs would more than double the mean residence time in the system. This doubling would create the potential for increasing the amount of both nutrient and oxygen-consuming materials in these reaches and would intensify the existing problems.

The relationship of D.O. to river discharge was somewhat more complex to analyze than was the chloride relationship, because D.O. disappeared from the bottom layers through biochemical utilization and was added to the surface layers through atmospheric reaeration.

The response spectra of D.O. percent saturation to river discharge exhibited behavior similar in long-period and semidiurnal (tidal) response to the chloride response spectra. The D.O. responses, however, showed a diurnal response also. This result appeared consistently in all the surveys and at most of the stations.

The cross-spectra of chlorides and D.O. percent saturation showed that there was a strong diurnal and 36-hour response of D.O. percent saturation to chlorides. These results suggest that there was a time lag between a change in chloride concentration and the approach of D.O. to equilibrium with that concentration.[1/]

1/It should be possible, with longer records and more detailed spectral analysis, to estimate reaeration coefficients for such systems.

Because of this time lag and because of the nonlinear interaction of the D.O. and river discharge, analysis of the D.O. regime was based primarily on the overall response results and the survey mean values.

Table 15 contains the overall responses of D.O. percent saturation to river discharge. The mean values of D.O. percent saturation are presented in Appendix Table B-1.

The variation in chloride structure with range of tide height has been discussed. Because of the sensitivity of D.O. concentration to chloride concentration, a corresponding effect of tide range on D.O. may be expected. Because of the non-conservative nature of D.O., it was not possible to analyze the effect of tide range on D.O. as directly and simply as was done for chlorides. Several simplifying assumptions were made:

(1) The overall response of D.O. to chloride was used with the previously estimated effects of tide range on chloride and the response of D.O. to river discharge to obtain a response factor of D.O. to river discharge per foot of tide range for each of the surveys. With this response factor the mean D.O. percent saturation for each survey was corrected to the mean tide range of 4.61 feet. These calculations are summarized in Table 16. The mean D.O. values corrected to mean tide range were assumed valid and were used for all further calculations of the effect of river discharge on D.O.

(2) As the turbulent structure of the system changed with changes in the current, a corresponding change in surface reaeration

TABLE 15

OVERALL RESPONSE OF DISSOLVED OXYGEN PERCENT SATURATION TO RIVER DISCHARGE

Station	Survey AA	AB	B	C	D	E
1S	.003763	.001731	.001515	.001344	.000470	.001099
1B	.002017	.002338	.000724	.000816	.000447	.001225
2S	.003339	.002707	.000762	.001084	.000362	.000942
2B	.001874	.001625	.000917	.000507	.000231	.000744
3S	.002823	.002028	.000758	.001065	.000366	.000807
3B	.001233	.003698	.000811	.000626	.000223	.000515
4S	.002589	.002161	.001082	.000983	.000240	.001012
4B	.002293	.002357	.001048	.000416	.000500	.001057
5S	.002292	.001924	.001347	.000842	.000431	.000986
5B	.003237	.001746	.000968	.001065	.000259	.000955
6S	.001326	.001543	.000926	.000651	.000426	.000645
6B	.001538	.002316	.000966	.000572	.000169	.000875
7S	.001937	.001671	.000942	.001052	.000580	.001035
7B	.002036	.003614	.000765	.000361	.000331	.000918
8S	.000942	.001813	.000988	.000760	.000384	.000642
8B	.002713	.002863	.000538	.000602	.000311	.000796
9S	.001208	.002101	.000778	.000846	.000591	.000835
9B	.000876	.002313	.000799	.000888	.000182	.000781
13S			.000784	.000588	.000290	.000475
13B			.000799	.000841	.000278	.000633
10S	.015973	.007471				
10B	.007228	.004641				
Mean (1-9) S	.002246	.001964	.001011	.000959	.000427	.000889
B	.001979	.002541	.000837	.000650	.000294	.000874
Mean (1-9) S & B	.002112	.002252			.000360	.000881
Ratio S/B (1-9)	1.134620	.773020			1.452830	1.016900

Ratio (1-9) $\frac{AA}{AB}$ $\frac{.038036}{.040549} = .938002$ $\frac{E}{D} = \frac{.015889}{.006503} = 2.44446$

TABLE 16

ANALYSIS OF D.O. RESPONSE TO RIVER DISCHARGE

AND CORRECTION FOR TIDE RANGE [1]

Survey	Stations	Response [2] Ft. Tide Range-cfs	Response Ft. Tide Range	Tide Range Correction	Corrected D.O. %Sat.	Mean Flow cfs
AA	Lower harbor	0.000488	0.135	-0.082	80.3	27,600
AB	1 thru 5 surface	0.000547	0.152	+0.081	96.0	27,700
B	and bottom	0.000243	0.064	+0.033	77.9	26,300
C		0.000213	0.041	+0.021	73.9	19,300
D		0.000080	0.013	+0.002	67.5	16,200
E		0.000162	0.022	-0.025	65.0	13,500
AA	Upper harbor	0.000685	0.189	-0.115	70.8	27,600
AB	6 thru 13 surface	0.000744	0.206	+0.109	96.0	27,700
B	and bottom	0.000203	0.053	+0.028	72.3	26,300
C		0.000174	0.034	+0.017	66.7	19,300
D		0.000080	0.013	+0.002	60.7	16,200
E		0.000133	0.018	-0.021	56.8	13,500

1/ Method of computing tide range correction: Take mean overall response of dissolved oxygen to river discharge for stations in area of concern and divide by mean tide range. This gives answer in % Sat./Ft. Tide Range-CFS. Multiply this value by mean river discharge giving % Sat./ Ft. Tide Range. Then multiply this value by the difference between the mean tide range and the observed tide range. This yields a % Sat. correction value for tide range.

2/ mg/l of D.O./cfs of river discharge.

characteristics would be expected. At all but very high river flows in this system, however, the current regime was dominated by tidal flow rather than river flow. Therefore, in relation to river discharge, surface reaeration, was constant or, at most, varied only slowly with changes in river discharge.

(3) Since the Cooper River was a clean stream, and was thoroughly aerated in its journey from Lake Moultrie to the harbor, high D.O. values in the incoming river water were assumed to exist upstream from the first significant pollution. (Values between 79 and 90 percent of saturation were obtained from field studies). Under isothermal conditions, then, the amount of D.O. advected into the system by the river was directly proportional to the river discharge, and the change in D.O. at harbor stations was dependent on the difference between D.O. in the river water and in the harbor itself.

(4) The strength and volume of the oceanic inflow along the bottom of the estuary was directly dependent upon the volume of the river discharge as well as on the geometry of the system; consequently, the amount of oxygen advected into the system in the oceanic inflow also depended directly on the volume of river flow. Since the volume of ocean inflow changed as a multiple of the river flow, the oxygen advected through this mechanism was assumed to obey some type of power law.

A mechanistic rationale of this type is necessary to postulate a form of empirical equation which can be used with the limited data available to correlate observations over the observed flow ranges and also to provide a reasonable basis for extrapolation to the low flow ranges.

The equation postulated for the Charleston Harbor system is

$$\ln \frac{1}{1-.01P} = KO^n + C, \qquad (1)$$

where

P = Percent saturation of dissolved oxygen,

O = River discharge in cfs

K, n, C are empirical constants

This equation contains a constant term plus a term which is a power function of the river discharge, and is consistent with the mechanism described. In the limits, the D.O. will approach 100 percent saturation at very high river discharges, and decreases to a low value at no river discharge.

The constants in this equation were evaluated from means of the intensive survey data.

The D.O. data from surveys B, C, D, and E were averaged for the upper harbor and for the lower harbor; and the averages were used to determine the constants in equation (1) separately for the upper harbor and lower harbor. As shown in Appendix Table B-2, the mean temperature for these four surveys ranged from 25 to 29° C, while the temperatures for surveys AA and AB were near 10 and 14° C, respectively. Because of this large discontinuity in temperature, which was only partially accounted for by the use of D.O. percent saturation, and because the mean river discharges during surveys AA and AB were only 5 percent greater than that during survey B, surveys AA and AB were not used in this analysis of D.O. percent saturation.

The equations developed from the analysis of the response of D.O. to river discharge in a vertically stratified estuary with the constants evaluated for Charleston Harbor from the intensive survey data are these:

