LONG RANGE SPOIL DISPOSAL STUDY

PART III

SUB-STUDY 2

NATURE, SOURCE, AND CAUSE OF THE SHOAL

U.S. ARMY ENGINEER DIST.
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study of the Delaware River dredging spoil disposal problems was undertaken by the U.S. Army Corps of Engineers, Philadelphia District. Part III, sub-study 2 of this study reports the results of the overall investigation on the nature of the shoals in the navigation channel and the anchorages, on their immediate and ultimate sources and the causes of the deposition of the materials in certain reaches of the navigation channel and in the anchorages. The hydraulic data

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410358 SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) presented reports freshwater inflows, tidal and salinity regimen plus sediment transport in the Delaware Estuary. An in-depth study is taken on the shoaling off Marcus Hook, Pa.

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(This Appendix is the source of those parts of the main report dealing with the same subject; it goes into far more detail.)

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FOREWORD

1. The "Long Range Spoil Disposal Study" of the Delaware River was conceived in response to a request of the Chief of Engineers that an overall engineering study of the problems involved in the maintenance of the Delaware River navigation channels and anchorages be made with a view to arriving at improved solutions.

2. Deep draft commerce moves 133 miles up the Delaware River. Over 100,000,000 tons of goods and commodities are handled on this river each year. In large part, this commerce relies on this man-made channel, which is 40 feet in depth. Maintenance of the channel and anchorages requires the removal of millions of cubic yards of material each year. Disposal of this material on shore cannot continue indefinitely because of diminishing disposal area availability. The overall study considered possible courses of action and resulted in seven reports, as follows:

PART I: "GENERAL DATA ON DELAWARE RIVER". This furnishes information and data that are pertinent to the entire study, but it has been superseded to some extent as a result of data obtained for the Part III, Substudy 2, investigation.

PART II – SUB-STUDY 1: "SHORT RANGE SOLUTION". This evaluates the remaining disposal area capacity in tems of the remaining life and considers any further desirable and acceptable disposal area developments.

PART III – SUB-STUDY 2: "NATURE, SOURCE, AND CAUSE OF THE SHOAL". This part of the overall investigation consists of obtaining and analyzing of a great amount of basic information on the nature of the shoals in the navigation channel and the anchorages, on their immediate and ultimate sources, and the causes of the deposition of the materials in certain reaches of the navigation channel and in the anchorages. (This is the part of the overall study reported upon herein.)

PART IV – SUB-STUDY 3: "DEVELOPMENT OF NEW DREDGING EQUIPMENT AND TECHNIQUE". This part of the overall investigation examines the present maintenance dredging equipment and procedures, and proceeds to the consideration of alternates for the time when nearby (within 5 to 10 miles) disposal areas on shore will no longer be available and dredged materials will have to be transported 25 to 50 miles prior to disposal.

PART V – SUB-STUDY 4: "PUMPING THROUGH LONG LINES". This examines the merits of transporting dredged materials many miles through pipelines.

PART VI – SUB-STUDY 5: "IN-RIVER TRAINING WORKS". This part of the overall study determines the potential of training works for the control of shoaling. It involves considerable hydraulic model testing.

PART VII – SUB-STUDY 6: "DELAWARE RIVER ANCHORAGES" considers the effect of man-made anchorages on shoaling problems and the merits of alternate solutions.

3. This report is "PART III – SUB-STUDY 2" and covers the subject "Nature, Source, and Cause of the Shoal". As this subject is of more general interest than those of the other reports, it was deemed desirable to include some of the material contained in PART I in order to include in one report all of the pertinent information bearing on this aspect of the overall investigation.

4. The investigation dealing with the nature, source and cause of the shoaling was planned and generally monitored by a Board of Consultants consisting of the following:

Dr. Leslie G. Bromwell
Consulting Engineer
Lakeland, Florida

Dr. Ray B. Krone
Professor of Civil Engineering
Univ. of California, Davis Campus

Dr. Arthur T. Ippen
Institute Professor
Director, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics
Massachusetts Institute of Technology

Dr. James Neiheisel
Chief, Geology and Petrographic Sec.
South Atlantic Division Laboratory
U.S. Army Engineer Division, South Atlantic

Mr. Clarence F. Wicker
Consulting Civil Engineer
West Chester, Pa.

5. The observational program and the data processing requested by the Board of Consultants were performed by the Philadelphia Army Engineer District and the major portion of the testing for the study was performed by the Corps of Engineers South Atlantic Division Laboratories. The Board of Consultants met four times during the study period to receive progress reports, review interim results and perform the principal analyses of the data. The Board also accepted responsibility for the preparation of the report setting forth the conclusions of the study. The report was prepared by Mr. Wicker with editorial assistance from the Board of Consultants and Philadelphia District personnel.

I. INTRODUCTION

THE PROBLEM

6. The Delaware Estuary is about 133 miles long and there is a navigation channel of various dimensions throughout virtually all of this distance, the authorized depth being 40 feet below mean low water except for the last six miles near the head of tide. In five of these six miles, the depth is 25 feet and in the last mile, it is 12 feet. Natural depths equal to or in excess of project depths existed only in the first six miles above the mouth. Elsewhere, the channel was created by dredging and along certain reaches of this important facility frequent redredging is necessary to maintain project dimensions.

7. The total shoaling of the Federally maintained man-made channel and appurtenant anchorages averages 8.2 million cubic yards each year. There is little or no shoaling in the first 57 miles above the mouth, but upstream of this point shoaling occurs in certain well-defined reaches. The distribution is given in the following tabulation:

TABLE 1

Miles above the Mouth		Average Annual Shoaling	Percent of Total
0 to 57		0	0
57 to 67		cy 1,330,000	16.1%
72 to 81		cy 3,292,000	40.0%
81 to 92		cy 1,911,000	23.2%
114 to 130		cy 1,133,000	13.7%
Scattering		cy 577,000	7.0%
	TOTALS	cy 8,243,000	100.0%

Although two of the above reaches are contiguous, each of these is considered to be a separate entity; the shoaling rate varies from a maximum at or near the center of the respective reaches and becomes relatively low at the ends. The table shows that the reach having by far the greatest shoaling is located between miles 72 and 81. Unfortunately, the problem of disposing of the dredged material here is extremely serious due to the extensive development of the shorelines. The study reported on herein largely concentrates on answering the following questions pertaining to this especially acute problem reach:

> What is the nature of this shoal?
>
> Where does the shoaling material come from?
>
> Why does this reach shoal so heavily?

This report presents all known facts bearing on these questions, including a detailed description of the estuary, its regimen, its shoaling propensities, and the characteristics of the watershed above tidewater. Some of the factual information required much field work, including the observation of currents and the collection of many samples of the water and of the bed of the estuary. The observation and laboratory methods employed, also the procedures used for study of the data, are described. The conclusions are explained in detail.

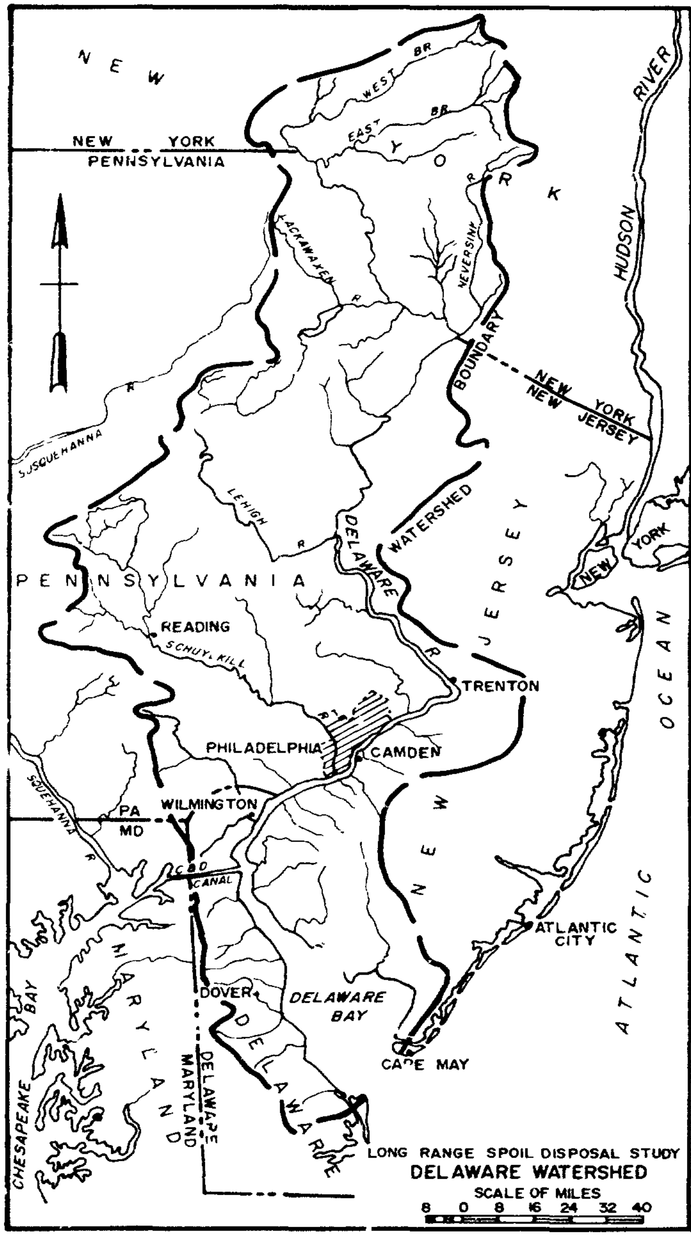
II. FACTS BEARING ON THE PROBLEM

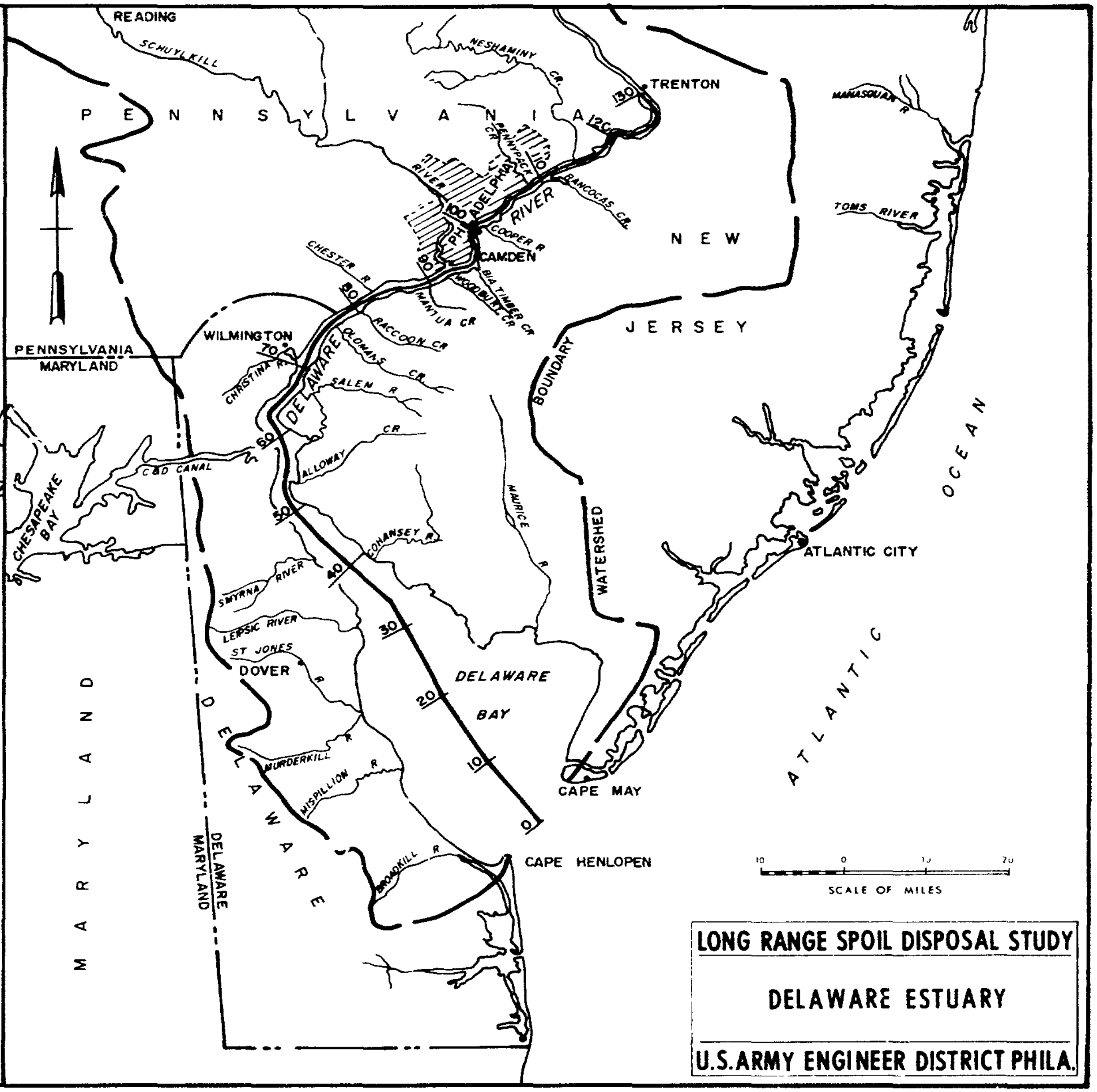
DESCRIPTION OF THE ESTUARY

8. Plate 1 shows the Delaware Estuary and its tributaries, also the overall watershed. The estuary proper has a length of about 133 miles measured along midstream, a width at the mouth of about 11 miles, a maximum width (about 12 miles above the mouth) of about 26 miles, and a minimum width at the head of tide of 800 ft. Upstream of the point of maximum width, the width decreases at a fairly uniform rate; it may be said that this estuary has the classic funnel shape that is characteristic of many estuaries. Its geometry is relatively simple in other respects. There are few islands having significant back channels, and therefore most of the flow is concentrated in one main channel. The cross-sectional geometry is such that it varies from a maximum at the point of greatest width to a minimum at the head of tide with rather remarkable uniformity. Plate 2 shows these characteristics.

9. From the mouth to mile 70, the estuary cuts through the Coastal Plain Province; thence to the head of tide, the course generally follows the Fall Line dividing the Coastal Plain and the Piedmont Provinces. At places, the Fall Line along the Delaware-Pennsylvania side of the estuary is quite close to the shoreline while at others it is as much as five miles distant. The Fall Line crosses the Delaware at the head of tide and thereby terminates the estuarine portion of the Delaware, thence trends across New Jersey in a northeast-southwest direction. In the downstream 60 miles of the estuary, the shoreline is marshy on both sides of the waterway and these marshes often extend considerable distances inland. Above mile 60, marshes are sometimes found along both shorelines while at other places there is relatively high ground.

10. The bed of the estuary is mostly fine to coarse sand in the midstream half and generally soft muds in the quarters along the shore, from the mouth to about mile 40. From mile 40 to mile 95, the bottom consists mostly of silt-size materials, although there are a few areas where fine sands are encountered. In the reach from mile 79 to mile 84 there are outcroppings of gneisses and schists along the westerly side. From mile 95 to mile 102, the materials encountered include some sands but mostly compact fines, and there is another outcropping of gneisses and schists near the upper end





LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY

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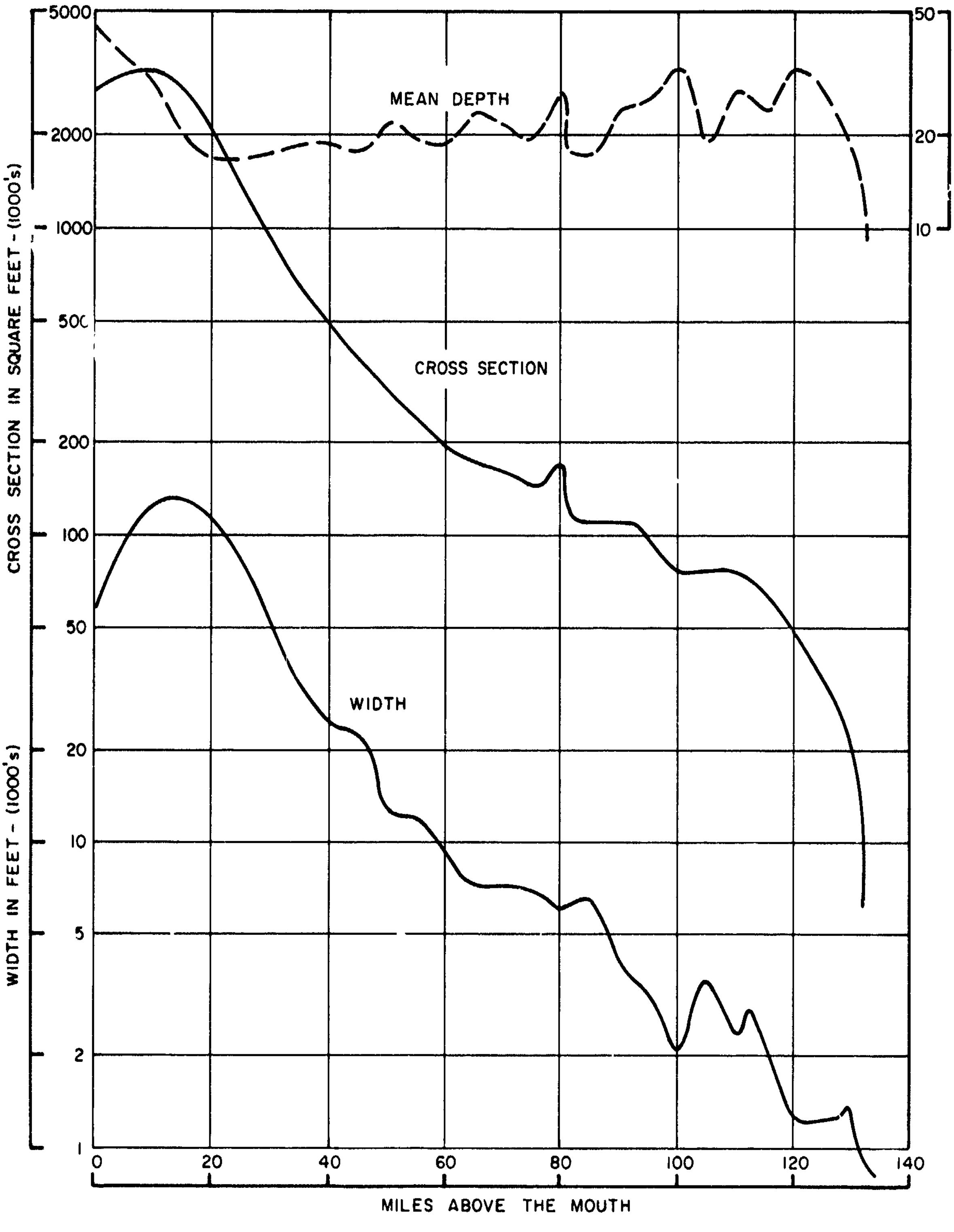

NOTE.
ABOVE DATA REFERRED TO
MID-TIDE ELEVATIONS

LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY
PHYSICAL CHARACTERISTICS

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of this reach. From mile 102 to the head of tide, the bottom is composed of mud, sand, and gravel, and there is a reach extending from mile 111 to 116 where the schists and gneisses again appear.

11. On the New Jersey side of the estuary, from the mouth to about mile 50, there are few man-made changes of the shoreline. From this point to the head of tide there are many spoil disposal areas, intermittent residential communities, and some industry. The largest municipalities are Camden, located between miles 90 and 100, and Trenton at the head of tide. The Delaware-Pennsylvania side is largely undeveloped and unchanged by man from the mouth to mile 55. From this point, much of the shoreline is occupied by industries, cities, and a few disposal areas for dredged materials. The principal municipalities are Wilmington, centering at about mile 68, Marcus Hook at mile 75, Chester at mile 80, and Philadelphia extending from mile 85 to mile 110. From Wilmington to the upper limits of Philadelphia, there are few portions of the shoreline not occupied by the works of man. Beyond the upstream limits of Philadelphia, there are several smaller communities and a substantial number of industries, but the state of development is not continuous.

12. In 1836, when the first improvements in the interest of navigation were undertaken, the controlling depths from the mouth to Philadelphia (mile 100) were of the order of 17 ft. From thence to the head of tide the controlling depth was 3 ft. The current (1973) state of the channel improvements is as follows:

TABLE 2

Reach	Channel Dimensions
Mouth to mile 6	Natural depths and widths adequate
Mile 6 to mile 40	40 ft. x 1000 ft.
Mile 40 to mile 96	40 ft. x 800 ft. (1)
Mile 96 to mile 104	(40 ft. x 400 ft.
	(35 ft. x 600 ft. (2)
Mile 104 to mile 128	40 ft. x 400 ft.
Mile 128 to mile 133	25 ft. x 300 ft. (3)
Mile 133 to mile 134 (4)	12 ft. x 200 ft.

(1) 800 ft. width in this reach is increased at bends
(2) Authorized depth is 37 ft. but this has not been dredged
(3) Authorization exists to increase this reach of channel from 25 ft. x 300 ft. to 35 ft. x 300 ft., but this work has not been undertaken.
(4) Total distance of 134 miles is measured along improved channels; it is about 1 mile greater than the length along the midstream line.

In addition to these channel improvements, four anchorages have been created and two others are authorized but not constructed. Those in existence are listed below:

TABLE 3

Anchorage	Location (Miles above mouth)	Existing Dimensions Width	Length	Depth
Marcus Hook	81	2300 ft.	13,650 ft.	40 ft.
Mantua Creek	92	1400 ft.(1)	11,500 ft.(1)	37 ft.(1)
Gloucester	96	550 ft.	3,500 ft.	30 ft.
Port Richmond	103	750 ft.	5,800 ft.	35 ft.

(1) Authorized dimensions are 2300 ft. in width, 11,500 ft. long and 40 ft. deep, but these modifications have not been effected.

HYDRAULICS (FRESH WATER INFLOWS)

13. The total drainage area tributary to the estuary amounts to 12,765 square miles, excluding 782 square miles of water surface in the estuary. The inferred total average annual inflow of fresh water, head of tide to the mouth, is 20,200 cfs; this is based on recording gage data governing the three major parts of the drainage area over long periods, and similar data for eight smaller tributaries during shorter periods. The following tabulation gives some detail on the geographic distribution of the drainage area and the fresh water inflows.

TABLE 4

Source of Inflow	Location, Miles above Mouth	Drainage Area Sq. Mi.	Drainage Area % of Total	Average Annual Inflow cfs	Average Annual Inflow % of Total	CSM
Delaware River at Trenton	133	6,780	53.1%	12,000	59.4%	1.77
Intermediate small tributaries	–	1,300	10.2%	1,810	9.0%	1.39
Schuylkill River at Philadelphia	93	1,909	15.0%	2,750	13.6%	1.44
Sub-totals	93	(9,989)	(78.3%)	(16,560)	(82.0%)	
Intermediate small tributaries	–	464	3.6%	650	3.2%	1.40
Christina-Brandywine near Wilmington	70	569	4.5%	750	3.7%	1.32
Sub-totals	70	(11,022)	(86.4%)	(17,960)	(88.9%)	
Intermediate small tributaries	–	1,743	13.6%	2,240	11.1%	1.29
Totals at mouth	0	12,765	100.0%	20,200	100.0%	

The table shows that most (88.9%) of the fresh water inflow enters the estuary in its upper 63 miles (47% of the total length). It also shows that the discharge per square mile is greatest from that part of the watershed located above the head of tide at Trenton.

14. There is a substantial variation of the mean monthly discharges, as shown by the following tabulation.

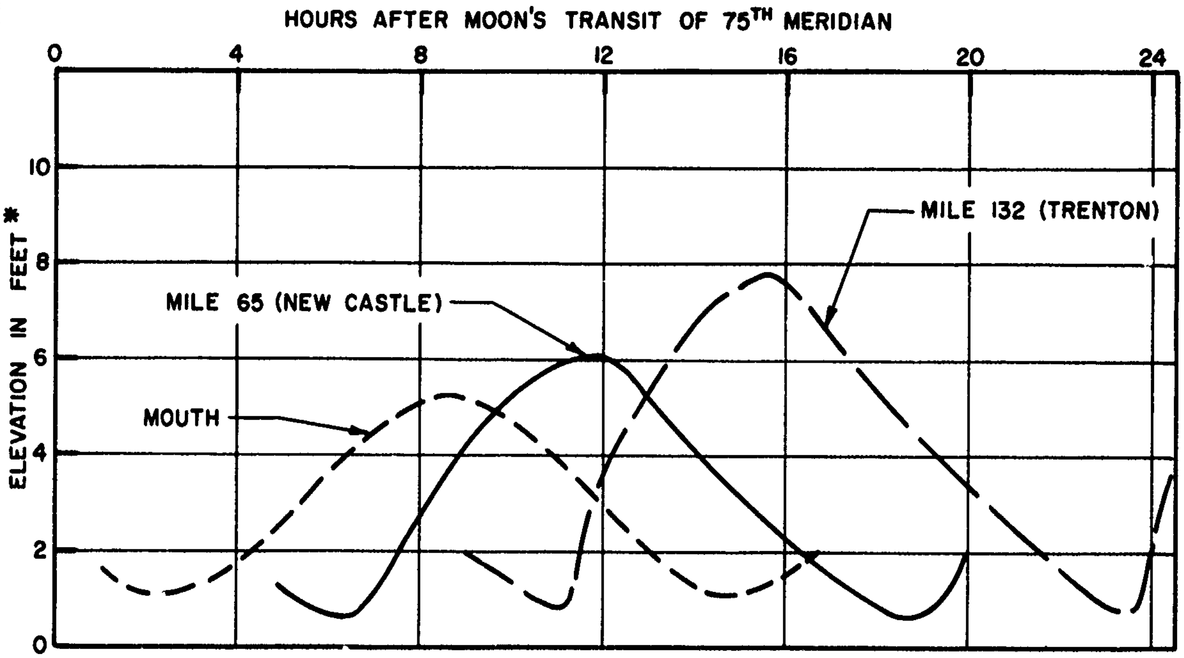
TABLE 5

Month	Mean Monthly Discharge as % of Total	Month	Mean Monthly Discharge as % of Total
October	4.2%	April	15.1%
November	7.6%	May	9.9%
December	8.8%	June	6.3%
January	9.1%	July	5.3%
February	9.5%	August	4.5%
March	15.6%	September	4.2%

The maximum observed discharge of the Delaware at Trenton was 329,000 cfs and the minimum was 1,220 cfs. The maximum and minimum discharges of the Schuylkill were 96,200 cfs and 284 cfs respectively. When these discharges are compared with the long-time mean values of 12,000 cfs and 2,750 cfs for these two principal points of entry of fresh water, it is apparent that the estuary receives a widely varying inflow of fresh water.

HYDRAULICS (TIDAL REGIMEN)

15. The tides of the Delaware Estuary are semidiurnal; there are two nearly equal high waters and two nearly equal low waters per lunar day. The mean range (commonly designated "Mn") is about four feet at the mouth and the variation of elevation with time plots as a curve closely approximating a sine curve, as shown on Plate 3. As this tidal undulation propagates up the estuary, its range, the elevation of a plane halfway between mean high and mean low water (designated Mean Tide Level, "MTL"), and the durations of rise and fall change with distance from the mouth. Typical mean tide curves at an intermediate point and at the head of tide are shown on Plate 3 also. It is seen that the range of tide increases as the distance from the mouth increases and that the shape of the curves departs from the near sine curve plot at the mouth to a much distorted configuration at the head of tide. The principal facts describing the tides of the estuary may be conveniently shown by plots of the range (Mn), Mean Tide Level (MTL), and the High and Low Water Lunitidal Intervals (HWI) and (LWI). Plate 4 shows these plottings. The range graph shows that the amplitude of the tidal undulation increases to about mile 40, decreases to about mile 60, then increases steadily to reach a maximum of nearly seven feet near the head of tide. The gradual increase to mile 40 is due to the conver-



* DELAWARE RIVER DATUM IS 2.90 FT. BELOW SEA LEVEL DATUM (1929)

LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY
TYPICAL MEAN TIDE CURVES

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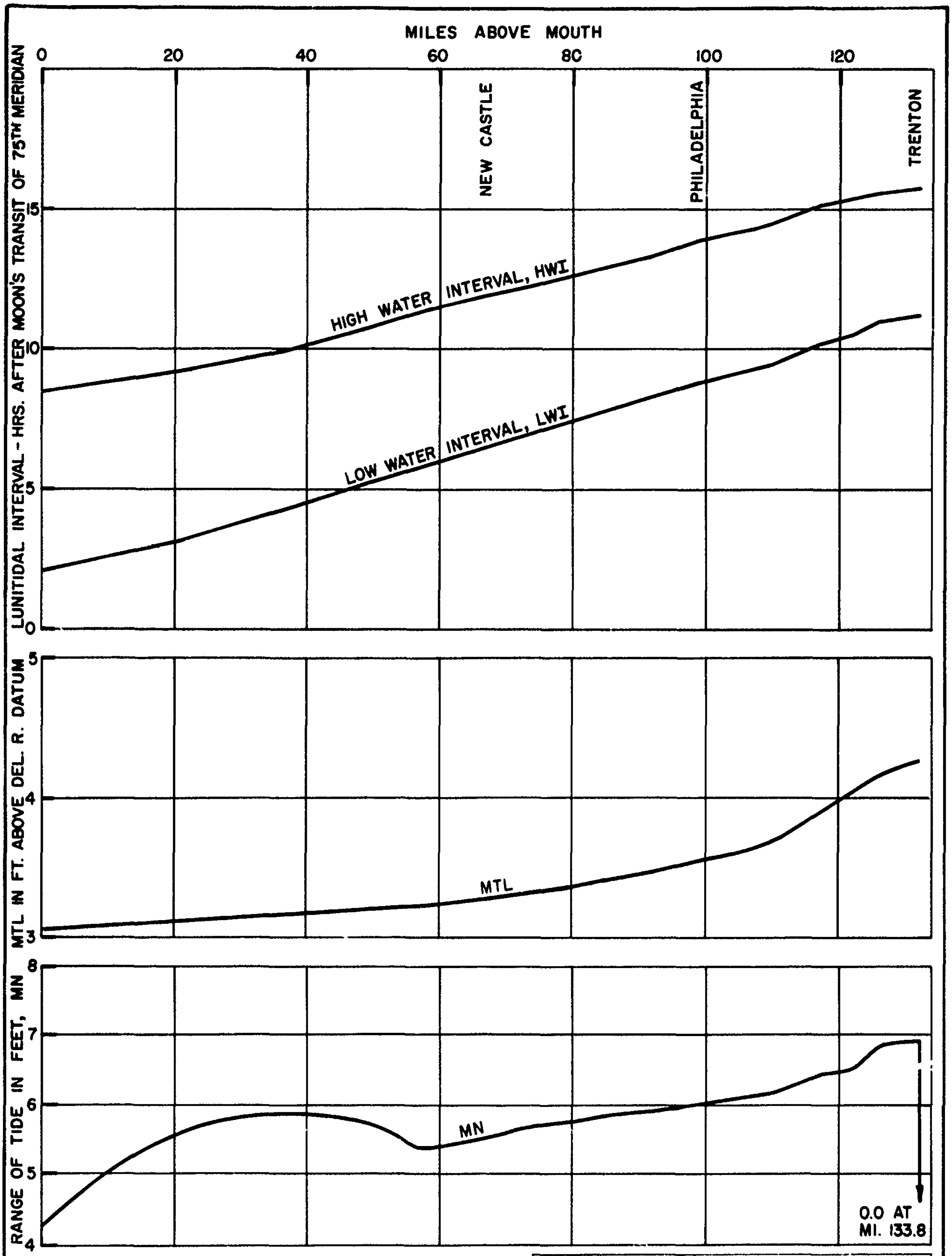

LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY MEAN TIDE VALUES

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PLATE 4

gance of both the width of the estuary and its cross-sectional areas, while the decrease from mile 40 to mile 60 is probably due to an abrupt decrease in width and area caused by a former island, the back channel of which has been closed. Upstream of mile 60, the range increases at a fairly uniform rate to its maximum just below the head of tide. The plot of mean tide levels shows a fairly uniform increase of elevation from the mouth, where the elevation is close to sea level datum, to mile 110; thence, the rate of increase is much greater. Near the head of tide, the elevation of mean tide level is about 1.4 ft. above sea level datum. Both high and low water lunitidal intervals increase at uniform rates towards the head of tide, but the plots gradually converge; the durations of rise decrease and the durations of fall increase. These differences are due to the fact that the speed of propagation of the tidal undulation is greater during the higher stages than at the lower.

16. The tide is, of course, not always at its mean conditions. There are complex but rhythmic variations due to astronomic forces and erratic variations due to changing meteorological conditions, and these combine to produce widely varying conditions. Near the time of New and Full Moon, the range (Spring Tide) is greater than near the times of the Quadratures (Neap Tide). In the Delaware, the Spring range averages about 11% greater than the mean range, and the Neap range averages about 24% less than the mean range. There is also a varying amount of diurnal inequality. The inequality of successive high water stages will be as much as 1.5 ft. near the times of New and Full Moon, but at this phase of the Moon, the low waters will have their least diurnal inequalities. Near the times of the Moon's Quadratures, the inequality of successive high waters is least and that of successive low waters is greatest, about 0.5 ft. Thus the range of the morning complete cycle (low water-high water-low water) near the times of New and Full Moon might be 7.3 ft. and that of the afternoon cycle might be 5.9 ft. Near the times of Quadratures, the morning complete cycle might have a range of 5.0 ft. while the succeeding complete cycle might have a range of 5.4 ft.

17. A strong northwest wind, if of sufficient duration, will lower the elevation of mean tide level significantly and cause abnormally low high and low waters. At Philadelphia, for example, the lowest recorded stage was 5.0 ft. below mean low water; this was attributal to the wind effect only. On the other hand, the extreme high water stage attained at Philadelphia of 5.2 ft. above mean high water was due to a combination of high upland flows and strong winds onshore in the ocean. During a great flood from the uplands, the tide in the upper reaches of the estuary is virtually extinguished but at points farther downstream a rise and fall in consonance with the tide can be seen, although its amplitude may be less than would be the case with a normal upland flow and mean tide level would be higher than normal. At some point downstream, the location depending on the magnitude of the upland flows, the range of tide would be approximately that expected during a normal upland flow and mean tide level also would be at its usual elevation.

18. As the tidal undulation propagates

upstream, it generates tidal currents but these are modified by the upland flows. The total ebb discharge is increased and the total flood discharge is decreased. For a hypothetical zero upland flow, the total ebb and flood discharges during a mean tidal cycle (mean low water-mean high water-mean low water) would be exactly equal, at the mouth about 93,000 millions of cubic feet. When the mean upland flow is 20,200 cfs at the mouth, the total discharge during the ebb phase of the current cycle, including tidal and non-tidal discharges, is 93,500 millions of cubic feet, and during the flood phase, it is 92,600 millions of cubic feet. During the mean upland flows, there is no flood discharge from a point about 130 miles above the mouth to the head of tide, although there is a large variation of stage due to the tide. The ebb discharges vary from a maximum to a minimum at the time when it would be expected that a flood discharge should be occurring. This point of no flood discharge shifts with the magnitude of the upland flows. During the greatest flood of record, it is likely that the discharge was in the ebb direction from the head of tide to a point about 66 miles above the mouth, even though there was a variation of stage at this location and downstream in consonance with the tide.

19. The currents that are the resultants of the tidal discharges and the flows from the uplands are of course related to the total discharges (tidal and nontidal) and the cross-sectional areas, but there is still another factor that modifies the currents – salinity. While the effects of salinity do not materially modify the total flood and ebb discharges or the variation of these discharges with time, modifications induced by salinity are of very great significance, as will be brought out later. It has been pointed out that the Delaware Estuary is of relatively simple geometry; its cross-sectional areas decrease at a fairly uniform rate from the maximum at a point about 12 miles above the mouth to the minimum at the head of tide. The mean total flood and ebb discharges also reduce at fairly uniform rates from their maxima at the mouth to minima at the head of tide. Since the average velocity in each cross-section is the discharge divided by the cross-sectional area, it follows that the average flood and ebb velocities throughout much of the estuary should be reasonably uniform. This would be the case in the Delaware if the geometry was indeed that of an idealized configuration, but it is such only in general terms. There are substantial departures of cross-sectional area from the idealized condition extending over relatively short distances, and at these locations the currents are accelerated or decelerated depending on whether the cross-sectional area is deficient or excessive. Ignoring these places, the mean flood and ebb current velocities throughout each successive cross-section are approximately equal at about 1.4 feet per second from mile 50 to mile 110. This reflects the fact that the fresh water discharges have little effect on the velocities in that section of the estuary and downstream thereof, but as the head of tide is approached, the relative significance of upland flows increases. As the head of tide is approached, the flood current disappears and the flow is in the ebb direction throughout the tidal cycle. As will be brought out later, departures from a

uniform system of current velocity due to irregularities of cross-sectional area may have important effects on scour and deposition of shoaling materials.

