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PHYSICAL HYDRAULIC MODELS:
ASSESSMENT OF PREDICTIVE CAPABILITIES

Report I

HYDRODYNAMICS OF THE DELAWARE RIVER ESTUARY
MODEL

by

Joseph V. Letter, Jr., and William H. McAnally, Jr.

Hydraulics Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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**Authors:** Joseph V. Letter, Jr., William H. McAnally, Jr.

**Performing Organization:** U.S. Army Engineer Waterways Experiment Station, Hydraulics Laboratory, P.O. Box 631, Vicksburg, Miss. 39180

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**Abstract:**

The purpose of this study is to define the reliability with which results of tests conducted in a physical model of the Delaware River Estuary can be used to predict the effects of modifications to the estuary. The Delaware River model at the Waterways Experiment Station was used to conduct tests to predict the effects of the navigation channel enlargement between Philadelphia and Trenton, and the results of the tests are compared with subsequent prototype data to determine the accuracy of the model predictions.

(Continued)
20. ABSTRACT (Continued).

Two prototype surveys provided tidal and current velocity data for the high- and low-freshwater discharge conditions in 1972, and the results of model tests duplicating those conditions were used to determine accuracy of model predictions. Tidal propagation, as measured by the range, phasing, and energy dissipation rates, was predicted as accurately as the model had been originally verified. The same is also true of current velocities. The trends of ebb predominance were observed to be similar in both model and prototype. A postconstruction model salinity test reproduced a 9-month prototype hydrograph occurring in 1965. Except for short-term fluctuations in the prototype, the model salinities were in close agreement with prototype measurements at all stations. The largest discrepancies occurred in the steepest portion of the salinity profile. It is concluded that, for projects involving estuarine modifications up to the scale of navigation channel enlargement, the physical hydraulic model, when carefully verified, can accurately predict the effects of the project on the estuarine system. Undue emphasis should not be placed upon absolute values at specific locations since discrepancies may occur due to scale effects or the dynamic nature of prototype conditions.
PREFACE

The research described herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) with funding by the Environmental Impact Program, Plan Formulation and Evaluation Studies of the General Investigations - Research and Development category funding of the Office, Chief of Engineers (OCE), U. S. Army.

Personnel of the Hydraulics Laboratory of WES performed this study during the period 1971 through 1974 under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory; F. A. Herrmann, Assistant Chief of the Hydraulics Laboratory; R. A. Sager, Chief of the Estuaries Division; and G. M. Fisackerly, Chief of the Harbor Entrance Branch. Messrs. Fisackerly, D. A. Crouse, W. H. McAnally, Jr., and J. V. Letter, Jr., conducted the study. This report was prepared by Messrs. Letter and McAnally.

Directors of WES during the course of this study and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.
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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

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PHYSICAL HYDRAULIC MODELS: ASSESSMENT OF PREDICTIVE CAPABILITIES

HYDRODYNAMICS OF THE DELAWARE RIVER ESTUARY MODEL

PART I: INTRODUCTION

Objectives

1. The primary objective of this study is to define the degree of accuracy to which the results of tests conducted in physical hydraulic models predict the changes induced by modifications to estuarine systems. A secondary objective is to improve modeling techniques such that the value of physical model studies may be increased.

2. The purpose of this report is to examine a model study of a Delaware River Estuary navigation project and to compare model predictions with prototype behavior.

Background

3. Physical hydraulic models have been successfully used for many years to predict the response of estuaries to alterations such as dredging, landfills, constricting works, and flow alterations. Model predictions of tidal elevations and phases, current velocities, circulation patterns, and salinity intrusion are considered to be highly reliable, yet little attention has been given to a careful comparison of model predictions and prototype conditions after the proposed modifications to the system have been made. Other phenomena, such as pollutant and sediment transport, which are considered to be reproduced only qualitatively in physical models, have similarly suffered from a lack of study to determine the relative merits of modeling them.

4. There are several reasons for the lack of comparison between model prediction and prototype behavior, which is termed postconstruction verification or model confirmation. The first is that resources are seldom available to follow up on a project if it appears to be
functioning satisfactorily. Other problems usually demand attention and money that might be applied to follow-up studies. Second, many projects are changed before construction due to considerations that are not pertinent to the model study, and thus detailed comparisons are not possible unless costly additional model tests are conducted. Finally, some model results show a project to be unfeasible, and so it is not constructed; consequently, comparison is not possible.

5. The increasing environmental awareness of recent years has resulted in a demand for more detailed model predictions of many estuarine phenomena. Recognizing the need for postconstruction verification of model studies to provide more reliable detailed results, Office, Chief of Engineers (OCE), authorized U. S. Army Engineer Waterways Experiment Station (WES) in 1971 to begin a study of the Delaware River Estuary as the first in a series of confirmation studies.

6. There are two conditions where postconstruction verification of a physical model prediction can be performed. In the first condition, the changes to the prototype estuarine system match one of the project plans tested in the model. In this case, the postconstruction prototype data are directly comparable to the model data if sufficient care is taken to match the prototype test conditions with those of the model plan test.

7. The other case occurs when the project constructed in the prototype is altered from the plan tested in the model, but the physical model is still in existence. If the cost is not prohibitive, necessary changes may be made in the model to duplicate the actual prototype construction, and additional model tests may be conducted. Postconstruction prototype data collection and changes in the model can proceed simultaneously, and then additional model tests can be performed when the prototype data are available. The model and prototype data can then be compared directly and analyzed.

8. The existing Delaware River Estuary model at WES was constructed in 1948 and 1949, and numerous studies covering a variety of phenomena have been conducted in it. The study best suited to a postconstruction verification was found to be that of the navigation channel
enlargement between Philadelphia and Trenton. Analysis of that project is the subject of this report.

Approach

9. Postconstruction verification of a physical model can be accomplished by two methods, the method being determined by the way data are compared for the analysis. The more direct method is to compare postconstruction prototype data with model test predictive data for a direct indication of the predictive capabilities of the model.

10. The other method is a comparison between prototype data prior to and after construction of the project being studied in light of the predictions of the effects of construction made by the model. If it is difficult to obtain postconstruction prototype data to match the model test conditions, and the model is no longer available for additional testing or additional tests would be expensive, then comparison of postconstruction prototype data with preconstruction prototype data can be very useful.

11. For either method of model confirmation, care must be taken to match the postconstruction prototype conditions during data collection with the conditions for the comparative test, whether preconstruction prototype or postconstruction model tests. The prototype data collection is planned for a period of time during which the conditions of tide, freshwater inflows, waves, and other pertinent phenomena are expected to be close to the comparative test conditions. However, the actual conditions during the data collection will vary from those expected. If the difference between comparative and postconstruction prototype test conditions is small, the data may be directly compared. However, if test conditions are considered too dissimilar, additional measures must be taken to make data analysis feasible. Using the direct method of comparison, if the model is still available, model tests can be performed to duplicate the conditions during the period of prototype data collection. Otherwise, the data must be analytically adjusted, or additional prototype data must be collected.
12. The prototype construction of the enlarged channel between Philadelphia and Trenton was of the same dimensions and alignment as one of the project plans tested in the model. The approach used for postconstruction verification of the Delaware River model is that of performing additional model tests without project modification in the model. The purpose is to duplicate prototype conditions during post-construction prototype data collection. The hydraulic data and salinity data are then compared for model and prototype postconstruction data.

The Delaware Estuary

13. The Delaware Estuary separates the State of New Jersey on the eastern shore from the States of Delaware and Pennsylvania on the western shore, and enters the Atlantic Ocean between Cape May, New Jersey, and Cape Henlopen, Delaware (Figure 1). The estuary extends about 134 miles,* measured along midstream, from the Capes to Trenton, New Jersey, and varies in width from 800 ft above Trenton to 2200 ft at Philadelphia to 27 miles at the widest portion of Delaware Bay and 12 miles at the Capes. Upstream from the point of maximum width, the width decreases at a fairly uniform rate (the estuary having a classic funnel shape) and can be accurately estimated by an exponential function. The geometry of the estuary in other respects is relatively simple. There are few islands with significant back channels; therefore, most of the flow is concentrated in one main channel. The cross-sectional area also varies with remarkable uniformity from a maximum at the point of greatest width to a minimum at the head of tide. The geometric characteristics of the estuary are illustrated in Figure 2.

14. The controlling depths in the estuary from the mouth to Philadelphia were of the order of 17 ft when the first improvements for navigation were undertaken in 1836. From Philadelphia to the head of tide, the controlling depth was 3 ft. As of 1973, the condition of

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.
Figure 1. Location map and original verification data stations
Figure 2. Delaware Estuary physical characteristics
channel improvements was as shown in Table 1. The channel stationing for the estuary is shown in Figure 3.

**Hydraulic characteristics**

15. The mean range of tide at the Capes is about 4.3 ft. The tidal range increases gradually through Delaware Bay to about 5.9 ft at Woodland Beach, gradually decreases to about 5.5 ft at Reedy Point, and then increases again steadily to about 6.8 ft at Trenton for mean freshwater discharge conditions. The mean tide level increases fairly uniformly from close to mean sea level (msl) at the mouth to about 0.7 ft above msl at Torresdale (sta -40) and then increases at a greater rate to about 1.4 ft above msl at the head of tide near Trenton (sta -160). Mean tidal ranges and elevations are presented along with the high- and low-water lunar intervals for the estuary in Figure 4.

16. The shape of the propagating tidal wave changes as it advances up the estuary. As the wave passes through the Capes, it is nearly a sine wave, but as it moves upriver it is deformed. The deformation is due to a faster rate of propagation at high water than at low water. Typical mean tide curves are shown in Figure 5 to illustrate the changing wave form.

17. The spring tidal ranges for the Delaware Estuary are approximately 11 percent greater than the mean tidal ranges, while the neap ranges are about 24 percent smaller than the mean tidal ranges. The diurnal inequality varies from maximums of 1.5 ft between successive high waters during spring tides and 0.5 ft between successive low waters during neap tides to no diurnal inequality near times of mean tides.

18. The tidal prism (exclusive of fresh water) at the Capes is about 93 billion cu ft, decreasing steadily to about 2.35 billion cu ft at Philadelphia.

19. The estuary has a total drainage area of about 13,540 square miles, 6,800 square miles of which lie above the head of tide at Trenton. The distribution of freshwater inflow over the estuary is shown in Table 2. The mean freshwater discharge is about 12,000 cfs at Trenton, about 16,500 cfs immediately below the mouth of the Schuylkill River, and about 20,200 cfs at the Capes. The mean monthly discharge exhibits
Figure 3. Location of channel stations
TIDE STATIONS

MODEL TEST DATA

TIDE .................................. MEAN
FRESHWATER DISCHARGE ....... 20,200 CFS (MEAN AT CAPES)
OCEAN SALINITY ................. 28,000 PPM (15,460 PPM CHLORINE)
* HEIGHTS REFER TO DELAWARE RIVER DATUM WHICH IS 2.90 FEET
   BELOW MEAN SEA LEVEL SANDY HOOK, 1929 ADJUSTMENT

Figure 4. General tidal characteristics
NOTE: ADAPTED FROM REFERENCE 2

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

STA 199 (NEW CASTLE)

STA -160 (TRENTON)

MOUTH

Figure 5. Delaware Estuary typical mean tide curves
a substantial variation as illustrated in Table 3.

