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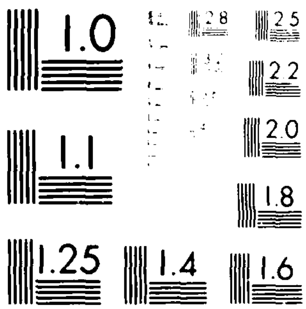

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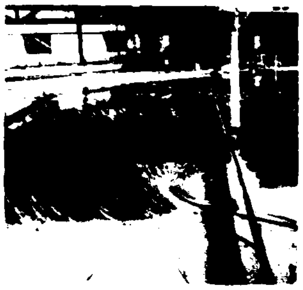

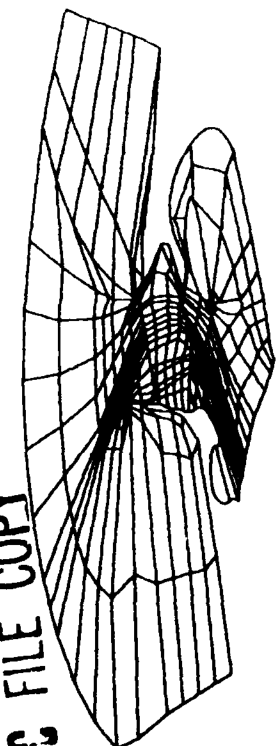

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TECHNICAL REPORT HL-83-16

COLUMBIA RIVER ESTUARY HYBRID MODEL STUDIES

Report 1

VERIFICATION OF HYBRID MODELING OF THE COLUMBIA RIVER MOUTH

by

William H. McAnally, Jr., Noble J. Brogdon, Jr.,
Joseph V. Letter, Jr., J. Phillip Stewart, William A. Thomas

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

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The Columbia Hybrid Modeling System was applied to the mouth of the Columbia River estuary to evaluate alternatives for reducing navigation channel maintenance dredging. The hybrid modeling method uses a physical hydraulic model, analytical techniques, and various numerical models in an integrated solution method that takes advantage of the strengths of each technique while avoiding its weaknesses. The methods accounted for the

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effect of tides, freshwater runoff, wind waves, and littoral currents on sediment transport, deposition, and erosion. The models were verified to satisfactorily reproduce observed prototype behavior.

PREFACE

The work described in this report was performed by the U. S. Army Engineer Waterways Experiment Station (WES) for the U. S. Army Engineer District, Portland (NPP). Development of the generalized computer programs used in the study was funded by Work Unit 31626 of the Improvement of Operation and Maintenance Techniques Research Program of the Corps of Engineers Civil Works Research Program sponsored by the Office, Chief of Engineers, U. S. Army. Preliminary work on the programs was funded by NPP. Mr. Harold D. Herndon was NPP liaison during the study.

Personnel of the Hydraulics Laboratory of WES performed this study during the period 1976 through 1981, under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory; F. A. Herrmann, Jr., Assistant Chief of the Hydraulics Laboratory; R. A. Sager, Chief of the Estuaries Division; M. B. Boyd, Chief of the Hydraulics Analysis Division; and G. M. Fisackerly, Chief of the Harbor Entrance Branch. The project was conducted and this report prepared by Messrs. W. H. McAnally, Jr., W. A. Thomas, J. V. Letter, Jr., N. J. Brogdon, Jr., and J. P. Stewart. Other WES personnel participating in the study were S. A. Adamec, D. P. Bach, B. Brown, Jr., C. J. Buford, B. P. Donnell, S. S. Grogan, S. B. Heltzel, J. T. Hilbun, V. E. LaGarde, M. A. Leggett, B. G. Moore, D. Murray, A. J. Page, D. T. Resio, R. J. Schneider, D. M. Stewart, and D. M. White.

Modifications to the computer code RMA-2V were made principally by Dr. I. P. King, Resource Management Associates (RMA). Other changes were made by personnel of the U. S. Army Hydrologic Engineering Center and WES project personnel. The code STUDH was written by WES personnel and Dr. R. Ariathurai, RMA, under the direction of Mr. Thomas. Computer code RMA-1 was written by RMA.

We gratefully acknowledge the many valuable contributions of Messrs. H. D. Herndon and G. Hartmann, NPP, and J. G. Oliver, U. S. Army Engineer Division, North Pacific. Persons providing valuable advice during the pilot study included Dr. R. B. Krone, University of California, Davis; Dr. D. C. Raney, University of Alabama; and Mr. H. L. Butler, Dr. J. R. Houston, Dr. C. L. Vincent, and Mr. C. J. Huval, WES. We also thank Dr. E. Partheniades, University of Florida, who suggested the hybrid approach to the

senior author in 1972 and Mr. Fisackerly, who had steadfastly supported the approach from its infancy.

Commanders and Directors of WES during the course of this study and the preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

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:

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet per second	0.02831685	cubic metres per second
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
square miles (U. S. statute)	2.589988	square kilometres

COLUMBIA RIVER ESTUARY HYBRID MODEL STUDIES

VERIFICATION OF HYBRID MODELING OF THE COLUMBIA RIVER MOUTH

PART I: INTRODUCTION

Objective

1. The overall objective of the Columbia River estuary model studies is to assist the U. S. Army Engineer District, Portland (NPP), in developing solutions to problems of constructing and maintaining a navigation channel through the estuary. The objectives of this portion of the studies were to evaluate the effectiveness of various improvement plans designed to reduce navigation channel dredging in the entrance to the estuary and to predict the changes in channel shoaling and salinity intrusion that would result from deepening the entrance channel.

2. This report describes the models and modeling methods that were used and presents the results of model verification. Results of model plan tests will be reported separately.

Background

3. The Columbia River estuary has been modeled several times. Large-scale physical models have been constructed at the University of California, Berkeley (O'Brien 1935), and the U. S. Army Engineer Waterways Experiment Station (WES) (Herrmann 1968), and numerical models have been applied by several investigators. In 1976, NPP asked WES to determine if newly developed numerical modeling techniques could be used to address some long-standing shoaling problems in the estuary. It was concluded in a pilot study that hybrid modeling--a combination of physical and numerical modeling techniques--offered the potential to provide better results than heretofore possible. Accordingly, NPP provided funds to develop the necessary tools for a hybrid model study of the estuary.

4. In 1976, a few experimental versions of two-dimensional numerical models for sediment transport had been developed but were relatively untested

and unknown. A review of available models showed that SEDIMENT 2H, a model developed at the University of California, Davis, by Drs. R. Ariathurai, R. C. McArthur, and R. B. Krone (1977) under funding by the Corps of Engineers Dredged Material Research Program, was the most suitable for use. It was selected for modification and use in the study.

5. The physical model of the estuary had been constructed at WES in 1961 and used for shoaling studies for a number of years. At the time of the pilot study, it had been inactive for several years. It was noted that inclusion of the physical model not only would offer the benefits of the hybrid modeling approach but also would provide an anchor of a relatively well-known method to a project with many innovative, but untested, elements. It was concluded, therefore, that reactivation of the physical model was an essential ingredient in developing a hybrid modeling approach to the Columbia River estuary.

6. Another newly developed numerical model which simulated wind wave generation and propagation offered the potential to permit consideration of the effects of short-period waves on sediment transport. Since the entrance of the Columbia is subjected to intense wave action, it was concluded that this new model should be included in a potential hybrid modeling plan for the estuary.

7. In late 1977, NPP was presented with a plan to develop a hybrid modeling scheme incorporating the existing physical model, a modified version of SEDIMENT 2H, the wave model, plus a number of other analytical and modeling techniques. NPP approved the plan and provided funds for its implementation. The product of that implementation is the subject of this report.

8. The presented plan was designed to address a list of potential studies provided by NPP. The original list included the following items:

a. Optimum length of north and south jetties.

b. Maintenance of a deepened entrance channel.

c. Fate of dredged material dumped in:

(1) Disposal area E.

(2) Disposal area at Tensey Point.

(3) Disposal area D.

(4) Disposal area at Desdemona Sands.

(5) Flow lanes.

d. Effect of Miller Sands rehandling sump.

e. Effect of jetty B on entrance channel shoaling.

f. Optimization of dike field at Brookfield Bar.

g. Optimization of dike field at Pillar Rock Bar.

h. Effect of closing Sand Island Gap.

i. Optimum design of Astoria Turning Basin.

j. Reduction of shoaling in Ilwaco Channel.

PART II: THE COLUMBIA RIVER ESTUARY

9. The Columbia River and its tributaries drain about 259,000 square miles* of the northwestern United States and southwestern Canada, discharging into the Pacific Ocean near Astoria, Oregon (Figure 1). As it approaches the sea, the lower Columbia River passes through the Cascade and then the Coast mountain ranges. The lower river, bounded by steep forested slopes, is deep

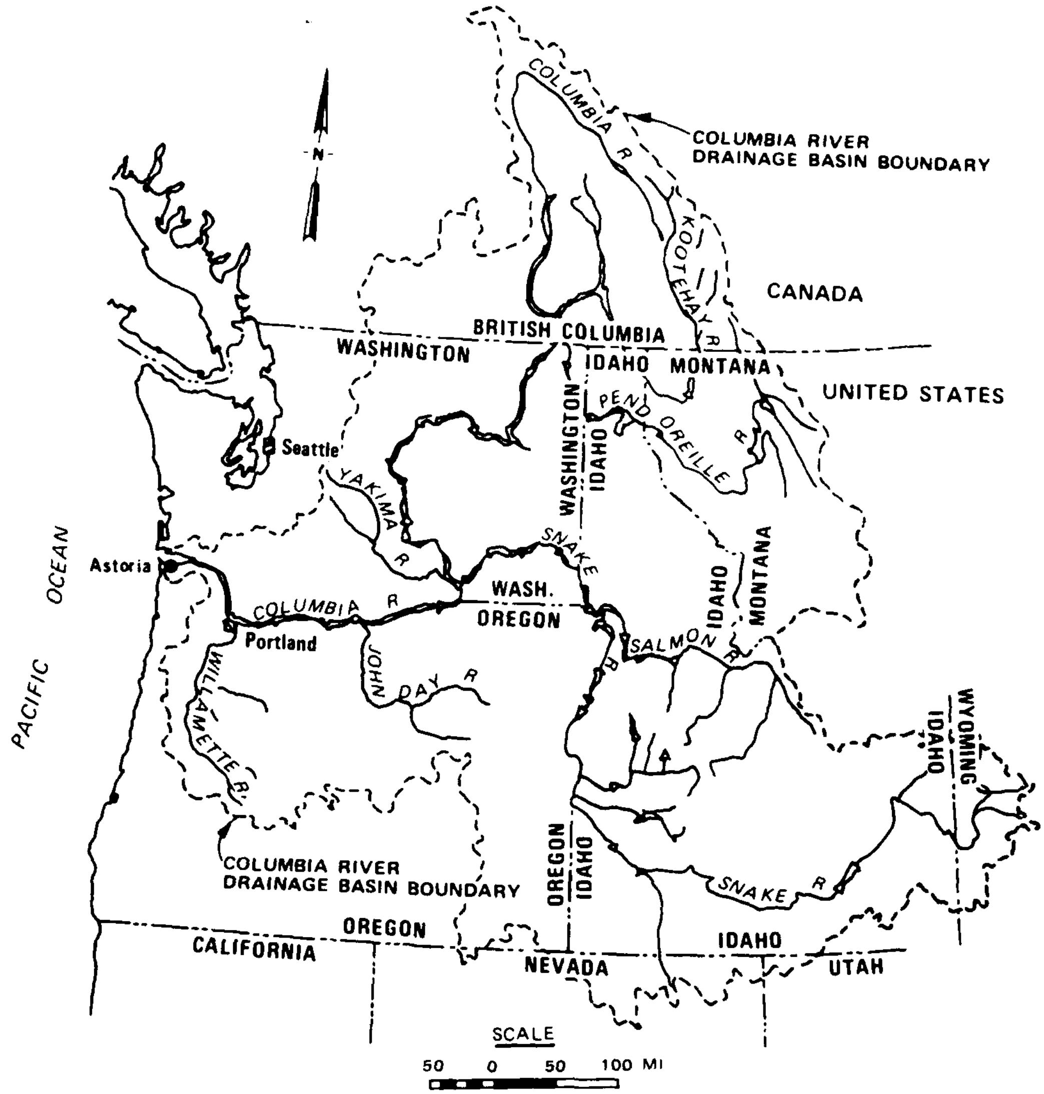


Figure 1. Site map

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is given on page 5.

and narrow until it widens into the estuary about 35 miles above the mouth.

10. The estuary consists of deep channels meandering past shallow bays, flats, and islands in a wide, coastal plain type estuary. It meets the Pacific between Cape Disappointment, Washington, on the north and Clatsop Spit, Oregon, on the south as shown in Figure 2. Between Altoona, 23 miles from the mouth, and Sand Island, near the mouth, the estuary is dominated by two deep channels separated by a broad area of shallows. The shallows are cut by a number of small, diagonal channels that connect the north and south channels. The coastline on either side of the entrance consists of sand beaches interrupted by occasional rocky headlands. The river varies in width from about 2,500 ft in the reaches near Portland to a maximum of about 9 miles in the middle of the estuary. At the entrance, it is about 2 miles wide.

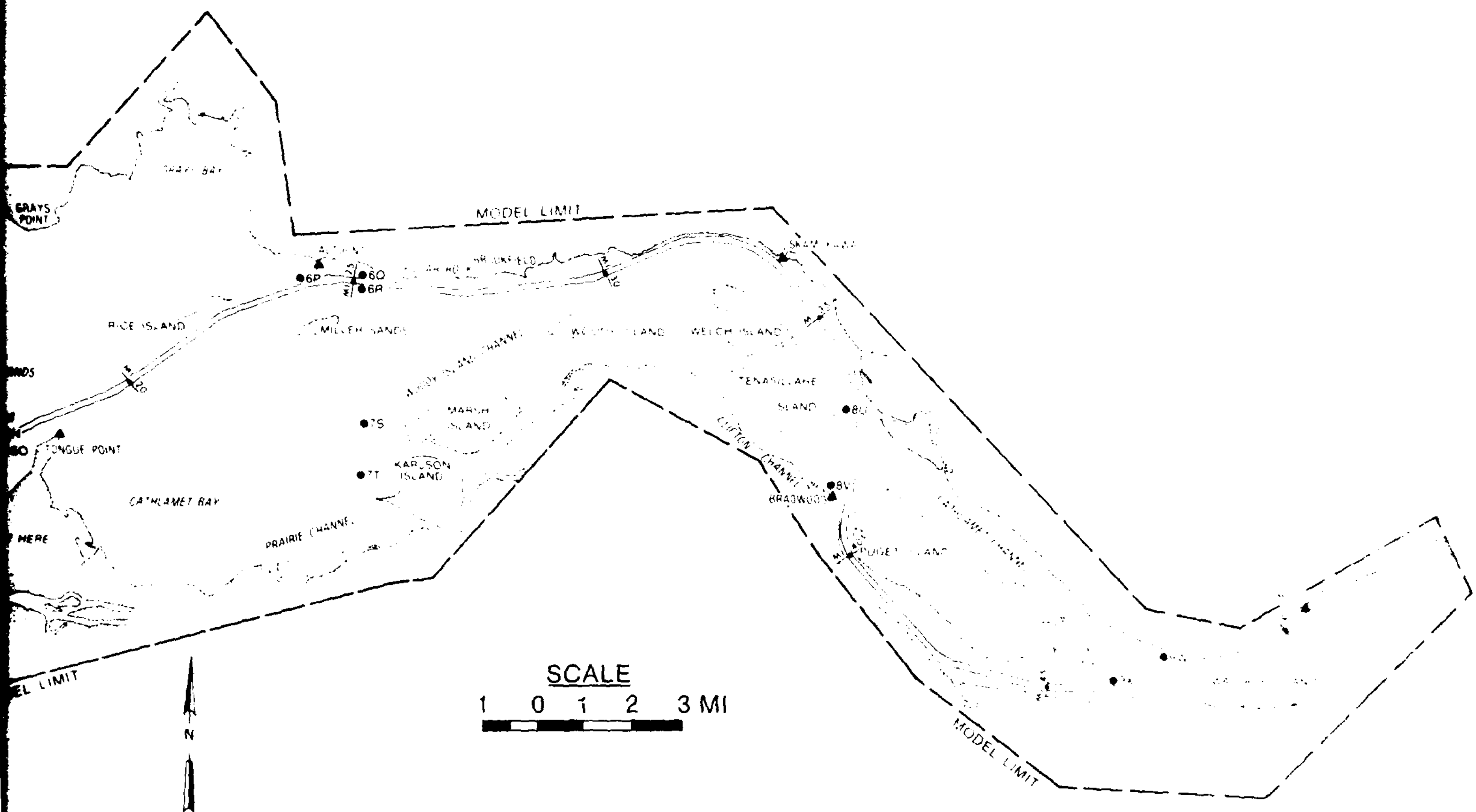
11. Locations on the river are described by distance in miles upstream of the mouth, termed Columbia River Miles (CRM). Downstream of about CRM 24, the datum plane for elevations is local mean lower low water (mllw) and upstream of that point, it is the Columbia River datum (CRD), which is basically a low water datum.

Riverflows

12. Flow from the upper Columbia River is dominated by snowmelt, causing low winter flows and spring freshets. Heavy winter precipitation over the lower basin boosts freshwater flow, sometimes causing winter freshets that approach the mean annual flow. The river typically begins to rise in March, peaks in June, and reaches its lowest flow in late summer or early fall. Average annual discharge at The Dalles (CRM 140) for the period of record is 194,000 cfs. At Beaver Army Terminal (CRM 53), the average flow is about 256,000 cfs, and the estimated average discharge at the mouth is 260,000 cfs (Herrmann 1970). Flow regulation by more than 35 multipurpose dams has reduced peak flows and increased minimum flows for stations below The Dalles.

13. Flow variations at The Dalles and farther downstream at Bonneville Dam (CRM 140) are the result of natural riverflow changes and fluctuations of discharge through the power plant due to diurnal power demand patterns. At low discharges, flow variations through the power plant can cause significant variation in hourly discharge rates. These power generation related flow variations are not noticeable in the estuary, however.

Figure 2. Columbia Riv



mbia River estuary and model limits

Tides

14. Tides in the Columbia River estuary are of the mixed type with two high waters and two low waters per day. During low flows, water-level fluctuations due to tides extend upstream to Bonneville Dam (CRM 145) on the main stem and to Willamette Falls on the Willamette River (Willamette River Mile 26.5). For freshet flows, tidal variations are noticeable only as far upstream as Oak Point, Washington (CRM 54). The estimated highest and lowest tide levels at the mouth are +12 ft mllw and -3 ft mllw, respectively. The average tidal prism volume for the estuary is estimated to be between 500,000 acre-ft (Lockett 1959) and 900,000 acre-ft (Herrmann 1970).

Currents

15. Currents in the estuary area are caused principally by the tide and freshwater inflow, with contributions by near-coastal, density, and wind-induced currents, plus mass transport by waves. The point at which the unidirectional riverflows begin to show reversal is dependent on river discharge and, to a lesser amount, on tidal range. During the Corps of Engineers current surveys of 1959-1960 (USAE Portland District 1960a), flow reversals in the main channel occurred at least as far upstream as CRM 53 at a river discharge of 169,000 cfs and CRM 25 at 380,000 cfs. Tidal ranges during these periods were 7 to 9 ft. During the record low flow of 85,000 cfs (due to closure of John Day Dam), a 4-hr current reversal occurred at CRM 70 (Clark and Snyder 1969). Wind-induced currents within the estuary may have a significant effect, but the large magnitude of tidal and freshwater flow currents tends to obscure them in deep water, except possibly during extreme events (Donnell and McAnally, in preparation).

16. Flow patterns in the estuary are variable; but in the salinity intrusion zone, they tend toward a typical upstream flow predominance near the bottom and downstream predominance near the surface. Flow in the north and south channels is nearly parallel to the bank lines but in the mid-estuary shallows, currents often flow diagonally (Lockett 1967). According to Lockett, the northern portion of the estuary (including the shallow middle area) carries a major portion of the flow (73 percent on the average) but varies in its flow and ebb predominance, producing a net clockwise flow (ebb

predominance on the south, flood predominance on the north) for riverflows of less than 165,000 cfs or greater than 190,000 cfs and a counterclockwise net flow for discharges between these two figures.

17. Currents in the immediate offshore area are subject to the same forces as those in the estuary, plus coastal current patterns. The coastal currents at the mouth tend toward the south in summer and north in winter with northward currents predominating (Sternberg et al. 1977). In water about 100 ft deep, the northward currents tend to be stronger than those to the south with maximum speeds of 1 to 2 fps being strongly correlated with storm winds (Sternberg et al. 1977). Nearshore currents have been studied with surface floats (Duxbury 1967) that showed substantial eddy formation around the jetties and with bottom drifters (Morse, Gross, and Barnes 1968) that showed net flow near the south jetty to be strongly into the mouth and flow near the north jetty to be northward.

Salinity

18. The estuary is usually classified as a partly mixed system that exhibits significant vertical salinity gradients without becoming completely stratified. The mixing condition varies, however, and the partly mixed classification may not hold to precise limits of salinity gradients. Burt and McAllister (1959) examined vertical salinity profiles and classified the estuary as partly mixed in January, April, and September, well mixed in March, and stratified in July.

19. Prior to the deepening of the navigation channel above the entrance from 35 to 40 ft below mllw, the salinity intrusion limit in the navigation channel ranged from CRM 17.5 at 400,000 cfs to CRM 24 at 125,000 cfs (Lockett 1963). At 200,000 cfs, the limit of intrusion increased from CRM 21 for the 35-ft channel to CRM 24.5 for the 40-ft channel (Lockett 1967). The location of the one part per thousand (ppt) isochlor moved 7 to 10 miles between high and low water during the 1959 Corps of Engineers Surveys (Portland District 1960b). During those surveys, which included freshwater discharges of 169,000, 383,000, and 558,000 cfs, the upstream limit of salinity intrusion was of the same order of magnitude in both the north and south channel areas, although significant lateral gradients existed (Portland District 1960b).

20. Outside the mouth, the Columbia River plume forms a well-defined

pool of low-salinity water that covers a substantial area. The plume moves under the influence of tidal currents, coastal currents, and wind, trending northward along the Washington coast during winter and standing off the Oregon coast in summer (Anderson 1963). Coastal waters outside the plume have an average salinity of 32.5 ppt at the surface and 33.9 ppt in deeper water (Duxbury 1972).

Meteorology

21. Winds in the estuary region exhibit seasonal patterns of mild, predominantly north-to-northwest winds in summer and stronger southerly winds in winter. Spring and fall winds alternate summer and winter characteristic patterns (Cooper 1958). The Coast Range causes winds to move nearly parallel to the coastline in the coastal area and the Columbia River gorge affects local wind patterns by channeling winds along the river, sometimes producing a strong east wind. Other than the gorge winds, the highest speeds are predominantly from the south to southwest during the winter.

22. The severe storm season occurs from October to April in the lower estuary with extratropical storms occurring several times per winter (National Marine Consultants 1961a). Lockett (1959) describes a typical winter storm as beginning with winds from the south quadrant, gradually moving clockwise over several days until the storm passes and wind is blowing from the west or northwest. The southerly wind is often of gale force at the coast for short periods.

23. Precipitation over the lower Columbia basin increases with altitude from the coast to the peaks of the Coast Range, averaging over 80 in./yr in some locations (Neal 1972). Coastal areas experience heaviest rainfall during the winter, causing high winter flows in the tributaries to the lower river.

Wave Climate

24. Wave climate at the Columbia River mouth is severe and wave heights greater than 20 ft are not uncommon. Wave-height estimates for the shore area are based on observations at the Columbia River lightship (O'Brien 1951) and in the shipping area offshore (USNWSC 1970), on hindcasts by National Marine Consultants (1961a and 1961b), and hindcasts by the Navy's Fleet Numerical

Weather Center. O'Brien demonstrated that the predominant wave direction is from the west, but that the predominant wave energy (proportional to height squared) is from the southwest. A statistical analysis of daily wave hindcasts is presented in PART IV.

25. Waves at the mouth are higher and longer from October to March with local seas generally higher than distantly generated swell. The predominant direction for swell is from the NW quadrant, whereas the predominant seas are from the N-NW in spring and summer and SW-SSE in fall and winter (Bourke, Glenne, and Adams 1971). Wave effects at the mouth are most pronounced for southerly waves since waves from that direction suffer little height reduction due to refraction. Waves at the mouth are refracted by the bottom configuration and by interaction with tidal currents. During ebb flows, waves often break over the outer bar due to the combined effects of wave shoaling and wave-current interaction. Wave refraction diagrams for various wave directions and periods are presented by National Marine Consultants (1961b).

Sediments

Sediment sources

26. Important sources of sediments to the estuary include a large supply from the lower Columbia River, from tributaries that flow directly into the estuary, bank and bottom erosion, littoral material brought in through the mouth, and windblown sediments. Upstream supply is at its maximum during the spring freshet, but local tributaries are likely to make their greatest contribution during winter runoff periods. The Columbia River is the ultimate source of most of the sediments of the estuary, and they are delivered from intermediate sources by erosion of deposits previously laid down by the river. This also applies to the beaches (Ballard 1964). This complicates identification of source by mineralogy since much, but not all, of the sediments will have a common set of minerals; and differences in mineral content may therefore be the reflection of sorting rather than source. Lockett (1967) used sediment sorting to conclude that sediments in the estuary navigation channel at about Astoria are from an upland source because of negative skewness in the size distribution, but sediments in the northern side of the estuary are derived from the ocean because of a positive skewness. Validity of the analysis has not been established.

Bottom sediment characteristics

27. Unlike many estuaries, the Columbia River estuary's bed is principally sand. Hubbell and Glenn (1973) found a typical sample to be 1 percent gravel, 84 percent sand, 12 percent silt, and 2 percent clay. Figures 3 and 4 show median grain sizes at a number of locations in the estuary. Data used in constructing the map consisted of surface samples taken in three collection programs in 1959, 1965, and 1977. The data show considerable variation in median size within each cross section, with the coarsest sizes usually, but not always, in the deep portion of the section. Fine sand sizes (0.62 mm to 0.125 mm) predominate, with a few sheltered or shallow-water samples in the silt size range.

28. Bed material texture through the estuary has been observed to demonstrate seasonal variations with sediments tending to be finer near the end of a low-flow period and coarser after a high discharge (Whetten, Kelley, and Hansom 1969; Forster 1972; Sternberg et al. 1977). Forster (1972) found that bottom sediments near Tongue Point and Harrington Point consisted of fine sand and "mud" prior to the December 1964 flood and of relatively coarse sand afterward. The change could have been due to removal of smaller-than-sand-sized particles from the bed, leaving the coarser material; erosion of top layers revealing a layer of coarser sediment; or covering of the bed with an additional layer of coarser sediment. Examination of radionuclide ratios led Forster to conclude that the postflood sediments were older (based on radionuclide concentration ratios) than those prior to the flood, suggesting that the latter two explanations are more likely to be correct than the first.

29. Ballard (1964) found that beach sands on Clatsop Spit became coarser in winter, whereas on the beaches north of the mouth the sands became finer in winter. He also reported that mineralogical analysis of the beach sands identifies them as being supplied by the Columbia River. He noted that the concentration of heavy minerals in beach sediments decreases rapidly with distance from the Columbia River mouth. It is not obvious whether supply of sediment or sorting was the cause of these differences.

30. Sand size sediments of the Columbia estuary consist predominantly of quartz and plagioclase feldspar with significant amounts of mica, magnetite, and black volcanic rock. Whetten, Kelley, and Hansom (1969) reported that downstream from Bonneville reservoir the relative quantities of quartz and potassium feldspars decrease in relation to plagioclase feldspar and

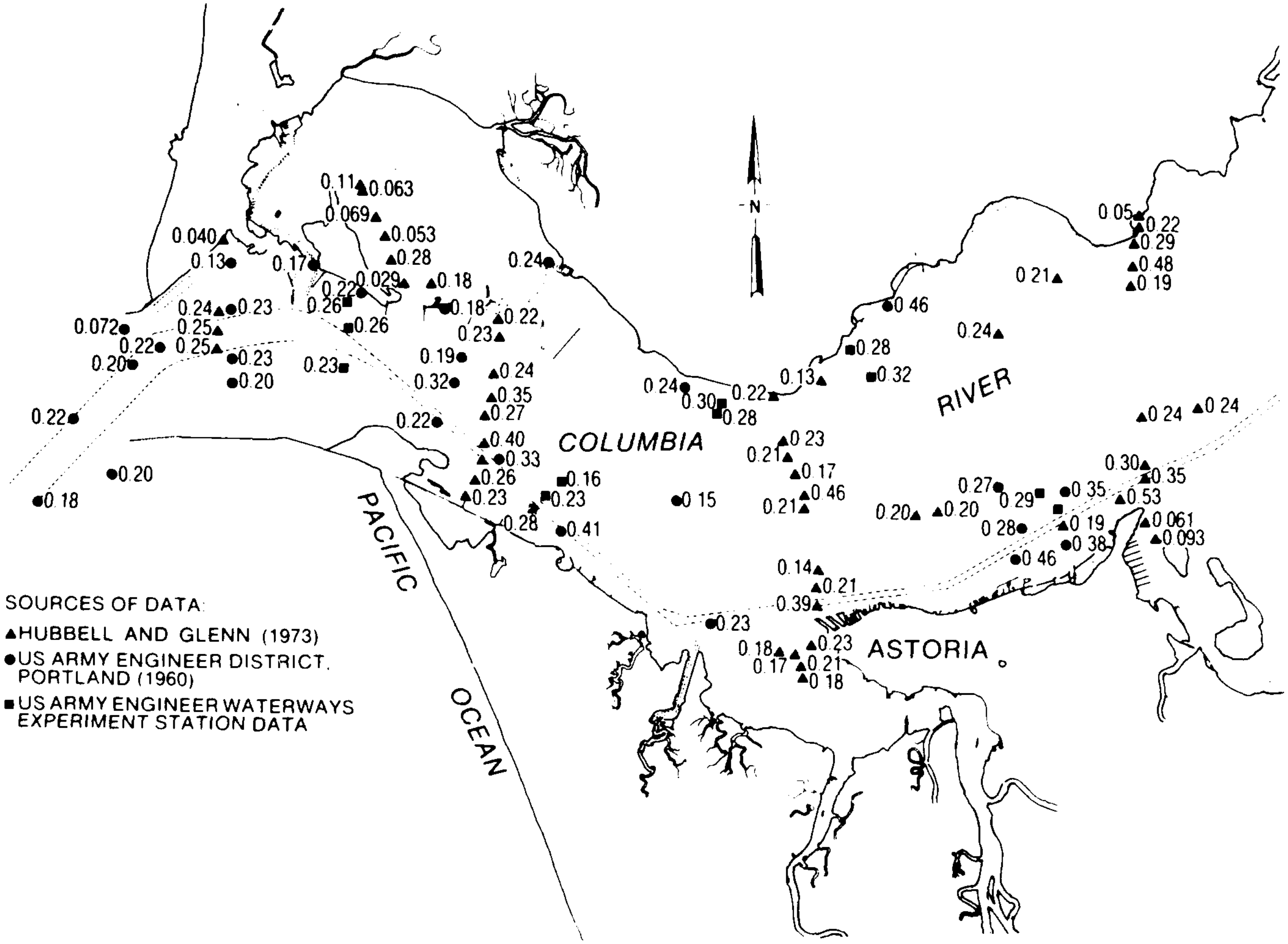


Figure 3. Bed sediment median grain sizes, lower estuary

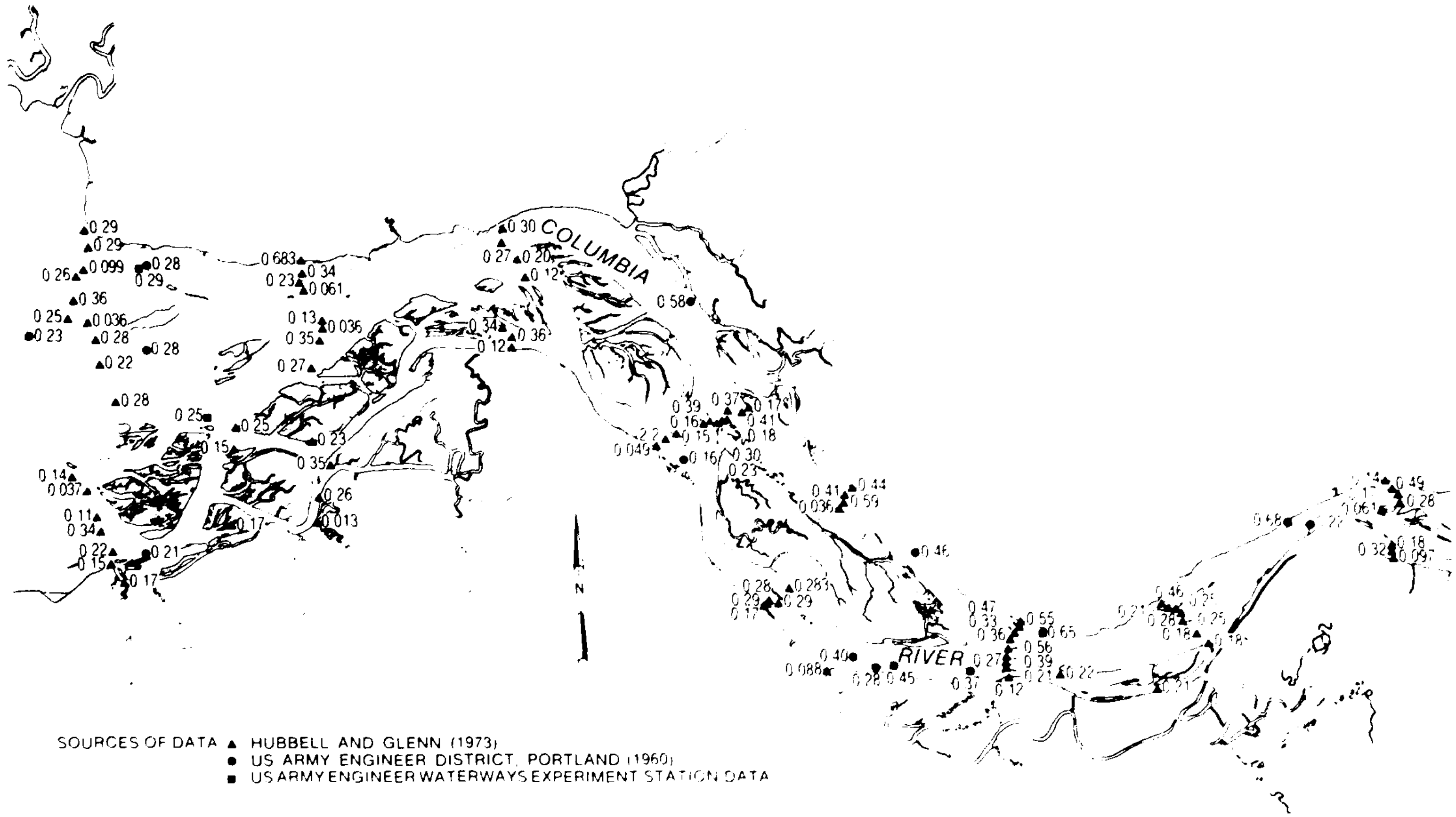


Figure 4. Bed sediment median grain sizes, upper estuary

volcanic lithic fragments. They attributed the changes in constituent magnitudes to the lower tributaries supplying more volcanic-derived particles than those upstream. Concentration of magnetite occurs in some locations, notably the south side of Sand Island.

31. Silts in the estuary are also predominantly quartz, feldspar, and mica. Clay particles are mostly montmorillonite, chlorite, and kaolinite (Forster 1972).

Sediment transport

32. Sand and some silt are transported near the estuary bottom, forming large sand waves that propagate in the direction of net transport. According to Whetten and Fullam (1967), surveys in July 1966 showed that 86 percent of the bottom between Longview (CRM 66) and Astoria (CRM 14) was covered with sand waves varying from 3 to 10 ft high and 60 to 400 ft long. During one survey, sand waves were observed (Hubbell, Glenn, and Stevens 1971) at CRM 7 in the navigation channel and on the adjacent gentle side slopes but not on the nearby shallow flats. Lockett (1959) reported sand waves in the entrance channel 5 to 10 ft high in April and November 1957.

33. Examination of sand wave profiles shows the direction of sediment transport since the forward face of the waves is steeper than the upstream face that sediment is climbing. This feature has been used to deduce some sediment transport patterns in the estuary. The technique has been applied by analysis of side scan sonar records by Hubbell, Glenn, and Stevens (1971) for a period in September 1968 when river discharge was about 120,000 cfs.

34. Tests using bed drifters (Morse, Gross, and Barnes 1968) during June-October 1968 showed that drifters released outside the estuary near the mouth and inside tend to move either inside to the Clatsop Spit shoal or onto the beaches north of the mouth. Studies at offshore disposal sites B and G (Figure 2) have shown (Sternberg et al. 1977) that in that area of water depths greater than 95 ft, sediment transport rates are rather low, with little or no transport occurring during the summer. They estimated that a small amount of sediment (830 yd^3/yr) was transported northward by storm wind-induced currents in 1975. In about 1958, NPP conducted a current survey in disposal area B which showed bottom currents directed predominantly toward the entrance channel. Combined with the experience from disposal operations and subsequent channel shoaling, it was shown that large quantities of material moved quickly from the disposal area back into the channel.

35. There are few estimates of sediment transport rates in the estuary. Estimates have been based on the usual assumption that unmeasured transport constitutes about 10 to 25 percent of the total sediment load, but the relative clarity of the water may make that a poor assumption for the Columbia. Hickson (1961) estimated that a total suspended load of 8 million cu yd/yr passed through the mouth to the sea. He estimated an unmeasured load transport rate of 3.5 million cu yd/yr. Other estimates are of the same order of magnitude.

36. At the mouth, sediment transport is modified by wave-induced littoral transport. Transport rates have not been estimated, but accretion on both sides of the entrance and the wave climate suggest substantial littoral transport rates in both directions. Ballard (1964) computed longshore wave energy flux near the Columbia using the hindcast data of National Marine Consultants and found that the combined sea and swell flux was northward during January to March, October, and December; southward during May to August and November; and nearly neutral in April and September. Ballard's analysis showed that seas had an overall northward predominance while swell had a southward predominance. Lockett (1965) cited beach erosion to the south of the mouth and deposition to the north following jetty construction and other observations to conclude that there is substantial littoral transport in both directions, but that net transport is to the south.

37. Lockett (1963) analyzed hydrographic surveys of the shorelines north and south of the entrance for 1877 and 1926, the period in which the jetties were built. He found that during those 50 years, accretion to the north of the mouth averaged 3.7 million cu yd/yr while erosion to the south averaged 7.5 million cu yd/yr. During the subsequent 32 years, accretion and erosion in each of those respective areas averaged about 4.1 million cu yd/yr. After an initial deepening following each episode of jetty building, progressive infilling of the entrance channel continued during these periods. This suggests a net littoral transport of 4 to 8 million cu yd/yr at the mouth of the Columbia. The gross amount moving past the entrance (after completion of infilling behind the jetties) is probably substantially more than this.