HYDRAULICS (SALINITY REGIMEN)

20. The salinity of the waters of the Delaware Estuary at any given point at any given time is the result of a complex relationship between the salinity of the Atlantic Ocean at the mouth, the upland flows, and the tidal discharges. According to observations by the U.S. Coast and Geodetic Survey, the mean of 63 months of data obtained at Delaware Breakwater was 28.8 parts per thousand (ppt); Delaware Breakwater is located a short distance upstream of the mouth on the west side of the estuary. Comparison of these data with 46 months of simultaneous observations in the Ocean at Atlantic City, which is 42 miles north of the mouth, shows that the salinity at Breakwater Harbor and Atlantic City was 28.8 ppt and 31.6 ppt respectively. These data are representative of the salinity, surface to bottom. Because of the Coriolis force, it is likely that the salinity on the east side of the mouth is somewhat higher than the observed 28.8 ppt on the west side, but data are not available to establish the exact relationship. For purposes of this report, it may be assumed that the salinity of the Atlantic Ocean just off the mouth lies between 29 and 30 ppt. There is a seasonal variation at Breakwater Harbor, with the low value occurring in April (27.6 ppt) and the high in August-November at 29.8 ppt, undoubtedly due to the fact that the greatest upland flows occur in April and the least in August-October.

21. At any given point in the estuary subject to salinity intrusions, the salinity varies from a maximum at or near the time of high water slack (the moment when the flood current ceases and the ebb sets in) to a minimum at or near the time of low water slack. With several weeks or more of sustained upland flows at or near the mean value, the upper limit of brackish water at high water slack is at mile 75. During a prolonged drought, the upper limit of brackish water has intruded as much as 110 miles above the mouth. Plate 5 shows a typical salinity profile at high water slack for a mean fresh water discharge at the mouth of 20,200 cfs.

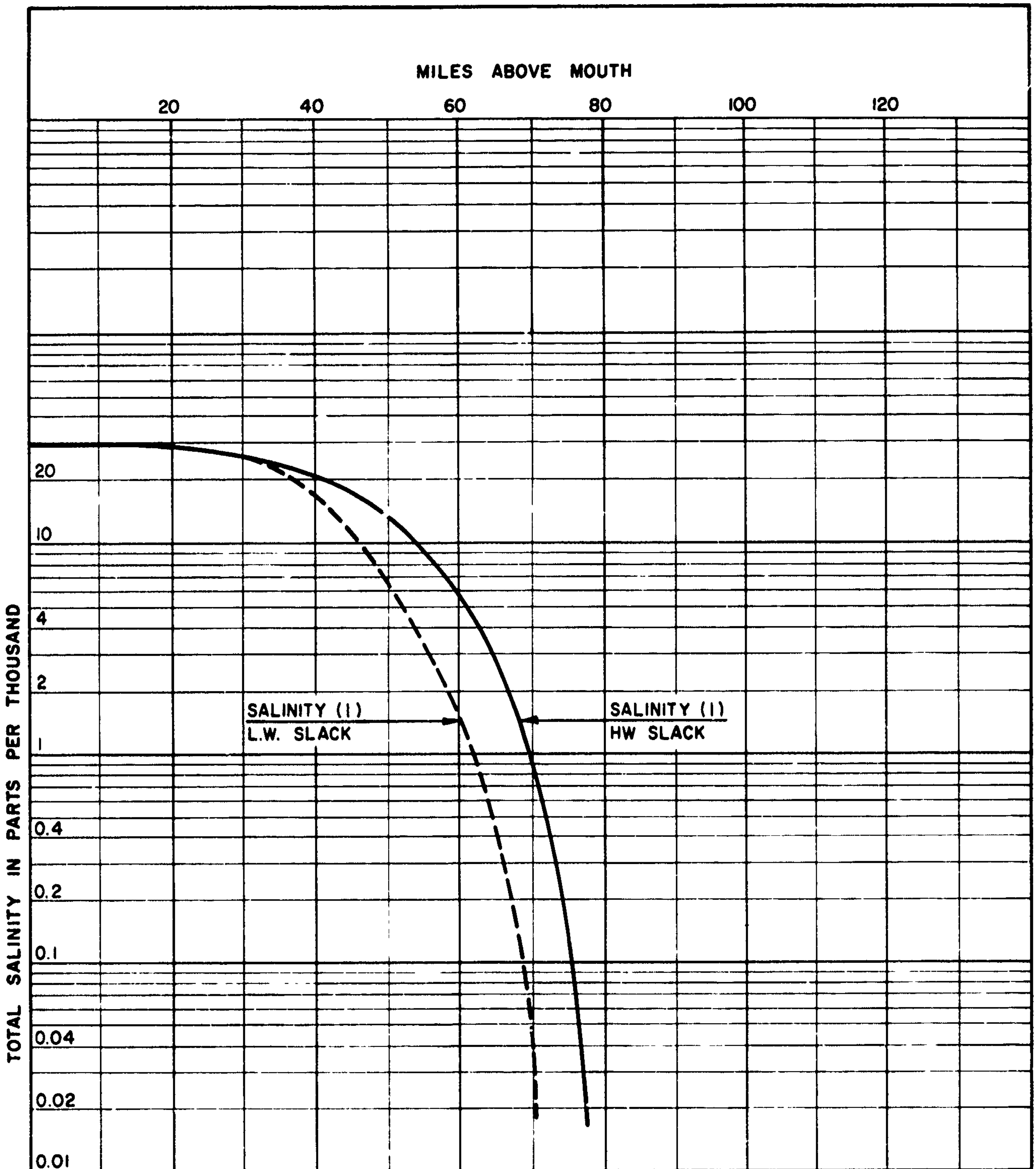
22. The characteristics of estuarine salinity intrusions are often described in such terms as highly stratified, partially mixed, and well-mixed. In a highly stratified estuary, there is an interface above which the water is essentially fresh and the direction of flow is downstream. Below the interface, the water has a salinity approximating that of the source water and the direction of the current is usually upstream. Partially mixed estuaries have considerably greater salinities at the bottom than at the surface and there is relatively rapid increase in salinity at some intermediate depth. Well-mixed estuaries have surface and bottom salinities that are not much different from each other and the rate of change between surface and bottom salinities is fairly uniform. According to Committee on Tidal Hydraulics Technical Bulletin No. 13, if a so-called Estuary Number is 0.15 or greater, the salinity condition is rated as well-mixed. Computation of the Estuary Number for the Delaware according to the equation in the referenced publication shows that

the value is 0.76 for a mean fresh water discharge at the mouth of 20,200 cfs. It would be necessary for the fresh water discharge to reach 55,000 cfs before the Estuary Number becomes 0.15. Therefore, it may be concluded that the Delaware Estuary is well-mixed at all fresh water discharges up to about 55,000 cfs, a fairly infrequent discharge. A great many observations of salinity extending from the mouth to well above the upper limits of brackish water confirm that there is never a great difference between the surface and bottom salinities. However, longitudinal gradients of salinities will still affect the velocity distributions over the depth. It is probable that the estuary becomes partly mixed for fresh water discharges greater than 55,000 cfs, but there are no data to show this.

23. There are one or more so-called velocity null points in every estuary. A null point is defined as that location where the currents at the bottom during the ebb and flood phases are exactly balanced. At the farthest upstream null point, the bottom flood currents downstream of that point predominate over the mean bottom ebb currents; upstream of that null point, the bottom ebb currents predominate over the bottom flood currents. The degree of predominance may be calculated by integrating the bottom flood and ebb currents separately throughout each of these phases to obtain their average velocities, then dividing the ebb value by the sum of the ebb and flood values. When the resulting ratio is 0.50, the ebb and flood average bottom velocities are obviously equal and there is no predominance; the place where such observations were made is the location of the null point. When it is found that the ratio exceeds 0.50, the ebb is predominant; when the ratio is less than 0.50, the flood is predominant. A study was made of a large number of full cycles of current velocity observations in a reach of the estuary extending from mile 9 to mile 64. The fresh water discharges were between 3,500 and 33,000 cfs. The following tabulation gives the results.

TABLE 6

Miles above Mouth	Number of Tidal Cycles: Bottom Flood Exceeds Bottom Ebb	Number of Tidal Cycles: Bottom Ebb Exceeds Bottom Flood
64	0	14
49	0	47
44	2	17
40	6	3
36	4	0
31	2	0
26	2	0
20	2	0
15	0	2
9	0	2



NOTES:

(1) AVERAGE OF TOP & BOTTOM SALINITIES UNDER MEAN TIDE & FLOW CONDITIONS. MEAN FLOWS ARE REPRESENTED BY A FRESH WATER DISCHARGE EQUIVALENT OF 16475 CFS AT AND INCLUDING THE SCHUYLKILL RIVER.

LONG RANGE SPOIL DISPOSAL STUDY

SALINITY PROFILES

U.S. ARMY ENGINEER DISTRICT PHILA.

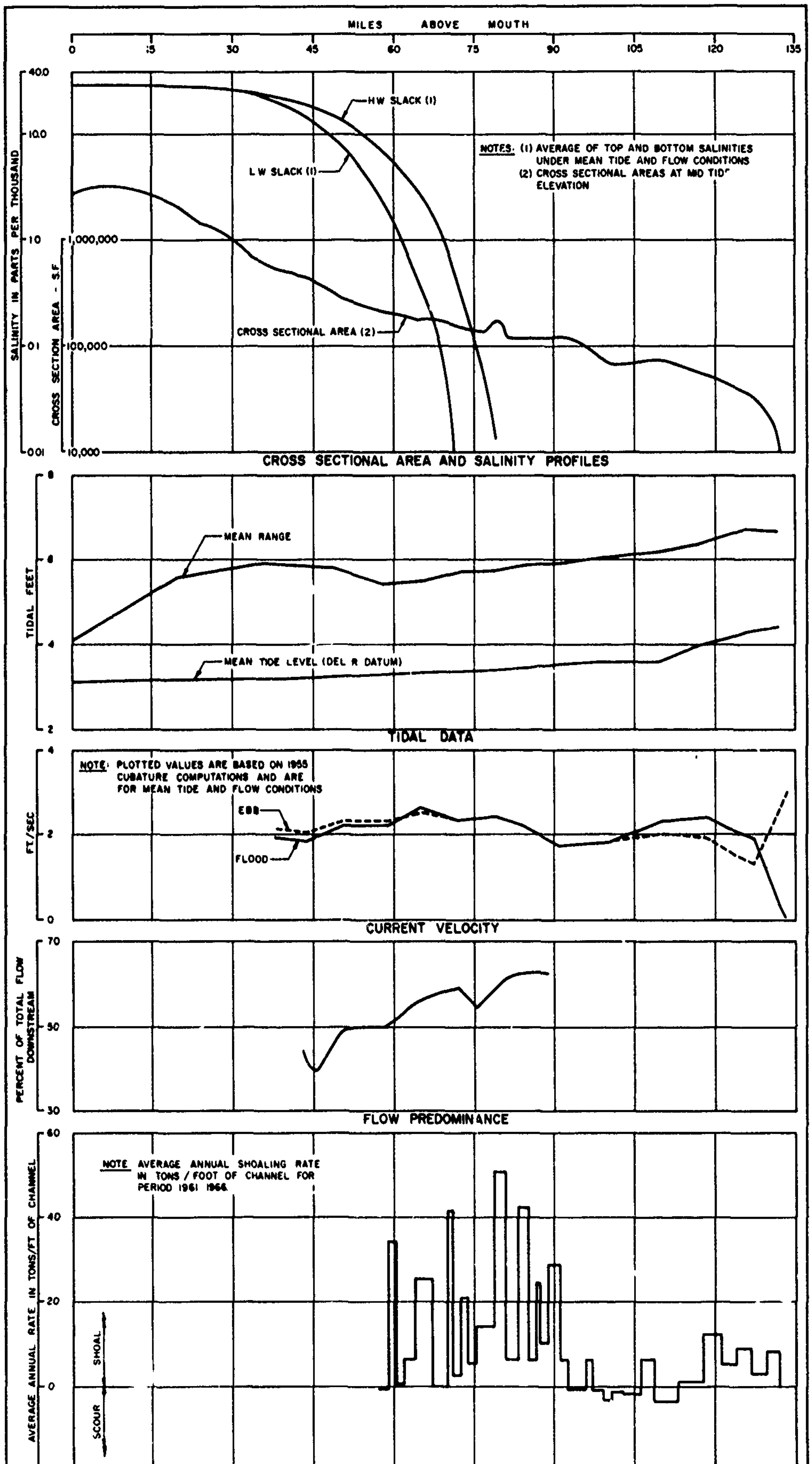
According to these observations, the upstream null point was always downstream of mile 49, for fresh water flows ranging from 3,500 to 33,000 cfs. At mile 44, the null point was generally downstream of that location, but it was occasionally upstream thereof. At mile 40, the null point was more often upstream of that location than downstream. At mile 36, mile 31, and mile 26, the flood was always predominate and the null point was always upstream somewhere. At mile 15 and mile 9, the ebb was always predominant and there must have been a second null point somewhere between mile 20 and mile 15.

24. Committee on Tidal Hydraulics Technical Bulletin No. 13 sets forth a different procedure for determining the location of null points. According to that publication, a null point during a mean fresh water discharge is located at mile 49, which is seen to be upstream of that shown by the observations tabulated above. It is possible that the observations were made at fresh water discharges somewhat greater than the mean value, which could account for the difference between the null point locations determined by the observations and that found by the procedures of Technical Bulletin No. 13. Extension of the computations in that publication shows that the location of the null point definitely shifts downstream when the fresh water discharge becomes greater than the mean rate. Regardless of the exact location of the upstream null point, all suspended solids originating upstream thereof, whether from the watershed above tidewater, erosion of the bed and banks of the estuary itself, or as wastes introduced in the form of suspended solids, cease their seaward net movement upstream of the upstream null point. Similarly, there is no mechanism that can result of a net transport of ocean sediments in the upstream direction between the mouth and the downstream null point, as the ebb current predominates over the flood current downstream of that null point. These two null points prevent shoaling of the navigation channel downstream of the upstream null point and upstream of the downstream null point; this explains the fact that there is virtually no shoaling anywhere below the upstream null point.

25. Plate 6 is a composite plotting of all of the hydraulic and salinity data discussed heretofore as well as certain data pertaining to shoaling and the contributions of suspended and dissolved solids. This shows the interrelationships of the several factors in the problem at hand.

CHARACTERISTICS OF THE BED OF THE ESTUARY

26. Approximately 140 samples of the bottom of the estuary were obtained as part of this investigation. The locations of the sampling are shown on Plate 7, which is seen to show additional sample locations from the ocean adjacent to the mouth of the estuary. The collection method and the methods used in analyses of the samples are described in detail in the Appendix. The results may be summarized as follows. The bottom samples vary both in texture and composition from sandier and more homogeneous sediments in Delaware Bay (mouth to mile 36) to heterogeneous and finer textured organic and inorganic admixtures upstream. The variation of texture by localities is



LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY HYDRAULIC AND SALINITY CHARACTERISTICS

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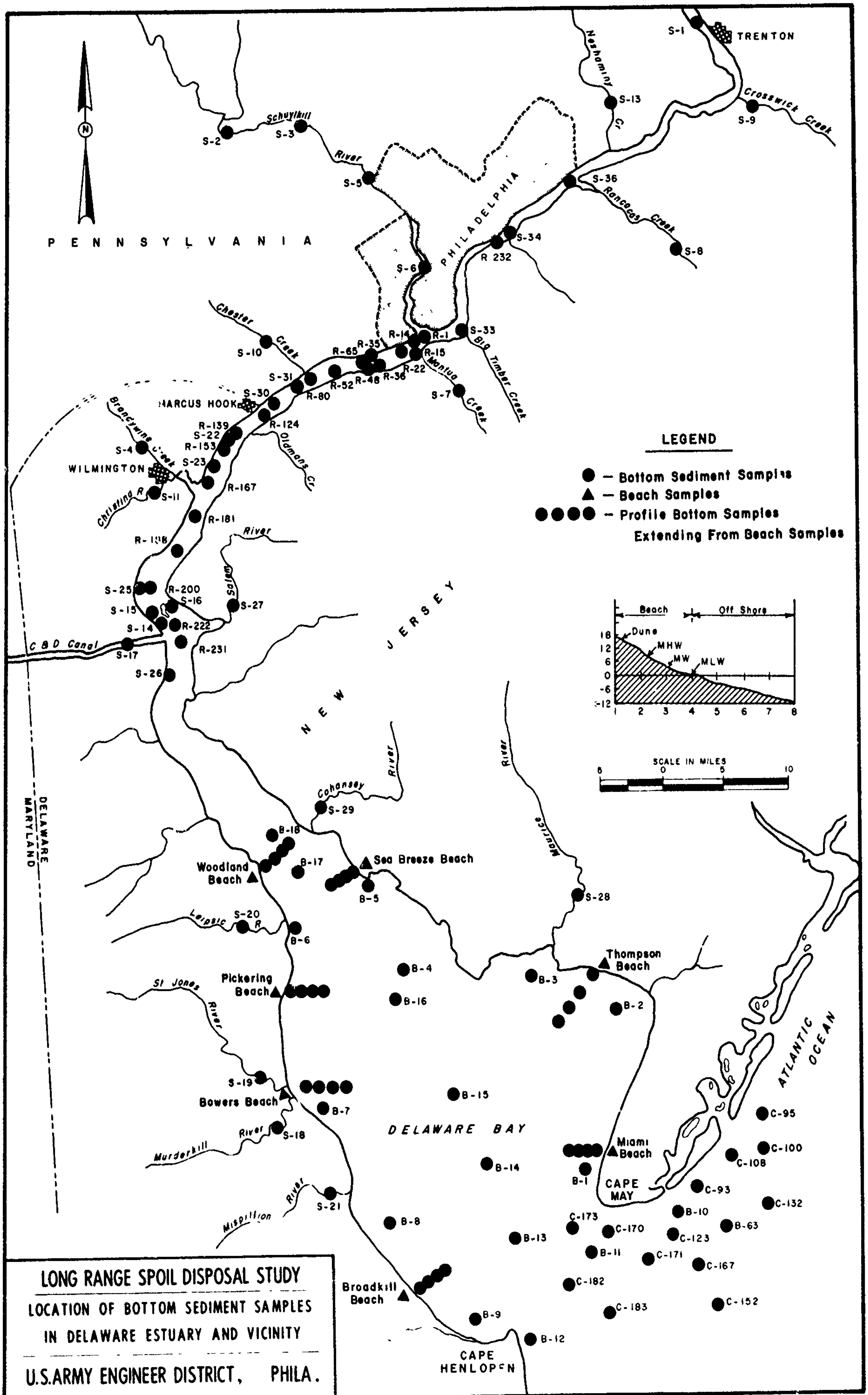

TRENTON
PENNSYLVANIA
PHILADELPHIA
NEW JERSEY
DELAWARE
MARYLAND
MARCUS HOOK
WILMINGTON
Schuylkill River
Chester Creek
Brandywine Creek
Christina R.
Neshaminy Cr.
Crosswick Creek
Rancocas Creek
Big Timber Creek
Mantua Creek
Oldmans Cr.
Salem River
C & D Canal
Cohansey River
Maurice River
Leipsic R.
St Jones River
Murderkill River
Mispillion River
DELAWARE BAY
ATLANTIC OCEAN
CAPE MAY
CAPE HENLOPEN
Woodland Beach
Sea Breeze Beach
Pickering Beach
Bowers Beach
Broadkill Beach
Thompson Beach
Miami Beach
LEGEND
— Bottom Sediment Samples
— Beach Samples
— Profile Bottom Samples Extending From Beach Samples
Beach
Off Shore
Dune
MHW
MW
MLW
SCALE IN MILES
LONG RANGE SPOIL DISPOSAL STUDY
LOCATION OF BOTTOM SEDIMENT SAMPLES IN DELAWARE ESTUARY AND VICINITY
U.S.ARMY ENGINEER DISTRICT, PHILA.

PLATE 7

shown on Plate 8, which is a three-way plot of the size distribution among sand-, silt-, and clay-size materials. The data shown thereon may be further summarized as follows.

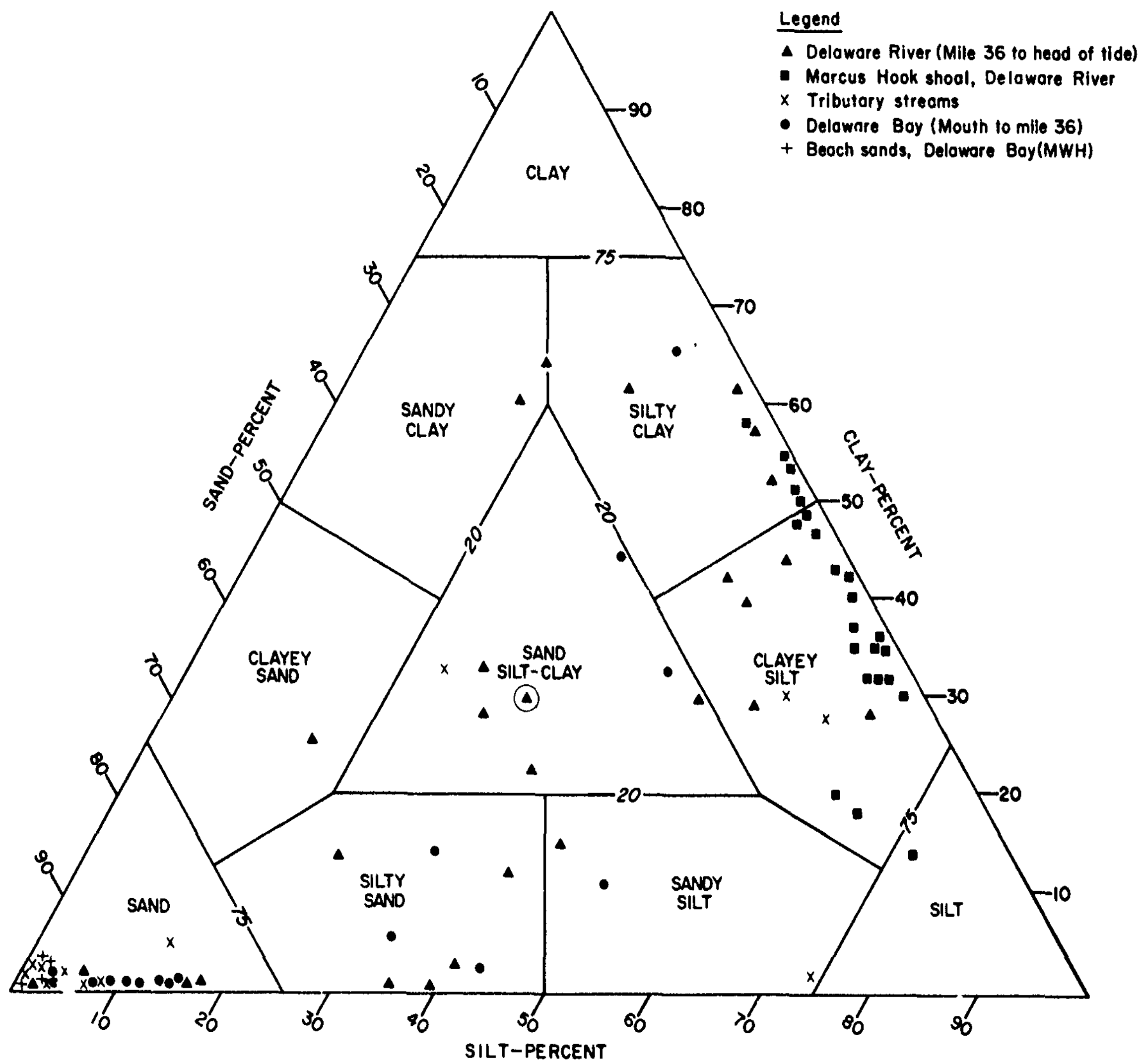
TABLE 7

Classification	Percent of Total Number of Samples in Each Locality: Mile 0 to Mile 36	Delaware Bay Beaches	Mile 36 to Mile 133	Marcus Hook Shoal	Tributary Streams
Sand	53%	100%	18%	0%	69%
Silty Sand	20	0	18	0	8
Sandy Silt	7	0	4	0	0
Clayey Sand	0	0	4	0	0
Sandy Clay	0	0	7	0	0
Sand-Clay-Silt	13	0	18	0	8
Silt	0	0	0	0	0
Clayey Silt	0	0	18	44	15
Silty Clay	7	0	14	56	0
Clay	0	0	0	0	0

Plate 8 and the foregoing tabulation bring out several salient points: The bottom materials of Delaware Bay and its beaches, also the tributary streams, are preponderantly admixtures largely of sand with some finer materials; the estuary above mile 36 has a wide range in texture including all the descriptive terms shown on Plate 8 except silt and clay; Marcus Hook shoal is composed of silty clay and clayey silts which constitute some of the finest textured materials of the estuary.

27. The bases of the data on Plate 8 and the foregoing tabulation are gradation curves developed after sieve and hydrometer analyses. Plate 9 shows the gradations of the materials in the three major shoals in the navigation channel: Pea Patch, mile 57 to 63; Marcus Hook, mile 71 to 80; and Fort Mifflin, mile 80 to 91.

28. The average compositions of the bottom sediments of the estuary, including a few sampling stations beyond the limits of the estuary proper, are shown in Table 8. It is obvious that quartz is the predominant mineral present at all localities except the Marcus Hook shoal. Marcus Hook shoal is exceptional in other respects, but in the opposite direction from that of the quartz exception. Marcus Hook shoal has more of five other principal constituents than does any other locality. Table 9 shows the weighted averages of the six principal constituents (which account for about 96% of the total) for the estuary proper, the estuary proper excluding Marcus Hook shoal, and for the Marcus Hook shoal alone. It also shows the ratios obtained by dividing the Marcus Hook shoal percentages by the percentages for the estuary proper excluding Marcus Hook shoal.



Nomenclature according to Shepard(1953)

Sand sizes: 2.00mm to 0.074 mm
Silt sizes: 0.074 mm to 0.002 mm
Clay sizes: < 0.002 mm
Example of interpretation. The circled ▲ near the center of the diagram is 30% clay, 33% silt, and 37% sand.

LONG RANGE SPOIL DISPOSAL STUDY

SAND-SILT-CLAY CONTENT IN DELAWARE ESTUARY AND BAY BOTTOM SEDIMENTS

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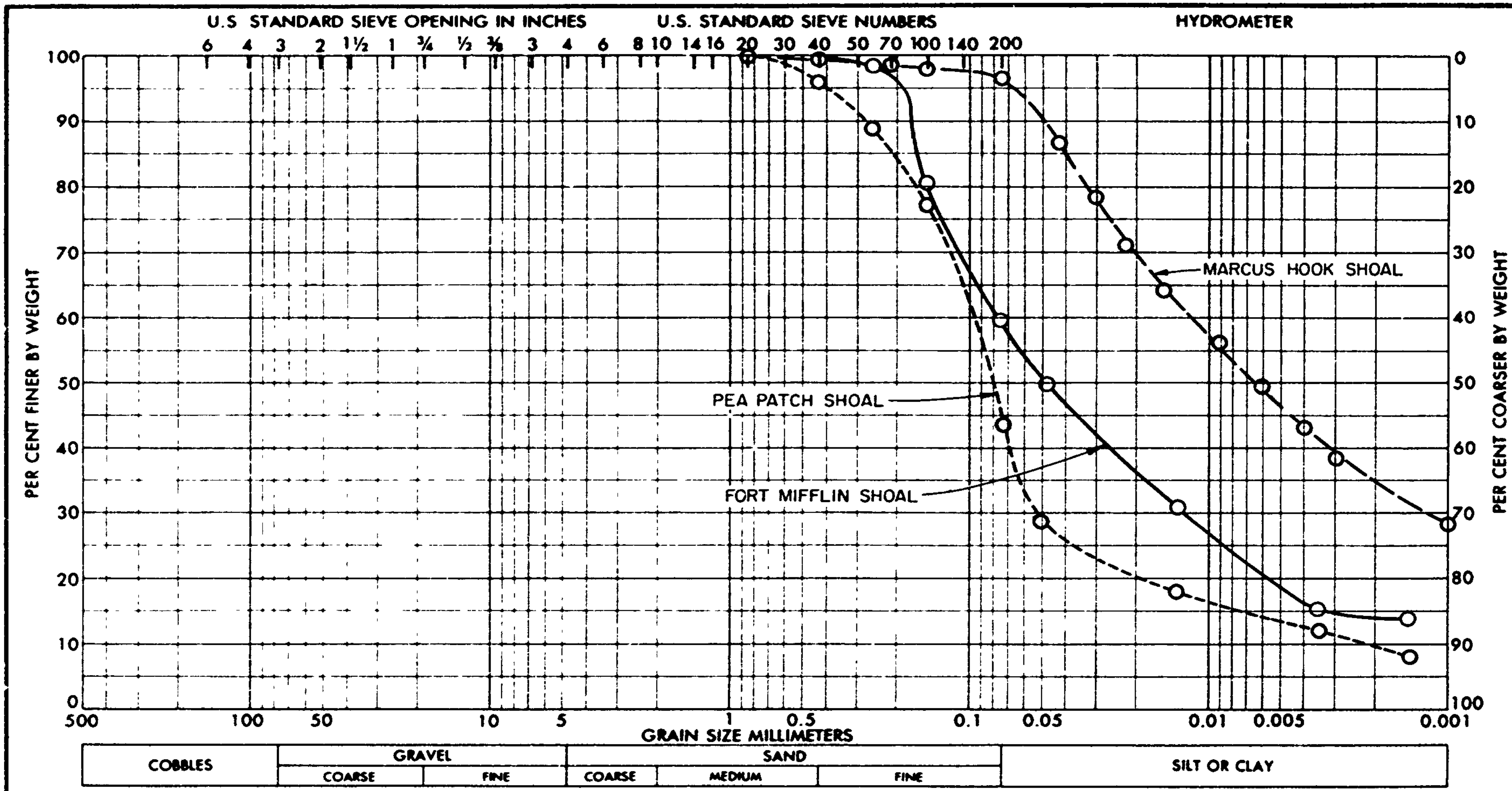

LOCATION	CLASSIFICATION	NAT W%	LL	PL	PI
FORT MIFFLIN SHOAL	DARK BROWN CLAYEY SAND (SC)	70.4	59	27	32
MARCUS HOOK SHOAL	GRAY ORGANIC CLAY (OH)		111	41	70
PEA PATCH SHOAL	BROWN SANDY SILT (ML)	22.7	27	23	4

GRADATION CURVES

LONG RANGE SPOIL DISPOSAL STUDY

SHOAL GRADATION DATA

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PLATE 9

TABLE 8
SUMMARY OF AVERAGE BOTTOM SEDIMENT COMPOSITION IN DELAWARE ESTUARY
FROM TRENTON, N.J. TO THE CAPES.

Constituents	Delaware River North of Trenton	Delaware River Trenton to Philadelphia	Schuylkill River	Fort Mifflin Shoal	Schuylkill River to Wilmington	Marcus Hook Shoal	Wilmington to Ship John Light	Pea Patch Island Shoal	Ship John to Capes	Vicinity of Capes
					Average % Composition of Samples					
Quartz	83.8	63.9	60.4	50.8	56.3	24.5	57.3	51.6	83.6	93.5
Feldspar	2.2	8.2	7.8	9.5	7.1	14.1	9.9	11.6	6.1	3.4
Mica	2.4	1.6	1.3	0.5	0.8	0.1	0.7	1.3	1.0	0.2
Clay Minerals	5.2	15.8	5.9	16.6	12.3	26.4	16.5	14.2	4.3	1.4
Heavy Minerals	2.3	2.1	0.8	0.3	1.3	0.1	1.1	1.1	2.8	0.5
Organic Matter	1.5	2.4	5.3	5.9	3.2	8.0	2.2	3.1	0.5	0.3
Coal	1.6	0.5	15.3	5.6	4.7	5.4	3.2	3.0	0.0	0.0
Diatoms	0.1	5.0	1.4	9.2	13.3	18.0	8.0	12.0	0.3	0.1
Amorphous Iron	0.4	0.3	1.4	1.4	0.8	3.1	0.7	1.8	0.1	0.1
Other	0.5	0.[illegible]	0.4	0.2	0.2	0.3	0.4	0.3	1.3	0.5
					Average % Clay Fraction					
Illite	50	57	65	53	65	61	65	50	59	72
Chlorite	26	29	18	25	15	18	20	20	26	23
Kaolinite	19	8	11	15	15	13	10	25	8	3
Montmorillonite	5	6	6	7	5	8	5	5	7	2
					Number of Bottom Samples					
Number Samples	4	5	13	6	20	12	11	6	15	3

NOTES: 1. Other includes calcite, shells, glauconite, and miscellaneous rock particles and slag.

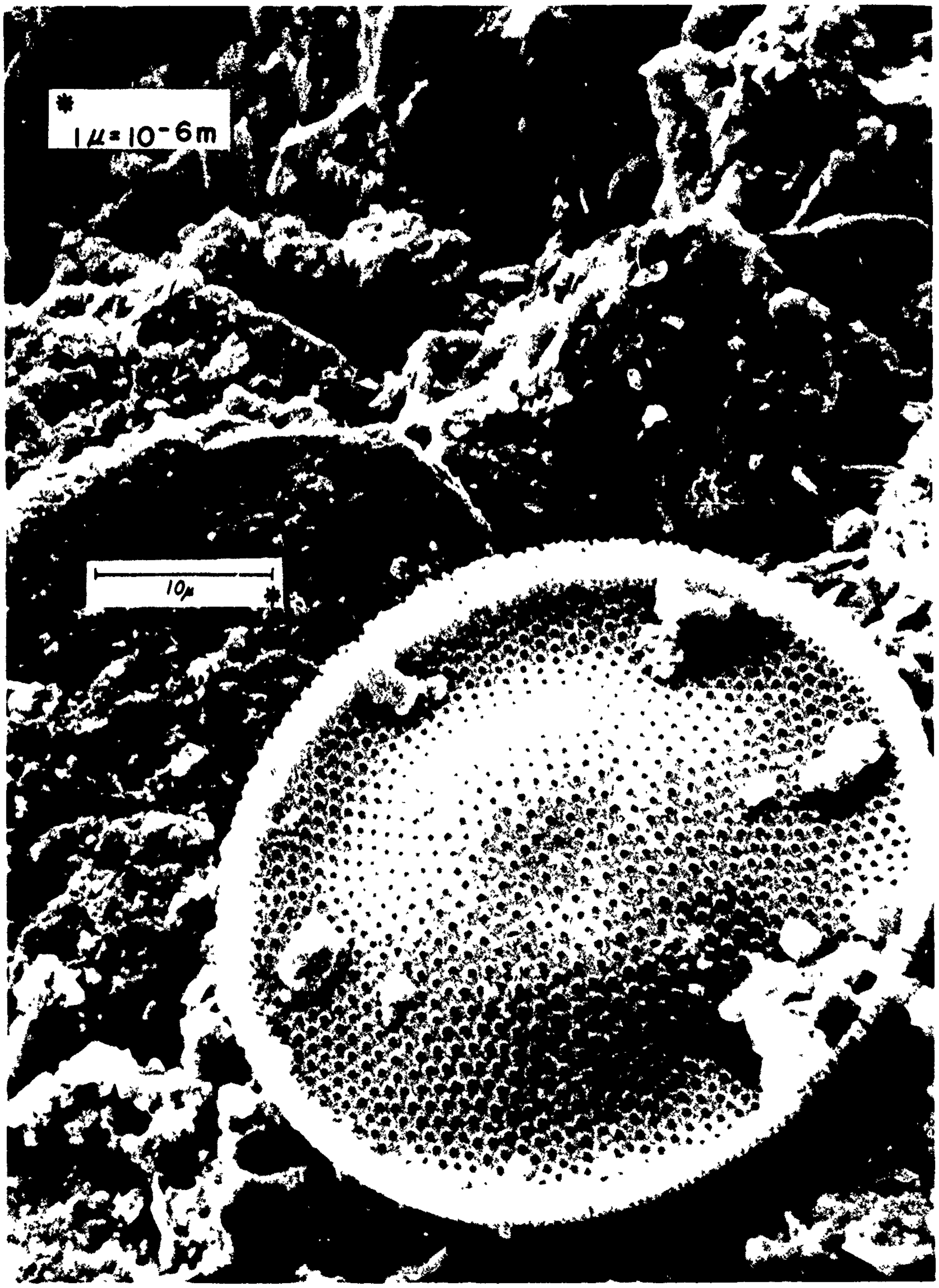
TABLE 9
PRINCIPAL CONSTITUENTS – AVERAGE % COMPOSITION OF SAMPLES

Constituent	Total Estuary Proper	Estuary Proper excl. Marcus Hook	Marcus Hook	Ratio: Marcus Hook/Est. Proper excl. Marcus Hook
Quartz	56.5%	62.6%	24.5%	0.39
Clay Minerals	14.3	12.0	26.4	2.20
Diatoms	9.7	8.1	18.0	2.22
Feldspar	9.1	8.1	14.1	1.74
Organic Matter	3.4	2.6	8.0	3.08
Coal	3.3	2.9	5.4	1.86
Totals	96.3%	96.3%	96.4%	

The above table plainly shows the uniqueness of the Marcus Hook locality in comparison with the remainder of the estuary. It happens that the navigation channel shoals more rapidly than elsewhere in this locality; it accounts for 40.0% of the total shoaling of the navigation channel.

29. Quartz and feldspar comprise the major portion of the sand and silt-size bottom sediments, but these minerals comprise very minor amounts of clay-size sediment. The quartz percentage is conspicuously lower in the three principal shoals, especially that at Marcus Hook, than elsewhere. The feldspar percentage is greater in each of the principal shoals than elsewhere. Clay minerals, principally illite, are concentrated most heavily in the shoal areas. The lowest concentrations are found in the bay, below mile 36, where the material is predominantly sand and silty sand. These minerals usually constitute dispersed particles of less than 2 micron size, but in the flocculated condition such as exists in the shoaling areas, the clay particles along with organic material comprise aggregate particles of the larger "flocs" of silt or fine sand size.