20. Mean maximum current velocities in the navigation channel between Philadelphia and the sea are of the order of 2.0 to 3.0 fps. The maximum velocities and durations of ebb currents are generally greater than those of flood currents, with the predominance of ebb currents increasing with distance upstream. The mean velocities on both flood and ebb are approximately 1.4 fps between sta -40 and 280. This reflects the fact that the freshwater discharge has little effect on the velocities in that part of the estuary and downstream thereof. As the head of tide is approached, the flood current vanishes, and the flow is ebb throughout the tidal cycle.

Salinity characteristics

21. The Delaware River Estuary is essentially a well-mixed estuary with little variation in salinity over the depth of the water column (normal maximum of less than 15 percent) and with very little difference in phasing of the current from surface to bottom for most of the estuary. The salinity for normal conditions of freshwater discharge is near ocean salinity (20 to 30 ppt) in the lower portions of Delaware Bay. Throughout the estuary, salinities decrease steadily with distance upstream until the water is completely fresh. The upper limit of salinity intrusion varies with freshwater discharge and, for mean discharge conditions, is a short distance downstream from the Pennsylvania-Delaware State line (sta 130). The farthest salinity excursion recorded reached sta -40 during a prolonged period of low freshwater discharge. At any given point within the limits of salinity intrusion, the salinity varies from a maximum at or near high-water slack to a minimum at or near low-water slack. The depth-averaged salinity profile for mean freshwater discharge is shown in Figure 6.

22. A weak saltwater wedge is usually formed during the turn of the current from ebb to flood in the vicinity of the steepest portion of the longitudinal salinity profile. This location varies with the extent of saline intrusion which is governed primarily by the freshwater inflows. In the reach between Ship John Shoal Light (sta 350) and Artificial Island (sta 280), the wedge tends to be most pronounced with
Figure 6. Salinity profiles

the turn of the current on the bottom leading the surface by about 1 hr, during which time the bottom salinities may be as much as 50 percent greater than the surface salinities. Still, the estuary is considered to be well-mixed.

23. There are two bottom velocity null points in the estuary. A null point is defined as the location where the currents during the ebb and flood phases are exactly balanced (i.e., the areas under the ebb and flood velocity curves are equal). The flow predominance is determined by separately integrating the ebb and flood velocities over their respective phases of a tidal cycle to obtain an average velocity for each that is weighted by the duration of the phase. The weighted ebb value is then divided by the sum of the weighted ebb and flood
values to give the degree of ebb predominance. If the ratio is less than 0.50, the flood flow is predominant; if greater than 0.50, the ebb flow is predominant. If the value is 0.50, then a null point exists. Upstream from the farthest upstream bottom null point, the ebb velocities predominate, while downstream from that point the flood currents predominate as far as the second null point. Consequently, there is no net seaward movement of sediment past the upstream null point, which is normally located off Artificial Island (about sta 280). The location of this upstream null point does not vary much for low to average discharges of fresh water. However, when extremely high discharges are encountered, this null point may be found well out into Delaware Bay. The second bottom null point is located seaward of Miah Maull Shoal Light, varying with freshwater discharge, between 15 and 20 miles from the mouth of the bay. Upstream from this seaward null point, the flood flow predominate, and seaward from it, the ebb flow predominates. Net sediment movement in the lower bay is, therefore, seaward rather than upstream. Since the upstream null point prevents sediment from moving downstream past Artificial Island, there is virtually no shoaling anywhere below that location.
PART II: THE MODEL

24. Authority for the original model study of the Delaware River and estuary was requested by the Philadelphia District on 11 June 1946 and was granted by OCE on 16 September 1946. During the calendar years of 1947 and 1948, prototype data were analyzed, and the model and appurtenances were designed. Model construction, conforming to a detailed hydrographic survey of 1942, began in September 1948 and was completed in February 1949. The original hydraulic and salinity verification was undertaken in March 1949 and completed in June 1950.

25. The Delaware River model reproduces the entire estuary of Delaware Bay and River, beginning at Capes May and Henlopen at the downstream end and extending to Trenton, New Jersey, at the upstream end, and includes a 3-mile reach of the Chesapeake and Delaware Canal. The tidal portions of all major tributaries are reproduced to correctly scaled lengths and cross sections, but for convenience, portions of the tributaries have been realigned to conform to the general alignment of the Delaware River to conserve shelter space. The model limits are shown in Figure 1.

26. The model is constructed in concrete (generally called a fixed-bed model) to linear scale ratios, model to prototype, of 1:1000 horizontally and 1:100 vertically. These linear ratios fix the following other modeling ratios: slope, 10:1; velocity, 1:10; time, 1:100; discharge, 1:1,000,000; and volume, 1:100,000,000. A salinity scale ratio of 1:1 was used for model operation. One prototype tidal cycle of 12 hr 25 min is reproduced in the model in 7.45 min. The model is approximately 750 ft long and 130 ft wide at the widest point and covers an area of about 30,000 sq ft.

27. The entire model bed was molded to conform to the latest hydrographic surveys at the time of construction. All channel shoals present in the surveys were omitted, and the channel through shoal reaches was molded to authorized dimensions. Periodically, as new studies were performed in the model, the model was remolded to reflect major changes in the prototype hydrography.
Model Verification

28. The accurate reproduction of various phenomena (tides, currents, salinity, shoaling, dispersion, etc.) is an important phase in preparing an estuary model for its ultimate use in evaluating the effects of proposed improvements. Verification of the Delaware River model consisted of four phases:

a. Hydraulic verification to ensure that tidal elevations and phasing and current velocities and directions in the model corresponded with observed prototype behavior.

b. Salinity verification to prove that salinity phenomena in the model corresponded to those of the prototype for similar conditions of tide, ocean salinity, and freshwater inflow.

c. Shoaling verification to affirm acceptable reproduction of the shoaling distribution pattern in the navigation channel.

d. Dye tracer verification to ascertain that the model was capable of reproducing flushing characteristics. Neither shoaling nor dye tracer studies are considered in this report.

Original hydraulic verification

29. The hydraulic verification of the Delaware River model ensured that the model tidal elevations and phasing and current velocities and directions were in agreement with the prototype. A series of hydraulic-adjustment tests preceded the hydraulic verification to obtain a proper reproduction of tidal phenomena in the Delaware Bay portion of the model, followed by a progressive adjustment of the frictional resistance of the model bed until tidal elevations and phasing throughout the model were in agreement with the prototype mean tidal data. Two types of roughness were used to furnish the required frictional resistance. Rough stucco was used in shallow portions of the model where boundary roughness alone would be sufficient, and thin metal strips were placed in the deeper portions to provide resistance throughout the depth of the channel.

30. After the tidal phenomena were reproduced in the model, slight refinements in model roughness were required in order to
reproduce current velocities properly. These refinements consisted of rearranging the roughness in various cross sections until all model velocities were in satisfactory agreement with the corresponding prototype measurements.

31. The accuracy of the reproduction of the prototype tidal phenomena in the model is illustrated in Plate 1. The tidal ranges and mean tide levels were reproduced with good accuracy (±0.2 ft). The high-water lunar interval varied by no more than 20 min. A detailed discussion of the accuracy of the original model verification is presented in Part IV.

32. Prototype current velocity data were available for each of the 74 velocity stations (Figure 1). Corresponding measurements made in the model, after adjustment of roughness, were compared with the prototype data. Typical examples of the agreement obtained are shown in Plates 2-7. The verification results for all 74 current velocity stations, as well as a more detailed description of the model and its hydraulic verification, are presented in Reference 3. Examination of these data indicates that the reproduction of prototype current velocities and distributions over a transverse cross section, both horizontally and vertically, was very good and close enough for all practical purposes of model investigation. Additional discussion of the original verification of current velocities is also presented in Part IV.

Original salinity verification

33. The model salinity verification involved tests of three characteristics of the salinity regime of the estuary:

a. Fluctuation of surface and bottom salinities over a single tidal cycle.

b. The advance of the salinity front because of prolonged very low freshwater discharge.

c. The advance and retreat of the salinity front over a prolonged period of time due to changes in the freshwater inflow.

34. The results of the single tidal cycle test for sta 275 are shown in Plate 8. This test was run with a mean tide and a constant freshwater inflow of 17,000 cfs at and including the Schuylkill River
and with mean discharges from the other tributaries downstream thereof, corresponding to the prototype conditions of 19-20 January 1932. Duplication of meteorological phenomena was not attempted in any of the model tests. As indicated by the test, the effects of tidal oscillation on the concentration and phasing of salinities were the same in the model as in the prototype.

35. Two tests to verify the ability of the model to duplicate the rate of advance of the salinity front during prolonged periods of low freshwater discharge were conducted. Each test covered a 2-month period: one from 10-11 August to 4-5 October 1932, and the other from 8-9 August to 6-7 October 1930. During both tests, a repetitive mean tide was used, and the corresponding prototype hydrographs were reproduced by changing the inflows each prototype day. The results of these tests are presented in Plates 9 and 10, indicating the model accurately duplicated the rate at which the salinity front advances up the estuary.

36. A 10-month salinity test was conducted to verify both the advance and the retreat of the salinity front in response to a changing hydrograph. It was run with a repetitive mean tide and the prototype hydrograph for the average daily discharges at and including the Schuylkill River for the period of 26 March 1931 to 9 February 1932. The hydrograph for the Christina River was also duplicated for the period, but the remainder of the downstream tributary inflows were mean flows. The accuracy with which the model reproduced the day-by-day position of the 50-ppm isochlor throughout the test period is shown on Plate 11.

37. The original salinity verification of the Delaware River model showed that the model was capable of reproducing all pertinent salinity phenomena of the prototype. The fluctuation of the salinity front with tidal action as well as with changes in the freshwater discharge was shown to be the same in the model and the prototype. A more detailed description of the original salinity verification is given in Reference 4.

Hydraulic reverification

38. A detailed hydrographic survey of the estuary in 1954 between channel sta 90 and 195 revealed sufficient changes in the hydrography
since the 1942 survey to warrant revision of the model. Consequently, the entire reach between these channel stations was reconstructed to conform to the 1954 survey.

39. The revision required that hydraulic and salinity phenomena in the reconstructed reach be reverified to ensure proper functioning of the model. This was accomplished during the period May–July 1955. At this time, roughness strips were replaced in approximately the same locations that had resulted in the original verification of the model. It was soon evident that the reverification of the current velocities required only very minor adjustment of the roughness and that the changes in the magnitude and direction of the current velocities from the original verification were not significant. Furthermore, the revision had no measurable effect on tidal elevations and phasing, since the tidal regimen of the model, on completion of the revision and reverification of current velocities, was in exact agreement with data presented in Plate 1.

40. Following the hydraulic reverification, a number of check tests were made to determine whether or not the model revision had affected salinity distributions in any way. The results showed conclusively that the revision had no measurable effect on the salinity regimen.

41. Since the reverification of the revised portion of the model had no measurable effect on the hydraulic or salinity regimens of the estuary, the model is assumed to be in the same condition as when originally verified, that is, in the state of initial calibration. For a more complete explanation of the revision and reverification refer to Reference 3.