38. Measured suspended sediment concentrations are usually low in the river and estuary. Hickson (1965), using a 1922 average measured suspended sediment concentration of 130 ppm on the Columbia just below the Willamette,

estimated an average annual suspended sediment discharge of 15.5 × 10^6 cu yd/yr. Suspended sediment concentrations measured at CRM 13 (Hubbell, Glenn, and Stevens 1971) in September 1969 (231,000 cfs) showed an average depth-integrated concentration of about 20 ppm. Measurements in May 1970 (468,000 cfs) at the same location resulted in an average depth-integrated concentration of 20 to 30 ppm. Analysis of sediment sizes in suspension showed that size concentrations reached a maximum of less than 10 percent of the total during peak flow velocities and were less than 1 percent much of the time. Silt size particle concentrations ranged from about 50 to 90 percent of the total and clay sizes made up from 10 to 50 percent. Conomos and Gross (1968) found that suspended sediment samples in the river predominantly had modal diameters in the silt size range.

Sedimentation patterns

39. Gross (1972) used Lockett's (1959) data and approximate sediment discharges to estimate that 35 percent of the river's sediment load is deposited in the lower estuary and 45 percent is deposited outside the entrance within 10 km of the mouth. Using radionuclide concentrations to compute both sediment supply and accumulation, Hubbell and Glenn (1973) estimated that 30 percent of fine sediments entering the estuary from upstream are retained. Hickson's measurements (paragraphs 35 and 38) imply a higher retention rate.

40. A study of depth changes in the estuary during the 90-year period between 1868 and 1958 by NPP showed significant filling of the estuary, particularly downstream from Astoria. Lockett (1963) computed the accumulated sediment volume between Sand Island and Tongue Point to be 77 million cu yd--an average depth change of 3 ft over the entire area. The accumulation pattern was not uniform. The central portion of the estuary became considerably shallower in the cross section near Astoria, whereas the southern channel depths were not appreciably altered.

41. Forster (1972) used 1963 measurements of relative radionuclide concentrations to deduce zones of recent deposition in the estuary. In general, the marginal areas demonstrated recent deposition, as did a large mid-estuary zone between Tongue Point and Harrington Point.

42. It has been suggested that construction of upstream dams would reduce the amount of sediment delivered to the estuary, but surveys of the upstream reservoirs (Whetten, Kelley, and Hansom 1969) have not shown a significant amount of year-to-year sediment accumulation. Sediments deposited

during the fall and winter appear to be flushed through the reservoirs during the spring freshet. In Bonneville, a relict sand bed is apparently being eroded and supplying additional sand to the lower river.

43. Outside the mouth, the river's sediment deposition lobe is skewed to the northwest and is growing in that direction. Studies of nearshore bathymetry for intervals from 1877 to 1977 show net erosion south of the mouth and net deposition to the north (Lockett 1963 and 1967, Sternberg et al. 1977). Sternberg et al. (1977) reported that annual depth changes are the same or less than sounding accuracy but that intervals greater than 3 years show the patterns cited above.

44. Shoaling patterns are best defined in the Federal navigation channel through the estuary and associated dredged material disposal sites. Many of these sites are surveyed frequently by the Corps of Engineers and maintenance dredging volumes are well documented. Most of the navigation channel shoaling occurs during the spring, but Lockett (1959) noted no other consistent correlation between shoaling and riverflow other than a trend toward entrance channel scouring during a rising river and shoaling during a falling or stationary river discharge.

Sources of Information

45. During the course of the pilot study and the early stages of implementation, an extensive search of the scientific literature was performed to locate and acquire published data from the Columbia. Even though the search was limited to data on the physical characteristics of the estuary, it resulted in a rather lengthy bibliography. Accessing desired information in such a large body of literature proved to be difficult, so a keyword index was compiled for the bibliography. In the hope that the bibliography and index will prove to be of continued use, they have been included with this report as Appendix A.

Field Surveys

46. Several field surveys were performed in 1977 and 1978 specifically to provide prototype data for the model verification reported herein. Water-surface elevations, current velocities, salinities, suspended sediments, and

water temperature were measured. Some of the data are presented in PART V: VERIFICATION, and details of the data collection program and the data are described in a separate report (McAnally and Donnell, in preparation).

PART III: MODELING METHODS

Hybrid Modeling

47. Solutions to coastal hydraulics problems are principally obtained by use of the four primary methods--field observations, analytical solutions, numerical models, and physical models. Any of these four may be the best single approach for solving a particular problem. Choosing between them requires knowledge of the phenomena that are important to the problem and an understanding of the strengths and weaknesses of the solution methods.

Field observations

48. Field (prototype) data collection and analysis serve both as an important aspect of the other solution methods and as an independent method. Alone, field data show the estuary as it behaved under a certain set of conditions prior to and at the time of measurement. By skillful scheduling of data collection, careful analysis, and luck, one can obtain estimates of the separate effects of tides, river discharge, wind, etc. Field data can reveal problem areas and define the magnitude of problems and can, to a limited extent, be used to estimate the estuary's response to different conditions of tide and river discharge. They can also be used in an attempt to identify changes caused by a modification to the estuary. Field data are an indispensable element in verification of numerical and physical models; they are used by the modeler to adjust his model and show that model results are reliable.

49. Obtaining sufficient temporal and spatial data coverage in the field is a formidable and expensive task; therefore available field data are often too sparse to describe an estuary in any but the most general terms. Those not intimately familiar with data collection and analysis often overestimate the accuracy and reliability of the data.

Analytical solution methods

50. Analytical solutions are recognized as a separate solution method, but they must be carefully defined in order to distinguish them from numerical models. Analytical solutions are those in which answers are obtained by use of mathematical expressions. These expressions or equations describe physical phenomena in mathematical terms and thus may be considered to be mathematical models of physical reality. For example, Manning's equation is a simple analytical model of the complex process of energy losses in open-channel flows.

A more rigorous and complete analytical model of the losses is included in the turbulent version of the Navier-Stokes equations, the Reynolds equations.

51. Analytical models usually combine complex, poorly understood phenomena into coefficients that are determined empirically. Manning's roughness coefficient, for instance, combines the various effects of energy dissipation into a single parameter. The degree of simplification of the analytical model dictates how it is solved. For example, Manning's equation can be solved directly, whereas the Reynolds equations must be simplified and solved by numerical methods.

52. If an analytical model can be solved by substituting values of the independent variables into the equation (a closed form solution), then the solution method is also analytical. The calculation may be performed by hand or by a computer, but the solution is still an analytical one.

53. The analytical solution method had advantages of speed and simplicity but it cannot provide many details. In estuaries, analytical solutions can be used for gross representations of tidal propagation and average cross-sectional velocities in simple geometries. Details of flow cannot be predicted. The usefulness of analytical solutions declines with increasing complexity of geometry or increasing detail of results desired.

Numerical modeling

54. Numerical modeling employs special computational methods, such as iteration and approximation, to solve mathematical expressions that do not have closed form solutions. A numerical model thus applies numerical (computational) analysis to solve mathematical expressions that describe the physical phenomena. The distinction between analytical solutions obtained by computer calculations and numerical modeling solutions may become blurred, but the distinction is a valid one that should be maintained. In this report, the computer programs used to solve the governing equations are referred to as generalized computer programs or codes. When the codes are combined with a geometric mesh (grid) and specified parameters representing a particular estuary, the combination is called a model.

55. Numerical models used in coastal hydraulic problems are of two principal types--finite difference and finite element. The finite difference method (FDM) approximates derivatives by differences in the value of variables over finite intervals of space and time. This requires discretization of space and time into regular grids of computation points. Finite difference

methods have been in widespread use for unsteady flow problems for about 15 years, whereas the finite element method (FEM) has only been widely applied to open-channel flow problems in the last 5 to 10 years. The latter method employs piecewise approximations of mathematical expressions over a number of discrete elements. The assemblage of piecewise approximations is solved as a set of simultaneous equations to provide answers at points in space (nodes) and time.

56. Numerical models are classified by the number of spatial dimensions over which variables are permitted to change. Thus in a one-dimensional flow model, currents are averaged over two dimensions (usually width and depth) and vary only in one direction (usually longitudinally). Two-dimensional models average variables over one spatial dimension, either over depth (a horizontal model) or width (a vertical model). Three-dimensional models solve equations accounting for variation of the variables in all three spatial dimensions.

57. Numerical modeling provides much more detailed results than analytical methods and may be substantially more accurate, but it does so at the expense of time and money. Models of sufficient detail may require very large computers to solve the large systems of equations and store results. Once a numerical model has been formulated and verified for a given area, it can quickly provide results for different conditions. Numerical models are capable of simulating some processes that cannot be handled in any other way. However, present models are limited by the number of dimensions and degree of resolution that are practical on today's computers. They are also limited by the modeler's ability to provide and accurately solve mathematical expressions that truly represent the physical processes being modeled. For example, at this time, available three-dimensional numerical hydrodynamic models produce results inferior to well-designed estuarine physical models.

Physical models

58. Physical scale models have been used for many years to solve coastal hydraulic problems. Careful observance of appropriate scaling requirements permits the physical modeler to obtain reliable solutions to problems that often can be solved no other way. Physical hydraulic models of estuaries can reproduce tides and other long waves, some aspects of short-period wind waves, longshore currents, freshwater flows, pollutant discharges, some aspects of sedimentation, and three-dimensional variations in currents, salinity, density, and pollutant concentration. Present practice does not

include simulation of water-surface setup and currents due to wind. Applicability of model laws and choice of model scales are dependent on which of these phenomena are of interest. Conflicts in similitude requirements for the various phenomena usually force the modeler to neglect similitude of some phenomena in order to more accurately reproduce the dominant processes of the situation. For example, correct modeling of tides and currents often requires that a model have different scales for vertical and horizontal lengths. This geometric distortion permits accurate reproduction of estuarine flows and is a common and acceptable practice, but it does not permit optimum modeling of short-period waves, which requires an undistorted-scale model for simultaneous reproduction of refraction and diffraction.

Hybrid method

59. The preceding paragraphs have described the four principal solution methods and some of their advantages and disadvantages. In practice, two or more methods are used jointly, with each method being applied to that portion of the problem for which it is best suited. For example, field data are usually used to define the most important processes and verify a model that predicts hydrodynamic conditions in an estuary. Combining two or more methods in simple ways has been common practice for many years. Combining physical modeling and numerical modeling to provide results not possible any other way is termed a hybrid solution method; combining them in a closely coupled fashion that permits feedback between the models is termed an integrated hybrid solution.

60. Judicious selection of solution methods in a hybrid approach can greatly improve accuracy and detail of the results. By devising means to combine results from several methods, the modeler can include effects of many phenomena that previously were neglected or poorly modeled. Examples of processes that are good candidates for hybrid modeling are (a) sediment transport and flow hydrodynamics or (b) tidal flows and short-period waves. In the first case, hydrodynamics drives the sediment transport process and by carefully designing the study, the feedback from bed change to hydrodynamics is minimal. In the second case, the interaction of the two processes is often dominated by one or the other such that they can be analyzed as independent events and the results combined. Processes that have a strong feedback loop, such as the hydrodynamics of freshwater-saltwater interaction, are not suitable for the hybrid approach and consequently should be analyzed together.

At present, the inadequacy of three-dimensional computational models requires that physical models be used for such studies.

The Columbia River Hybrid Modeling System

61. The hybrid solution method is being used to provide solutions to a number of Corps of Engineers problems in the Columbia River estuary. The Columbia study technique is innovative in that a number of solution methods are being applied in an integrated approach using the most advanced modeling and analysis techniques available to coastal engineers.

62. The keystone of the Columbia hybrid method studies was the Corps' existing physical hydraulic model of the estuary. The physical model is complemented by a variety of field, analytical, and numerical methods to provide a rigorous hybrid solution method that is briefly described in the following paragraphs. In the following, the term "the method" is understood to mean the specific collection of techniques that is being applied to the Columbia.

Organization of the hybrid method

63. Figure 5 shows the general sequence of steps performed in applying the hybrid solution to the Columbia River mouth studies. The following paragraphs describe the operations involved in general application of the method. These procedures may vary somewhat for separate studies.

64. Eighteen utility codes were used in the method to process data as it passed between models. Major codes included CODE1, an interactive program that solicited physical model input data from a keyboard operator and wrote them to formatted disc files for further manipulation; CODE24, which read the physical model data files, checked the data for reasonableness, converted velocities to depth-integrated flows, and wrote a file of boundary condition updates for use in the hydrodynamic model RMA-2V; ENGMET, which converted hydrodynamic data to metric units, interpolated them in time, and prepared the data for input to the sediment transport model STUDH; and GET, which accessed STUDH output tapes, extracted bed change data, and wrote an output file containing information needed for assembling several events into a 1-year simulation.

Step 1: For a given problem

65. Each problem was tested for existing conditions (base test) and one or more plans that represented potential changes in estuary configuration

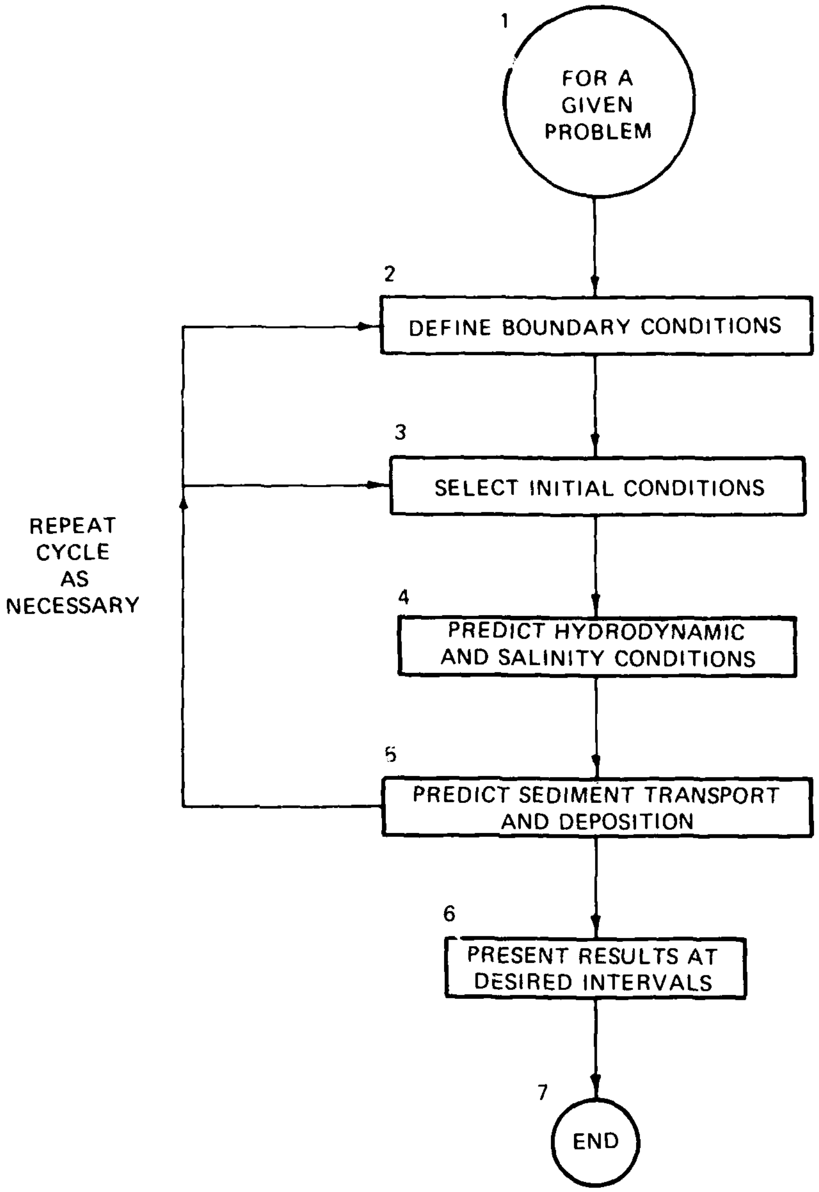


Figure 5. Steps in the hybrid solution process

(channel or structure changes). Results of each plan were compared with base test results.

<u>Step 2: Define boundary conditions</u>

66. Riverflow was defined at the upstream boundary of the physical model by adding representative tributary discharges to flows at The Dalles. The time-varying discharge was then schematized into a number of constant

flow periods to represent a typical hydrograph.

67. A representative tide range and a constant source salinity were defined for the physical model ocean boundary.

68. Representative (in terms of contribution to sediment transport), singular wave heights, periods, and directions over the immediate offshore area were computed using daily wave hindcasts by the U. S. Navy Fleet Numerical Weather Center (FNWC).

69. Upstream sediment supply was computed by means of calculated current velocities and the Ackers-White (1973) analytical method.

70. All boundary conditions were defined in separate operations and stored in data files. During each pass through the method's steps (Figure 5), desired boundary condition combinations and sequences were extracted.

Step 3: Select initial conditions

71. Initial conditions (water levels, salinities, currents, sediment concentration, and bed elevation) to be used were specified, and the WES-LaGarde data management system extracted and schematized previously digitized bed elevations over the estuary at the beginning of the solution cycle.

Step 4: Define hydrodynamic and salinity conditions

72. Required river discharge was introduced in the upper end of the physical model and the required tide and constant source salinity were generated at the ocean boundary of the physical model. Water-surface elevations and three-dimensional current structure and salinities were measured on a coarse grid over the area of interest in the physical model. Current and elevation data were then interpolated to the fine grid required by the numerical sediment model by use of the numerical hydrodynamic model RMA-2V. Data collection points in the physical model corresponded exactly with computation points in the numerical models.

73. Propagation, refraction, and diffraction of ocean wind waves approaching the entrance were modeled using a version of Resio and Vincent's (1977) modification of Barnett's spectral numerical wave model for the area of interest. Wave heights were converted to near-bed orbital velocities and amplitudes and were interpolated to the grid required by sediment model.

74. Longshore currents in the surf zone were predicted by the analytical technique of Longuet-Higgins (U. S. Army CERC 1977) using wave-refraction results to describe representative wave conditions in the surf zone. Longshore

currents were linearly superposed on tidal currents predicted by the physical and numerical models.

75. All hydrodynamic results were written to computer files for use by the sediment model.

Step 5: Predict sediment transport, deposition, and erosion

76. Sediment transport, deposition, and erosion were modeled by application of the numerical model STUDH using hydrodynamic data generated by Step 4. Depth changes were monitored and computations halted when changes became large enough to change hydrodynamic response of the system. Real-time periods of up to a few days were modeled and then deposition and erosion rates were extrapolated until the period to be modeled was completed or until new hydrodynamics and transport computations were required by depth changes. Step 6 produced graphic and tabular displays of results as shown in PART V: VERIFICATION.

Repeat cycle as necessary

77. When depth changes required new hydrodynamic results, the process returned to initial conditions (Step 3) to update bathymetry and pass through an abbreviated hydrodynamic step (unit discharge was assumed constant and velocities were recomputed) again before resuming sediment modeling. When a period of modeling was complete for a given combination of hydrodynamic events, the process returned to the boundary conditions (Step 2) for the next period to be modeled.

Description of the Models

Physical model

78. The Columbia River estuary model reproduces approximately 350 square miles of the prototype area, including the Columbia River to mile 52; the Pacific Ocean from 9 miles north of the north jetty to 6 miles south of the south jetty and offshore well beyond the 120-ft contour; Youngs, Baker, and Grays Bays; Youngs, Lewis and Clark, Grays, and Deep Rivers; and the extensive system of sloughs and other tidal tributaries that affect tidal action throughout the model area. The limits of the area reproduced are shown in Figure 2.

79. The model was constructed to linear scale ratios, model to

prototype, of 1:500 horizontally and 1:100 vertically. From these basic ratios, the following scale relations were computed by the Froudian relations: slope 5:1, velocity 1:10, time 1:50, discharge 1:500,000, and volume 1:25,000,000. The salinity ratio for the model was 1:1. One prototype tidal cycle (diurnal tide) of 24 hr and 50 min was reproduced in the model in 29 min 48.5 sec. Lambert grid coordinates were used for horizontal control, and mllw, the Columbia River datum, and the National Geodetic Vertical Datum (NGVD - 1947 adjusted) were used for vertical control. The model was approximately 500 ft long and 130 ft wide at its widest point and covered an area of about 48,000 sq ft. It was completely enclosed to protect it and its appurtenances from the weather and to permit uninterrupted operation.

80. When constructed in 1961, the original model was molded to conform to prototype hydrographic conditions that existed in 1959. The navigation channel was molded in removable blocks so that desired alterations could readily be made. For studies reported herein, the model was altered from the original 1959 hydrographic conditions. The ocean, entrance area, Baker Bay, and Columbia River up to about CRM 9.5 were remolded to conform to 1976 hydrographic conditions. The remainder of the model was essentially left intact as originally molded. However, areas and islands such as Miller Sands, which had changed significantly since 1959, were remolded to conform to most recent surveys.

81. The model was equipped with the necessary appurtenances to reproduce and measure all pertinent phenomena such as tidal elevations, saltwater intrusion, current velocities, freshwater inflow, dispersion characteristics, and shoaling distribution and patterns. Apparatus used in connection with the reproduction and measurement of these phenomena included a primary tide generator and recorder, secondary tide generator, tide gages, salinity meters, salinity samplers, chemical titration equipment, current velocity meters, freshwater inflow measuring devices, skimming and measuring weirs, and shoaling material injection and recovery apparatus. This equipment is described in detail by Herrmann (1968).

Finite element modeling

82. Two of the numerical models used in this effort employ the finite element method to solve the governing equations. To help those who are unfamiliar with the method to better understand this report, a brief description of the method is given here. For a more thorough treatment, see Zienkiewicz (1971) or Desai (1979).

83. The finite element method approximates a solution to equations by dividing the area of interest into smaller subareas, which are called elements. The dependent variables (e.g., water-surface elevations and sediment concentrations) are approximated over each element by continuous functions which interpolate in terms of unknown point (node) values of the variables. An error, defined as the deviation of the approximation solution from the correct solution, is minimized. Then, when boundary conditions are imposed, a set of solvable simultaneous equations are created. The solution is smooth and continuous over the area of interest.

84. In one-dimensional problems, elements are line segments. In two-dimensional problems, the elements are polygons, usually either triangles or quadrilaterals. Nodes are located on the edges of elements and occasionally inside the elements. The interpolating functions may be linear or higher order polynomials. Figure 6 illustrates a quadrilateral element with eight nodes and a linear solution surface.

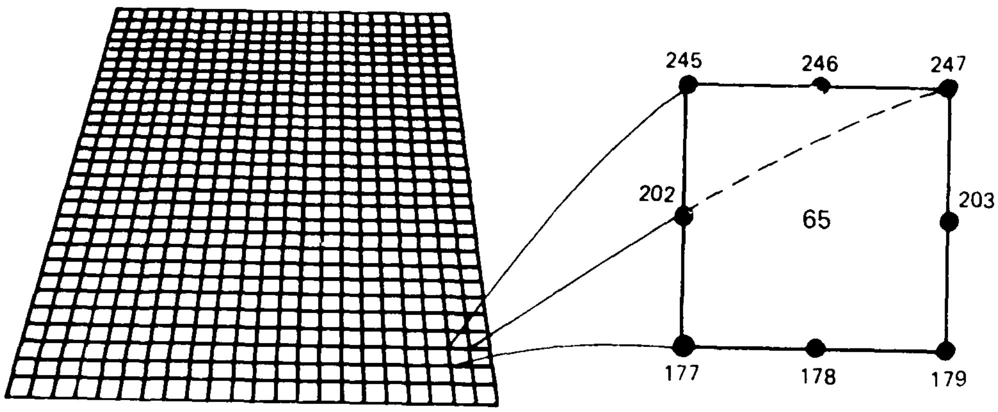
85. Most water resource applications of the finite element method use the Galerkin method of weighted residuals to minimize error. In this method the residual, the total error between the approximate and correct solutions, is weighted by a function that is identical with the interpolating function and then minimized. Minimization results in a set of simultaneous equations in terms of nodal values of the dependent variable (e.g., water-surface elevations or sediment concentration). Time-dependent problems can have the time portion solved by the finite element method, but it is generally more efficient to express derivatives with respect to time in finite difference form.

RMA-2V

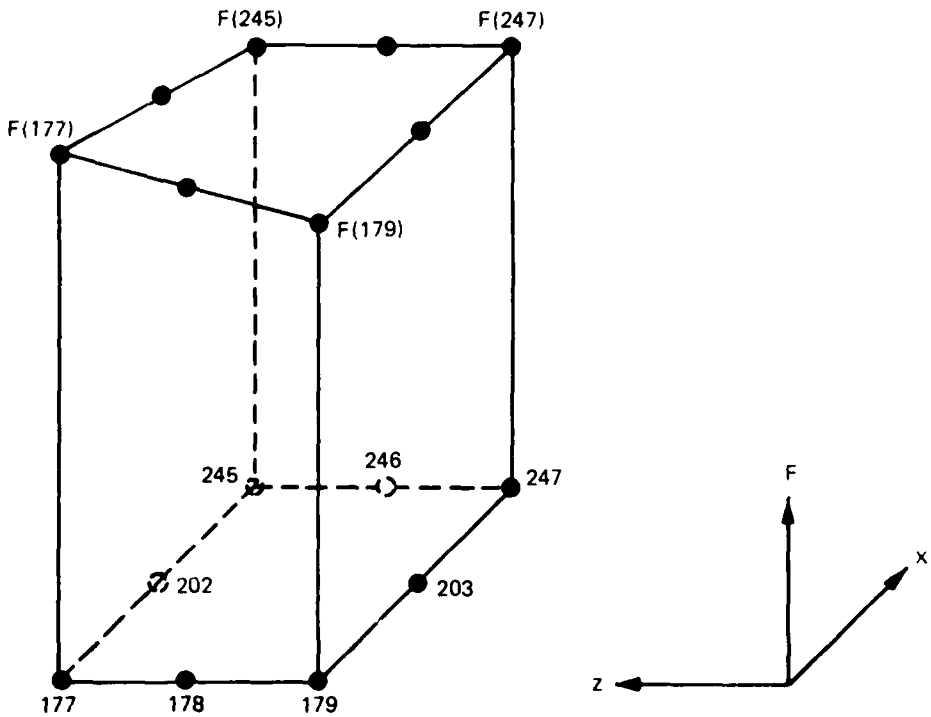
86. The generalized computer program RMA-2V solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The form of the solved equations is

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} + g\frac{\partial h}{\partial x} + \frac{\partial a_o}{\partial x} - \frac{\varepsilon_{xx}}{\rho}\frac{\partial^2 u}{\partial x^2} - \frac{\varepsilon_{xz}}{\rho}\frac{\partial^2 u}{\partial z^2}$$

$$- 2\omega w \sin\phi + \frac{gu}{C^2 h}\left(u^2 + w^2\right)^{1/2} - \frac{\xi}{h}V_a^2 \cos\psi = 0 \qquad (1)$$



a. Eight nodes define each element



b. Linear interpolation function

Figure 6. Two-dimensional finite element mesh

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} + g\frac{\partial h}{\partial z} + g\frac{\partial a_o}{\partial z} - \frac{\varepsilon_{zx}}{\rho}\frac{\partial^2 w}{\partial x^2} - \frac{\varepsilon_{zz}}{\rho}\frac{\partial^2 w}{\partial z^2} + 2\omega u \sin\phi$$

$$+ \frac{gw}{C^2 h}\left(u^2 + w^2\right)^{1/2} - \frac{\xi}{h} V_a \sin\psi = 0 \qquad (2)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial z}(wh) = 0 \qquad (3)$$

where

u = horizontal flow velocity in the x direction*

t = time

x = distance in the x direction (longitudinal)

w = horizontal flow velocity in the z direction

z = distance in the z direction (lateral)

g = acceleration due to gravity

h = water depth

a_o = elevation of the bottom

ε_{xx} = normal turbulent exchange coefficient in the x direction

ρ = fluid density

ε_{xz} = tangential turbulent exchange coefficient in the x direction

ω = angular rate of earth's rotation

ϕ = latitude

C = Chezy roughness coefficient

ξ = coefficient relating wind speed to stress exerted on the fluid

V_a = wind velocity

ψ = angle between wind direction and x axis

ε_{zx} = tangential turbulent exchange coefficient in the z direction

ε_{zz} = normal turbulent exchange coefficient in the z direction

87. The Chezy roughness formulation of the original code was modified in the input portion so that Manning's n roughness coefficients are specified by nodes. A short input routine computes elemental Chezy coefficients from input Manning's n values and initial water depth.

88. Equations 1, 2, and 3 are solved by the finite element method using

* For convenience, symbols are listed and defined in the Notation (Appendix C).

Galerkin weighted residuals. The elements may be either quadrilaterals or triangles and may have curved (parabolic) sides. The shape functions are quadratic for flow and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form

$$f(t) = f(o) + at + bt^c \qquad t_o \leq t < t_1 \tag{4}$$

which is differentiated with respect to time, and cast in finite difference form. Letters a, b, and c are constants. It has been found by experiment that the best value for c is 1.5 (Norton and King 1977).

89. The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson iteration. The computer code executes the solution by means of a front-type solver that assembles a portion of the matrix and solves it before assembling the next portion of the matrix. The front solver's efficiency is largely independent of bandwidth and thus does not require as much care in formation of the computational mesh as do traditional solvers.

90. The code RMA-2V is based on the earlier version RMA-2 (Norton and King 1977) but differs from it in several ways. First, it is formulated in terms of velocity (v) instead of unit discharge (vh), which improves some aspects of the code's behavior; it permits drying and wetting of areas within the grid; and it permits specification of turbulent exchange coefficients in directions other than along the x- and z-axes.

Wave model

91. A wave model provided estimates of wave conditions over the entrance area by refracting and diffracting deepwater waves shoreward and through the entrance to the upper limits of the finite element mesh used for hydrodynamics and sedimentation. The computer code was developed by Resio and Vincent (1977) of WES.

92. The model considered waves as a spectrum of energies, both in direction and frequency, propagating components shoreward in the first computational phase, then diffusing the components alongshore in the second phase. This two-phase computational procedure was stepped across a uniform grid as a front with an explicit finite difference scheme. The model did not take into

consideration wave-current interactions, reflection, or frictional losses.

93. The model was supplied with the deepwater wave height, period, and direction along with the limits of the uniform geometric grid, cell size, and water depths at each point of the grid. The average energy of this wave was computed as

$$E = \left(\frac{H}{4}\right)^2 \rho g \tag{5}$$

where

E = energy

H = wave height

ρ = water density

g = acceleration due to gravity

The computed energy was assumed to represent a spectrum of waves with a directional energy spectrum represented by a cosine to the fourth power and a frequency spectrum as described by Kitaigordskii (1962)

$$E_1(f) = \begin{cases} \dfrac{\alpha g^2 f^{-5}}{(2\pi)^4} \exp\left[1 - \left(\dfrac{f}{fm}\right)^4\right] & \text{for } f < fm \\ \\ \dfrac{\alpha g^2 f^{-5}}{(2\pi)^4} & \text{for } f \geq fm \end{cases} \tag{6}$$

where

α = Phillip's equilibrium coefficient ($\approx 7.4 \times 10^3$)

f = wave frequency

fm = maximum wave frequency

So the energy components were described by

$$E_2(f,\theta) = E_1(f)\phi(\theta - \theta_o) \tag{7}$$

where

θ = wave direction

θ_o = mean direction via ray tracing

and

$$\phi(\theta - \theta_o) = \frac{8}{3\pi} \cos^4 (\theta - \theta_o) \tag{8}$$

In order to fit this spectrum to the wave conditions given as input, the value of the coefficient α was solved for each computational run, with fm corresponding to the input wave period.

94. The model propagated each wave spectral component one row shoreward across the grid by simple ray tracing techniques with subsequent regrouping of energy into predetermined 22.5-deg wave direction windows. The diffractive effects were then included by applying a diffusion step in which the diffusion was proportional to the second derivative (alongshore direction) of the wave energy for each component.

95. The wave energy field produced by the model must be transformed to near-bottom wave orbital velocities and excursion lengths for input to the sediment model. Therefore, the wave spectrum was integrated at each grid location to determine the total wave energy and the wave height was computed

$$H = 4 \sqrt{\frac{E}{\rho g}} \tag{9}$$

From this wave height, the orbital excursion length near the bottom was computed by

$$A_o = \frac{H}{\left[\sinh\left(\frac{2\pi h}{L}\right)\right]} \tag{10}$$

where

h = water depth

L = wavelength

and the maximum orbital velocity was computed as

$$u_{om} = A_o \frac{\pi}{T} \tag{11}$$

where T is the wave period

96. The wavelength was computed by linear wave theory for the depth of water at each computational point based on the assumption that the wave period T , as input for deepwater conditions, remained unchanged.

STUDH

97. The generalized computer program STUDH solves t.. depth-integrated convection-dispersion equation in two horizontal dimensions for a single sediment constituent. The form of the solved equation is

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) + \alpha_1 C + \alpha_2 \tag{12}$$

where

C = concentration of sediment

u = velocity in x direction

w = velocity in z direction

D_x = dispersion coefficient in x direction

D_z = dispersion coefficient in z direction

α_1 = coefficient of concentration dependent source/sink term

α_2 = coefficient of source/sink term

STUDH is related to the generalized computer program SEDIMENT II (Ariathurai, MacArthur, and Krone 1977) developed at the University of California, Davis, under the direction of R. B. Krone. STUDH is the product of joint efforts of WES personnel (under direction of W. A. Thomas) and R. Ariathurai, now a member of Resource Management Associates.

98. The source/sink terms in Equation 12 are computed in routines that treat the interaction of the flow and the bed. Separate sections of the code handle computations for clay bed and sand bed problems. In the tests described here, only sand beds were considered. The source/sink terms were evaluated by first computing a potential sand transport capacity for the specified flow conditions, comparing that capacity with the amount of sand actually being transported, and then eroding from or depositing to the bed at a rate that would approach the equilibrium value after sufficient elapsed time.

99. The potential sand transport capacity in these tests was computed by the method of Ackers and White (1973), which uses a transport power (work rate) approach. It has been shown to provide superior results for transport under steady-flow conditions (White, Milli, and Crabbe 1975) and for combined waves and currents (Swart 1976). WES flume tests have shown that the concept is valid for transport by estuarine currents.

100. The total load transport function of Ackers and White is based upon a dimensionless grain size

$$D_{gr} = D \left[\frac{g(s - 1)}{\nu^2}\right]^{1/3} \tag{13}$$

where

D = sediment particle diameter

g = acceleration due to gravity

s = specific gravity of the sediment

v = kinematic viscosity of the fluid

and a sediment mobility parameter

$$F_{gr} = \left[\frac{\tau^{n}\,\tau'^{\,1-n}}{\rho g\ D(s - 1)}\right]^{1/2} \tag{14}$$

where

τ = total boundary shear stress

τ' = boundary surface shear stress

n = a coefficient expressing the relative importance of bed-load and suspended-load transport, given in Equation 16

The surface shear stress is that part of the total shear stress which is due to the rough surface of the bed only, i.e. not including that part due to bed forms and geometry. It therefore corresponds to that shear stress that a plane bed would exert on the flow.

101. The total sediment transport is expressed as an effective concentration

$$G_p = C\left(\frac{F_{gr}}{A} - 1\right)^{m} \frac{sD}{h}\left(\sqrt{\frac{\rho}{\tau}}\,U\right)^{n} \tag{15}$$

where U is the average flow velocity, and for $1 < D_{gr} \le 60$

$$n = 1.00 - 0.56 \log D_{gr} \tag{16}$$

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{17}$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^{2} - 3.53 \tag{18}$$

$$m = \frac{9.66}{D_{gr}} + 1.34 \tag{19}$$

For $D_{gr} > 60$

$$n = 0.00 \tag{20}$$

$$A = 0.17 \tag{21}$$

$$C = 0.025 \tag{22}$$

$$m = 1.5 \tag{23}$$

102. Bed shear stresses for combined waves and currents are calculated by STUDH using the equation

$$\tau'_{wc} = \left(\frac{f_w u_{om} + f_c U}{u_{om} + U}\right) \frac{\rho}{2} \left(U + \frac{u_{om}}{2}\right)^2 \tag{24}$$

for surface shear stress (plane beds) and

$$\tau_{wc} = \frac{1}{2} f_c \rho u^2 + \frac{1}{4} f_w \rho u_{om}^2 \tag{25}$$

for total shear stress, where

f_w = shear stress coefficient for waves

f_c = shear stress coefficient for currents

U = current speed

u_{om} = maximum wave orbital velocity near the bed

ρ = density of water

Equations 24 and 25 are based on the work of Jonsson (1966), and Bijker and Swart (Swart 1976). Development of the equations is given by McAnally and Thomas (1981).

103. Using Equations 24 and 25 for shear stresses in the Ackers-White equations (Equations 13-23) results in a potential sediment concentration, G_p. This value is the depth-averaged concentration of sediment that will occur if an equilibrium transport rate is reached with a nonlimited supply of sediment. The rate of sediment deposition (or erosion) is then computed as

$$R = \frac{G_p - C}{t_c} \tag{26}$$

where

C = present sediment concentration

t_c = time constant

For deposition, the time constant is

$$t_c = \text{larger of} \begin{cases} \Delta t \\ \\ \dfrac{C_{Ld} h}{V_s} \end{cases} \tag{27}$$

and for erosion it is

$$t_c = \text{larger of} \begin{cases} \Delta t \\ \\ \dfrac{C_{Le} h}{U} \end{cases} \tag{28}$$

where

Δt = computational time-step

C_{Ld} = response time coefficient for deposition

h = water depth

V_s = sediment settling velocity

C_{Le} = response time coefficient for erosion

U = average current speed

104. Equation 12 is solved by the finite element method using Galerkin weighted residuals. Like RMA-2V, which uses the same general solution technique, elements are quadrilateral and may have parabolic sides. Shape functions are quadratic. Integration in space is Gaussian. Time-stepping is performed by a Crank-Nicholson approach with a weighting factor (theta) of 0.66. The solution is fully implicit and a front-type solver is used similar to that in RMA-2V.

PART IV: APPLICATION OF THE MODELS

Physical Model

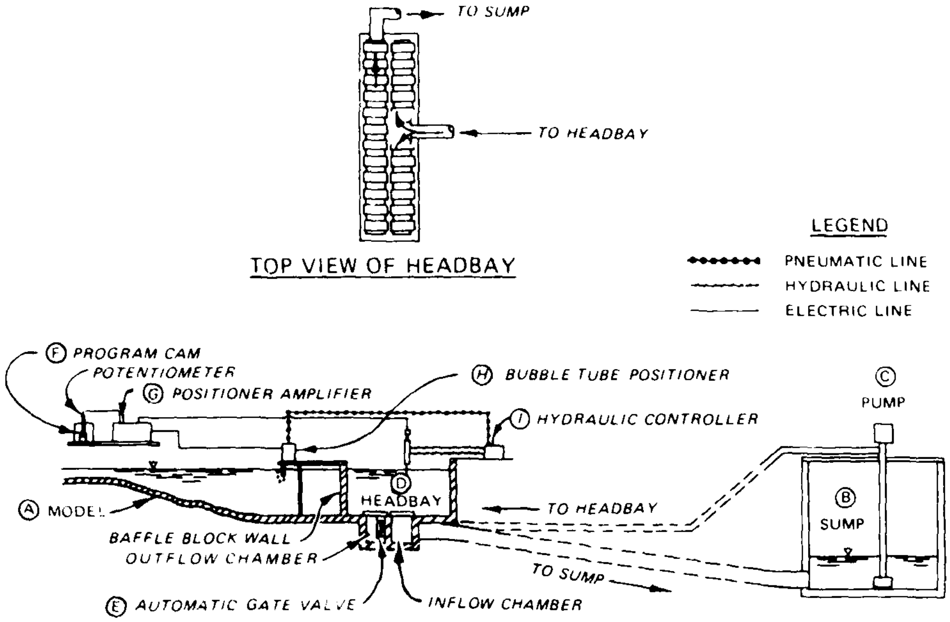
Operation

105. Prior to data collection of any type in the physical model, it was operated a number of cycles to establish stable hydrodynamic and salinity conditions. Achieving a stable condition was hastened by installing an impervious vertical-lift gate across the model immediately upstream of the Astoria Bridge. The model upstream from the gate was flooded with fresh water while the area downstream was flooded with salt water from the storage sump. As the gate was removed, tide, freshwater inflow, skimming weir, etc., operation was initiated. The tide generator system and its operation are shown in Figure 7.