upper harbor

$$\ln \frac{1}{1-0.01P} = (4.08 \times 10^{-5})Q^{0.985} + 0.363 \qquad (2)$$

lower harbor

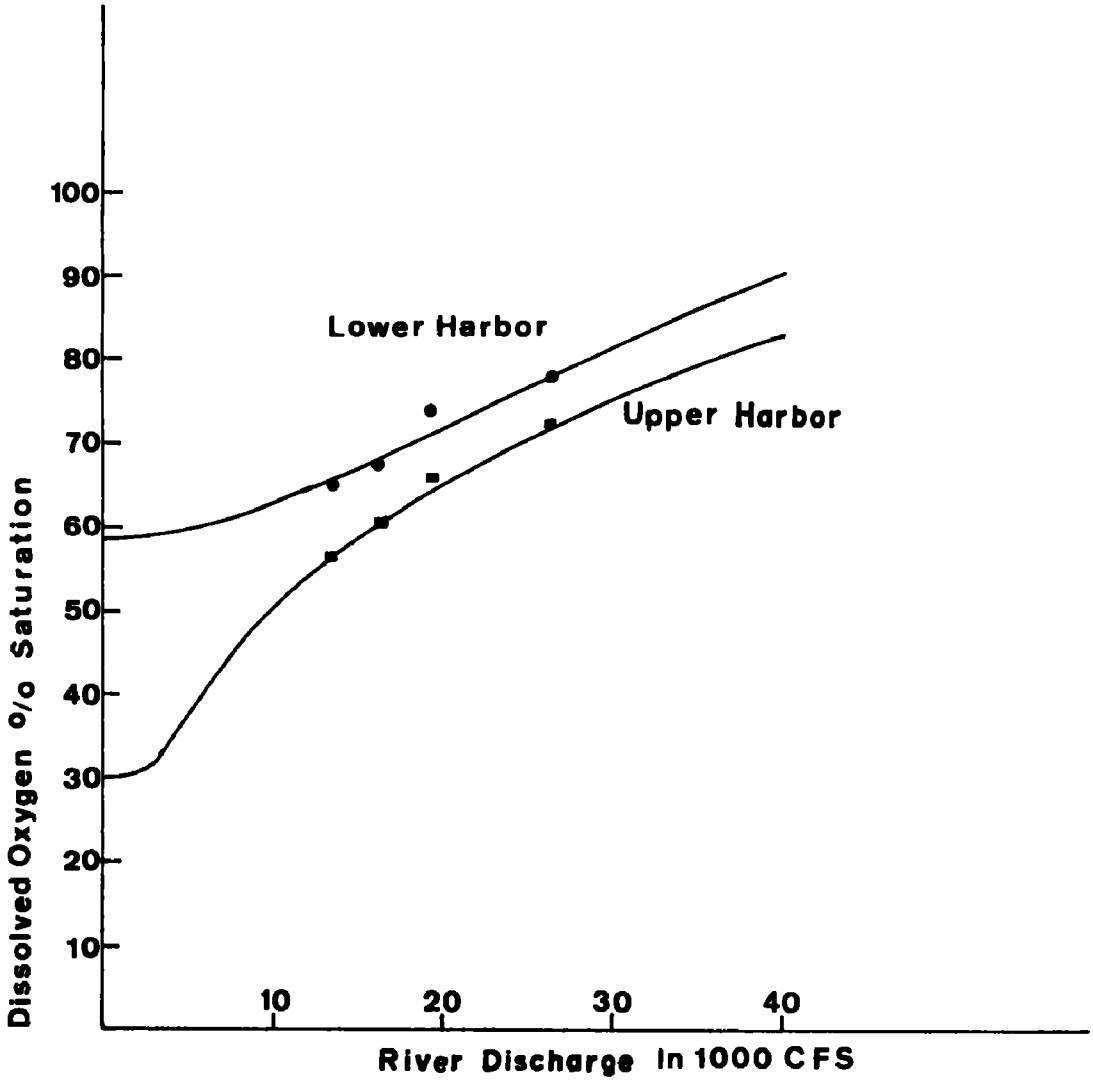
$$\ln \frac{1}{1-0.01P} = (1.87 \times 10^{-9})Q^{1.93} + 0.875 \qquad (3)$$

These equations produce the lines sketched in Figure 15, which show the existing relationship of D.O. percent saturation to river discharge in the Charleston Harbor system. Each plotted point shown represents the mean for either upper or lower harbor for a particular intensive survey.

Figure 15 is a plot of equations 2 and 3 and illustrates a probable relationship between dissolved oxygen in the harbor and river discharge. This figure may be interpreted as follows:

(1) In both the upper and lower harbor, some D.O. would be present even with no river flow. The five stations in the upper harbor would have an average of about 30 percent of saturation, while in the lower harbor the average would be nearly 60 percent of saturation with no river inflow. These results represent the effect of reaeration in adding dissolved oxygen to the harbor. It is assumed that D.O. addition caused by tidal action alone would be small with no river inflow; i.e., little mixing with tidal surges would occur.

RESPONSE OF DISSOLVED OXYGEN PERCENT SATURATION TO RIVER DISCHARGE



Lines fitted from mathematical model (Not from observed data)

● Mean of DO data from lower harbor.

■ Mean of DO data from upper harbor.

FIGURE 15

(2) At low river flows, D.O. in the upper harbor would respond much more rapidly to changes in river discharge than would D.O. in the lower harbor. This reflects the advection of D.O. from the unpolluted part of the Cooper River into the polluted areas. The change in slope of the curves suggests the development of a vertically stratified system with increasing river discharge. Above about 20,000 cfs both the upper and lower harbors have the same type and degree of stratification. Between 10,000 and 20,000 cfs the stratification begins to alter; in the lower harbor there is a gradual change to a vertically mixed system, while in the upper harbor the D.O. regime passes through a zone in which advective D.O. input from the river discharge alone continues to be significant even though advection of D.O. from the ocean decreases rapidly with the breakup of stratification in the lower harbor. At river discharges less than 5000 cfs, the processes of surface reaeration would provide the major source of oxygen to the entire harbor.

(3) Reasoning from the assumption that D. O. in the harbor is primarily replenished by oceanic inflow under stratified conditions, the following observations are made. The difference in the exponents on Q (the river discharge) in the upper and lower harbors (0.985 and 1.93, respectively) gives a qualitative idea of how greatly the river discharge might affect the inflow of water from the ocean along the bottom of the estuary. Since Q itself appears as an exponent in equation (2), the oceanic inflow, particularly in the lower harbor, would increase at a high rate relative to increasing river discharge.

PREDICTION OF FUTURE WATER QUALITY

Estimates of future water quality are based on the following assumptions:

(1) Fresh water discharge from the Cooper River into Charleston Harbor will be reduced to 3000 cfs.

(2) The quality of the inflowing fresh water will be about the same as it is now.

(3) Industrial waste loadings will be about the same as at present in both quantity and character.

(4) All major sources of human waste will receive at least primary treatment with chlorination of the effluent.

Within a period of five years all of the political entities discharging municipal wastes to Charleston Harbor will be legally required to provide primary treatment of their wastes. The bulk of the sewage presently entering the lower part of the harbor is from the City of Charleston. This untreated municipal waste causes high coliform concentrations and the formation of sludge beds around the Battery and Shute's Folly Island, in Town Creek and down to the Battery, and in the lower part of the Ashley River.

There are five major areas of concern when considering the effect of a reduction in river discharge on water quality in Charleston Harbor:

(1) Coliform organism concentrations.

(2) The stabilization of sludge beds , and their future extent.

(3) The quantity and distribution of toxic materials in the system.

(4) The potential for nutrient buildup near the sewage outfalls, particularly in harbor coves and beaches.

(5) The quantity and distribution of D.O. in the system.

COLIFORM CONCENTRATIONS

Primary treatment and chlorination of about 80 percent of the total amount of the domestic sewage entering Charleston Harbor will result in total coliform counts of less than 1000 organisms per 100 ml over most of the harbor. This is the upper limit for swimming and other water contact sports set by the South Carolina State Health Department. This estimate is based on observed coliform counts made during the intensive survey program and on an increased dieoff rate for coliform organisms in the presence of the more saline conditions existing over much of the harbor at reduced river discharges.

Small amounts of untreated sewage entering the harbor from storm drains will create some localized areas of moderate[1/] coliform concentrations. These areas will be close to shore and may occur from the Battery up the eastern side of the Charleston peninsula as far as Goose Creek. There may also be some localized areas along the Ashley River. A thorough implementation of connections to the sewage interceptor system should keep such areas at a minimum.

1/"Moderate" is defined here as total coliform counts averaging more than 1000 organisms per 100 ml with counts frequently above 30,000 organisms per 100 ml.

SLUDGE BEDS

Over a period of several years the existing sludge beds formed by the present untreated municipal waste discharges will disappear as the organic material is stabilized, i.e., if adequate waste treatment is provided, and no new settleable organic material is added to the harbor.

After the construction of municipal sewage treatment facilities, industrial wastes will be the primary sources of sludge beds in Charleston harbor. Future sludge deposits will be closer to their parent outfalls. There will be very few and small sludge banks in the lower harbor. The Ashley River will contain sludge beds from the Virginia-Carolina Chemical Plant to the railroad bridge several miles downstream. These beds will cause some oxygen depletion in reaches of the Ashley River, but the large volumes of estuary water in comparison with the quantities of present industrial waste discharge suggest that this depletion will not be a severe drain on the oxygen resources of the Ashley system. By contrast, the Cooper River below the West Virginia Pulp and Paper Company will have extremely active sludge beds and there will be some sludge present down as far as the Grace Memorial Bridge.

TOXIC MATERIALS

Toxic materials contained in the industrial waste effluents discharged into the Ashley River may be extremely damaging to the biota under reduced flow conditions. There has been a steady decline in fish populations in the Ashley River near the industrial

waste outfalls over the past several years. Reduced flow conditions would result in an increase in the amount of time necessary to remove waste materials from the area. An increase in toxicity of the aquatic environment will develop unless proper industrial pollution control practices are initiated.

NUTRIENT BUILDUP

Nutrient buildup, if it occurs, will be caused primarily by municipal waste discharges in the Ashley and Wando Rivers, both of which have little fresh water flow. These rivers will be unstratified with reduced flows in the Cooper River; and unless outfalls are well located, i.e., in harbor areas characterized by thorough mixing and flush-out qualities, tidal action will cause a gradual dispersion of effluents throughout both the Ashley and Wando systems. The potential does exist for a nutrient buildup which could result in nuisance growths of algae, but the extent to which such nuisance growths could develop cannot be quantitatively evaluated with present information.