**Previous Channel Enlargement Model Study**

42. In 1951, the proposed channel enlargement tested in the model consisted of deepening and widening the previous 25-ft-deep by 300-ft-wide channel between sta 0 and -150 to 40 ft deep by 400 ft wide. The degree to which the channel enlargement affected the hydraulic and
salinity characteristics of the estuary can best be seen by an examination of the original model test results, since both base and plan tests were run under the same conditions of tide and freshwater discharge. The tests are described in Reference 1.

43. For the studies in the model to predict the effects of channel enlargement on estuarine processes, data were first collected with existing, preenlargement channel conditions (usually called base tests). Then, the section of the model between Philadelphia and Trenton was remolded to the proposed channel dimensions, and plan tests were conducted for identical conditions of tide and freshwater inflow.

44. The hydraulic tests were performed with mean tide and freshwater discharge conditions in the estuary. Tides were observed in the model at all permanent tide gages, and current velocities were measured at surface, middepth, and bottom at 10,000-ft intervals along the center line of the navigation channel between Philadelphia and Trenton. Tide gage and channel station locations are shown in Figures 1 and 3, respectively.

45. The predicted effects of the channel enlargement on tidal phenomena are presented in Plate 12. In model tidal ranges, the enlargement caused slight increases upstream from Torresdale and decreases downstream from Torresdale. Mean tide level was lowered slightly at all stations upstream from Reedy Point. The occurrence of high and low waters was slightly earlier at Burlington and all stations upstream thereof.

46. Plates 13-18 illustrate the predicted effects of the channel enlargement on current velocities for mean conditions of tide and discharge. These are only a few stations of those tested and are presented to give an indication of the effects of enlargement as predicted by the model. The velocities in the enlarged portion of the channel were generally reduced, the greatest reductions occurring in narrow reaches of the river where the enlargement increased the cross-sectional area by the greatest percentage. At the two stations in the unenlarged portion of the channel (Plates 13 and 14), the velocities were relatively unaffected, indicating that the channel enlargement upstream from
Philadelphia should have little influence on current velocities in the remainder of the estuary.

47. Experience had shown that a sustained freshwater discharge of about 10,600 cfs (slightly less than mean inflow) at and including the Schuylkill River was required to hold the critical 50-ppm isochlor in the vicinity of the Delaware-Pennsylvania State line (channel sta 127+500). Therefore, three separate salinity tests with neap, mean, and spring tides were performed with the 10,600-cfs discharge. The results of these tests are presented in Plates 19-21. These data represent bottom salinities along the channel center line at the time of high-water slack. For all three tests, salinities decreased slightly in the portion upriver of the State line where increased salinity was feared by industrial interests. Seaward of the Delaware-Pennsylvania State line, the salinities increased slightly in all tests. This slight steepening of the salinity gradient along the axis of the estuary was due to the reduction in the tidal ranges between channel sta -25 and 230 caused by the channel enlargement. This reduction in tidal energy resulted in a lesser amount of tidal mixing in this portion of the estuary. The greatest effect was with spring tide conditions, and the smallest effect was with neap tide conditions. Overall, the effect of the channel enlargement upon salinity intrusion in the three model tests with normal freshwater discharge conditions was small.

48. A fourth salinity test was performed in the model with extreme low freshwater discharge and mean tide to investigate the influence of channel enlargement on extreme cases of salinity intrusion. After obtaining a stable salinity profile under mean discharge conditions, a Delaware River discharge at Trenton of 1800 cfs and a Schuylkill River inflow of 500 cfs were used throughout the remainder of the test. Data were taken for 220 cycles after the initiation of the low discharge. The results of measurements of bottom salinities along the channel center line at high water are shown in Plates 22 and 23. Plate 22 shows a comparison of existing and proposed channel salinity profiles after 145 and 220 cycles. Plate 23 presents the salinity as a function of time at sta 120, 65, and -75 for the existing and
proposed channels. As indicated by the curves, the upstream extent of salinity intrusion is less for the proposed channel than for the existing channel; and bottom salinities upstream from the Delaware-Pennsylvania State line were generally reduced by the plan. Although the tidal ranges were increased by the channel enlargement upstream from about sta -50, the increased cross-sectional area of the channel (approximately 20%) caused a reduction in the current velocities upstream of Philadelphia, and longitudinal tidal dispersion was therefore reduced.

49. Based in part on the results of the model tests, the decision was made to construct the enlarged channel. For a more detailed description and discussion of this model study, refer to Reference 1.
PART III: DESCRIPTION OF TESTS

50. The purpose of the following tests is to determine the accuracy with which the Delaware River model predicted the effects of the channel enlargement between Philadelphia, Pennsylvania, and Trenton, New Jersey. Some of these tests were conducted over 20 yr after the channel revision in the model. However, the model was still operating in a predictive state as indicated by periodic checks to ensure that the original model calibration was still valid. Prototype data were collected several years after the channel enlargement was constructed. It was then necessary to conduct additional model tests to duplicate the freshwater inflow and tidal conditions during the postconstruction prototype surveys.

Prototype Surveys

Current velocities

51. Detailed current velocity data were obtained during two surveys of the Delaware River conducted by WES on 31 March and 1 April 1972 and 30 October through 2 November 1972. Station locations for these surveys are designated in Figure 7. For the March-April survey, velocities were measured at all 14 stations, whereas only 7 stations were metered during the October-November survey. Fewer velocity stations were metered for the second date because of the unavailability of boats. At each of the stations, velocities were measured 2 ft below the surface, at middepth, and 2 ft above the bottom. Readings were taken at half-hour intervals for 13 hr.

52. Current speeds were measured with a direct-reading, vertical axis, cup-type current meter. Current direction was determined by a remote-reading magnesyn compass that indicates the magnetic north azimuth of the direction from which the current is flowing. These directional readings have been interpreted as either flood or ebb flow.

Hydrographs

53. Discharge observations of the Delaware River at Trenton and
Figure 7. Postconstruction verification data stations
Philadelphia and of the Schuylkill River at Philadelphia for the period of the two current velocity surveys were obtained from the Philadelphia District.

54. For the salinity tests of 1965 prototype conditions, discharge observations for the Delaware at Trenton and all the major tributaries entering the river below Trenton were supplied by the U. S. Geological Survey (USGS). These hydrographs were revised by the Philadelphia District to reflect contributions of groundwater seepage and some of the smaller tributaries during the periods of critical low flows.

Tides

55. Tidal elevations at half-hour intervals during the period of the current surveys were provided for the Philadelphia gage by the Philadelphia District. Data at the other gages were taken at 2-hr intervals by the USGS. These tide gage stations are shown in Figure 7.

Salinities

56. Daily maximum and minimum middepth salinities for the Delaware River prototype for seven of the eight fixed salinity stations (Figure 7), excluding Miah Maull Shoal Light, were compiled and furnished by the Philadelphia District. The district offices also supplied periodic surface profiles and locations of the bottom 250-ppm isochlor. The data covered the period of March through November 1965. Salinities were not measured during the 1972 velocity surveys because the areas of primary interest in those surveys (upstream of Philadelphia) were upstream of the limits of saltwater intrusion.

Postconstruction Model Tests

57. Three model tests (two hydraulic and one salinity) were performed in the Delaware River model with the enlarged channel under the same tidal and freshwater inflow conditions that prevailed during the prototype surveys (see paragraphs 51-56). Test results for those conditions illustrate the accuracy of model predictions for effects of channel enlargement on hydraulic phenomena under both low and
high freshwater discharges and on the salinity regimen for prolonged periods of extremely low discharge.

58. The method employed for determining a representative constant river inflow at Trenton for the postconstruction model hydraulic verification tests should be noted. From previous model experience, it has been found that to obtain an inflow that would give the proper influence on hydraulic phenomena over the entire estuary, the prototype Trenton discharge should be averaged over a 7-day period prior to data collection. However, in the tests performed for postconstruction verification, the current velocity data were collected in the upper reach of the river between Philadelphia and Trenton. Therefore, to determine the appropriate model inflow at Trenton for the hydraulic tests, the prototype discharge was averaged for 3 days prior to the prototype surveys. For the salinity test, the appropriate hydrographs were used at the various model inflow points.

59. The model data stations for the tests are shown in Figure 7. Model velocity measurements for the two hydraulic tests were made only at stations where corresponding prototype data were obtained. Tests 1 and 2 involved 7 and 14 stations of velocity data, respectively. Tidal elevations were measured at 14 gages during both tests. During the salinity test, 8 sampling stations were used.

Hydraulic test 1

60. The first postconstruction hydraulic verification test was performed to determine the accuracy of model tide and velocity predictions of the effects of channel enlargement for low freshwater discharge conditions. During the prototype current survey of October-November 1972, the Delaware River had a freshwater inflow of approximately 5,000 cfs at Trenton compared to the mean discharge of 12,000 cfs. The remainder of the inflows to the system were mean flows. A list of those mean flows reproduced in the model is given in Table 2. The model was operated with a source salinity of 31 ppt in the ocean and a tidal range at Miah Maull of 5.1 ft with a mean tide level of 3.9 ft above Delaware River datum, which is 2.9 ft below mean sea level at Sandy Hook, 1929 adjustment. This operating procedure was used to
duplicate tidal conditions at Delaware Memorial Bridge (sta 180), which was the most seaward prototype tide gage operated during the prototype surveys.

61. Tidal elevations were recorded at the tide gages shown in Figure 7. Current velocities were measured for test 1 at sta 95, 0, -15, -50, -65, -75, and -85. Readings were taken at the surface, mid-depth, and bottom over a complete tidal cycle.

Hydraulic test 2

62. The second postconstruction hydraulic verification test was performed under the high discharge conditions of the March-April 1972 prototype survey. The appropriate model inflow at Trenton, computed as described previously, was approximately 18,000 cfs, and the remainder of the inflows to the system were the mean flows as shown on Table 2. The model was again operated with a source salinity of 31 ppt in the sump and a tidal range of 5.1 ft with a mean tide level of 3.95 ft above Delaware River datum at Miah Maull.

63. Tidal elevations were recorded at the same tide gages as for test 1. The current velocity stations for test 2 were the 14 stations upstream of Philadelphia. Readings were again taken at the surface, middepth, and bottom over complete tidal cycles.

Model repeatability test

64. A separate test was performed on the Delaware River model for the purpose of determining the repeatability of the model. It was desired to know how well the model would repeat a velocity reading at a particular time during the tidal cycle from one cycle to the next, over a prolonged period of time.

65. The test was run with mean tide and freshwater discharge and involved four velocity stations in the river above Philadelphia (sta 0, -15, -75, and -85). This section of the model was chosen because the postconstruction verification velocity stations were located in that vicinity. Only middepth velocities were measured. Velocity measurements were made during 24 consecutive tidal cycles.

66. During the 24 tidal cycles, data were taken on the prototype hour, or every 36 sec in the model. The results obtained were
then statistically analyzed for each station at every hour of the prototype lunar tidal cycle.

Salinity test

67. In the summer of 1965, the Delaware River Basin suffered one of the worst droughts of record. During this period of extremely low freshwater flow, which was lower than was tested for original model verification, the saltwater intrusion in the estuary reached critical proportions. As a result, there was a wealth of prototype salinity data measured for the purpose of monitoring the location of the upstream limit of the maximum concentration for potable use.