30. Diatoms rank third among the principal constituents of the bottom sediments of the estuary (See Table 9). They are described as opaline diatoms and range in size from 74 to 5 microns with optimum concentration at 20 micron size. As their density is less than that of other bottom sediments, the volume percentage in a shoal is greater than their weight percentage. Table 8 shows that the greatest concentration occurs in the Marcus Hook shoal. The diatom that predominates is called *Coscinodiscus*. This diatom is absent in fresh water and is poorly represented in the marine locations of the bay. A number of factors affect diatom populations in estuaries, including temperature, salinity, turbulence, nutrients, light, and pollutants. The effects of pollutants which contain imbalanced nutrients, generally favor fewer species but greater populations of the species adapted to the pollution. Phosphorus is present in greater abundance in the Marcus Hook vicinity than elsewhere in the estuary, a fact which correlates with



Scanning Electron Micrograph (2420x) of Coscinodisus species of diatom frustule in Marcus Hook shoal sediments. This diatom variety is more abundant in this shoal than at other locations in the estuary.

PLATE 10

the highest diatom occurrence in that locality. It is of interest to note that the occurrence of diatoms in the shoals of the estuary prior to 1946 was several times lower than presently occurs (1972). Plate 10 shows *Coscinodiscus* as revealed by a scanning electron microscope.

31. Organic matter ranks fifth among the principal constituents of the bottom sediments of the estuary. It ranges from trace amounts in the bay to 8% by dry weight, with the greatest concentrations occurring in the organic clayey silts of of the shoals, especially that in the Marcus Hook vicinity. The term organic matter refers to a variety of amorphous organic materials which include vegetation debris, animal wastes from sewage, and organic chemical effluents from industry and municipalities which have not decomposed and accumulate as part of the bottom sediment in the estuary. While diatom frustucles and anthracite coal also include a considerable portion of the bottom sediments with origin from the organic realm, these materials are not included as organic matter in this investigation. Analyses of the organic matter using chromatography techniques disclosed that 80 to 95 percent of the organic matter is proteinaceous matter and that the amino acid portion of this proteinaceous matter in the estuary differs upstream and downstream of the Marcus Hook locality. The "fatty acid" content is higher in the Fort Mifflin area, which is close to one of the major treated sewage outfalls of the City of Philadelphia. Hydrocarbons were found to be relatively higher in the bottom sediments seaward of Wilmington. The generally high content of organic matter is due to the polluted condition of the river water, which inhibits the oxidation of organic materials.

32. The last of the six principal constituents of the bottom sediments of the estuary (see Table 9) is coal. This is anthractie, and it reached the Delaware principally from the Schuylkill watershed. A much less important source was the Lehigh watershed, far upstream from the head of tide of the estuary. A washing technique used in preparing the anthracite for the market was responsible; the wash water was discharged into the nearest creek, thence it gradually worked its way downstream to the Schuylkill and the Lehigh. A study made in 1946 resulted in methods for preventing the further introduction of anthracite fines and other materials from the mines into the Schuylkill, and the removal of millions of cubic yards of the accumulated deposits in the Schuylkill itself. The study included determinations of the percentages of anthracite and other mine wastes in the tidewater portion of the Schuylkill and in the Delaware both upstream and downstream of the mouth of the Schuylkill. Similar determinations were made during the present investigations, and the results of the 1946 and the present work are shown in Table 10. All work on the clean-up of the Schuylkill was completed in 1955. Table 10 shows that there has been a considerable reduction of anthracite content in the tidewater portion of the Schuylkill and in the Delaware in the 17 years since completion of the work, but it seems likely that anthracite fines will be found in the bottom sediments for a long time in the future.

TABLE 10
PERCENT ANTHRACITE MINE WASTES

Location	Percent Dry Weight 1946	1972
Schuylkill River:		
Fairmount Dam to University Ave.	53.0%	43.4%
University Ave. to Passyunk Ave.	53.0	29.9
Passyunk Ave. to mouth	42.0	15.3
Delaware River:		
Mouth of Schuylkill to a point 10 miles upstream	12.0	1.1
Mouth of Schuylkill to Marcus Hook	5.0	3.4
Marcus Hook to Pea Patch Is.	3.0	2.1

33. Table 9 shows that the six principal constituents of the bottom sediments account for about 96% of the total. The remainder is made up of so-called heavy minerals, amorphous iron, mica, calcite, shells, glauconite, and miscellaneous rock particles and slag. Also present are phosphorous and very small quantities of arsenic and heavy metals such as mercury, lead, nickel, copper, zinc, and cadmium. Although their concentrations are small, many of these other ingredients of the bottom sediments are of significance from either the viewpoint of the overall quality of the estuary and its waters or from a diagnostic viewpoint. Some of these materials may also be significant as flocculating agents. They will be discussed later in this report.

34. The foregoing descriptions of the compositions of the bottom sediments are based on samples that for the most part were collected in 1969. As it was felt possible that the compositions may have been different in earlier years, four disposal areas that had been used for long times were examined in detail. Samples were taken at depths below the surface that were probably representative of the fills that were made during several brackets of years. However, only one of these disposal areas was used exclusively from one shoal; the other three were used for more than one shoal and it would therefore be difficult, if not impossible, to correlate these results with samples of the shoals themselves made in 1969. Fortunately, this one disposal area (Oldmans Creek) was used for the deposit of shoal material from the Marcus Hook vicinity where the most serious shoaling throughout the navigation channel occurs. Table 11 compares the composition of the materials in that disposal area with the 1969 composition of the shoal itself.

35. Prior to 1955, the method of dredging consisted of the use of hopper dredges on the shoal, and pipeline dredges to rehandle the dredged material ashore. The hopper dredges dumped their loads in basins that were dredged deeper than the surrounding bed of the estuary and the pipeline dredge pumped the accumulated material ashore behind enclosing dikes. In addition, the hopper dredges pumped beyond overflow in the interest

TABLE 11
COMPARISON OF COMPOSITION OF MATERIAL IN OLDMANS CREEK DISPOSAL AREA WITH SAMPLES OF THE SHOAL COLLECTED IN 1969

Material	Samples from the disposal area Pre 1946	1946–58	1958–62	Samples from the Shoal 1969
	% Average Composition of Total Sample			
Quartz	59.8	30.5	43.5	24.5
Feldspar	2.0	9.1	6.6	14.1
Organic Materials	4.8	10.3	9.3	8.0
Coal	1.0	1.8	2.3	5.4
Diatoms	1.0	9.7	9.0	18.0
Clay Minerals	29.0	33.0	24.8	26.4
Fe_2O_3	2.0	4.8	3.8	3.1
PO_4	0.3	0.6	0.5	0.7
	mg/1000g of dry solids			
Mercury	1.7	0.9	0.8	2.7*
Lead	80	200	230	200*
Nickel	15	53	72	50*
Copper	40	60	60	60*
Zinc	2150	280	440	400*
Cadmium	2	1	3	2*
Arsenic	20	25	26	25*

*Average of composite samples MH 6–1 (1969), MH 11–1 (1969) & MH 72 (1972)

of obtaining the so-called economic load. The material that overflowed was finer than that retained in the hoppers. There was also a loss of fines in the dumping process, with the result that the materials rehandled into the disposal area were heavier and coarser than the texture and composition of the shoal itself. Because it was found that these procedures were in effect contributing to the shoaling of the channel, and because it was also found that the texture of the shoal itself was gradually becoming finer, a very important change was made in the dredging process. This was done in two steps: The first involved the use of a so-called sump rehandler; the second involved the provision of facilities on the hopper dredge such that the material was pumped directly ashore. In both cases, the material removed from the shoal was placed in the disposal area totally; there was no loss of material. It follows that these basically different methods of dredging and pumping the dredged materials into disposal areas would result in changes of the characteristics of the materials retained in the disposal areas. Certainly the materials retained in the disposal areas prior to 1955 have a smaller percentage of fines than those placed after 1955, and it is possible that other differences may have resulted that were due entirely to the dredging and disposal processes. However, there are differences that may have been caused by basic changes in the shoal. Table 11 shows that it is likely that there was a marked decrease in the amount of quartz, an increase in the feldspar content, a great increase in the diatoms, and an increase in the phosphates. Among the heavy metals present, mercury, lead, nickel and copper show substantial increases and zinc is present in the shoal in a smaller quantity than in the disposal area in earlier years.

CHARACTERISTICS OF THE WATERS OF THE ESTUARY

36. One of the more important characteristics of the waters of the estuary, salinity, has already been discussed. This is not the only one involved in the transport and deposition of sediments. Some of the other factors are temperature, pH (hydrogen ion concentration), Eh (measure of state of oxidation or reduction of the water system), DO (dissolved oxygen), fecal coliforms, and suspension of such heavy metals as zinc and iron.

37. The temperature of the water at Philadelphia varies seasonally from a maximum of about 80°F to a minimum of about 34°F. Detailed information on temperatures throughout the estuary is not available, but available data indicate that it is likely that maximum temperatures upstream of Philadelphia are probably lower, those in the reach extending 30 miles downstream of Philadelphia are about the same, and those downstream of that point are probably lower than at Philadelphia. The minimum given for Philadelphia is fairly close to that experienced throughout the estuary. It is also likely that there are local concentrations of heat due to the use of the estuary's waters for cooling purposes at industries, especially at electric generating plants. Water temperature affects water viscosity, which is a factor in the transport of sediments; viscosity decreases with increasing temperatures, and the competence of water to keep materials in suspension decreases with decreasing viscosities, all other factors remaining constant.

38. pH values do not appear to vary seasonally, but they do change with location. Upstream of Philadelphia, there is a fairly uniform trend from neutral at Philadelphia (pH = 7) to pH = 7.4 near the head of tide. Downstream of Philadelphia, the water becomes more acid to attain the lowest value of pH = 6.5 approximately, at a point about 30 miles downstream. Thence, the trend reverses and the water becomes less acid and becomes neutral about 45 miles below Philadelphia. Overall, pH decreases from the highest value near the head of tide to its lowest value 63 miles downstream, thence it increases. The increasing acidity is probably due to the inflow of sewage and industrial wastes in the upper and middle portions of the estuary, and the gradual recovery downstream thereof is due to the increasing dilution by seawater. There apparently is a relationship between pH values and the electric charge on particle surfaces, as shown by a phenomenon called electrophoresis, which is defined as the migration of suspended particles under the influence of an electric field. When the pH is such that the velocity of migration is zero, flocculation of suspended particles is more likely to occur. This pH is called the "isoelectric point." It has been found that the various constituent minerals have isoelectric points at var-

ious pH values, but at Marcus Hook it appears that the optimum isoelectric pH for the composite sample is in the vicinity of 6 and higher. It has been found that the pH at Marcus Hook is generally in the vicinity of 6.8.

39. Dissolved oxygen in the waters of the Delaware varies with location and seasonally. There is a so-called "Dissolved oxygen sag" that generally centers in the Marcus Hook vicinity; upstream and downstream of this reach, the dissolved oxygen content is greater at all seasons of the year. During the months of June and July 1969, for example, the DO value at Marcus Hook (mile 80) was approximately 1.8 while 20 miles upstream and downstream the values were 2.2 and 3.4 respectively. In March 1969, the DO at Marcus Hook was 4.6 while the values 20 miles upstream and downstream were about 8.5. The significance of dissolved oxygen in the water lies in the fact that it facilitates digestion of organic wastes by micro-organisms. When the DO value becomes very low, organic debris accumulates more rapidly and becomes part of the shoal.

40. Fecal Coliform counts show variations with location in the estuary and seasonally. The highest counts, regardless of season, are at Philadelphia; in July 1969, the average was about 220,000 per milliliter. At Marcus Hook, the count was 130,000 per milliliter in the same month. In March 1969, the counts at Philadelphia and Marcus Hook were 5000 and less than 1000 respectively. Plainly, there is much organic matter in the Delaware to help account for the shoaling.

41. Normally, the concentrations of total iron were found to range from 0.6 mg/l at mile 122.5 to 1.0 mg/l at mile 84. The concentration increases to 1.2 mg/l at Marcus Hook (mile 78), then increases erratically to 1.8 mg/l at mile 61. The concentration then appears to begin a decreasing trend, reaching a value of 1.6 mg/l at mile 55. It is suspected that the relatively high total iron is probably significant in the flocculation process at Marcus Hook shoal. It is noted that the June 1969 readings for total iron were anomalously high, ranging from 6 to 8 mg/l. No satisfactory explanation has been found for this phenomenon and no other readings in the period of record studied (1967–73) approached this range of values. All other metals normally occur in amounts less than 0.1 mg/l although all metals occasionally showed higher

TABLE 12

DISTRIBUTION OF DRAINAGE AREA BETWEEN PHYSIOGRAPHIC DIVISIONS

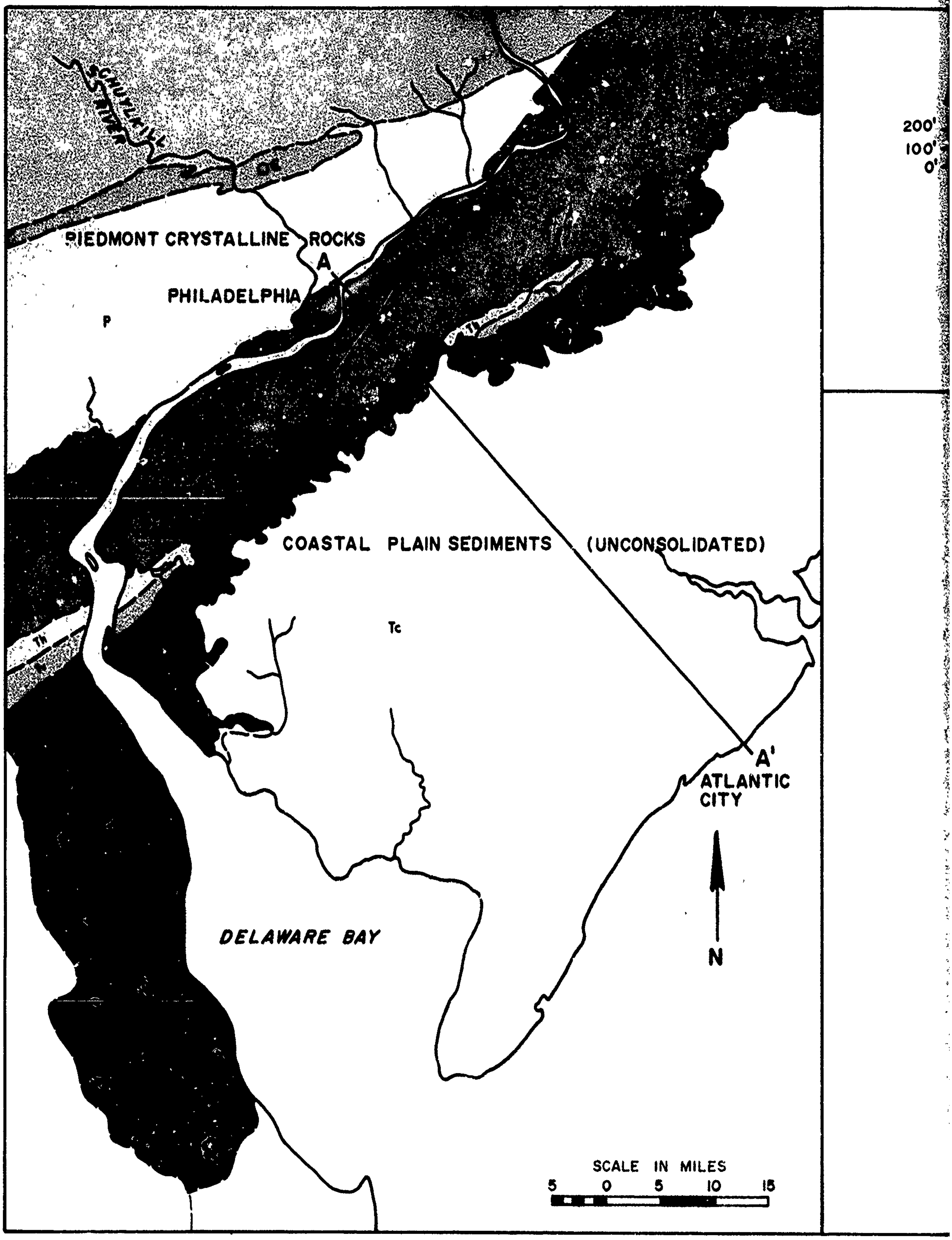
Appalachian Highlands drainage area above Trenton	6,780 Sq. Mi.
Additional Appalachian Highlands drainage area below Trenton	3,235 Sq. Mi.
Total Appalachian Highlands drainage area	10,015 Sq. Mi. (78%)
Total Atlantic Coastal Plain drainage area	2,750 Sq. Mi. (22%)
Total drainage area	12,765 Sq. Mi.

concentrations (up to 1.0 mg/l) at various points and at various times in the estuary.

42. The drainage area tributary to the Delaware Estuary lies within two of the major physiographic divisions of the United States, the Appalachian Highlands and the Atlantic Coastal Plain. Table 12 shows the distribution of the total drainage area between these two divisions. The Fall Line divides these two divisions. Plate 11 shows this Line as the boundary between the Atlantic Coastal Plain (the "K" formation, i.e., Cretaceous) and the Piedmont Crystalline Rocks formation. This boundary tends to run in a NE–SW direction closely bordering the Pennsylvania-Delaware side of the estuary from the vicinity of Wilmington to Trenton, where it crosses into New Jersey and terminates the estuary. Most of the drainage area above Trenton was glaciated at least three times and possibly four times during the last million years. The last ice sheet, known as the Wisconsin, retreated from the region about 10,000 years ago. Terminal moraines are found along several broad bands in the lower 30 miles of that portion of the watershed adjoining the upper limit of the estuary. The Appalachian Division is subdivided into Provinces, the most important of which (in the Delaware watershed) are the Applachian Plateau and the Piedmont. The underlying rocks of the Appalachian Plateau are sandstone, shale, and nonmarine conglomerates. The unconsolidated sediments consist of unsorted materials ranging in size from clay to large boulders. Sand and gravel are abundant where the materials are derived largely from sandstone, but clay predominates where the parent rocks are mostly shale. In the broad upland areas the till is generally less than 30 feet thick; in some places it is very thin. This Province is rugged, well-forested, and relatively thinly populated. The Piedmont's underlying rocks include granite, gneiss, schist, soft shale, sandstone, diabase, basalt, argillite, limestone and dolomite. The soils in this Province are deep and well-drained and are derivatives of the parent rocks listed above. This Province does not have so much forest cover as the Appalachian Plateau and it is extensively cultivated for agriculture. There are numerous towns and cities in this region. The rocks of the Atlantic Coastal Plain are usually at great depths below the surface, and the soils are marine laid deposits, mostly sands, silts and clays. This Division displays relatively slight relief, it contains numerous marshy areas, and the better drained portions are extensively cultivated for agriculture. Much of this part of the watershed is occupied by cities, towns, and suburban areas.

COMPARISON OF SHOALING AND SUPPLIES OF SHOALING MATERIALS

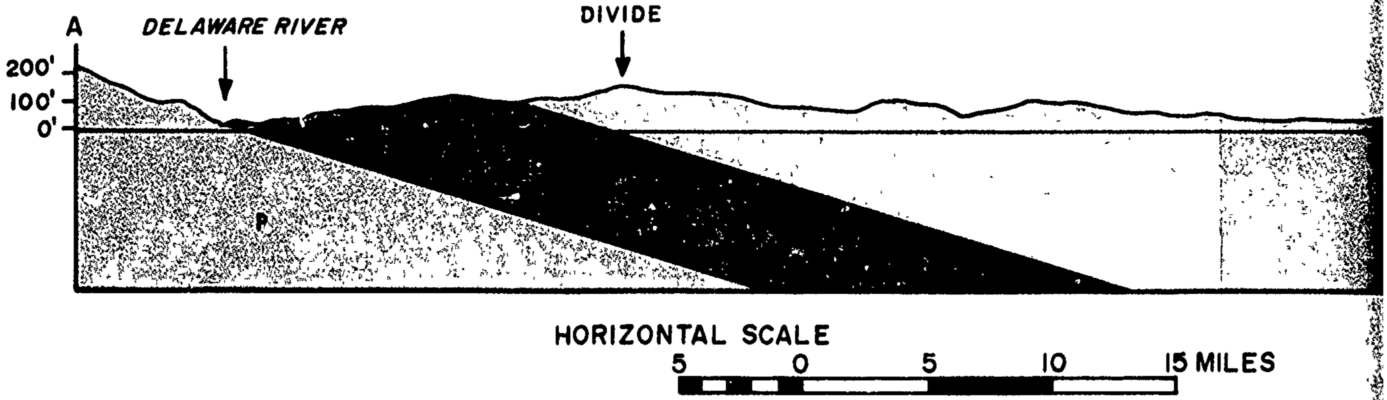
43. Under this heading, it is proposed to discuss the inflow of shoaling materials from all sources, beyond the estuary itself, supplies from within the estuary, for example, those due to erosion of the bed and banks of the waterway, and the shoreline to shoreline shoaling. If completely accurate information were available, the total shoaling should be equal to the total of the inflow of sediment and that resulting from erosion of the bed and banks of the estuary.



SCHUYLKILL RIVER
PIEDMONT CRYSTALLINE ROCKS
A
PHILADELPHIA
P
COASTAL PLAIN SEDIMENTS (UNCONSOLIDATED)
Tc
A'
ATLANTIC CITY
N
DELAWARE BAY
SCALE IN MILES
5 0 5 10 15
200'
100'
0'

2

SECTION A – A'



EXPLANATION

TERTIARY

Tc COHANSEY SAND

KIRKWOOD FORMATION

VINCETOWN SAND

Th HORNERSTOWN MARL

CRETACEOUS

INCLUDES: THE FOLLOWING FORMATIONS RED BANK SAND, NAVESINK MARL, MOUNT LAUREL & WENONAH SANDS MARSHALL-TOWN FM, ENGLISHTOWN, WOODBURY & MERCHANTVILLE CLAY; NONMARINE SEDIMENTS SUCH AS MAGOTHY, RARITAN, PATAPSCO, PATUXENT

TRIASSIC

Tr TRIASSIC SEDIME
& IGNEOUS INTRU

ORD-CAMB

ORDOVICIAN & C
CARBONATE FOR

PALEOZOIC

P PALEOZOIC & PRE
SCHIST, GRANITE,
CRYSTALLINE RO

NOTE: 1. SECTION A-A AFTE
PAPER 381 PLATE
2. GEOLOGIC MAP AFT
MAP OF DELAWARE
ADJACENT NEW JE

LONG RANG
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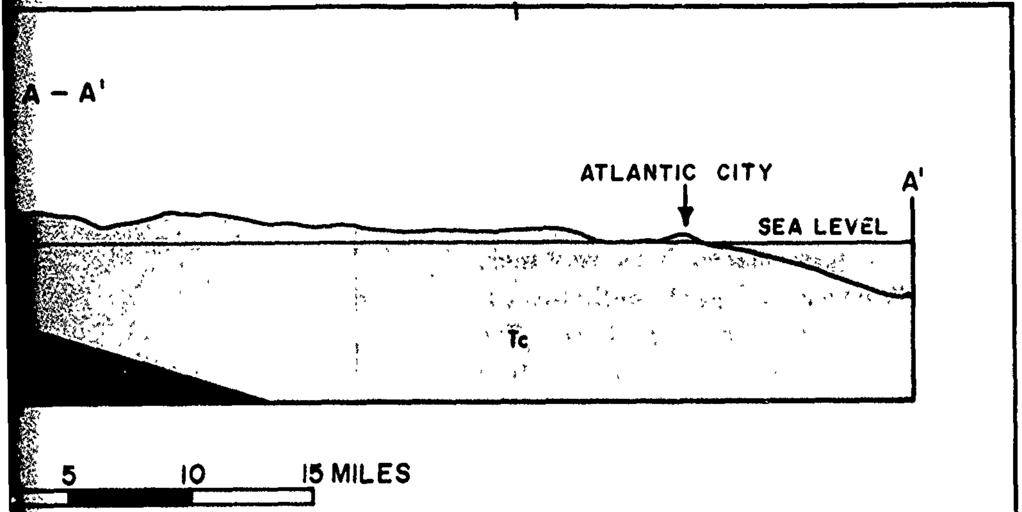
3



NATION

TRIASSIC

Tr TRIASSIC SEDIMENTARY FORMATIONS & IGNEOUS INTRUSION

ORD-CAMB

ORDOVICIAN & CAMBRIAN CARBONATE FORMATIONS

PALEOZOIC

P PALEOZOIC & PRECAMBRIAN GNEISS, SCHIST, GRANITE, & OTHER RELATED CRYSTALLINE ROCKS

NOTE: 1. SECTION A-A AFTER USGS PROFESSIONAL PAPER 381 PLATE 6.
2. GEOLOGIC MAP AFTER USGS GEOLOGIC MAP OF DELAWARE RIVER BASIN AND ADJACENT NEW JERSEY.

LONG RANGE SPOIL DISPOSAL STUDY

GENERALIZED GEOLOGIC MAP AND SECTION OF DELAWARE ESTUARY AND VICINITY

U. S. ARMY ENGINEER DISTRICT
PHILADELPHIA

PLATE 11

44. All possible sources of sediment inflow are listed below:

1) Erosion of upland areas and bed and banks of non-tidal watercourses;

2) Scour of bed of the estuary;

3) Erosion of banks of estuary;

4) Dredging;

5) Storm and sanitary sewer outfalls;

6) Industrial pollutants;

7) Natural organic processes, i.e., the accumulation of remains of marine organisms, vegetal and animal;

8) The Atlantic Ocean.

9) Airborne settleable particulates

45. The contributions from the upland areas tributary to the estuary can best be determined by sediment discharge observations in the tributary streams. Such observations have been made at the following locations.

TABLE 13

SEDIMENT STATIONS ON TRIBUTARIES OF DELAWARE ESTUARY

Tributary and Observation Location	Drainage Area Sq. Mi.	Period of Record	Sampling Frequency*
Delaware River – Trenton	6,780	9/49 to present	D
Crosswicks Cr. – Extonville	84	5/58 to 9/60	I
		2/65 to present	W
Neshaminy Cr. – Langhorn	210	11/56 to 7/58	I
Schuylkill River – Manayunk	1,810	11/47 to present	D
Wissahickon Cr. – Fort Washington	41	10/63 to present	W
White Clay Cr. – Newark	88	8/63 to 12/64	W
		1/65 to present	M
Brandywine Cr. – Wilmington	314	12/46 to 9/61	D
		7/62 to 7/63	I
		7/63 to present	W
Maurice River – Norma	113	2/65 to present	W
Total	9,440		

Note: *Sampling Frequency Code: D = Daily
W = Weekly
M = Monthly
I = Intermittent

The total drainage area tributary to the estuary is 12,765 sq. mi., exclusive of the water surface area of the estuary itself. Of this total, 9,440 sq. mi. have been gaged for sediment discharge, which is 74%. The table also shows that 8,904 sq. mi. have been gaged daily, which accounts for 70% of the total drainage area. It is considered that this mass of data affords a reasonably accurate indication of the contribution of sediment from the tributary area above tidewater. This material settles out in the estuary; hydraulic conditions indicate that little, if any, is flushed out to the ocean (see paragraph 24 of this report). Analysis of these records, and inferences for the the contributions from the ungaged areas, results in the finding that the contributions from all upland sources averages 1,402,000 tons per year.

46. From the head of tide to Channel Station +212+000 (Mile 61), the net change in the estuary beyond the limits of the navigation channel and the anchorages has been scour, although some of the reaches have shoaled moderately. Below Channel Station +212+000, the only comparable data ends at Channel Station +275+000 (mile 50). These deteminations are based on comparisons of the two latest shore to shore surveys available. Table 14 summarizes these data.

TABLE 14

EROSION OF BED OF ESTUARY
(Beyond Channel and Anchorage Limits)

Miles above Mouth	Channel Stations	Reach	Net Scour Cubic Yards per year
132 to 102	-160 to 0+000	Trenton to Philadelphia	1,609,000
102 to 61	0+000 to +212	Philadelphia to Bulkhead Bar Rge.	1,022,000
61 to 50	+212 to +275	New Castle Rge. to Baker Rge.	-
50 to 0	+275 to Mouth	Liston Rge. to Mouth	(no data)
		Net Change	2,631,000

Some part of the scour listed above is not due to natural causes, but to borrow for landfill purposes or due to removal of commercial sand and gravel.

47. Erosion of the banks of the estuary as a source of sediment is not considered a significant contributor. Much of the shoreline is bulkheaded or revetted, and the remainder is marshy with vegetation that resists erosion. There is no appreciable amount of recession.

48. Dredging is listed in paragraph 44 as a possible source of sediment contributions. Certainly, the net result of all dredging in the estuary is a loss of material in the bed of the estuary, but it is possible that some of the dredging is so carried out that materials are placed in suspension. This material ultimately settles out in the estuary, and thus is a contribution to the shoaling at these places. There are three kinds of dredging performed in the estuary: Maintenance of navigation facilities; dredging performed for the purpose of obtaining fill; and dredging to obtain commercial sand and

gravel. Most of the dredging performed in maintaining the navigation facilities is by means of direct pumpout hopper dredges. They are so operated as to cease pumping when the hoppers are filled to capacity; they are no longer operated to permit overboard flow of the hoppers in the interest of obtaining a more dense load. When the hoppers are filled, the dredge moves to an unloading point, where the contents are pumped out to enclosed disposal areas. The passage of the dredge over the shoal with its trailing drags possibly stirs up some of the shoal material, but it is considered that this quantity is negligible in the overall picture. Some maintenance dredging of navigation facilities is performed by pipeline hydraulic dredges. These pump the material directly into enclosed disposal areas. It is possible that the operation of the cutter head is such that more material is stirred up than is sucked in by the pumps. However, a study of one of these dredges conducted when it was suspected that such was the case showed that the losses were negligible. There is some maintenance of navigation facilities performed by means of bucket dredges, using scows to transport the material to a semi-enclosed rehandling basin where it is dumped and than pumped into a confined disposal area by a pipeline dredge. This process is perhaps the most likely of all dredging methods to contribute sediment that may cause shoaling elsewhere, but the volume thus dredged is relatively small and the operations are under careful surveillance by the Corps of Engineers. Dredging to obtain borrow for landfill purposes (a relatively infrequent occurrence) is performed by pipeline hydraulic dredges; the same comments as given for dredging of navigation facilities with such equipment apply. Whenever material is pumped, it is in the form of a slurry containing a considerable quantity of water. The slurry is retained in the disposal area (or in an area being filled) until the major portion of the solids contained in the slurry settles out. However, a small amount of the solids remains in suspension and passes out of the disposal area, usually reentering the estuary. The effluent from the disposal area (or landfill operations) which contains solids ranging from 0 to 13.5 grams per liter and averages 8 grams per liter represents a substantial contribution and is included in the sediment balance. Dredging for commercial sand and gravel once was carried out on a large scale in the estuary above Philadelphia, but such operations are now on a much smaller scale. The dredge removes the material from the bottom by means of an endless chain of buckets. The material is then processed aboard the dredge into various sizes, washed clean of fines, and the wash water is discharged overboard. Although it is likely that the fine material in the wash water contributes a measureable quantity of suspended sediments, the amounts have not been determined. It is assumed that this source of sediment is not significant in an overall sediment budget. In summary it is found that all dredging activities carried out in Delaware Estuary contribute 385,000 tons per year.

49. A study by the FWPCA of the storm and sanitary sewers discharging directly into the estuary showed that a total of 574,000 tons of solids was discharged per year. This included 441,000 tons of dissolved solids and 133,000 tons of

suspended solids.

50. Studies of the contributions of solids by industrial outfalls showed that the total quantity of solids discharged was 875,000 tons per year; of this total, 818,000 tons were in the form of dissolved solids and 57,000 tons were suspended solids.

51. The next source of shoaling material listed in paragraph 44 results from natural organic processes. The appendix discusses diatom production in detail. It shows the diatom content of samples from a number of locations in the estuary and, in addition, the diatom contributions to the major shoals as follows: Ft. Mifflin shoal, 48,900 tons per year; Marcus Hook shoal, 180,700 tons per year; and Pea Patch Island Shoal, 61,600 tons per year. Several lines of analysis were employed in an effort to arrive at a reasonable value of average annual diatom production in the estuary. The first of these is based upon the assumption that diatom accumulation is not confined to the navigation channels and anchorage facilities of the estuary. Diatoms surely exist in waters of the estuary outside of the areas maintained by public or private interests. The appendix shows that diatom production is related to a number of factors, including temperature, salinity, turbulence, nutrients, light and pollutants. The temperature of the waters of the estuary is not significantly different in the shallower protion of any given cross section than that in the navigation channel or anchorages, nor is there any significant difference in salinity and probably not in the nutrients and pollutants. Because of the foregoing facts it is believed that diatom production occurs throughout the waters of the estuary and that considerable deposition of diatom remains is taking place in the shallower portions of the bed of the estuary. It was assumed, in this analysis, that the annual rate of diatom production throughout the waters of the estuary could be defined on an areal basis and this value, determined by dividing the diatom contribution to an individual shoal by the area of the shoal, could be used to determine the total shore to shore production in a given reach of the estuary. The rates per square foot were computed as shown below:

Shoal	Diatom Contribution Tons/Year	Diatom Contribution $(lbs/yr)x10^6$	Shoal Surface Area $S.F.x10^6$	Diatom Contribution lbs/S.F./Yr
Ft. Mifflin	48,900	97.8	62.5	1.6
Marcus Hook	180,700	361.4	72.2	5.0
Pea Patch Island	61,600	123.2	37.6	3.3

Diatom production in 20,000 foot lengths of the estuary were then estimated by extrapolating to an assumed zero rate at Channel Station 60+000 (mile 91), interpolating between the rates for the three evaluated shoaling reaches, and extrapolating to zero at Channel Station 252+000 (mile 52). The surface areas of the same 20,000 ft. lengths of the estuary were determined, and these were multiplied by the estimated diatom production rates in pounds per square foot to determine the total production. It was found that this amounted to 2,300,000 tons per year. The second method of analysis is based upon the observed diatom content in samples taken in the navigation channel and anchorages. In order to arrive at the average annual diatom contribution rate, the average diatom content at various locations was estimated from Table 1 of the Appendix. These values were the ones used to determine the diatom production by multiplying the average diatom content by the shoaling rate for each area. The results of this analysis are shown below.

I. Federally Maintained Channel and Anchorage Areas.

Area (River Sta-Miles)	Average Diatom Content (%)	Average Shoaling Rate (Tons per year)	Estimated Diatom Production (Tons/Yr.)
135 to 90	5	818,000	40,900
90 to 85	10	866,000	86,600
85 to 70	15	1,698,000	254,700
70 to 55	10	1,209,000	120,900
SUBTOTAL – Est. Diatom Production in Fed. Mtnd. Areas			503,100

II. Other Areas, Federally & Privately Maintained.

Area	Avg. Diatom Content	Avg. Shoaling Rate	Est. Diatom Production
Pea Patch Is. Back Channel	12	374,000	44,900
Misc. slips, docks & pvt. channels	11	1,286,000	141,500
Wilmington Harbor	14	353,000	49,400
Schuylkill River	1.4	217,000	3,000
Misc. Tributary Channels	5	24,000	1,200
SUBTOTAL – Est. Diatom Production in other Areas.			240,000
TOTAL – Est. Annual Diatom Production in Estuary. (Tons/Yr.)			743,100

It is apparent that 2,300,000 tons per year is based on the assumption that all of the diatoms in the channel and anchorage shoals were produced there. It is probable that part of the diatoms found in these shoals were produced beyond channel limits and transported to the channel and anchorage shoals. Therefore, 2,300,000 tons is too great. However, the 743,100 tons per year assumes that all diatoms produced in the estuary are transported to the channels and anchorages, and that none remain in the areas where they were produced. Neither of these assumptions is entirely valid. However, there are no data available to determine the losses of diatoms from the areas beyond channel and anchorage limits. Therefore, it is necessary to conclude that the average annual production lies somewhere between the two extreme values, 2,300,000 and 743,000 tons per year. For the purposes of comparisons between the shoaling and the supplies of shoaling materials, the contributions due to diatoms is taken as the average of these two values, 1,500,000 tons per year (rounded).

52. Another possible source of shoaling materials listed in paragraph 44 is the Atlantic Ocean. This can be eliminated as a source of the shoaling of the navigation channel and anchorages of the Delaware Estuary for the following reasons:

a) There is virtually no shoaling of the navigation channel from the mouth to mile 57:

b) There is a null point in the estuary somewhere between mile 15 and mile 20 (see paragraph 24 hereof), such that the bottom ebb currents predominate over the bottom flood currents;

c) The Appendix shows that the constituents of the shoals beginning at mile 57 do not agree with the constituents of the materials composing the continental shelf.

53. The final source of shoaling materials listed in paragraph 44 is airborne settleable particulates. In the early 1960's, settled airborne particulates measured at various local stations in the Philadelphia region amounted to approximately 900 tons per square mile per year. (Ten years later, the amount determined was about 300 tons per square mile per year.) It can be reasonably assumed that equivalent amounts of airborne materials fell on the surface of the estuary between the head of tide at Trenton and the null point at mile 49, a section that contains approximately 105 square miles of water surface. Accepting the 900 tons per year per square mile figure because it represents approximately the same time period of much of the remainder of the data, it is seen that the total material available from this source was 95,000 tons per year. Much of the settled particulates falling on land areas adjacent to the estuary eventually finds its way into the estuary during storms and is accounted for under contributions from storm sewers and tributary streams.