DISSOLVED OXYGEN

The analysis of the dissolved oxygen distribution that would exist in the harbor after rediversion has been developed from a quasi-empirical mathematical model of the D.O. system as related to river discharge. It has been shown that under existing waste load conditions the degree of saturation of harbor water with dissolved oxygen was extremely sensitive to the Cooper River inflow, especially in areas represented by the upper harbor sampling stations. The lower harbor stations reflected a similar sensitivity to river discharge but to a lesser degree.

The results of the analyses of the D.O. mathematical model combined with those of the hydraulic model studies and the known changes that will occur in municipal waste disposal practices suggest the following future D.O. patterns in the harbor. In the lower harbor, the rediversion of the Cooper River will cause an initial reduction in mean dissolved oxygen levels. These levels will gradually be increased after municipalities contiguous to the harbor install sewage treatment plants and existing sludge deposits are oxidized or stabilized.

In the upper harbor, the situation will be considerably different. The reduction of inflow will result in a rather large decrease in the mean dissolved oxygen percent saturation. The organic materials discharged into this area will remain there for longer periods of time which will result in a much greater oxygen consumption. The major waste discharges in the upper harbor area are of industrial origin, and industries are not presently subject to the same regulatory laws as the municipalities. It can be expected then, that large volumes of untreated industrial wastes will result in the depletion of the oxygen resources in some areas of the upper harbor to the point where periods of septicity will occur, especially during the late summer. Even if industrial waste treatment were to become mandatory, an immediate improvement would not be noticeable. The existing sludge deposits contain enough organic materials to cause rather severe D.O. depletion. A satisfactory future water quality condition can be obtained by removal of the existing sludge beds and elimination of all untreated waste discharges.

BIBLIOGRAPHY

1. Ashley River Pollution Study, Summary Report, Southeast Water Laboratory: Athens, Georgia; August, 1965.

2. Bain, R. C., Jr. and McCarty, J. C., Nutrient-Productivity Studies in San Francisco Bay. Central Pacific Basins Water Pollution Control Project Report No. 65 - 1 U.S.P.H.S. San Francisco, California, July, 1965.

3. Boyce, W. E. and DiPrima, R. C., Elementary Differential Equatics and Boundary Value Problems. Wiley, New York, N.Y., 1965.

4. Chapin, W. C. and Steiner, L. E., Second Year College Chemistry. Wiley, New York, N.Y., 1943.

5. Chemical Analytical Procedures (A Report), Raritan Bay Project.

6. Churchman, C. W., Ackoff, R. L., and Arnoff, E. L., Introduction to Operations Research. Wiley, New York, N.Y., 1966.

7. Collected Reprints, Volume 6. Collected Reprints, 1958 - 1961, Volume V. Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Md. February, 1963 (V); 1965 (VI).

8. Contamination Dispersion in Estuaries, Delaware River Hydraulic Model Investigation. U.S. Army Corps of Engineers, Waterways Exp. Station, Misc. Paper No. 2 - 332, Report I, Vicksburg, Mississippi, April, 1959.

9. Course Manual, Chemical Analyses for Water Quality, Water Supply and Pollution Control Training. Robt. A. Taft San. Engineering Center, Cincinnati, Ohio; December, 1961.

10. Effects of Polluting Discharges on the Thames Estuary; Water Pollution Research Technical Paper No. 11; Department of Scientific and Industrial Research; Her Majesty's Stationery Office, London, England, 1964.

11. Eldridge, E. F., Industrial Waste Treatment Practice. McGraw-Hill, New York, N.Y., 1942.

12. Fair, G. M.; Moore, E. W., and Thomas, H. A., Jr.; The Natural Purification of River Muds and Pollutional Sediments. Journal of San. Eng. Div., Amer. Soc. of Civ. Eng.; Vol. 13, No. 2: 270-307. March, 1941; Vol. 13, No. 4: 756-779, July, 1941; Vol. 13, No. 6: 1209-1228, Nov., 1941.

13. Fair, G. M. and Geyer, J. C., Water Supply and Waste-Water Disposal. Wiley, New York, N.Y., 1959.

14. Feigl, F., Spot Tests in Inorganic Analysis. Elsevier, Amsterdam, The Netherlands, 1958.

15. Gunnerson, C. G., Optimizing Sampling Intervals in Tidal Estuaries. Journal of the San. Eng. Div., Amer. Soc. of Civil Eng., Vol. 92, No. SA-2, April, 1966.

16. Harleman, D. R. F., Jordaan, J. M., Jr., and Lin, J. D., The Diffusion of Two Fluids of Different Density in a Homogeneous Turbulent Field. M.I.T. Hydrodynamics Lab, Tech. Report No. 31 February, 1959.

17. Report on Sewage Treatment for Charleston, South Carolina, Hazen & Sawyer, and Louis Y. Dawson, Inc., May, 1965.

18. Hoelscher, R. P.; Arnold, J. N.; Pierce, S. H., Graphic Aids in Engineering Computation. McGraw-Hill, New York, N.Y., 1952.

19. An Investigation of the Pollution into Charleston Harbor. Dept. of Civ. Eng., The Citadel, Charleston, S.C., December, 1965.

20. Jenkins, D., A Study of Methods Suitable for the Analysis and Preservation of Nitrogen Forms in an Estuarine Environment. Sanitary Engineering Research Laboratory, SERL Report No. 65-13. Univ. of Calif., August, 1965.

21. Klein, L., River Pollution: I. Chemical Analysis, River Pollution: II. Causes and Effects. Butterworth's, London, England. I., 1959, II., 1962.

22. Kleinberg, J.; Argersinger, W. J., Jr.; Griswold, E., Inorganic Chemistry. Heath, Boston, Mass.; 1960.

23. Kolthoff, I. M. and Sandell, E. B., Testbook of Quantitative Inorganic Analysis. MacMillan, New York, N.Y., 1964.

24. Krone, R. B., Methods for Tracing Estuarial Sediment Transport Processes; Hydraulic Eng. Lab and San. Eng. Research Lab., Univ. of Calif., Berkeley, Calif., Oct. 1960.

25. Lee, T. S. and Sillen, L. G., Chemical Equilibrium in Analytical Chemistry. Interscience; New York, N.Y., 1959.

26. Manual on Industrial Water and Industrial Waste Water. ASTM Special Tech. No. 148-f, ASTM, Philadelphia, Pa., 1963.

27. Murray, R. W. and Reilley, C. N., Electroanalytical Principles, Interscience; New York, N.Y., 1963.

28. Neiheisel, J., Source of Materials and Cause of Sediment Deposition in Charleston Harbor. U.S. Army Engineer Division Laboratory, South Atlantic,; July, 1965.

29. O'Connor, D. J., Estuarine Distribution of Nonconservative Substances. Journal of San. Eng. Div., Amer. Soc. of Civil Eng.; Vol. 91, No. SA-1:23-42. February, 1965.

30. O'Connell, R. L. and Walter, C. M., A Study of Dispersion in Hilo Bay, Hawaii. TA & I, Div. Water Supply and Pollution Control, Public Health Service, September, 1963.

31. O'Connell, R. L. and Walter, C. M., Hydraulic Model Tests of Estuarial Waste Dispersion. Journal of the San. Eng. Div., Amer. Soc. of Civil Eng., SA-1, January, 1963.

32. Oxygen Relationships in Streams (A Seminar). Tech. Report W58-2. Robt. A. Taft San. Eng. Center, Public Health Service, Cincinnati, Ohio, 1958.

33. Pearson, E. A. (Ed.), Waste Disposal in the Marine Environment. Pergamon Press, New York, N.Y., 1960.

34. Perlis, S., Theory of Matrices. Addison-Wesley, Reading, Mass., 1958.

35. Pickard, G. L., Descriptive Physical Oceanography. Pergamon Press, New York, N.Y., 1963.

36. The Port of Charleston, S.C., Part 2, Part Series No. 13., The Bd. of Eng. for Rivers and Harbors, Corps of Engineers, U.S. Army. U.S. Gov't. Printing Office, Washington, D.C., 1961.

37. Report upon the Extent, Effects and Limitations of Waste Disposal into San Diego Bay. San Diego Regional Water Pollution Control Board, 1952.

38. Simmons, H. B., Some Effects of Upland Discharge on Estuarine Hydraulics. Proceedings, Amer. Soc. of Civ. Eng., Vol. 81, Paper No. 792, Sept., 1955.

39. Smart, W. M., Combination of Observations. Cambridge Univ., Press, 1958.

40. Snell, F. D. and Snell, C. T., Colorimetric Methods of Analysis. Van Nostrand, Princeton, N.J.; 1953.

41. Southgate, B. A. and Preddy, W. S., Discharge of Sewage and Industrial Wastes to Estuaries. Journal of the Royal Sanitary Institute, Reprint No. 216, April, 1952.

42. Southgate, B. A., Treatment and Disposal of Industrial Waste Waters. His Majesty's Stationery Office, London, England, 1948.

43. Standard Methods for the Examination of Water and Wastewater Including Bottom Sediments and Sludges. Amer. Pub. Health Assoc., Inc., New York, N.Y., Sept., 1960.

44. Standard Methods for the Examination of Water, Sewage and Industrial Wastes. Amer. Pub. Health Assoc., Inc., New York, N.Y., 1955.

45. Strickland, J. D. H. and Parsons, T. R., A Manual of Sea Water Analysis. Fisheries Research Board of Canada, Bull. No. 125, Ottawa, 1965.

46. Stock, J. T., Amperometric Titrations. Interscience, New York, N.Y.; 1965.

47. Tarzwell, C. M. (Ed.), Biological Problems in Water Pollution (3rd Seminar, 1962). Robt. A. Taft Sanitary Eng. Center, Public Health Service, Cincinnati, Ohio, 1965.