106. The number of cycles required for stability varied, depending on the freshwater discharge and tide condition. All salinity tests reported herein were conducted with a freshwater discharge of 140,000 cfs introduced into the model at river mile 52. Fresh water was not introduced in the model at any other point. Normal stability time for this discharge required about 6 tidal cycles; however, to achieve the highest possible order of stability, the model was operated at least 12 tidal cycles prior to collection of water samples.

107. In order to keep the model and sump in balance, skimming weirs were operated in the ocean area to remove the exact volume of water that had been introduced at the freshwater source of the model. By the time the fresh water had passed through the model to the skimming weirs, it had mixed with the salt water. Therefore a diluted mixture was returned to the supply sump, resulting in a lowering of the desired salt concentration. In order to compensate for this dilution and maintain a constant salinity concentration in the supply sump, salt brine was continuously added. This was accomplished by passing water (usually from supply sump) over rock salt stored in a Lixator adjacent to the sump. The rate of brine introduced and sump salinity concentration were carefully monitored to ensure that a constant source of salinity concentration was maintained throughout the test period.

108. Information from the physical model was obtained in several forms. The following paragraphs briefly describe the types of data collected and the method used to record such information. The types of model data collected



OPERATION OF THE TIDE GENERATOR SYSTEM

The water surface in the model (A) is higher than in the sump (B). A pump (C) discharges a constant flow of water into one side of the chambered headbay (D). Gravity discharge from the model back to the sump is controlled by an automatic, rolling-gate valve (E). If the valve is opened so that more water leaves the model than is being pumped in, the water-surface elevation in the model is lowered. If the valve is partially closed so that less water leaves than is being pumped in, the water surface rises.

The desired tide is programmed by a radially eccentric cam (F). The mechanical signal generated by the cam is converted to an electrical signal by the positioner amplifier (G) and transmitted to the bubble tube positioner (H). The bubble tube positioner moves an air bubbler tube in the same direction that the water surface should go to produce the desired tide. The air pressure sensed by the bubble tube serves as input to one side of a hydraulic controller (I). The pressure difference (error in water-surface elevation) between the bubble tube pressure and a preset controller pressure is amplifed 50,000 times by the controller and is used to move the automatic gate valve (E) as necessary to obtain the correct water-surface elevation. An electronic feedback from the automatic gate valve through the positioner amplifier (G) moves the bubble tube positioner in the same direction as the valve, thus minimizing undesirable system oscillations.

The following describes the sequence of operations that would occur in the simple case of the tide controller raising the water-surface elevation from a steady-state condition.

1. The program cam (F) indicates that the water surface is to rise 1 in. A potentiometer converts this mechanical signal to a voltage and transmits it to the positioner amplifier (G).
2. The positioner amplifier amplifies the signal and transmits it to the bubble tube positioner (H), which rises 1 in.
3. The air pressure in the bubble tube is reduced by its decreased submergence.
4. The differential between the bubble tube pressure and a preset pressure is converted to hydraulic pressure and amplified by the hydraulic controller (I).
5. The amplified hydraulic pressure differential activates a hydraulic pressure cylinder atop the automatic gate valve (E), causing it to close slightly.
6. The downward movement of the gate valve is converted to an electrical signal by another potentiometer, and the signal is transmitted back to the positioner amplifier (G).
7. The positioner amplifier causes the bubble tube positioner to move down a small amount and thus slows down the rate of gate valve closure.
8. The system continues to respond to the changing water-surface elevation until the desired 1-in. rise is accomplished.

Figure 7. Schematic of tide control

were as follows: tidal elevations, current velocity and directions, salinity concentrations, surface current patterns, sediment tracer tests, and movies.

Tidal elevations

109. Both permanent and portable point gages graduated to 0.001 ft (0.1 ft prototype) were used to measure water-surface elevations at half-hour intervals throughout the tidal cycle.

Current velocity

110. Current speed measurements were obtained with miniature Price-type current meters. Each meter had five cups, constructed of a light plastic and 0.04 ft (4 ft prototype) in diameter, mounted on a horizontal wheel 0.08 ft (40 ft prototype) in diameter. The center of the cups was 0.05 ft (5 ft prototype) from the bottom of the frame. The meters were calibrated frequently and were capable of measuring speeds as low as 0.03 fps (0.3 fps prototype). Current directions were observed at the same location and intervals as were speeds using a very lightweight vane (Figure 8) which pivoted

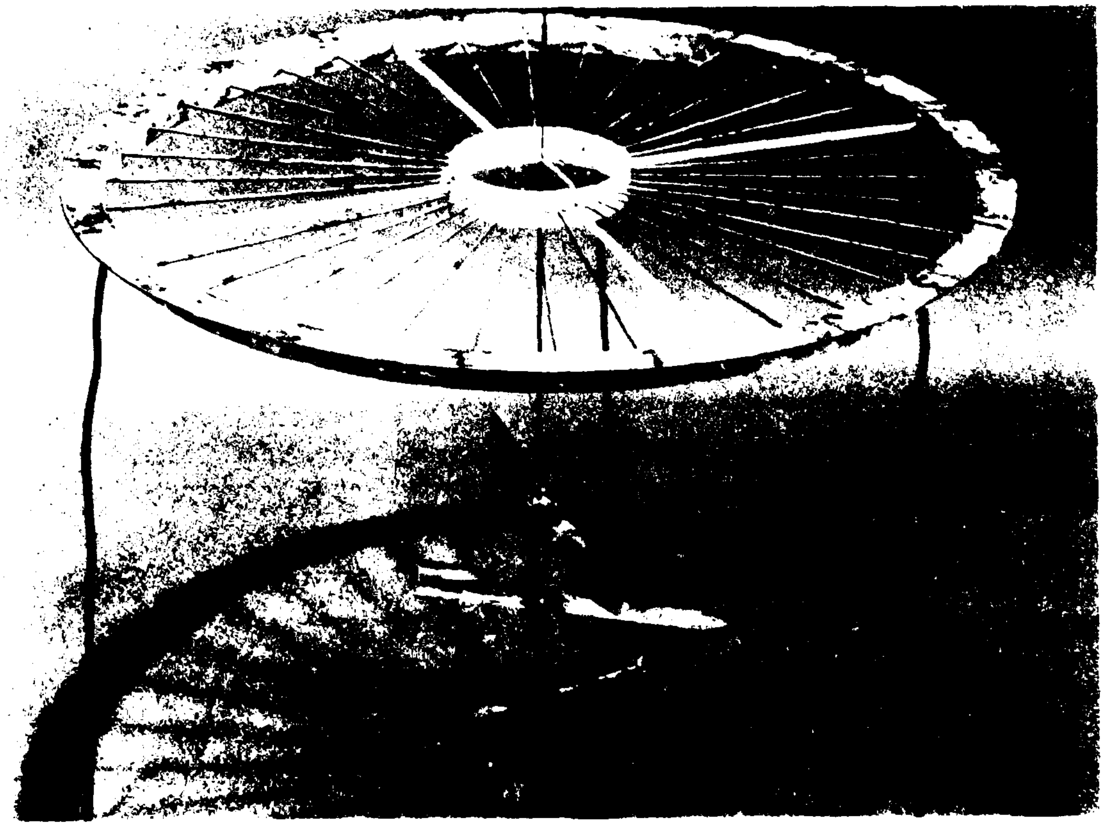


Figure 8. Current direction measuring apparatus

with the currents on a small diameter rod. Direction was read in tens of degrees from north.

Salinity measurements

111. Prior to collection of water samples for salinity concentration measurements, the model was operated to establish salinity stability. This procedure is discussed in detail in paragraphs 105-107. Water samples were drawn into collection vials by a vacuum apparatus and stored for later determination of salinity concentrations. The water samples were collected on the hour over a complete tidal cycle. All salinity concentrations for samples taken from the model were determined by use of conductivity cells specially built and calibrated for this purpose.

Surface current patterns

112. Current data for several tests conducted in the model were collected and recorded photographically. Surface current pattern photographs were used to construct composite mosaics with which to evaluate proposed channel realignments, effectiveness of groins, etc. The mosaics and/or individual photographs also provided a means for current velocity analysis, especially in areas too shallow for measurements with the velocity meter. The mosaics were prepared from time-exposure photographs of confetti floating on the water's surface. A bright light was flashed immediately prior to closing of camera lens, resulting in a bright spot near the end of each confetti streak, indicating the direction of flow. Current velocities were determined from the photographs by measuring the total length of the confetti streaks and comparing the lengths with the velocity scale presented in the mosaic or photograph. Photographs in most instances were taken at hourly (prototype) intervals throughout a complete tidal cycle (24.84 hr). Because of their size and number, the photographic mosaics are not included in this report, but copies are on file at WES and NPP.

Movies

113. Time-lapse movies were used to monitor movement of simulated dredged material that had been placed in proposed disposal areas over a period of several tidal cycles. On one occasion, movies were utilized to track the movement of a model of the dredge Biddle as it was moved by tidal and wave action after losing power and anchor.

Accuracy of measurements

114. Measurements of tidal elevations in the model were made with point

gages graduated to 0.001 ft, or 0.1 ft prototype. The limitations of the current velocity meters used in the model should be considered in making close comparisons between model and prototype velocity data. The center line of the meter cup was about 0.05 ft above the bottom of the frame; therefore, bottom velocity measurements in the model were actually obtained at a point 5.0 ft (prototype) above the bottom, instead of about 2.0 ft as in the prototype metering program. The model velocities were determined by counting the number of revolutions in a 10-sec interval (which represented a period of about 8 min in the prototype), as compared with about a 1-min observation in the prototype. The horizontal spread of the entire meter cup wheel was about 0.11 ft in the model, representing about 55 ft in the prototype, as compared with less than 1.0 ft for the prototype meter. Thus the distortion of area (model to prototype) results in comparison of prototype point velocities with model mean velocities for a much larger area. The same is true for the vertical area, since the height of the meter cup was about 0.04 ft (4.0 ft prototype) as compared with only a few inches for the prototype meter.

115. All model salinity measurements presented in this report were made with a salinity meter (conductivity type) and are considered to be accurate within 0.5 ppt in the higher ranges and 0.2 ppt in the lower ranges. The model samples were collected at the bottom, middepth, and surface elevations. The elevations of the bottom and middepth samplers were fixed in the model and were not allowed to vary with the tide as was the surface sampler. Simultaneous water samples were drawn into vials from the three elevations by means of a vacuum system, whereas the prototype salinities were measured in place at successive depths. Similar to the model velocity data, the model salinity data also represent an average over a much larger prototype area, since the vacuum sampling system used in the model drew the sample from a radius of about 1/2 to 1 in. (100 ft in the prototype).

RMA-2V

116. RMA-2V was used as part solution method and part interpolating device. The sediment model required that flow depth and velocity be specified at nearly 1,000 points, many more than could be practically measured in the physical model. Yet because of the complex three-dimensional flow structure in the estuary and because of the lack of a well behaved three-dimensional

numerical model, data from the physical model were essential. In the final form of the application, flows and depths were measured at a number of locations in the physical model and used as both exterior and interior boundary condition specifications in the numerical hydrodynamic model, RMA-2V.

Computational mesh

117. The base computational mesh for the numerical hydrodynamic model, shown in Figure 9, was identical with that used by the numerical sediment model. It consisted of 290 quadrilateral elements and 967 nodes. Using the finite element method's strengths, the boundaries are represented by curved element sides, and most elements are concentrated within the mouth where the

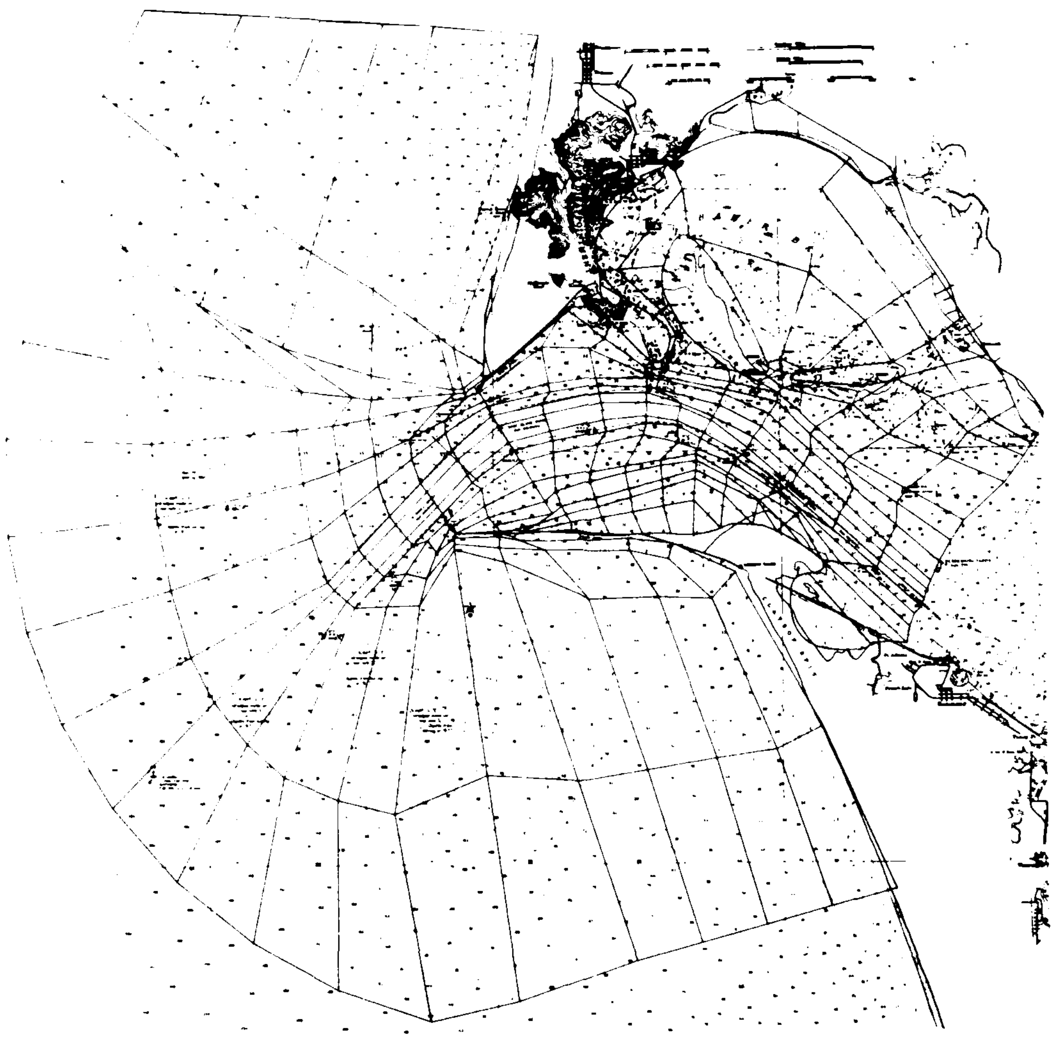


Figure 9. RMA-2V and STUDH computational mesh

most detail was desired. The navigation channel is described by a row three elements wide between jetty A and the 50-ft contour offshore.

Bathymetry

118. Bathymetric data input to the model was derived from 1976 National Ocean Survey (NOS) charts and Corps of Engineers condition surveys of the entrance. These data were digitized and stored on magnetic tape. The data management system code RETPNT interpolated to obtain bed elevations at node locations in the computational mesh, converted them to an arbitrary datum plane 200 ft below NGVD, and wrote a bathymetric data file that was processed by RMA-1. RMA-1 is a preprocessor utility code that generates a data file containing all geometric and bathymetric data used by RMA-2V and STUDH. Punched card input to RMA-1 was used to revise bed elevations at specific nodes when necessary.

Boundary conditions

119. Slip flows parallel to the boundary were specified at nearly all solid boundary nodes along curved boundaries. Zero flow (no slip) was specified at the tips of the jetties and at the intersection of the shore boundaries with the north and south ocean boundaries of the numerical model. All water boundaries had either discharge or water-surface elevation specified. Figure 10 shows nodes at which time-dependent conditions were specified. Along the ocean boundary, nodes had water-surface elevations specified at each time-step. Data were from the physical model control tide gage, which was near one of the boundary nodes. At the upstream boundary, discharge was specified at all nodes. Physical model velocity measurements at the flow-specified corner nodes shown in Figure 10 were converted to depth-integrated x- and y-direction discharges by the utility code CODE24, which also interpolated to obtain discharges at those nodes for which physical model data were not collected.

120. Processing physical model data and placing them in a format suitable for use by RMA-2V were accomplished in two steps. First, the data recorded from the physical model were keyed in to the computer and loaded into disc files. Keying in of the data was greatly facilitated midway through the project by development of CODE1, a utility code that queried the keyboard operator for data, compared input against preset constraints to ensure reasonableness, and then wrote the necessary disc file.

121. Conversion of physical model data into boundary condition

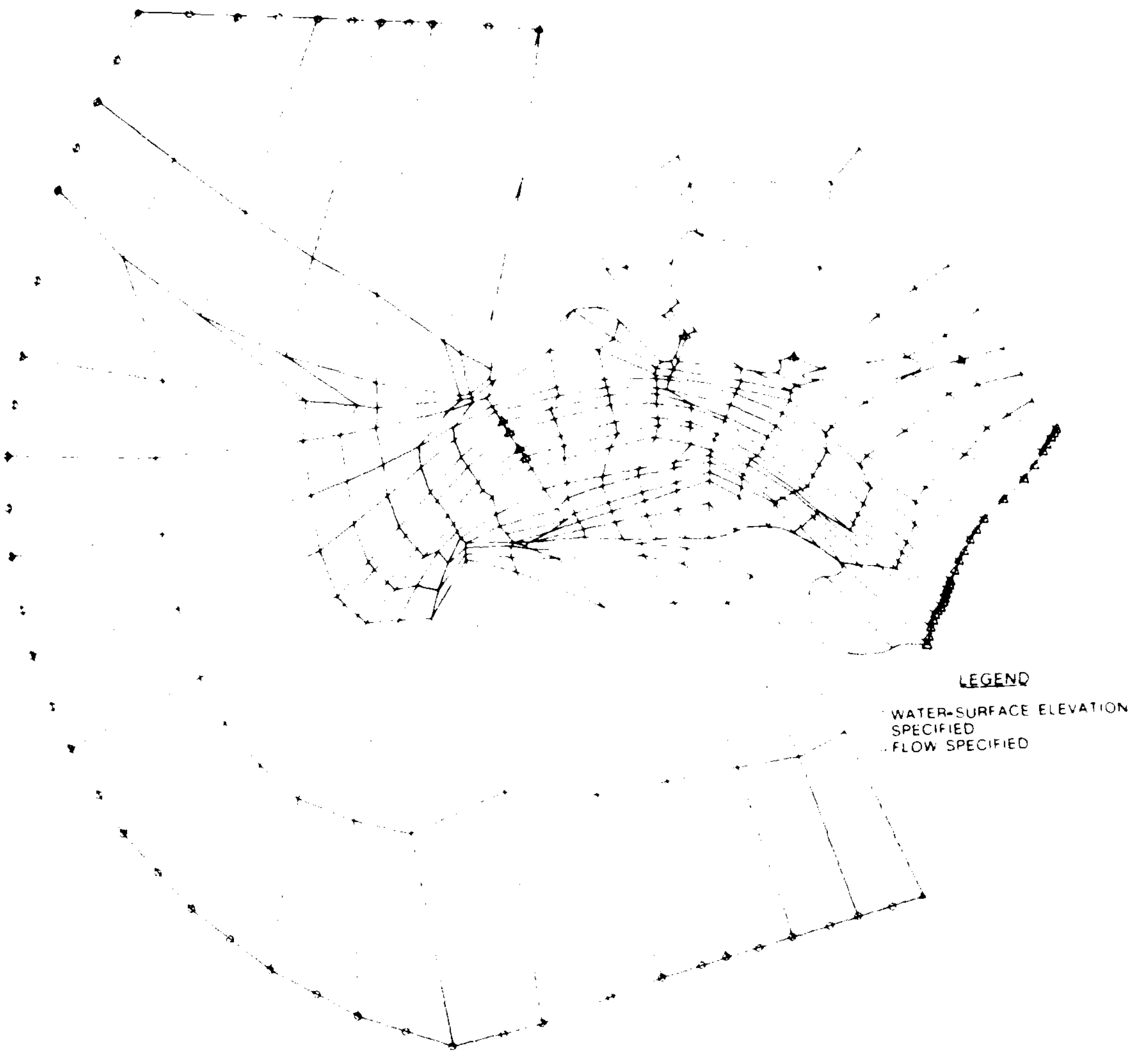


Figure 10. Boundary condition nodes in computational mesh

specifications for RMA-2V was performed by the utility code CODE24. CODE24 read disc files containing physical model velocities and water-surface elevations, computed x- and y-direction component velocities, and numerically integrated the component velocities over depth using the Riemann sum method. Computed unit discharges and water-surface elevations were then interpolated in space and time, if required, and written to a disc file in a coded format that was read directly by RMA-2V.

122. In initial applications, most of the corner nodes across the mouth range (near the jetty tips) also had discharge specified via CODE24. However,

on several trials, integration of physical model velocities did not satisfy mass continuity and using them as internal boundary conditions to RMA-2V caused strange results or even instabilities in the output. In the final applications, only four nodes on the mouth range were used as internal boundary conditions. In addition, three nodes in the openings to Baker Bay had discharge specified.

Time-steps/iterations

123. After considerable experimentation in the mesh development and verification stages, a time-step of 60 min was selected as providing the best combination of accuracy, resolution, and low cost. Differences between results at this time-step size and those of much shorter time-steps were quite small and were confined to zones of very low velocities in the ocean area.

124. Four iterations were used to converge on the initial, steady-state solution at the beginning of each run. For subsequent time-steps, two iterations were employed.

Wave Modeling

125. The computational mesh used in the wave analysis consisted of a grid 108 columns (N-S) by 88 rows (E-W) with a grid spacing of 1,000 ft. The mesh extended oceanward to depths well over 200 ft and inland beyond the limits of the finite element mesh. Bathymetric data were digitized from the 1976 NOS chart. Data were then interpolated to assign depths at every node in the computational mesh.

126. Prototype deepwater wave information was obtained from FNWC hindcasts in the form of daily significant wave heights, periods, and directions. A statistical analysis was performed for 1969-1976 to define typical frequencies of occurrence for combinations of wave height, period, and direction for each month of the year and annually. Wave roses resulting from the analyses are shown in Appendix B.

Littoral Currents

127. Littoral currents were computed for the surf zone for each of the wave conditions used in the tests. A wave-refraction model (Dobson 1967), applied to the wave grid, predicted breaker heights and angles along the

shoreline for each wave direction. These data were input to the computer code LITVEL, which computed the alongshore currents at the boundaries of the finite element grid by the modified Longuet-Higgins technique (CERC 1977). These currents were extended across the interior portion of the grid by assuming them to be parallel to the shoreline on either side of the river mouth and parallel to a line connecting the tips of the jetties across the mouth. The volume rate of flow of alongshore transport computed at the boundaries was conserved in extending it across the computational mesh.

Creation of Hydrodynamic Events

128. As described in the preceding paragraphs, hydrodynamic data were generated to account for tides, riverflow, wave propagation, and littoral currents. Combining these data into discrete events so as to adequately represent a typical year's hydrodynamics was accomplished as follows.

a. The wave contribution to sediment transport, as given by the wave transport algorithm in STUDH, was computed for each wave condition from the statistical analysis of the FNWC daily wave hindcasts including the full ensemble of heights, periods, and directions.

b. The sediment transport rates for each wave condition of the full statistical ensemble were integrated, weighting the transport by the frequency of occurrence to derive a total gross transport computation for a typical year.

c. A percentage flow exceedance curve was created for flows at CRM 52 by adding the average minor tributary flows to daily discharges from Bonneville Dam on the Columbia and Salem on the Willamette River for the period 1969 to 1976. From the curve, four riverflows--140,000, 220,000, 300,000, and 550,000 cfs--were selected for use in discretizing the typical year of river discharge.

d. Durations were assigned to the four riverflows in a manner that retained the shape of the exceedance curve and produced a mean discharge equal to the average annual flow.

e. For each discretized discharge, the waves occurring during the periods covered by that discharge in the typical year were statistically analyzed for the full ensemble of wave conditions, and processed through the transport algorithm of STUDH to yield a gross transport associated with each of the four discharges.

f. From the full ensemble of wave heights and directions developed from the statistical analysis of the FNWC daily wave hindcasts, the following seven wave conditions were selected to represent a typical year--20SW15, 10SW10, 10WW15, 10WW10, 10NW10, 05NW05, and no waves. (The first two numbers represent the wave height in feet, the two letters the wave direction, and the last two numbers the wave period in seconds.)

g. These seven wave conditions were assigned durations to schematize the waves during each schematized riverflow period in a manner that preserved the gross transport due to wave energy during that discharge period. Therefore, the total wave transport for all four discharges equals the gross transport for a typical year (as computed in a above). The resulting 17 joint wave-riverflow events and durations are listed in Table 1.

129. After the initial verification was complete, it was recognized that operating the physical model for 4 discharges and the sediment model for 17 events for each plan required time and cost too much for the project to bear. Therefore the 17 events shown in Table 1 were reduced to the 5 events shown in Table 2 by an analogous process. A comparison test for a typical year confirmed the approach's validity by demonstrating that results for the 5 events in Table 2 were comparable to the full 17 events. In the subsequent final verification, described in PART V of this report, only the 5-event sequence was used.

Superposition of hydrodynamics

130. Synthesized current velocity data sets were created by linearly superposing tidal current and freshwater velocities at each node predicted by RMA-2V and littoral current velocities predicted by LITVEL. Since LITVEL velocities were constant for each wave condition, the appropriate LITVEL set of velocities was added to the tidal and freshwater velocities at each time-step of RMA-2V output. Superposition of currents and orbital wave velocities was performed internally by STUDH for use in sediment transport computations.

Sedimentation Modeling

131. Sediment transport, deposition, and erosion were modeled with STUDH and a postprocessor code, ACE. Input to STUDH consisted of five sets of currents and water-surface elevations (one tidal cycle of data for each event, a combination of RMA-2V output and littoral currents) and five corresponding sets of wave data at every node in the computational mesh. The mesh was the same as that described for RMA-2V.

132. Original bathymetry of the entrance area was that shown on the 1976 NOS chart of the entrance area. Depths at land boundaries were deepened slightly to prevent drying of shallows. Initial bathymetry for all test runs was obtained by running STUDH for about 20 days and using the final bed elevation at each node as the initial bed elevation for all test runs of the model. This reduced troublesome perturbations of the bed caused by model start-up.

133. Boundary sediment concentrations were set to zero at the ocean boundary. This is a reasonable approximation for the deepwater nodes since the transport rates and depths there result in very small equivalent concentrations, and is permissible for the shallow-water nodes since there was a large area of the mesh in which the model could generate the correct concentration by eroding the bed. At the upstream water boundary of the mesh, the potential sediment transport as given by the Ackers-White equations was specified as the concentration.

134. Five separate runs of STUDH were made for each test. Each run consisted of one tidal cycle using one of the five events, beginning with the same initial bathymetry each time. The bed change at each node over the tidal cycle was written to an output file.

135. After completion of the STUDH runs, the code ACE extrapolated the single cycle results at each node into a 1-year prediction by multiplying the one cycle bed change for each event by the duration of that event as shown in Table 2. The code performed initial dredging of the channel such that any node with a depth shallower than project depth plus overdepth (elevation of -50 ft mllw for a 48-ft channel) was dredged to -50 ft. Then it added the extrapolated 1-year bed change to each node and computed dredging quantities by elements, applying the same dredging criteria as initial dredging. Output from ACE consisted of annual depth change at all nodes and annual dredging quantities by river mile and position in the channel (north quarter, middle half, south quarter). Depth changes were plotted as contour maps.

Data Management

136. Data management consists of data storage, retrieval, manipulation, and display. For the Columbia entrance hybrid modeling study, a data management system (DMS) was constructed to satisfy the project's unique needs. It

included the WES Data Management System A developed by V. E. LaGarde, some graphics routines, and a number of utility codes developed expressly for this effort.

137. System A consists of methods for spatial data digitization, grid transformation, accession, manipulation, and display (LaGarde and Heltzel 1980). Major use was made of the codes FACGRD, which converts randomly spaced data to a uniformly gridded format, and RETPNT, which interpolates gridded bathymetric and wave data to node point locations in the finite element mesh.

Limitations of the Method

138. The preceding sections have described the models and how they were applied in the Columbia hybrid modeling method. Hundreds of approximations, simplifications, and assumptions have been made in this approach, and only part of them are explicitly stated in this report. Each approximation, simplification, and assumption can be arguably justified as necessary or desirable, but the net result must be considered only an approximation to an incredibly complex system and its processes. The authors believe that the hybrid method described here is presently the most advanced sedimentation modeling method in the world; but in comparison to the complex interaction of processes at mouth of the Columbia River estuary, it is still simple.

139. One minor limitation requires special mention. The sediment model does not take bottom slope into account in the sediment computations; thus it will not directly reproduce sloughing of side slopes into a freshly dredged channel nor preferential transport of bed load down the side slopes into the channel. These effects are indirectly included by virtue of adjustment to prototype dredging volumes, which include material contributed by side-slope effects. It is to be expected that slope readjustment may be more pronounced after initial channel deepening (other than normal maintenance) and that transitory effect will not be predicted by the model. After initial side-slope readjustment, model predictions will be essentially correct despite the side-slope effect.

140. The most severe limitation of the approach is treatment of the sediment transport processes in a two-dimensional sense. Sediment transport is a three-dimensional process, and in the mouth of the Columbia it is particularly strongly three-dimensional. The partial two-dimensional approach

described here is aided by the use of the physical model, which satisfactorily describes the three-dimensional flow structure; but the conversion of the flow field from three to two dimensions and consideration of sediment transport only in two dimensions are still significant simplifications.

141. A more thoroughly three-dimensional modeling approach was prevented by the lack of practical three-dimensional numerical models. When this study was begun in 1976, there was not even a practical two-dimensional model for sand transport, and three-dimensional sediment models were only a remote possibility. At present (1983), there are a handful of two-dimensional sediment transport models that can be considered viable production tools, and two experimental three-dimensional models are being used by the Corps of Engineers.

142. This effort is the first application of this hybrid method. Because of its newness, we have much less intuitive insight into how good the answers it produces are than we have for traditional approaches. Thus we must use its results with care, avoiding either being blinded by its virtuosity or dismayed by its defects.

PART V: VERIFICATION

Field Data

143. Field measurements of water-surface elevations, current speed and direction, salinity, and suspended sediment were collected in 1977 and 1978 to supply data for verification of the models. The data used here were collected at the stations shown in Plate 1 on 16 and 17 June 1977 and at the stations shown in Plate 2 on 7 and 8 June 1978. A description of the data collection program and a listing of the data are given by McAnally and Donnell (in preparation). River discharge at The Dalles was about 125,000 cfs during the 1977 survey and 225,000 cfs during the 1978 survey.

144. Data for verification of the sediment model were considerably more difficult to obtain. During the surveys described above, suspended sediment samples were taken, but to compare model results with them absolutely would have required careful matching of boundary conditions (riverflow and tides) and hydraulics (currents and local waves) in all steps of the modeling. This would involve rather more effort than the comparison warranted, so the suspended sediment concentrations measured in the field were used to determine if model results using typical boundary conditions were in a reasonable range.

145. Volumes of dredged material for each year were extracted from the Annual Report of the Chief of Engineers (OCE) and are tabulated by fiscal year in Table 3. The volumes of Table 3 are grouped by characteristic dredging activity. During the period 1959-1974, the entrance channel was nominally dredged to the design depth of 48 ft below mllw plus 2 ft of allowable overdepth to account for dredging inaccuracies. Examination of condition surveys of the channel for the period shows that in some areas depths of 50 ft were obtained by dredging, but seldom was the entire channel width as deep as 48 ft. This was due to a lack of dredging capacity in relation to the shoaling rate, which resulted in a partially maintained channel, with primarily the north side maintained. Beginning in 1973, disposal area E (Figure 2) next to the north jetty was used and dredging production increased sharply because of more rapid disposal of the dredged material. The average annual dredged volume for 1959-1974 is 2.6 million cu yd, but that number reflects dredging capacity not dredging need.

146. In 1975, the dredge Essayons was put into service at the mouth of

the Columbia and advance maintenance dredging (intentional overdredging to reduce the interval between required dredgings) was begun. For the first time in a number of years, the full design width of a 48-ft-deep channel was obtained. Up to 3 ft of advance maintenance dredging was ordered and all of that plus 2 ft of allowable overdepth was achieved at mile 0; however, at mile -1 only about 1 ft of overdredging was accomplished. In 1979, authorized advance maintenance dredging was increased to 5 ft and that amount (plus 2 ft allowable overdepth) was again achieved at mile 0. Upstream of mile 0, 1 to 3 ft overdredging was obtained and 1 to 2 ft overdredging was obtained at mile 1. Average annual dredged volume for the period 1976-1979 was 5.4 million cu yd.

147. Attempts to use differences between individual hydrographic surveys of the mouth as a quantitative measure of shoaling were unsuccessful. WES and NPP experience showed that uncertainty in vertical control was at least equal to the amount of average annual depth change of the entrance. Areas of rapid deposition or erosion could be identified, but the quantity of material accumulating could not be computed with confidence. Finally, a set of previously computed annual depth comparisons over the period 1959 to 1968 was selected as representative of the overall pattern of average bed change in the entrance. These data were used to construct a scour/fill map and a longitudinal profile of shoaling volume distribution in the navigation channel. These results are presented in the section on sedimentation verification.

Physical Model

148. The verification of the Columbia River estuary model was accomplished in two phases: (a) hydraulic verification, which ensured that tidal elevations and current velocities were in proper agreement with the prototype, and (b) salinity verification, which ensured that salinity phenomena in the model corresponded to those of the prototype for similar conditions of tide, ocean salinity, and freshwater inflow.

Tidal verification

149. The objective of the model tidal adjustment was to obtain an accurate reproduction of prototype tidal elevations and tidal phases throughout the model. Prototype tidal data from nine recording tide gages (Plates 1 and 2) were available to verify the accuracy of the model tidal adjustment.

150. The procedure followed was to adjust the tide generator in such a manner that the tides generated in the model ocean would cause an accurate reproduction of prototype tide at the jetty A gage, then to adjust model roughness until prototype tidal elevations and times of occurrence were reproduced to scale throughout the model.

151. Comparisons of model and prototype tidal data for the two tide conditions reproduced in the model are presented in Plates 3-9. These plates show tidal elevations for the 16 June 1977 and 7 June 1978 tide conditions at Jetty A, Point Adams, Ilwaco, Hungry Harbor, Tongue Point, Altoona, Skamokawa, Bradwood, and Light 77. In addition, data were obtained at Pier 1 during the 7 June 1978 survey (Plate 7). High- and low-water levels and range of tide profiles at locations along the channel are presented in Figures 11 and 12 for the 16 June 1977 and 7 June 1978 tide conditions, respectively.

152. Verification of tide elevations and ranges for the 7 June 1978 tide conditions was within 1.0 ft and generally within 0.5 ft of the prototype. Verification of the tides for the June 1977 survey was not as good. The greatest discrepancy occurred during verification of the 16 June 1977 tidal conditions at gages Bradwood and Light 77, both located near the upstream limits of the model. Low-water elevations at these two locations were 2.0 and 1.7 ft lower than those observed in the prototype, while higher high water elevations were 1.0 and 0.2 ft lower, respectively. This resulted in the model having a greater than prototype tide range at these two locations of 0.9 ft and 1.5 ft, respectively.

Current verification

153. The objective of the model current adjustment was to obtain an accurate reproduction of prototype current velocities and distribution (lateral and vertical) throughout the model. Prototype current velocity data were available at 22 locations on 9 ranges for the June 1977 condition, and at 24 locations on 9 ranges for the June 1978 condition. Locations of stations for the two conditions are shown in Plates 1 and 2, respectively. Prototype observations were made at the surface, middepth, and bottom where depth permitted for a period of 25 hr at each station.