54. All sources of shoaling materials discussed in paragraphs 45 to 53, except erosion of the bed and banks of the estuary itself, were evaluated in terms of tons; the products of the erosion were expressed in cubic yards. Later, shoaling will be discussed preparatory to the making of comparisons between the rates of contributions and the rates of shoaling. While much of the shoaling data also are expressed in cubic yards, it was found desirable to convert all contributions and shoaling to tons, because: a) Reliable data are available for converting cubic yards to tons for both erosion and shoaling quantities, whereas there are uncertainties about conversions of some of the contributions from tons to cubic yards; b) Fewer items must be converted from cubic yards to tons than would have to be converted from tons to cubic yards.

55. It is not possible to assume a constant factor for accomplishing a conversion from cubic yards to tons, as the density, the texture, the particle size distribution, and the degree of saturation vary from place to place. Much data were available for this important phase of the investigation These included in situ wet densities and specific weights (i.e., the dry weight of the solids per unit volume of the deposit in place) for a large number of samples, not only for the Delaware but also for eight other waterways. The Delaware Estuary data are in two groups, one for harpoon samples (disturbed) and the other for undisturbed samples. Harpoon samples considered to be representative of various reaches of the estuary were selected and average densities for these reaches determined. The computations of specific weight were based on assumed gas content ranging from 0 to 5% by volume and a range of specific gravity of the solids from 2.55 to 2.65. These assumptions were based on laboratory testing of both disturbed and undisturbed samples. The undisturbed samples were taken at four locations in the Marcus Hook shoal, using three-inch diameter thin-walled Shelby tubes and a fixed-piston sampler. At three of the four locations, samples were taken at various depths below the top of the shoal, while at the fourth location, only one sample was taken. Seventeen samples were available for detailed analyses, including the following: Total (wet) weight and dry (specific) weight; grain size distribution; specific gravity; Atterberg Limits; organic matter; and consolidation parameters. A summary of the results is shown in Table 15. Plate 12 is a plot of the total (wet) unit weight and the dry (specific) weight for the Marcus Hook undisturbed samples; for a great many Delaware Estuary harpoon samples (assuming gas content ranging from 0 to 5% and specific gravity of the solids ranging from 2.55 to 2.65); and data from eight other waterways. While there is scatter of the points, a good trend is apparent. It is of especial interest to note that the harpoon sample results are quite consistent with the undisturbed sample results. The curve shown is that of the best-fit relationship using all of the data.

56. Table 16 summarizes the contributions from all sources discussed in paragraphs 45 to 53, and it also shows the conversion of the products of the erosion of the bed and banks of the estuary from cubic yards, as originally evaluated, to tons. The significance of dissolved solids as contributors to the shoaling is doubtful. There are some who argue that all of the dissolved solids entering the estuary from sewers and industries ultimately wind up in the shoals. Others believe that some of the dissolved solids act as precipitants and thus become part of the shoals, while other dissolved solids remain in solution indefinitely, and thus never become part of the shoals.

57. Table 17 lists the average annual shoaling of the navigation channel and the anchorages by reaches, also the best estimates of the shoaling of tributary channels, dock areas, and slips. The shoaling rate for each reach was determined as follows:

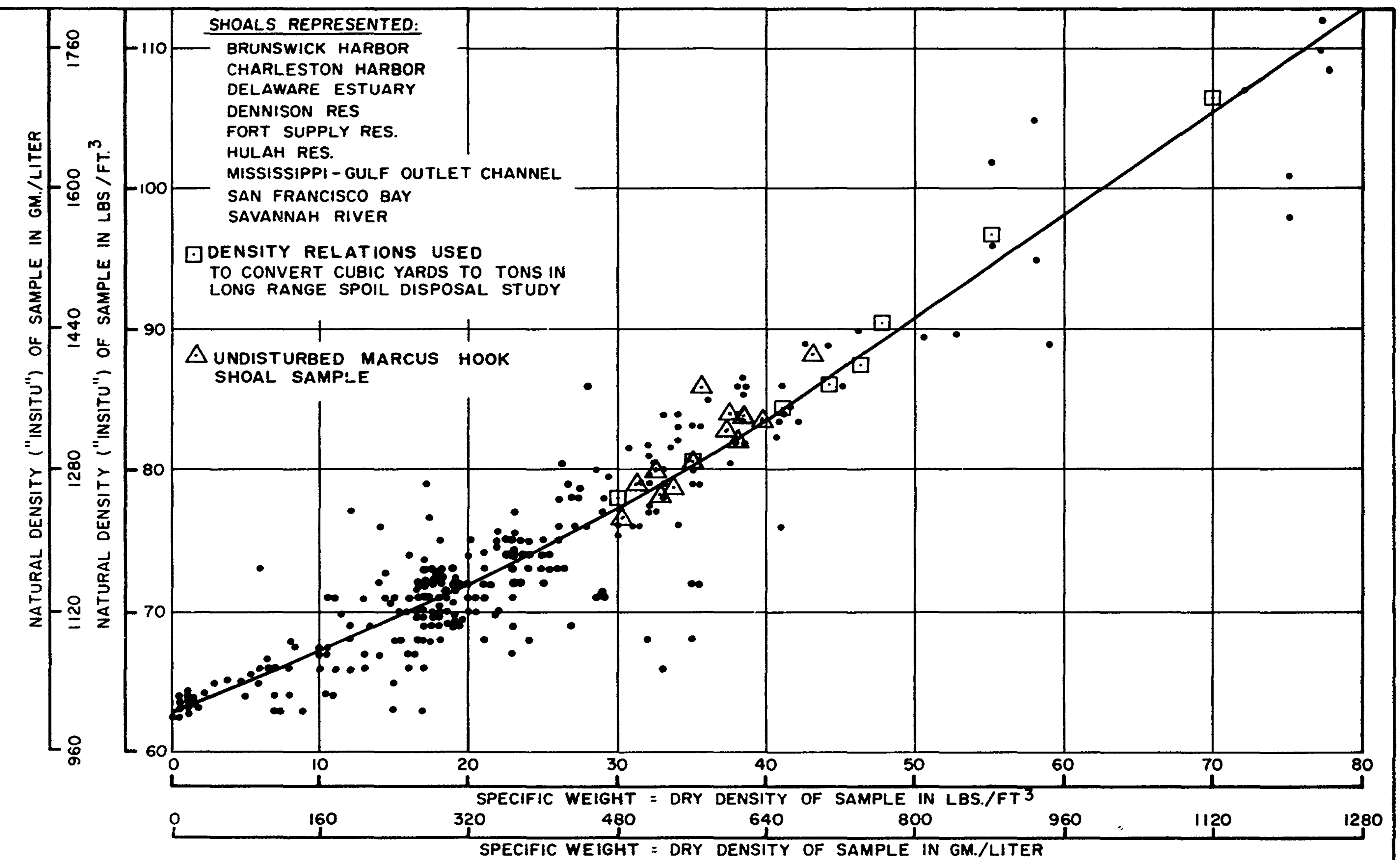
TABLE 15

SUMMARY OF LABORATORY CLASSIFICATION TESTS

MARCUS HOOK UNDISTURBED SAMPLES

Boring & Sample No.	Depth (ft.)	Classification (1)	Water Content (%)		Unit Weight (PCF)		Atterberg Limits			Specific Gravity
			Average	Range	Total	Dry	LL	PL	PI	
RB13–S1 (2)	42.5–44.5	Organic Sandy Silty CLAY (OH)	57.5	35.7–67.2	94.2	59.8	60	32	28	2.56
RB14–S1	38.7–40.7	Organic Sandy Silty CLAY (OH)	110.2	100.7–126.4	83.4	39.7	87	39	48	2.51
–S2	41.7–43.7	Organic Silty CLAY (OH)	133.4	107.5–153.0	79.0	33.9	101	40	61	2.50
–S3	45.7–47.7	Organic Sandy Silty CLAY (OH)	135.4	122.0–142.3	78.3	33.3	73	34	39	2.53
RB15–S1	18.2–20.2	Organic Sandy Silty CLAY (OH)	104.3	85.6–119.1	88.2	43.1	89	36	53	2.55
–S2	20.5–22.5	Organic Silty CLAY (OH)	139.2	122.1–160.1	85.6	35.8	111	41	70	2.54
–S3	23.0–25.0	Organic Silty CLAY (OH)	143.7	119.4–164.6	79.7	32.7	113	39	74	2.49
–S4	26.4–28.4	Organic Silty CLAY (OH)	119.1	116.2–122.3	82.5	37.6	97	39	58	2.47
–S5	32.0–34.0	Organic Silty CLAY (OH)	116.2	110.4–121.8	83.4	38.6	101	34	67	2.56
–S6	35.7–37.7	Organic Silty CLAY (OH)	136.5	129.9–144.1	78.2	33.1	105	40	65	2.53
–S7	41.0–43.0	Organic Silty CLAY (OH)	110.7	93.8–125.3	83.6	39.7	122	46	76	2.58
RB16–S1	20.5–22.5	Organic Silty CLAY (OH)	151.1	130.5–173.0	76.4	30.4	118	41	77	2.54
–S2	23.5–25.5	Organic Silty CLAY (OH)	150.2	133.7–168.2	78.8	31.5	117	41	76	2.59
–S3	26.5–28.5	Organic Silty CLAY (OH)	128.3	115.7–143.6	80.5	35.2	101	40	61	2.53
–S4	33.5–35.5	Organic Silty CLAY (OH)	123.4	117.7–128.0	83.8	37.5	101	41	60	2.49
–S5	38.0–40.0	Organic Silty CLAY (OH)	117.7	110.5–126.4	82.1	37.7	111	40	71	2.58
–S6 (2)	42.0–44.0	Organic Sandy Silty CLAY (OH) (layered)	44.5	32.1–59.1	105.3	72.9	50	26	24	2.62

NOTES: (1) Classification in accordance with Unified Soil Classification System.
(2) Represents original natural river bottom sediments below shoal.



LONG RANGE SPOIL DISPOSAL STUDY

NATURAL "INSITU" SHOAL DENSITY VS. DRY DENSITY

U.S. ARMY ENGINEER DISTRICT PHILA.

PLATE 12

TABLE 16

CONTRIBUTIONS OF SOLIDS FROM PROBABLE SOURCES

Source	In Situ Density g/l	Suspended Solids Cubic Yards per year	Suspended Solids Tons per year	Dissolved Solids Tons per year
Tributary drainage area			1,402,000	
Erosion of bed and banks:				
Trenton to Philadelphia	1700	1,609,000	1,524,000	
Philad 'phia to Bulkhead B. Rge.	1530	1,022,000	760,000	
Dredging			385,000	
Storm and sanitary sewers			133,000	441,000
Industrial pollutants			57,000	818,000
Diatom production			1,500,000	
Atlantic Ocean			0	
Airborne particulates			95,000	
		Totals	5,856,000	1,259,000

a) The volumes above a selected base elevation (–65.0 ft.) were calculated by computer using the average end area method. This was done for two channel examinations from the years 1961–62 and 1965–66.

b) Since the survey lines were not coincident, it was necessary to adjust the soundings to even 1,000 ft. stations. This was done by interpolation. Even 1,000 ft. stations were chosen only as a matter of convenience.

c) For each 1,000 ft. section of the channel the volume was determined by subtracting the 1961–62 volume from the 1965–66 volume.

d) The quantity of material removed by contract dredging between the survey dates for each 1,000 ft. section was added to the volume computed in step (c).

e) The results obtained in step (d) were converted to tons using the correct conversion factor for each reach.

f) The quantity of dredging performed by Corps of Engineers hopper dredges was reported in terms of cubic yards; however, these values were obtained from the change in displacement of the hopper dredge light and loaded, i.e., tons. Accordingly, the reported volumes were converted back to tons and values for 1,000 ft. stations were derived. These results were added to the results obtained in step (e).

g) The numbers derived in step (f) were divided by the time span in years, and the results are the average annual shoaling rates for the various reaches.

58. A method similar to that outlined above was used to determine the average

annual shoaling rates of Wilmington Harbor, Schuylkill River, and other tributaries. The shoaling rates in non-Federal projects, e.g., the channel behind Pea Patch Island, slips, and dock areas, were based on estimates furnished by the individual firms, or non-Federal agencies, involved.

TABLE 17

AVERAGE ANNUAL SHOALING IN DELAWARE ESTUARY (1961–66)

Miles above Mouth	Channel Stations (1000's of feet)	Reach Description	Density g/l	Shoaling tons x 10^3	
131 to 130	– 153 to – 150	Trenton to Cochran Ranges	1350	+ 32	
130 to 129	– 150 to – 148	Cochran to Biles Id. Ranges	1350	0	
129 to 127	– 148 to – 132	Biles Id. to Whitehill Ranges	1350	+113	
127 to 120	– 132 to – 96	Whitehill to Landreth Ranges	1380	+255	
120 to 114	– 96 to – 63	Landreth to Beverley Ranges	1550	+373	
114 to 102	– 63 to 0	Beverley to Harbor Ranges	1550	0	
		(Sub-total, Philadelphia to Trenton)			+773
102 to 101	0 to + 4	Port Richmond Anchorage	1450	+ 61	
102 to 92	0 to + 55	Philadelphia Harbor Ranges	1450	– 16	
92 to 88	+ 55 to + 77	W. Horseshoe to Billingsport Rge.	1450	+390	
91 to 89	+ 61 to + 72	Mantua Creek Anchorage	1450	+276	
88 to 81	+ 77 to + 113	Billingsport to Chester Ranges	1550	+650	
81 to 78	+ 113 to + 131	Chester to Marcus Hook Ranges	1245	+799	
78 to 72	+ 131 to + 164	Marcus Hook to Bellevue Ranges	1295	+449	
80 to 78	+ 118 to + 131	Marcus Hook Anchorage	1245	+164	
72 to 71	+ 164 to + 167	Cherry Island Range	1295	– 1	
71 to 70	+ 167 to + 175	Cherry Island Range	1295	+227	
70 to 67	+ 175 to + 188	Cherry Id. to Deepwater Pt. Range	1295	– 10	
67 to 60	+ 188 to + 221	Deepwater Pt. to Bulkhead Bar Rge.	1400	+516	
60 to 57	+ 221 to + 235	New Castle Range	1400	+313	
		(Sub-total, Philadelphia to the Sea)			+3818
	Total, Federal Channels and Anchorages in Main Estuary				+4591
	Non-Federal navigation facilities in Main Estuary				
	Channel behind Pea Patch Island		1400	+ 374	
	Miscellaneous dock areas and slips		1450	+1286	
		(Sub-total, Non-federal facilities)			+1660
	Tributary Channel Shoaling				
	Schuylkill River		1300	+217	
	Wilmington Harbor (Christina River)		1240	+353	
	Miscellaneous tributary channels		1250	+ 24	
		(Sub-total, tributary channels)			+ 594
Total, all shoaling in channels of main estuary and its tributaries					+6845

59. Table 18 compares the contributions of materials with the shoaling; it repeats the figures in Tables 16 and 17 to facilitate the comparison, except for the dissolved solids listed in Table 16. It is considered unlikely that these will be precipitated out in significant quantities to become parts of the shoals.

TABLE 18

COMPARISON OF SHOALING AND SUPPLIES OF SHOALING MATERIALS

Item	Tons per Year	
Shoaling and Location		
Between Philadelphia and Trenton	773,000	
Between Philadelphia and the Sea	3,317,000	
Anchorages	501,000	
Non-Federal navigation facilities	1,660,000	
Tributary stream channels	594,000	
Total	6,845,000	6,845,000
Contribution and source		
Inflow from watershed	1,402,000	
Erosion of bed and banks of estuary	2,284,000	
Dredging	385,000	
Storm and sanitary sewers	133,000	
Industrial pollutants	57,000	
Diatom production	1,500,000	
Airborne particulates	95,000	
Total	5,856,000	5,856,000
Difference, shoaling in excess of contribution =		989,000

Approximately 86% of the shoaling is accounted for by the evaluated contributions. The reason for this disparity is not known. However, it is of interest to note that the comparison would result in much closer agreement if: (1) The result of the first method of analysis of diatom production were assumed to be correct (This results to agreement within 3%) or (2) the dissolved solids contributed by industry and storm and sanitary sewers are assumed to precipitate and settle into the shoals (this results in agreement to within 4%).

THE TRANSPORT AND DEPOSITION OF SOLIDS

60. One of the prime objectives of the overall investigation is to determine why the Marcus Hook shoaling rate is so great. The shoaling here amounts to 40%

of the total, and disposal area capacity is in scarce supply. After careful consideration of the data required to answer this question, and of the difficulties and cost of obtaining adequate data, it was decided to study a typical cross-section of this shoaling reach in detail, and simultaneously, two other cross-sections, one upstream and the other downstream of Marcus Hook. The cross-sections selected were at Channel Station 90+000 (mile 86), Channel Station 124+000 (mile 79), and Channel Station 180+000 (mile 68). The rate of shoaling at Station 90+000 is relatively light, that at Station 124+000 is extremely heavy, and that at Station 180+000 is zero.

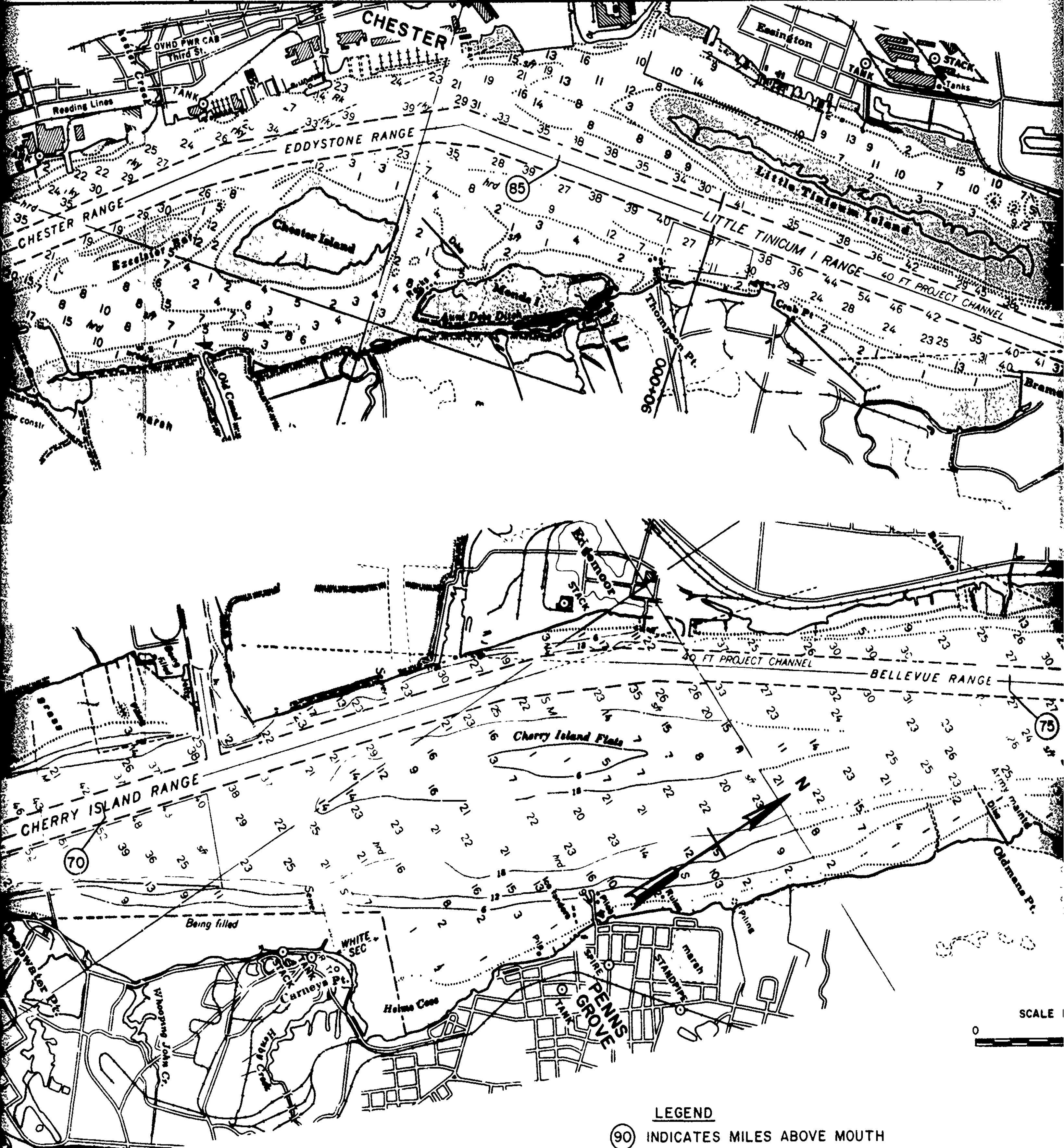
61. Plate 13 shows the hydrography of the reach of the estuary from Station 90+000 to Station 180+000, and of portions of the estuary upstream and downstream. All three of the selected cross-sections are seen to be in straight reaches of the estuary and of the navigation channel, and bends upstream and downstream of the cross-sections are not considered to be of significant magnitude. Tinicum Island, which is about 2½ miles in length, is a feature of the cross-section at Station 90+000. However, the back channel becomes very shallow in its upstream reaches, and previous investigations have shown that the currents therein are of very low velocity. Therefore, observations in the main channel east of the island would include almost all of the discharges of the estuary at Station 90+000. Station 124+000 is inclusive of Marcus Hook Anchorage, but there are no complicating features. Station 180+000 is just downstream of the Delaware Memorial Bridges. These structures are close together, but the clear spans are 2,000 ft. in length and there are only four piers per bridge to complicate the flows; it is considered that the effects of these bridges on observations at Station 180+000 would be negligible. Plate 14 shows these three cross-sections. The plotted hydrography is the average of two surveys made about two months apart, and there were no significant differences. The plots also show the cross-sectional areas of each cross-section, referred to Delaware River Datum (DRD); this datum, used for all surveys, is about 0.5 ft. below local mean low water for the three cross-sections. Table 19 summarizes the hydraulic characteristics of the three cross-sections.

TABLE 19

HYDRAULIC CHARACTERISTICS OF CROSS-SECTIONS (REFERRED TO DRD)

	Cross-sectional Area, Square Feet			Maximum Depth, ft	Mean Depth, ft.
Station	Main Channel	Back Channel	Total	Main Channel	Main Channel
90+000	78,540	15,200	93,740	46.0	26.6
124+000	149,920	–	149,920	44.0	30.3
180+000	148,190	–	148,190	48.5	26.1


MARCUS HOOK
STACKS
MATCH LINE
MARCUS HOOK RANGE
40 FT PROJECT CHANNEL
CHESTER RANGE
Reading Lines
OVHD PWR CAB
Third St.
TANK
dangerous rock area
Excelsior Bar
Raccoon I.
Bridge under constr
OVHD. PWR. CAB
AUTH. CL. 110 FT.
marsh
Old Canal
124+000
80
DELAWARE MEMORIAL FIXED BRIDGES
Pigeon Pt.
Pipeline
CHERRY ISLAND RANGE
Cable Area
70
New Castle Flats
Being filled
Deepwater Pt.
Whooping John Cr.
180+000
OVERHEAD PIPELINES AND POWER CABLES
66
Piling
Travis Cove
TANK
Church Landing
Salem Canal
Cedar Pt.
Brandrift Beach
Pennsville
Churchtown



LEGEND

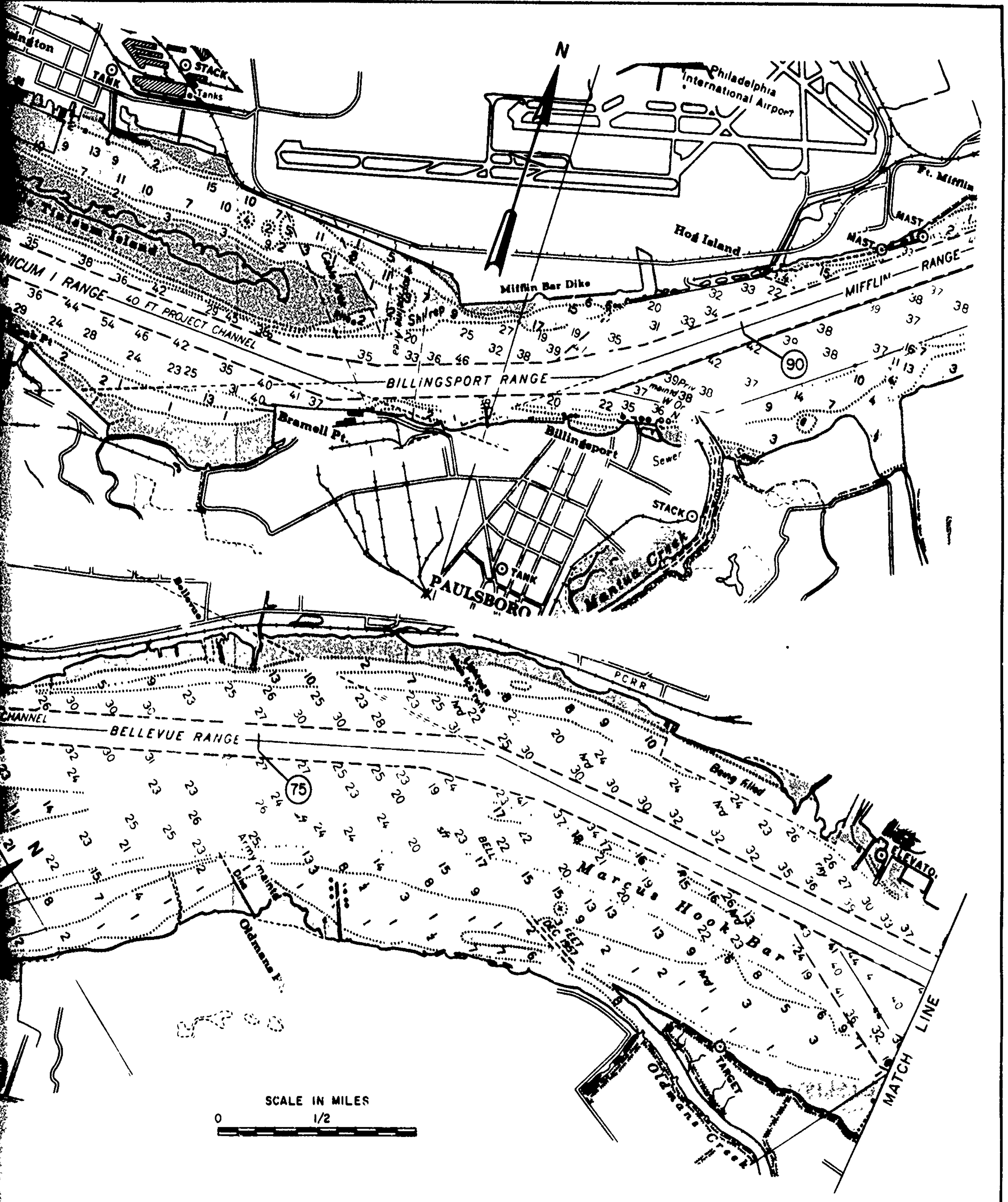
(90) INDICATES MILES ABOVE MOUTH

NOTES

1 SOUNDINGS IN FEET BELOW S.L.D.

2 REPRODUCED FROM U.S.C.& G.S. CHARTS 294 & 295

3



ABOVE MOUTH

T BELOW SL D
USC. & G.S.

LONG RANGE SPOIL DISPOSAL STUDY

DELAWARE ESTUARY-HYDROGRAPH
MILE 66 TO 91

U.S.ARMY ENGINEER DISTRICT PHILA.

PLATE 13

Although the back channel cross-sectional area at Station 90+000 amounts to about 16% of the total, the flows therein are not considered to be significant.

62. The cross-sections shown on Plate 14 indicate the locations where observations of currents and the collection of samples for determinations of suspended solids and dissolved solids were undertaken. It is seen that there were three locations occupied in each cross-section, making a total of nine observation points where work was performed continuously and simultaneously during complete tidal cycles. The plan of study contemplated that observations would be made for three tidal cycles, beginning at a slack water and continuing through the next two slack waters: One of these sets of observations would be made during a low freshwater discharge, one during an approximately mean freshwater discharge, and another during a fairly high freshwater discharge. Thus, there would be three series of observations, which were designated as Series A, Series B, and Series C. To facilitate the identification of the water samples, a numbering sequence was devised assigning a number to each sampling location for all three cross-sections, and the letters "A", "B", and "C" were added to designate the series. The numbers of the observation locations were as shown below:

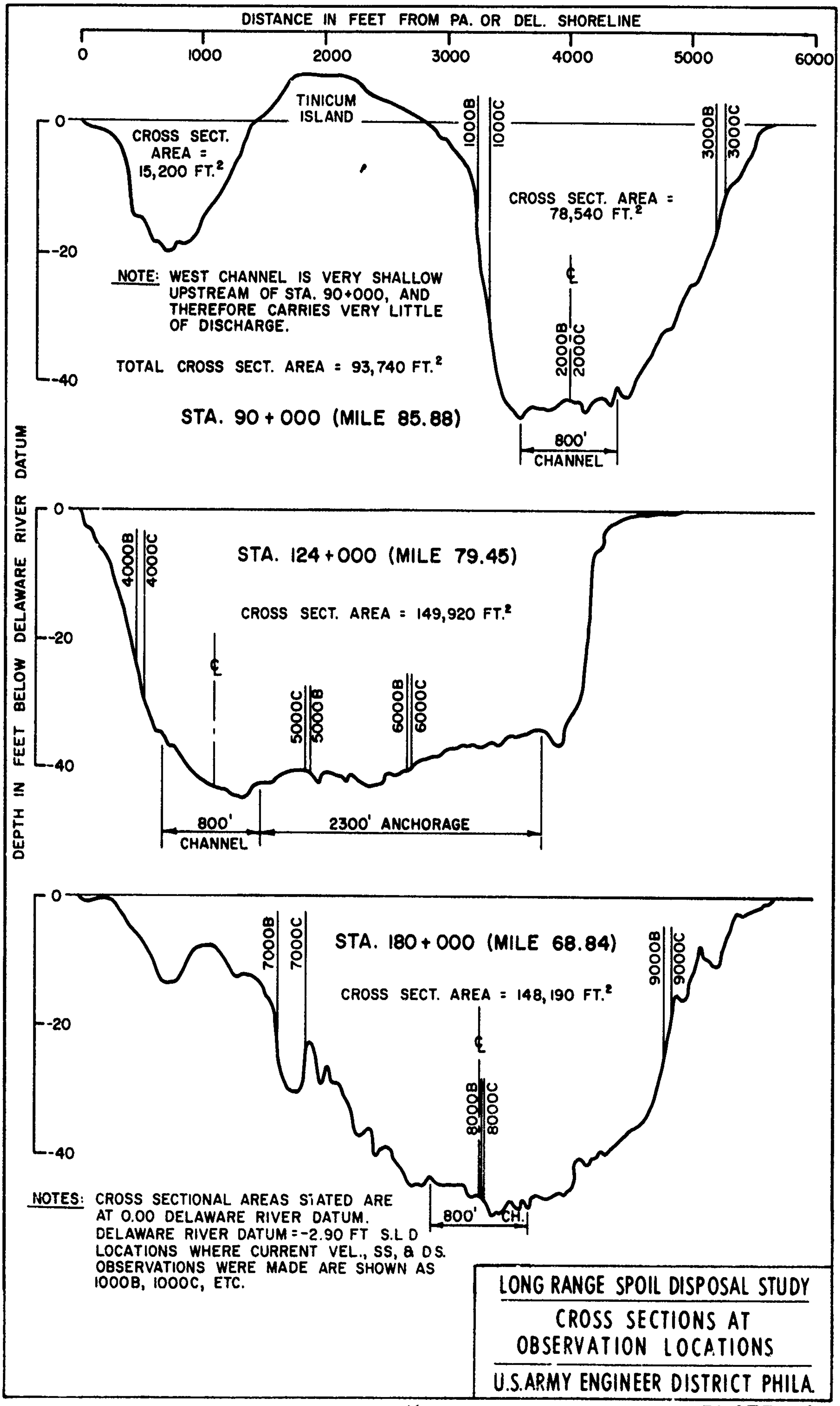
Numbering of Observation Locations

Station	West of Channel	Channel	East of Channel
90+000	1000	2000	3000
124+000	4000	5000	6000
180+000	7000	8000	9000

Water samples were identified by sampling location, series, depth, and time of sampling.

63. The instrument array was made up as follows: At the top was a current direction indicator, followed below by a dampening plate to reduce oscillation of the array due to the effect of wave action on the boat. Directly below the plate was a Price-type current meter to which was attached the intake line of the flow-through pump sampler. At the bottom of the array was a bottom sensor to locate the silt-water interface. Observations were made at distances above the silt-water interface to be thus determined. These distances were 1, 2, 4, 8, 16 and, where the water depth permitted, 32 feet above the silt-water interface. The array was held in an essentially vertical position by a 100 pound stream-lined lead weight having fins, and the cable supporting all of this equipment was wound on a reel aboard the observation boat. The boat was held firmly in place by two anchors, the lines to which were always kept taut.

64. Water samples were obtained by a continuously operating pump to which was connected a 3/8" I.D. hose leading to the intake at the current meter. With the instrument array at a given distance above the silt-water interface, the hose was purged of water from a previous position above the bottom, then a 250 cc water sample was collected. The temperature was read from an in-line thermometer, then the velocity was recorded, then the current direction. The array was then raised to the next point in the vertical. A group of observations was com-



DISTANCE IN FEET FROM PA. OR DEL. SHORELINE
0
1000
2000
3000
4000
5000
6000
DEPTH IN FEET BELOW DELAWARE RIVER DATUM
TINICUM ISLAND
CROSS SECT. AREA = 15,200 FT.²
1000B
1000C
3000B
3000C
CROSS SECT. AREA = 78,540 FT.²
NOTE: WEST CHANNEL IS VERY SHALLOW UPSTREAM OF STA. 90+000, AND THEREFORE CARRIES VERY LITTLE OF DISCHARGE.
TOTAL CROSS SECT. AREA = 93,740 FT.²
2000B
2000C
STA. 90 + 000 (MILE 85.88)
800' CHANNEL
0
-20
-40
4000B
4000C
STA. 124 + 000 (MILE 79.45)
CROSS SECT. AREA = 149,920 FT.²
5000C
5000B
6000B
6000C
800' CHANNEL
2300' ANCHORAGE
7000B
7000C
STA. 180 + 000 (MILE 68.84)
CROSS SECT. AREA = 148,190 FT.²
9000B
9000C
8000B
8000C
800' CH.
NOTES: CROSS SECTIONAL AREAS STATED ARE AT 0.00 DELAWARE RIVER DATUM.
DELAWARE RIVER DATUM = -2.90 FT S.L.D
LOCATIONS WHERE CURRENT VEL., SS, & DS. OBSERVATIONS WERE MADE ARE SHOWN AS 1000B, 1000C, ETC.
LONG RANGE SPOIL DISPOSAL STUDY
CROSS SECTIONS AT OBSERVATION LOCATIONS
U.S. ARMY ENGINEER DISTRICT PHILA.

menced at one foot above the silt-water interface at an even twenty-minute interval at all nine locations, then the next observation was made two feet above the silt-water interface, etc., until the last of the group, at either 16 or 32 feet above the interface depending on the depth of water, was made. Then, at the next even twenty-minute interval, a new group of observations was commenced at one foot above the silt-water interface.

65. The first series of observations was made on 18 November 1968, when the freshwater discharge at Marcus Hook was estimated to be 15,600 cfs. The weather was poor and high winds made it very difficult to keep the equipment in operating condition. The bottom sensors at six locations were damaged beyond repair and the net result of the effort was negligible. The next series, Series B, was run on 15 May 1969, when the estimated freshwater discharge was 12,300 cfs at Marcus Hook. This run was successful insofar as the operation itself was involved; there was an external mishap that may or may not have had an effect on the results. A portion of the disposal area dike at Pigeon Point, specifically at Channel Station 176+000, failed at some undetermined time between 1500 hours on 14 May 1969 and 0620 hours on 15 May 1969. It was known that the dike was intact at the beginning of this period, and it is also known that a spill amounting to about 1,200,000 cy had ended by the end of the period. The "B" Series of observations began at 0800 hours on 15 May 1969. The possible effects of this spill on the observations will be discussed later. The "C" Series observations was made on 23 July 1969, when the estimated freshwater discharge at Marcus Hook was 9,800 cfs. This run was not as successful as was the "B" Series, but the results nevertheless provided adequate data.

66. The water samples were analyzed at the Corps of Engineers South Atlantic Division Laboratory for suspended solids and dissolved solids contents. These results, together with the velocity readings, current direction data, water temperatures, and concurrent tide observations at each cross-section, amounted to an immense quantity of data for each of the runs. While neither the "B" nor the "C" Series was without gaps of missing data (due to instrument failures) it is conservatively estimated that the two runs produced about 15,000 "bits" of data to be assimilated and analyzed. After routine checking, the first step in reducing the data into more readily assimilated form consisted of plotting all of the data obtained at each location on master sheets, one sheet per location. The plots consisted of graphs against time as the abscissa, as follows: Tide; Current Velocity at each of the five or six distances above bottom; suspended solids at each of the five or six distances above bottom; and dissolved solids at each of the five or six distances above bottom. Current directions and temperatures were not plotted in detail, as it was seen that there was very little difference with respect to time and distance above bottom, except, of course, a change in direction of approximately 180° when the current direction reversed.