68. This period was chosen for checking the model salinity verification because of the availability of prototype data and the extremely low freshwater inflow that occurred. The model was started and operated with a constant inflow until the initial salinity profile was reproduced. Then the prototype 9-month hydrograph (March-December 1965) was duplicated in the model, and surface and bottom salinities at the times of high- and low-water slacks were measured at the salinity stations shown in Figure 7. The model surface and bottom measurements were averaged for comparison with prototype middepth salinities at each of these stations. This averaging technique was acceptable because previous prototype salinity measurements had shown that there is very little difference between surface and bottom salinities in the Delaware and that the salinity gradient from surface to bottom is quite uniform. For every other tidal cycle in the model, the exact location of the 250-ppm isochlor at the bottom at high-water slack was determined.

69. This test (including prototype data collection) was performed for conditions of the enlarged navigation channel upstream from Philadelphia. Thus, although this salinity study was conducted several years before the present study was initiated, the test results can be considered a valid indication of postconstruction verification.

Data Accuracy

Prototype data

70. The USGS reports that tidal elevation data for the Delaware
River were accurate to within \( \pm 0.1 \) ft. The threshold speed of the direct-reading, cup-type current meters used for current velocity measurements was about 0.2 fps, and the accuracy was about \( \pm 0.2 \) fps for the range of values obtained during the surveys. The magnesyn compass used to determine current direction had a precision of \( \pm 2 \) deg, but accuracy was dependent upon the balance of the sensing unit and the strength of the current. For current speeds greater than 1 fps, accuracy was about \( \pm 5 \) deg. The accuracy of the prototype salinity data is unknown, but the governing factor would have been the sampling technique used.

**Model data**

71. Tidal elevations could be read in the model to within \( \pm 0.001 \) ft (0.1 ft prototype). The current velocity meters used had a threshold velocity of about 0.03 fps (0.3-fps prototype) and an accuracy of \( \pm 0.02 \) fps (0.2-fps prototype). Model salinity concentrations could be determined accurately to within approximately \( \pm 4 \) percent. The accuracy of the model data was, of course, also quite dependent on the precision with which the measurements (or samples) were obtained from the model at the desired time. If the measurement (or sample) was taken a few seconds too early or late, the observed water level, velocity, or salinity could be different from that recorded at the proper observation time.
PART IV: RESULTS AND DISCUSSION

Tidal Propagation

72. Tidal data from the tests conducted are presented several ways in this section. First, comparative plots of model and prototype tidal elevations versus time are given where prototype data were available, and on these plots most of the tidal characteristics may be observed. In addition, the times and elevations of high and low water, tide ranges, and mean tide levels have been plotted as they vary along the length of the estuary. The mean tide levels have been calculated by averaging the hourly tidal elevations.

73. The tidal data also have been examined in terms of the energy dissipation rate. The technique was adapted from that found in Chapter 10 of Reference 5. The average rate of energy dissipation occurring in a reach of the estuary was calculated by the following procedure:

a. The energy flux past a station was computed by the equation

\[ P_x = \frac{\gamma \sigma}{2} b_0 \frac{\sigma}{k} e^{\delta x} \left( \frac{\eta_H}{2} \right)^2 \]

where

- \( x \): distance along the estuary axis, positive downstream
- \( \gamma \): unit weight of water
- \( b_0 \): river width at \( x = 0 \) (Trenton) = 1000 ft
- \( \sigma \): tidal wave frequency = 1.41 \times 10^{-4} \text{ radians/sec}
- \( k \): average tidal wave number = constant = 5.8 \times 10^{-6} \text{ radians/ft}
- \( \delta \): constant of exponential width change = 6.7 \times 10^{-6} \text{ ft}^{-1}
- \( \eta_H \): half tidal range

b. The value of energy flux passing the upstream limit of a given reach of the estuary was subtracted from the energy flux passing the downstream limit of the reach.

c. The difference was divided by the mass of water in the reach. The result was assumed to be the rate of energy dissipation per unit mass within that reach.
The presence of a reflected wave such as occurs in the Delaware makes this computation yield an apparent energy dissipation rate that is less than the true value, since energy loss in the reflected wave would appear as an energy gain in the upstream direction. Because both model and prototype values were computed using the same technique, it would appear that both would suffer equally in the analysis, but there are exceptions. For example, if the model has a stronger reflected wave due to end effects or scale distortion and if the increased energy of the reflected wave results in a larger downstream energy loss, then the apparent model energy dissipation rate will be artificially low even if the frictional characteristics of that section are correct.

The computation is rather sensitive to errors in tidal range since the half tidal range is squared. For this reason and because of the reflected wave effect, the absolute values computed for each reach should not be overemphasized. Despite these drawbacks, the technique permits additional insight into the behavior of both prototype and model.

Original verification

The original tidal verification of the model is described in Reference 3 and will be only briefly discussed in the following paragraphs.

Plate 1 shows the comparison of model and prototype tide ranges, mean tide levels, and times of high and low water. The model tide range was within 0.2 ft of the prototype at all stations, with the maximum discrepancy occurring upstream from Florence (sta -110). The mean tide level was similarly very close. The high-water lunar interval (time of occurrence of high water) was virtually identical in model and prototype while that of low water varied by no more than 20 min.

A bar graph showing apparent energy dissipation rates for both model and prototype is given in Plate 24. The prototype rate was rather high between sta 325 and 225 and then relatively constant from sta 225 upstream to -125. The last reach from sta -125 to -160 was high again. The model exhibited the same pattern, though individual reaches vary as much as 30 percent from the prototype. The average energy dissipation rate from sta 425 to the head of tide was $9.3 \times 10^{-4} \text{ ft}^2/\text{sec}^3$ in
the prototype and $9.6 \times 10^{-4}$ ft$^2$/sec$^3$ in the model.

Test 1

79. Model and prototype half-hourly tidal elevations at sta 180, 110, 15, -20, and -80 are shown in Plates 25 and 26 for the 5000-cfs discharge test. The attempt to match the tide at sta 180 was not completely successful, due in part to differences in shape between the mean tide used for model tests and the observed prototype tide for that date. The prototype tide curves represent an average tide for the 2 days of the prototype survey.

80. The times of high and low water are plotted in Plate 27. Model stations for which no prototype data are available have been included. Starting in phase with the prototype at sta 180, the model low water first slightly lagged and then preceded the prototype. The maximum phase shift occurred for high water at sta -20 where the model preceded the prototype by about 20 min. This is within the accuracy of the original verification.

81. Plate 27 also shows the tide range and mean tide level variation along the estuary. The performance of the model was quite good, with a maximum deviation of 0.4 ft in range (about 6 percent) at sta -20. The agreement in mean tide level is good except above sta -80, where the model rose to about 0.6 ft above the prototype at sta -130, if the prototype curve is assumed linear in that area. The original verification data (Plate 1) showed a slight rise in mean tide level between sta -80 and -130, so the error was probably about 0.1 ft less than the plot makes it appear.

82. In Plate 28, high- and low-water elevations tended to climb sharply in the model above sta -80. This may have been due in part to the concentration of tributary discharges in the model at Trenton.

83. Plate 29 illustrates the apparent energy dissipation rate for the low-flow test. The prototype rate between sta 180 and 120 was quite close to that of the original verification data (Plate 24) but dropped between sta 120 and -130. Above sta -130, the rate returned to its previous level but lacked the sharp peak at the upstream end of the estuary that occurred previously for the unenlarged channel.
(Plate 24). The model exhibited the same trends as the prototype and appeared to provide the correct distribution of energy losses along the estuary.

84. The average apparent energy dissipation rates between sta 180 and -130 were $6.5 \times 10^{-4}$ ft$^2$/sec$^3$ in the prototype and $6.7 \times 10^{-4}$ ft$^2$/sec$^3$ in the model, a difference of about 2 percent. The prototype rate for this reach in the original verification was $9.3 \times 10^{-4}$ ft$^2$/sec$^3$, while the model rate was $9.6 \times 10^{-4}$ ft$^2$/sec$^3$, a difference of 3 percent.

Test 2

85. Tidal elevations for sta 180, 15, -20, and -80 are illustrated in Plates 30 and 31 for the 18,000-cfs discharge test. Again, the match at the downstream station was not precise although the times of high and low water corresponded. The model mean tide level at sta 180 was about 0.3 ft lower than the prototype.

86. Plate 32 presents the times of high and low water. These curves show good agreement between prototype and model with a maximum deviation of 15 min, which occurred at sta 15 for low water.

87. At the stations upstream from 180, the high-water elevations were too low, resulting in too small a tide range. Tide ranges and mean tide levels are also plotted in Plate 32. Upstream of sta 180, the model range remained a fairly constant 0.3 to 0.4 ft low, while the mean tide level was low by about 0.1 to 0.2 ft until sta -110. Plate 33 demonstrates that the error in tide range was due primarily to deficiencies in high-water elevations between sta 180 and -80.

88. Plate 34 shows the apparent energy dissipation rates for the high-flow condition. Prototype data for sta 110 were not available for this test, so the long reach between sta 180 and 15 was used for the computation. The average dissipation rate for this reach in both model and prototype was quite close to the average rate in test 1 and the original verification. The same overall pattern is observed in model and prototype except for the extreme upstream reaches where the prototype, but not the model, had a rather high apparent energy dissipation rate, as was observed in the original verification.

89. The average energy dissipation over the entire reach of
interest was quite similar to that for the low-flow test. For the prototype, the average value between sta 180 and -130 was $7.6 \times 10^{-4}$ ft$^2$/sec$^3$; for the model, it was $7.5 \times 10^{-4}$ ft$^2$/sec$^3$, a difference of about 1 percent. This difference compares favorably with the original verification.

Current Velocities

90. Several methods of analysis were used to compare the model and prototype current velocities. First, the current velocities are plotted versus time over a tidal cycle at each velocity station for surface, middepth, and bottom readings. Then computations of the average flood and ebb velocities for model and prototype at each station are tabulated. The ebb predominance of the flow over a tidal cycle is presented graphically for model and prototype for the bottom velocities at each station.

91. In addition, the velocity data were analyzed statistically in the following way:

a. The algebraic differences between corresponding model and prototype velocities (model - prototype) were determined, taking flood velocities as positive and ebb velocities as negative. On the flood phase, if the model flow was greater than the prototype flow, a positive difference was calculated; if the prototype flow was greater, a negative difference was calculated. On the ebb phase, a greater model flow yielded a negative difference, while a greater prototype flow yielded a positive difference.

b. For the purpose of separate ebb and flood computations, each difference in velocities was classified on ebb or flood phase according to the direction of the prototype velocity. If the prototype velocity was ebb, then the difference between model and prototype velocities was considered a difference during the ebb phase of the tidal cycle. Similarly, a flood velocity for the prototype classified the difference on flood phase. If the prototype velocity was zero, the corresponding difference was not included in the separate ebb or flood statistical computations.

c. At each depth at each station, the mean difference and the standard deviation of the differences were computed separately for ebb and flood phases of the tidal cycle.
d. The mean difference and the standard deviation from the mean were computed for all the data over a complete tidal cycle at each depth at each station.

e. The statistical analysis was also performed on the data for all depths at each station, as a single sample (essentially this yields the depth-averaged mean difference, etc.), for the ebb and flood phases and over the entire tidal cycle.

f. Finally, a statistical analysis was performed on all the data in each test as a single sample (all depths at all stations over a full tidal cycle). In addition to the mean difference and the standard deviation, the moment coefficients of skewness and kurtosis were computed for the overall statistical analysis.