154. The procedure followed for adjustment of current velocities was to reproduce each of the two tidal and discharge conditions in turn and adjust the model roughness distribution (but retain the total amount of roughness from the tidal verification) until the current velocities at each metering

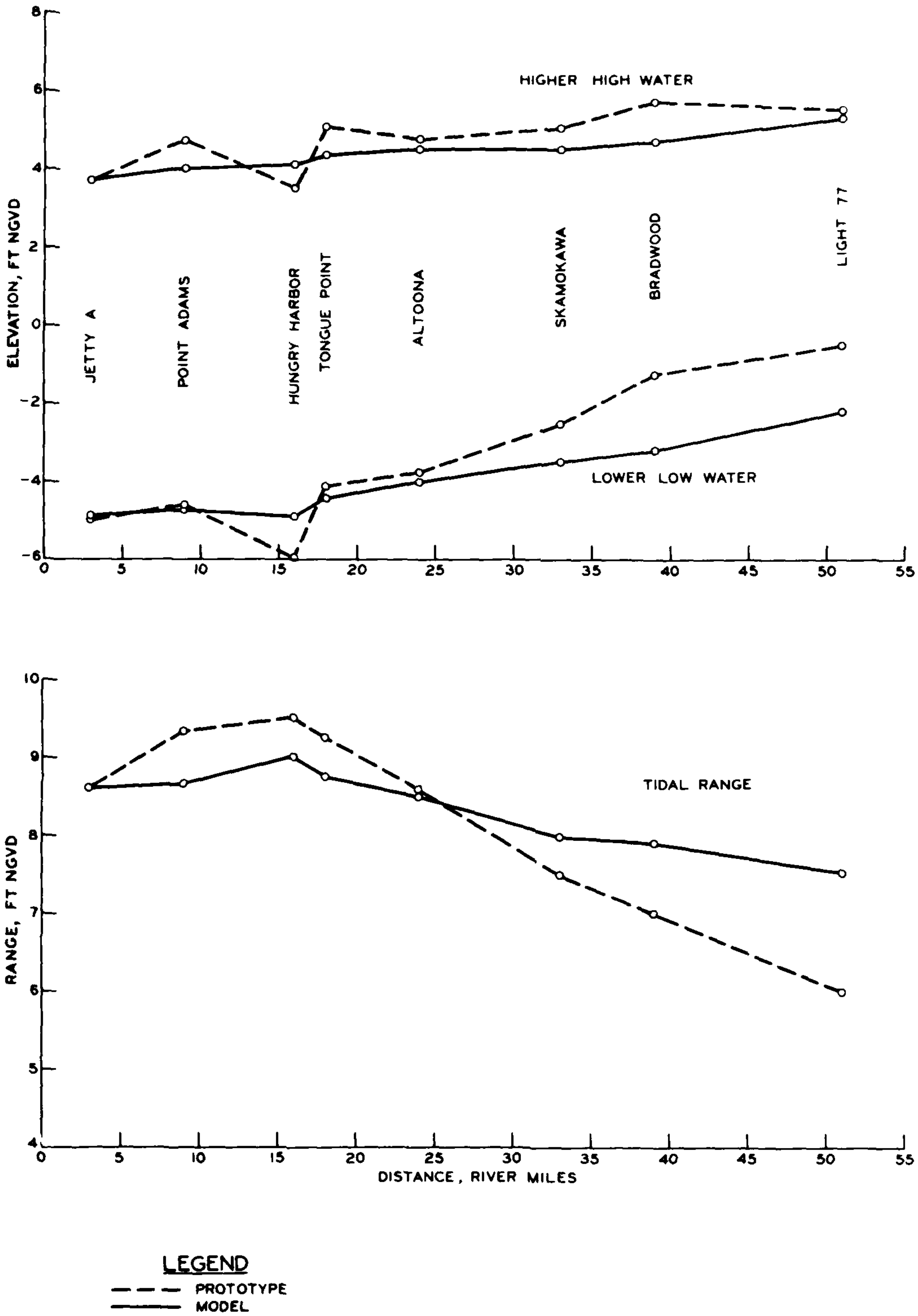


Figure 11. Tide profiles for June 1977 survey

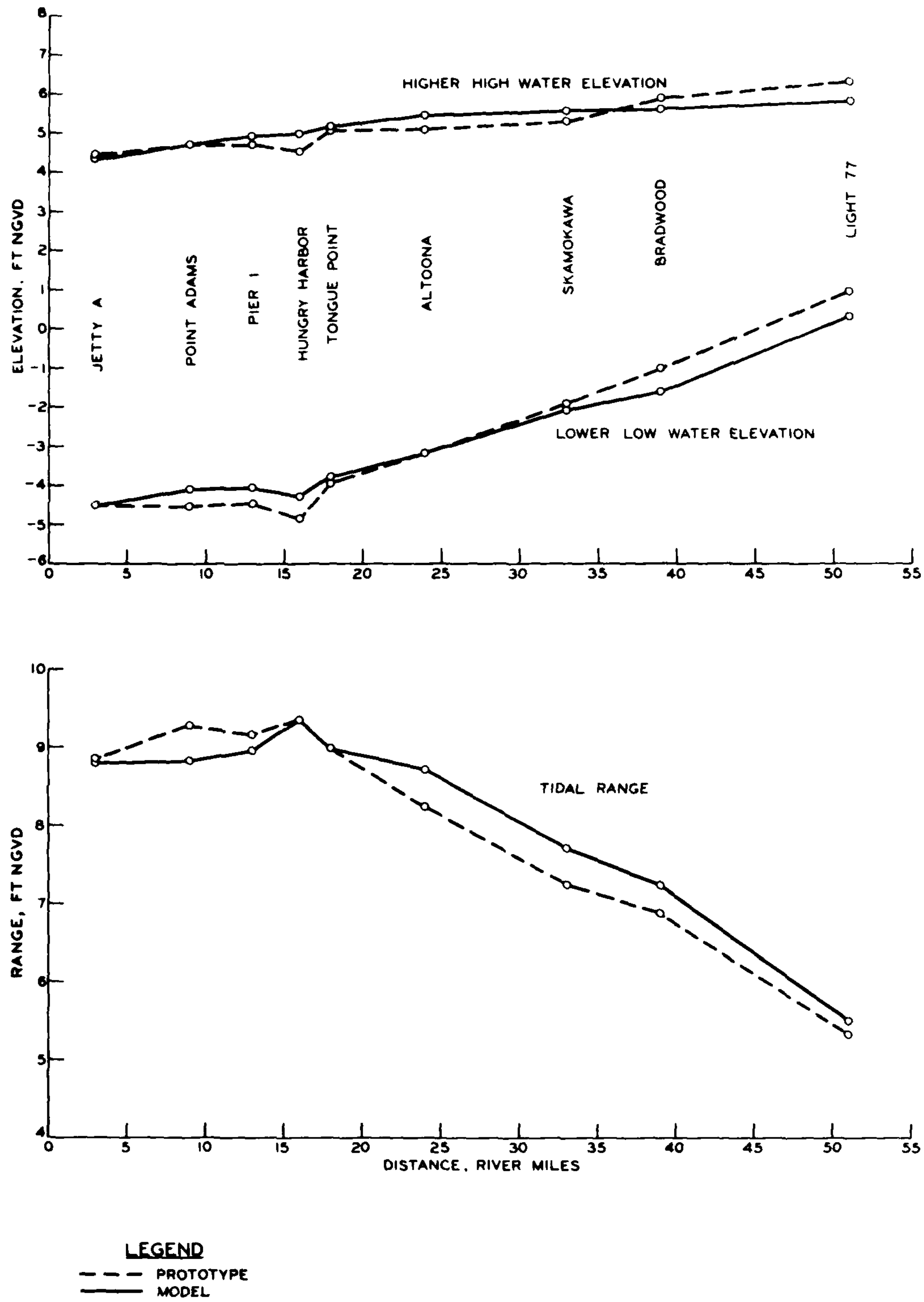


Figure 12. Tide profiles for June 1978 survey

station were reproduced in the model to an acceptable accuracy.

155. Comparisons of model and prototype current velocities for all stations on each prototype survey date are shown in Plates 10-56. Prototype measurement intervals were hourly and model measurements were made half-hourly. These measurements were plotted and smooth curves were drawn through the points. The agreement obtained throughout the model is considered to be very satisfactory.

156. Because stations were located in different positions during each of the above prototype surveys, each verification period will be discussed individually. A complete tidal cycle of prototype current and salinity data was not available for model comparison at stations located generally downstream from about mile 10. This skip in data usually occurred during periods of peak or maximum velocity and resulted from the inability of the survey boats to stay on station during these maximum velocity periods. However, data that were obtained were useful in the verification phase of the model study to show accuracy of phase and magnitude of lower current speeds.

157. 16 June 1977 survey period. Comparison of model and prototype data at range 1 (Plates 10-12), shows that the model is reproducing the magnitude of the smaller currents and phase reasonably accurately. Maximum ebb currents at sta 1B and 1C were generally higher (about 1.0 fps) than those observed in the prototype at the middepth and bottom elevations, while surface depth maximum ebb currents in the model were slightly low. Maximum flood currents were generally greater than observed prototype currents.

158. Prototype current data at range 2 (Plates 13-15), were not complete; however, the gap occurred after the period of maximum currents. These data show that the model was reproducing maximum currents accurately (generally within 1.0 fps), with an exception noted at sta 2F bottom depth. Model currents at this location and depth were greater than prototype observations by about 2 to 3 fps. Peak ebb currents in the model at range 2 were generally occurring about 1 to 2 hr earlier than prototype observations. There was no significant difference in phase of peak flood currents.

159. Model maximum velocity data observed at range 3 (Plates 16-18) were generally higher by 1 to 2 fps than observed prototype data. The time of occurrence of maximum currents in the model generally occurred 1 to 2 hr later than in the prototype. This phase difference was more evident during peak ebb current periods than during peak flood current periods.

160. Sta 4K and 4L data (Plates 19-20) showed that model currents were generally about 0.5 to 2.0 fps lower than prototype data at the surface and middepth elevations, while about 1.0 fps higher than prototype data at the bottom depth. Maximum differences generally were observed in ebb currents. Peak flood velocities were generally within 1.0 fps of the prototype. Very little difference between model and prototype was noted in phasing of currents at this range.

161. Model and prototype comparisons of currents at the three stations on range 5 are shown in Plates 21-23. These data show that model maximum ebb currents were generally slightly lower than prototype currents at the middepth and surface depths while slightly higher at the bottom depth. Maximum flood currents observed in the model were lower (generally less than about 1.5 fps) than those observed in the prototype. The prototype data points at the middepth and bottom depths at about hour 20 appear to be in error. The phases of currents at each of the three stations were in fair agreement.

162. Range 6 data (Plates 24-26) showed that model maximum current velocities, both ebb and flood, were generally about 0.5 to 1.5 fps higher than those observed in the prototype. This trend held at all depths measured. There was a rather long gap in the prototype data at sta 6P; however, it appears that the above trend would hold true at this location also. The phasing of slacks and time of peak ebb and flood velocities were in exceptionally good agreement at each of the three stations on this range.

163. Range 7 data (Plates 27 and 28) showed that model currents were generally slightly greater than those observed in the prototype, generally about 0.5 to 1.5 fps. Phasing of slack periods and timing of maximum currents, again as at range 6, were in excellent agreement.

164. Model current velocities at sta 8U (Plate 29) were in excellent agreement with those of the prototype, with respect to both magnitude and phase. Data at sta 8V (Plate 30) showed that the model current velocities were generally about 0.5 to 1.0 fps higher than prototype observations during flood periods and lower than prototype observations at about the same magnitude during ebb periods. Sta 9W and 9X (Plates 31 and 32) were located at about mile 46. These model and prototype data were in good agreement. Model flood currents at each depth were somewhat greater than prototype observations, while model ebb currents were about equal to or slightly greater than prototype observations.

165. 7 June 1978 survey period. Prototype data at range 13 (Plates 33-35) were very sparse. Neither the maximum ebb nor maximum flood currents were measured during the prototype survey; however, the data that were obtained correspond fairly well to the model data.

166. During the 7 June 1978 prototype survey, three stations (12A, 11A, and 11B) were monitored in the entrances to Baker Bay. Comparisons of model with prototype current velocities at these locations are shown in Plates 36-38. At sta 12A, located in the Ilwaco entrance channel, model current data were collected only at middepth. These data showed currents generally higher than those of the prototype. The greater difference occurred during periods of ebb flow, when maximum model current velocities were about 3.0 fps greater than prototype observations. Maximum flood velocities observed in the model were about 1 to 2 fps higher than those observed in the prototype. Comparisons of model and prototype phases of currents at sta 12A were fairly good. Model and prototype data at sta 11A, located near the entrance channel to Chinook, compared very well as phase and maximum current velocities were very close. Data sta 11B, located in Sand Island Gap, showed that observed model maximum ebb current velocities were generally in excess of prototype velocities by about 1 to 2 fps, while maximum flood current velocities were about 0.5 to 1.0 fps lower than prototype observations. The phase of currents and slack periods of model and prototype compared very well at sta 11B.

167. Comparison of model and prototype current observations at range 1 (Plates 39 and 40) was very good. Maximum model currents were slightly lower than prototype currents. Comparison of phase and slack periods showed good agreement.

168. Range 2 had three stations (Plates 41-43). Model currents at these stations were slightly greater than prototype currents, generally by less than 2.0 fps at the times of maximum currents. The phases of currents and slacks were in very good agreement.

169. Range 3 data showed that the magnitudes of model and prototype currents were in good agreement (Plates 44-46). The phases of model currents and slack periods were generally about 1 hr later than those of the prototype at sta 3A. Overall, however, the agreement was very good at range 3.

170. Range 5 data showed that maximum model current velocities at sta 5A and 5B (Plates 47 and 48) were generally in good agreement with prototype observations (these two stations are located along the sides of the

navigation channel). Maximum ebb current velocities at sta 5A, surface and middepth were exceptions, as the difference between model and prototype velocities was about 1.5 fps. Data collected at sta 5C, located in the turning basin opposite Tongue Point docking facilities, showed that model current velocities were generally about 0.5 to 1.0 fps higher than observed prototype observations (Plate 49). The phase and slack periods at each of the three range 5 stations were in excellent agreement with the prototype.

171. Data were collected at two stations (Plates 50 and 51) on range 6. Sta 6A model data showed ebb current velocities greater than prototype velocities by about 1 to 3 fps, while flood current velocities were about equal or slightly lower than those observed in the prototype. Model and prototype current velocity data obtained at sta 6B were in excellent agreement, as both magnitude of current velocities and phase matched very well.

172. Range 10, located near Brookfield, consisted of three sampling stations (Plates 52-54). Model ebb velocities at sta 10A and 10B were generally lower than prototype velocities. The greatest differences were generally about 0.5 to 1.0 fps. Flood current velocities were slightly higher than prototype measurements, generally within 0.5 fps. Phases of currents were in good agreement at these two locations. Model and prototype data collected at sta 10C were also in good agreement. Model ebb velocities were slightly greater than prototype velocities.

173. Model and prototype data at range 8 are shown in Plates 55 and 56. Currents at these two locations were almost 100 percent in the ebb direction throughout the tidal cycle. The model reproduced this prototype condition; however, maximum ebb current velocities measured in the model were generally about 0.5 to 1.5 fps higher than those observed in the prototype.

Salinity verification

174. The objective of the model salinity verification was to obtain an accurate reproduction of the vertical and lateral distribution of prototype salinities throughout the model. Reproduction of prototype salinity phenomena in the model required the maintenance of the proper salinity in the ocean water supply system and the establishment of the proper mixing environment. The prototype salinity data used in this phase of the study were obtained simultaneously with the above hydraulic data. Salinity observations were made hourly in the prototype and model. These data were plotted and smooth curves drawn through the points. Comparisons of prototype and model are shown in

Plates 57-90. The agreement demonstrated between model and prototype is considered good. It is pointed out that no additional adjustment of the model roughness was necessary to obtain the agreement shown in Plates 57-90. These data substantiate the model adjustment of tides and currents and indicate that the upland fresh water was being properly mixed with salt water from the ocean supply.

175. 16 June 1977 survey period. Large gaps in the prototype data at range 1 made it difficult to accurately compare model and prototype salinity concentrations at this location; however, sufficient prototype data were available to indicate that model salinity concentrations in this area were too low. The data shown in Plates 57-59 indicate that model salinities at range 1 average approximately 2 to 3 ppt lower than those observed in the prototype at all three depths. Greater differences between model and prototype were noted at the surface depth.

176. Data collected at range 2 (Plates 60-62) show that model salinities were generally lower than prototype salinities on an average of about 2 to 4 ppt. Maximum and minimum salinity values in the model were generally within 1 to 2 ppt. Exceptions were noted at the surface depth where differences were generally larger than those observed at the middepth and bottom elevations. Overall, model and prototype agreement at this range was good.

177. Data collected at range 3 (Plates 63-65) showed that model salinities at sta 3G and 3H were generally lower than observed prototype concentrations at the surface and higher than prototype concentrations at middepth and bottom depth. This trend was reversed at sta 3J, as model salinity concentrations were higher than prototype concentrations at the surface and lower than prototype concentrations at middepth and bottom. Unlike data at range 2, the greatest differences between model and prototype data occurred at the bottom depth. Several rather large differences occurred, some as great as 15 ppt; however, maximum and minimum salinity concentrations of model and prototype were in fair agreement.

178. The model and prototype salinity data comparisons at range 4 (Plates 66 and 67) were exceptionally good. Surface data in the model were slightly higher than prototype data, while middepth and bottom salinities were generally slightly lower. An exception to this was observed at sta 4L, bottom depth, where model salinities were generally slightly higher than prototype salinities. Overall, the verification at range 4 was excellent.

179. Model and prototype data comparisons at range 5 are shown in Plates 68-70. These data show model salinities at all but one depth to be about equal to or slightly higher than prototype salinities. The only depth where model salinities were lower than prototype salinities occurred at sta 5N, bottom depth. Excluding this depth, differences between model and prototype data were generally less than about 2 to 3 ppt.

180. In the prototype, only a trace of salinity was measured at sta 6P (Plate 71); in the model, salinity values less than 0.5 ppt were measured. This indicates that model salinity intrusion was slightly farther upstream than that measured in the prototype.

181. <u>7 June 1978 survey period.</u> Prototype data on range 13 (Plates 72-74) were exceptionally sparse; however, model data matched fairly well within those points that were available. Model data appear to have been slightly lower than prototype data at the surface. On the other hand, maximum salinities at middepth and bottom generally compared fairly well, an indication that vertical mixing in the model was not as efficient as that in the prototype.

182. Data collected at sta 12A (Plate 75) showed that model salinity concentrations were lower than prototype concentrations at each depth monitored, except at the times of minimum salinities. The greatest differences between model and prototype occurred at the bottom at the time of higher high tide where differences were as great as 20 ppt. However, these extremely large differences occurred for only a short period during the total cycle. Sta 11A data (Plate 76) showed model salinity concentrations lower than observed prototype concentrations at the surface and greater than prototype observations at the middepth and bottom. Maximum differences as great as 20 ppt occurred at the bottom depth during the period of minimum salinity concentrations. Sta 11B data (Plate 77) show model salinities lower than prototype salinities at the surface and middepth, while being generally higher than prototype salinities at the bottom. As at sta 11A, the greatest differences occurred at the bottom depth during the period of minimum salinity concentrations.

183. Sta 1B and 1C prototype data had gaps in them but were sufficient to indicate that model salinity results were in good agreement, particularly at sta 1B (Plate 78). Agreement of model and prototype salinity concentrations at sta 1C (Plate 79) was not quite as good as was achieved at sta 1B. Sta 1C model salinities were generally about 2 to 10 ppt lower than prototype

observations. The greatest differences were more evident at the surface and middepth.

184. Model salinities on range 2 (Plates 80-82) were generally lower than prototype values, particularly during periods in the tidal cycle of maximum salinities. Minimum salinity values in the model were in excellent agreement with the prototype. The greatest differences between model and prototype were generally less than 5.0 ppt and occurred at middepth and bottom.

185. Range 3 model salinity data (Plates 83-85) were lower than prototype data at the surface and middepth elevations at each of the three stations and higher than prototype data at the bottom elevations. The largest difference (about 10 ppt) occurred at the bottom depths during the period in the cycle of maximum salinity concentrations. These data indicate that the model was not quite achieving the proper vertical mixing in this area.

186. Only traces of salinity concentrations were measured at ranges 5 and 6 (Plates 86-90). Maximum model salinity concentrations measured at sta 5B (located in the deep hole off Tongue Point) were about 5 to 8 ppt higher than those observed in the prototype.

RMA-2V

187. Verification of RMA-2 was a fairly brief effort. Initially, various time-step sizes were tested as described in paragraph 123. Then results at some nodes were compared with physical model measurements obtained at the same locations and overall flow patterns were compared with photographs of physical model surface currents. Node locations are shown in Plate 91 and velocities are plotted in Plates 92-95. The physical model velocities were converted to depth-averaged values by the technique described in paragraph 121. Test conditions in the physical model for the RMA-2V verification were 300,000-cfs freshwater discharge and 7.2-ft tidal range.

188. At node 119 (Plate 92) current velocities are in fairly good agreement between the physical and numerical models. In the x-direction (eastward), the positive (flood) maximum magnitudes are about 1 fps higher; otherwise, magnitude, directions, and phases generally compare well. At node 123, just downstream of node 119, the two models were in very good agreement, with only a 30-min phase lag in the numerical model x-direction velocities when changing from ebb to flood.

189. At node 131 (Plate 92), just beyond the jetty tips, both models show ebb flows to be much stronger than flood flows. The physical model exhibits a sudden sharp reduction in magnitude during both ebb phases, probably due to density-induced current reversal at the bottom. As would be expected, the numerical model merely smooths the discontinuity. Node 219 velocities (Plate 93) show excellent agreement between the two models. Node 278, located near node 119, demonstrates some of the same velocity differences noted at the latter node. The maximum ebb magnitudes in the x-direction were somewhat high (about 1 fps) in the numerical model and there was a 30-min phase lag between the two curves during the change from ebb to flood. Unlike node 119, positive z-direction (northward) currents had a notably higher magnitude (less than 1 fps) in the numerical model at node 278.

190. At node 282 (Plate 94), x-direction velocities were in very good agreement; but the numerical model showed negligible z-direction (cross-channel) flows, whereas the physical model had z-direction velocities of up to 1 fps. This indicates some misdirection of the flow at that point.

191. Velocities at node 290 (Plate 94) were in good agreement except for the sharp reduction in ebb velocity as observed at node 131. The cause is probably the same in both cases. Node 294 is also similar to node 131, but the numerical model velocities were generally low on ebb and high on flood, indicating more rapid deterioration of the ebb phase jet than in the physical model. Agreement at node 378 was excellent as shown in Plate 93.

192. The x-direction velocities at node 396 (Plate 95) were substantially higher in the numerical model during the second ebb phase (as much as 2 fps) and slightly higher in the first ebb (as much as 1 fps); otherwise, agreement was good. A similar pattern and a phase shift are noted at nodes 400 and 453 which were just seaward of node 396. At node 484 (Plate 93), agreement was quite good.

193. In summary, the agreement between numerical and physical models was very good within the entrance and fair outside the entrance. Ebb jet velocities outside the entrance tended to be low on the south side and high on the north side of the channel.

Waves

194. Results of the wave propagation model and littoral current

computations were not verified to prototype data. Results from these tasks were inspected for reasonableness and then were used by the sediment model. The impact of waves and littoral currents on results of the sediment model were inspected for reasonableness. Since the wave information was needed only for its agitation effect on the sediment, this approach was considered adequate. The first trials showed a larger wave effect than was considered reasonable, so the input waves were reduced from significant waves heights to mean wave heights. Results from the latter were considered more correct and were used thereafter.

Sedimentation

195. Verification of sedimentation modeling consisted of systematically varying grain sizes, dispersion coefficients, and to a lesser extent, event durations to obtain shoaling patterns and dredged volumes similar to those observed in the prototype.

196. Initial trial runs with a uniform grain size (and associated fall velocity) of 0.2 mm demonstrated insufficient deposition. Noting somewhat higher grain sizes in the prototype between CRM 0 and +1 (see Figure 3), that zone was assigned larger grain sizes (0.35-mm maximum) against a background of uniform 0.2 mm everywhere else. Trials of this distribution improved agreement with the prototype but did not permit large enough deposition. In subsequent trials, the maximum grain size was raised to 0.35 mm, tapering gradually to 0.2 mm elsewhere. The exaggeration in maximum grain size may have been necessitated in part by the two-dimensional models' inability to reproduce bottom flow predominance. The specified grain sizes are shown in Figure 13.

197. Lateral distribution of shoaling was improved slightly by decreasing dispersion coefficients in both the x- and z-directions from a value of 500 m^2/sec during early trials to 250 m^2/sec in the final verification.

198. Durations of the various events were modified slightly from those computed from prototype data. Initial runs showed that the 20SW15 condition caused far too much bed change, so its duration was reduced from 19 days to 1 day. The other 18 days were distributed among the other events. The final set of event durations were as shown in Table 2.

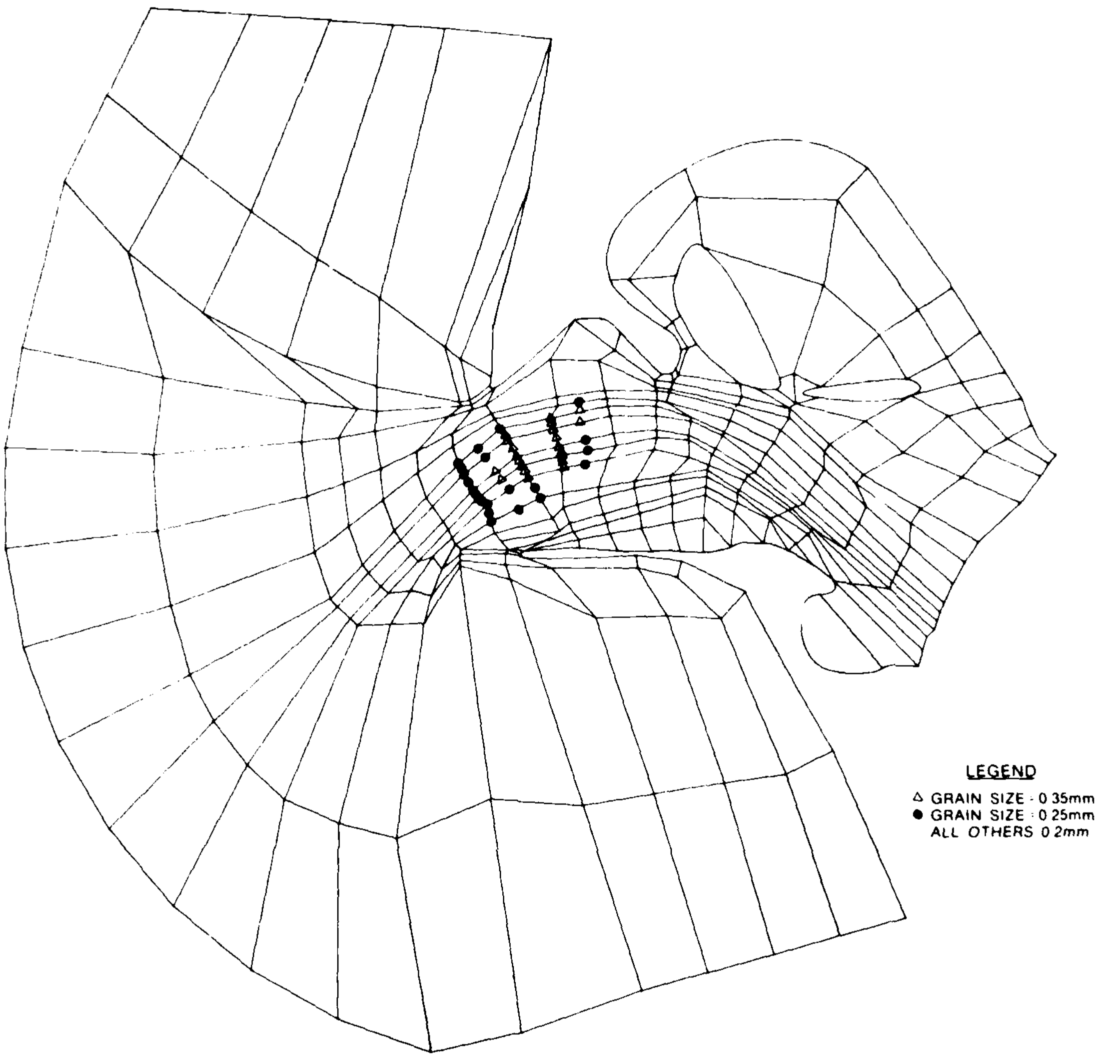


Figure 13. Grain sizes used in STUDH

Dredged volumes

199. Comparison of model and prototype dredged volumes is difficult because prototype dredging is subject to vagaries of weather, availability of dredging equipment, variation in depth obtained, imprecise measurement, and some inaccuracy in location. For this verification, several forms of model dredging were tested in order to obtain comparisons with the several periods of characteristic dredging noted in paragraphs 145 and 146. First, a test with no overdredging was performed to compare with the period 1959-1975, when little or no overdepth was obtained. These results, shown below, are in

general agreement (from information supplied by NPP, prototype volumes have been split 80 percent landward of CRM 0 and 20 percent seaward of CRM 0). River mile locations and shoaling sections are shown in Figure 14.

River Mile	Dredged Volumes millions of cu yd — Prototype 1959-1975	Model No Overdredging
2 - 0	2.1	2.5
0 - -2	0.5	0.6
Total	2.6	3.1

200. Dredged volumes for the years 1976-1979 are now compared with model tests using 2-ft overdredging seaward of mile 0 and 5-ft overdredging landward of mile 0. These results, which correspond to the actual prototype dredging approach during that period, agree reasonably well with prototype volumes.

River Mile	Dredged Volumes millions of cu yd — Prototype 1976-1979	Model, 2- and 5-ft Overdredging
2 - 0	4.3	3.5
0 - -2	1.1	1.3
Total	5.4	4.8

201. These results show that the overall dredging volume and distribution are satisfactorily similar in light of the difficulty in modeling actual dredging practice.

Shoaling distribution

202. Distribution of shoaling along the navigation channel is illustrated for model and prototype in Figure 15. The plot shows percent of total shoaling as a function of longitudinal location at 1000-ft intervals along the channel between CRM 1.6 and -0.3. Prototype data are average values over the period 1959-1968, using observed depth change between the end of one year's dredging and the beginning of the next year's dredging. Thus the effect of deposition during the dredging season is not included in the results. The model curve in Figure 15 shows excellent agreement with the prototype except

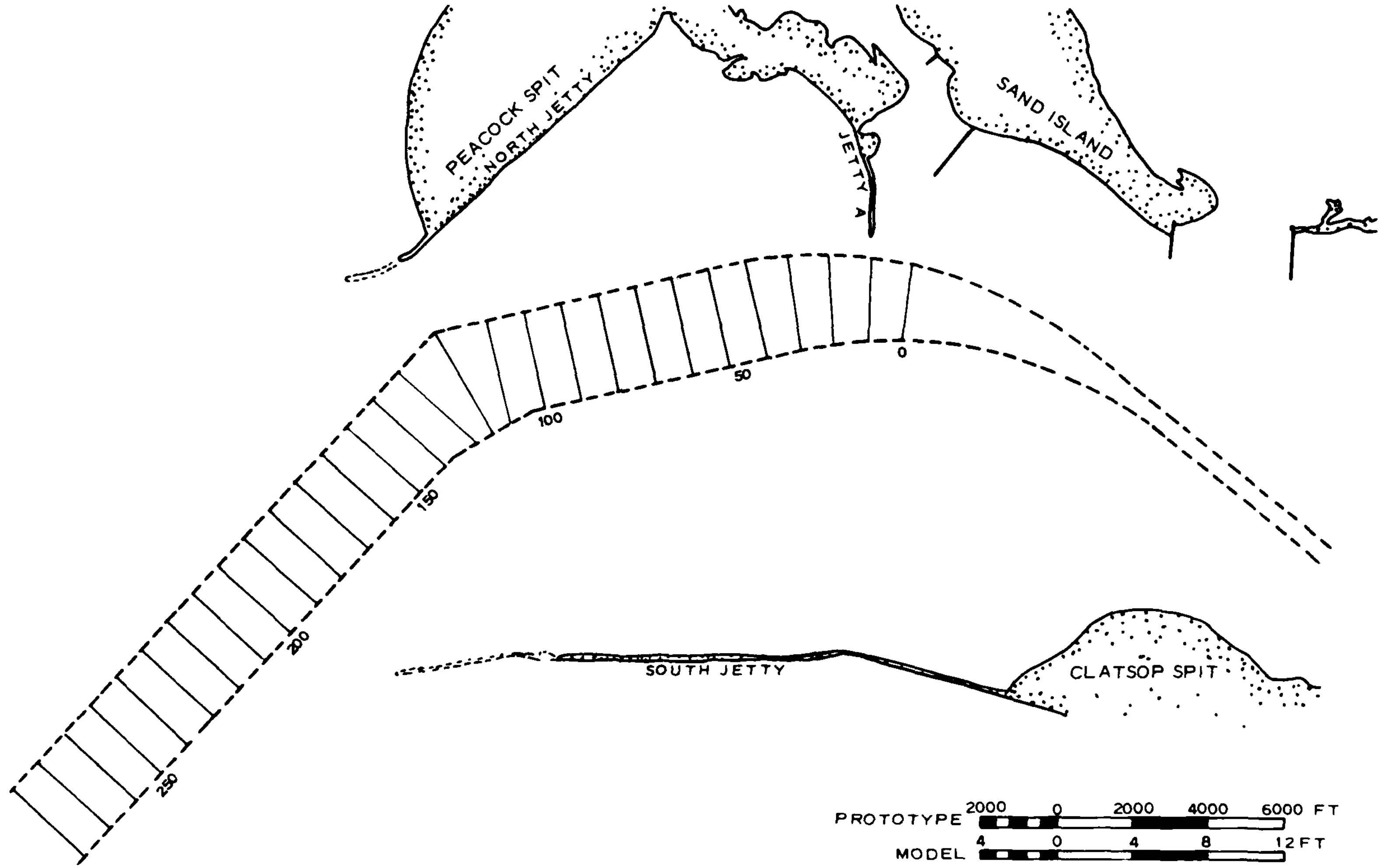


Figure 14. Shoaling distribution sections

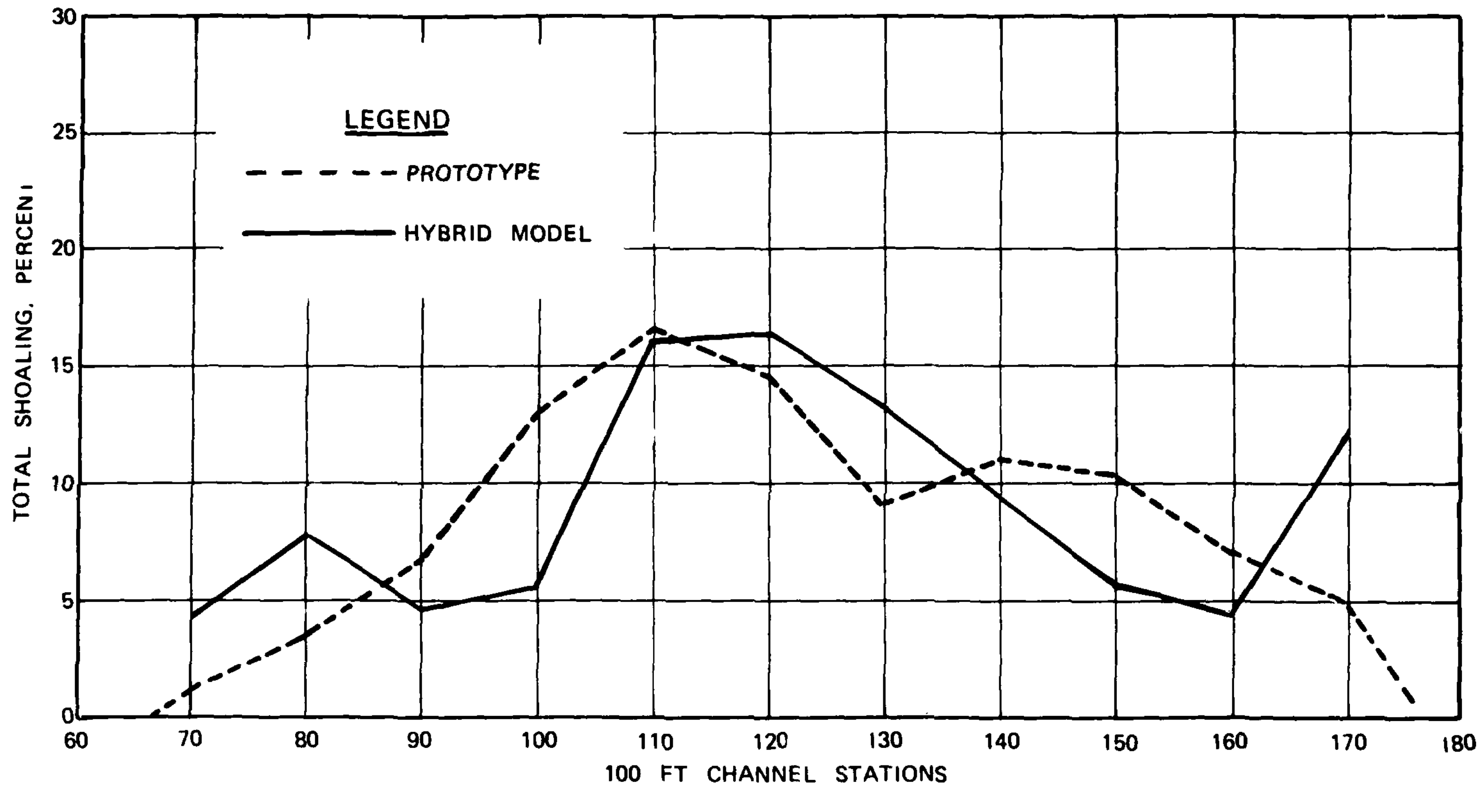


Figure 15. Distribution of shoaling volumes along the navigation channel

at sta 170 (mile -0.3), where the model shows formation of a bar that was not shown in the prototype data.

Scour and fill patterns

203. The annual average prototype shoaling pattern between postdredging and predredging surveys from 1959-1967 is shown in Figure 16. The predominant shoal extends upstream from the south side of the channel at CRM 0 to about CRM 1, where it fills the entire channel width and tapers off on the north side of the channel above CRM 2. Another shoal appears in the south half of the channel between CRM -1/2 and -1-1/4. The model shoaling pattern for a full typical year, illustrated in Figure 17, shows the same pattern in the shoal between CRM 0 and 2 but with a greater magnitude of change in the center of the channel. The model shoal seaward of CRM 0 covers a considerably larger area and consists of greater depth changes than that of the prototype in that area.

204. In summary, the numerical model produced dredging quantities in good agreement with those from the prototype. The distribution in shoaling along the axis of the navigation channel agreed well with the prototype distribution except for too much deposition at about CRM -0.3. The model's shoaling pattern is also quite similar to that of the prototype except for too much deposition in the offshore bar. The excess deposition may be due to an incorrect distribution of flow in the hydrodynamic model results as described in paragraph 193.