48. Tracer Studies and Pollutional Analyses of Estuaries. State Water Pollution Control Board, Sacramento, Calif., Publication No. 23, 1961.

49. Training Course Manual, Recent Developments in Water Microbiology. Robt. A. Taft San. Eng. Center, Cincinnati, Ohio, 1964.

50. Trewartha, G. T., An Introduction to Climate. McGraw-Hill, New York, N.Y., 1954.

51. Tully, J. P., Oceanography and Prediction of Pulp Mill Pollution in Alberni Inlet. Fisheries Research Board of Canada, Bulletin No. LXXXIII; Ottawa, 1949.

52. Von Arx, W. S., Introduction to Physical Oceanography. Addison Wesley, Reading, Mass., 1962.

53. Wastler, T. A., Application of Spectral Analysis to Stream and Estuary Field Surveys, I. Individual Power Spectra. Robt. A. Taft San. Eng. Center, Public Health Service, Cincinnati, Ohio, Nov., 1963.

54. Wiegel, R. L., Oceanographical Engineering. Prentice-Hall, Englewood Cliffs, N. J., 1964.

55. Young, J. C. and Clark, J. W., Second Order Equation for BOD, Journal of San. Eng. Div., Amer. Soc. of Civil Eng.; Vol. 91, No. SA-1; 43-57, February, 1965.

APPENDIX A

SUMMARY OF ROUTINE SURVEY DATA

TABLE A-1

SUMMARY OF ROUTINE MONITORING

Station	Quality Parameters											
	Total Coliform				Fecal Coliform				Dissolved Oxygen-mg/l			
	Max. Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date
1S	46,000	10/27/64	520	9/24/64	4,300	10/13/64	40	1/28/65	9.60	1/25/65	4.40	8/23/65
1B	7,200	9/30/64	90	2/01/65	1,800	9/29/64	5	3/01/65	9.50	2/11/65	4.32	8/05/65
2S	46,000	10/27/64	500	12/07/64	5,200	5/27/65	40	12/07/64	9.60	1/25/65	4.39	8/23/65
2B	20,200	6/10/65	400	9/09/65	5,000	9/30/64	20	1/28/65	9.20	2/08/65	3.95	8/10/65
3S	52,000	7/29/65	660	6/03/65	6,200	8/12/65	50	1/28/65	9.70	2/04/65	3.73	8/05/65
3B	30,000	9/16/65	1,000	9/09/65	3,000	5/27/65	90	12/03/64	9.52	2/04/65	3.79	8/23/65
4S	86,000	10/13/64	600	2/01/65	7,140	7/29/65	80	2/01/65	9.65	1/28/65	3.23	8/26/65
4B	15,000	4/29/65	440	3/01/65	4,300	10/28/64	11	8/30/65	9.23	2/08/65	3.60	8/26/65
5S	30,000	10/28/64	300	10/06/64	2,200	9/02/65	30	2/01/65	9.50	2/08/65	4.35	8/23/65
5B	12,800	10/29/64	360	9/09/65	1,120	7/29/65	20	2/01/65	9.10	2/08/65	4.05	8/23/65
6S	68,000	10/14/64	440	9/02/65	14,400	9/02/65	70	9/24/64	9.95	2/08/65	2.67	8/26/65
6B	76,000	10/29/64	940	12/08/64	5,000	9/29/64	70	12/08/64	9.40	2/08/65	3.15	8/26/65
7S	91,000	10/14/64	1,000	9/16/65	6,400	6/03/65	140	2/15/65	9.55	2/08/65	3.98	6/10/65
7B	12,200	10/01/64	160	8/05/65	1,400	8/03/65	46	1/28/65	9.85	1/25/65	3.85	8/10/65
8S	40,500	4/29/65	1,200	7/08/65	7,100	4/29/65	180	2/08/65	10.75	2/01/65	3.10	8/26/65
8B	35,000	10/14/64	1,400	3/01/65	7,150	4/29/65	60	3/01/65	9.20	2/08/65	2.99	8/26/65
9S	18,000	9/02/65	40	8/09/65	2,900	9/16/65	11	8/23/65	9.75	2/08/65	3.56	8/26/65
9B	14,800	2/18/65	370	8/09/65	1,500	4/29/65	28	8/23/65	9.60	2/08/65	3.23	8/26/65
10S	47,000*	9/02/65	220	10/01/64	5,700*	9/02/65	50*	7/15/65	10.46	1/28/65	2.82*	8/26/65
10B	32,500*	7/15/65	620	1/28/65	4,630*	9/02/65	50	1/28/65	10.30	2/04/65	2.61	8/26/65

* Station 13, which replaced Station 10 during 5-65

TABLE A-1 - cont'd

Station	Quality Parameters											
	5 Day B.O.D.				Chloride in mg/l				pH			
	Max Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date
1S	7.0	9/24/64	0.5	9/02/65	17,300	10/08/64	4,200	10/27/64	8.6	2/8/65	6.7	10/21/64
1B	6.6	9/24/64	0.2	9/02/65	18,900	12/08/64	9,950	8/09/65	8.6	2/8/65	7.1	9/30/64
2S	7.2	9/24/64	0.6	1/28/65	16,150	4/29/65	2,700	10/27/64	8.5	2/4/65	7.0	2/18/65
2B	2.7	9/24/64	0.4	2/15/65	18,000	12/08/64	7,400	2/08/65	8.3	2/4/65	7.1	2/15/65
3S	7.1	9/30/64	0.6	12/03/64	12,300	8/26/65	2,300	8/05/65	8.5	2/4/65	6.5	10/29/64
3B	3.4	9/24/64	0.2	12/02/64	17,950	4/29/65	3,700	2/18/65	8.4	2/4/65	7.2	9/29/64
4S	3.5	10/28/64	0.2	12/03/64	13,700	9/23/64	3,100	10/28/64	8.3	2/4/65	7.0	8/26/65
4B	2.3	9/24/64	0.1	9/02/65	17,250	8/30/65	6,500	10/27/64	8.5	2/4/65	7.0	8/26/65
5S	3.0	10/28/64	0.5	12/03/64	18,000	7/15/65	3,400	10/28/64	8.4	2/4/65	7.3	2/26/65
5B	3.2	9/23/64	0.3	12/03/64	16,600	9/23/64	4,100	8/09/65	8.5	2/4/65	7.1	10/14/64
6S	4.2	9/28/64	0.6	6/10/65	15,500	5/20/65	2,050	8/05/65	8.6	2/4/65	7.0	8/26/65
6B	4.7	9/28/64	0.3	12/03/64	15,150	8/30/65	2,500	10/13/64	8.4	2/4/65	7.0	8/26/65
7S	3.1	10/28/64	0.3	12/03/64	12,200	9/09/65	3,200	10/27/64	8.3	2/4/65	7.1	8/26/65
7B	4.2	10/14/64	0.2	12/03/64	15,700	12/08/64	5,500	10/29/64	8.4	2/4/65	7.1	2/18/65
8S	2.8	10/28/64	0.4	9/02/65	8,200	9/23/64	800	10/27/64	8.5	2/4/65	6.9	8/26/65
8B	7.2	9/24/64	0.2	9/02/65	13,300	12/03/64	2,100	10/28/64	8.3	2/4/65	7.0	8/26/65
9S	5.2	10/01/64	0.5	12/03/64	8,600	8/26/65	2,200	2/18/65	8.4	2/4/65	7.0	10/21/64
9B	5.0	10/01/64	0.3	9/02/65	11,800	9/09/65	4,050	10/27/64	8.4	2/4/65	7.0	8/26/65
10S	82.2	10/28/64	0.6*	9/02/65	6,000*	9/09/65	15	2/18/65	9.0	2/4/65	6.4	9/24/64
10B	>15.0	10/13/64	0.2	10/28/64	9,700*	6/15/65	19	10/27/64	8.9	2/4/65	6.4	9/24/64