92. The statistical parameters were computed by the following equations:

\[
\text{Mean difference} = \left( \frac{1}{N} \right) \sum_{i=1}^{N} d_i
\]

\[
\text{Standard deviation} = S = \left[ \frac{1}{N} \sum_{i=1}^{N} (d_i - d_{\text{mean}})^2 \right]^{1/2}
\]

\[
\text{Moment coefficient of skewness} = \left( \frac{1}{S^3 N} \right) \left[ \sum_{i=1}^{N} (d_i - d_{\text{mean}})^3 \right]
\]

\[
\text{Moment coefficient of kurtosis} = \left( \frac{1}{S^4 N} \right) \left[ \sum_{i=1}^{N} (d_i - d_{\text{mean}})^4 \right]
\]

where

- \( N \) = number of differences in the sample
- \( d_i = V_m - V_p \) = velocity differences; \( i = 1, 2, \ldots, N \)
- \( V_m \) = model velocity
- \( V_p \) = prototype velocity
The mean difference gives an indication of the relative net flow between the model and prototype. A positive mean difference is evidence that the model freshwater flow (as determined by channel velocity measurements) is low relative to that in the prototype, while a negative mean difference points toward too great a model freshwater flow. Unfortunately, the mean difference hides the fact that a positive and negative difference of the same magnitude cancel each other; hence, it is possible to have a mean difference of 0.0 when not a single data comparison between model and prototype was the same. This is required, however, in order to determine the relative magnitudes of net discharge over the tidal cycle between model and prototype.

93. In determining the accuracy with which the model velocities compare with the prototype velocities, in terms of the general magnitude of the differences, the standard deviation is of greatest value. It gives the half width of a band about the mean difference within which the majority of the differences lie. Thus, it is a measure of the scatter of the data about the mean. For a normal distribution, 68 percent of the differences would lie within the band.

94. The moment coefficient of skewness is a measure of the asymmetry of the frequency distribution of the differences about the maximum frequency. A positive skewness implies that the mean difference is greater than the velocity difference occurring with maximum frequency (mode). A negative skewness occurs when the mean difference is less than the mode. Thus, for a distribution with a positive skewness, more occurrences are distributed on the positive side of the mode than the negative side. The opposite is true when the skewness is negative. If there is no skewness (a value of 0.0), the frequency distribution is symmetric about the mean difference which coincides with the mode.

95. The moment coefficient of kurtosis gives an indication of the peakedness of the frequency distribution. A numerical value of 3.0 for the coefficient of kurtosis is found for a normal distribution. If the kurtosis is greater than 3.0, then the frequency distribution is more peaked about the maximum frequency; if less than 3.0, the frequency distribution is not very peaked but is more evenly distributed. Assuming
that the mean difference is small, then a coefficient of kurtosis equal to or greater than 3.0 would indicate good general agreement between model and prototype current velocities for the test, with a large number of differences close to zero. If the value of the coefficient of kurtosis was much less than 3.0, then poor agreement would generally be found.

Original model verification

96. The original verification velocity data were analyzed in the same manner as the postconstruction data to obtain a standard for comparison of the agreement obtained between model and prototype velocities in the postconstruction tests. Statistical analyses were performed on the original verification data, and the mean model and prototype velocities on flood and ebb phases of the tidal cycle were computed. The original verification data analyzed included 63 of the 74 current velocity stations used for the original verification. The stations not included were omitted from the analysis because there were conflicting prototype data with which model data could be compared. The results of the computations of mean flood and ebb velocities are presented in Table 4, and the results of the statistical analyses are shown in Table 5. The data in these tables will be referred to during the discussion of the postconstruction test results.

Test 1

97. The comparative plots for model and prototype current velocities for the 5000-cfs discharge test are presented in Plates 35-41. The model velocities turned from ebb to flood earlier at sta 95 surface and sta 0 middepth than at other depths at these stations. As a result, the ebb durations at these locations were about 0.5 hr shorter than those of both prototype data and model at the other depths at these stations. At sta -15 and -50, the surface model flood velocities were somewhat low relative to middepth model flood velocities. Maximum flood and ebb velocities in the model were generally low by about 0.7-1.8 fps at sta -50 at all three depths. At sta -15 (middepth and bottom) and sta -35 (middepth), maximum flood velocities were high by about 1.0 fps. Overall, the model velocities agreed very well with the prototype velocities. Furthermore, the agreement was of the same quality as the original
model verification, as seen in Plates 35-41.

98. The mean flood and ebb velocities in model and prototype for test 1 are shown in Table 6. Due to missing prototype data at sta 95 (hr 8.5-10.5) and sta -65 (hr 5.5-6.0 and 7.5-8.0), the average flood velocities may be high at sta 95, and the average ebb velocities may be low at sta -65. However, this error is not large except where very large segments of prototype data are unavailable, as at sta -85 where middepth velocities are missing for hr 3.5-11.0. For this latter case, the average middepth ebb velocity has been omitted from the table. The average variation of the mean model velocity from mean prototype velocity on the flood phase is 27 percent as compared to 21 percent for similar computations made with the original model verification data. On ebb flow, the average variation was 19 percent, the same value computed for the average variation on ebb flow for the original verification of the model. The maximum variations of the mean model velocities from prototype mean velocities were 82 percent for flood flow (sta -15, bottom) and 65 percent for ebb flow (sta -75, bottom); this compares very well with the maximum variations of original verification data of 81 percent on flood flow (sta 4B, bottom) and 91 percent on ebb flow (sta 6B, bottom).

99. In Table 7, the results of the statistical analyses on flood flow velocities show a maximum magnitude of mean differences between model and prototype velocities of 1.06 fps for test 1 (sta -50, surface) as compared to 1.24 fps for the original verification (sta 6F, bottom). At about 75 percent of the measurement points, however, the mean difference was less than 0.4 fps. The average magnitude of mean differences was approximately equal in test 1 and the original verification (0.30 and 0.36 fps, respectively). The maximum standard deviation of the differences was 0.76 fps as compared to 1.29 fps for the original verification of model current velocities. The average standard deviation for test 1 and the original verification was 0.41 and 0.50 fps, respectively.

100. The results of the analyses on ebb flow velocities for test 1 show a maximum magnitude of the mean differences to be 0.49 fps (sta
-50, surface), as compared to a maximum of 1.22 fps for the original verification (sta 9F, surface). However, the mean difference between model and prototype velocities was less than 0.3 fps at about 75 percent of the measurement points. The average magnitude of mean differences was found to be 0.18 fps as compared to 0.38 fps in the analysis of the original verification data. A value of 0.77 fps was computed in test 1 for the maximum standard deviation of differences in contrast to a value of 1.26 fps for the original verification. The average standard deviation was 0.31 fps, while for the original verification data, the corresponding value was 0.52 fps on ebb flow.

101. For test 1, all the statistical parameters computed in either flood or ebb separate analyses are within the agreement obtained for the original model verification. This is also the case for the analyses performed at each station over a full tidal cycle. The maximum magnitude of mean differences for test 1 calculated over a complete tidal cycle was 0.23 fps (sta +95, surface; sta 0, middepth) as compared with 0.78 fps (sta 9F, surface) for the original verification. (The average magnitude of mean difference was 0.12 fps with a corresponding value of 0.22 fps for the original model verification.) The maximum standard deviation was 0.90 fps, compared to 1.22 fps for the original verification. The average standard deviation for test 1 was found to be 0.47 fps in comparison with 0.64 fps for the original verification over a full tidal cycle.

102. The statistical analysis of all the test 1 data at all stations and all depths over a complete tidal cycle as a single sample indicated a mean difference of 0.03 fps as compared to a value of 0.05 fps for the similar analysis of all the original verification data. The standard deviation of all the velocity differences was 0.51 fps, compared to 0.72 fps for the original verification. Test 1 data had a moment coefficient of skewness for the overall analysis of 0.04, compared to a value of 0.28 for the original verification. The moment coefficient of kurtosis was 4.37 as compared to 3.47 for the original model verification. Thus, the distribution of the differences for test 1 was nearly symmetric about a mean difference that was very close
to zero (0.03 fps). This compares well with the original verification which was positively skewed with a larger mean difference (0.05 fps). A comparison of the moment coefficients of kurtosis shows that the distribution of differences for test 1 is more peaked near zero than for the original verification. These statistical data indicate that the general agreement between model and prototype velocities is somewhat better for test 1 than was obtained for the original verification.

103. Ebb predominance computations at each station for bottom depth are presented in Plate 42 for test 1. The maximum difference between model and prototype values at a particular station is 14 percent at sta -85. The average magnitude of difference is about 6.5 percent. The overall trend is the same in model and prototype, and both reach their minimums of 47.5 and 50.0, respectively, at sta -50.

Test 2

104. The model and prototype current velocities for the 18,000-cfs discharge test are plotted for comparison in Plates 43-56. Because of missing prototype data at all three depths at sta -10 (hr 5.5-7.0), -75 (hr 4.5-5.5), and -81 (hr 4.0-8.5), average ebb velocities at these stations may be slightly low. Maximum ebb and flood model velocities were low by 0.5-1.5 fps at surface and middepth at sta -10, -50, and -120. Maximum surface and middepth model velocities at sta -28 and -40 were also 0.5-1.2 fps low relative to prototype velocities on the flood phase. Middepth velocities on the flood phase were also low for the model at sta -35 and -90 by 1.3 and 1.8 fps, respectively. The magnitude of model velocities at sta -20 is high at all depths, on both ebb and flood phases by about 0.5 and 1.2 fps, respectively. The bottom flood flows in the model appear to be too great by about 0.5 fps relative to surface and middepth model flood flows at sta -15 and -40. The duration of ebb flow in the model was 30-40 min too short at the surface at sta 0, -10, -75, -85, -90, and -100 and at the middepth at sta -81, -85, -90, and -100; at sta -15, the surface and middepth ebb duration was 30 min too long in the model. It can be seen that the model and prototype velocities at sta -20 (Plate 46) are about 30 min out of phase throughout the tidal cycle. Furthermore, it appears that the
prototype data are in error, since they are also about 30 min out of phase with the closest stations both upstream and downstream. The overall agreement between model and prototype velocity data is very good for test 2 when viewed in light of the agreement obtained for the original model verification.

105. Results of computations of the mean flood and ebb velocities for model and prototype for test 2 are shown in Table 8. The average variation of the mean model flood velocity from the mean prototype flood velocity was 26 percent as compared to 21 percent for the original model verification. On ebb phase, the average variation was 20 percent, compared with 19 percent for the original verification. The maximum variation of mean velocities on flood phase was 89 percent (sta -20, bottom), compared with 81 percent for the original verification of model velocities (sta 4B, bottom). The maximum variation of the model mean velocity from the prototype mean velocity on ebb phase was 68 percent (sta -120, bottom) compared with 91 percent for the original verification ebb velocities (sta 6B, bottom).

106. In Table 9, the results of the statistical analyses on flood flow velocities indicated a maximum magnitude of mean difference between model and prototype velocities of 0.79 fps for test 2 (sta -50, middepth) as compared to a maximum of 1.24 fps in the original model verification analysis (sta 6F, bottom). At about 75 percent of the measurement points, however, the mean difference was less than 0.5 fps. The average magnitude of mean differences was approximately equal in test 2 and the original verification (0.32 and 0.36 fps, respectively). The maximum standard deviation of the differences was 0.97 fps as compared with 1.29 fps in the original model verification. The average standard deviation of the differences in velocities for all the stations in test 2 was 0.40 fps, compared to 0.50 fps in the original verification analysis on flood flow.