67. The master sheets ultimately included additional graphs, but before the

computations necessary for these were undertaken, the plots of current velocities, suspended solids, and dissolved solids were carefully reviewed to spot questionable points for further checking. Also, the current velocity data were examined to make certain that there had been no systematic error and to assure that the times of current reversals were reasonable. Tables 20A and 20B give the results of comparisons of the observed tides and the currents. It is seen that the durations of flood and ebb and the intervals between the time of high and low water tide and the reversals of current direction are reasonably consistent. The peak velocities compare reasonably well with the ranges of tide during the respective phases of the current. The tables show that some of the current reversals were inferred. These inferences were made by comparison with adjacent location, also comparable locations in the adjacent cross-section. Consideration was also given to the lags observed in the other Series; i.e., if the time of current reversal at location 2000B was missed but was observed at location 2000C, the relation to the time of tide was helpful also in inferring the missing data.

68. After completion of the analyses described above, the current velocity data and the suspended and dissolved solids data were programmed for computer computations which initially resulted in determinations of the products of current velocity and suspended solids for each distance above bottom, also the products of current velocity and dissolved solids for each distance above bottom. These results were also plotted against time on the master sheets. The eighteen master sheets (one for each of the nine locations of the two Series) were necessarily large and are not a part of this report; they are on file in the District Office for study by anyone interested in these details.

69. The next steps in the analyses involved additional computer operations to determine the total transports of suspended and dissolved solids for each group of observations in the vertical, i.e., those beginning on an even 20 minutes of time at one foot above the silt-water interface, then 2 ft., 4 ft., 8 ft., 16 ft., and (if possible) 32 ft. above the same reference level. The products of current velocity and suspended solids, also the products of current velocity and dissolved solids, were multiplied by factors determined as shown in Table 21, Columns 1, 2, and 3. Table 21 is an example of the method used in computing the suspended solids transport in pounds per second for one of the three segments of the total cross-section.

70. Computations in a like manner were made for the other two segments of the cross-section. As the basic observations at all three of the locations in each cross-section were made at the same times, the sum of the three results gave the total transport in the cross-section in pounds per second at even 20 minute intervals. As pointed out before, there were occasional gaps in the observations due to instrument failures. It was necessary to infer the missing data in order to arrive at continuous results for the entire current cycle. In all cases, at least one of the three locations provided data at the times when data were missed at one (or rarely two) of the locations. It was found that

TABLE 20A
COMPARISON OF CURRENTS AND TIDES
SERIES B – 15 MAY 1969

Location	Distance above Bottom ft.	Slack Water Times			Durations of		Time of Tide			Slack Water Lag after Tide Time			Peak Velocity		Range of Tide	
		LWSl Hrs.	HWSl Hrs.	LWSl Hrs.	Flood Hrs.	Ebb Hrs.	LW Hrs.	HW Hrs.	LW Hrs.	LWSl Hrs.	HWSl Hrs.	LWSl Hrs.	Flood fps	Ebb fps	Rise ft.	Fall ft.
1000B	1	8.75	13.83	20.65*	5.08	6.82	7.55	12.80	19.65	1.20	1.03	1.00	1.79	2.35	5.77	5.35
1000B	16	8.67	14.08	20.57*	5.41	6.49	7.55	12.80	19.65	1.12	1.28	0.92	2.43	2.91	5.77	5.35
2000B	1	8.83	14.58	20.77*	5.75	6.19	7.55	12.80	19.65	1.28	1.78	1.12	2.47	2.10	5.77	5.35
2000B	32	9.17	14.50	21.10*	5.33	6.60	7.55	12.80	19.65	1.62	1.70	1.45	3.20	3.12	5.77	5.35
3000B	1	8.67	13.67	20.42	5.00	6.75	7.55	12.80	19.65	1.12	0.87	0.77	1.65	1.23	5.77	5.35
3000B	16	8.67	13.83	20.42	5.16	6.59	7.55	12.80	19.65	1.12	1.03	0.77	2.14	1.54	5.77	5.35
4000B	1	7.77*	13.08	19.83	5.31	6.75	7.35	12.65	19.50	0.42	0.43	0.33	**	1.82	6.06	5.24
4000B	16	7.85*	13.08	19.92	5.23	6.84	7.35	12.65	19.50	0.50	0.43	0.42	**	2.04	6.06	5.24
5000B	1	8.43*	14.33	20.50	5.90	6.17	7.35	12.65	19.50	1.08	1.68	1.00	1.89	1.89	6.06	5.24
5000B	32	8.35*	14.42	20.42	6.07	6.00	7.35	12.65	19.50	1.00	1.77	0.92	3.12	3.12	6.06	5.24
6000B	1	8.35*	13.92	20.42	5.57	6.50	7.35	12.65	19.50	1.00	1.27	0.92	1.68	2.04	6.06	5.24
6000B	32	8.35*	14.25	20.42	5.90	6.17	7.35	12.65	19.50	1.00	1.60	0.92	2.60	2.78	6.06	5.24
7000B	1	7.50*	13.17	19.50	5.67	6.33	6.67	12.03	18.75	0.83	1.14	0.75	2.44	1.91	5.73	5.12
7000B	16	7.67*	13.33	19.67	5.66	6.34	6.67	12.03	18.75	1.00	1.30	0.92	3.22	3.26	5.73	5.12
8000B	1	8.08	13.58	20.17	5.50	6.59	6.67	12.03	18.75	1.41	1.55	1.42	2.48	2.41	5.73	5.12
8000B	32	8.33	13.67	20.33	5.34	6.66	6.67	12.03	18.75	1.66	1.64	1.58	3.54	3.69	5.73	5.12
9000B	1	7.17*	13.50	19.17	6.33	5.67	6.67	12.03	18.75	0.50	1.47	0.42	2.91	1.00	6.73	5.12
9000B	32	7.33*	13.67	19.33	6.34	5.66	6.67	12.03	18.75	0.66	1.64	0.58	3.59	1.72	5.73	5.12

NOTES: Locations 1000, 2000, & 3000 are at Channel Station 90+000
Locations 4000, 5000, & 6000 are at Channel Station 124+000
Locations 7000, 8000, & 9000 are at Channel Station 180+000

* Denotes an inferred value
** Denotes missing data

TABLE 20B

COMPARISON OF CURRENTS AND TIDES

SERIES C – 23 JULY 1969

Location	Distance above Bottom Ft.	Slack Water Times			Durations of		Time of Tide			Slack Water Lag after Tide Time			Peak Velocity		Range of Tide	
		HWSl Hrs.	LWSl Hrs.	HWSl Hrs.	Ebb Hrs.	Flood Hrs.	HW Hrs.	LW Hrs.	HW Hrs.	HWSl Hrs.	LWSl Hrs.	HWSl Hrs.	Ebb fps	Flood fps	Fall ft.	Rise ft.
1000C	1	8.50	15.50	21.17	7.00	5.67	7.25	14.40	19.80	1.25	1.10	i.37	1.93	2.10	4.73	4.93
1000C	32	8.75	15.83	21.42	7.08	5.59	7.25	14.40	19.80	1.50	1.43	1.62	2.85	2.72	4.73	4.93
2000C	1	9.25*	15.75*	21.92*	6.50	6.17	7.25	14.40	19.80	2.00	1.35	2.12	**	1.87	4.73	4.93
2000C	32	9.50*	16.08*	22.17*	6.58	6.09	7.25	14.40	19.80	2.25	1.68	2.37	**	3.30	4.73	4.93
3000C	1	8.42	15.50	21.05*	7.08	5.55	7.25	14.40	19.80	1.17	1.10	1.25	**	1.94	4.73	4.93
3000C	16	8.58	15.67	21.25*	7.09	5.58	7.25	14.40	19.80	1.33	1.27	1.45	**	2.16	4.73	4.93
4000C	1	7.60*	14.75	20.17	7.15	5.42	7.12	14.40	19.60	0.48	0.35	0.57	1.28	1.56	4.78	5.08
4000C	16	7.60*	14.75	20.17	7.15	5.42	7.12	14.40	19.60	0.48	0.35	0.57	1.72	1.83	4.78	5.08
5000C	1	8.87*	15.42	21.43*	6.55	6.01	7.12	14.40	19.60	1.75	1.02	1.83	1.61	2.08	4.78	5.08
5000C	32	8.95*	15.33	21.52*	6.38	6.19	7.12	14.40	19.60	1.83	0.93	1.92	2.62	3.05	4.78	5.08
6000C	1	8.83	15.08	21.40*	6.25	6.32	7.12	14.40	19.60	1.71	0.68	1.80	1.26	1.48	4.78	5.08
6000C	32	8.92	15.42	21.48*	6.50	6.06	7.12	14.40	19.60	1.80	1.02	1.88	2.48	2.52	4.78	5.08
7000C	1	7.17	14.75	19.92	7.58	5.17	6.67	13.40	19.05	0.50	1.35	0.87	2.27	2.12	4.35	4.82
7000C	16	7.08	15.08	20.17	8.00	5.09	6.67	13.40	19.05	0.41	1.68	1.12	2.38	2.02	4.35	4.82
8000C	1	7.83	15.00	20.30*	7.17	5.30	6.67	13.40	19.05	1.16	1.60	1.25	1.98	2.35	4.35	4.82
8000C	32	7.92	15.25	20.38*	7.33	5.13	6.67	13.40	19.05	1.25	1.85	1.33	3.27	3.22	4.35	4.82
9000C	1	8.25	14.42	20.72*	6.17	6.30	6.67	13.40	19.05	1.58	1.02	1.67	1.34	2.11	4.35	4.82
9000C	20	8.00	14.67	20.47*	6.67	5.80	6.67	13.40	19.05	1.33	1.27	1.42	1.67	3.04	4.35	4.82

NOTES: Locations 1000, 2000, & 3000 are at Channel Station 90+000
Locations 4000, 5000, & 6000 are at Channel Station 124+000
Locations 7000, 8000, & 9000 are at Channel Station 180+000

* Denotes an inferred value
** Denotes missing data

there were good relationships between the transports at the three locations; when these were established, they were used to infer the missing data. As an example, the observers at Location 6000B were unable to make their observations from 1000 hours to 1120 hours; but those at Locations 4000B and 5000B were successful. After 1120 hours, the observations at all three locations were made well. The sums of the transports at Locations 4000B, 5000B, and 6000B for 1140 hours and several thereafter were compared with the sums at Locations 4000B and 5000B at the same times. The ratios were 2.35, 2.43, 2.38, and 2.60 for an average of 2.44, and this ratio was then applied to the sums at Locations 4000B and 5000B to obtain the inferred sum of all three locations.

TABLE 21
EXAMPLE OF COMPUTATIONS OF SUSPENDED SOLIDS TRANSPORT
LOCATION 5000B at 1120 HOURS

Observation position. (Distance in feet above silt-water interface)	Lower and upper limits of vertical column thru which observation is applicable – feet.	Portion of vertical column thru which observation is applicable – feet.	Current velocity – fps	Suspended solids – ppm	Current velocity times ppm suspended solids.	Pounds suspended solids per second **	Pounds suspended solids per second per sq. ft. of Column 3 portion of vertical column one foot wide.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	0.0						
1		1.5	1.46	668.0	975.3	.0608	0.0912
	1.5						
2		1.5	1.96	480.5	941.8	.0587	0.0881
	3.0						
4		3.0	2.25	407.5	916.9	.0571	0.1713
	6.0						
8		6.0	2.47	280.2	692.1	.0431	0.2586
	12.0						
16		12.0	2.68	187.0	501.2	.0312	0.3744
	24.0						
32		22.0	2.90	106.2	308.0	.0192	0.4224
	46.0*						
						Total	1.4060

Weighted average $= \frac{1.4060}{46} = 0.0306$ pounds suspended solids per second per sq. ft. of vertical column one foot wide.

Total transport in portion of Channel Station 124+000 cross-section for which observations at Location 5000B are applicable is: 0.0306 pounds suspended solids per second per sq.ft. times 65,700 sq. ft.*** equals 2008.1 pounds per second.

NOTES: * denotes depth at tide elevation at 1120 hours

** $\frac{\text{Column 6 times weight one cf of water at observed salinity and temperature}}{1{,}000{,}000}$

*** Cross-sectional area at tide elevation at 1120 hours

71. Plate 15 presents plots of the suspended solids transport in pounds per second against time for the Series B and C observations at Channel Stations 90+000, 124+000, and 180+000. The plotted points are the sums of the data at the three positions occupied in each cross-section; in some cases, the sums were inferred on the basis of the observed data at two of the three positions (sometimes only one), but most of the points are based on three sets of data. The plots also show the total upstream and downstream transports in tons. Table 22 summarizes these data, also the concurrent rises and falls of the tide.

TABLE 22

TOTAL TRANSPORT OF SUSPENDED SOLIDS

Series	Channel Station 90+000				Channel Station 124+000				Channel Station 180+000			
	Flood		Ebb		Flood		Ebb		Flood		Ebb	
	SS Tons	Tide Rise Ft.	SS Tons	Tide Fall Ft.	SS Tons	Tide Rise Ft.	SS Tons	Tide Fall Ft.	SS Tons	Tide Rise Ft.	SS Tons	Tide Fall Ft.
B	4,176	5.77	5,139	5.35	13,653	6.06	16,240	5.24	28,710	5.73	28,800	5.12
C	2,994	4.93	3,313	4.73	8,101	5.08	6,354	4.78	18,211	4.82	22,680	4.35

72. The tabulated data show that there are relationships between the concurrent range of tide and the total transports, disregarding other considerations, but as will be shown later, these relationships are not simple proportionalities. The other considerations, referred to above are:

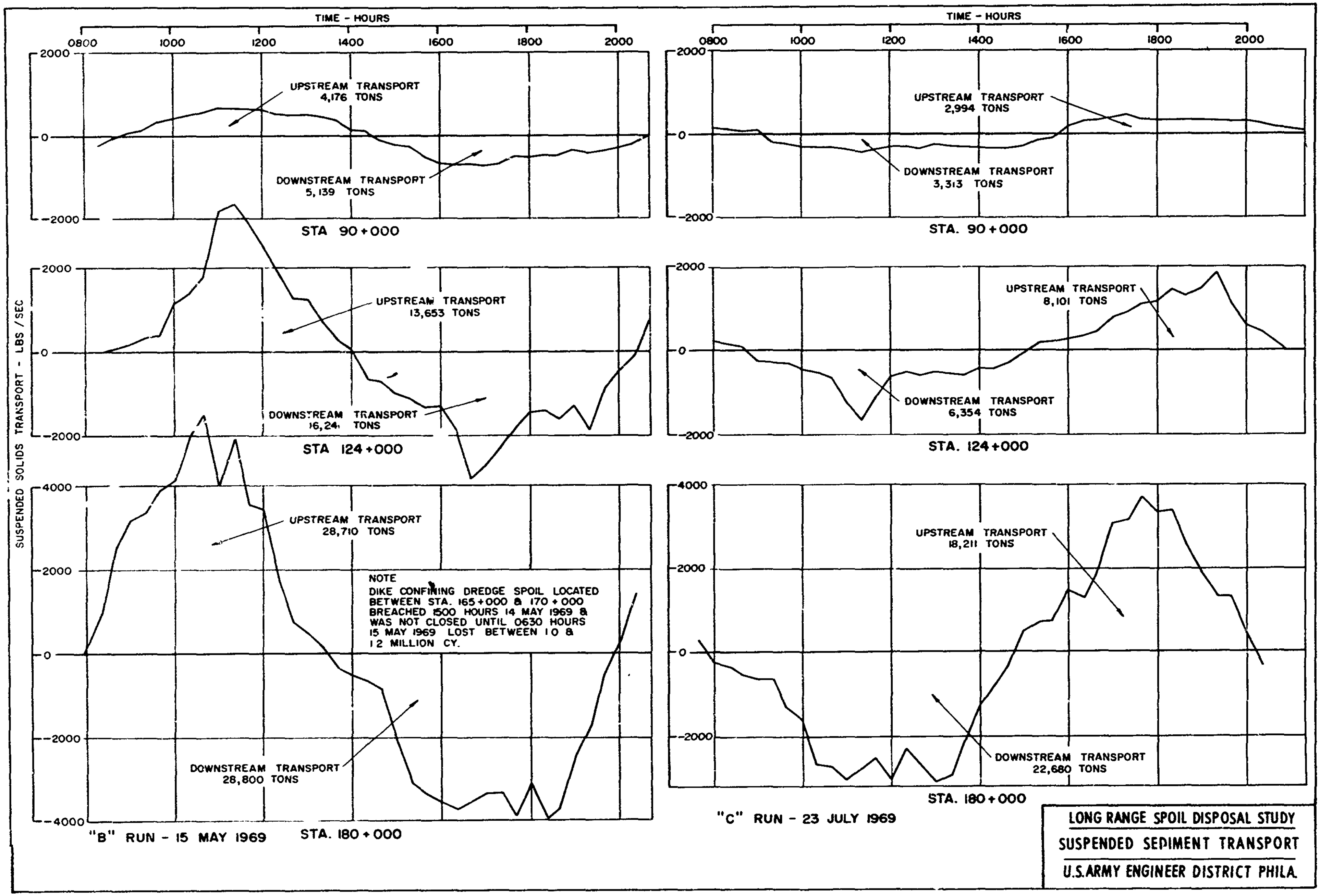
a) The freshwater discharges at Marcus Hook, i.e., Channel Station 124+000, were 12,300 cfs for Series B and 9,800 cfs for Series C;

b) The average contributions of sediment from upland sources for the five days preceeding the starts of the Series B and C observations, based on observations including about 85% of the total drainage area at Station 124+000, were 1,010 tons per day for Series B and 260 tons per day for Series C;

c) The salinities during the Series B observations were a little lower than those during the Series C observations;

d) The failure of the disposal area dike at Channel Station 176+000 a short time before the start of the Series B observations.

None of these differences between the two series (except possibly the dike failure, which will be discussed later) appear to be of sufficient importance to mitigate against an attempt to adjust the total transports of suspended sediment on the basis solely of the tidal differences. Such adjustments are obviously required in any event to bring the flood and the ebb phases of each series into a common tidal condition (note that Tabl. 22 shows that there were substantial differences between the



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tides of the two phases). Because conditions, other than tidal, that prevailed during the two series are not greatly different (except, again, the dike failure), adjustments for tides also may show whether consistent results were obtained.

73. Accordingly, adjustments to values corresponding to mean tides were made as described below. These adjustments were made separately for the flood and ebb phases for each of the three cross-sections and for each series. The total transport of suspended sediment at a given cross-section during a flood or an ebb current, Q_{so}, is:

$$Q_{so} = \int_{\pi}^{o} K A_o V_o g_{so} \, dt \approx \overline{K} \overline{A}_o \overline{V}_o \overline{g}_{so}$$

$$D \; 3{,}600 \text{ sec.} \approx \overline{K} \overline{A}_o \overline{V}_o \overline{g}_{so}$$

where $\overline{K}$ is an approximately constant value consisting of the product of the slightly variable (in this part of the estuary) correction for the weight of a cubic foot of water on the basis of the observed salinity values, and other (constant) values as shown in Table 21 as well as the 3,600 sec per hour in the last of the above three expressions; $\overline{A}_o$ is the observed cross-sectional area; $\overline{V}_o$ is the observed current velocity; $\overline{g}_{so}$ is the observed suspended solids value; and D is the duration of the flood or ebb current. The bars over the factors indicate average values that prevailed during a given phase of the current cycle (flood or ebb). The average cross-section during an observed flood or ebb current must be adjusted to that which would exist during a mean tide. Thus:

$$\frac{\overline{A}_m}{\overline{A}_o} = \frac{(H + HTL_m) \, W}{(H + HTL_o) \, W}$$

where $\overline{A}_m$ and $\overline{A}_o$ are respectively the average cross-sectional areas during a mean tide and during the observed flood or ebb, H is the mean depth (Table 20), W is the width, and HTL_m and HTL_o are respectively the half-tide levels during a mean and during the observed flood or ebb. The current velocities may be adjusted by the ratio of the ranges of tide, thus:

$$\frac{\overline{V}_m}{\overline{V}_o} = \frac{T_m}{T_o}$$

where $\overline{V}_m$ and $\overline{V}_o$ are respectively the current velocities during a mean tide and those during the observations of flood or ebb, while T_m and T_o are the mean and observed ranges of tide. Theoretically, the freshwater velocities (i.e., those due to upland freshwater inflow into the estuary) should be added to the flood current as observed and subtracted from the observed ebb current before applying the ratio of ranges of tide. However, the freshwater velocities are so low compared with the true tidal currents at the three cross-sections as to make this refinement unnecessary. The suspended sediment observations must also be adjusted. The concentration of suspended solids in flowing water is a function of the current velocity. According to Vanoni et al, (ASCE Hydraulics Division Journal, Vol. 97, HY 4) the relationship may be expressed as:

$$g_{so} \propto V_o^n$$

where g_{so} is the concentration of suspended sediment and V_o is the corresponding current velocity. The exponent of of V is usually 2 or somewhat greater.

Then:

$$\frac{g_{sm}}{g_{so}} \propto \left[\frac{\bar{V}_m}{\bar{V}_o}\right]^2$$

and

$$\frac{g_{sm}}{g_{so}} \propto \left[\frac{\bar{V}_o \frac{T_m}{T_o}}{\bar{V}_o}\right]^2$$

The adjusted sediment transport, Q_{sm}, corresponding to a mean tide, is then:

$$Q_{sm} = K \bar{A}_m \bar{V}_m \bar{g}_{sm}$$

Substituting for $\bar{A}_m$, $\bar{V}_m$, and $\bar{g}_{sm}$ the expressions derived above:

$$Q_{sm} = K \bar{A}_o \frac{H + HTL_m}{H + HTL_o} \cdot V_o \frac{T_m}{T_o} \cdot g_{so}\left(\frac{T_m}{T_o}\right)^2 =$$

$$K A_o V_o g_{so} \frac{H + HTL_m}{H + HTL_o}\left(\frac{T_m}{T_o}\right)^3$$

but $K \bar{A}_o \bar{V}_o \bar{g}_{so} = Q_{so}$

Then $Q_{sm} = Q_{so} \frac{H + HTL_m}{H + HTL_o}\left(\frac{T_m}{T_o}\right)^3$

74. The tide observations, which were made visually on staffs, appear to be questionable in some cases. There were no weather conditions during either the B or the C Series to account for the aberrations (which were not great). However, since the ratio of mean to observed ranges is to be cubed, modifications of the observed tibe data were made before using them in the above equation for adjusting the data in Table 22. Of lesser importance in the above equation are the half-tide levels, but these also were modified. Table 23 sets forth the tide data as observed, the adjustments made, and the methods used. In the 17 mile reach of Delaware Estuary involved in the work, it is reasonable to expect that there would be nearly equal ratios between the observed ranges of tide and the long-time means at the three cross-sections. It should also be found that the differences between half-

TABLE 23
ADJUSTMENTS OF OBSERVED TIDES (RANGE)

Series	Channel Station Ft.	Mean Range Ft.	Obs. Rise Ft.	Ratio Obs./Mn	Adj. Rise Ft.	Obs. Fall Ft.	Ratio Obs./Mn	Adj. Fall Ft.
B	90+000	5.85	5.77	0.9863	5.98	5.35	0.9145	5.36
B	124+000	5.73	6.06	1.0576	5.86	5.24	0.9145	5.25
B	180+000	5.58	5.73	1.0269	5.71	5.12	0.9176	5.11
			Av.	1.0236		Av.	0.9155	
C	90+000	5.85	4.93	0.8427	5.06	4.73	0.8085	4.72
C	124+000	5.73	5.08	0.8866	4.95	4.78	0.8342	4.63
C	180+000	5.58	4.82	0.8638	4.82	4.35	0.7796	4.51
			Av.	0.8644		Av.	0.8074	

Note: The average ratios were applied to the mean range values to obtain the adjusted rises and falls of tide during the observations.

Table 23 continued on next page.

TABLE 23 (Continued)

HALF-TIDE LEVELS

Series	Channel Station Ft.	HTL (Mean) Ft.	HTL During Rise Obs. Ft.	HTL During Rise Adj. Ft.	HTL During Fall Obs. Ft.	HTL During Fall Adj. Ft.
B	90+000	3.42	3.42	3.49	3.62	3.80
	Diff.	-0.06	+0.10	-0.06	+0.31	-0.06
B	124+000	3.36	3.52	3.43	3.93	3.74
	Diff.	-0.07	-0.16	-0.07	-0.26	-0.07
B	180+000	3.29	3.36	3.36	3.67	3.67
	Aver.	3.36	3.43	3.43	3.74	3.74
Aver. of Mean HTL			3.36	3.36	3.36	3.36
Adjustments			+0.07	+0.07	+0.38	+0.38
C	90+000	3.42	4.48	4.69	4.38	4.52
	Diff.	-0.06	+0.28	-0.06	+0.23	-0.06
C	124+000	3.36	4.76	4.63	4.61	4.46
	Diff.	-0.07	-0.12	-0.07	-0.21	-0.07
C	180+000	3.29	4.64	4.56	4.40	4.39
	Aver.	3.36	4.63	4.63	4.46	4.46
Aver. of Mean HTL			3.36	3.36	3.36	3.36
Adjustments			+1.27	+1.27	+1.10	+1.10

Note: The differences between the average observed HTL and the average HTL at the three cross-sections during a mean tide were applied to the Mean HTL's to get the adjusted HTL's.

HIGH AND LOW TIDES DERIVED FROM ABOVE RISES, FALLS, & HTL'S

Station	LW		Rise HTL		Rise Rge.		HW		Fall HTL		Fall Rge.		LW	
Series	Obs.	Adj.	Obs.	Adj.	Obs.	Adj	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.
90B	0.53	0.50	3.42	3.49	5.77	5.98	6.30	6.48	3.62	3.80	5.35	5.36	0.95	1.12
124B	0 49	0.50	3.52	3.43	6.06	5.86	6.55	6.36	3.93	3.74	5.24	5.25	1.31	1.11
180B	0.50	0.51	3.36	3.36	5.73	5.71	6.23	6.22	3.67	3.67	5.12	5.11	1.11	1.11
Station	HW		Fall HTL		Fall Rge.		LW		Rise HTL		Rise Rge.		HW	
Series	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.
90C	6.75	6.88	4.38	4.52	4.73	4.72	2.02	2.16	4.48	4.69	4.93	5.06	6.95	7.22
124C	7.00	6.78	4.61	4.46	4.78	4.63	2.22	2.15	4.76	4.63	5.08	4.95	7.30	7.10
180C	6.58	6.64	4.40	4.39	4.35	4.51	2.23	2.13	4.64	4.56	4.82	4.82	7.05	6.95

Note: The adjustments to the observed high and low tide elevations are based on the above adjustments to the ranges and half-tide levels. One-half the adjusted range was subtracted from the adjusted HTL to get the adjusted low water elevation and added to get HW.

tide levels would be essentially constant. Table 23 shows that neither of these tests conformed with expectations. The differences in the ratios of ranges can be accounted for by errors in reading the tide staffs; there is always some wave action in this reach of the Delaware. The variations of the half-tide differences can be explained in part by the difficulty of visually reading the staffs, but the table makes it apparent that all of the staffs were not set to the same datum.

75. The maximum adjustments shown in Table 23 were as follows: High tides, 0.27 ft; Low Tides, 0.20 ft; Ranges, 0.22 ft; and Half-Tide Levels, 0.21 ft. Many of the adjustments were very small and in five cases, no adjustments were necessary.

76. After making the adjustments, the total transports of suspended solids were shown in Table 24. The observed transports tabulated in Table 23 are repeated in Table 24 to show how the observed and adjusted values compare.

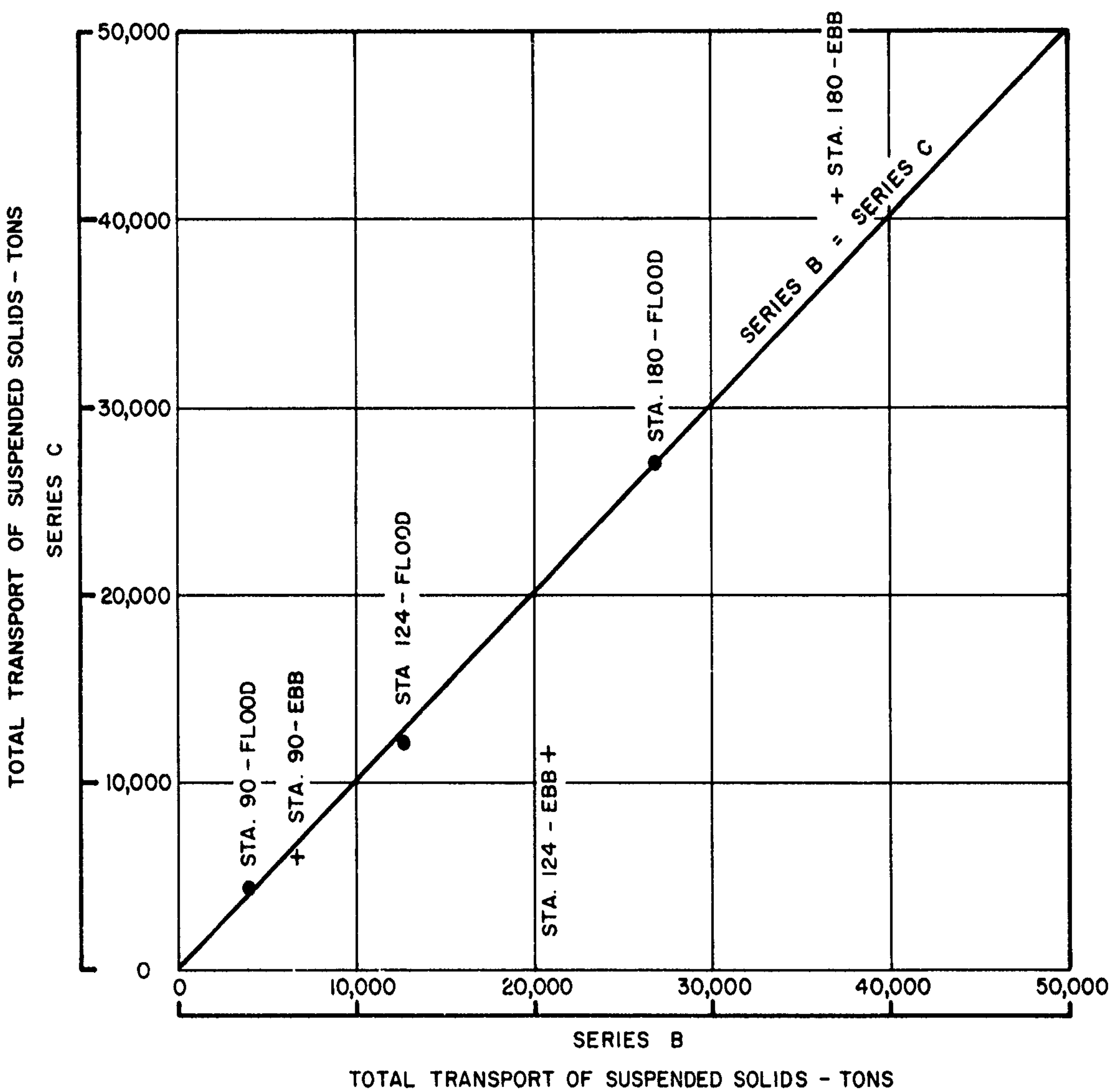
TABLE 24

OBSERVED AND ADJUSTED TOTAL TRANSPORT OF SUSPENDED SOLIDS (TONS)

Series	Channel Station 90+000				Channel Station 124+000				Channel Station 180+000			
	Flood		Ebb		Flood		Ebb		Flood		Ebb	
	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.
B	4,176	3,901	5,139	6,600	13,653	12,737	16,240	20,875	28,710	26,729	28,800	37,021
C	2,994	4,444	3,313	6,091	8,101	12,103	6,354	11,658	18,211	27,803	22,680	41,403

If all factors involved in the transport of suspended solids had been identical during the B and the C Series, and if the observations had been perfect, it would be reasonable to expect that the transported quantities would have been identical. Thus, if the adjustments made were reasonable, and if the assumption that conditions involved in the transport phenomenon were sufficiently close to equality (except the dike failure at Station 176+000, which preceeded the beginning of the Series B observations by a short time), the adjusted values shown above should have been approximately equal during the same phases of current and the same cross-sections. Plate 16 facilitates comparison of the adjusted values for the B and C Series. The line shown indicates equality of the B and C Series. It is apparent that all of the adjusted values except that for the Ebb at Station 124+000 are reasonably close to the equality line. Considering the predominance of ebb transports over flood, it is seen that it would be necessary that the Series C value for the Station 124+000 Ebb should be greater. All of the steps involved in determining the observed value and the subsequent adjustment have been rechecked, and no way is seen to change this plotted value.

77. It has been pointed out that the failure of the disposal area dike at Channel Station 176+000 may have affected the Series B observations. The available



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data concerning the failure, stated in paragraph 65, are repeated here. It is known that the dike was intact at 15.00 hours on 14 May 1969 and that about 1,200,000 cy had been lost from the disposal area by 6.33 hours on 15 May 1969, at which time no further losses were taking place. Thus, it is not known exactly when the breach took place or when the spillage ended. The Series B observations, made 15 May 1969, began at the following times: Station 180 - 8.00 hours; Station 124 - 9.00 hours; Station 90 - 8.00 hours. The following table shows observed and inferred times of slack waters at Stations 180, 124, and 90 covering the period when the breach occurred and before and after that period. The inferences are based on the assumption that the intervals between successive high water slacks and successive low water slacks are 12.42 hours.

Dates	HWSl, 1 ft. above bottom			LWSl, 1 ft. above bottom		
	Sta. 180	Sta. 124	Sta. 90	Sta. 180	Sta. 124	Sta. 90
5/14/69	(12.74)	(13.49)	(13.74)	(19.66)	(20.01)	(20.41)
5/15/69	(1.16)	(1.91)	(2.16)	8.08	8.43	8.83
5/15/69	13.58	14.33	14.58	20.17	20.50	20.77

Note: The inferred values are enclosed in ( )

The use of the observations one ft. above bottom is based on the assumption that the bulk of the spilled material probably was transported close to the bottom.

78. It is likely that the times of slack water at Station 176+000, where the bank failure occurred, are essentially the same as those at Station 180. The table shows that the current was ebb at 15.00 hours on 14 May 1969, when the dike was known to be intact, and that the current reversed from ebb to flood at 19.66 hours. That flood current ended at Station 176 at 1.16 hours on 15 May, then the current was ebb until 8.08 hours. Thus, if the failure occurred shortly after 15.00 hours on 14 May, the initial slug of the resulting abnormally turbid water would be transported downstream, then it would turn and travel upstream. In the meanwhile, additional slugs of water contaminated by the outflow from the disposal area would also travel downstream, but these would not go as far before reversing direction. By 19.7 hours, a slug then introduced into the estuary would initially travel upstream, presumably adding its turbidity to the residual turbidity due to some earlier slug. To determine the travel of slugs entering the estuary at various times, instantaneous current velocity profiles were plotted for the reach from Station 124 to 220. These were based on the observations one foot above bottom at Stations 124 and 180, assuming that the currents for cycles preceeding the commencement of the Series B observations were the same as those observed. It was also necessary to infer the times of slack waters at Station 220, and to assume that the currents at Station 180, with this time adjustment, were applicable to Station 220. The currents one foot above bottom were used because it appears reasonable to believe that the movement of the spill materials would be close to the bottom.

79. The instantaneous current velocity profiles made it possibly to determine, for various starting times of slugs, the times and locations where the excursions of these slugs ended, and the times when the slugs passed Station 180. No slug could reach Station 124; it was found that a slug entering at 19.7 hours on 14 May ended its upstream excursion at Station 150, and no slug entering either earlier or later would reach as far upstream. The data resulting from this analysis are tabulated below:

Slug Start @ Sta. 176	End Upstream Excursion		Slug @ Sta. 180	End Downstream Excursion		Slug @ Sta. 180	End Upstream Excursion		Slug @ Sta. 180
Time	Sta.	Time	Time	Sta.	Time	Time	Sta.	Time	Time
14–19.7	150	15–1.6	15–7.5	182	15–8.0	15–8.0	158	15–13.8	15–18.2
14–22.7	154	15–4.6	15–4.5	201	15–7.6	15–12.0	176	15–14.0	15–15.0
15–1.7	–	–	15–3.0	211	15–7.7	–	187	15–13.5	–
15–4.0	–	–	15–4.5	200	15–7.8	15–11.5	176	15–14.0	15–15.6
15–6.3	–	–	15–7.5	182	15–8.0	15–9.0	158	15–13.8	15–18.2

The data are to be interpreted as follows: A slug entering at Sta 176 at 19.7 hours on 14 May (shown as 14-19.7) at low water slack would move upstream with the ensuing flood current to Station 150, reaching there at 15-1.6, then move downstream with the ebb current to Station 182 at 15-8.0, passing Station 180 at 15-7.5, which is 0.5 hours before the start of the observations there. It would turn at Station 182 and then move upstream, passing Station 180 again at 15-8.0, and terminate its upstream excursion at Station 158 at 15-13.8. On the ensuing downstream excursion, it would again pass Station 180 at 15-18.2, but it cannot again pass Station 180 on the next upstream excursion before the observations ended at 15-20.2. It thus appears that there were effects of the spillage throughout the entire period of the observations at Station 180, assuming that the spill was in fact distributed rapidly rather than accumulating near the location of the spill and assuming also that the contamination was conservative, i.e., that the quantity placed in suspension initially remained thus indefinitely.