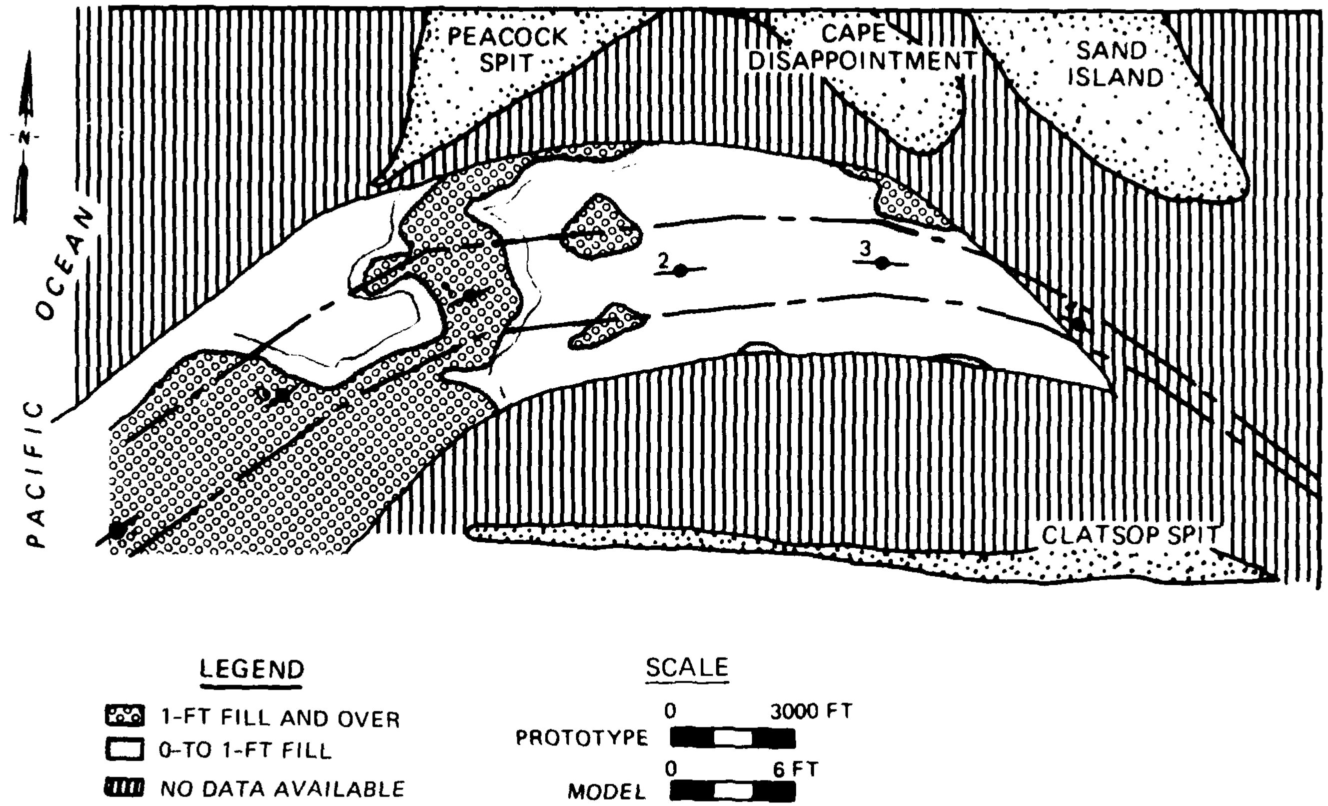


Figure 16. Prototype annual average shoaling pattern, 1959-1968

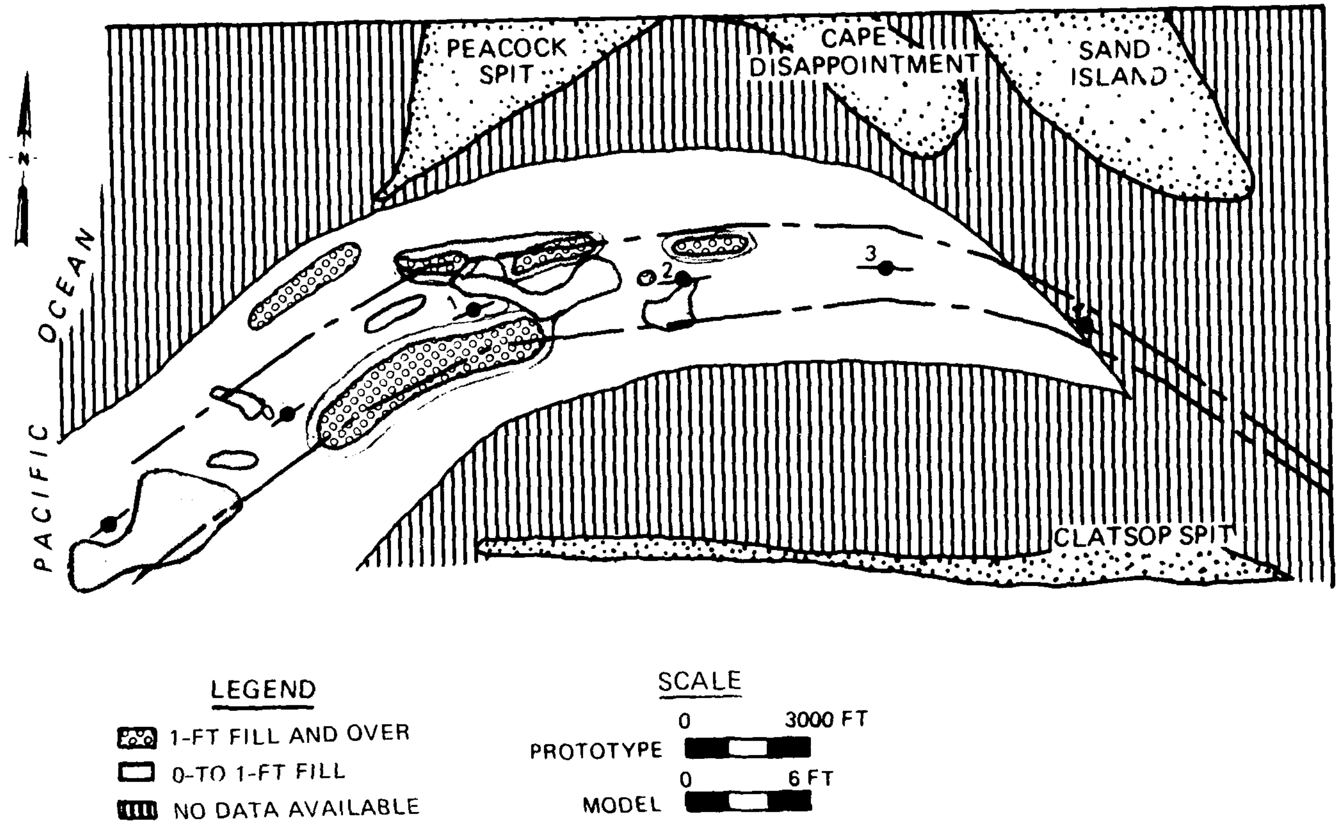


Figure 17. Model shoaling patterns, typical year

PART VI: CONCLUSIONS

205. A hybrid modeling method has been developed to address a wide range of sedimentation problems in the Columbia River estuary. The method has been applied to the problem of shoaling in the navigation channel at the mouth of the estuary. The Columbia hybrid modeling method integrates field data, analytical techniques, a physical model, and numerical models into a solution technique that uses each method to do those things it performs best. The resulting approach retains the strengths of each method while avoiding many of the weaknesses of each. The primary disadvantage is that the numerical models used are two-dimensional, resulting in some inaccuracy of describing transport in the strongly three-dimensional flow structure of the estuary mouth. Despite this limitation, the Columbia hybrid modeling method yields results that are believed to be superior to any other presently available technique.

206. The Columbia River estuary physical model has been verified to satisfactorily reproduce observed prototype water-surface elevations, current velocities, and salinities. Results of model predictions of changes in hydraulics from model base test results are considered reliable indications of expected prototype behavior. The Columbia entrance hybrid model has been verified to yield satisfactorily accurate reproductions of total dredged volume, longitudinal channel shoaling distribution, and cross-channel shoaling patterns. The model overpredicts shoaling on the outer bar. Results of model predictions can be considered reliable indications of the effects of possible modifications to the entrance in terms of changes from the base condition, so long as those modifications do not severely alter the flow regime. The models are not expected to predict the initial reestablishing of side slopes due to a channel deepening.

REFERENCES

Ackers, P., and White, W. R. 1973 (Nov). "Sediment Transport: New Approach and Analysis," Journal, Hydraulics Division, American Society of Civil Engineers, No. HY11.

Anderson, G. C. 1963 (Dec). "Columbia River Effluent in the Northeast Pacific Ocean, 1961, 1962: Selected Aspects of Phytoplankton Distribution and Production," Technical Report No. 96, University of Washington, Seattle, Wash.

Ariathurai, R., MacArthur, R. C., and Krone, R. C. 1977 (Oct). "Mathematical Model of Estuarial Sediment Transport," Technical Report D-77-12, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Ballard, R. L. 1964. "Distribution of Beach Sediments near the Columbia River," Technical Report No. 98, University of Washington, Department of Oceanography, Seattle, Wash.

Bourke, R. H., Glenne, B., and Adams, B. W. 1971 (Feb). "The Nearshore Physical Oceanographic Environment of the Pacific Northwest Coast," Ref 71-45, Oregon State University, Corvallis, Oreg.

Burt, W. V., and McAllister, W. B. 1959 (Aug). "Recent Studies in the Hydrography of Oregon Estuaries," Technical Report No. 9, Ref 59-2, Oregon State University, Department of Oceanography, Corvallis, Oreg.

Clark, S. M., and Snyder, G. R. 1969 (Nov). "Timing and Extent of a Flow Reversal in the Lower Columbia River," Limnology and Oceanography, Vol 14, No. 6.

Conomos, T. J., and Gross, M. G. 1968. "Mixing of Columbia River and Ocean Waters in Summer," Journal, Sanitary Engineering Division, American Society of Civil Engineers.

Cooper, W. S. 1958 (Jun). "Coastal Sand Dunes of Oregon and Washington," Memoir 72, Geological Society of America, Boulder, Colo.

Desai, C. S. 1979. Elementary Finite Element Method, Prentice-Hall, Englewood Cliffs, N. J.

Dobson, R. W. 1967. Some Applications of a Digital Computer to Hydraulic Engineering Problems, M.S. Thesis, Stanford University, Calif.

Donnell, B. P., and McAnally, W. H., Jr. "Spectral Analysis of Columbia River Estuary Currents" (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Duxbury, A. C. 1967. "Currents at the Columbia River Mouth," Photogrammetric Engineering, Vol 33, No. 3.

__________. 1972. "Variability of Salinity and Nutrients off the Columbia River Mouth," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, Wash.

Forster, W. O. 1972. "Radionuclide Distribution in Columbia River and Adjacent Pacific Shelf Sediments," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, Wash.

Gross, M. G. 1972. "Sediment-Associated Radionuclides from the Columbia River," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, Wash.

Herrmann, F. A., Jr. 1968 (Dec). "Model Studies of Navigation Improvements, Columbia River Estuary; Hydraulic and Salinity Verification," Technical Report No. 2-735, Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

__________. 1970 (Jun). "Tidal Prism Measurements at Mouth of Columbia River; Hydraulic Model Investigation," Miscellaneous Paper H-70-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Hickson, R. E. 1961. "Columbia River Ship Channel Improvement and Maintenance," Journal, Waterways and Harbors Division, Proceedings, American Society of Civil Engineers, Vol 87, No. WW3.

__________. 1965. "Columbia River Stabilization and Improvement for Navigation," Symposium on Channel Stabilization Problems, TR1, Vol 3, Chapter 4, Committee on Channel Stabilization, U. S. Army Corps of Engineers.

Hubbell, D. W., and Glenn, J. L. 1973. "Distribution of Radionuclides in Bottom Sediments of the Columbia River Estuary," Professional Paper 433-L, U. S. Geological Survey.

Hubbell, D. W., Glenn, J. L., and Stevens, H. H., Jr. 1971. "Studies of Sediment Transport in the Columbia River Estuary," Proceedings, 1971 Conference on Estuaries of the Pacific N.W., Circular No. 42, Engineering Experiment Station, Oregon State University, Corvallis, Oreg.

Jonsson, I. G. 1966. "The Friction Factor for a Current Superimposed by Waves," Basic Research Progress Report No. 11, Technical University of Denmark, Copenhagen.

Kitaigordskii, S. A. 1962. "Applications of the Theory of Similarity to the Analysis of Wind-Generated Wave Motion as a Stochastic Process," Bulletin Acad. Sci., U.S.S.R. Geophys. Sev. No. 1, 73.

LaGarde, V. E., III, and Heltzel, S. B. 1980. "A Data Management System for Finite Element Method Models," Proceedings, 3rd International Conference on Finite Elements in Water Resources, University of Mississippi, University, Miss.

Lockett, J. B. 1959. "Interim Consideration of the Columbia River Entrance," Journal, Hydraulics Division, Proceedings, American Society of Civil Engineers, Vol 85, No. HY1.

__________. 1963. "Phenomena Affecting Improvement of the Lower Columbia Estuary and Entrance," Misc. Pub. 970, Federal Interagency Sedimentation Conference of the Subcommittee on Sedimentation, Jackson, Miss., U. S. Department of Agriculture.

__________. 1965. "Some Indications of Sediment Transport in the Vicinity of the Columbia Estuary and Entrance, Oregon and Washington," Transactions of the XI Congress, International Association for Hydraulic Research, Leningrad.

__________. 1967. "Sediment Transport and Diffusion: Columbia Estuary and Entrance," Journal, Waterways and Harbors Division, Proceedings, American Society of Civil Engineers.

McAnally, W. H., Jr., and Donnell, B. P. "Hydraulic Surveys of the Columbia River Estuary" (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

McAnally, W. H., Jr., and Thomas, W. A. "Shear Stress Computations in a Numerical Model for Estuarine Sediment Transport" (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Morse, B. A., Gross, M. G., and Barnes, C. A. 1968. "Movement of Seabed Drifters near the Columbia River," Journal, Waterways and Harbors Division, Proceedings, American Society of Civil Engineers.

National Marine Consultants, Inc. 1961a. "Oceanographic Study for Columbia River Entrance," Santa Barbara, Calif.

__________. 1961b. "Wave Statistics for Three Deep Water Stations Along the Oregon-Washington Coast," Santa Barbara, Calif.

Neal, V. T. 1972. "Physical Aspects of the Columbia River and Its Estuary," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, Wash.

Norton, W. R., and King, I. P. 1977 (Feb). "Operating Instructions for the Computer Program RMA-2," Resource Management Associates, Lafayette, Calif.

O'Brien, M. P. 1935. "Models of Estuaries," Transactions, American Geophysical Union.

__________. 1951. "Wave Measurements at the Columbia River Light Vessel, 1933-1936," Transactions, American Geophysical Union, Vol 32, No. 6.

Office, Chief of Engineers, Department of the Army. "Annual Report of the Chief of Engineers," Washington, D. C.

Resio, D. T., and Vincent, C. L. 1977 (Aug). "A Numerical Hindcast Model for Wave Spectra on Water Bodies with Irregular Shoreline Geometry; Test of Nondimensional Growth Rates," Miscellaneous Paper H-77-9, Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Sternberg, R. W., et al. 1977. "Aquatic Disposal Field Investigations, Columbia River Disposal Site, Oregon; Appendix A, An Investigation of the Hydraulic Regime and Physical Nature of Bottom Sedimentation," Technical Report D-77-30, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Swart, D. H. 1976 (Sep). "Coastal Sediment Transport, Computation of Longshore Transport," R968, Part 1, Delft Hydraulics Laboratory, The Netherlands.

U. S. Army Coastal Engineering Research Center, CE. 1977. Shore Protection Manual, Washington, D. C.

U. S. Army Engineer District, Portland. 1960a. "Interim Report on 1959 Current Measurement Program, Columbia River at Mouth, Oregon and Washington," (4 Vols), Portland, Oreg.

__________. 1960b. "Summary of Interim Report on 1959 Current Measurement Program, Columbia River at Mouth, Oregon and Washington," Portland, Oreg.

U. S. Naval Weather Service Command. 1970. "Summary of Synoptic Meteorological Observations, North American Coastal Marine Areas," Vols 9 and 10.

Whetten, J. T., and Fullam, T. J. 1967. "Columbia River Bed Forms," Proceedings of the 12th Congress of the International Association for Hydraulic Research.

Whetten, J. T., Kelley, J. C., and Hansom, L. G. 1969. "Characteristics of Columbia River Sediment and Sediment Transport," Journal of Sedimentary Petrology, Vol 39, No. 3.

White, W. R., Milli, H., and Crabbe, A. D. 1975. "Sediment Transport Theories: An Appraisal of Available Methods," Report Int 119 (Vols 1 and 2), Hydraulics Research Station, Wallingford, England.

Zienkiewicz, O. C. 1971. The Finite Element Method in Engineering Science, McGraw-Hill, London.

Table 1

Seventeen Events of Wave and Riverflow

Wave Condition	Discharge, cfs	Duration, days
No waves	300,000	66
10SW10		24
10WW10		64
10NW10		29
20SW15		14
No waves	550,000	17
20SW15		5
10WW15		16
10NW10		7
No waves	220,000	25
10SW10		7
10WW10		16
10NW10		11
No waves	140,000	29
10SW10		7
10WW10		14
05NW05		9
Total		360

Table 2

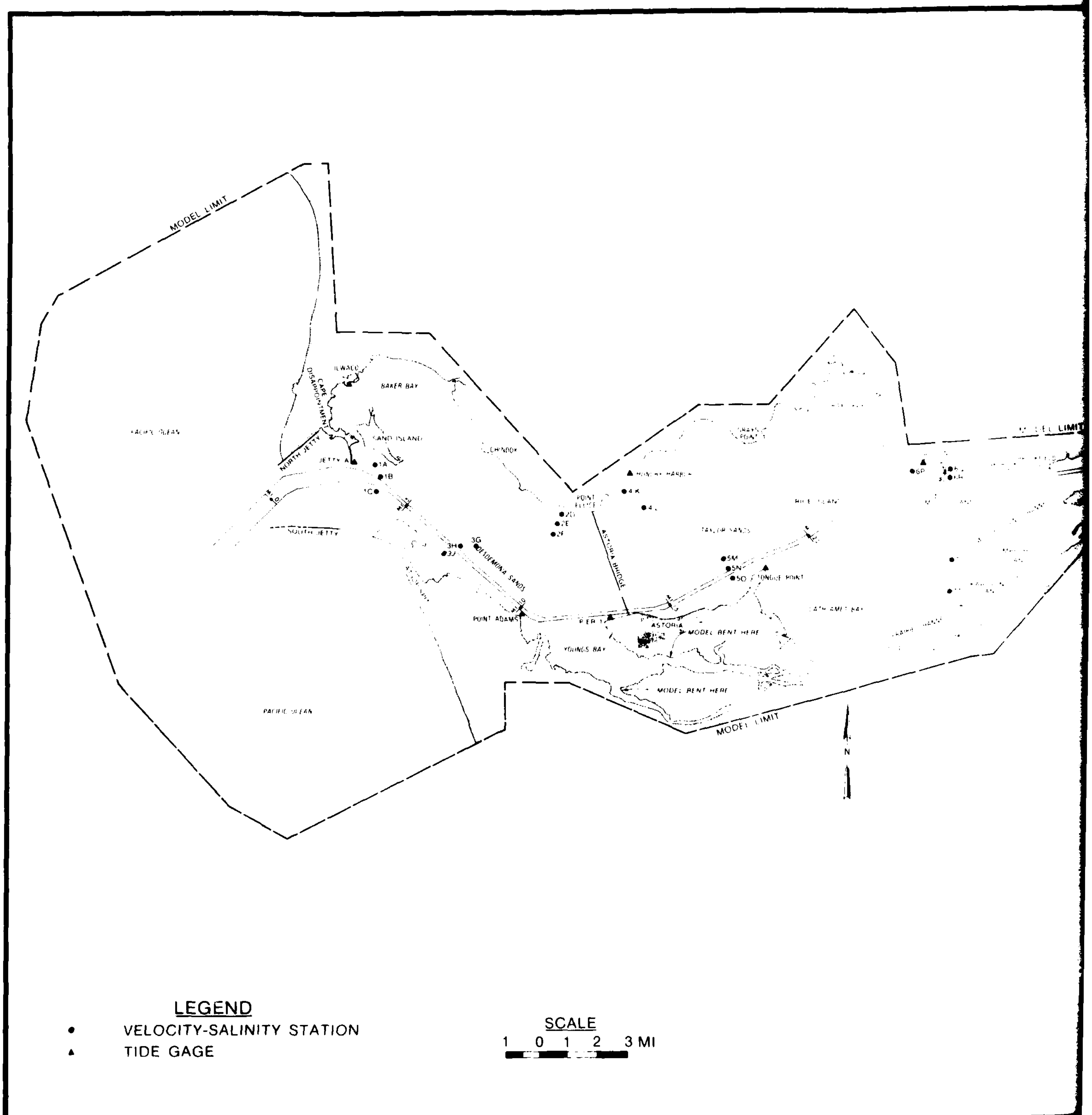
Five Events

Wave Event	Discharge, cfs	Duration, days
None	300,000	139
10SW10		56
10WW10		112
10NW10		57
20SW15		1
Total		365

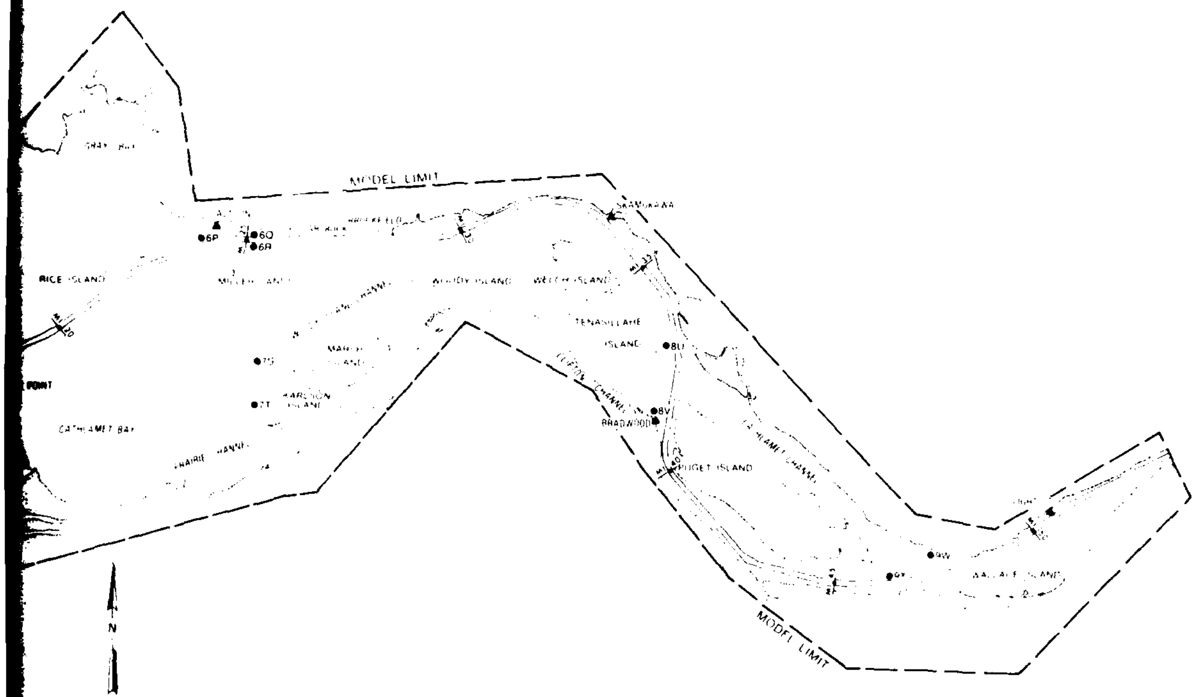
Table 3

Prototype Dredged Volumes, Millions of Cubic Yards

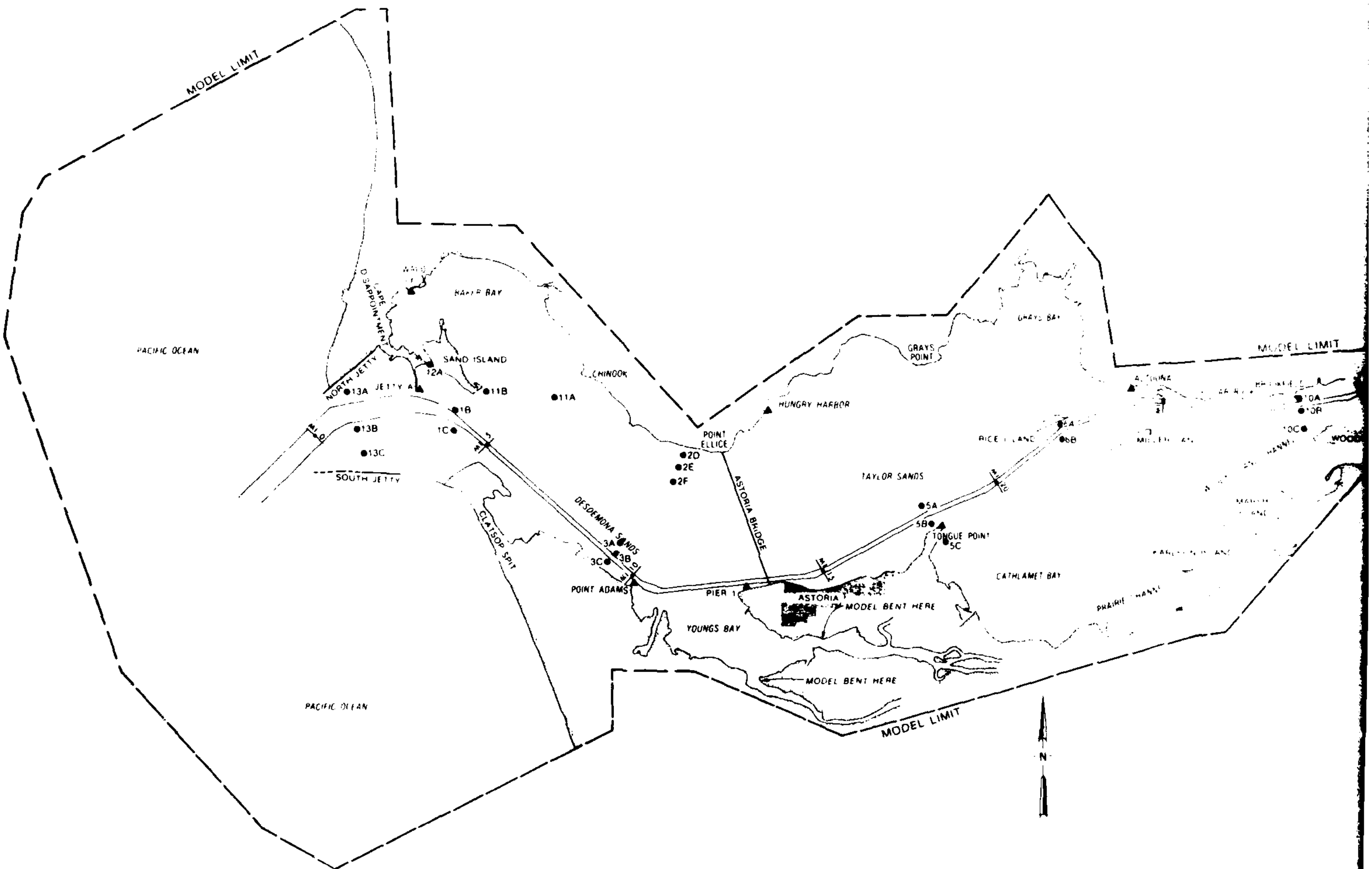
1959-1975		1976-1979	
FY	Volume	FY	Volume
59	2.3	76	3.4
60	1.6	76T	3.2
61	2.3	77	6.9
62	2.3	78	4.1
63	2.2	79	5.2
64	2.7	Avg	5.4
65	2.6		
66	2.2		
67	2.2		
68	1.5		
69	2.0		
70	1.5		
71	1.7		
72	2.9		
73	3.8		
74	3.7		
75	6.1		
Avg	2.6		



MODEL LIMIT
ILWACO
CAPE DISAPPOINTMENT
BAKER BAY
SAND ISLAND
NORTH JETTY
JETTY A
1A
1B
1C
SOUTH JETTY
PACIFIC OCEAN
2D
2E
2F
3G
3H
3J
DESDEMONA SANDS
POINT ADAMS
ASTORIA BRIDGE
ASTORIA
YOUNGS BAY
MODEL BENT HERE
MODEL BENT HERE
4K
TAYLOR SANDS
5M
5N
5O
TONGUE POINT
MODEL LIMIT
MODEL LIMIT
N
LEGEND
VELOCITY-SALINITY STATION
TIDE GAGE
SCALE
1 0 1 2 3 MI



VERIFICATION
STATION LOCATION
JUNE 1977 SURVEY



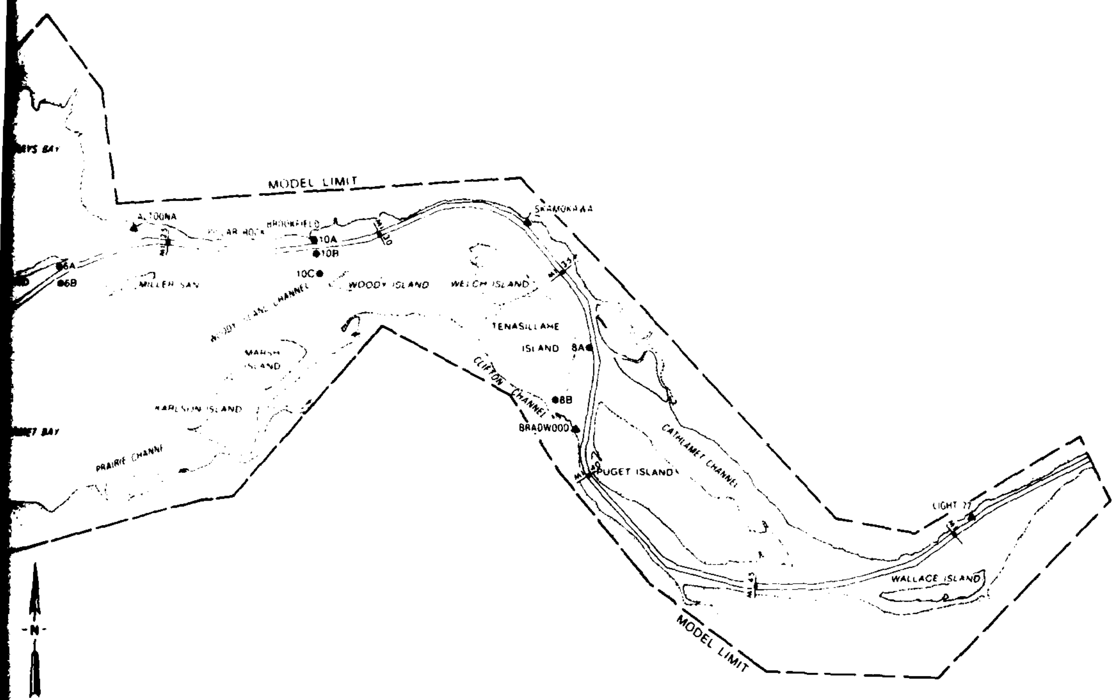
LEGEND

● VELOCITY-SALINITY STATION

▲ TIDE GAGE

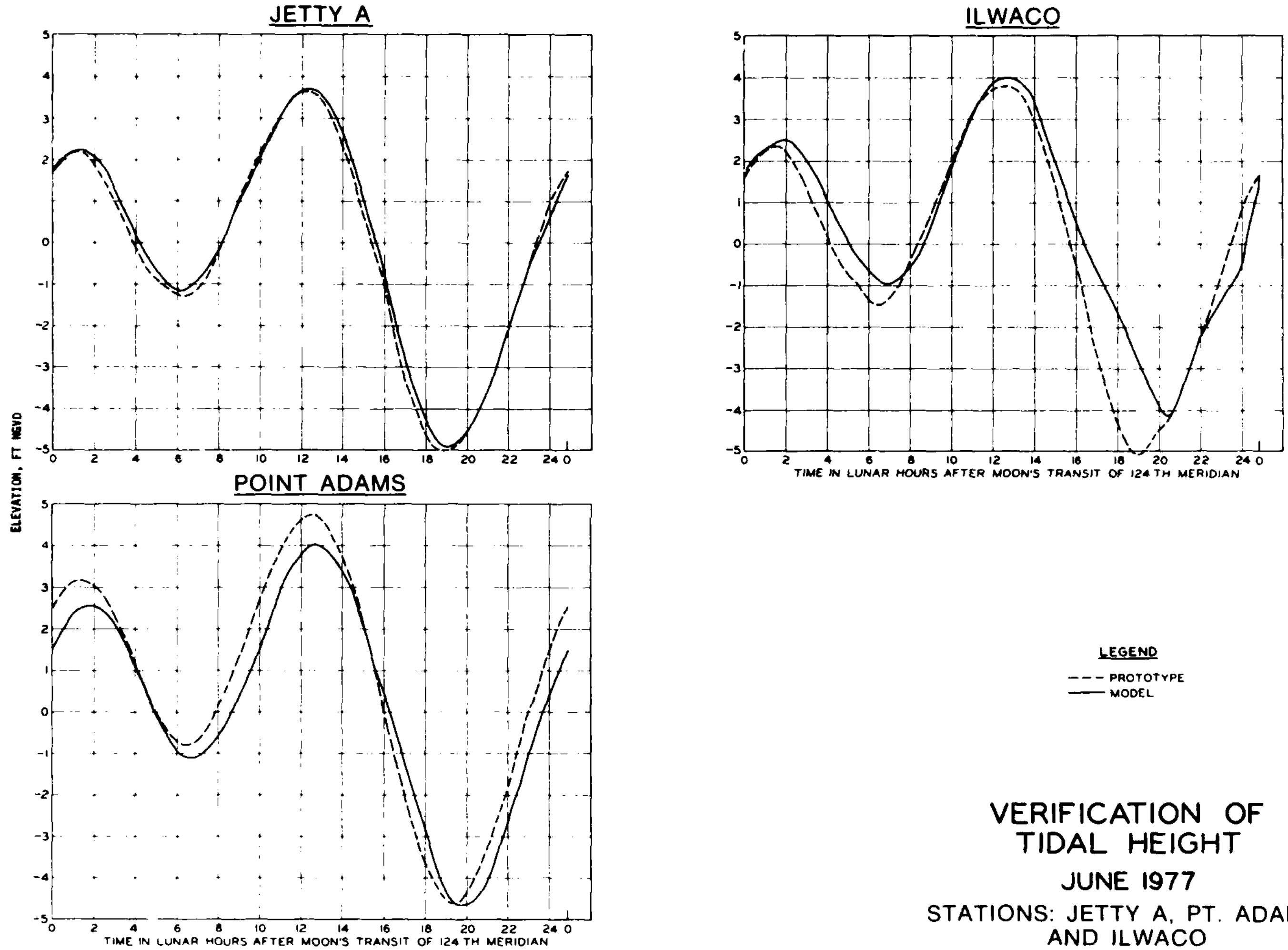
SCALE

1 0 1 2 3 MI

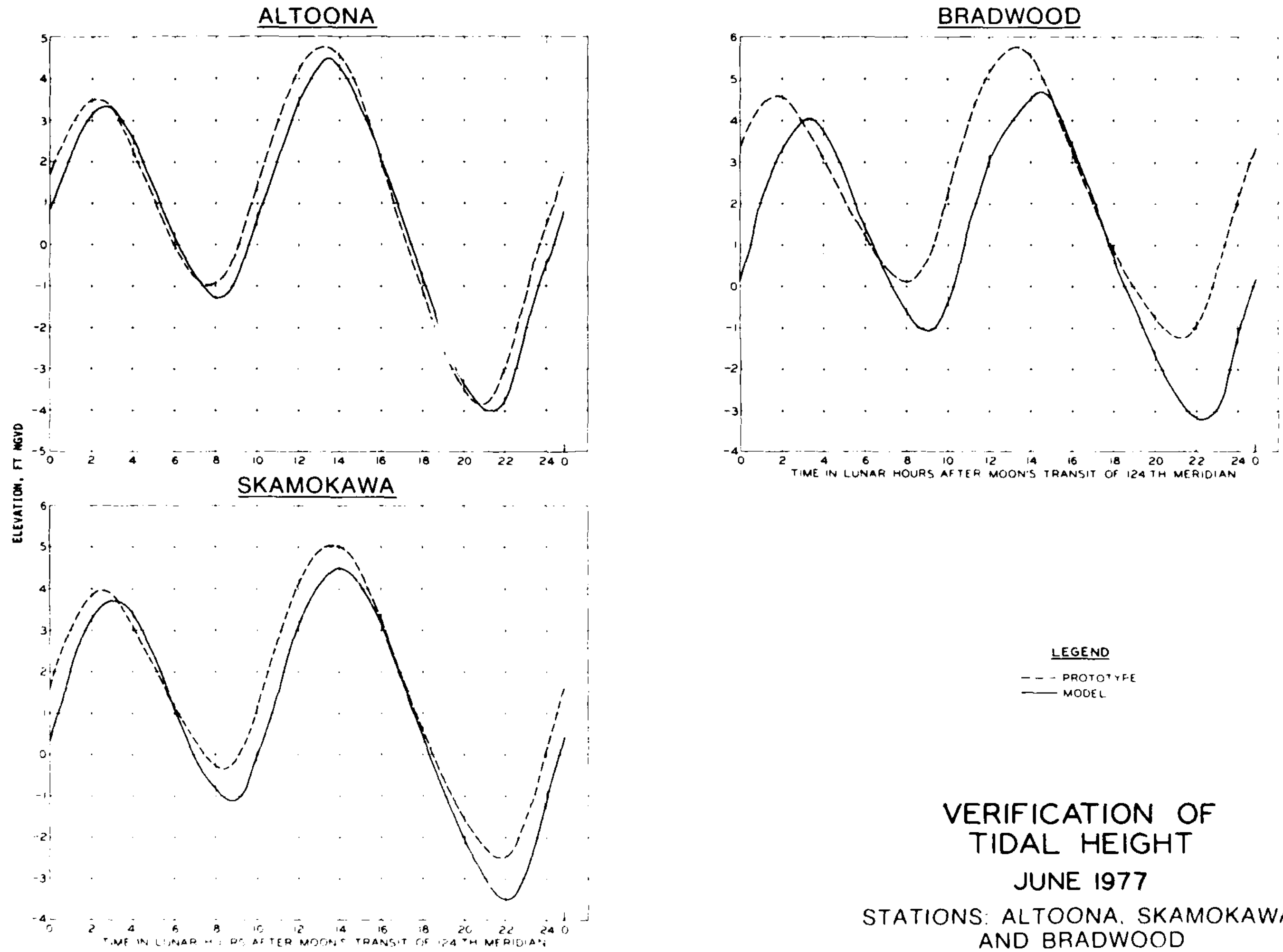


VERIFICATION
STATION LOCATION
JUNE 1978 SURVEY

PLATE 2

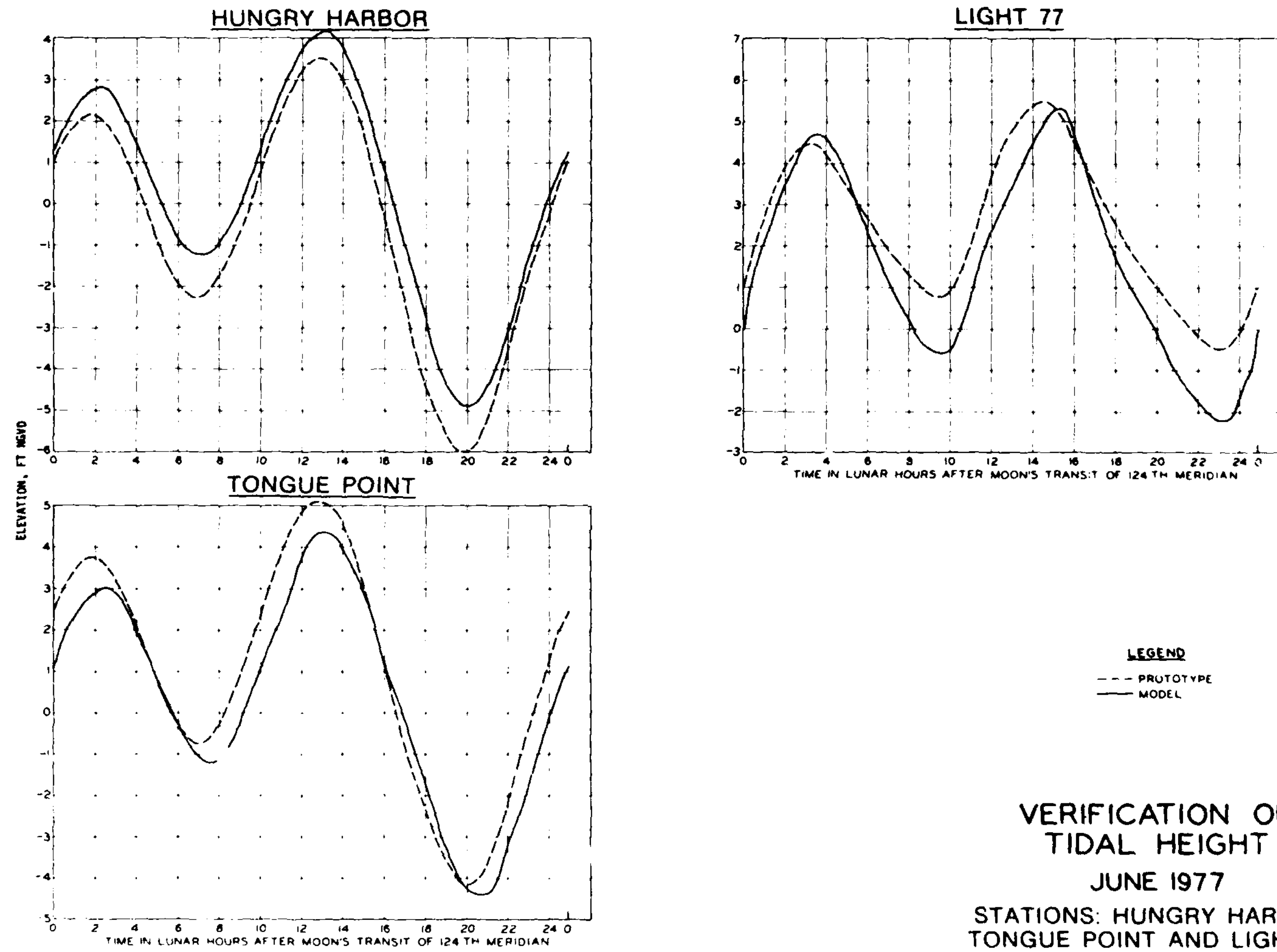


VERIFICATION OF
TIDAL HEIGHT
JUNE 1977
STATIONS: JETTY A, PT. ADAMS,
AND ILWACO



VERIFICATION OF
TIDAL HEIGHT
JUNE 1977
STATIONS: ALTOONA, SKAMOKAWA, AND BRADWOOD

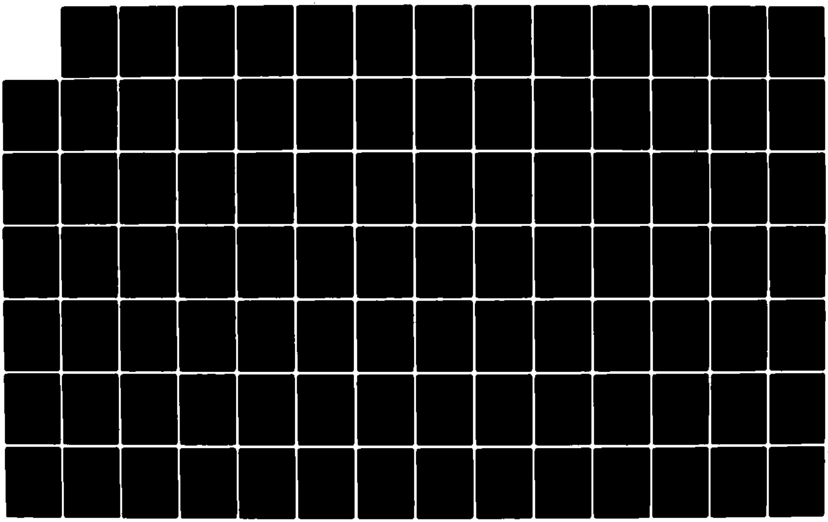
PLATE 4

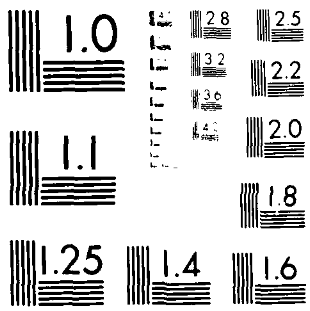


VERIFICATION OF
TIDAL HEIGHT
JUNE 1977
STATIONS: HUNGRY HARBOR, TONGUE POINT AND LIGHT 77

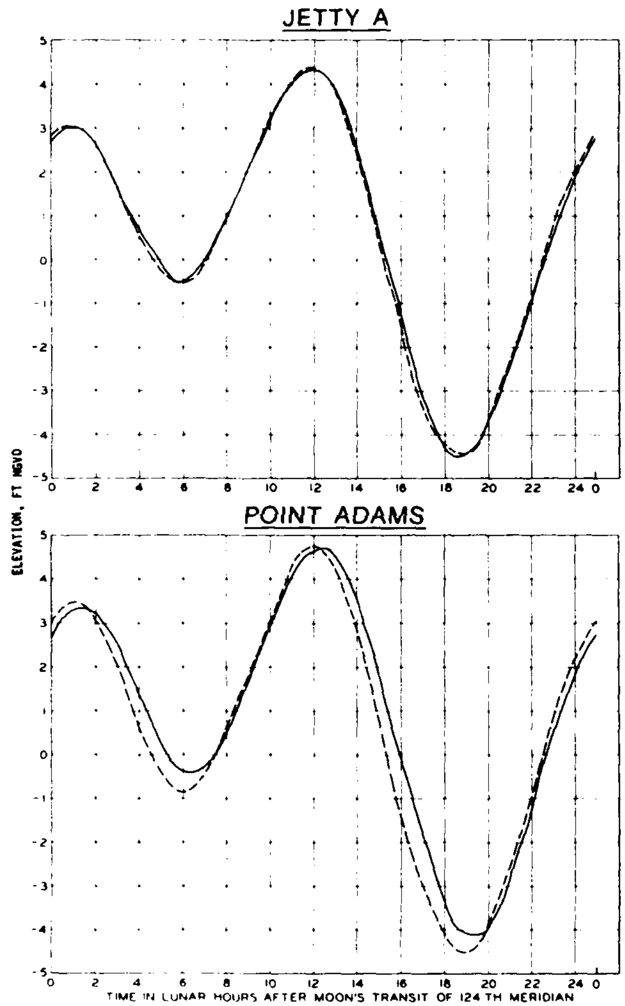
AD-A134 978 COLUMBIA RIVER ESTUARY HYBRID MODEL STUDIES REPORT 1 VERIFICATION OF HYBR..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS HYDRA.. 2/3 -