107. On ebb flow, the results show a maximum magnitude of mean difference between model and prototype velocities of 0.95 fps (sta -10, surface) for test 2 as compared with a maximum of 1.22 fps (sta 9F, surface) in the original model verification. At about 75 percent of the
measurement points, however, the mean difference between model and prototype ebb velocities was less than 0.35 fps. The average magnitude of mean differences on ebb phase analyses was 0.29 fps in contrast to an average of 0.38 fps for the original verification analysis. The maximum standard deviation of the differences at a station depth was 0.75 fps, compared to a maximum of 1.26 fps in the original verification. The average standard deviation for test 2 was 0.33 fps, compared to an average of 0.52 fps in the original verification analysis on ebb flow.

108. The results of the analysis of the differences over the full tidal cycle showed excellent comparison of test 2 agreement with the agreement of the original verification data between model and prototype velocities. The maximum magnitude of the mean differences over a full tidal cycle was 0.44 fps (sta -10, surface) in contrast to a maximum of 0.78 fps (sta 9F, surface) in the original verification. An average magnitude of mean differences of 0.15 fps compared well with an average of 0.22 fps for the original verification. The value of the maximum standard deviation of differences over a full cycle was 0.88 fps; for the original model verification, the corresponding value was 1.22 fps. The average standard deviation for test 2 was 0.49 fps as compared to 0.64 fps for the original verification over a full tidal cycle.

109. The statistical analysis of all the data at all stations and all depths over a complete tidal cycle for test 2 as a single sample showed a mean difference of 0.02 fps as compared to a value of 0.05 fps for the similar analysis of all the original verification data. The standard deviation of all the velocity differences was 0.55 fps as compared to 0.72 fps for the original verification analysis. The moment coefficient of skewness determined by this analysis was -0.14, compared with a value of 0.28 for the original verification. The moment coefficient of kurtosis was 2.99 as compared to a value of 3.47 for the original verification. Thus, the distribution of velocity differences for test 2 was somewhat negatively skewed with a mean difference very close to zero (0.02 fps). The degree of skewness was only half of that of the original verification. The peakedness of the distribution, as indicated by the kurtosis, was somewhat less for test 2 than
for the original verification, but was of the same order of magnitude with a mean difference closer to zero. The agreement obtained between model and prototype velocities is very good relative to that obtained for the original model verification.

110. The results of ebb predominance computations at each station for bottom depth are presented in Plate 57 for test 2. The maximum magnitude of difference between model and prototype ebb predominance values is 20 percent at sta -120 toward the upper end of the model; the maximum difference for test 1 data was 14 percent at sta -85. The maximum difference in test 2 over the same reach of channel stations observed in test 1 is only 11 percent at sta -40. The average difference for test 2 stations is approximately 6 percent, the same as for test 1. The overall trend in the curves is the same for both model and prototype with both reaching their lowest values of 53.4 and 50.6, respectively, at sta -15.

111. The results of the velocity analyses are summarized in Tables 10 and 11. The average and maximum variations of the model from prototype mean velocities on flood and ebb phases are shown in Table 10. Values are listed for the original model verification and for both tests 1 and 2 of the postconstruction verification study. All postconstruction parameters computed agree well with the corresponding values calculated from original verification data. The statistical data computed for the original verification and for the postconstruction tests are summarized in Table 11. In every case, the postconstruction parameters are within the overall agreement obtained in the original model verification of current velocities.

Repeatability test

112. The results of the model repeatability test are given in Table 12. At sta 0, -15, -75, and -85, middepth velocities were measured hourly for 24 consecutive tidal cycles. For each hour in the tidal cycle, the mean velocity and the standard deviation about the mean velocity are listed. As shown in the data, the average standard deviation determined was approximately 0.1 fps. This indicates that model velocities at a given location normally will repeat to within
0.1 fps for identical tests. If when comparing with prototype velocity data the model is within 0.1 fps, then it may be considered in excellent agreement. It should be noted also that this measure of fluctuation in the model readings includes variations due to instrument error and human error, inconsistency in generating exactly the same tide from cycle to cycle, and the possibility that freshwater inflows may not be exactly constant.

Salinity Intrusion

113. The results of the salinity intrusion test for the prototype low-flow period in 1965 are presented in Plates 58-61. The model and prototype middepth salinities measured at high- and low-water slack of the tidal cycle at Miah Maull, Reedy Island Jetty, Delaware Memorial Bridge, Chester, Fort Mifflin, Pier II at Philadelphia, Bridesburg, and Torresdale are shown in Plates 58-60. Except for short-term fluctuations at the various stations, caused primarily by wind effects in the prototype, the agreement between model and prototype salinity concentrations was very good for all stations throughout the duration of the test. The largest discrepancies at a data station occurred when the steepest portion of the salinity profile advanced past the station. With a steep salinity gradient along the estuary, a small difference in the location of a saline front can give a large difference in the measured salinity.

114. Plate 61 shows the location of the 250-ppm isochlor over the test period for model and prototype at the bottom. The solid line represents the exact location at bottom in the model, as determined in every other tidal cycle at high-water slack. The solid black points designate the location in the prototype at bottom at high-water slack, while the open points represent the approximate location as could best be determined by interpolation of prototype surface salinity measurements. The agreement between model and prototype bottom locations of the 250-ppm isochlor concentration is very good for the entire test period.
115. No statistical analysis of the salinity test was undertaken because analogous salinity tests were not included in the original salinity verification, and interpretation of the results of such an analysis would be difficult.
116. The channel deepening project between Philadelphia and Trenton caused significant, but not large, changes in the hydrodynamic and salinity regimen of the estuary. The magnitude of the changes induced is much larger than the fluctuations due to the imperfect repeatability of the model, but not great enough to strain the initial calibration of the model. Therefore, the deepening project constituted a valid test of the capability of the model to predict the changes in the estuarine system caused by projects of that scale.

117. The original verification was considered to be very good, and this study concluded that the accuracy of the model predictions was as good as the original verification. Tidal phenomena, current velocities, and the salinity regimen of the estuary have been predicted by the model with accuracy for the postconstruction conditions. The Delaware River model may be considered reverified for the portion of the model tested in this study.

118. The results of this study show the validity of the Delaware River model predictions but also show the necessity of interpreting them in general terms rather than for specific point values. The model is very accurate for predicting changes and general trends for the estuary, but a particular value at a particular time and place should not be considered to be completely quantitative in all cases. When physical hydraulic models are used with proper caution to avoid too literal an interpretation of the results, they are of significant value as a decision-making tool.
REFERENCES

1. U. S. Army Engineer Waterways Experiment Station, CE, "Delaware River Model Study; Effects of Proposed Channel Enlargement Between Philadelphia and Trenton," Technical Memorandum No. 2-337, Report 3, Jan 1952, Vicksburg, Miss.


3. U. S. Army Engineer Waterways Experiment Station, CE, "Delaware River Model Study; Hydraulic and Salinity Verification," Technical Memorandum No. 2-337, Report 1, May 1956, Vicksburg, Miss.


Table 1
Condition of Channel Improvements

<table>
<thead>
<tr>
<th>Reach</th>
<th>Channel Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth to sta 500</td>
<td>Natural depths and widths adequate</td>
</tr>
<tr>
<td>Sta 500 to 330</td>
<td>40 by 1000 ft</td>
</tr>
<tr>
<td>Sta 330 to 43</td>
<td>40 by 800 ft*</td>
</tr>
<tr>
<td>Sta 43 to 0</td>
<td>40 by 400 ft</td>
</tr>
<tr>
<td>Sta 0 to -125</td>
<td>35 by 600 ft**</td>
</tr>
<tr>
<td>Sta -125 to -160</td>
<td>40 by 400 ft</td>
</tr>
<tr>
<td>Sta -160 to -165</td>
<td>25 by 300 ft†</td>
</tr>
</tbody>
</table>

* In this reach, the 800-ft width is increased at the bends.
** Authorized channel depth is 37 ft but has not been dredged. This is in addition to 40- by 400-ft channel.
† Authorization exists to increase this reach of channel from 25 by 300 ft to 35 by 300 ft, but the work has not been undertaken.

Table 2
Distribution of Freshwater Inflow

<table>
<thead>
<tr>
<th>Source of Inflow</th>
<th>Location</th>
<th>Mean Inflow</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Miles Above</td>
<td>Channel</td>
</tr>
<tr>
<td></td>
<td>Mouth</td>
<td>Station*</td>
</tr>
<tr>
<td>Delaware River at Trenton</td>
<td>133</td>
<td>-160</td>
</tr>
<tr>
<td>Intermediate small</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>tributaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schuylkill River at Philadelphia</td>
<td>93</td>
<td>57</td>
</tr>
<tr>
<td>Subtotal</td>
<td>93</td>
<td>57</td>
</tr>
<tr>
<td>Intermediate small</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>tributaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Christina-Brandywine near Wilmington</td>
<td>70</td>
<td>170</td>
</tr>
<tr>
<td>Subtotal</td>
<td>70</td>
<td>170</td>
</tr>
<tr>
<td>Intermediate small</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>tributaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total at mouth</td>
<td>0</td>
<td>548</td>
</tr>
</tbody>
</table>

* Positive stations are measured seaward from Allegheny Avenue, Philadelphia, and negative stations are measured upstream thereof in thousands of feet.
Table 3
Monthly Variation in Total Discharge

<table>
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<tr>
<th>Month</th>
<th>Mean Monthly Discharge Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
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</tr>
<tr>
<td>February</td>
<td>9.5</td>
</tr>
<tr>
<td>March</td>
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<td>April</td>
<td>15.1</td>
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<td>May</td>
<td>9.9</td>
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<tr>
<td>June</td>
<td>6.3</td>
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<tr>
<td>July</td>
<td>5.3</td>
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<tr>
<td>August</td>
<td>4.5</td>
</tr>
<tr>
<td>September</td>
<td>4.2</td>
</tr>
<tr>
<td>October</td>
<td>4.2</td>
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<tr>
<td>November</td>
<td>7.6</td>
</tr>
<tr>
<td>December</td>
<td>8.8</td>
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Table 4
Mean Flood and Ebb Velocities for Original Verification

<table>
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<tr>
<th>Velocity Station</th>
<th>Mean Flood Velocity, fps</th>
<th>Mean Ebb Velocity, fps</th>
<th>Velocity Station</th>
<th>Mean Flood Velocity, fps</th>
<th>Mean Ebb Velocity, fps</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Prototype</td>
<td>Model</td>
<td>Variation, %</td>
<td>Prototype</td>
<td>Model</td>
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<tr>
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<td>1.86</td>
<td>2.06</td>
</tr>
<tr>
<td>middepth</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2.65</td>
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<tr>
<td>middepth</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A all depths</td>
<td>1.79</td>
<td>2.28</td>
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<td>2.28</td>
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<td>2.00</td>
<td>2.76</td>
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<tr>
<td>middepth</td>
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<td></td>
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<tr>
<td>bottom</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B all depths</td>
<td>1.77</td>
<td>2.32</td>
<td>+31</td>
<td>1.92</td>
<td>2.32</td>
</tr>
<tr>
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<td>2.81</td>
<td>+2</td>
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<td>2.81</td>
</tr>
<tr>
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<td>2.40</td>
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<td>1.40</td>
<td>2.19</td>
</tr>
<tr>
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<td>+6</td>
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<td>-4</td>
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<td>2.55</td>
</tr>
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<td>2.66</td>
<td>+27</td>
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<td>2.66</td>
</tr>
<tr>
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<td>1.27</td>
<td>2.45</td>
</tr>
<tr>
<td>6F all depths</td>
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<td>2.55</td>
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<td>2.35</td>
<td>2.55</td>
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</tbody>
</table>
| (Continued)
### Table 4 (Concluded)