* Station 13, which replaced Station 10 during 5-65

TABLE A-1 - cont'd

Station	Quality Parameters											
	Ammonia-N				Nitrate-N				Total Phosphate			
	Max. Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date	Max. Value	Date	Min. Value	Date
1S	0.7	2/1/65	0.3	2/18/65	0.1	2/08/65	<0.1	2/11/65	0.23	9/28/64	<0.1	1/28/65
1B	0.9	2/8/65	0.4	2/18/65	0.1	2/08/65	<0.1	2/11/65	0.35	2/08/65	0.02	1/28/65
2S	0.6	2/1/65	0.3	2/11/65	0.1	2/08/65	<0.1	2/11/65	0.29	9/30/64	0.02	1/28/65
2B	0.8	2/8/65	0.3	2/18/65	0.1	2/04/65	<0.1	2/15/65	0.54	2/04/65	0.02	1/28/65
3S	0.8	2/8/65	0.2	2/04/65	0.2	2/18/65	<0.1	2/01/65	1.11	2/08/65	0.04	1/28/65
3B	0.7	2/8/65	0.3	2/18/65	0.2	2/18/65	<0.1	2/01/65	1.03	2/08/65	0.05	1/28/65
4S	0.5	2/4/65	0.4	2/18/65	0.1	2/08/65	<0.1	2/15/65	0.17	2/08/65	0.02	1/28/65
4B	0.6	2/4/65	0.4	2/15/65	0.1	2/08/65	<0.1	2/15/65	0.34	2/08/65	0.03	1/28/65
5S	0.6	2/1/65	0.3	2/11/65	0.1	2/08/65	<0.1	2/11/65	0.17	9/29/65	0.02	12/07/64
5B	0.7	2/1/65	0.4	2/15/65	0.1	2/08/65	<0.1	2/11/65	0.25	2/08/65	0.02	12/07/64
6S	0.5	2/4/65	0.2	2/01/65	0.2	2/11/65	0.1	2/15/65	0.19	2/08/65	0.05	1/28/65
6B	0.7	2/4/65	0.3	3/01/65	0.1	2/15/65	<0.1	2/11/65	0.23	2/08/65	0.04	12/07/64
7S	0.7	2/8/65	0.2	2/11/65	0.1	2/08/65	<0.1	2/15/65	0.21	9/28/64	0.02	12/07/64
7B	0.9	2/8/65	0.3	2/11/65	0.1	2/08/65	<0.1	2/11/65	0.24	2/08/65	0.04	1/28/65
8S	0.6	2/4/65	0.3	2/11/65	0.2	2/11/65	0.1	2/04/65	0.19	1/25/65	0.03	1/28/65
8B	0.7	2/1/65	0.2	2/11/65	0.2	2/04/65	<0.1	2/15/65	0.28	2/04/65	0.02	2/15/65
9S	0.6	2/8/65	0.4	2/15/65	0.2	2/18/65	<0.1	2/11/65	0.18	2/08/65	0.04	2/04/65
9B	0.6	2/1/65	0.4	2/18/65	0.2	2/08/65	<0.1	2/15/65	0.57	2/18/65	0.04	2/04/65
10S	0.6	2/18/65	0.4	2/11/65	0.1	2/15/65	<0.1	2/11/65	0.35	9/29/64	0.02	12/02/64
10B	0.9	3/1/65	0.4	2/15/65	0.1	2/11/65	<0.1	3/01/65	0.23	2/15/65	0.02	1/28/65

TABLE A-1 - cont'd

Station	Quality Parameter: Water Temperature °C — Max. Value	Date	Min. Value	Date
1S	29.5	5/20/65	9.4	2/4/65
1B	29.0	8/23/65	9.2	2/1/65
2S	29.1	8/23/65	9.0	2/4/65
2B	29.1	8/23/65	9.4	1/25/65
3S	28.8	8/23/65	9.1	2/4/65
3B	30.0	8/23/65	8.5	2/1/65
4S	29.6	8/26/65	9.2	2/4/65
4B	29.2	8/26/65	9.6	2/1/65
5S	29.0	8/23/65	9.0	2/4/65
5B	29.0	8/23/65	9.2	2/1/65
6S	30.5	8/26/65	8.7	2/4/65
6B	29.5	8/26/65	8.9	2/1/65
7S	29.5	8/26/65	8.7	2/4/65
7B	29.0	8/12/65	8.9	2/1/65
8S	30.5	8/26/65	8.9	3/1/65
8B	29.5	8/26/65	8.5	2/1/65
9S	30.0	8/26/65	8.9	2/4/65
9B	29.5	8/26/65	8.9	2/1/65
10S	30.5	8/26/65	8.6	2/4/65
10B	29.5	8/26/65	8.6	2/4/65

APPENDIX B

SUMMARY OF INTENSIVE SURVEY DATA

TABLE B-1

MEAN VALUES OF PERCENT SATURATION OF DISSOLVED OXYGEN

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	91.8	88.0	83.0	81.5	76.0	72.7
Bottom	88.0	92.5	81.6	76.7	77.1	75.3
Station 2						
Surface	95.2	86.9	74.9	72.5	68.4	66.3
Bottom	89.4	88.2	71.0	68.6	66.8	66.0
Station 3						
Surface	91.1	86.9	74.7	69.9	63.3	65.8
Bottom	87.3	87.0	68.2	67.5	59.2	61.7
Station 4						
Surface	87.2	85.6	74.0	69.5	65.8	64.5
Bottom	85.2	87.8	68.3	66.9	64.5	65.4
Station 5						
Surface	85.6	85.8	77.1	72.3	68.5	68.2
Bottom	84.3	90.1	72.8	72.6	63.7	68.7
Station 6						
Surface	82.0	85.4	72.4	64.2	62.7	59.2
Bottom	83.0	87.2	66.1	62.9	58.4	60.7
Station 7						
Surface	83.3	85.0	73.3	70.1	65.6	63.0
Bottom	84.0	86.4	68.9	68.7	61.5	65.6
Station 8						
Surface	83.5	86.4	71.3	65.6	63.2	56.3
Bottom	83.0	85.5	64.0	60.2	56.2	56.9
Station 9						
Surface	85.0	80.2	75.0	74.5	66.9	62.7
Bottom	84.1	84.1	65.0	64.8	58.5	58.9
Station 10						
Surface	75.4	86.6	Discontinued			
Bottom	79.7	83.8				
Station 13						
Surface			75.4	63.9	61.6	55.7
Bottom			65.0	52.7	49.9	49.9

TABLE B-2

MEAN VALUES OF WATER TEMPERATURES

(^{o}C)

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	10.4	14.2	25.4	27.5	28.2	27.3
Bottom	10.6	13.9	25.9	27.1	27.6	27.3
Station 2						
Surface	10.3	14.1	25.5	27.7	28.5	27.3
Bottom	10.6	13.8	24.9	27.2	28.0	27.3
Station 3						
Surface	10.6	14.6	25.6	28.0	28.7	27.6
Bottom	10.7	14.2	25.2	27.7	28.4	27.4
Station 4						
Surface	10.2	13.8	25.5	27.8	28.5	27.3
Bottom	10.4	13.7	24.9	27.2	28.0	27.3
Station 5						
Surface	10.3	14.1	26.0	27.6	28.5	26.1
Bottom	10.6	14.1	25.1	27.2	27.9	27.5
Station 6						
Surface	9.9	13.9	25.7	27.9	28.6	27.2
Bottom	10.2	13.7	25.1	27.4	28.1	27.2
Station 7						
Surface	10.1	14.0	25.6	27.7	28.5	27.4
Bottom	10.4	13.9	25.1	27.2	28.0	27.3
Station 8						
Surface	9.8	13.9	25.8	27.1	28.8	27.3
Bottom	10.2	13.7	25.1	27.5	28.3	27.2
Station 9						
Surface	10.3	14.6	25.7	28.1	28.9	27.4
Bottom	10.4	13.9	25.2	27.6	28.6	27.3
Station 10						
Surface	10.2	14.1	Discontinued			
Bottom	9.7	13.8				
Station 13						
Surface			25.6	28.1	28.8	27.1
Bottom			25.3	27.5	28.5	27.0

TABLE B-3

MEAN VALUES OF CHLORIDES

(g/l)

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	6.67	7.39	9.09	11.20	11.70	13.14
Bottom	9.73	14.73	14.85	15.70	16.23	14.86
Station 2						
Surface	5.13	5.81	7.01	8.62	9.22	11.47
Bottom	7.59	12.66	13.53	13.73	13.83	12.94
Station 3						
Surface	4.68	4.83	7.72	8.50	9.08	10.39
Bottom	6.77	9.82	9.70	11.73	11.89	11.44
Station 4						
Surface	4.65	4.76	6.40	7.87	8.93	10.19
Bottom	7.94	12.53	13.28	13.20	12.79	12.61
Station 5						
Surface	5.49	4.71	6.43	8.63	9.05	11.28
Bottom	8.10	13.97	12.63	12.52	13.94	13.10
Station 6						
Surface	2.05	1.93	4.18	5.06	6.58	8.20
Bottom	4.56	11.37	9.64	11.48	11.80	10.63
Station 7						
Surface	3.67	3.80	5.24	7.35	8.39	9.34
Bottom	6.14	11.69	10.95	13.01	12.11	11.82
Station 8						
Surface	1.18	1.62	2.51	3.67	4.93	6.00
Bottom	4.37	8.83	8.43	9.24	10.90	9.69
Station 9						
Surface	3.17	3.73	5.58	7.15	7.76	8.45
Bottom	4.12	8.92	8.78	9.89	9.57	9.67
Station 10						
Surface	.17	.79	Discontinued			
Bottom	.36	5.03				
Station 13						
Surface			1.48	2.95	3.38	4.12
Bottom			6.03	8.07	8.57	6.83

TABLE B-4

MEAN VALUES OF TOTAL COLIFORMS

(ORGANISMS/100 ml)

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	2870	10590	11250	8710	6080	4010
Bottom	2010	2140	2150	1260	1320	1300
Station 2						
Surface						
Bottom						
Station 3						
Surface	8450	20850	24150	20860	24170	13810
Bottom	6350	11040	12320	11370	11810	7660
Station 4						
Surface	5390	16380	26780	26870	24040	15700
Bottom	3790	3570	6530	2750	3420	6140
Station 5						
Surface						
Bottom						
Station 6						
Surface						
Bottom						
Station 7						
Surface						
Bottom						
Station 8						
Surface	5930	16110	20630	17840	13800	9590
Bottom	6900	7050	13120	8670	5510	7020
Station 9						
Surface	2590	4730	7500	3440	4350	3720
Bottom	3440	2720	4090	4020	2340	2620
Station 10						
Surface	4890	2560	Discontinued			
Bottom	4850	3060				
Station 13						
Surface			22070	21640	14650	13220
Bottom			8560	6910	8360	8450

TABLE B-5

MEAN VALUES OF FECAL COLIFORMS

(ORGANISMS/100 ml)