80. In the light of the foregoing, reexamination of Plate 16 is in order. It has been shown that the breach in the disposal area dike could not have had an effect on the observations at Station 124, and accordingly, those at Station 90 were not affected. Thus, the strange relationship between the Series B and C for Station 124 Ebb shown on the Plate remains unexplained. The analyses show that it is likely that all of the observations at Station 180 during the B Series may have been affected by the dike failure. The effect would logically be to cause increases in the total transports of suspended sediments during the B Series over what would have been found if the dike had not failed. There is no way to determine numerically what these increases may have been, but it is pointed out that the Series B observations at Station 180 do not appear excessive in comparison with the Series C ob-

servations. It is conceivable that the Series C observations at Station 180 may have been affected despite the fact that the Series C observations were made about five weeks after the dike breach. If this is the case, then both the Series B and the Series C observations at Station 180 resulted in transports of suspended sediment that were abnormally high due to the breach of the disposal area dike, but it is possible that the net quantity of suspended solids in transport, i.e., that during the flood phase minus that of the ebb phase is meaningful.

81. The adjusted total transports of suspended solids given in Table 24 are repeated in Table 25, below, and these numbers are followed by the net suspended solids transported per 12.42 hours and per 24 hours, also the freshwater inflows to the estuary and the average salinity one ft. above the bottom during the observations.

TABLE 25

COMPARISON OF SUSPENDED SOLIDS TRANSPORTED WITH VIRGIN SEDIMENT INFLOWS, FRESHWATER INFLOWS, AND SALINITY

Series	Adjusted Suspended Solids Transported: Flood Phase Tons	Ebb Phase Tons	12.42 Hr. Net Tons	24.00 Hr. Net Tons	24 Hr. Virgin Inflow Tons	Freshwater Inflow cfs	Bottom Salinity ppt
			Station 90+000				
B	+ 3,901	− 6,600	− 2,699	− 5,215	989	12,050	0.124
C	+ 4,444	− 6,091	− 1,647	− 3,183	259	9,610	0.188
Aver.	+ 4,172	− 6,346	− 2,173	− 4,199	624	10,830	0.156
			Station 124+000				
B	+12,737	−20,875	− 8,138	−15,726	1,007	12,270	0.150
C	+12,103	−11,658	+ 445	+ 860	263	9,780	0.236
Aver.	+12,420	−16,266	− 3,846	− 7,433	635	11,025	0.193
			Station 180+000				
B	+26,729	−37,021	−10,292	−19,888	1,049	12,850	0.316
C	+27,083	−41,403	−14,320	−27,671	284	10,530	1.312
Aver.	+26,906	−39,212	−12,306	−23,779	666	11,690	0.814

82. The data tabulated above show that there are very large differences between the quantity of suspended solids in transport and the inflows of virgin sediments, at all three cross-sections. The differences become greater at each successive cross-section in the downstream direction. While it cannot be said that the quantities in transport were precisely evaluated, it is improbable that they are sufficiently in error to negate the finding that there is far more material being transported than can be accounted for by the inflows of virgin sediments during the observations. Thus,

the estuary itself appears to be the immediate source of shoaling material for the navigation channel and the anchorages, and this accounts for the fact that shoaling rates as experienced are fairly uniform during each year, to a great extent regardless of the volume of contributions of virgin sediment during the year. In effect, the estuary is a regulating storage reservoir for the influx of new material entering the system. When this is at a low rate, as it was during the observations, the accumulated deposits are drawn upon to supply material for channel and anchorage shoaling. When the influx is large, some is temporarily stored as a source of supply for future shoaling of the channel and the anchorages and some causes immediate shoaling of these facilities. The rate of channel and anchorage shoaling balances out over a long period and approximates the rate of influx of new material entering the system.

83. A portion of the sediment in the estuary is in transport during the ebb and flood currents, the rates depending on the current velocities. At slack waters, most of the load is temporarily dropped, but when the strength of the ensuing phase of current becomes adequate to cause scour, some (perhaps all in non-shoaling reaches) begins to move again. However, the current velocity must be greater to produce scour of a given sediment than is needed to keep that same sediment in motion. Thus, in the irregular tidal regimen described in paragraph 16 of this report, the ensuing current phase may not attain current velocities adequate for resuspension of all of the material deposited at slack water; the remainder is temporarily stored, even in some non-shoaling reaches. The storage capacity of the estuary, in terms of square feet of bottom area per linear foot of estuary, increases in the downstream direction. Thus, larger quantities of temporarily stored material are available for movement passing Station 180+000 than at Station 90+000, neither of which shoal progressively. This explains why the quantities in transport at Station 180+000, are greater than those at Station 90+000, as shown in Tables 24 and 25. It is now in order to present data resulting from the observations that may show why the shoaling at Station 124+000 and vicinity thereof is so great.

84. The basic observations were described in some detail in paragraphs 63 through 66 of this report. It is desirable to summarize that description here. Briefly, observations were made at nine locations, three at each of three cross-sections at Channel Stations 90+000, 124+000 and 180+000. They consisted of current velocity and direction determinations, the collection of water samples for suspended sediment and dissolved solids analyses and temperature measurements. At each of the nine locations a series of observations beginning at one foot above the silt-water interface was started at the same time, then the instrument array was raised to 2 ft above the interface, then 4 ft, 8 ft, 16 ft and (if the water depth permitted) 32 ft above the interface. Two series of such observations were made, and these were designated Series B and Series C; a third series was attempted, but the weather was such as to make it necessary to terminate the run. During the attempt, the bottom sensors proposed for determining the exact location of the silt-water interface were found to be impracticable, and a number of these instruments were damaged beyond

repair. It was accordingly necessary to locate the silt-water interface by other methods, which may or may not have been entirely satisfactory. In general, the interface was located by lowering the current meter until it ceased to register a velocity, then it was raised one foot above that elevation. This determination was frequently checked by soundings made by means of a fathometer. As it was usually found that the suspended sediment value became greater as the silt-water interface was approached, it is thus possible that the values determined were in some cases too large (when the sample was taken too close to the interface) and in others, when the sample was taken too far from the interface, too small. Such differences would be especially significant for the readings supposedly made one foot above the interface, but not so significant for readings at greater distances above the interface. While the suspended sediment determinations would be greater at say 0.5 ft above the interface than at exactly 1.0 ft above the interface, the current velocities would be somewhat less 0.5 ft above than at 1.0 ft above the interface.

85. After examining the data plotted on the master sheets, it was concluded that it was desirable to smooth the graphs by computing sliding, or moving, averages. A vertical profile was begun on the even hour, the next at 20 minutes after the hour, and the next at 40 minutes after the hour. These three values were averaged and plotted at 20 minutes after the hour. Similarly, the values determined at 20 minutes, 40 minutes and that at the next even hour were averaged and the result plotted at 40 minutes after the first even hour, etc. Thus, every plotted point on a second series of graphs, one for each of the nine locations, represented the average of three observations and these were plotted at the time of the middle one of the three. There are objections to such a procedure, of course, as it may be that great significance should be attached to the fluctuations. However, in view of the question about the exact location of the interface, as discussed above, and in view of the probability that no convincing analysis of the fluctuations could be made even if the observations had been perfect in all respects, it was felt that the sacrifice of some detail would be justified. The basic data for current velocities, suspended sediment, and dissolved solids were programmed for computer determinations of sliding averages for each distance above the estimated silt-water interface, and the plotted results show much more understandable graphs. All of the available sliding averages were plotted on master sheets, and some of the data thus derived are plotted on Plates 17 through 34. These drawings show the current velocities, suspended solids, and dissolved solids: (a) one foot above the silt-water interface; (b) the corresponding values at the greatest distance above the interface (mostly 32 feet above, but in some cases 16 feet above); and (c), the average of all of the suspended and dissolved solids values observed in the vertical profile. These selected values are considered to be indicative of what was taking place at the three cross-sections, and the format facilitates visual comparisons. Table 26 summarizes especially significant data obtained from the eighteen plates. The values tabulated are those one foot above the silt-water interface, but the eighteen plates show that the values 32 feet (generally) above the interface and the average values vary in step very well with those

TABLE 26

PEAK CURRENT VELOCITIES, SUSPENDED SOLIDS, AND SALINITIES, ONE FOOT ABOVE INTERFACE (SILT-WATER)

Station	Location	Flood Current Phase					Ebb Current Phase				
		Max. Current Vel.		Max. Sus. Solids		Max Sal.	Max Current Vel.		Max. Sus. Solids		Max. Sal.
		Time (1)	fps	Time (1)	ppm	ppt	Time (2)	fps	Time (2)	ppm	ppt
90+000	1000B	2.1	1.7	2.5	80	0.18	3.4	2.2	2.1	100	0.16
	2000B	2.9	2.3	(1.3)	(90)	0.17	2.7	2.0	1.0	120	0.16
	2000B			5.0	100						
	3000B	1.8	1.6	3.8	50	0.17	1.2	1.1	0.8	60	0.16
	1000C	2.8	1.9	1.2	150	0.18	4.2	1.9	(1.5)	(60)	0.31
	1000C								6.6	90	
	2000C	–	–	–	–	–	–	–	–	–	–
	3000C	–	–	–	–	–	–	–	–	–	–
124+000	4000B	2.6	1.1	2.6	190	0.16	2.9	1.6	2.3	220	0.17
	4000B								(4.2)	(215)	
	5000B	3.5	1.8	2.9	530	0.17	5.2	1.9	3.0	510	0.16
	5000B			(4.5)	(390)				(4.7)	(290)	
	6000B	3.5	1.3	3.5	290	0.16	3.9	1.8	3.1	160	0.27
	4000C	2.3	1.4	0.0	130	0.23	4.4	1.3	1.2	190	0.26
	4000C								(6.8)	(150)	
	5000C	3.0	1.9	(0.0)	(70)	0.34	2.2	1.5	1.5	340	0.26
	5000C			4.0	230				(6.6)	(80)	
	6000C	3.0	1.4	4.4	510	0.28	2.6	1.1	2.1	90	0.42
180+000	7000B	2.9	2.1	3.5	310	0.39	4.3	1.7	2.5	410	0.43
	7000B								(5.0)	(390)	
	8000B	1.5	2.2	(2.4)	(430)	0.47	4.5	2.4	1.8	790	0.47
	8000B			3.8	890				(5.5)	(160)	
	9000B	2.7	2.6	3.7	190	0.45	1.9	0.9	2.9	390	0.45
	7000C	3.3	1.7	3.8	150	1.50	4.8	2.1	6.2	170	1.70
	8000C	2.0	2.3	(2.7)	(270)	2.00	4.2	2.0	2.5	670	2.20
	8000C			5.0	360				(5.9)	(400)	
	9000C	3.0	1.9	0.9	480	1.90	2.2	1.3	3.0	380	2.10

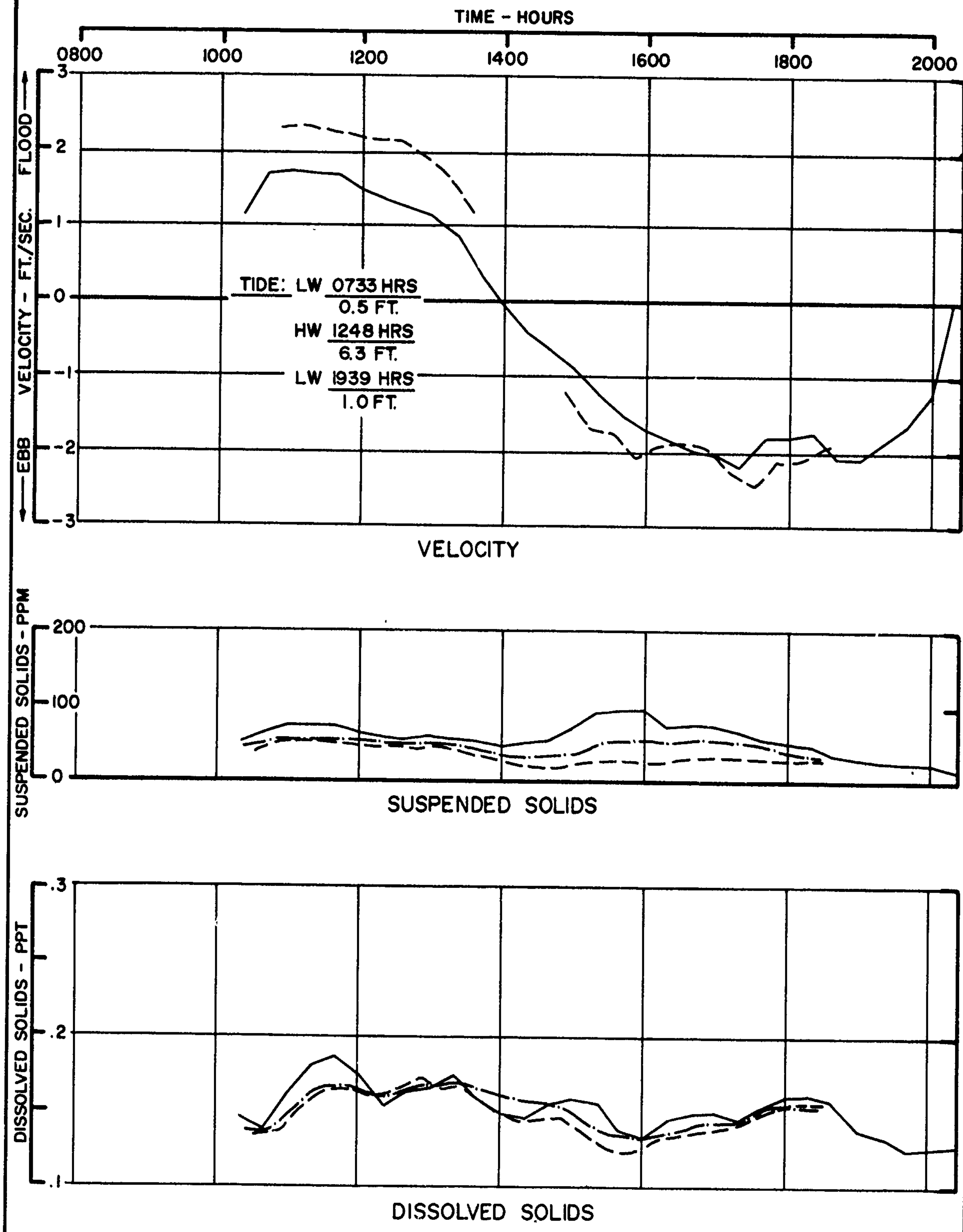
NOTES: (1) Times shown are in hours after LW Slack
(2) Times shown are in hours after HW Slack
Suspended solids values *not* inclosed in parentheses ( ) are the maxima
Suspended solids values inclosed in parentheses ( ) are those where a second distinct surge occurs.

one foot above the interface. The tabulated data give the times and values of maximum current velocities and those of the maximum values of suspended solids. In some cases, there were second pronounced peaks of suspended solids, and these are also tabulated. The times shown are in hours after the time of high water slack current or low water slack current. The table shows that the times of peak current velocity do not generally compare well with the times of peaks of suspended solids, contrary to a preconceived expectation that the times of peak suspended solids would be a little after the times of peak current velocities. It is also seen that there is very little relationship between the peak current velocities and the peaks of suspended solids, contrary to another preconception; it seemed reasonable to expect that the greater the current velocity, the greater the peak concentration of suspended solids. Although the salinities during the C Series are greater than those during the B Series, the peak values of suspended solids during the C Series are generally somewhat lower than those during the B Series, once more not as expected. Another key point is that the peaks at Station 180+000 are much greater than those at Station 90+000.

86. The data on these moving average sheets were analyzed to determine variations of current velocities, dissolved solids, and suspended solids versus distance above the silt-water interface at the same time. As stated before, each point was plotted on the master sheets at the time of the middle of the three observations used in computing each average value. Since these mid-times were not identical for each point in the vertical observed, the graphs were read to obtain sets of data representing conditions at all points above the interface at the same times. The times at which values of current velocity, dissolved solids, and suspended solids were read were those at and near the times of approximate maximum current velocities. In some cases, the currents do not have well-defined peak values; therefore, three sets of readings for each of the three variables were made at and near the maximum velocities. Plates 35 and 36 show some of these plots, the six examples selected being those at the middle location of the three in each cross-section for each series.

87. The middle row of data in Plates 35 and 36 show that the study region is located at the upper end of ocean water intrusion under the freshwater flow conditions prevailing during Series B and C. The salinities diminish from about 1 ppt at location 8000C to about 0.2 ppt at location 5000C, and from about 0.3 ppt at 8000B to about 0.1 ppt at 5000B; the data show that the intrusion of saline water was greater during the Series C observations, when the freshwater flow was slightly lower than it was during the Series B observations. Increasing concentrations of dissolved solids near the bed relative to concentrations near the water surface are not pronounced, indicating the well mixed character of the flow in the study region.

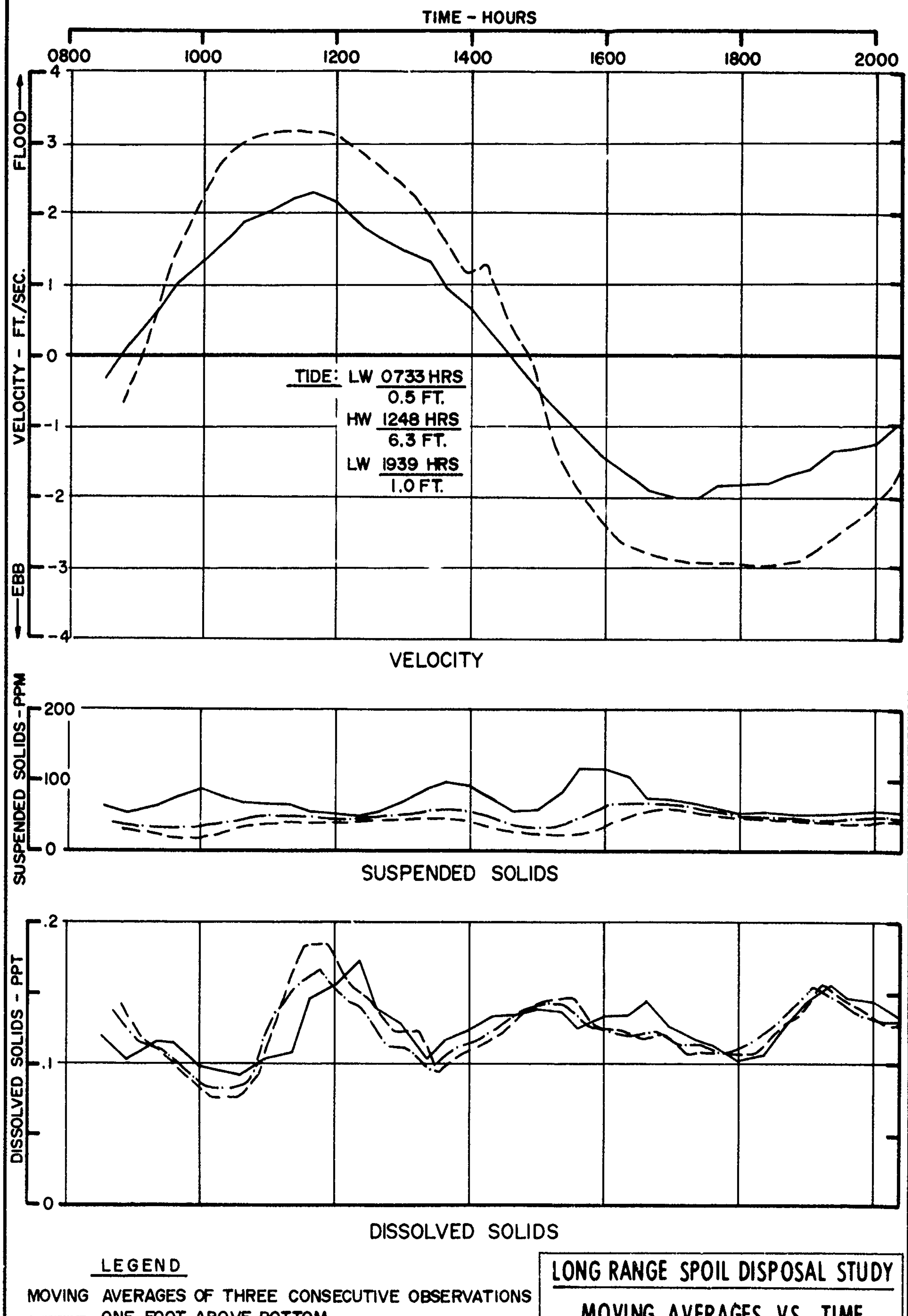
88. The suspended solids concentrations shown in the first row of data of Plates 35 and 36 are comparable to the dissolved solids concentrations and have comparable effects on the fluid density. Gradients of suspended solids concentration are apparent in the figures for locations 5000 and 8000. These concentration gradients indicate that the suspended particles have



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
—·— WEIGHTED AVERAGE
---- 16 FT ABOVE BOTTOM
LOCATION DESIGNATION 1000B = STA. 90+000 (MILE 85.88), 750 FT. WEST OF ℄

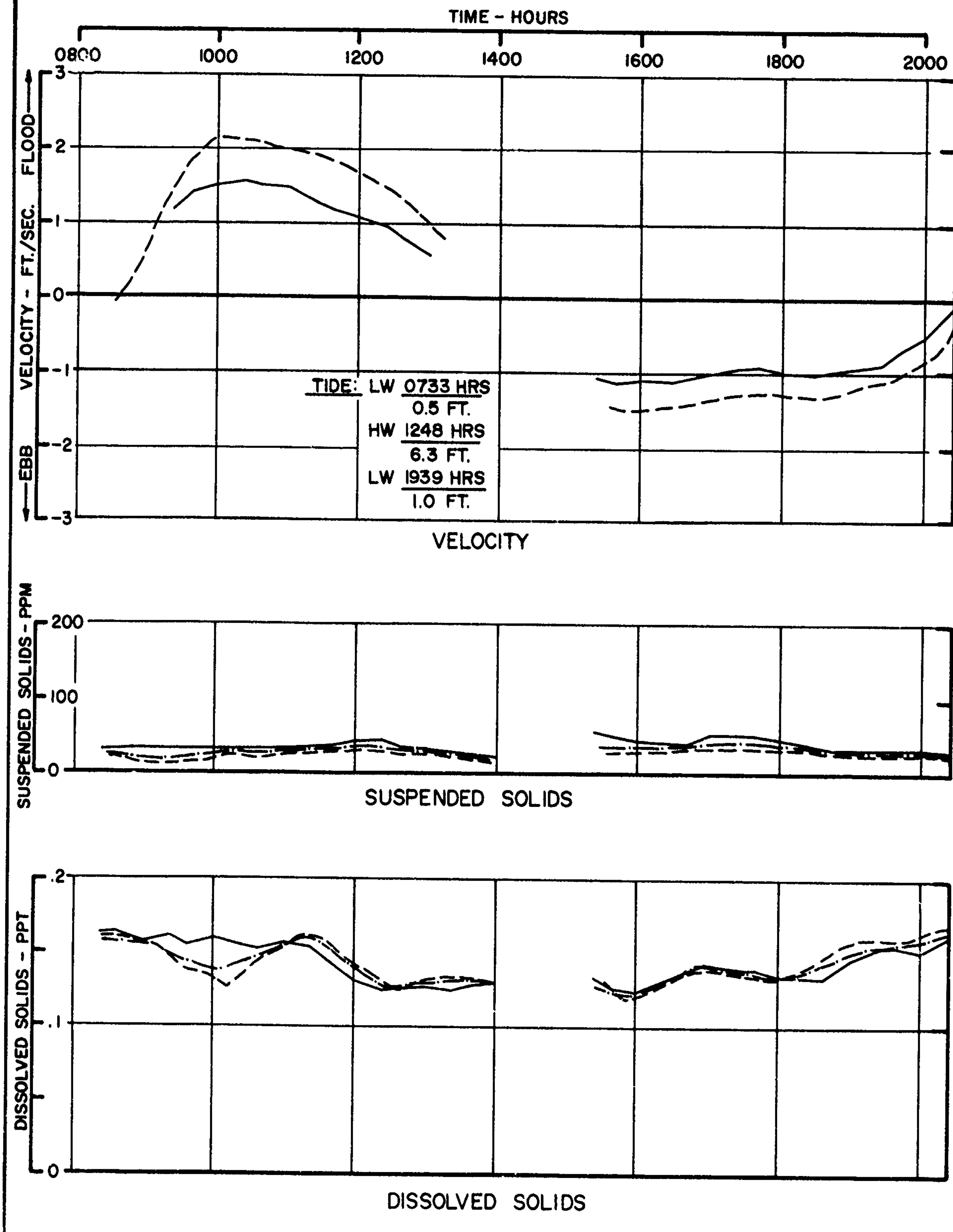
LONG RANGE SPOIL DISPOSAL STUDY
MOVING AVERAGES VS. TIME
1000 B-15 MAY 1969
U.S. ARMY ENGINEER DISTRICT PHILA.



LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
2000 B- 15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



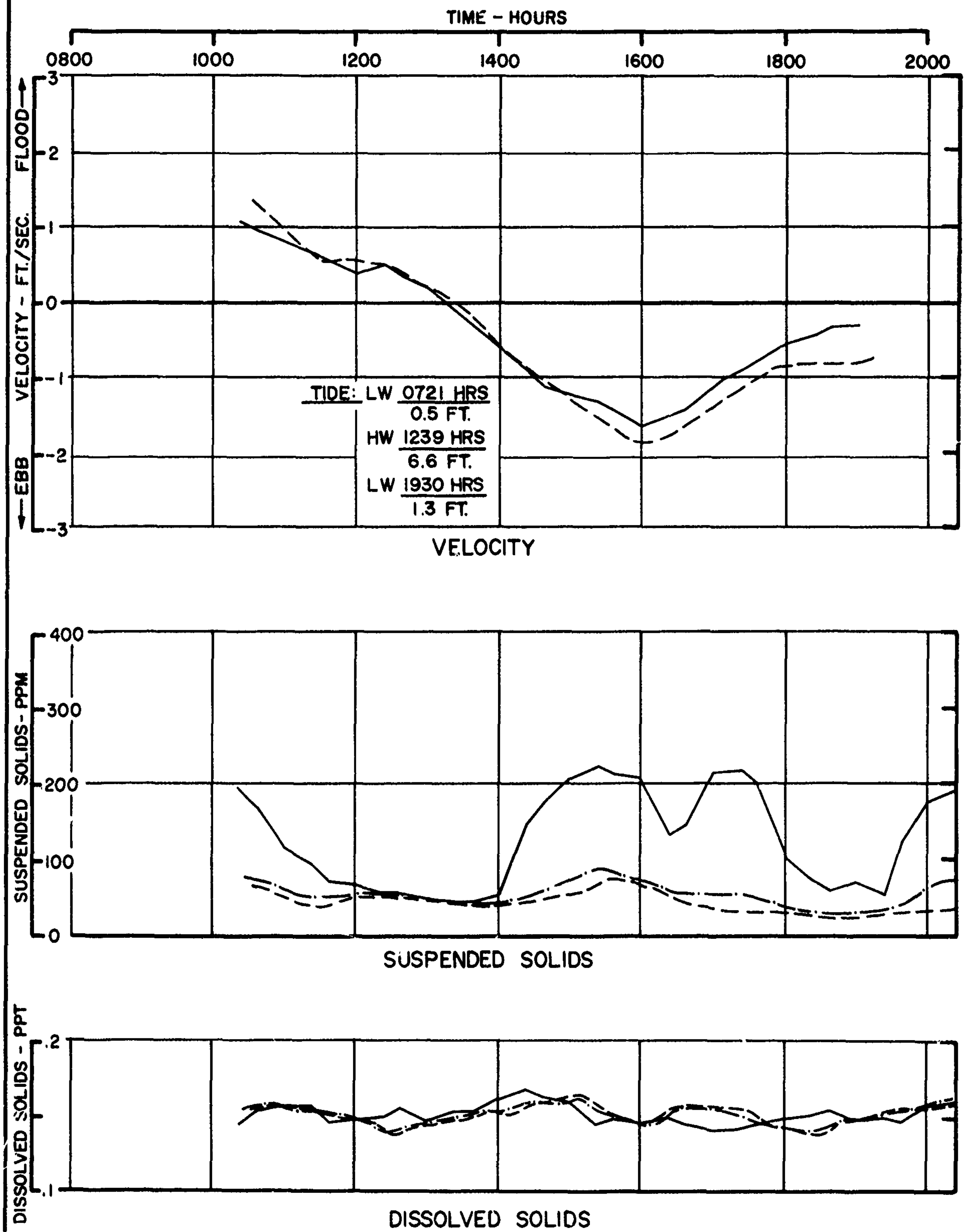
LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
—·— WEIGHTED AVERAGE
- - - - 16 FT. ABOVE BOTTOM
LOCATION DESIGNATION 3000 B = STA. 90+000 (MILE 85.88), 1200 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
3000 B - 15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

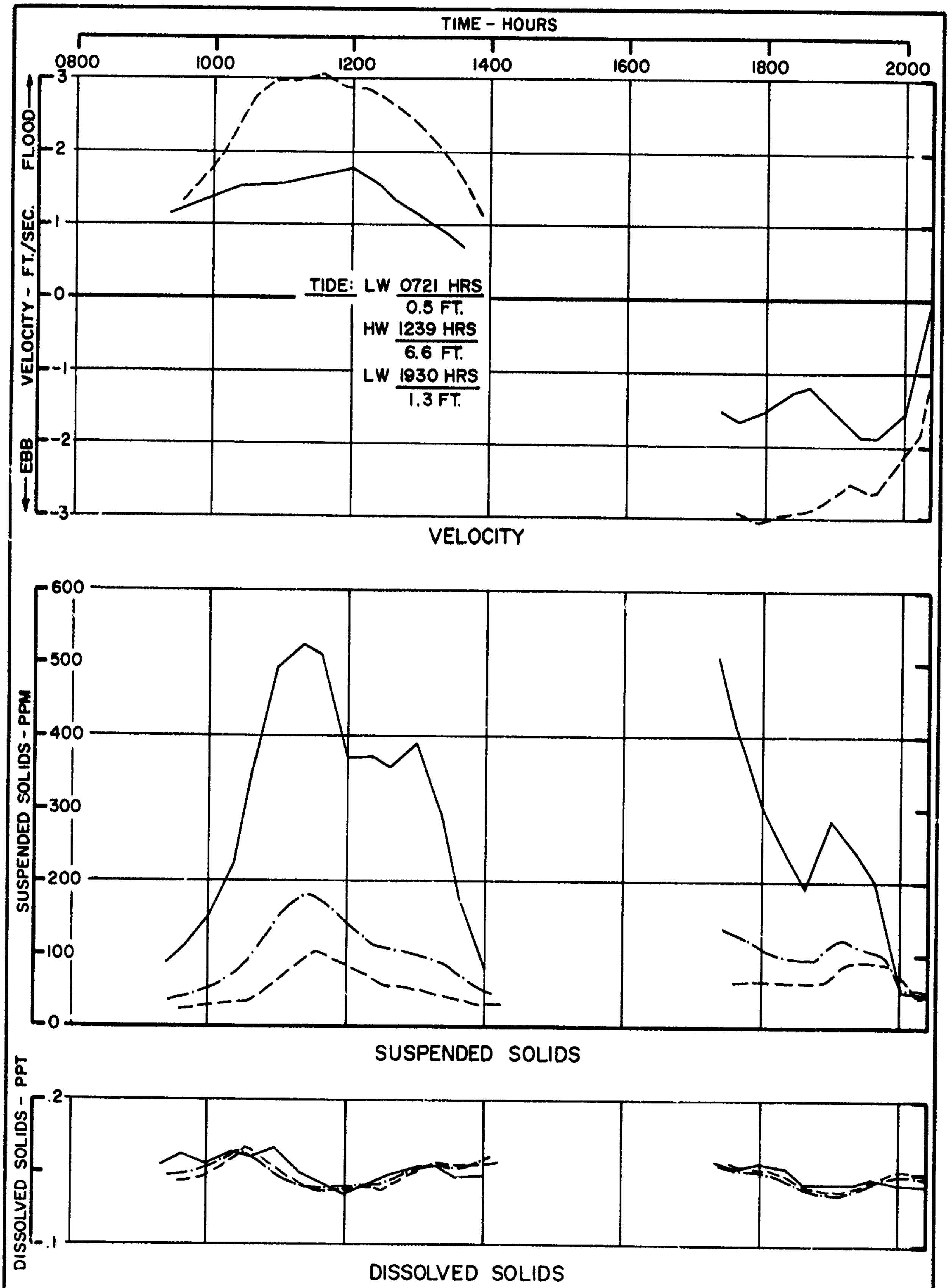
- - - - 16 FT. ABOVE BOTTOM

LOCATION DESIGNATION 4000 B = STA. 124+000 (MILE 79.45), 650 FT. WEST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
4000 B - 15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

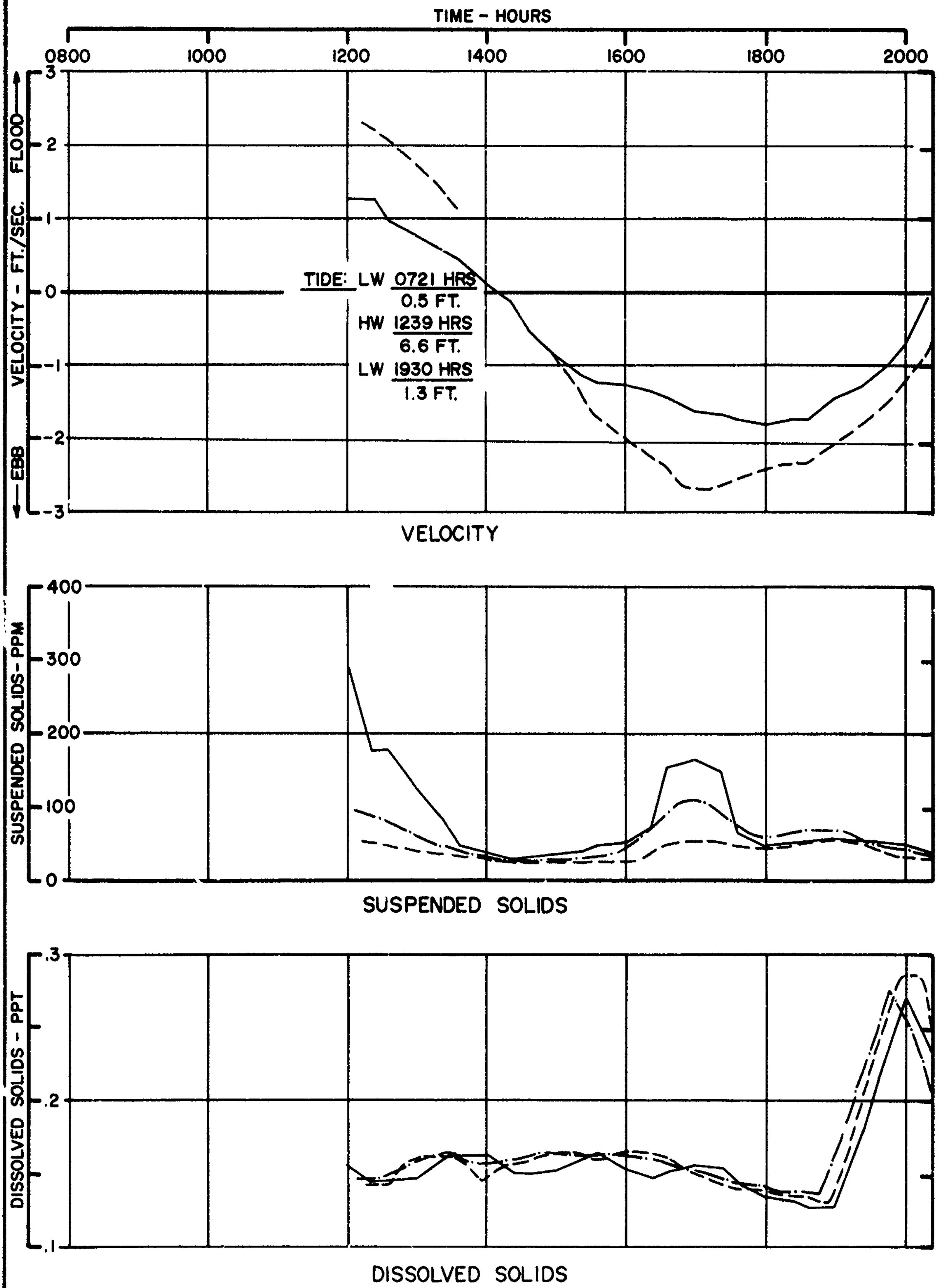
- - - - 32 FT. ABOVE BOTTOM

LOCATION DESIGNATION 5000B = STA. 124+000 (MILE 79.45), 800 FT EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
5000 B-15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

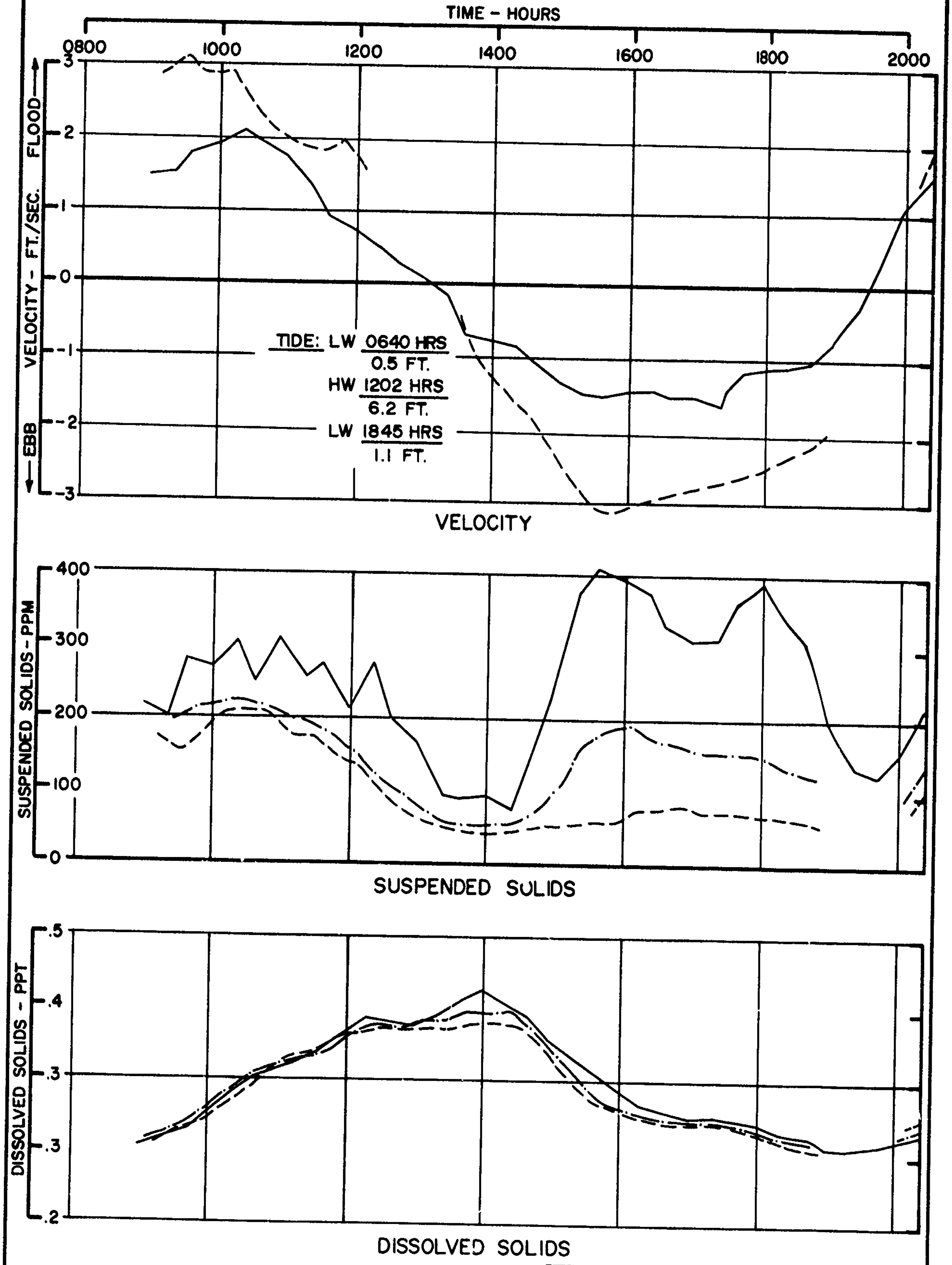
MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
—·— WEIGHTED AVERAGE
– – – 32 FT. ABOVE BOTTOM
LOCATION DESIGNATION 6000 B = STA. 124+000 (MILE 79.45), 1600 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
6000 B-15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.