<table>
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<tr>
<th>Velocity Station</th>
<th>Mean Flood Velocity, fps</th>
<th>Mean Ebb Velocity, fps</th>
<th>Mean Flood Velocity, fps</th>
<th>Mean Ebb Velocity, fps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prototype</td>
<td>Model</td>
<td>Variation, %</td>
<td>Prototype</td>
</tr>
<tr>
<td>34 middepth</td>
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<td>2.30</td>
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<td>2.63</td>
</tr>
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</tr>
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<td>2.09</td>
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<td>6A surface</td>
<td>2.23</td>
<td>2.20</td>
<td>-1.41</td>
<td>2.26</td>
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<td>34 middepth</td>
<td>1.50</td>
<td>1.47</td>
<td>-1.41</td>
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<td>1.10</td>
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</tr>
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<td>-1.41</td>
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<td>2.47</td>
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<tr>
<td>Station</td>
<td>Velocity</td>
<td>Mean Difference, fps</td>
<td>Standard Deviation, fps</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>----------</td>
<td>----------------------</td>
<td>-------------------------</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>On</td>
<td>On Complete</td>
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<td>On</td>
</tr>
<tr>
<td>S1 all depths</td>
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<td>-0.01</td>
<td>-0.11</td>
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<tr>
<td>S2 all depths</td>
<td>0.54</td>
<td>-0.11</td>
<td>0.61</td>
<td>0.02</td>
</tr>
<tr>
<td>S3 all depths</td>
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<td>0.04</td>
<td>0.20</td>
<td>-0.10</td>
</tr>
<tr>
<td>S4 all depths</td>
<td>-0.06</td>
<td>0.01</td>
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<td>0.20</td>
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<tr>
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<td>0.01</td>
<td>0.08</td>
<td>-0.09</td>
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**Table 5**

Results of Statistical Analyses for Original Verification
<table>
<thead>
<tr>
<th>Velocity Station</th>
<th>Mean Flood Velocity, fps</th>
<th>Mean Ebb Velocity, fps</th>
<th>Variation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prototype</td>
<td>Model</td>
<td>Variation</td>
</tr>
<tr>
<td>+95 surface</td>
<td>2.00</td>
<td>1.85</td>
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<td>+95 middepth</td>
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<td>1.67</td>
<td>-6</td>
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<td>+95 bottom</td>
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<td>1.64</td>
<td>+11</td>
</tr>
<tr>
<td>+95 all depths</td>
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<td>1.72</td>
<td>-2</td>
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<td>0 surface</td>
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</tr>
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<td>0 middepth</td>
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<td>1.62</td>
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<tr>
<td>0 bottom</td>
<td>1.12</td>
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</tr>
<tr>
<td>0 all depths</td>
<td>1.50</td>
<td>1.65</td>
<td>+10</td>
</tr>
<tr>
<td>-15 surface</td>
<td>1.05</td>
<td>1.05</td>
<td>0</td>
</tr>
<tr>
<td>-15 middepth</td>
<td>1.17</td>
<td>1.65</td>
<td>+41</td>
</tr>
<tr>
<td>-15 bottom</td>
<td>0.89</td>
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<tr>
<td>-15 all depths</td>
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<td>2.01</td>
<td>0.96</td>
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<tr>
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<td>-39</td>
</tr>
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<td>-12</td>
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Table 7
Results of Statistical Analyses for Test 1

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All data as single sample

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<th>Standard Deviation, fps</th>
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<td>On Ebb</td>
</tr>
<tr>
<td>All</td>
<td>-</td>
<td>--</td>
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<td>Velocity Station</td>
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<td>Mean Ebb Velocity, fps</td>
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<td>--------------------------</td>
<td>------------------------</td>
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Table 9
Results of Statistical Analyses for Test 2

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<td>On Ebb</td>
</tr>
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<td>0 surface</td>
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All data as a single sample -- -- 0.02 -- -- 0.55
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<th>Original Model Verification, %</th>
<th>Test 1, %</th>
<th>Test 2, %</th>
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<td>Maximum variation:</td>
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<tr>
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<td>68</td>
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* Variations are computed by dividing the magnitude of the difference between model and prototype mean velocities by the prototype mean velocity.
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<th>Ebb</th>
<th>Complete Cycle</th>
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<td>0.32</td>
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Table 12
Results of Model Repeatability Test*

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<td>1.61</td>
<td>0.53</td>
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</tr>
</tbody>
</table>

Average standard deviation over tidal cycle: 0.09, 0.10, 0.09, 0.12

* All numerical values are in feet per second (fps).
TIDE STATIONS

TRENTON  FLORENCE  BURLINGTON  TREMONT  PHILDELPHIA  FORT MIFLIN  BALTIMORE  MARCUS HOOK  EDGEWATER  REEDS POINT  ARTIFICIAL ISLAND  WOODLAND BEACH  SHIP JOHN LIGHT

FEET PROTOTYPE

RANGE OF TIDE

FEET ABOVE NAV

MEAN TIDE LEVEL

1000-FT CHANNEL STATIONS FROM ALLEGHENY AVENUE, PHILADELPHIA

MODEL TEST DATA

TIDE FRESHWATER DISCHARGE 2000 FT³ (MEAN AT CAPES)

OCEAN SALINITY 28,000 PPM (15,460 PPM CHLORINE)

LEGEND

- MODEL

- PROTOTYPE

Heights refer to Delaware River datum which is 250 feet below mean sea level Sandy Hook, 1928 adjustment.

ORIGINAL VERIFICATION
TIDAL OBSERVATIONS

PLATE 1
PLATE 2

MODEL TEST DATA

TIDE MEAN
FRESHWATER DISCHARGE 20,200 CFS (MEAN AT CAPES)
OCEAN SALINITY 28,000 PPM (15,480 PPM CHLORINE)

ORIGINAL VERIFICATION
VELOCITY OBSERVATIONS
STATION 8-F
SURFACE

MIDDEPTH

BOTTOM

MODEL TEST DATA
TIDE MEAN
FRESHWATER DISCHARGE 20,200 CFS (MEAN AT CAPES)
OCEAN SALINITY 28,000 PPM (15,480 PPM CHLORINE)

LEGEND
--- MODEL
---- PROTOTYPE

ORIGINAL VERIFICATION
VELOCITY OBSERVATIONS
STATION 8-A

PLATE 3
SURFACE

MIDDEPTH

BOTTOM

MODEL TEST DATA
TIDE
FRESHWATER DISCHARGE ... 20,200 CFS (MEAN AT CAPE S)
OCEAN SALINITY ..... 28,000 PPM (15,470 PPM CHLORINE)

LEGEND

ORIGINAL VERIFICATION
VELOCITY OBSERVATIONS
STATION 8-B

PLATE 4
MODEL TEST DATA
TIDE MEAN
FRESHWATER DISCHARGE 20,200 GFS (MEAN AT CAPES)
OCEAN SALINITY 28,000 PPM (15,460 PPM CHLORINE)

LEGEND
- - MODEL
- - PROTOTYPE

ORIGINAL VERIFICATION VELOCITY OBSERVATIONS
STATION 8-C

PLATE 5
STA 28 - MIDDEPTH

STA 29 - MIDDEPTH

STA 30 - MIDDEPTH

MODEL TEST DATA
TIDE MEAN
FRESHWATER DISCHARGE 20,200 CFS
OCEAN SALINITY 28,000 PPM

LEGEND

MODEL

PROTOTYPE

ORIGINAL VERIFICATION VELOCITY OBSERVATIONS
STATIONS 28, 29, AND 30

PLATE 6
STA 56-A (CHANNEL STA 31+000)

STA 57 (CHANNEL STA 19+050)

STA 58 (CHANNEL STA -8+050)

MODEL TEST DATA

TIDE
FRESHWATER DISCHARGE... 20,000 CFS (MEAN AT CAPES)
OCEAN SALINITY............. 28,000 PPM (15,460 PPM CHLORINE)

LEGEND

ORIGINAL VERIFICATION
VELOCITY OBSERVATIONS
STATIONS 56-A, 57, AND 58

PLATE 7
NOTES: MODEL OPERATED FOR MEAN CONDITIONS WITH SUMP SALINITY = 15,460 PPM CHLORINE.

PROTOTYPE DATA OBSERVED 19-20 JAN 1932.

TO CONVERT PPM CHLORINE TO PPM TOTAL SALT, MULTIPLY BY 1.81.

LEGEND

MODEL SALINITY

PROTOTYPE SALINITY

BOTTOM SALINITY (MODEL PROTOTYPE)

SURFACE SALINITY (MODEL PROTOTYPE)

ORIGINAL VERIFICATION TYPICAL SALINITY CYCLE
CHANNEL STATION 275
NOTE: THE PROTOTYPE PROFILES SHOWN HAVE BEEN ADJUSTED TO MEAN HIGH-WATER SLACK CONDITIONS FROM OBSERVATIONS MADE AUG 10-11 AND OCT 4-5, 1932.

LEGEND
- INITIAL MODEL OBSERVATION
- FINAL MODEL OBSERVATION

ORIGINAL VERIFICATION OF SURFACE SALINITY PROFILES
TEST 1
NOTE: THE PROTOTYPE PROFILES SHOWN HAVE BEEN ADJUSTED TO MEAN HIGH-WATER SLACK CONDITIONS FROM OBSERVATIONS MADE AUG 8-9 AND OCT 6-7, 1930.

LEGEND
- INITIAL MODEL OBSERVATION
- FINAL MODEL OBSERVATION

ORIGINAL VERIFICATION OF SURFACE SALINITY PROFILES
TEST 2
MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON TIDAL PHENOMENA

NOTE: FRESHWATER DISCHARGE AT AND INCLUDING SCHYLLKIL RIVER = 16,475 CFS (MEAN)
MODEL TEST DATA
TIDE - MEAN
SUMP SALINITY - 15,840 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER - 16,475 CFS (MEAN)

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON CURRENT VELOCITIES
CHANNEL STATION 185 + 750
MODEL TEST DATA

TIDE - MEAN
SUMP SALINITY - 15,460 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER - 16,475 CFS (MEAN)

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON CURRENT VELOCITIES
CHANNEL STATION 60

PLATE 14
MODEL TEST DATA

TIDE - MEAN
SUMP SALINITY - 15,480 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER - 16,475 CF5 (MEAN)

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON CURRENT VELOCITIES

CHANNEL STATION - 20

PLATE 15
SURFACE

MIDDEPTH

BOTTOM

MODEL TEST DATA
TIDE - MEAN
SUMP SALINITY - 15,460 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER - 16,475 CFS (MEAN)

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON CURRENT VELOCITIES
CHANNEL STATION = 60

PLATE 16
MODEL TEST DATA

TIDE - MEAN
SUMP SALINITY-15,460 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING
SCHUYLKILL RIVER - 16,475 CF5 (MEAN)

MODEL PREDICTION OF THE
EFFECTS OF CHANNEL ENLARGEMENT
ON CURRENT VELOCITIES

CHANNEL STATION -100

PLATE 17
MODEL TEST DATA
TIDE - MEAN
SUMP SALINITY = 15,460 PPM CHLORINE (28,000 PPM TOTAL SALT)
FRESHWATER DISCHARGE AT AND INCLUDING SCHUYLEKILL RIVER = 16,475 CFS (MEAN)

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON CURRENT VELOCITIES
CHANNEL STATION = 120

PLATE 18
Model prediction of the effects of channel enlargement on bottom salinity

Neap tide

Note: Discharge at and including Schuylkill River = 10,600 CFS

Sump salinity = 15,460 PPM chlorine.