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	240	430	2180	920	1340	720
Bottom	180	80	400	220	260	280
Station 2						
Surface						
Bottom						
Station 3						
Surface	770	1210	5400	2900	4160	2100
Bottom	490	400	2670	1320	1690	1300
Station 4						
Surface	450	740	6060	2960	2690	1640
Bottom	270	110	1570	390	880	860
Station 5						
Surface						
Bottom						
Station 6						
Surface						
Bottom						
Station 7						
Surface						
Bottom						
Station 8						
Surface	540	590	3690	2660	830	1340
Bottom	440	200	3280	870	480	1010
Station 9						
Surface	200	190	1480	360	380	490
Bottom	220	100	850	420	190	350
Station 10						
Surface	350	150	Discontinued			
Bottom	510	100				
Station 13						
Surface			3420	2460	1100	2120
Bottom			2100	620	700	970

TABLE B-6

SURFACE TO BOTTOM CHLORIDE RATIOS

Surveys 1965	AA 3/3-7	AB 3/23-27	B 6/21-25	C 7/19-23	D 8/16-20	E 9/20-24	Slack Tide Runs
Station 1	.707	.498	.619	.728	.720	.886	.733
Station 2	.695	.498	.529	.648	.683	.933	.820
Station 3	.754	.524	.845	.748	.789	.918	.900
Station 4	.645	.405	. 45	.619	.741	.816	--
Station 5	.710	.343	.520	.721	.653	.868	.927
Station 6	.558	.212	.552	.462	.621	.808	--
Station 7	.661	.333	.497	.580	.715	.794	--
Station 8	.462	.371	.424	.417	.473	.636	--
Station 9	.838	.509	.678	.748	.830	.885	.915
Station 10	.890	.764	Discontinued				
Station 13			.371	.420	.473	.645	.612
Mean Ratio of 1 thru 9	.670	.410	.572	.630	.692	.838	.784
Mean Ratios All Stations	.692	.445	.552	.609	.670	.819	
Average River Discharge cfs	27,600	27,700	26,300	19,300	16,200	13,500	

TABLE B-7

MEAN VALUES OF 5-DAY BOD

(mg/l)

Surveys	AA	AB	B	C	D	E
1965	3/3-7	3/23-27	6/21-25	7/19-23	8/16-20	9/20-24
Station 1						
Surface	0.8	0.65	0.9	0.7	0.6	0.7
Bottom	0.8	0.5	1.0	0.5	0.5	0.7
Station 2						
Surface	0.8	0.7				
Bottom	0.95	0.6				
Station 3						
Surface	0.9	0.8	1.0	0.7	0.8	0.9
Bottom	1.1	0.7	1.4	0.7	0.6	1.0
Station 4						
Surface	0.8	0.8	1.2	0.7	0.6	0.8
Bottom	1.0	0.6	1.0	0.5	0.4	0.8
Station 5						
Surface	0.8	0.8				
Bottom	0.9	0.5				
Station 6						
Surface	1.0	1.0				
Bottom	1.0	0.7				
Station 7						
Surface	0.9	0.9				
Bottom	1.0	0.6				
Station 8						
Surface	1.0	1.0	1.3	0.9	0.8	1.0
Bottom	1.3	0.8	1.0	0.6	0.6	0.9
Station 9						
Surface	1.0	0.8	1.3	0.8	0.9	0.9
Bottom	1.1	0.7	1.1	0.7	0.6	0.9
Station 10						
Surface	9.5	4.8	Discontinued			
Bottom	6.4	2.1				
Station 13						
Surface			1.3	1.2	0.7	1.0
Bottom			0.9	1.1	0.5	0.8

TABLE B-8

MEAN VALUES OF AMMONIA

(mg/l NH_3-N)

Station	Survey AA	AB	B	C	D	E
1S	0.2	0.2	0.3	0.2	0.3	0.3
1B	0.2	0.2	0.3	0.3	0.4	0.2
2S	0.2	0.2	0.2	0.2	0.3	0.2
2B	0.2	0.2	0.3	0.3	0.4	0.2
3S	0.2	0.3	0.3	0.3	0.4	0.3
3B	0.2	0.2	0.3	0.3	0.4	0.3
4S	0.2	0.2	0.3	0.2	0.3	0.2
4B	0.2	0.2	0.3	0.3	0.4	0.3
5S	0.2	0.2	0.2	0.2	0.3	0.3
5B	0.2	0.2	0.3	0.2	0.4	0.3
6S	0.2	0.2	0.2	0.2	0.3	0.2
6B	0.2	0.2	0.2	0.3	0.4	0.3
7S	0.2	0.2	0.2	0.2	0.3	0.3
7B	0.2	0.2	0.2	0.3	0.4	0.3
8S	0.2	0.2	0.2	0.2	0.3	0.2
8B	0.2	0.2	0.2	0.3	0.4	0.3
9S	0.2	0.2	0.2	0.2	0.3	0.3
9B	0.2	0.2	0.2	0.2	0.4	0.3
10S 1/	0.3	0.3	-	-	-	-
10B	0.3	0.2	-	-	-	-
13S	-	-	0.2	0.2	0.3	0.2
13B	-	-	0.2	0.2	0.4	0.3

1/ Station 10 was replaced by Station 13 after Survey AB.

TABLE B-9

MEAN VALUES OF NITRATE

(mg/l NO_3-N)

Station	Survey AA	AB	B	C	D	E
1S	0.2	0.1	0.1	0.1	0.1	0.1
1B	0.2	0.1	0.1	0.1	0.1	0.1
2S	0.2	0.1	0.1	0.1	0.1	0.1
2B	0.2	0.1	0.1	0.1	0.1	0.1
3S	0.2	0.1	0.1	0.1	0.1	0.1
3B	0.3	0.1	0.1	0.1	0.1	0.1
4S	0.2	0.1	0.1	0.1	0.1	0.1
4B	0.2	0.1	0.1	0.1	0.1	0.1
5S	0.2	0.1	0.1	0.1	0.1	0.1
5B	0.2	0.1	0.1	0.1	0.1	0.1
6S	0.3	0.1	0.1	0.1	0.1	0.1
6B	0.2	0.1	0.1	0.1	0.1	0.1
7S	0.2	0.1	0.1	0.1	0.1	0.1
7B	0.3	0.1	0.1	0.1	0.1	0.1
8S	0.3	0.1	0.1	0.1	0.1	0.1
8B	0.4	0.1	0.1	0.1	0.1	0.1
9S	0.2	0.1	0.1	0.1	0.1	0.1
9B	0.3	0.1	0.1	0.1	0.1	0.1
10S	0.3	0.2	-	-	-	-
10B	0.4	0.1	-	-	-	-
13S	-	-	0.1	0.1	0.1	0.1
13B	-	-	0.1	0.1	0.1	0.1

TABLE B-10

MEAN VALUES OF ORGANIC NITROGEN

(mg/l)

Station	Survey AA	AB	B	C	D	E
1S	0.3	0.2	0.3	0.2	-	-
1B	0.4	0.2	0.3	0.2	-	-
2S	0.2	0.2	0.3	0.3	-	-
2B	0.4	0.2	0.3	0.3	-	-
3S	0.4	0.3	0.4	0.4	-	-
3B	0.5	0.2	0.5	0.5	-	-
4S	0.3	0.3	0.3	0.4	-	-
4B	0.4	0.2	0.3	0.3	-	-
5S	0.3	0.2	0.4	0.4	-	-
5B	0.3	0.2	0.3	0.4	-	-
6S	0.4	0.3	0.3	0.4	-	-
6B	0.3	0.2	0.3	0.3	-	-
7S	0.3	0.3	0.3	0.3	-	-
7B	0.4	0.2	0.3	0.4	-	-
8S	0.5	0.3	0.3	0.3	-	-
8B	0.4	0.2	0.3	0.3	-	-
9S	0.4	0.2	0.4	0.4	-	-
9B	0.6	0.2	0.3	0.4	-	-
10S	0.4	0.3	-	-	-	-
10B	0.4	0.2	-	-	-	-
13S	-	-	0.3	0.3	-	-
13B	-	-	0.3	0.4		

TABLE B-11

MEAN VALUES OF TOTAL PHOSPHATES

($mg/l\ PO_4$)

Station	Survey AA	AB	B	C	D	E
1S	0.14	0.1	0.1	0.1	0.2	0.1
1B	0.19	0.1	0.1	0.2	0.2	0.2
2S	0.14	0.2	0.1	0.2	0.2	0.2
2B	0.30	0.2	0.2	0.2	0.2	0.2
3S	0.4	0.4	0.3	0.4	0.4	0.3
3B	0.4	0.2	0.3	0.3	0.3	0.4
4S	0.2	0.1	0.1	0.2	0.2	0.3
4B	0.2	0.2	0.1	0.2	0.2	0.2
5S	0.2	0.1	0.1	0.2	0.1	0.2
5B	0.2	0.1	0.1	0.2	0.2	0.2
6S	0.2	0.1	0.1	0.1	0.1	0.2
6B	0.2	0.2	0.1	0.2	0.2	0.2
7S	0.2	0.1	0.1	0.2	0.2	0.2
7B	0.2	0.2	0.1	0.2	0.2	0.2
8S	0.2	0.1	0.1	0.1	0.2	0.2
8B	0.4	0.2	0.1	0.2	0.2	0.2
9S	0.2	0.1	0.1	0.2	0.2	0.2
9B	0.3	0.1	0.1	0.3	0.3	0.2
10S	0.2	0.2	-	-	-	-
10B	0.3	0.2	-	-	-	-
13S	-	-	0.1	0.1	0.1	0.1
13B	-	-	0.1	0.2	0.1	0.2