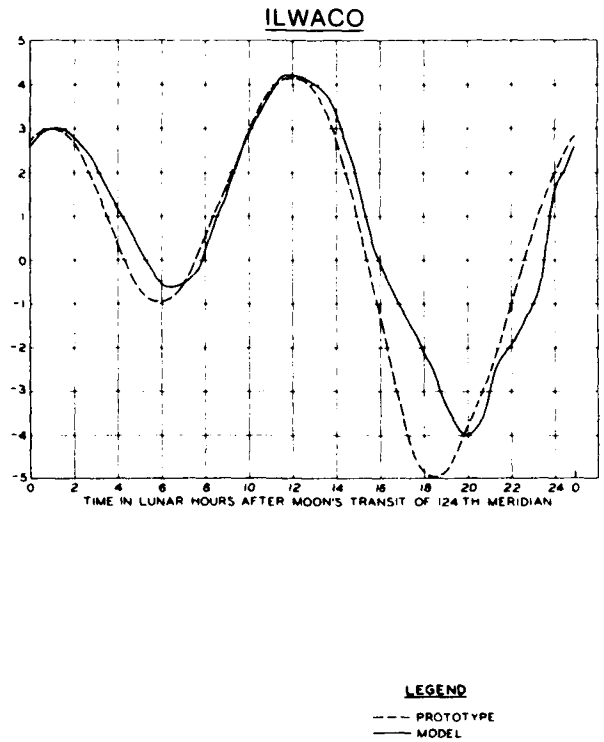
UNCLASSIFIED W H MCANALLY ET AL. SEP 83 WES/TR/HL-83-16 F/G 13/2 NL





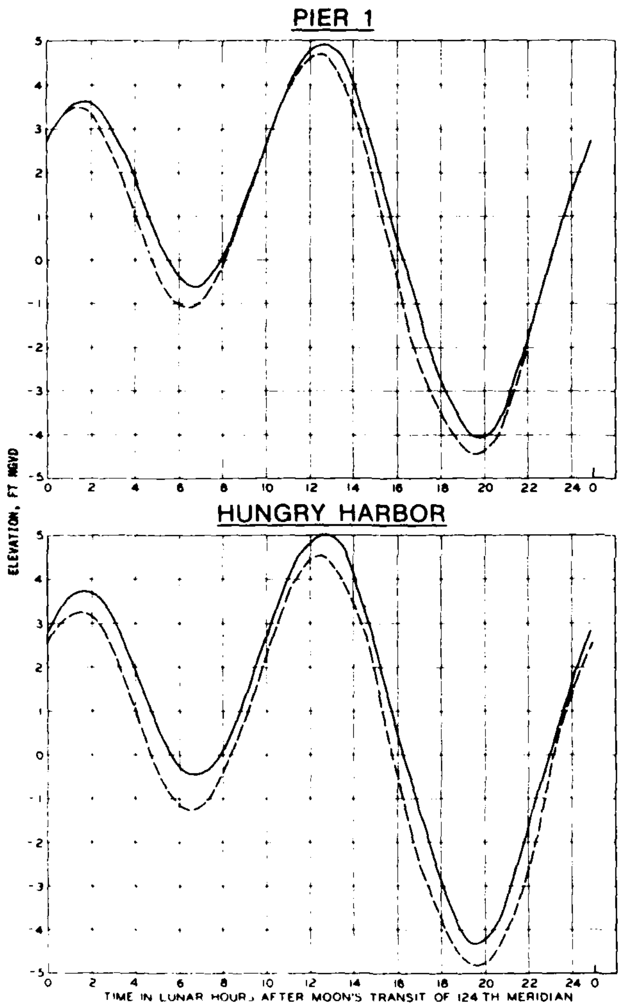
MICROCOPY RESOLUTION TEST CHART

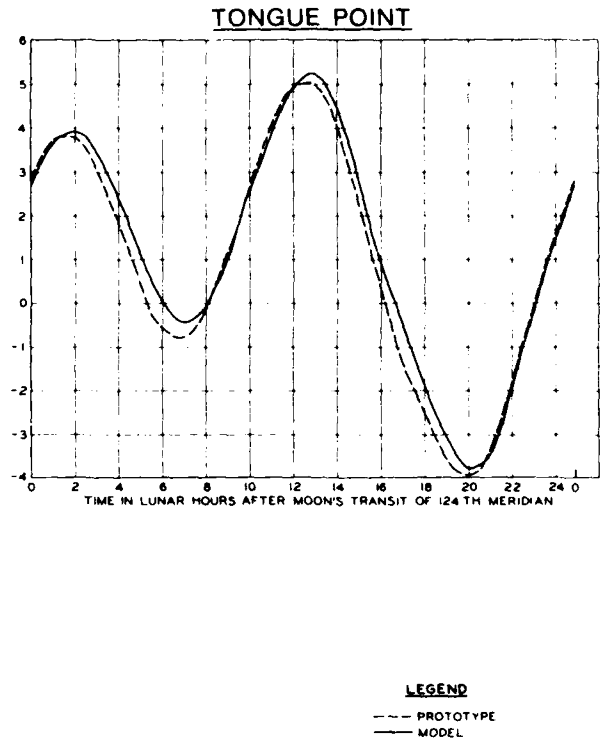




VERIFICATION OF
TIDAL HEIGHT
JUNE 1978
STATIONS: JETTY A, PT. ADAMS,
AND ILWACO

PLATE 6

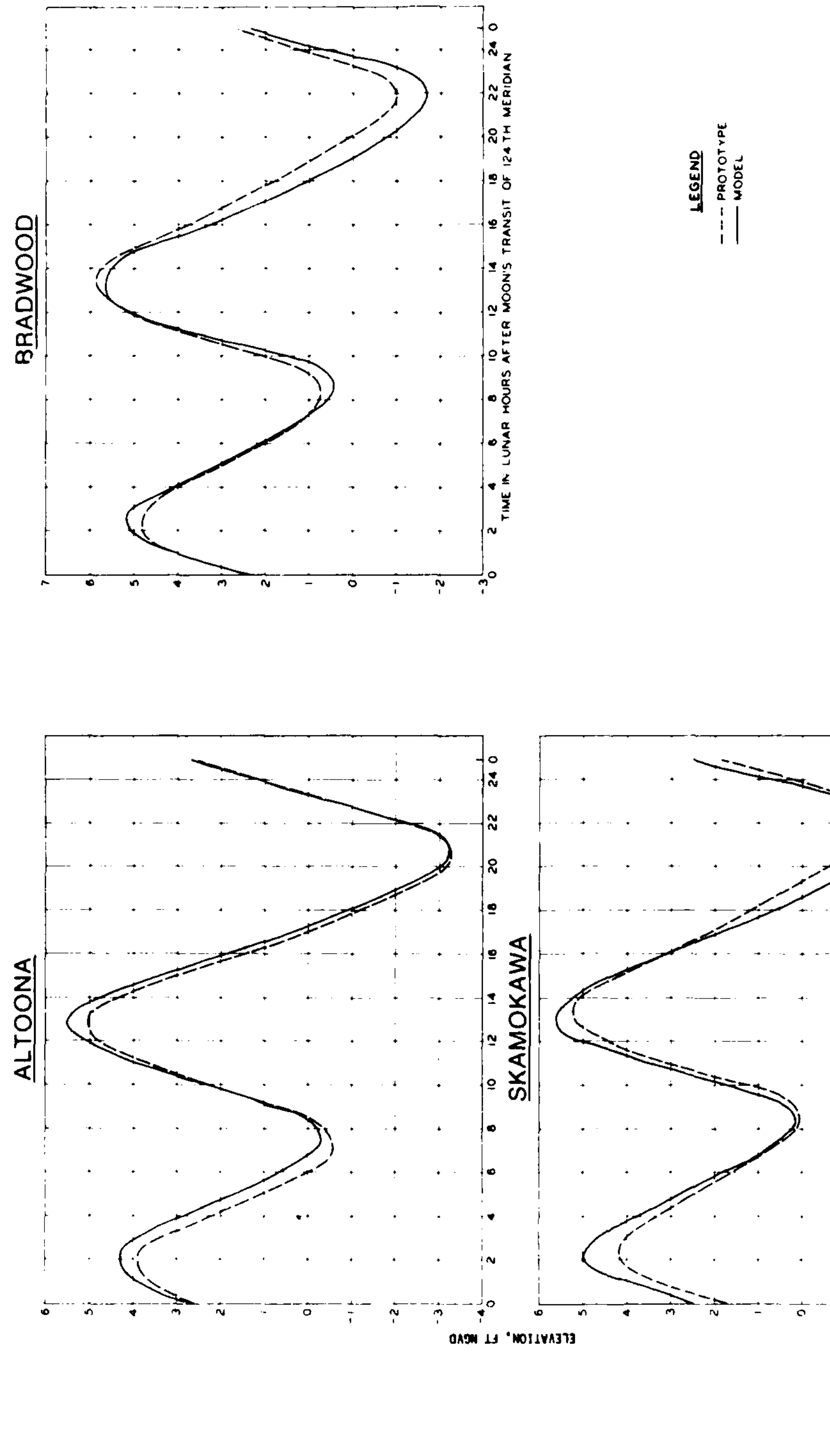




VERIFICATION OF TIDAL HEIGHT

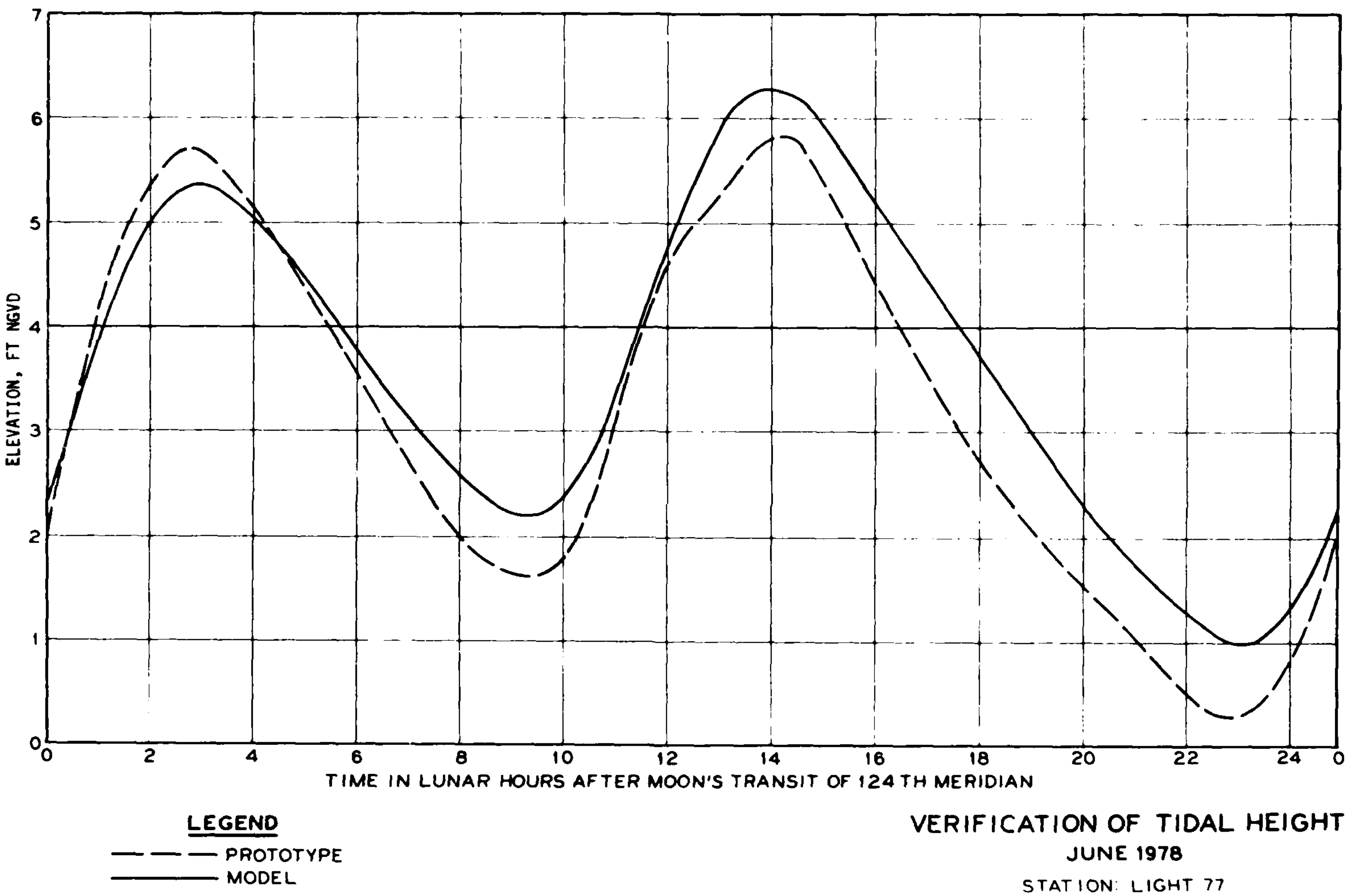
JUNE 1978

STATIONS: PIER 1, HUNGRY HARBOR, AND TONGUE POINT

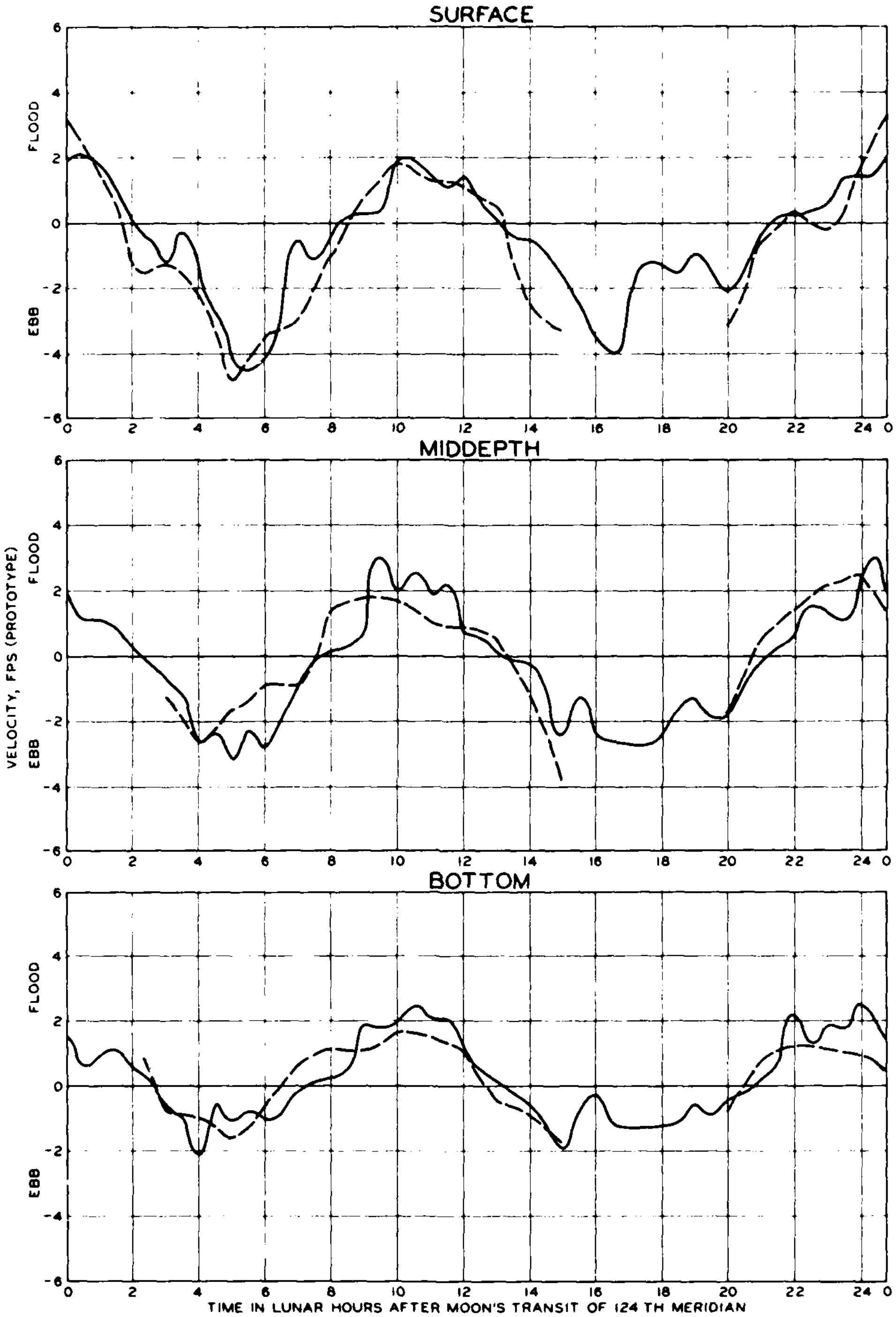


VERIFICATION OF
TIDAL HEIGHT
JUNE 1978
STATIONS: ALTOONA, SKAMOKAWA,
AND BRADWOOD

PLATE 8



VERIFICATION OF TIDAL HEIGHT
JUNE 1978
STATION: LIGHT 77



LEGEND

- – – – PROTOTYPE
- ——— MODEL

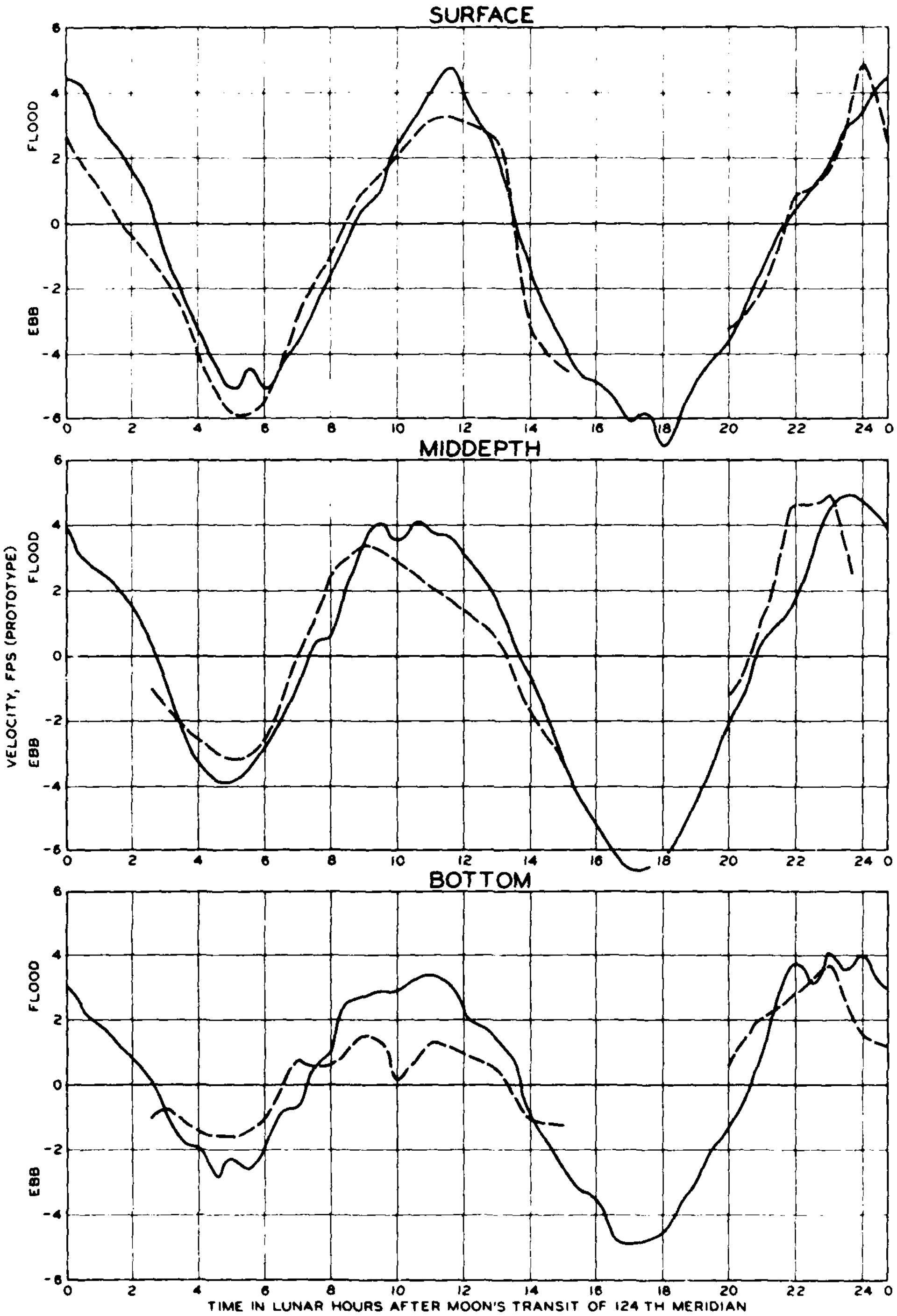
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 1-A



LEGEND

– – – PROTOTYPE

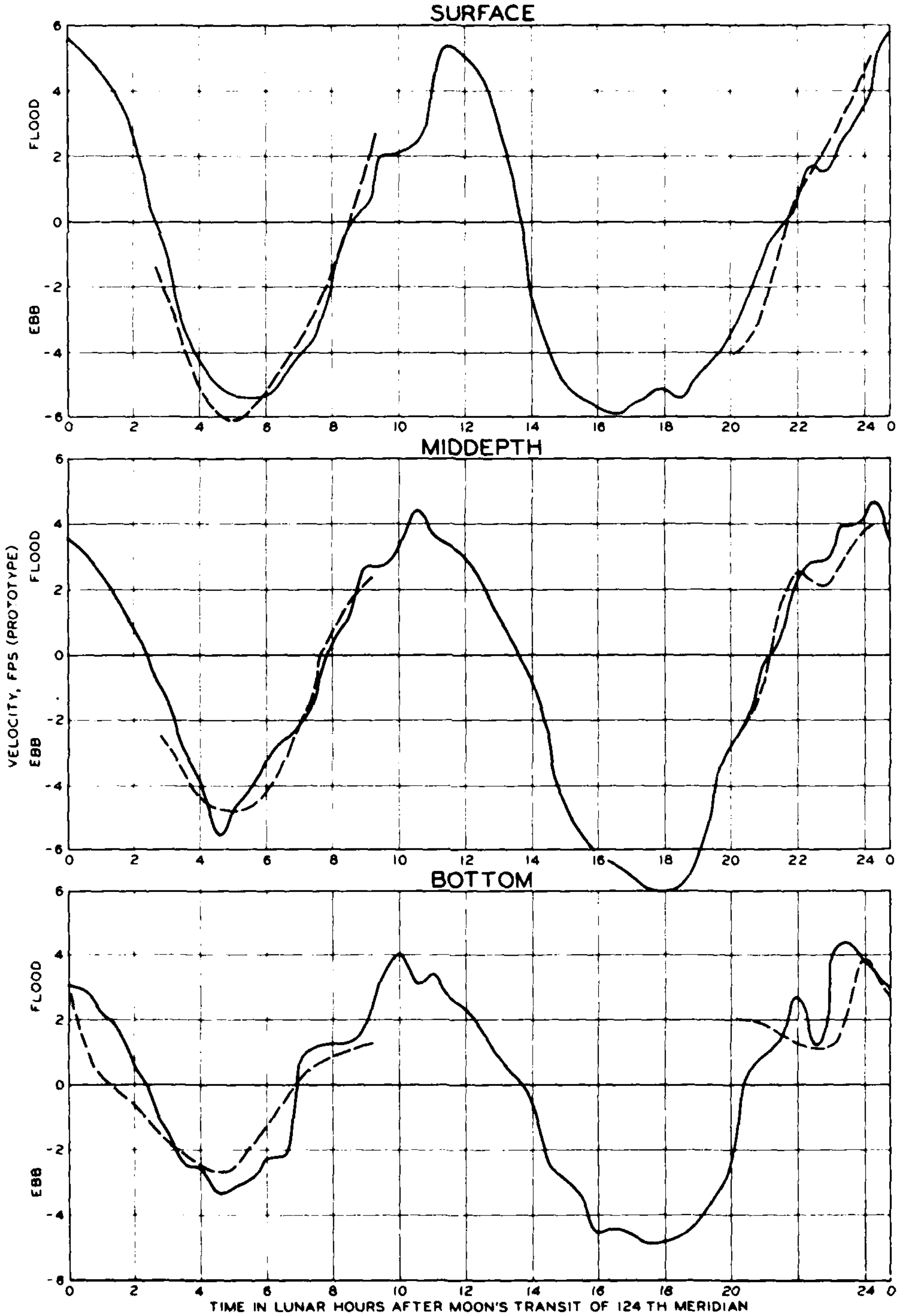
——— MODEL

MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 1-B

PLATE 11



LEGEND

– – – PROTOTYPE

——— MODEL

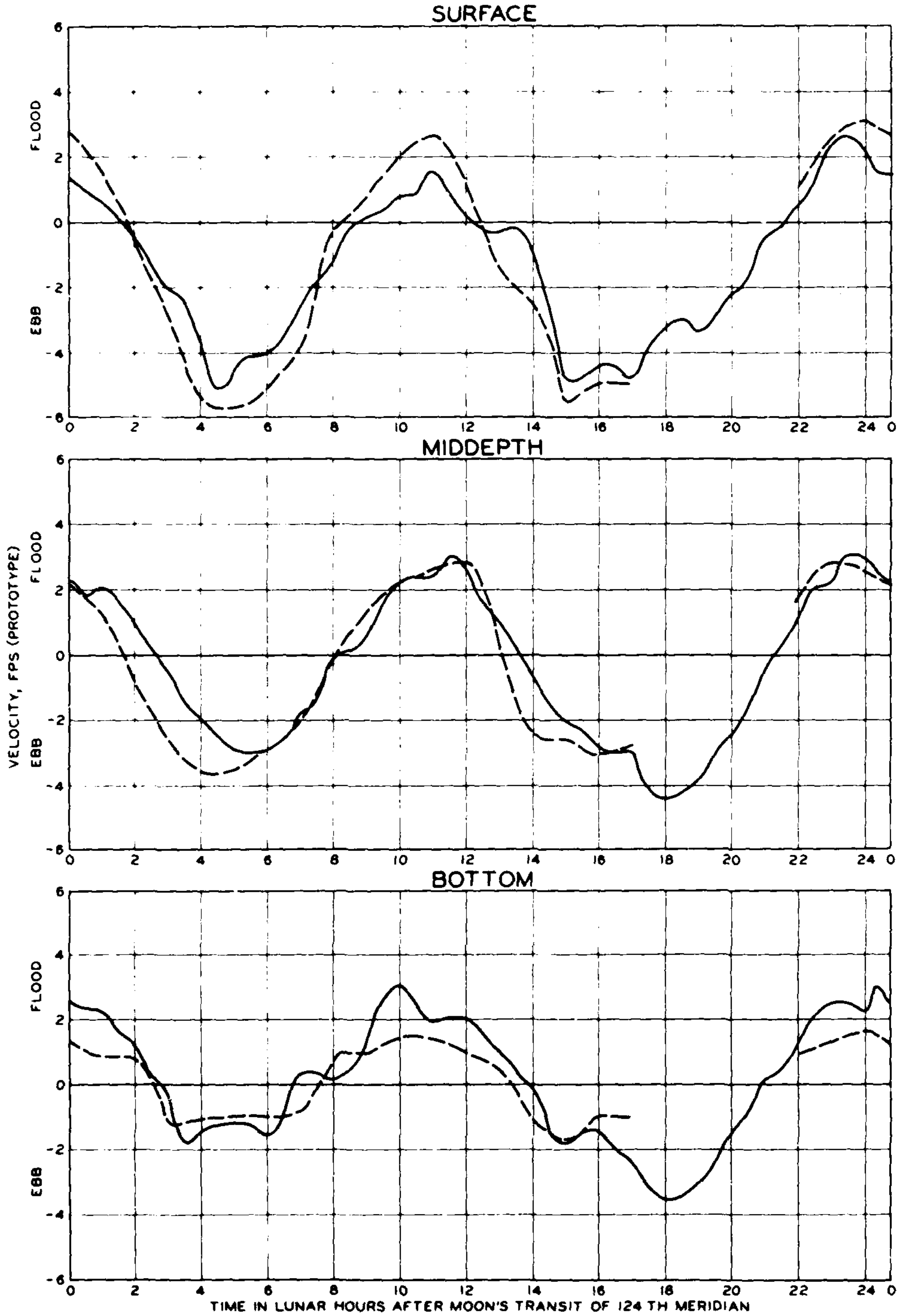
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 1-C



LEGEND

- - - PROTOTYPE

——— MODEL

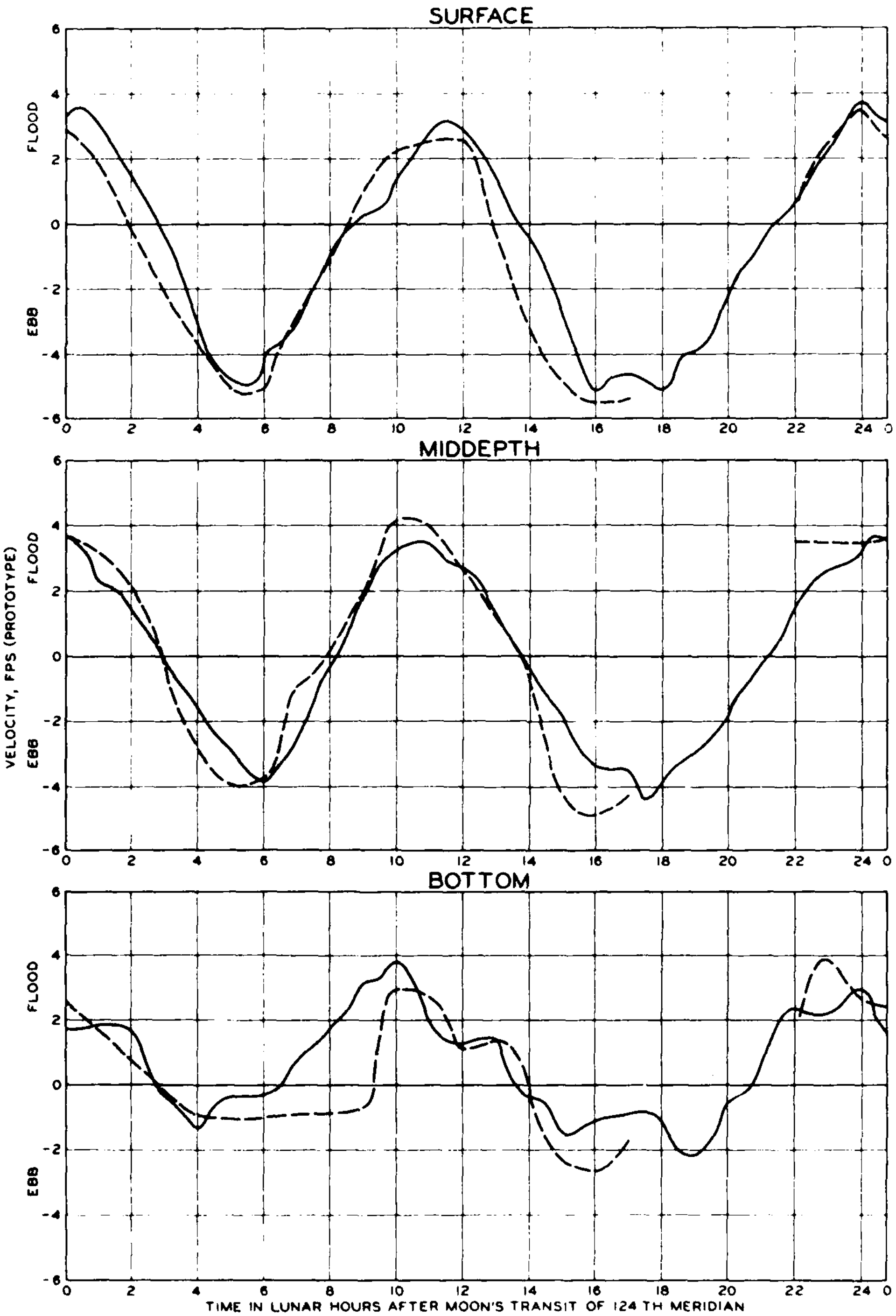
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 2-D