PLATE 22



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

- - - - 16 FT. ABOVE BOTTOM

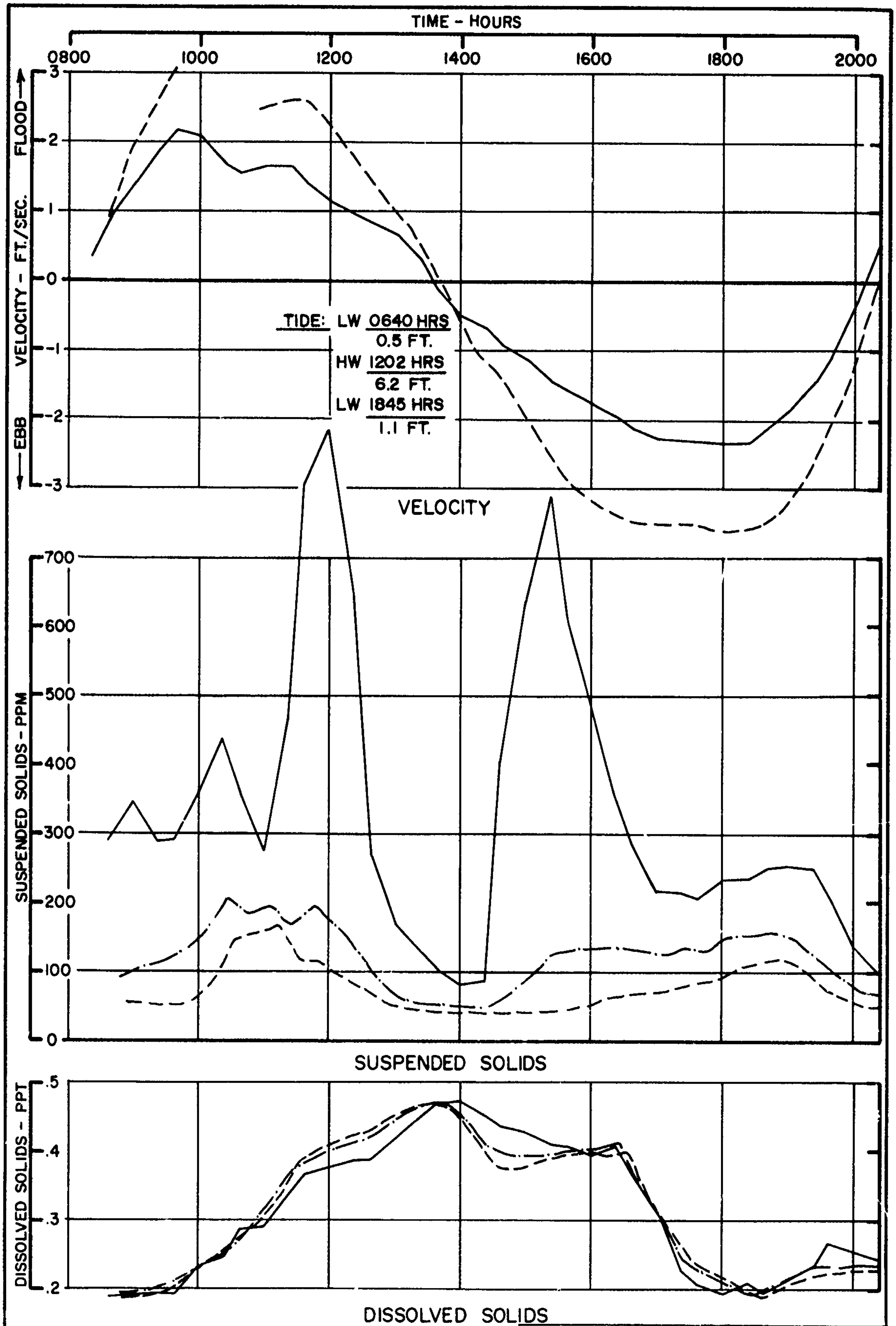
LOCATION DESIGNATION 7000 B = STA. 180+000 (MILE 68.84), 1650 FT. WEST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
7000 B-15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.

PLATE 23

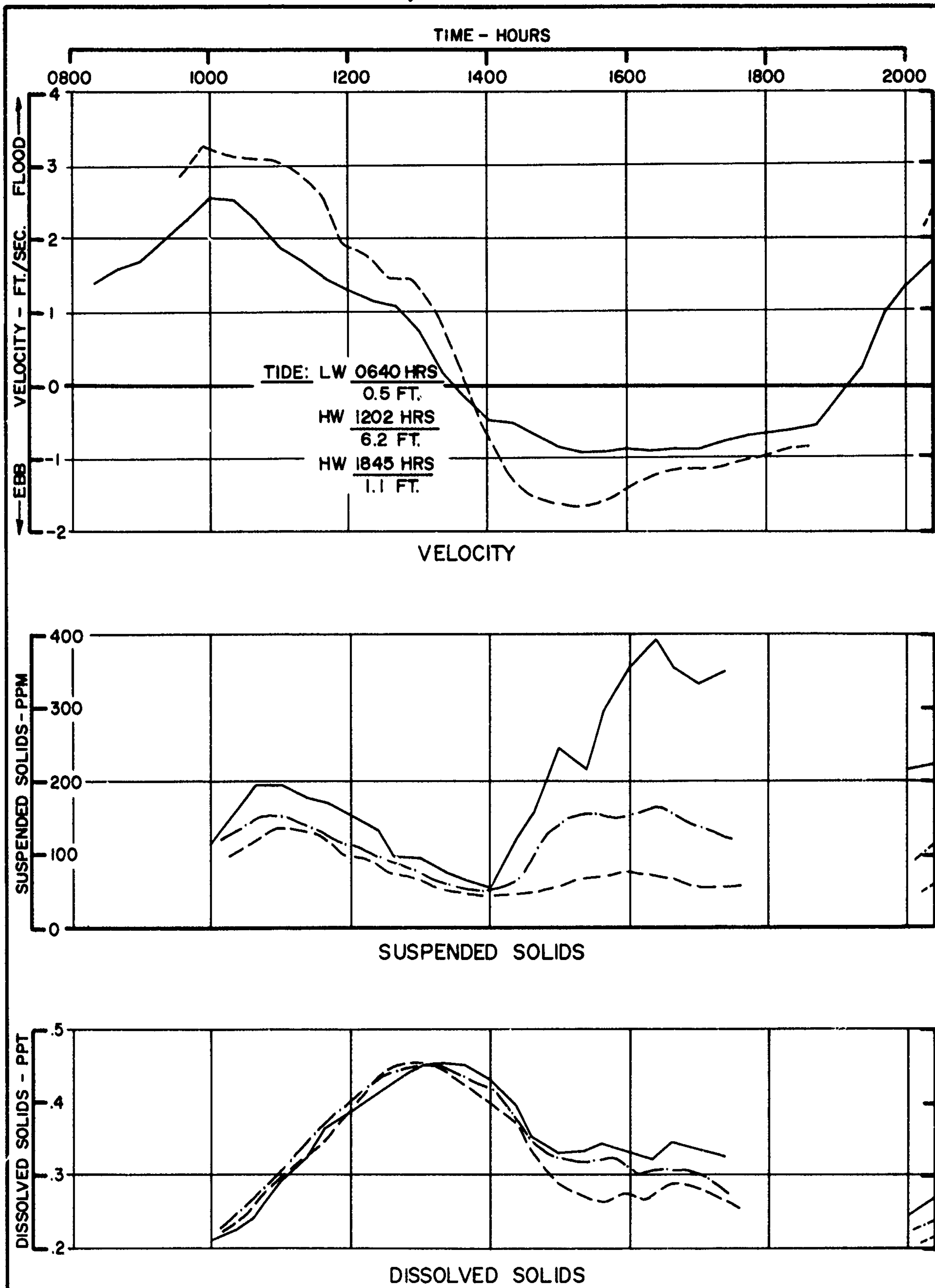


FOR LEGEND SEE PLATE (9000B)
LOCATION DESIGNATION 8000B = STA. 180+000
(MILE 68.84), 15 FT EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
8000 B-15 MAY 1969

U.S.ARMY ENGINEER DISTRICT PHILA.



LEGEND

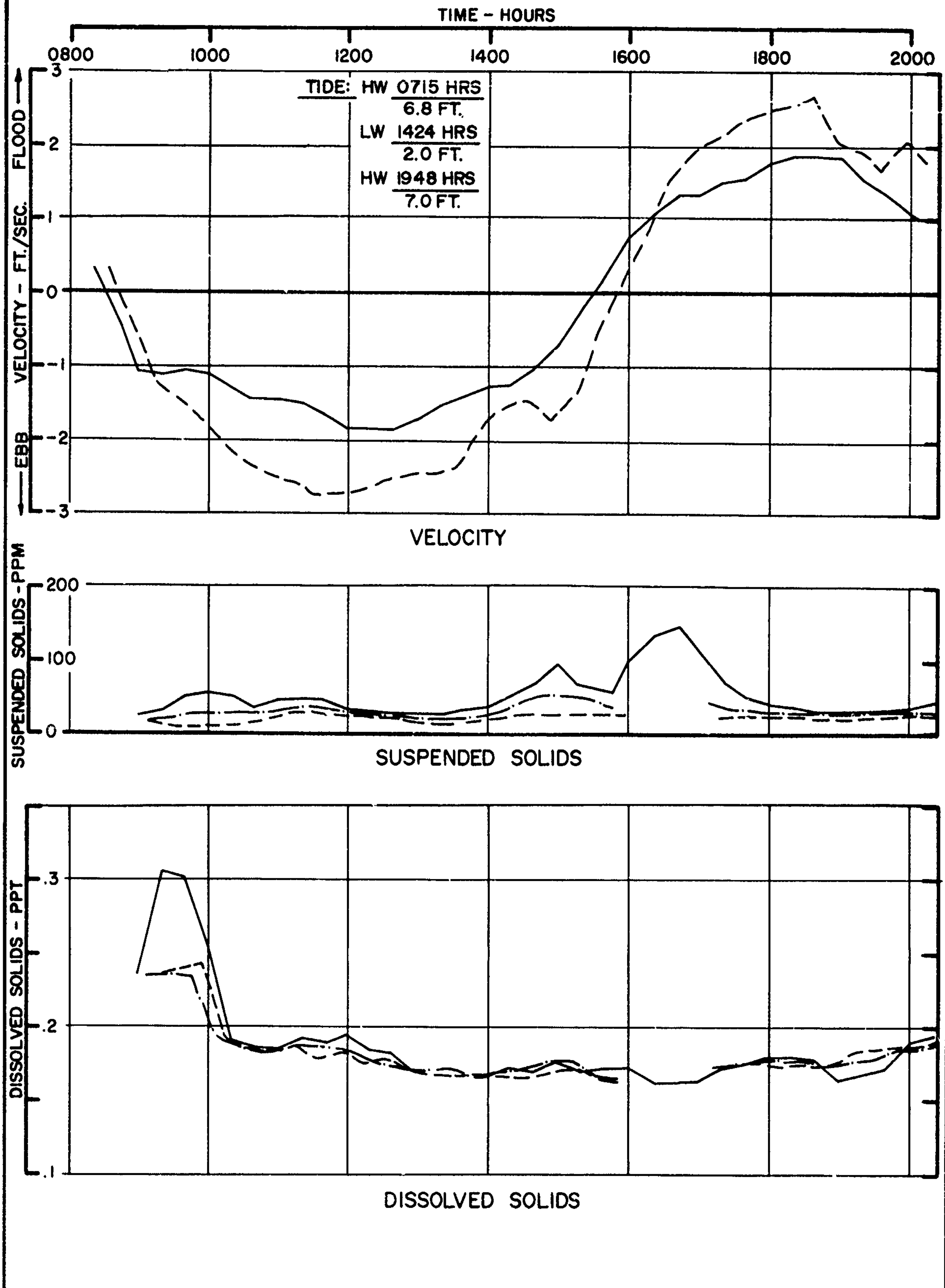
MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
— — WEIGHTED AVERAGE
---- 32 FT. ABOVE BOTTOM
LOCATION DESIGNATION 9000B = STA. 180+000 (MILE 68.84), 1500 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
9000 B-15 MAY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.

PLATE 25



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

— — WEIGHTED AVERAGE

- - - - 32 FT. ABOVE BOTTOM

LOCATION DESIGNATION 1000C = STA. 90+000 (MILE 85.88), 650 FT WEST OF ℄

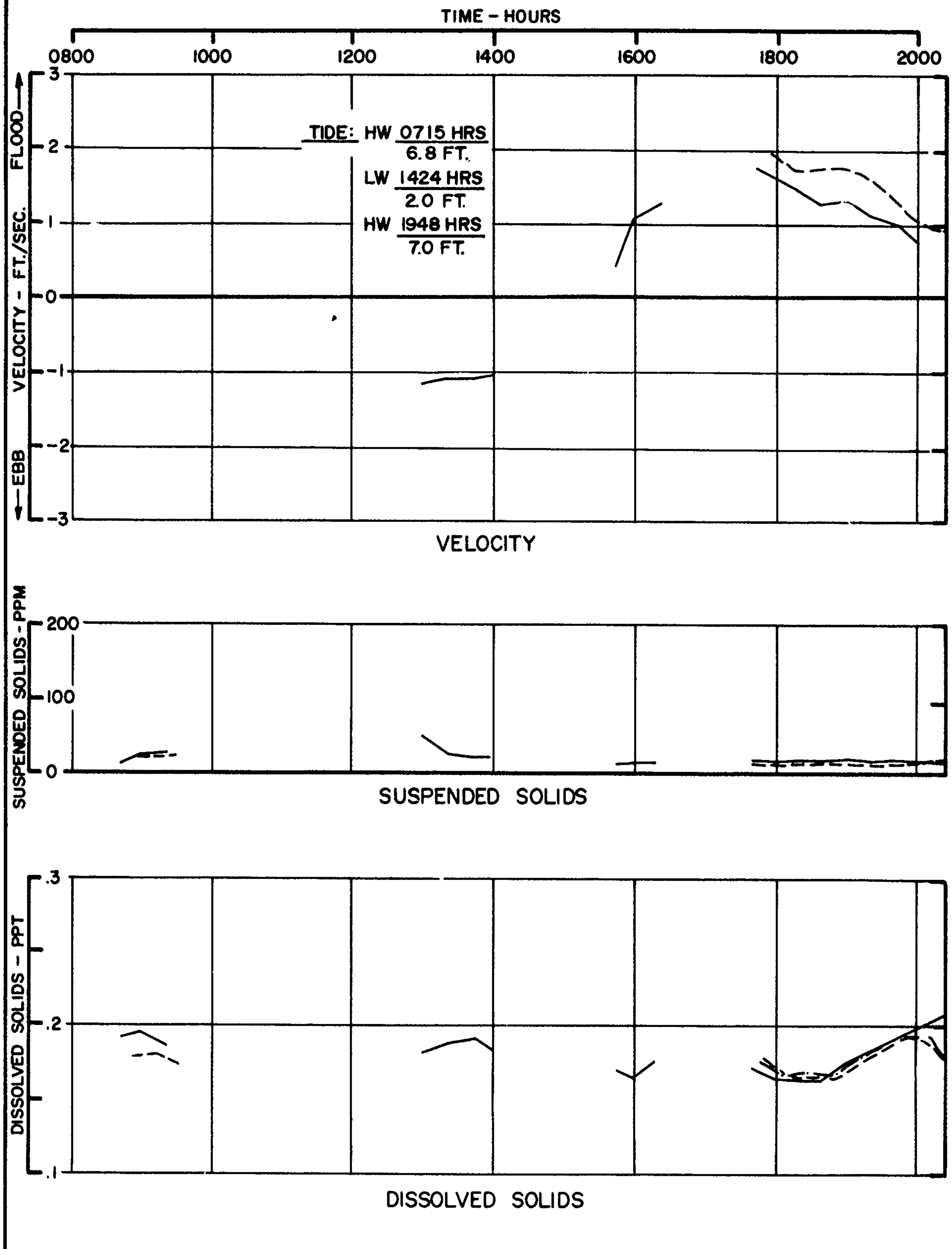
LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME

1000 C-23 JULY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.

PLATE 26



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

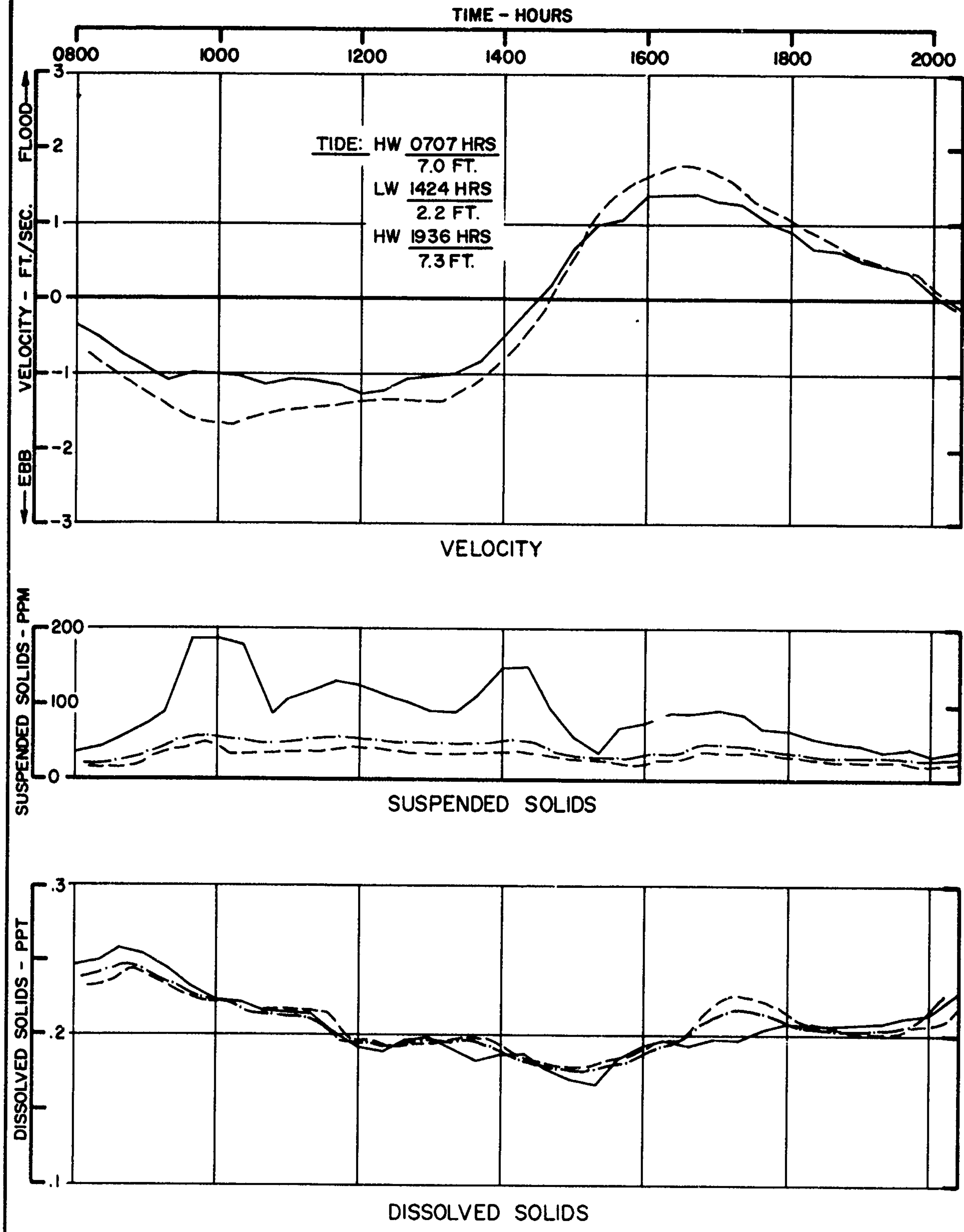
- - - - 16 FT. ABOVE BOTTOM

LOCATION DESIGNATION 3000C = STA. 90+000 (MILE 85.88), 1270 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
3000 C-23 JULY 1961

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

- - - - 16 FT. ABOVE BOTTOM

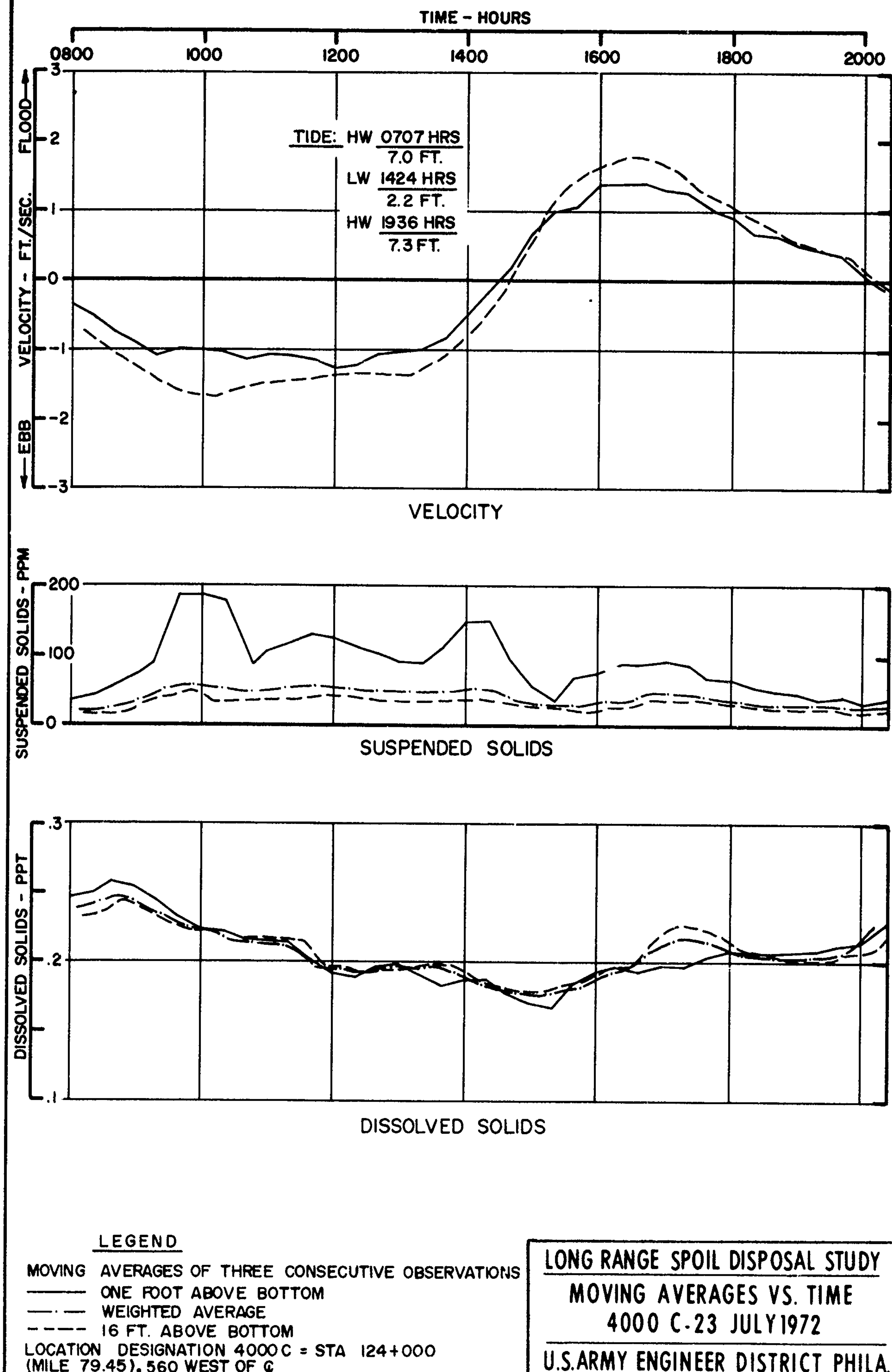
LOCATION DESIGNATION 4000C = STA 124+000 (MILE 79.45), 560 WEST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME

4000 C-23 JULY 1972

U.S. ARMY ENGINEER DISTRICT PHILA.

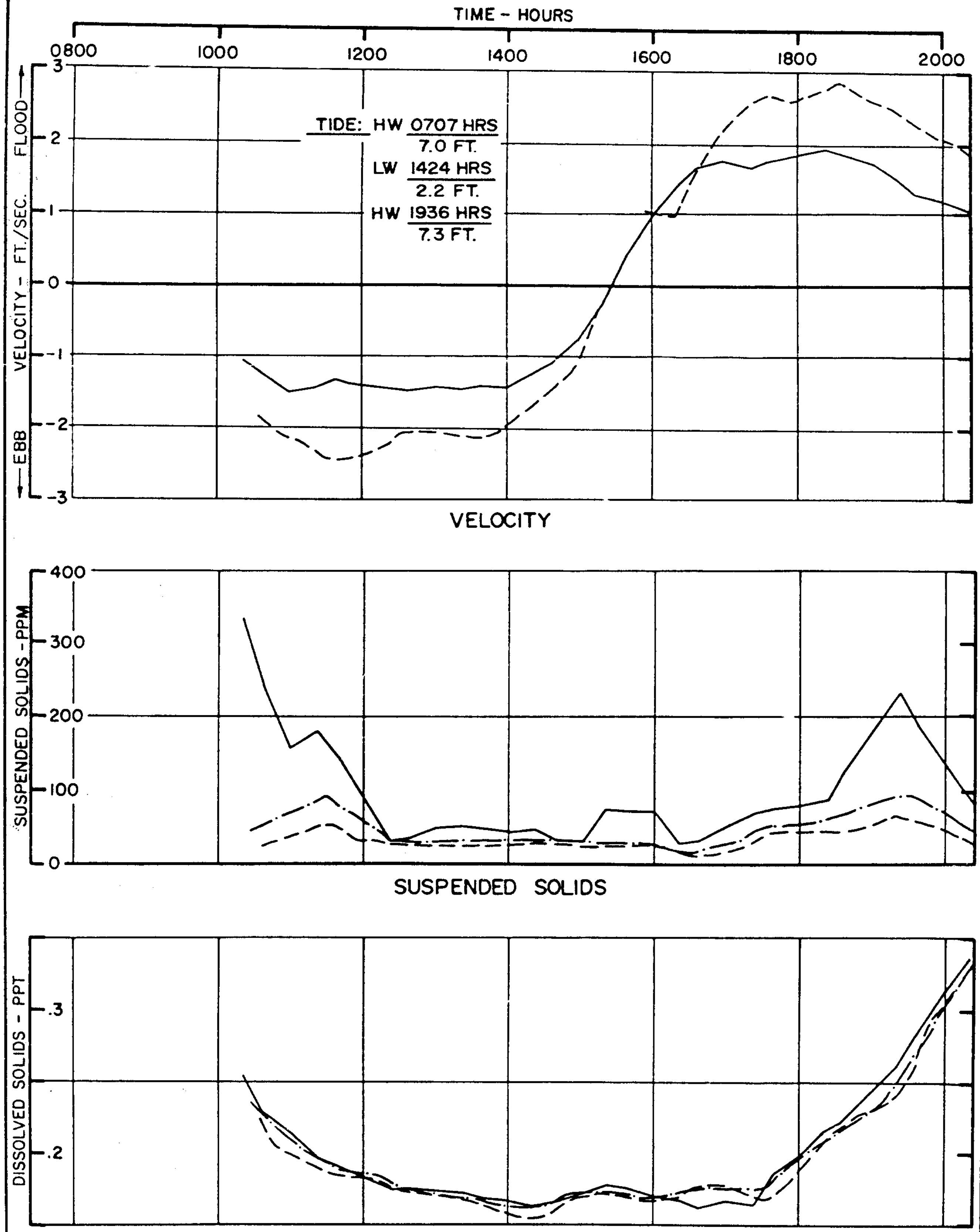


LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME

4000 C-23 JULY 1972

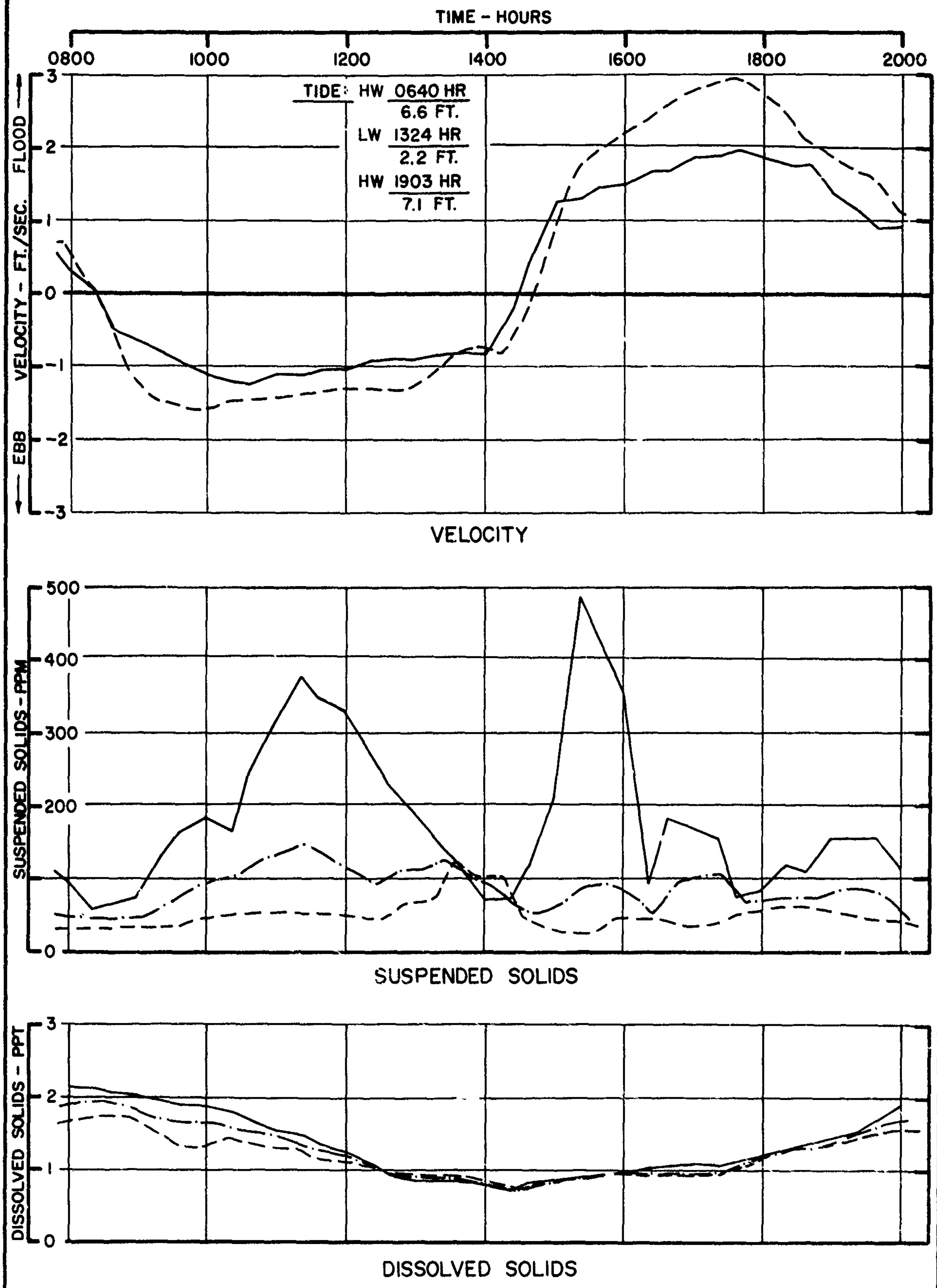
U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
—·— WEIGHTED AVERAGE
---- 32 FT. ABOVE BOTTOM
LOCATION DESIGNATION 5000 C = STA. 124+000 (MILE 79.45), 760 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY
MOVING AVERAGES VS. TIME
5000 C-23 JULY 1969
U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

—·— WEIGHTED AVERAGE

– – – – 20 FT. ABOVE BOTTOM

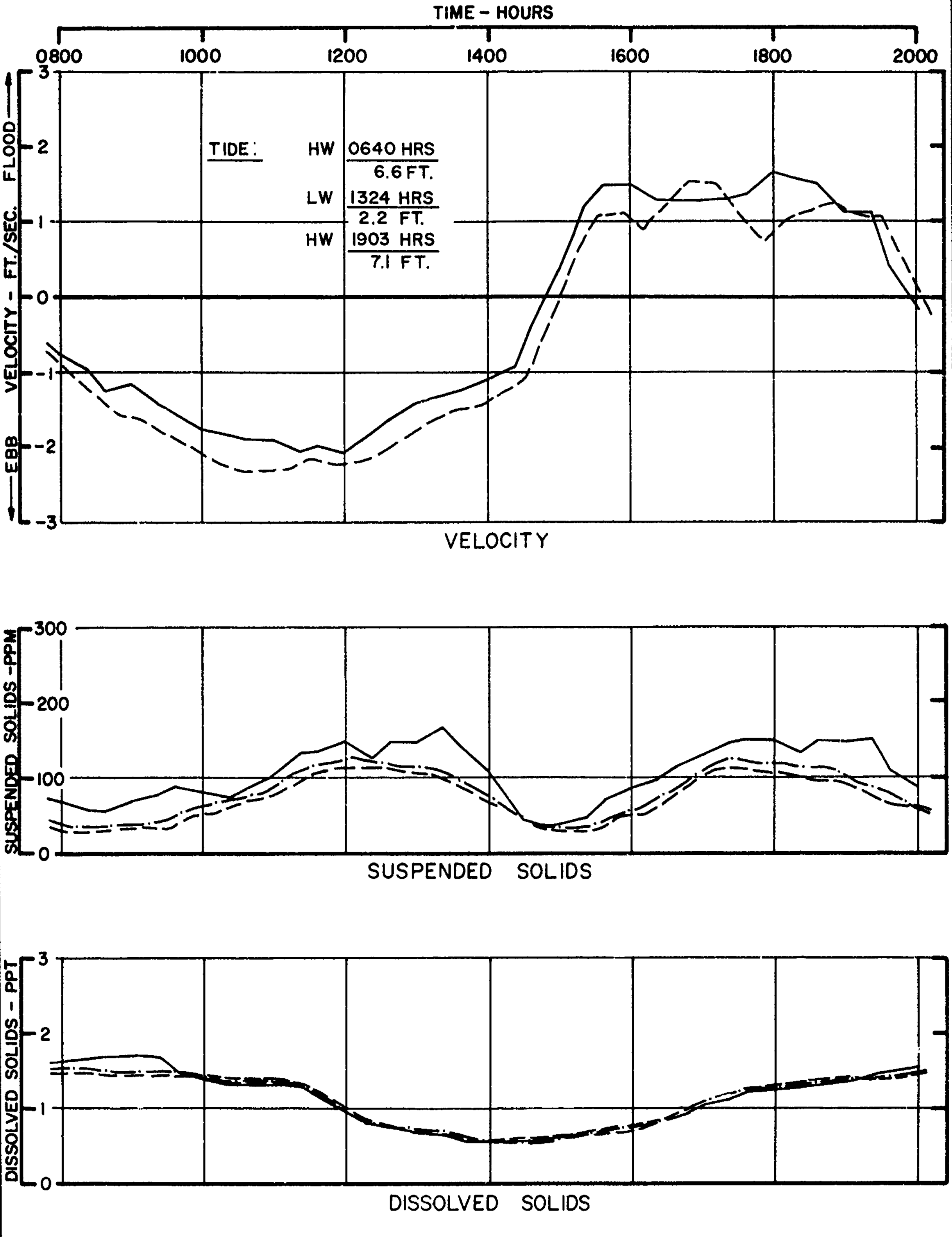
LOCATION DESIGNATION 9000 C = STA. 180+000 (MILE 68.84), 1560 FT. EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME

9000 C-23 JULY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



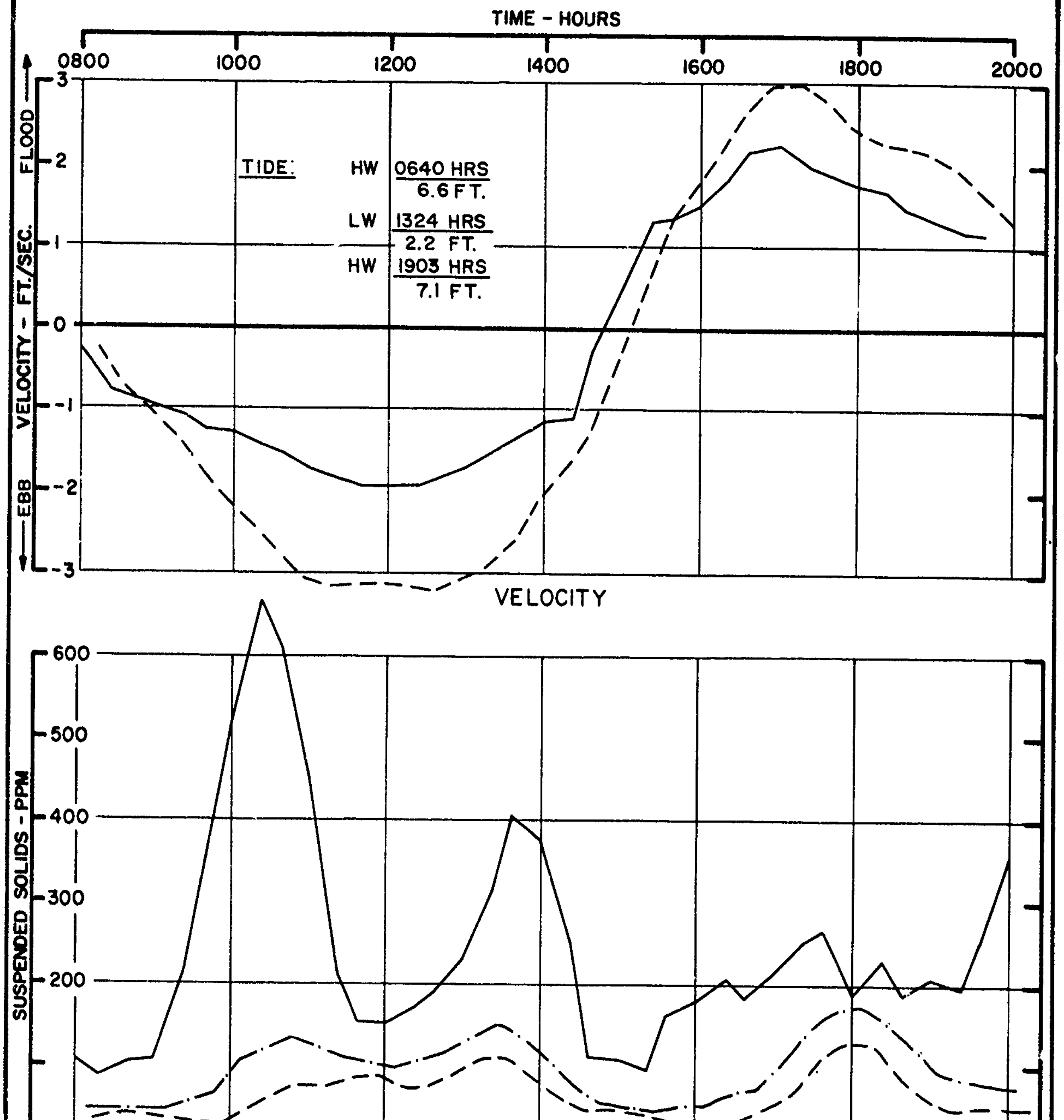
LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS
——— ONE FOOT ABOVE BOTTOM
—·— WEIGHTED AVERAGE
- - - - 16 FT. ABOVE BOTTOM
LOCATION DESIGNATION 7000 C = STA 180+000 (MILE 68.84) 1430 FT. WEST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
7000 C-23 JULY 1969

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

— — WEIGHTED AVERAGE

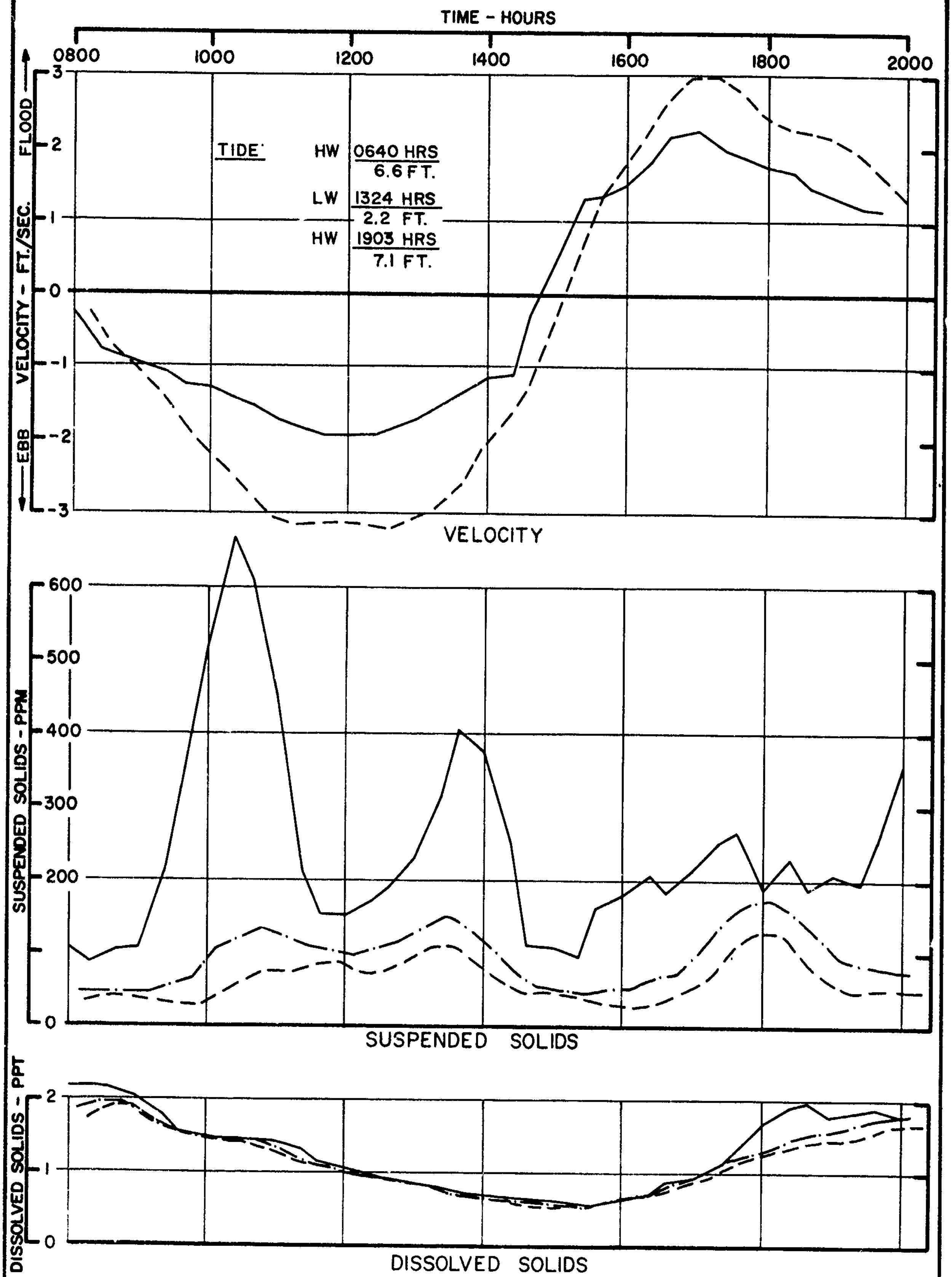
- - - - 32 FT. ABOVE BOTTOM

LOCATION DESIGNATION 8000 C = STA. 180+000 (MILE 68.84) 30 FT EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
8000 C-23 JULY 1965

U.S. ARMY ENGINEER DISTRICT PHILA.



LEGEND

MOVING AVERAGES OF THREE CONSECUTIVE OBSERVATIONS

——— ONE FOOT ABOVE BOTTOM

— — WEIGHTED AVERAGE

- - - - 32 FT. ABOVE BOTTOM

LOCATION DESIGNATION 8000 C = STA. 180+000 (MILE 68.84) 30 FT EAST OF ℄

LONG RANGE SPOIL DISPOSAL STUDY

MOVING AVERAGES VS. TIME
8000 C-23 JULY 1965

U.S. ARMY ENGINEER DISTRICT PHILA.

significant settling velocities. Plates 21, 24, 30, and 33 show that the suspended solids concentrations near the bed drop to low levels at times of slack water, confirming the observation that the particle settling velocities are much higher than those of the clay and silt mineral particles that comprise the shoal.

89. The small density gradients caused by increases in dissolved and suspended solids concentrations with depth below the water surface are sufficient to affect the velocity profiles. There is uncertainty about the elevations of the current measurements above the bed, as described in paragraph 84, but the relative positions of the measurements are correct, and the uncertainty should be less than ± 0.5 ft. Several of the velocity profiles at locations 5000 and 8000, shown in Plates 35 and 36, show deviations in the concentration gradients, and the slopes, indicated by "A" on the plots, are flatter where there are concentration gradients. The slopes can be compared to those for boundary controlled flow of water having uniform density:

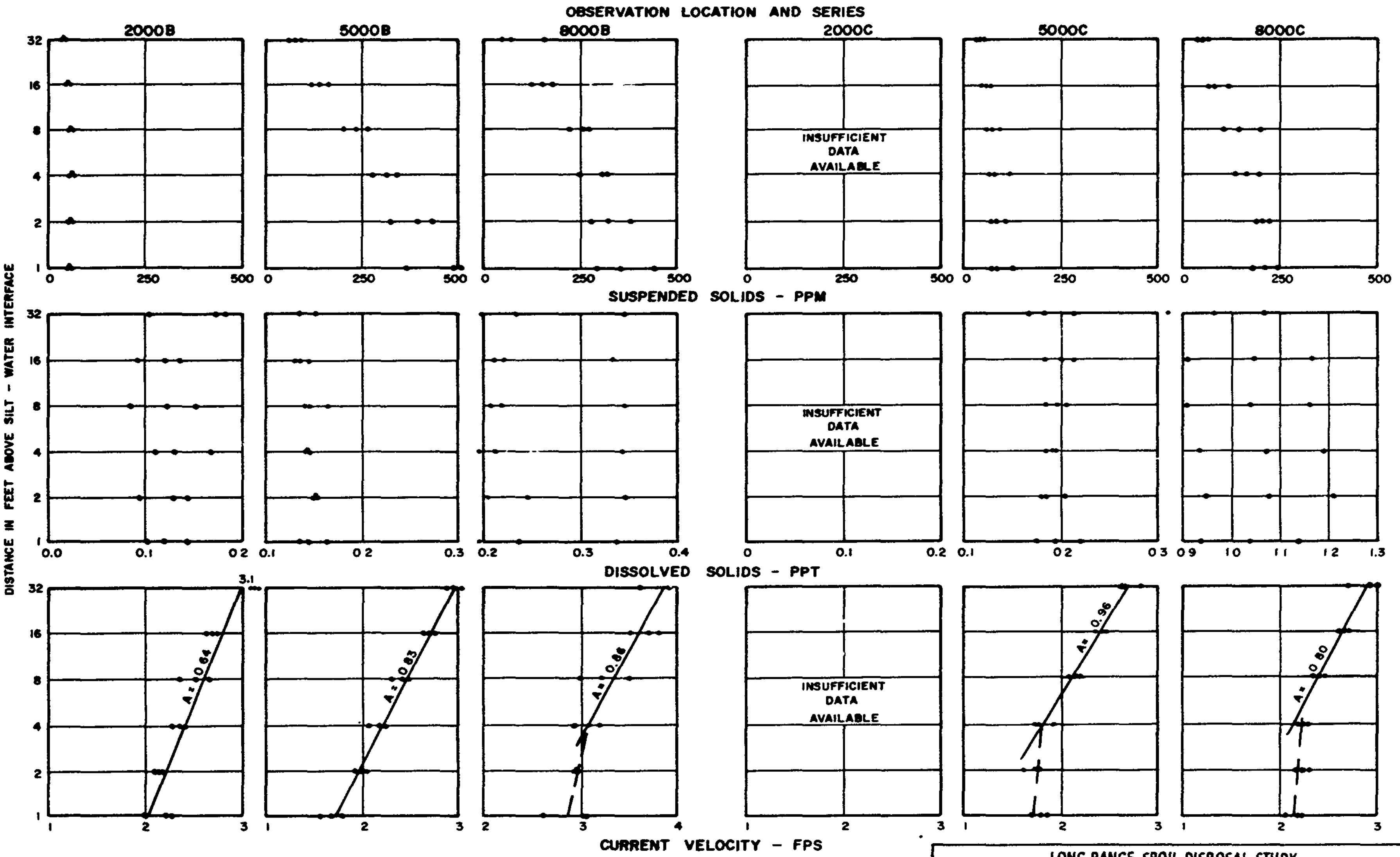
$$\frac{\bar{u}}{u_*} = \frac{2.30}{K} \log (3.32\, Ru_*/\nu),$$

where $\bar{u}$ is the average (over the profile) velocity, u_* the friction velocity, K is Karman's constant, R is the hydraulic radius, and ν is the kinematic viscosity. Uniformly dense clear water having an average velocity of 2.5 ft/sec, which is comparable to those observed, would plot as a straight line having a slope of 0.42. All of the observed slopes of portions of the curves having logarithmic distributions are flatter, indicating that even these small density gradients must be significant. These flatter slopes provide enhanced internal shearing which, as shown in Committee on Tidal Hydraulics Technical Bulletin No. 19 (Krone), promotes aggregation of suspended particles. As the material is moved back and forth with the tide the smaller suspended aggregates diffuse upward into the region of enhanced shearing and collect less aggregated material. As aggregates grow they tend to settle into the lower depths. This process scavenges dispersed clay and silt mineral particles brought downstream from the watershed.

90. It would be desirable to be able to calculate shear stresses from the velocity profiles near the bed. In view of the lack of precision in knowledge of vertical positions, however, such a determination is not possible with these data. An estimate can be made from the relation:

$$u_z = \frac{2.30}{K} u_* \log (9.04\, zu_*/\nu),$$

where u_z is the velocity at z distance above the bed, and the remaining symbols are as previously defined. Using the 2 ft velocities for u_z and calculating u_*, the bed shear stress, τ_0, then $\tau_0 = \rho u_*^2$ where ρ is the suspension density. Results of such a calculation for averages of the 2 ft velocities shown in Plates 35 and 36 yielded the data in Table 27.

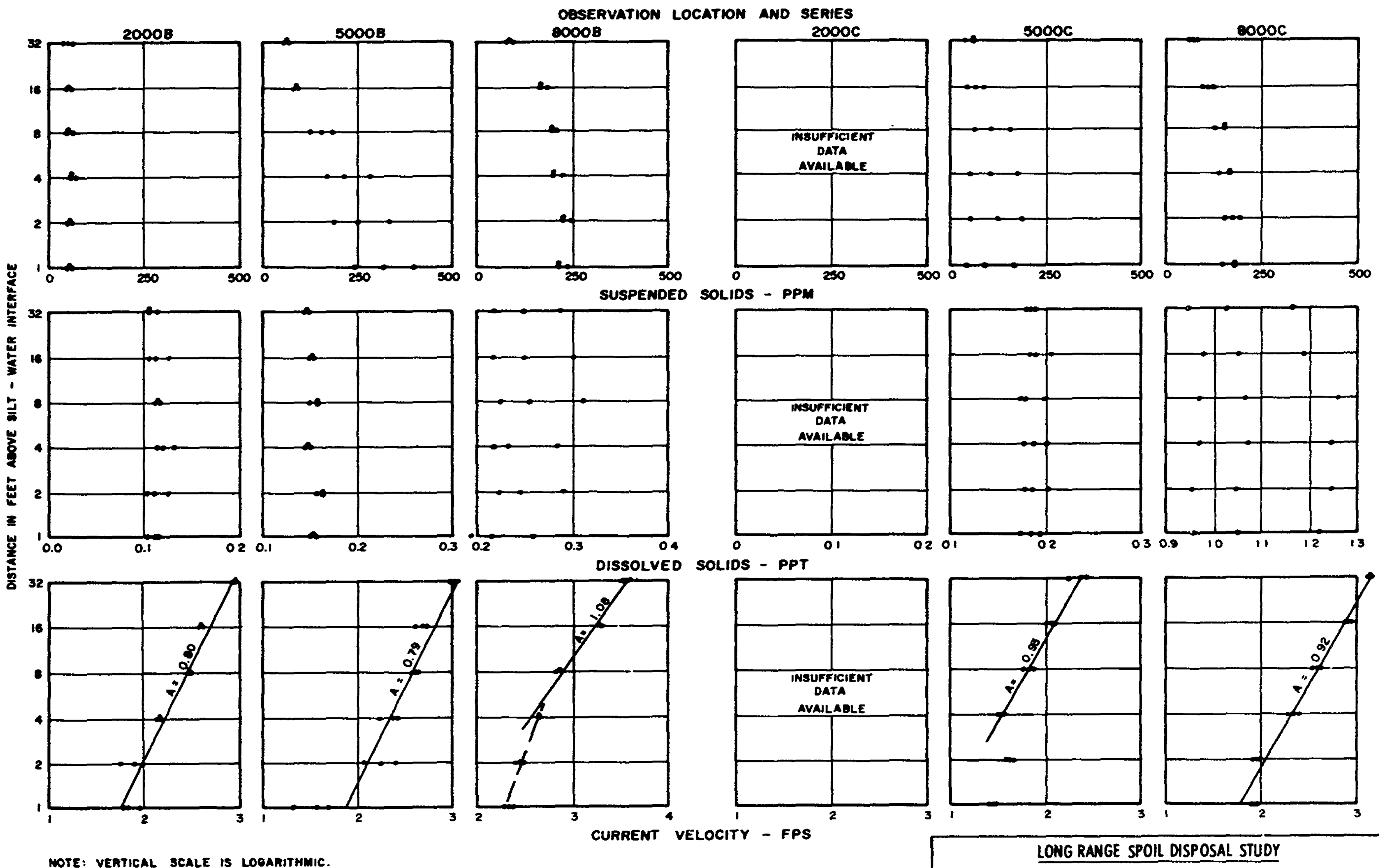


NOTE. VERTICAL SCALE IS LOGARITHMIC.

LONG RANGE SPOIL DISPOSAL STUDY

FLOOD CURRENT VERTICAL PROFILES CURRENT VELOCITY, DISSOLVED SOLIDS & SUSPENDED SOLIDS

U.S.ARMY ENGINEER DISTRICT PHILA.



LONG RANGE SPOIL DISPOSAL STUDY

EBB CURRENT VERTICAL PROFILES CURRENT VELOCITY, DISSOLVED SOLIDS & SUSPENDED SOLIDS

U.S. ARMY ENGINEER DISTRICT PHILA.

TABLE 27

CALCULATED BED SHEAR STRESSES

Location	Flood		Ebb	
	Average Velocity at 2ft., ft./sec.	Bed shear stress, dy/cm2	Average Velocity at 2 ft., ft./sec.	Bed shear stress, dy/cm2
2000B	2.1	4.8	1.9	4.0
5000B	2.0	4.4	2.2	5.3
8000B	2.9	9.0	2.4	6.2
2000C	–	–	–	–
5000C	1.7	3.2	1.6	2.9
8000C	2.2	5.3	2.0	4.4

The aggregate shear strengths in the Delaware Estuary, according to test results reported in University of California SERL Report 63-8 (Krone) in Table IX "Wilmington District",* are as follows:

TABLE 28

DELAWARE ESTUARY AGGREGATE PROPERTIES

Order of Aggregation	Shear Strength dynes/cm2
0	21
1	9.4
2	2.6
3	1.2

Comparisons of the data in Tables 27 and 28 show that beds composed of second and third-order aggregates would be scoured, and possibly first order aggregates at location 8000 during stronger flood flows.

Note: *"Wilmington District" is an erroneous designation; the samples tested were shipped from the Wilmington, Delaware, sub-office of Philadelphia District. They were taken from typical shoals in the Delaware Estuary.

III. DISCUSSION

92. In paragraph 7 of this report, the purpose of this investigation was succinctly stated as follows:

With respect to the Marcus Hook shoal,
1) What is the nature of this shoal?
2) Where does the shoaling material come from?
3) Why does this reach shoal so heavily?

The facts developed during this investigation bearing on these aspects of the purpose are considered below.

WHAT IS THE NATURE OF THE MARCUS HOOK SHOAL?

93. Plate 9 shows that the materials comprising the Marcus Hook shoal are of very small size; 94% passes the 200 mesh sieve (0.075mm), the median diameter is 0.006mm, and 30% of the materials is smaller than 0.001mm. The Marcus Hook shoal materials are conspicuously smaller than the materials in the Fort Mifflin and the Pea Patch shoals. Plate 8 (and Table 7 which summarizes Plate 8) shows that the Marcus Hook shoal also is conspicuously different from the materials in the remainder of the estuary and in its tributary streams. It contains 44% clayey silt and 56% silty clay, and nowhere else is there such a preponderance of such materials. The peculiarity of the Marcus Hook shoal carries over to the minerals present, as may be seen by study of Table 8. Table 9 summarizes Table 8, and shows that quartz is the predominant mineral in all parts of the estuary except Marcus Hook shoal, where clay minerals are slightly more plentiful than is quartz. Table 9 also shows that the Marcus Hook shoal contains more feldspar, more diatoms, more organic matter, and more coal than is found elsewhere in the estuary. In short, the Marcus Hook shoal is unique in comparison with the materials in the remainder of the estuary. The following Table 29 summarizes the characteristics of the Marcus Hook shoal.

TABLE 29

CHARACTERISTICS OF THE MARCUS HOOK SHOAL
(A summary of Plates 8 and 9, also Tables 7, 8, & 9)

<u>Size:</u>

94% passes 200 sieve (0.074mm); Median Diameter, 0.006mm; 30% is finer than 0.001mm, and about 44% is clayey silt and 56% is silty clay.

<u>Composition:</u>

24.5% is quartz; 26.4% is composed of clay minerals; 14.1% is feldspar; 18.0% is diatoms; 8.0% is organic matter; and 5.4% is anthracite (coal).

WHERE DOES THE SHOALING MATERIAL COME FROM?

94. Shoaling of navigation channels and other facilities in estuaries often is due primarily to contributions from nearby sources rather than directly to contributions from the watershed above tidewater, or from the ocean. Nearby sources might include the bed of the estuary itself, solids produced by organisms, for example

diatoms, and inflows of pollutants. It is believed that this is the case for many of the shoaling areas of the Delaware Estuary, almost certainly for the shoals that form in the vicinity of Marcus Hook. Shoaling rates in the Marcus Hook area for the main navigation channel, Marcus Hook Anchorage, the approach channels to docks, and at the docks themselves, are fairly constant. Table 16 lists all known sources of solids. Excluding dissolved solids, the data therein show that the principal source *external* to the estuary is the watershed above tidewater; the ocean cannot contribute to the Marcus Hook shoal, or for that matter any shoal of significance in Delaware Estuary. However, contributions from the watershed above tidewater vary greatly in both short term and long term rates. It follows, then, that the fairly constant rates of shoaling must be accounted for by reasonably constant supplies of material. Plate 15 and Table 25 show that there are very large quantities of suspended solids in transport during both flood and ebb currents at all three cross-sections where the detailed observations were made. Presumably, these suspended solids include not only materials scoured from the bed of the estuary, including diatoms, but also locally introduced materials such as industrial pollutants and materials discharged from storm and sanitary sewers. After adjustments for the rather large tidal differences that prevailed during the B and C Series of observations, Table 25 shows that there is not much difference between the resulting values. The freshwater discharges, which were about 60% of the mean, also were not greatly different, a fact that makes it reasonable to find that the transported quantities are similar under the same tidal conditions. It is regretted that a third series of observations was not made to determine the transported quantities of suspended solids at the three cross-sections during a relatively high freshwater discharge, but it seems probable that the quantities would not be significantly greater than those found during the Series B and C observations. In other words, it is believed that the principal cause of large variations in the total discharges of suspended solids is tidal differences, and therefore, the quantities in transport *during a given tidal condition* would vary less than the contributions of suspended solids from the watershed above tidewater. While the transported quantities probably vary much with the varying tidal conditions, monthly mean values would not be much different month after month during a fairly wide variation of freshwater discharges. Hence, the relatively constant shoaling rates experienced in the Marcus Hook area are explained by a relatively constant supply of material derived from the quantities in transport.

95. Table 25 also shows that the derived 24-hour quantities in transport are much greater than the contemporaneous 24-hour quantities contributed from the watershed. Most of the suspended solids in transport is deposited at slack water (see Plates 17 to 34). At localities not subject to cumulative shoaling, these temporarily deposited sediments are scoured when the ensuing current builds up adequate strength, but at localities subject to cumulative shoaling, not all of the deposited material is resuspended. As almost all of the material dredged from the accumulating shoals is removed from the estuary and placed behind dikes, the materials available to maintain the quantities in transport would diminish and ultimately

become very small if contributions from the watershed above tidewater did not take place; diatoms and locally introduced materials are not contributed in quantities adequate to support the observed transported quantities. The estuary serves as a temporary storage reservoir for materials contributed from the watershed. When the rates of these contributions are high, as is the case during floods and freshets, some of the material received by the estuary is deposited in the channel, but a far greater portion is deposited on the much larger bottom areas beyond channel and anchorage limits. Some of the materials deposited beyond the limits of these navigation improvements remains there until greater than normal tidal currents occur in consonance with the widely varying tidal regimen, and they thereupon go into transport. Thus, although the bed of the estuary is the primary supplier of shoaling material, this source must be replenished from time to time by materials from the watershed, supplemented by the locally introduced material and by diatoms.

96. The sources responsible for replenishing the bed of the estuary are as follows: Delaware River upstream of Trenton; Coastal Plain streams; Piedmont streams; Schuylkill River; Diatoms; Industrial pollutants; Sewage. These sources contribute to the Marcus Hook shoal as tabulated in Table 30.

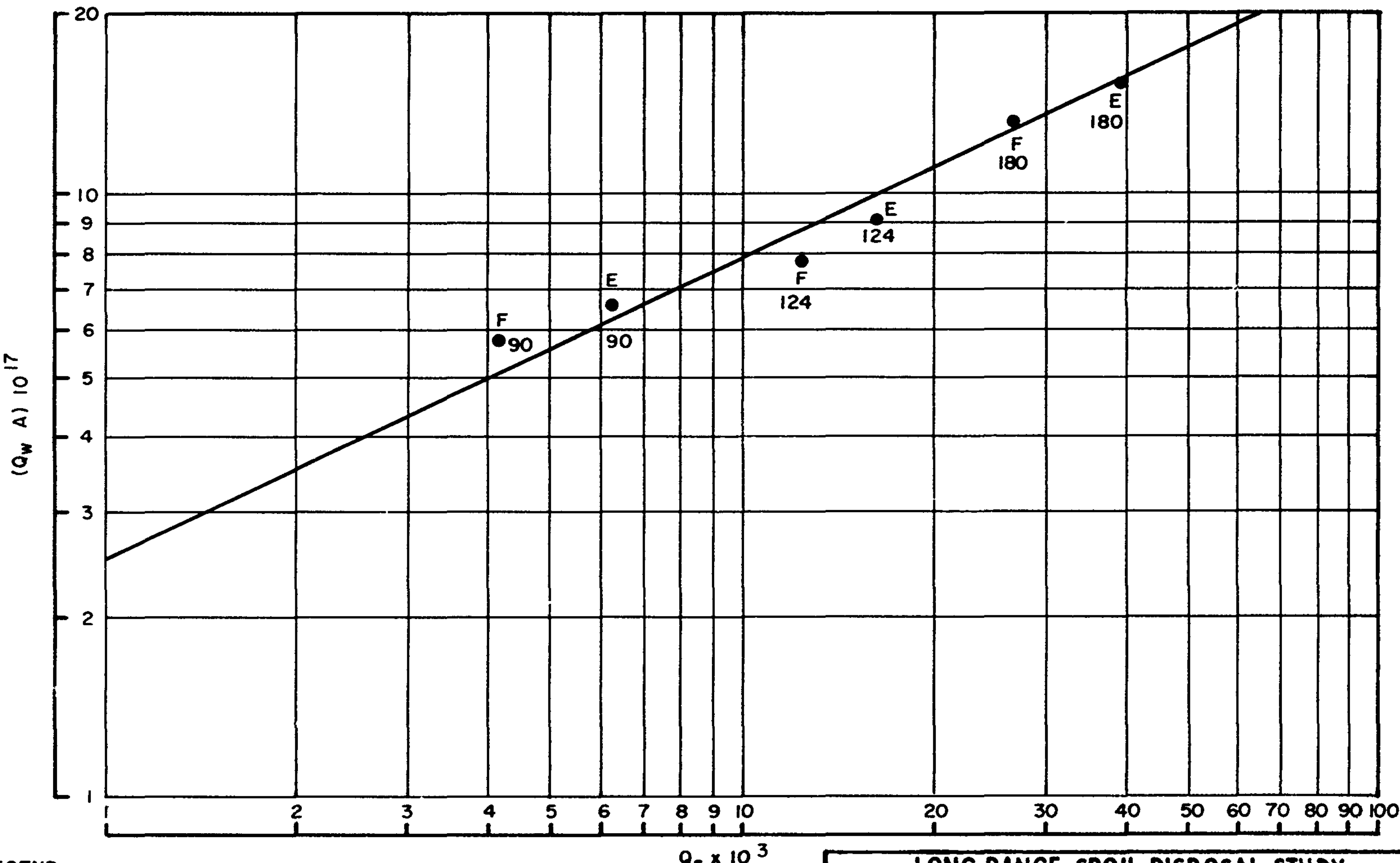
TABLE 30

CONTRIBUTIONS TO MARCUS HOOK SHOAL

Source	Percent of Total
Delaware River upstream of Trenton	46%
Coastal Plain Streams	3%
Piedmont Streams	8%
Schuylkill River	19%
Diatoms	18%
Sewage	4%
Industrial Pollutants (Amorphous Iron Oxide)	2%
	100%

The tabulation shows that 76% of the Marcus Hook shoal has an ultimate source in the watershed beyond tidewater, and that 24% is supplied by effluents from industry outfalls, sewer outfalls, and by diatoms. These are the ultimate sources of supply for the Marcus Hook shoals, but the primary source is the material transported back and forth with the flood and ebb currents.

97. The comparison of shoaling and supplies of shoaling materials made in Table 18 shows that there was slightly more shoaling than can be accounted for by the contributions, excluding the dissolved solids. It is unlikely that dissolved solids are precipitated in significant quantity to become part of the shoal. The period 1961-66, used for determinations of channel and anchorage shoaling rates, included



LEGEND

Q_w = TOTAL WATER DISCHARGE, FT.^{3}

A = AREA OF ESTUARY BED WITHIN RESPECTIVE TIDAL EXCURSION, FT.^{2}

Q_s = TOTAL QUANTITY OF SUSPENDED SOLIDS IN TRANSPORT, TONS.

90F, 90E ETC ∴ CHANNEL STATION AND CURRENT PHASE.

LONG RANGE SPOIL DISPOSAL STUDY

TRANSPORT OF SUSPENDED SOLIDS RELATED TO ESTURINE PARAMETERS

U.S.ARMY ENGINEER DISTRICT PHILA.

WHY DOES IT STOP?

99. The reasons for the cumulative deposition of suspended solids in the Marcus Hook vicinity are:

a) The disproportionately large cross-sectional areas in the vicinity, due to the existence of Marcus Hook Anchorage and to the approaches to docks and the dock areas themselves;
b) The effects of salinity.

The three cross-sections studied in detail, Channel Station 90+000, 124+000, and 180+000, were selected because there is no cumulative shoaling at Stations 90+000 and 180+000, while there is rapid shoaling at Station 124+000. The following Table 31 compares the cross-sectional areas, the mean discharges corresponding the mean tides, and the resulting mean current velocities throughout each cross-section.

TABLE 31

COMPARISON OF CROSS-SECTIONAL AREAS, FLOOD AND EBB MEAN DISCHARGES, AND CURRENT VELOCITIES AT CHANNEL STATIONS 90+000, 124+000, AND 180+000.

Channel Station ft.	Distance above mouth miles	X-Sectional area sq. ft.	Mean Discharge Flood cfs	Mean Discharge Ebb cfs	Mean Current Vel. Flood fps	Mean Current Vel. Ebb fps
90+000	86	78,800*	172,800	180,300	2.20	2.30
124+000	79	149,900	207,500	198,000	1.38	1.33
180+000	69	148,200	281,200	267,000	1.90	1.80

*Note: Excludes the hydraulically inefficient back channel

The above data plainly show that the cross-sectional area at Channel Station 124+000 is far too large in comparison with those of the non-shoaling cross-sections upstream and downstream. In its natural state, it is likely that the cross-sectional area at Channel Station 124+000 was of the order of 100,000 sq. ft.; the existing cross-section is thus about 50% too large in relation to the discharges. If it was now 100,000 sq. ft. in area, the resulting current velocities would approximate those shown above for Channel Station 90+000 and 180+000.

100. It is of great significance that the net transport of suspended solids at Channel Station 124+000 is not always downstream, as is the case for the other two cross-sections. Table 26 shows that the net transport during the C Series of observations was upstream, and it also shows that the salinity during the C Series was appreciably greater than that during the B Series. This may account for the net transport upstream. Perhaps, when the salinity attains some critical value, perhaps 0.24 ppt, there always is a small net transport upstream, at Station 124+000. In other words, the regimen in this locality is such that much more material is received to accumulate in the shoal, from both upstream and downstream, than is transported downstream.

101. It is also of interest to note, again, (as Plate 6 shows) that the normal salinity profile (i.e., that during mean

tides and mean freshwater discharges) indicates that salinity increases rapidly downstream of the Marcus Hook vicinity and that there is little salinity upstream thereof. Salinity not only tends to produce net upstream flows near the bottom, however small the difference may be, but also it is a very important factor in flocculation. Materials in transport in the Marcus Hook vicinity that might remain in suspension, were the water essentially devoid of salinity, would be precipitated out as flocs when there is even a relatively insignificant taint of salinity.

102. Thus, all factors combine to produce deposition of the suspended solids in transport at Marcus Hook. These include the excessive cross-sectional area, the tendency for salinity to produce slight upstream preponderances of currents near the bottom in the upstream direction, and the capability of even slightly saline water to flocculate sediment. The fact that the materials composing the Marcus Hook shoal are quite fine in comparison with the materials elsewhere in the estuary adds weight to the above hypotheses.

IV. CONCLUSIONS

103. This investigation has produced answers to the questions that constitute the purpose of the work that are reasonably satisfactory. In an estuary of the magnitude of the Delaware, shoaling is an exceedingly complicated phenomenon due to the widely varying regimen, hydraulic, freshwater discharges, and salinity. The answer to the question as to the characteristics of the Marcus Hook shoal is as conclusive as could reasonably have been desired; it is believed that the shoal material is very adequately described. The answer as to the sources of the material in the shoal is adequate. Undoubtedly, most of the shoal material ultimately comes from the watershed above tidewater, but it is also likely that its immediate principal source is the bed of the estuary beyond the limits of the navigation improvements. The answer to the question as to why the Marcus Hook locality shoals so rapidly is almost certainly correct; the Marcus Hook locality has cross-sectional areas that are out of proportion to the discharges, and the resulting average currents are much lower than those in non-shoaling areas upstream and downstream. This unfortunate condition is further worsened by the effects of salinity on currents and on flucculation. The answers to the sources of the Marcus Hook shoal and as to the reasons for the rapidity of the accumulation are not rigorously proven by the available facts; it would have been helpful had there been observations not only at the three cross-sections during two tidal cycles, but also at several additional cross-sections during more than two tidal cycles, especially during a tidal cycle when the freshwater discharge was considerably greater than those that prevailed

during the B and C Series of observations. However, it is doubted that the essential findings of a much more extensive investigation would have been materially different from those developed.

104. The investigation undoubtedly has added much to the knowledge concerning shoaling of navigation improvements in estuaries. Possibly the most significant finding was that large quantities of material are moved back and forth with the currents, and the lack of agreement of the net movements with contributions from sources beyond tidewater. This finding helps explain why shoaling of estuary navigation channels is often a relatively constant phenomenon while contributions from sources beyond the estuary are widely variable.