TABLE B-12

SUMMARY OF pH DATA

Station	Survey AA			Survey AB			Survey E		
	Max.	Med.	Min.	Max.	Med.	Min.	Max.	Med.	Min.
1S	7.60	7.4	6.90	7.90	7.6	7.10	7.70	7.4	7.20
1B	7.70	7.6	7.10	7.90	7.8	7.30	7.80	7.5	7.20
2S	7.80	7.3	6.90	7.90	7.5	7.00	7.70	7.4	7.10
2B	7.70	7.4	7.00	8.00	7.8	7.20	7.80	7.4	7.00
3S	7.70	7.1	6.70	7.80	7.4	7.10	7.70	7.3	7.00
3B	7.80	7.4	6.60	8.00	7.7	7.00	7.70	7.4	7.00
4S	7.70	7.2	6.50	7.90	7.5	7.10	7.70	7.4	7.10
4B	7.70	7.4	6.90	8.00	7.8	7.40	7.80	7.5	7.00
5S	7.80	7.4	6.90	7.80	7.5	7.20	7.70	7.5	7.00
5B	7.80	7.5	6.80	8.00	7.8	7.40	7.80	7.5	7.20
6S	7.60	7.2	6.70	7.60	7.2	6.90	7.60	7.4	7.00
6B	7.70	7.3	6.80	7.90	7.7	7.20	7.70	7.5	7.00
7S	7.60	7.3	6.70	7.80	7.4	7.10	7.70	7.4	7.10
7B	7.80	7.4	6.90	8.00	7.8	7.40	7.70	7.5	7.20
8S	7.60	7.2	6.80	7.70	7.2	7.00	7.80	7.3	7.00
8B	7.90	7.3	6.60	8.00	7.7	7.30	7.70	7.4	7.10
9S	7.60	7.3	6.90	7.80	7.4	7.10	7.70	7.4	7.10
9B	7.70	7.2	6.90	7.90	7.7	7.20	7.60	7.4	7.20
10S	10.10	7.6	6.90	8.80	7.3	7.00			
10B	9.90	7.4	6.80	7.80	7.4	6.90			
13S							7.50	7.2	7.00
13B							7.60	7.3	7.00

TABLE B-13

SUMMARY OF TURBIDITY, TOTAL SOLIDS AND VOLATILE SOLIDS

(Turbidity in Jackson Units,
Total Solids in mg/l,
Volatile Solids in mg/l)

	Mean Values					
	Survey AA			Survey AB		
Station	Turbidity	Tot.Solids	Vol.Solids	Turbidity	Tot.Solids	Vol.Solids
1S	36.61	36.39	10.88	15.66	17.46	6.76
1B	78.00	65.15	18.76	35.23	33.93	9.20
2S	30.72	29.57	9.13	18.85	20.42	6.57
2B	130.00	101.38	33.04	31.53	32.17	8.75
3S	44.76	43.07	10.59	19.29	21.07	6.41
3B	123.50	103.24	21.07	155.92	30.96	8.33
4S	39.28	32.00	10.21	15.40	19.60	6.29
4B	92.78	73.47	24.21	248.00	33.40	7.66
5S	54.26	44.01	9.40	16.13	20.10	5.49
5B	79.73	57.59	16.93	257.00	29.00	8.60
6S	49.50	42.85	12.40	16.90	26.63	5.76
6B	69.15	55.30	16.20	225.33	25.06	7.10
7S	44.68	37.13	11.52	16.60	25.50	6.33
7B	87.00	67.46	18.28	211.00	24.96	6.48
8S	61.86	57.84	13.75	20.73	28.43	6.62
8B	106.10	92.50	20.43	243.00	30.82	7.62
9S	54.94	42.32	13.41	16.90	21.06	5.72
9B	108.55	73.88	18.89	228.66	25.13	6.18
10S	64.20	52.86	13.13	20.63	27.24	7.52
10B	77.31	55.70	16.97	200.66	22.96	5.89

APPENDIX C

DATA RELATING CHLORIDE CONCENTRATIONS TO RIVER DISCHARGE AND TIDAL FACTORS

TABLE C-1

OVERALL RESPONSE OF CHLORIDE

CONCENTRATION TO RIVER DISCHARGE

(mg/l/cfs)

Station	Survey AA	AB	B	C	D	E
1S	1.292	1.844	.294	.362	.103	.167
1B	1.935	1.623	.318	.298	.086	.152
2S	1.513	1.563	.115	.155	.088	.209
2B	1.475	2.139	.413	.193	.135	.203
3S	.827	.500	.088	.157	.052	.084
3B	1.638	1.852	.411	.328	.111	.133
4S	1.050	.655	.250	.156	.077	.156
4B	2.186	1.684	.300	.204	.089	.188
5S	1.637	.756	.212	.149	.090	.140
5B	2.317	1.329	.238	.254	.077	.158
6S	.737	.408	.358	.136	.060	.181
6B	1.509	1.698	.550	.245	.101	.231
7S	1.008	.758	.124	.089	.094	.166
7B	1.984	1.762	.292	.214	.137	.171
8S	.633	1.062	.165	.079	.139	.121
8B	2.451	1.931	.444	.251	.088	.157
9S	.466	.654	.192	.117	.028	.068
9B	.798	2.073	.358	.172	.053	.088
10S	.049	.354	--	--	--	--
10B	.370	2.434	--	--	--	--
13S	--	--	.030	.117	.049	.096
13B	--	--	.456	.384	.110	.206
Mean S	0.921	0.855	0.183	0.152	0.0812	0.1436
B	1.666	1.853	0.378	0.254	0.0974	0.1646
Mean S & B	1.294	1.354	0.281	0.203	0.0893	0.1541
Ratio S & B	0.553	0.461	0.484	0.598	0.834	0.872

TABLE C-2

ANALYSIS OF CHLORIDE RESPONSES TO TIDE RANGES

Survey	Mean Tide Range (ft.)	Surface Response mg/l/cfs	Bottom Response mg/l/cfs	Differences		
				Tide Range (ft.)	Surface Response mg/l/cfs	Bottom Response mg/l/cfs
AA	5.22	0.921	1.666			
				1.14	.066	0.187
AB	4.08	0.855	1.853			
B	4.09	0.183	0.378			
C	4.11	0.152	0.254			
D	4.42	0.0812	0.0974			
				1.34	.062	0.067
E	5.76	0.1436	0.1646			

TABLE C-3

SLACK TIDE SALINITY MEASUREMENTS

RATIOS OF SURFACE/BOTTOM CHLORIDES

Cooper River Mile	1/13/66 HWS	1/14/66 LWS	1/14/66 HWS	1/17/66 LWS	Mean	Regular Sampling Station	Intensive Survey E Min.-Max.
7	.696	.738	.759	.739	.733	1	.712-1.220
8	1.064	.790	.839	.782	.869		
9	--	.784	.797	.754	.778		
10	--	1.117	.741	.924	.927	5	.497-1.163
11	--	.815	.732	.859	.802		
12	--	.536	.570	.650	.585	7	.504- .941
13	--	.525	.754	.565	.615	8	.339-1.134
14	.406	.632	.383	.482	.476		
15	.391	.476	.445	.919	.558		
16	.418	.547	.498	.461	.481		
17	.523	.454	.499	.820	.574		
18	.512	.560	.516	.858	.612	13	.381-1.081
19	.393	.869	--	.759	.674	10	
21	.932	--	--	--	.932		
Average River Discharge	8620						
Ashley River							
2	.697	--	.843	.930	.823	2	
3	.689	--	.785	.946	.807		
4	.956	.999	.720	.893	.892		
5	.777	.973	.817	.986	.888	3	
6	.837	1.003	.887	.953	.920		
Wando River							
1	.782	1.036	.732	.986	.884		Mean of all except Cooper River Mile 21
2	.848	.997	.844	.983	.918		
3	.841	.990	.827	1.001	.915	9	
4	1.126	.975	.898	.990	.997		
							.760

TABLE C-4

SALINITY PROFILE STUDY

Station	Date	Tide Condition	River Discharge cfs	Chlorides Surface mg/l	Chlorides Bottom 1/ mg/l	Ratio (S/B) Surface/Bottom
1	12/16/65	LWS*	10900	10500	16100	.652
	12/02/65	HWS**	21800	13380	18330	.730
	12/16/65	LWS	10900	12130	14060	.863
	12/02/65	HWS	21800	14020	18130	.773
2	11/09/65	LWS	8100	10960	11660	.940
	10/27/65	HWS	11500	11540	17630	.655
3	11/02/65	LWS	11900	10990	13350	.823
	10/29/65	HWS	12900	9150	14890	.615
4	10/27/65	LWS	11500	7500	9440	.794
	11/01/65	HWS	13400	12240	18370	.666
5	12/08/65	LWS	21400	10600	11460	.925
	12/03/65	HWS	21100	10170	16300	.624
6	11/10/65	LWS	9400	7750	10260	.755
	11/01/65	HWS	13400	7040	17250	.408
7	12/08/65	LWS	21400	8770	9740	.900
	12/03/65	HWS	21100	7630	14340	.532
8	11/19/65	LWS	9200	6070	9580	.634
	11/10/65	HWS	9400	12690	14310	.887
9	11/19/65	LWS	9200	9490	9450	1.004
	11/09/65	HWS	8100	11630	14070	.827
13	12/08/65	LWS	21400	3110	4440	.700
	11/10/65	HWS	9400	7870	11560	.681

Mean Values	Flow Range	No. Values	S/B Ratio	Flow Range	No. Values	S/B Ratio
	8000 - 8500	(2)	.884	12000 - 12500	(0)	
	8500 - 9000	(0)		12500 - 13000	(1)	
	9000 - 9500	(4)	.739	13000 - 13500	(2)	.537
	9500 - 10000	(0)				
	10000 - 10500	(0)		21000 - 21500	(5)	.736
	10500 - 11000	(2)	.753	21500 - 22000	(2)	.752
	11000 - 11500	(0)				
	11500 - 12000	(3)	.757			

1/ Bottom values are the averages of measurements made at 15, 20 and 25 foot depths.