LEGEND

– – – PROTOTYPE

——— MODEL

MODEL TEST DATA

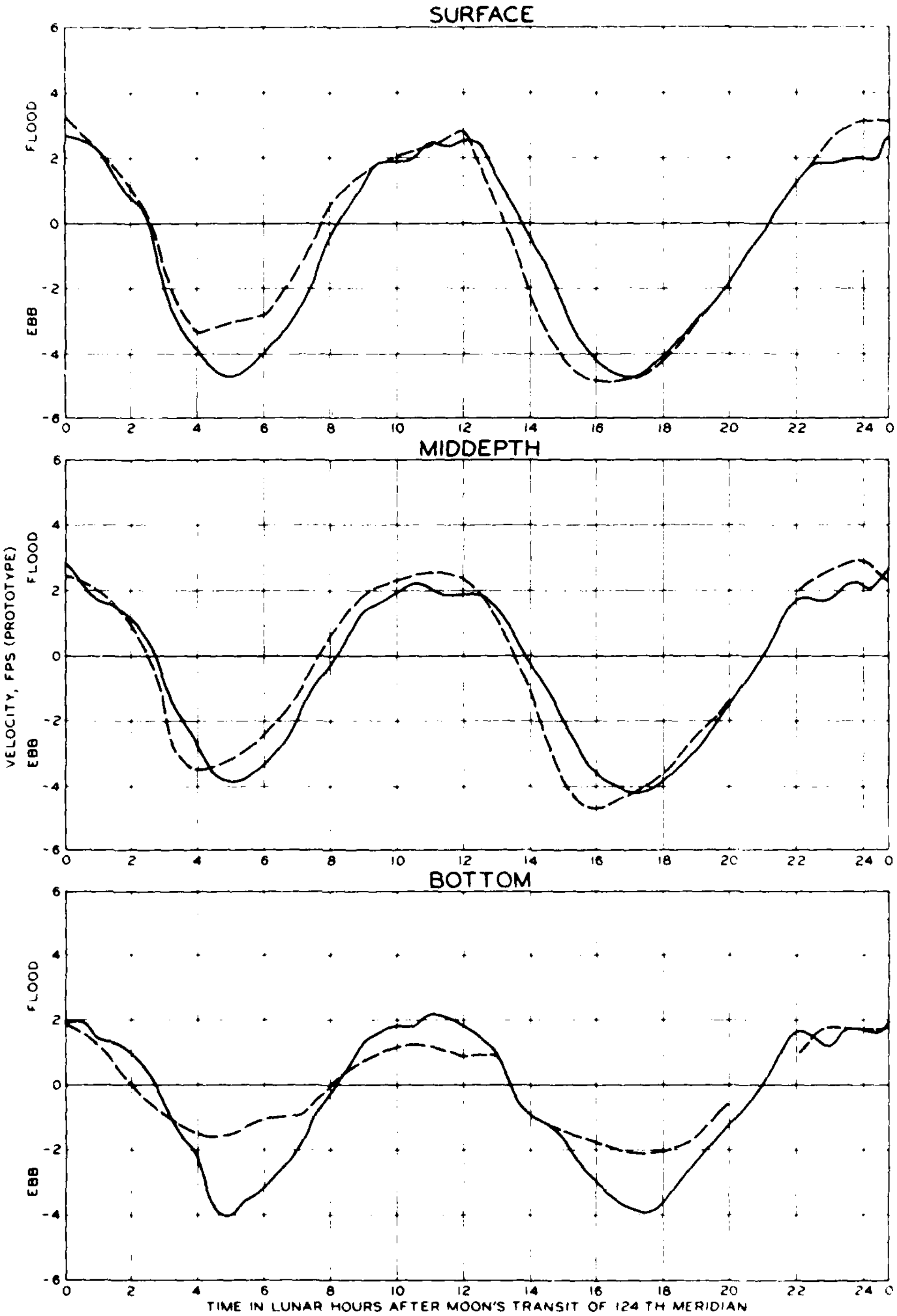
TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 2-E

PLATE 14



LEGEND

— — — PROTOTYPE

——— MODEL

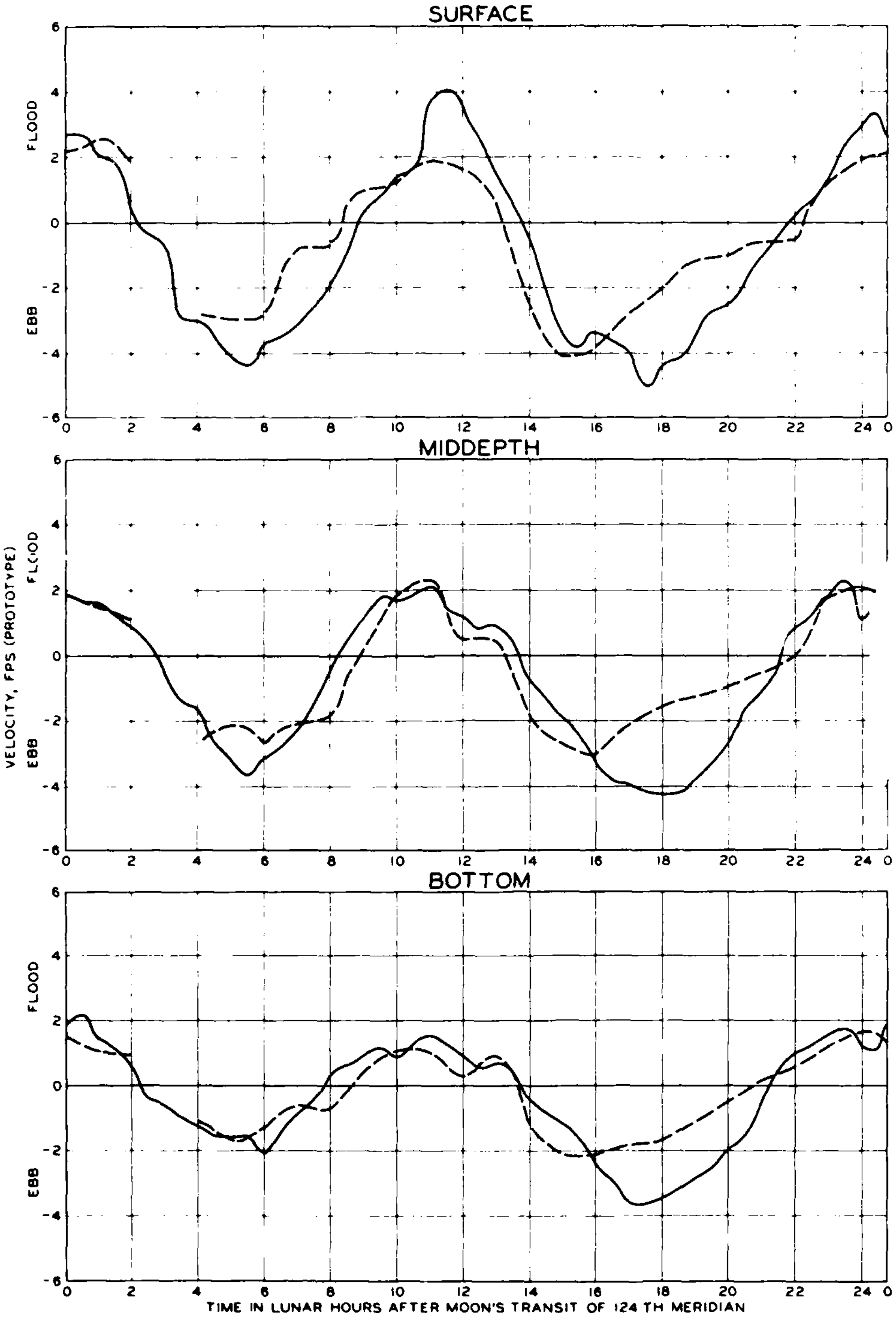
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 2-F



LEGEND

— — — PROTOTYPE

——— MODEL

MODEL TEST DATA

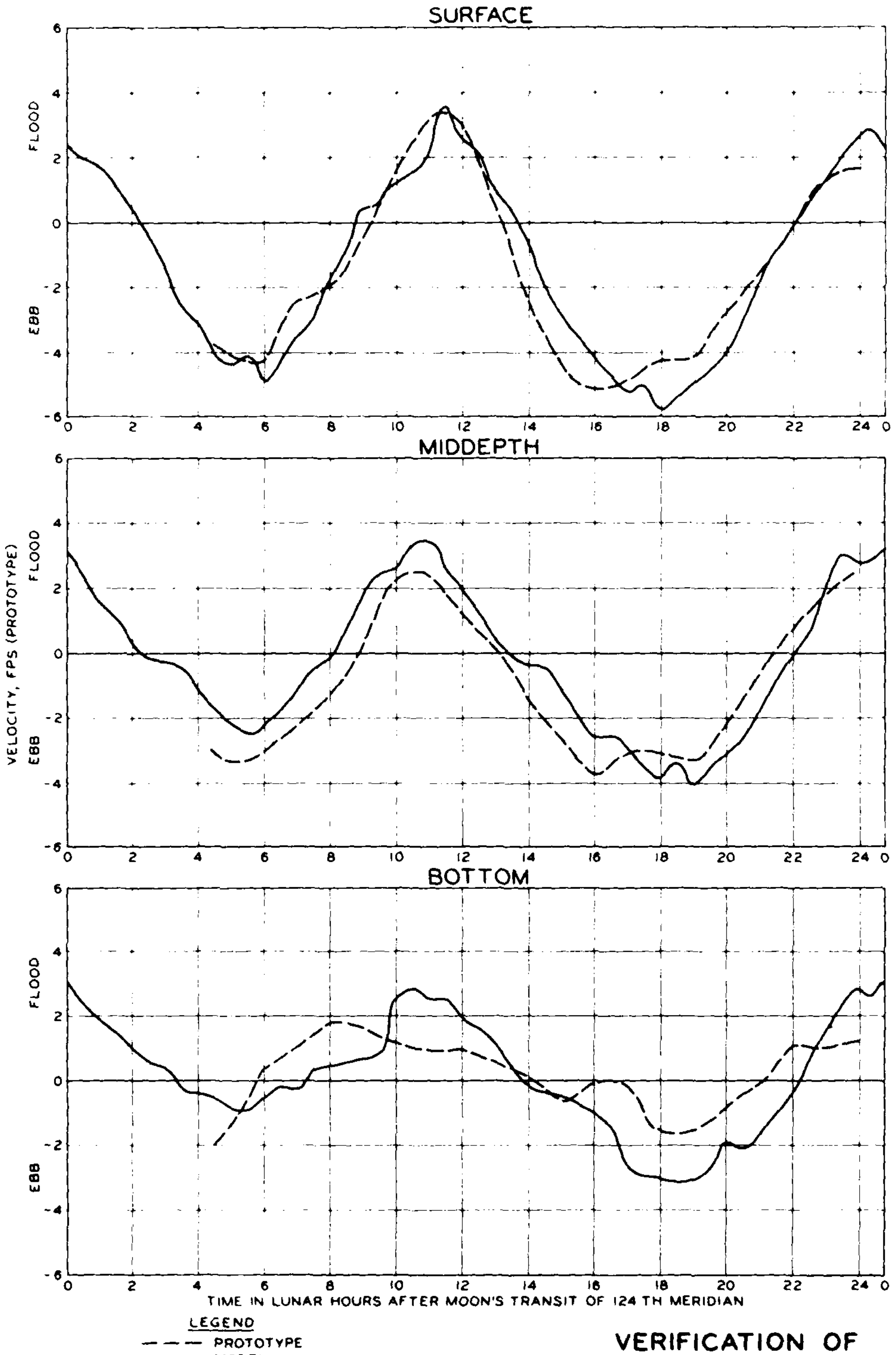
TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 3-G

PLATE 16



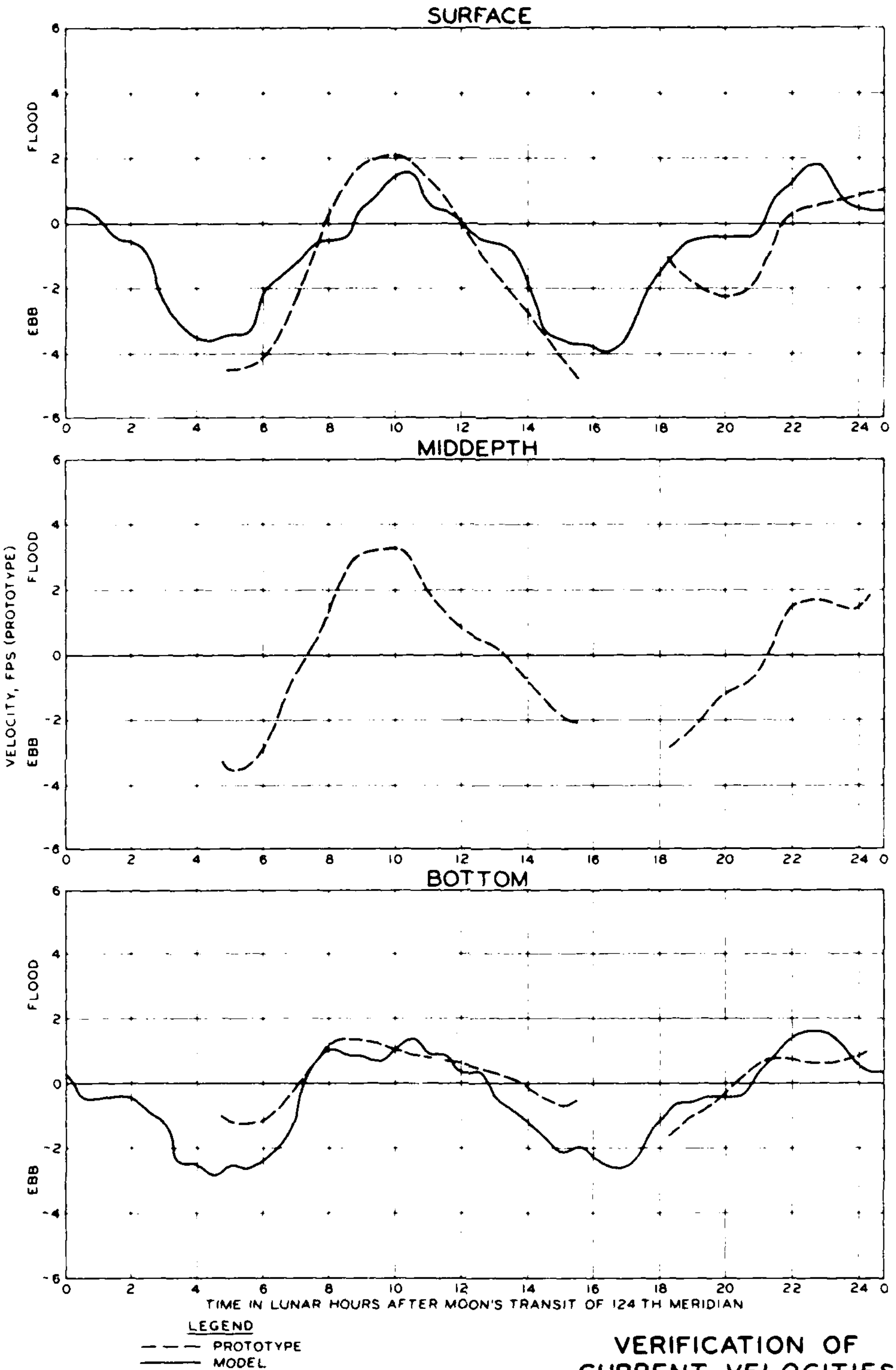
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

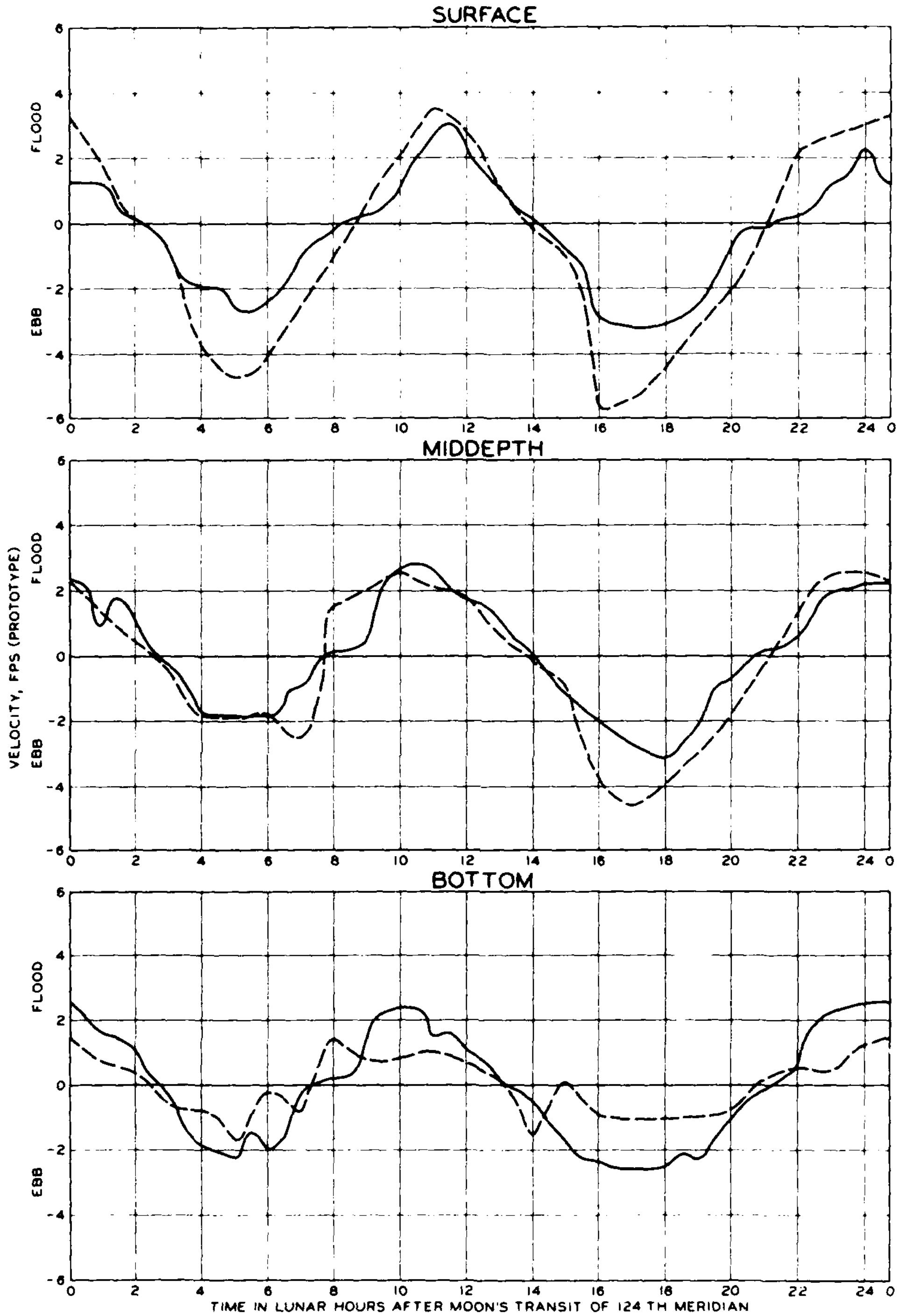
STATION 3-H



MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 3-J



LEGEND

– – – – PROTOTYPE
———— MODEL

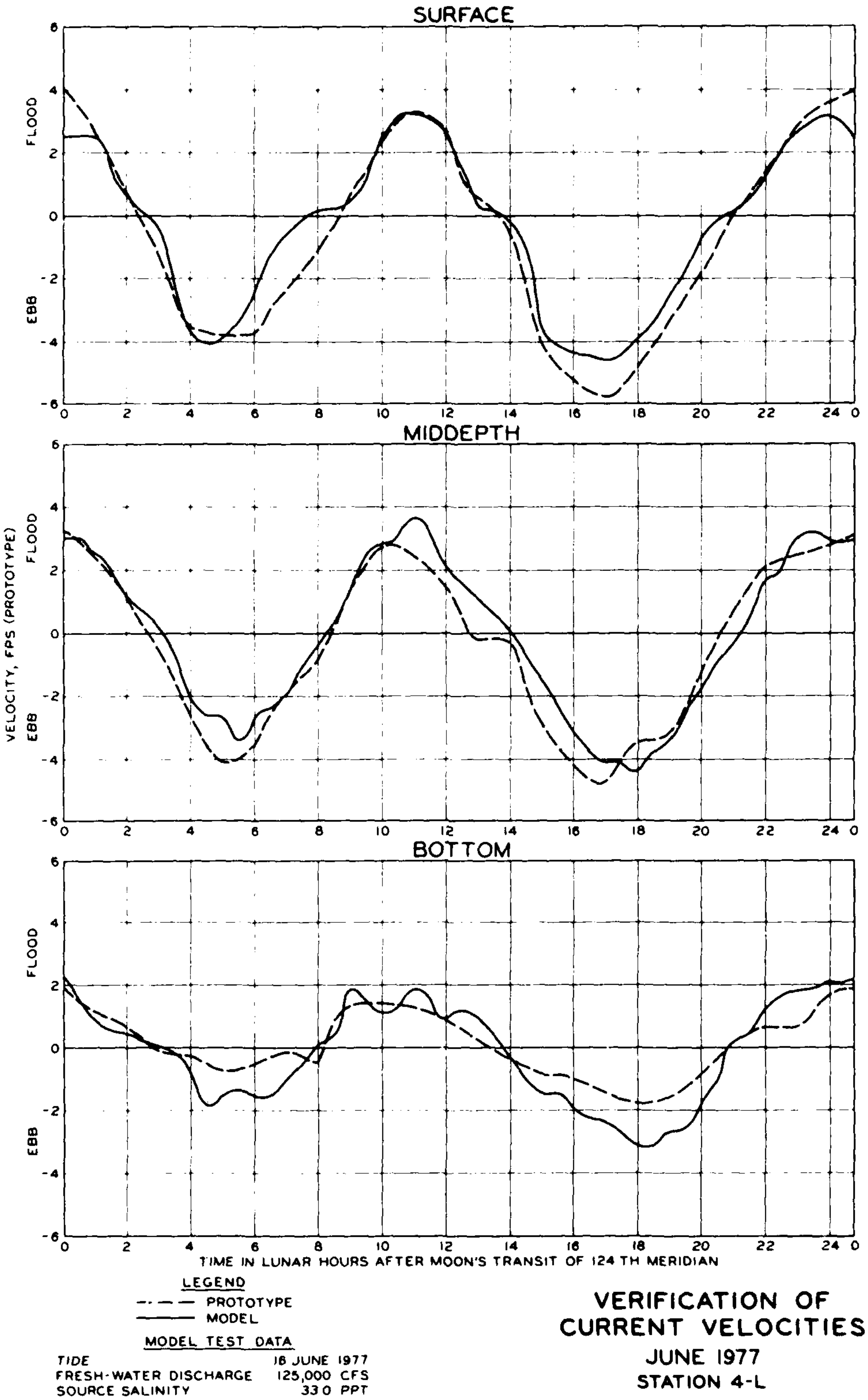
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

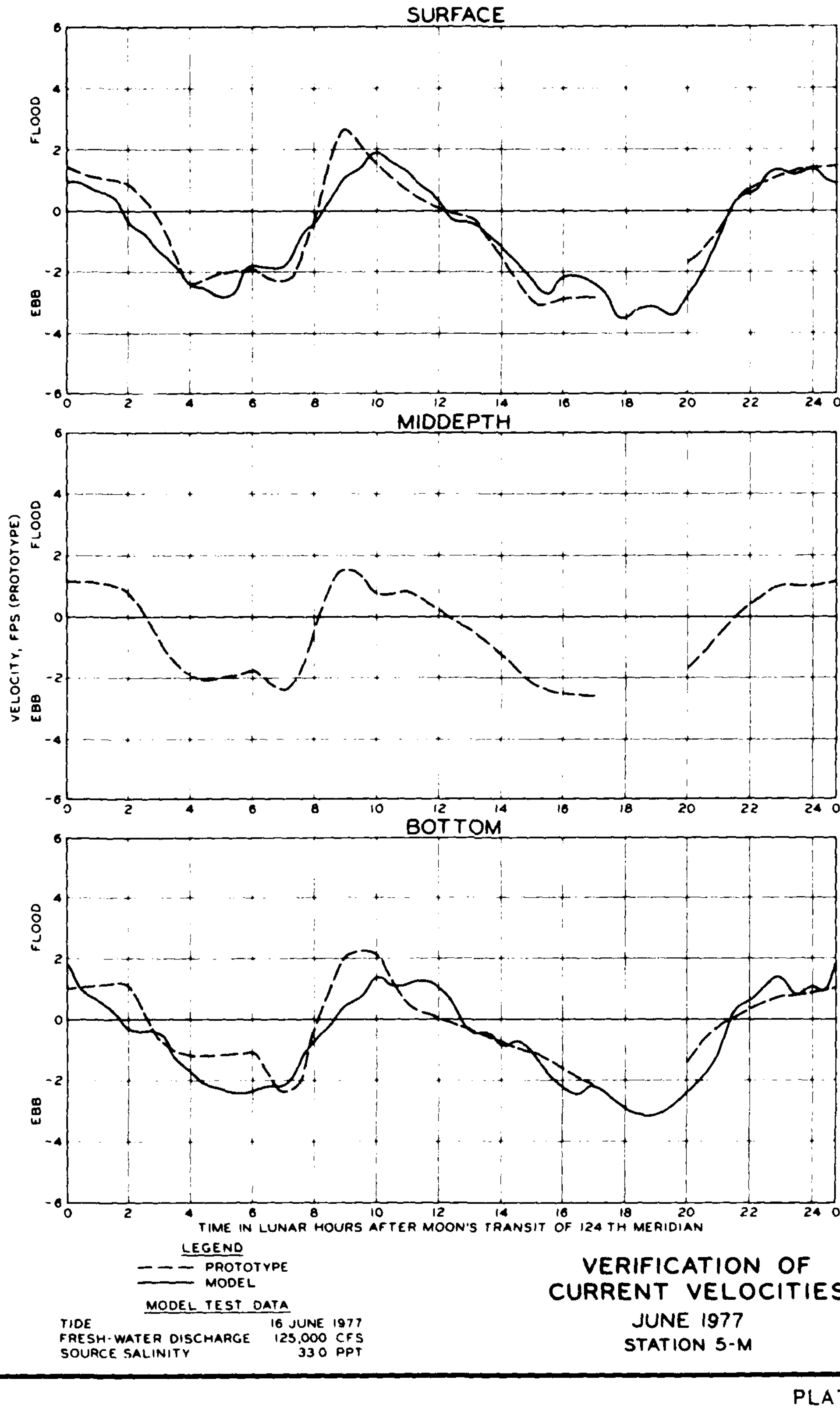
JUNE 1977

STATION 4-K



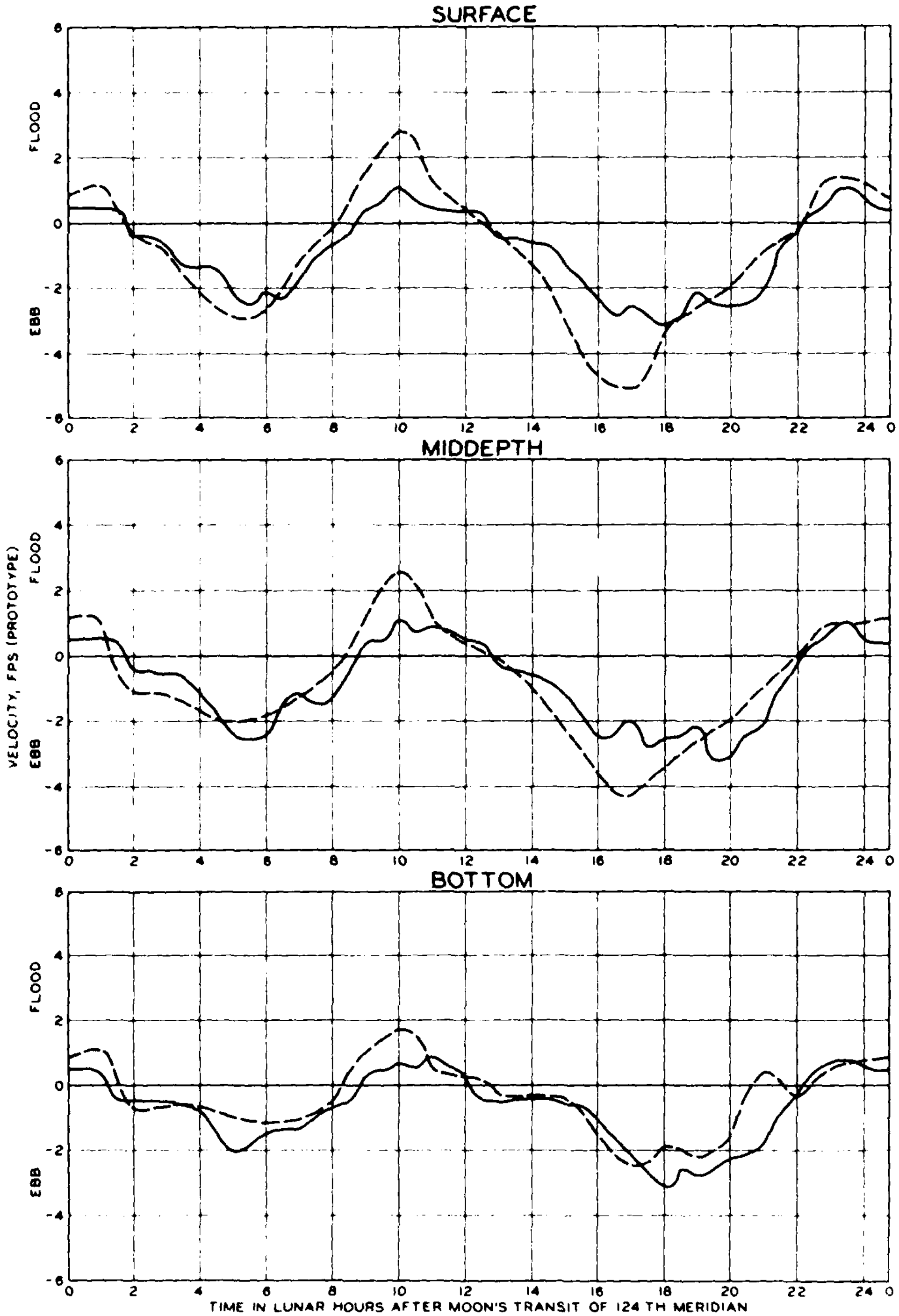
VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 4-L

PLATE 20



VERIFICATION OF CURRENT VELOCITIES
JUNE 1977
STATION 5-M

PLATE 21



LEGEND

— — — PROTOTYPE

——— MODEL

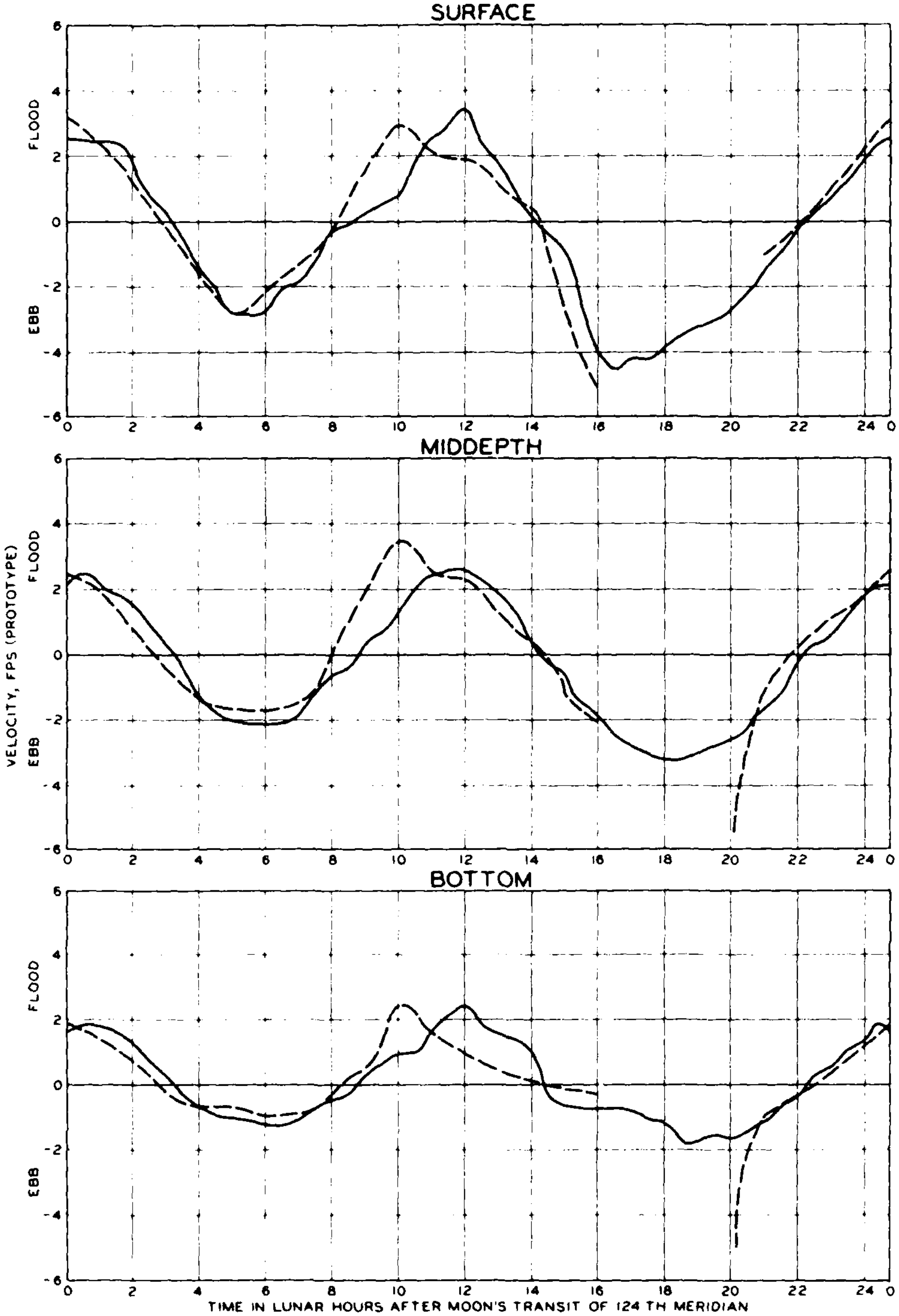
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 5-N



LEGEND

– – – PROTOTYPE

——— MODEL

MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 5-0

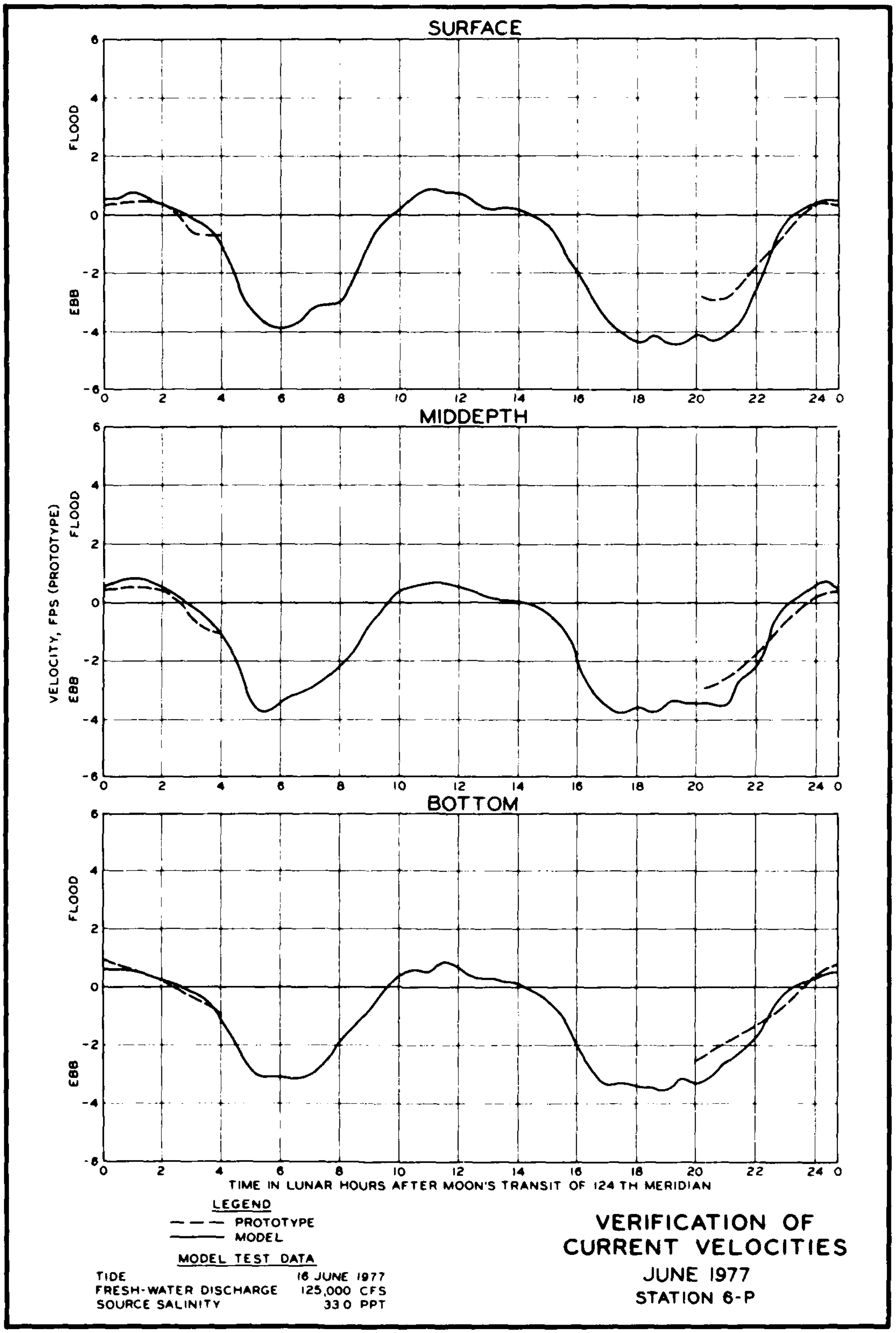
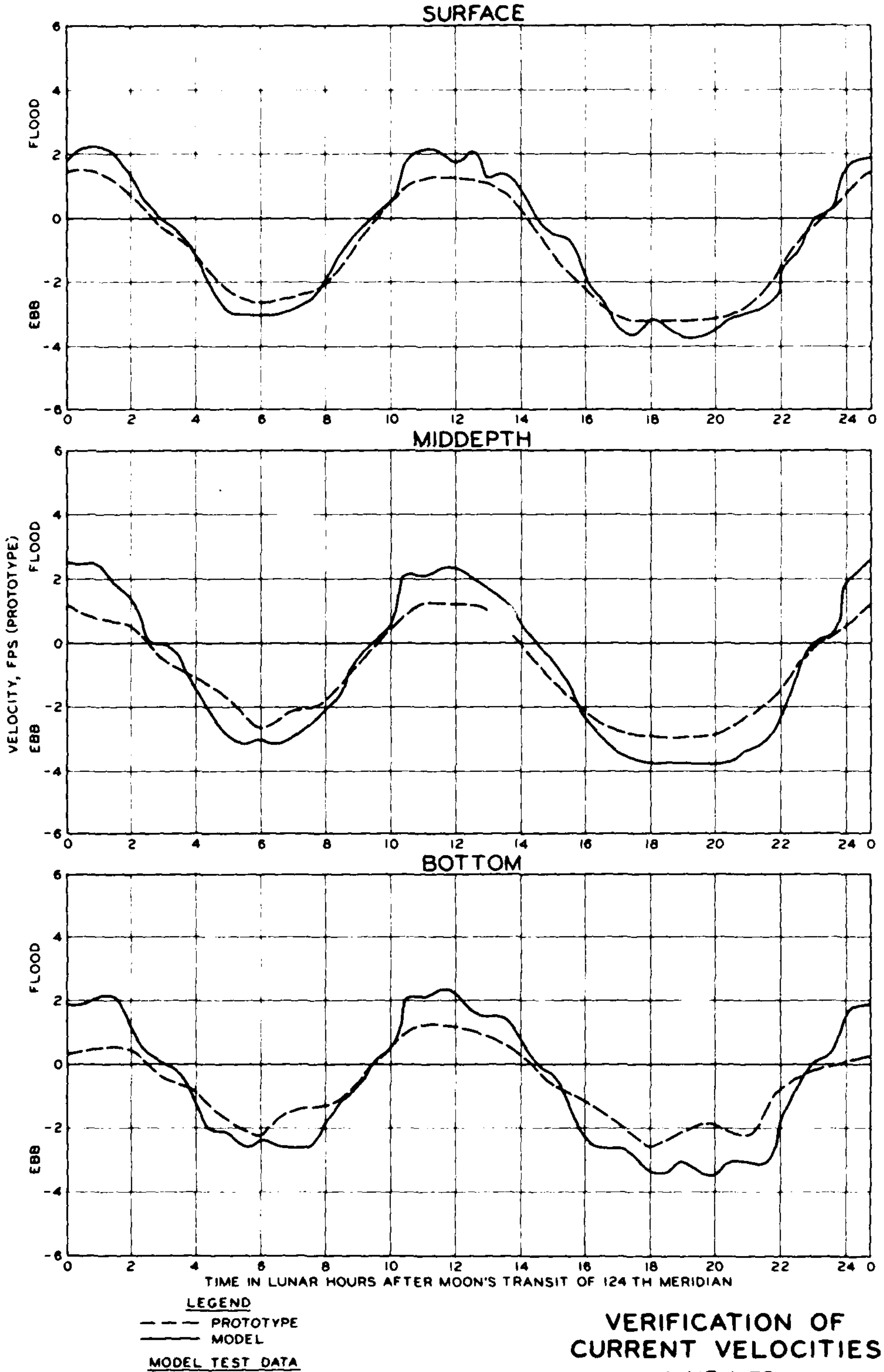