To convert PPM chlorine to PPM total salt, multiply by 1.81.
NOTE: DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER = 10,600 C.F.S
SUMP SALINITY = 5,440 PPM CHLORINE.
TO CONVERT PPM CHLORINE TO PPM TOTAL SALT, MULTIPLY BY 1.81.

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON BOTTOM SALINITY
MEAN TIDE
NOTE: DISCHARGE AT AND INCLUDING SCHUYLKILL RIVER = 10,600 CFS
SUMP SALINITY = 15,460 PPM CHLORINE.
TO CONVERT PPM CHLORINE TO PPM TOTAL SALT, MULTIPLY BY 1.81.
NOTE: THE FOLLOWING FRESHWATER DISCHARGES WERE INTRODUCED THROUGHOUT TEST:
DELAWARE AT TRENTON 1800 CFS
SCHUYLKILL 500 CFS
SALEM 520 CFS
SUMP SALINITY = 15,480 PPMchlorine.
TO CONVERT PPMchlorine TO PPM TOTAL SALT, MULTIPLY BY 1.81.

MODEL PREDICTION OF THE EFFECTS OF CHANNEL ENLARGEMENT ON BOTTOM SALINITY
MEAN TIDE
NOTE: THE FOLLOWING FRESHWATER DISCHARGES WERE INTRODUCED THROUGHOUT TEST:
DELAWARE AT TRENTON 1800 CFS
SCHUYLKILL 500 CFS
SALEM 520 CFS
SUMP SALINITY IS 15,460 PPM CHLORINE.

TO CONVERT PPM CHLORINE TO TOTAL SALT, MULTIPLY BY 1.81.

CHANNEL STATIONS REFER TO ALLEGHENY AVENUE, PHILADELPHIA.
DELAWARE MEMORIAL BRIDGE (STA 180)

CHESSTER (STA 110)

PHILADELPHIA (STA 15)

TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND
--- PROTOTYPE
--- MODEL

VERIFICATION OF POSTCONSTRUCTION TIDAL HEIGHTS
CHANNEL STATIONS 180, 110 AND 15
TEST 1

PLATE 25
TEST CONDITIONS

- DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
- TIDAL RANGE AT MIAH MAULL 5.1 FT
- OCEAN SALINITY (TOTAL SALT) 31.0 PPT
- DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND

- - - PROTOTYPE
- - - MODEL

VERIFICATION OF POSTCONSTRUCTION TIDAL HEIGHTS
CHANNEL STATIONS -20 AND -80
TEST 1

PLATE 26
NOTE: FRESHWATER DISCHARGE AT TRENTON = 5000 CFS}
MEAN TIDE
NOTE: FRESHWATER DISCHARGE AT TRENTON = 2000 CFS
MEAN TIDE

LEGEND

- - - - PROTOTYPE

- - - - MODEL

VERIFICATION OF POSTCONSTRUCTION HIGH- AND LOW-WATER ELEVATIONS
TEST 1
NOTE: FRESHWATER DISCHARGE AT TRENTON = 5000 CFS

ENERGY DISSIPATION RATE PER UNIT MASS \((10^6 \text{ ft}^2/\text{sec}^3)\)

TRENTON
FIELDSBORO
FLORENCE
BURLINGTON
PALMYRA
PHILADELPHIA
FORT MIFFLIN
CHESTER

DELAWARE MEMORIAL BRIDGE
NEW CASTLE

ARTIFICIAL ISLAND
WOODLAND BEACH
SHIP JOHN LIGHT

LEGEND
MODEL

APPROXIMATE RATE OF TIDAL ENERGY DISSIPATION

TEST 1
DELAWARE MEMORIAL BRIDGE (STA 180)

PHILADELPHIA (STA 15)

PALMYRA (STA -20)

TEST CONDITIONS
- DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
- TIDAL RANGE AT MAW MAULL 5.1 FT
- OCEAN SALINITY (TOTAL SALT) 31.0 PPT
- DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATIONS 180, 15, AND -20
TEST 2

LEGEND
- - - PROTOTYPE
- - - MODEL

PLATE 30
TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MAHL MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CF3

LEGEND

PROTOTYPE

MODEL

VERIFICATION OF POSTCONSTRUCTION TIDAL HEIGHTS
CHANNEL STATION – 80
TEST 2

PLATE 31
NOTE: FRESHWATER DISCHARGE AT TRENTON = 18,000 CFS
MEAN TIDE
Energy Dissipation Rate per Unit Mass (10^4 ft^2/sec^3)

Trenton
Fieldsboro
Florence
Burlington
Palmyra
Philadelphia
Fort Mifflin
Chester
Delaware Memorial Bridge
New Castle
Artificial Island
Woodland Beach
Ship John Light
Miah Maull Light

Tidal Energy Dissipation
Test 2

NOTE: Freshwater discharge at Trenton = 18,000 CFS
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT NAU MALL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION 95
TEST I
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 11-7-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND

--- PROTOTYPE

--- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION 0
TEST I

PLATE 36
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MIAN MUALL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND

- - - PROTOTYPE
- - - - MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -15
TEST 1

PLATE 37
TEST CONDITIONS
DUPICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -50
TEST I

PLATE 38
TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

DELaware RIVER MODEL
POSTCONSTRUCTION VERIFICATION

VERIFICATION OF
POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -65
TEST 1

PLATE 39
TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MAR MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND
- - - - PROTOTYPE
--- --- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -75
TEST 1
TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 11-2-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELANARE RIVER INFLOW AT TRENTON 5000 CFS

LEGEND
--- PROTOTYPE
- --- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -85
TEST I

PLATE 41
VERIFICATION OF POSTCONSTRUCTION BOTTOM EBB PREDOMINANCE
TEST 1
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

LEGEND

--- PROTOTYPE
--- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION 0
TEST 2

PLATE 43
**TEST CONDITIONS**

- Duplication of Prototype Conditions: 4-1-72
- Tidal Range at Miah Mauil: 5.1 ft
- Ocean Salinity (Total Salt): 3.10 PPT
- Delaware River Inflow at Trenton: 18,000 CFS

**LEGEND**

- PROTOTYPE
- MODEL

**VERIFICATION OF POSTCONSTRUCTION VELOCITIES**

**CHANNEL STATION -10**

**TEST 2**

PLATE 44
TEST CONDITIONS

- DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
- TIDAL RANGE AT MAHAL DEE 5.1 FT
- OCEAN SALINITY (TOTAL SALT) 31.0 PPT
- DELANARE RIVER INFLOW AT TRENTON 18,000 CFS

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -15
TEST 2

PLATE 45
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MAHL MAHUL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CF5

LEGEND

--- PROTOTYPE
- - - MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -20
TEST 2

PLATE 46
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MAUL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

LEGEND

--- PROTOTYPE
-- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -28
TEST 2

PLATE 47
TEST CONDITIONS

- DUPLICATION OF PROTOTYPE CONDITIONS: 4-1-72
- TIDAL RANGE AT MAHL MAHULL: 5.1 FT
- OCEAN SALINITY (TOTAL SALT): 31.0 PPT
- DELAWARE RIVER INFLOW AT TRENTON: 18,000 CFS

LEGEND

- PROTOTYPE
- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION: -35
TEST 2

PLATE 48
TEST CONDITIONS

DUPLICATION OF prototype CONDITIONS 4-1-72
Tidal range at Miah Maull 5.1 ft
Ocean salinity (total salt) 31.0 PPT
Delaware River inflow at Trenton 18,000 CFS

LEGEND

--- prototype
- - - - model

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -40
TEST 2

PLATE 49
TEST CONDITIONS
DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MAUL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

LEGEND
- - - PROTOTYPE
- - - MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -50
TEST 2

PLATE 50
TEST CONDITIONS

DUPlication OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

VERIFICATION OF
POSTCONSTRUCTION VELOCITIES
CHANNEL STATION - 75
TEST 2

PLATE 51
TEST CONDITIONS

- DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
- TIDAL RANGE AT MIAH MAUL 5.1 FT
- OCEAN SALINITY (TOTAL SALT) 31.6 PPT
- DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

VERIFICATION OF POSTCONSTRUCTION VELOCITIES

CHANNEL STATION -81
TEST 2

PLATE 52
TEST CONDITIONS

DUPLICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MIAH MAULL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELWARE RIVER INFLOW AT TRENTON 18,000 CFS

LEGEND

----- PROTOTYPE
--- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION - 85
TEST 2
TEST CONDITIONS

DUPLICAITON OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MIAH MAU LL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -90
TEST 2

PLATE 54
TEST CONDITIONS
DUPICATION OF PROTOTYPE CONDITIONS 4-1-72
TIDAL RANGE AT MAUL 5.1 FT
OCEAN SALINITY (TOTAL SALT) 31.0 PPT
DELWARE RIVER INFLOW AT TRENTO 18,000 CF5

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION - 100
TEST 2
TEST CONDITIONS

- DUPLICATION OF prototype conditions 4-1-72
- TIDAL RANGE AT MIAH MAULL 5.1 FT
- OCEAN SALTINITY (TOTAL SALT) 31.0 PPT
- DELAWARE RIVER INFLOW AT TRENTON 18,000 CFS

LEGEND

- PROTOTYPE
- MODEL

VERIFICATION OF POSTCONSTRUCTION VELOCITIES
CHANNEL STATION -120
TEST 2

PLATE 56
VERIFICATION OF POSTCONSTRUCTION BOTTOM EBB PREDOMINANCE
TEST 2
TOTAL FLOW AT THE CAPES

MIAH MAULL LIGHT (STA 431)

REEDY ISLAND JETTY (STA 265)

LEGEND
- MAXIMUM
- MINIMUM
- MAXIMUM
- MINIMUM

NOTE: CHLORIDE CONCENTRATION X 1.64 = CHLORINE CONCENTRATIONS X 1.81 = TOTAL SALTS

PLATE 58
LEGEND

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MAXIMUM AND MINIMUM SALINITY MEASUREMENTS
DELaware MEMORIAL BRIDGE, CHESTER, AND FORT Mifflin
MIDDEPTH-MEAN TIDE, 1965 HYDROGRAPH

PLATE 59
TOTAL FLOW AT THE CAPES

LEGEND

● LOCATION FURNISHED BY PHILADELPHIA DISTRICT
○ LOCATION INTERPOLATED FROM SURFACE PROFILES

LOCATION OF 250 PPM ISOCHEMOR
BOTTOM DEPTH
1965 HYDROGRAPH-MEAN TIDE

PLATE 61
In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

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