* Low water slack.

** High water slack.

TABLE C-5

ANALYSIS OF CHLORIDE DATA FOR UPPER AND LOWER HARBOR AREAS

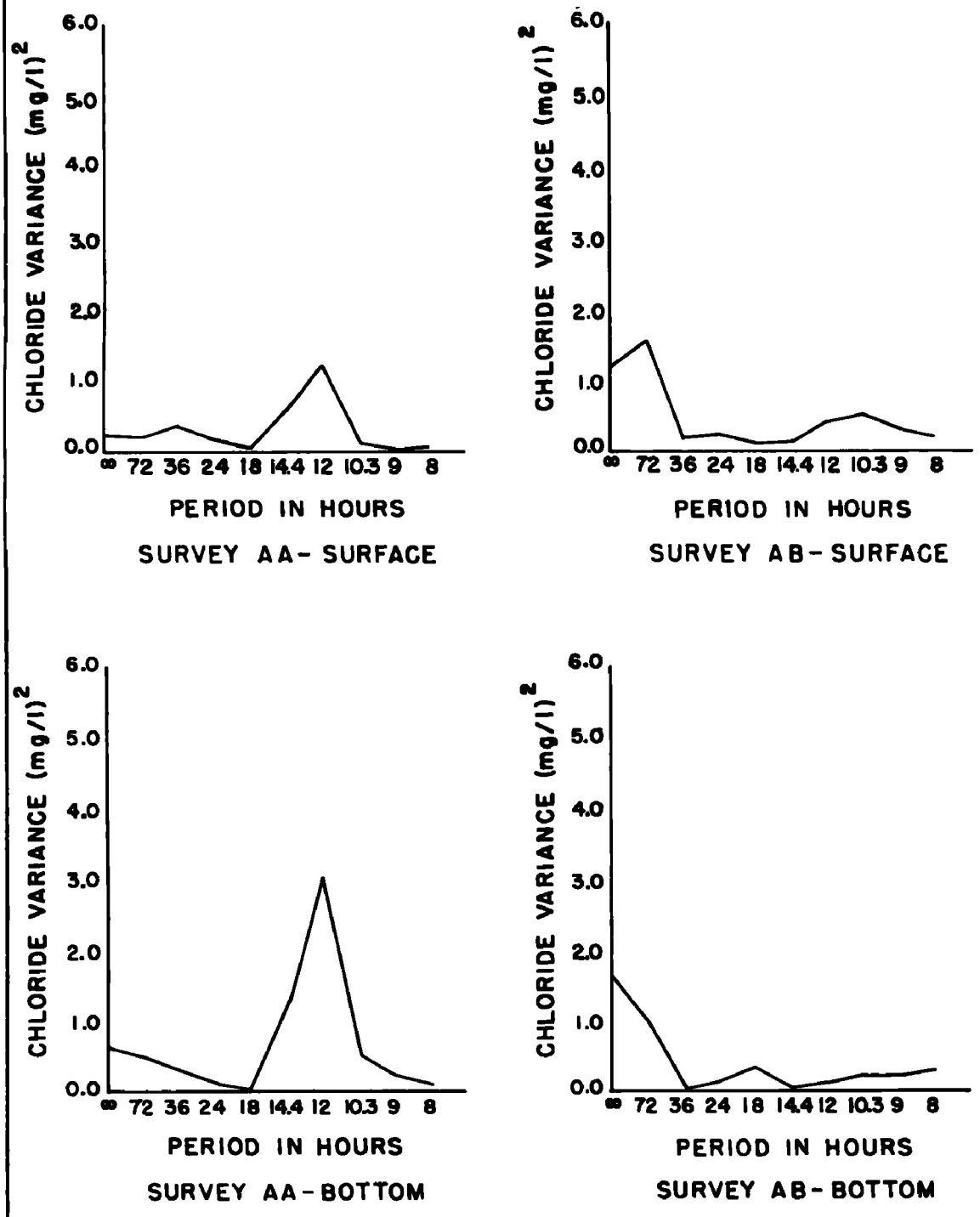
Source of Data	Intensive Surveys AA	AB	B	C	D	E	Differences in Overall Response Between Surveys Shown AB and AA	D and E	Salinity Profile Studies	Slack Tide Runs 7700 cfs
Lower Harbor										
Ratios of Means (Surface/Bottom)	.702	.454	.600	.693	.717	.884			.751 (11,400 cfs)	.840
Overall Response*										
Surface	1.264	1.064	.192	.196	.082	.151	.200	.069		
Bottom	1.910	1.725	.336	.255	.100	.167	.185	.067		
Ratio (S/B)	.662	.617	.571	.769	.820	.904				
Upper Harbor										
Ratios of Means (Surface/Bottom)	.682	.438	.504	.525	.622	.754			.774 (9,400 cfs)	.702
Overal Response*										
Surface	.579	.647	.174	.108	.074	.126	-.068	.052		
Bottom	1.422	1.980	.420	.253	.098	.171	-.558	.073		
Ratio (S/B)	.407	.327	.414	.427	.755	.737				

Lower Harbor: Stations 1, 2, 3, 4, 5
Upper Harbor: Stations 6, 7, 8, 9, 13(10)

* Units in mg/l/cfs

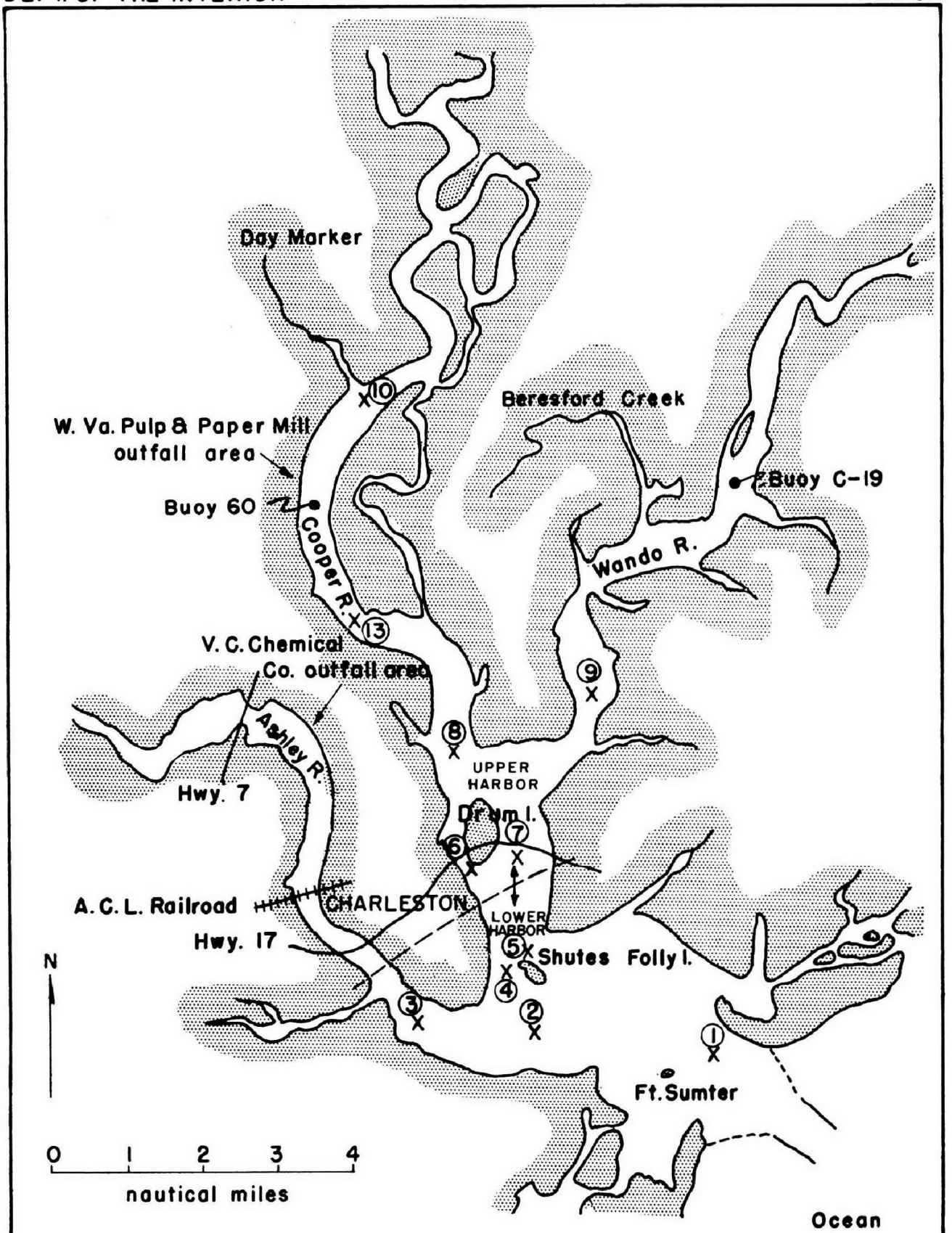
DEPT. OF THE INTERIOR FWPCA

STATION 1



RESPONSE SPECTRA
CHLORIDES TO RIVER DISCHARGE

FIGURE C-1



CHARLESTON HARBOR
Sampling Locations

FIGURE 2