SURFACE
MIDDEPTH
BOTTOM
VELOCITY, FPS (PROTOTYPE)
FLOOD
EBB
TIME IN LUNAR HOURS AFTER MOON'S TRANSIT OF 124 TH MERIDIAN
LEGEND
PROTOTYPE
MODEL
MODEL TEST DATA
TIDE 16 JUNE 1977
FRESH-WATER DISCHARGE 125,000 CFS
SOURCE SALINITY 33.0 PPT
VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 6-P

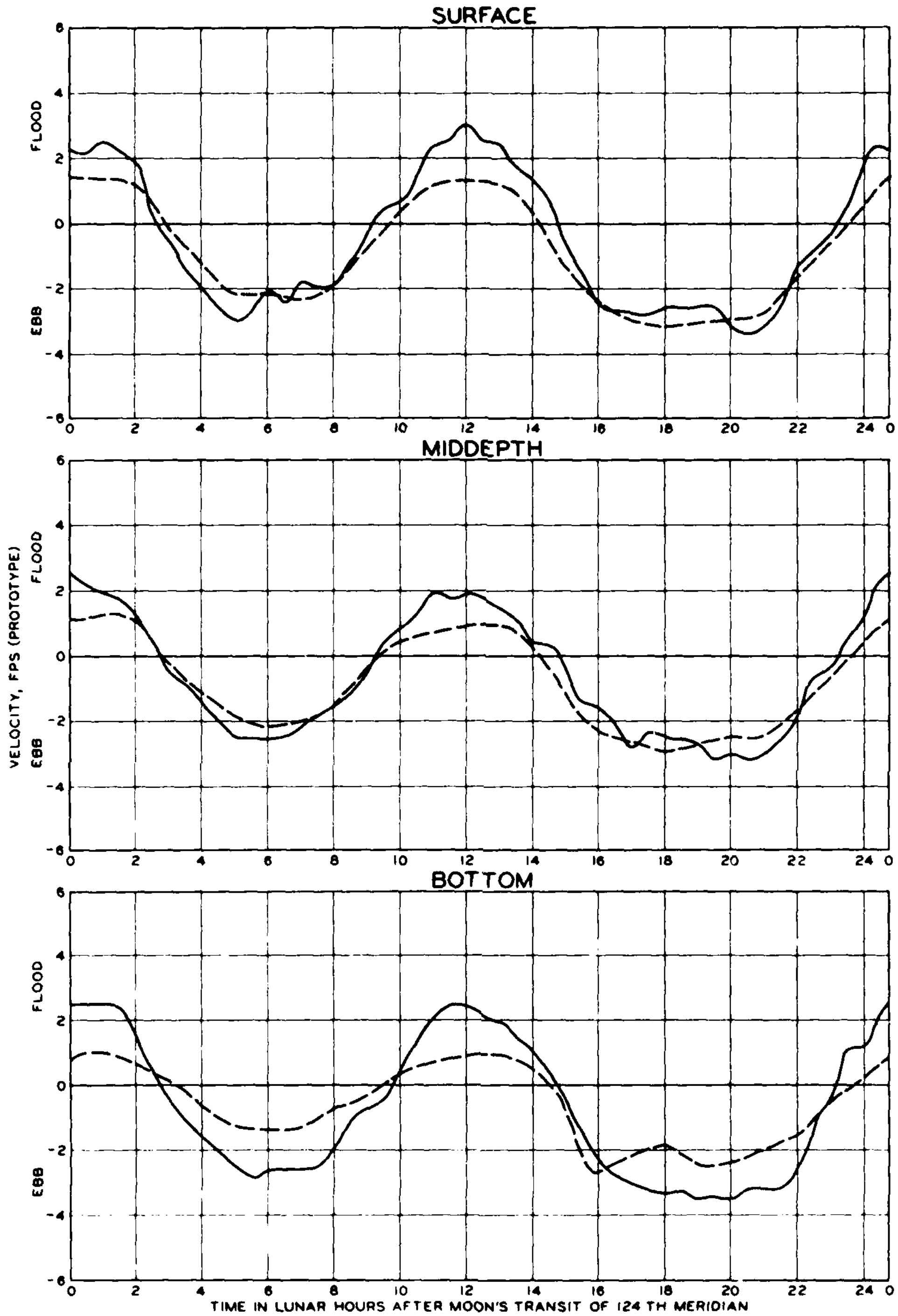
PLATE 24



MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES
JUNE 1977
STATION 6-Q



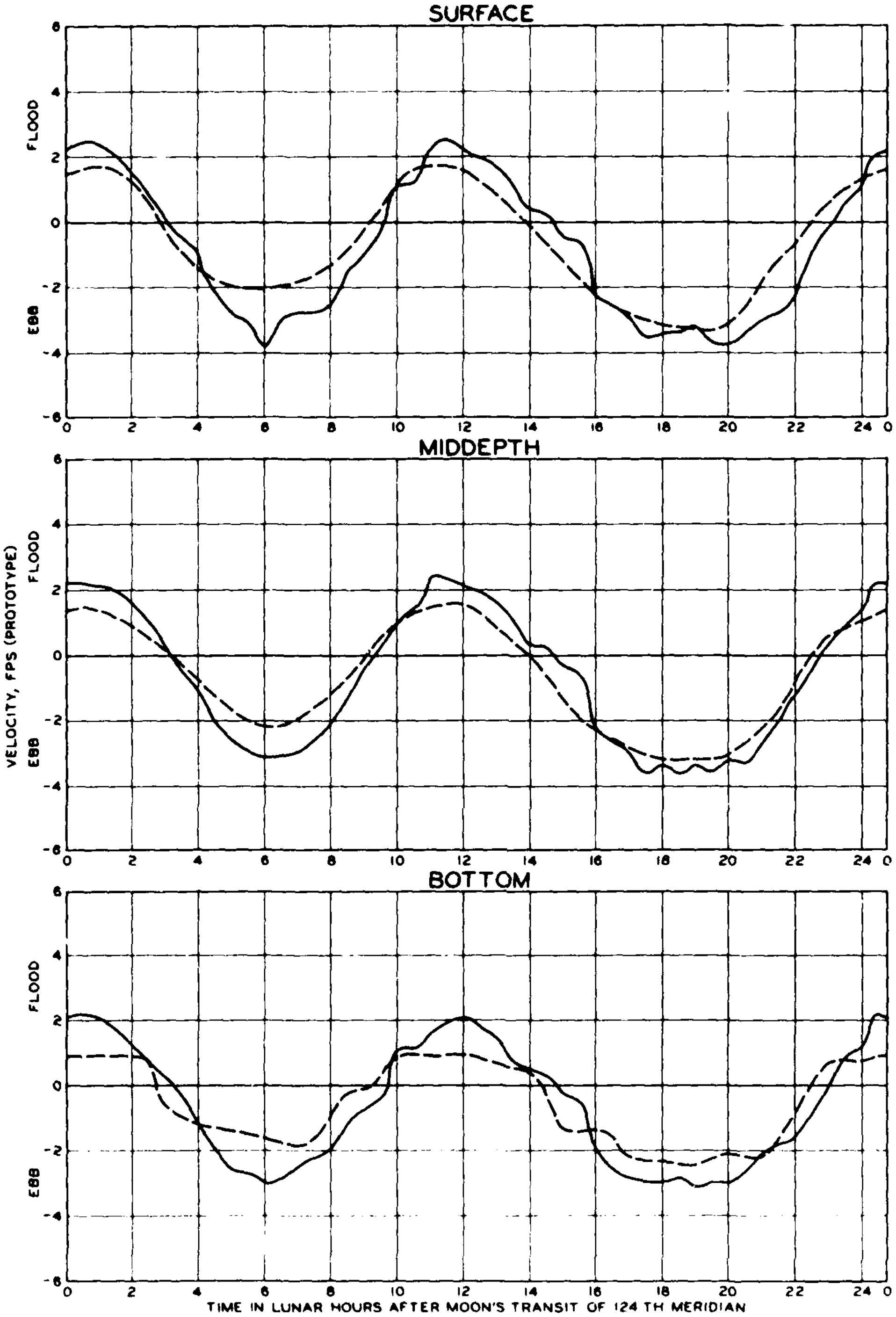
LEGEND

— — — PROTOTYPE
——— MODEL

MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES
JUNE 1977
STATION 6-R



LEGEND

— — — PROTOTYPE

——— MODEL

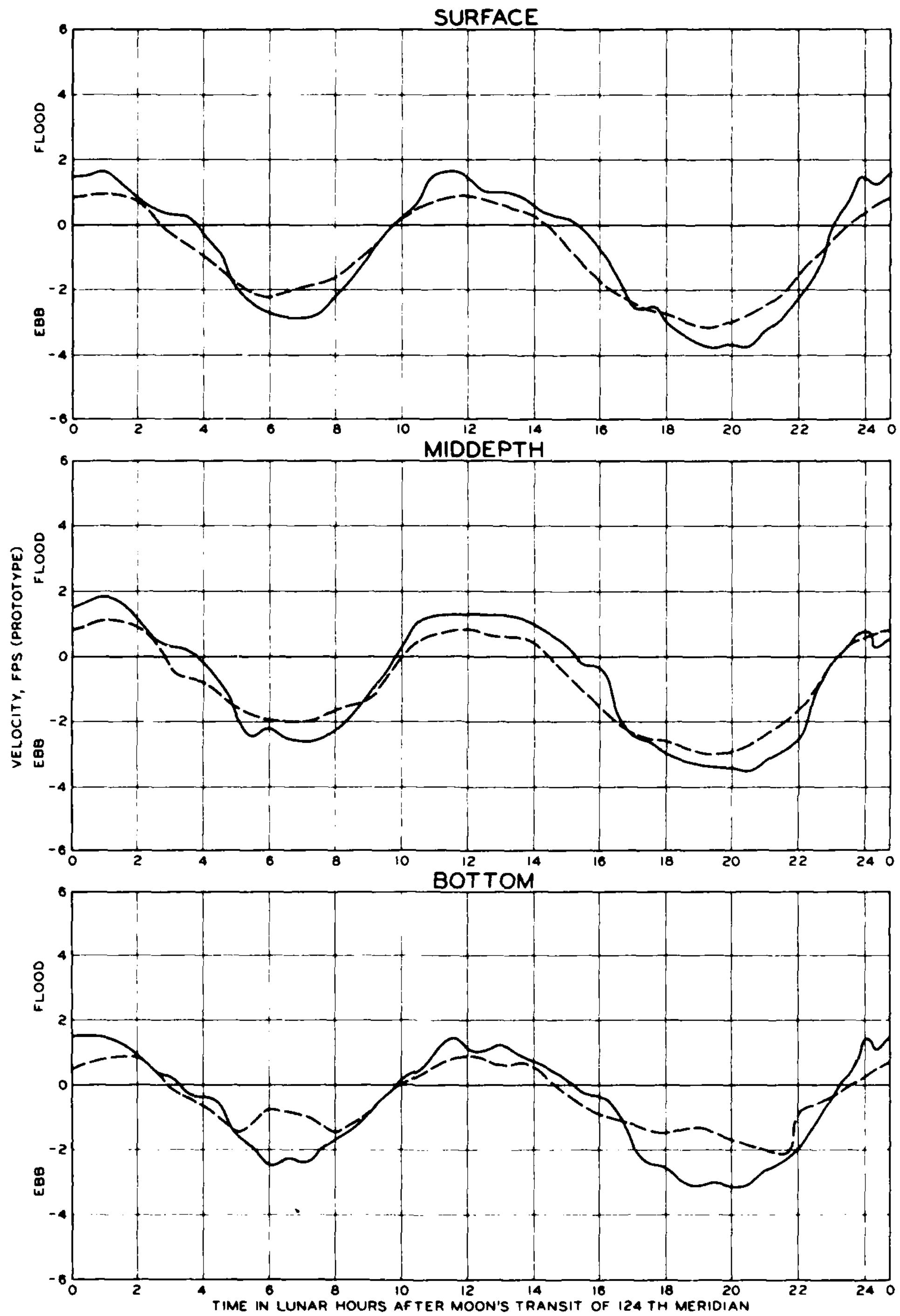
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 7-S



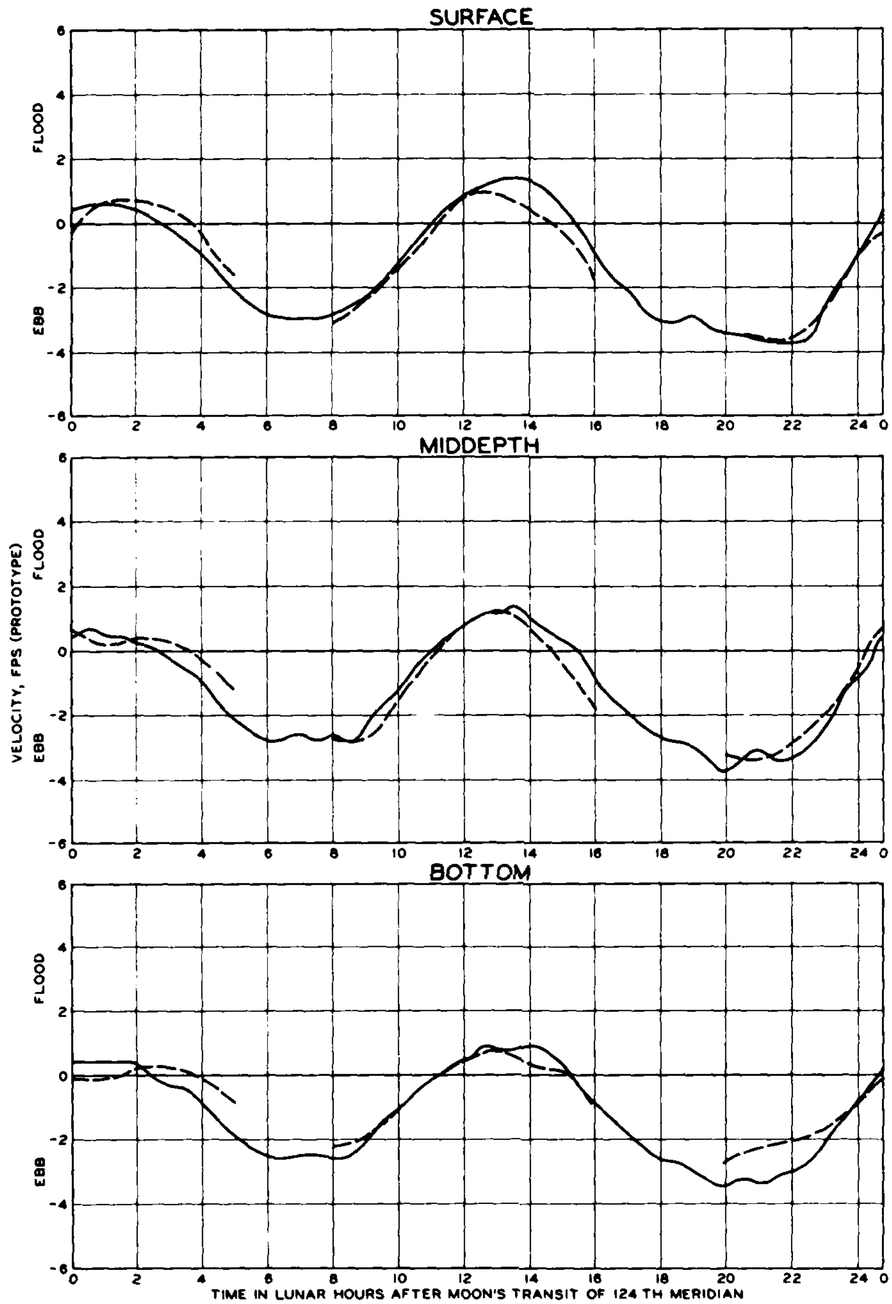
LEGEND

– – – PROTOTYPE
——— MODEL

MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES
JUNE 1977
STATION 7-T



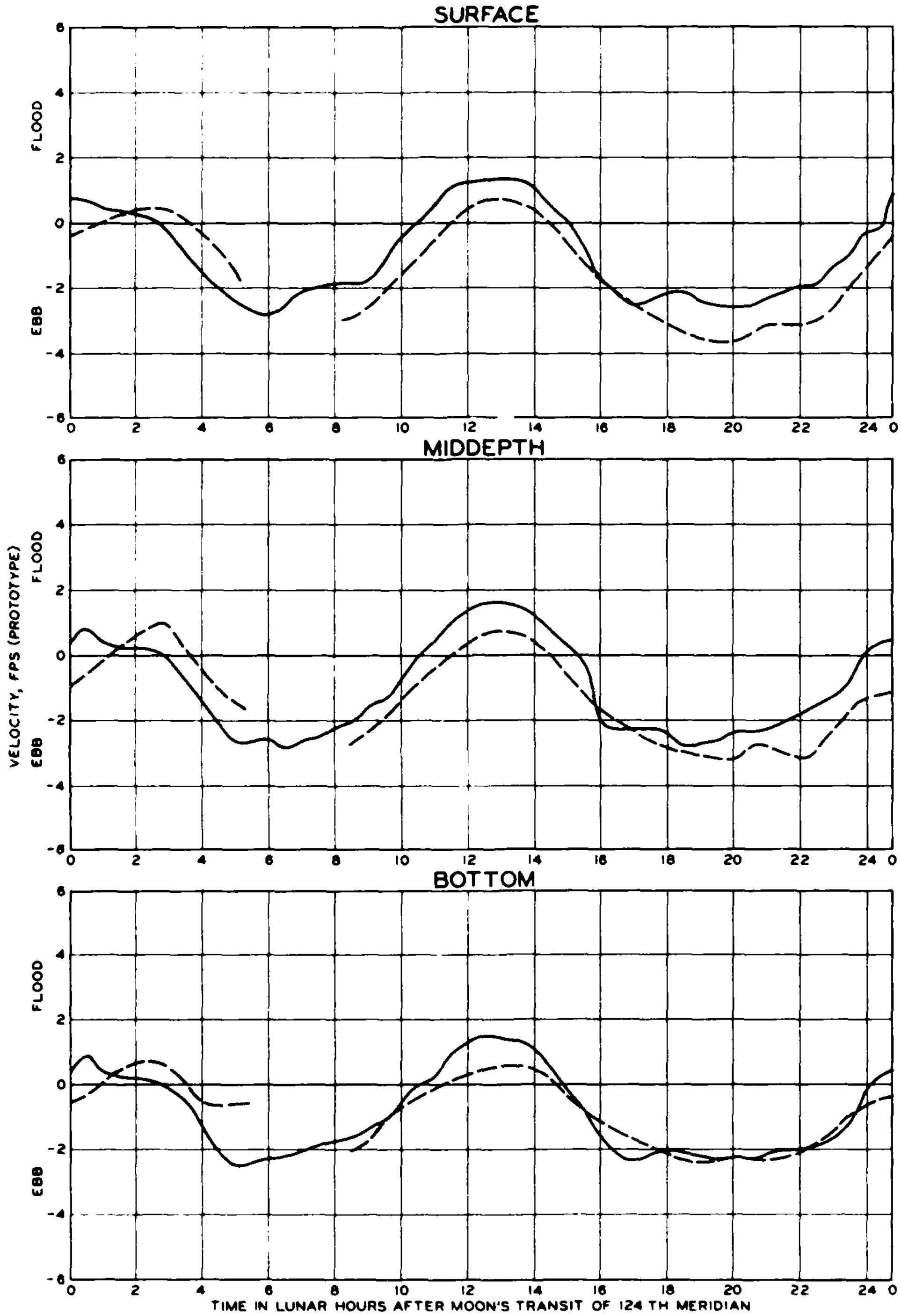
LEGEND
- – – – PROTOTYPE
- ——— MODEL

MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES
JUNE 1977
STATION 8-U

PLATE 29



LEGEND

— — — PROTOTYPE

——— MODEL

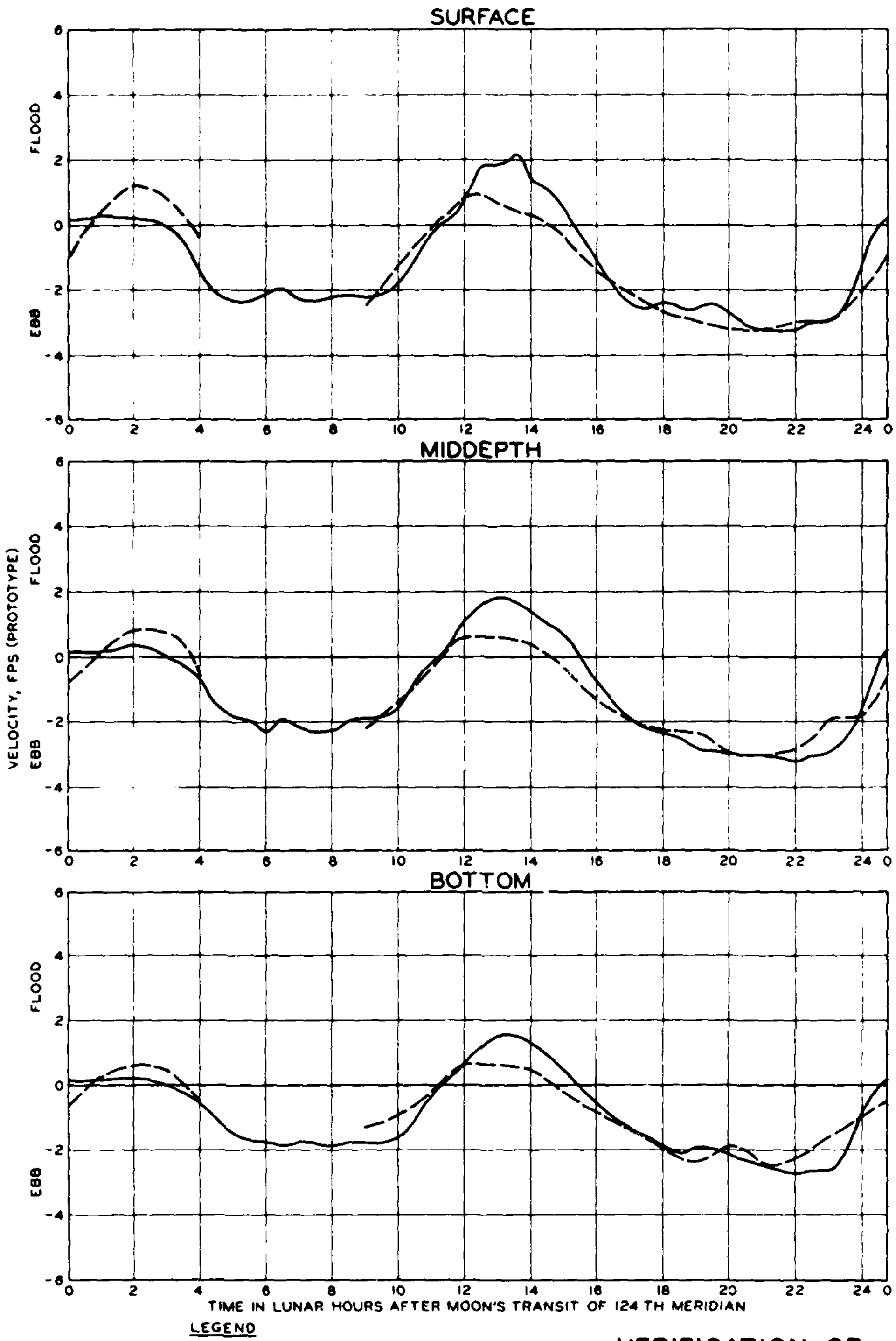
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

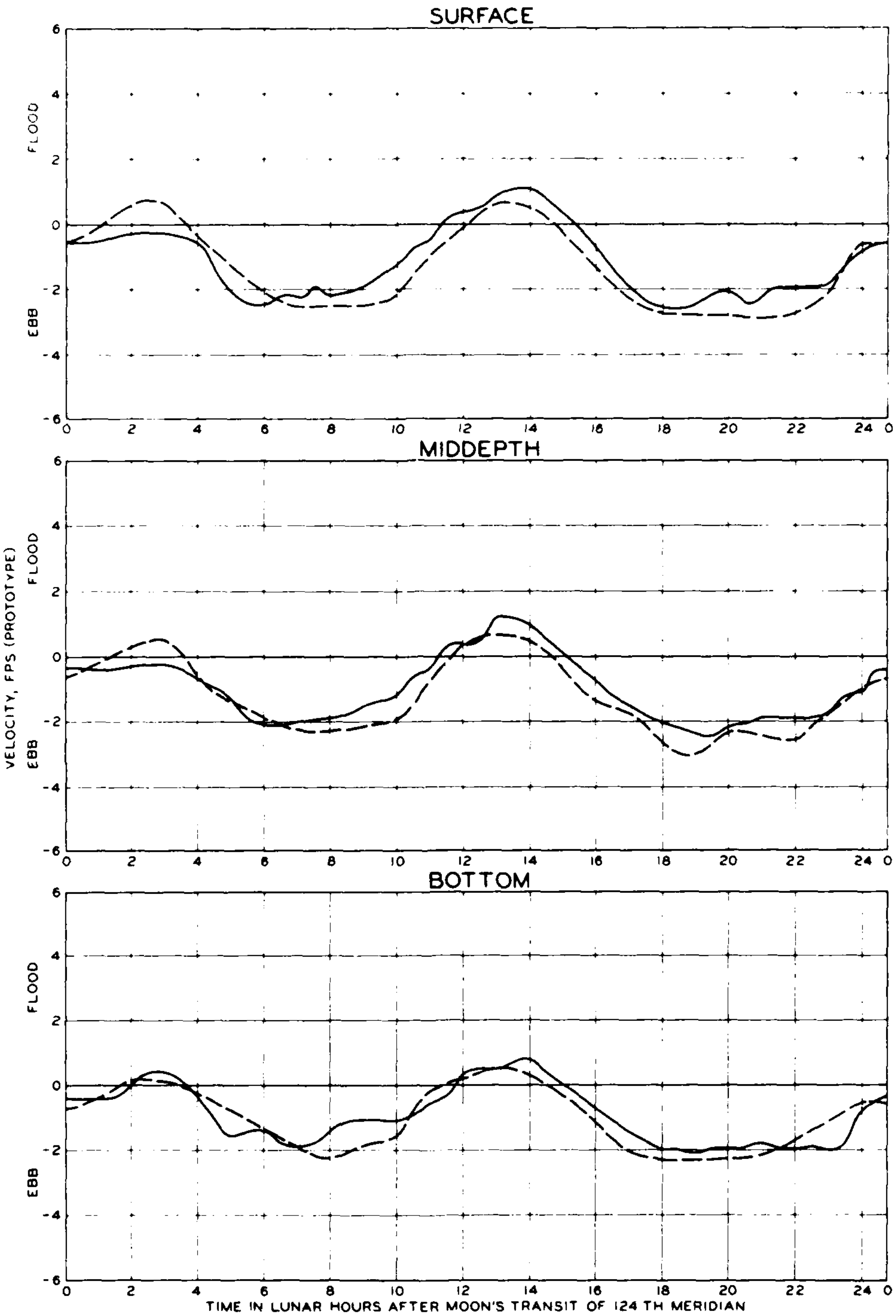
STATION 8-V



MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES
JUNE 1977
STATION 9-W



LEGEND

— — — PROTOTYPE
——— MODEL

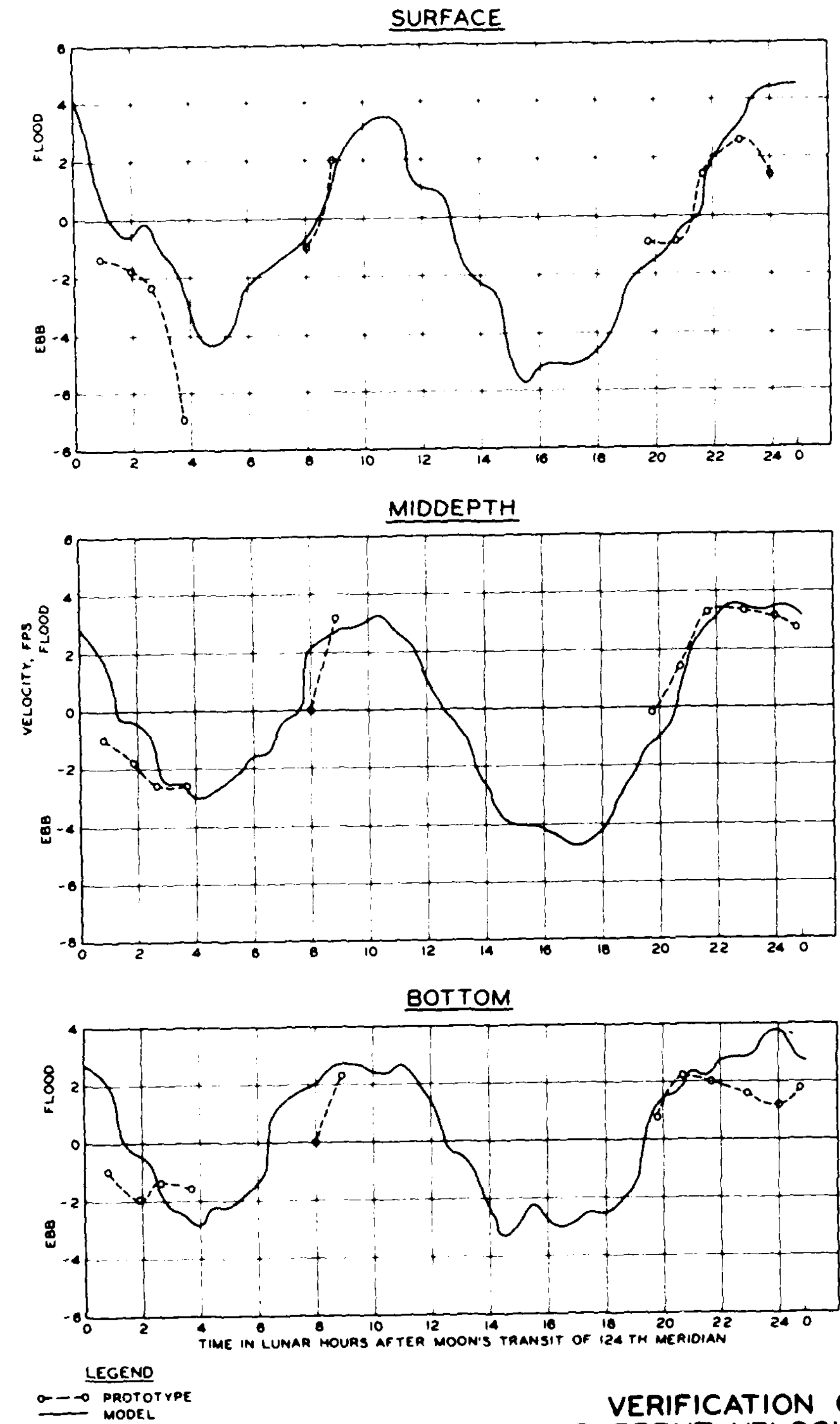
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1977

STATION 9-X



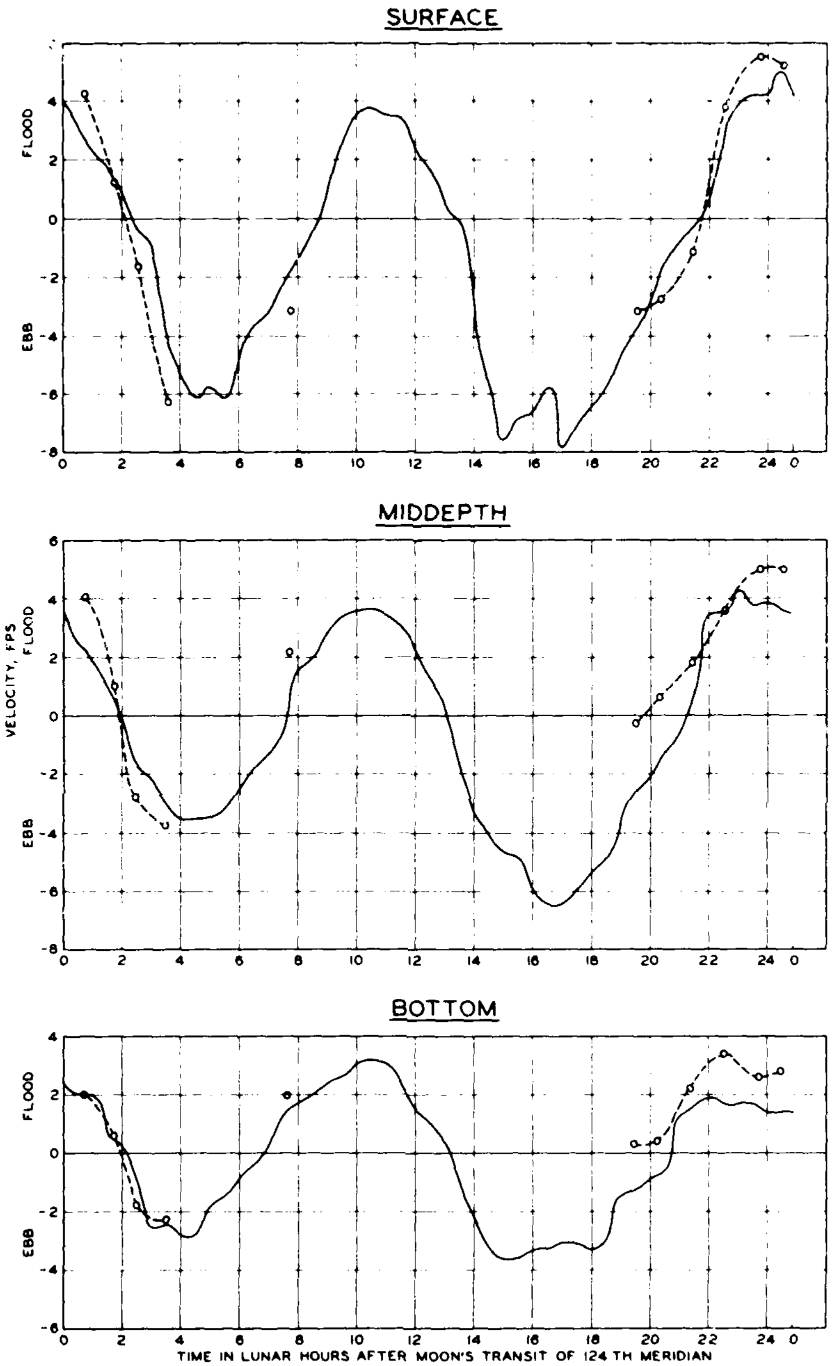
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 13A



LEGEND

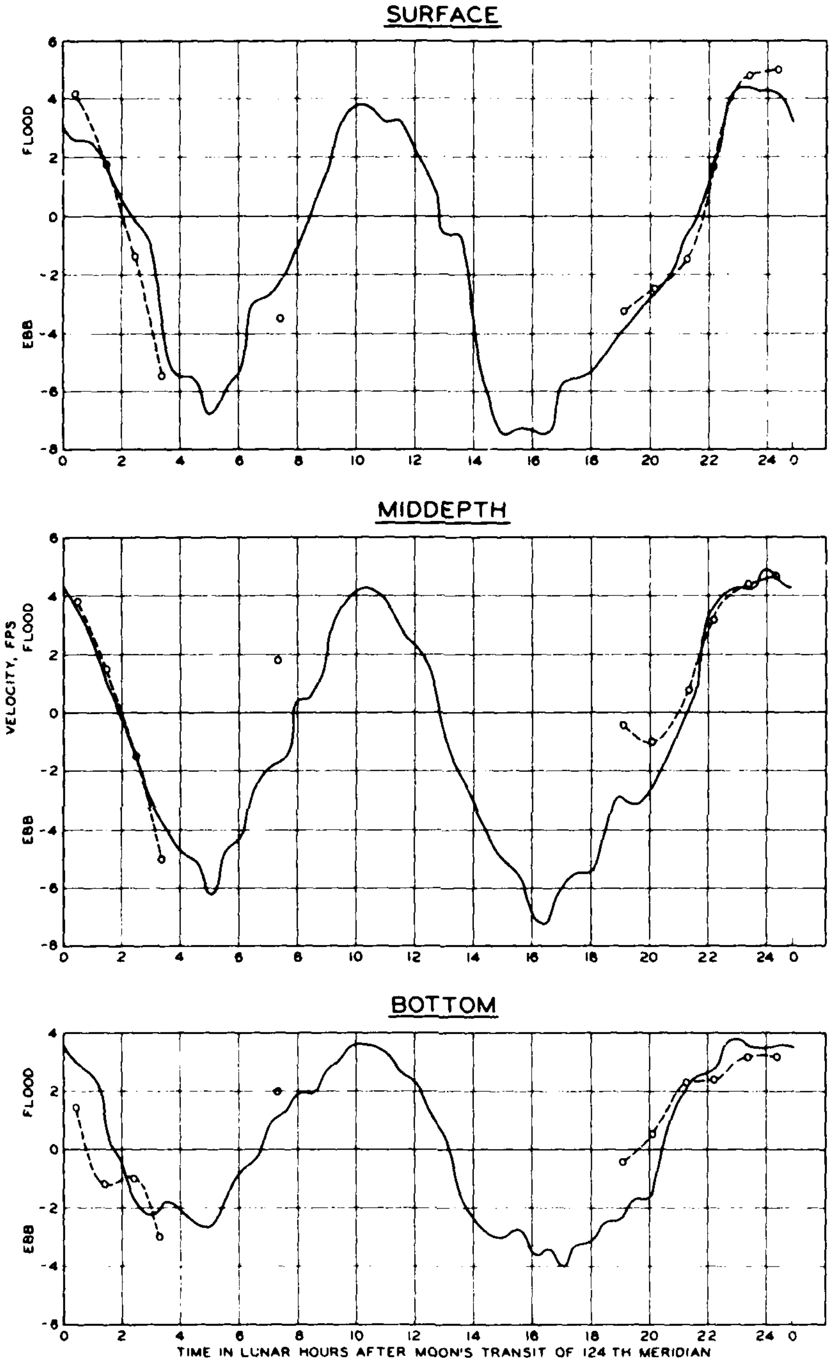
o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 13B



LEGEND

o- - -o PROTOTYPE
——— MODEL

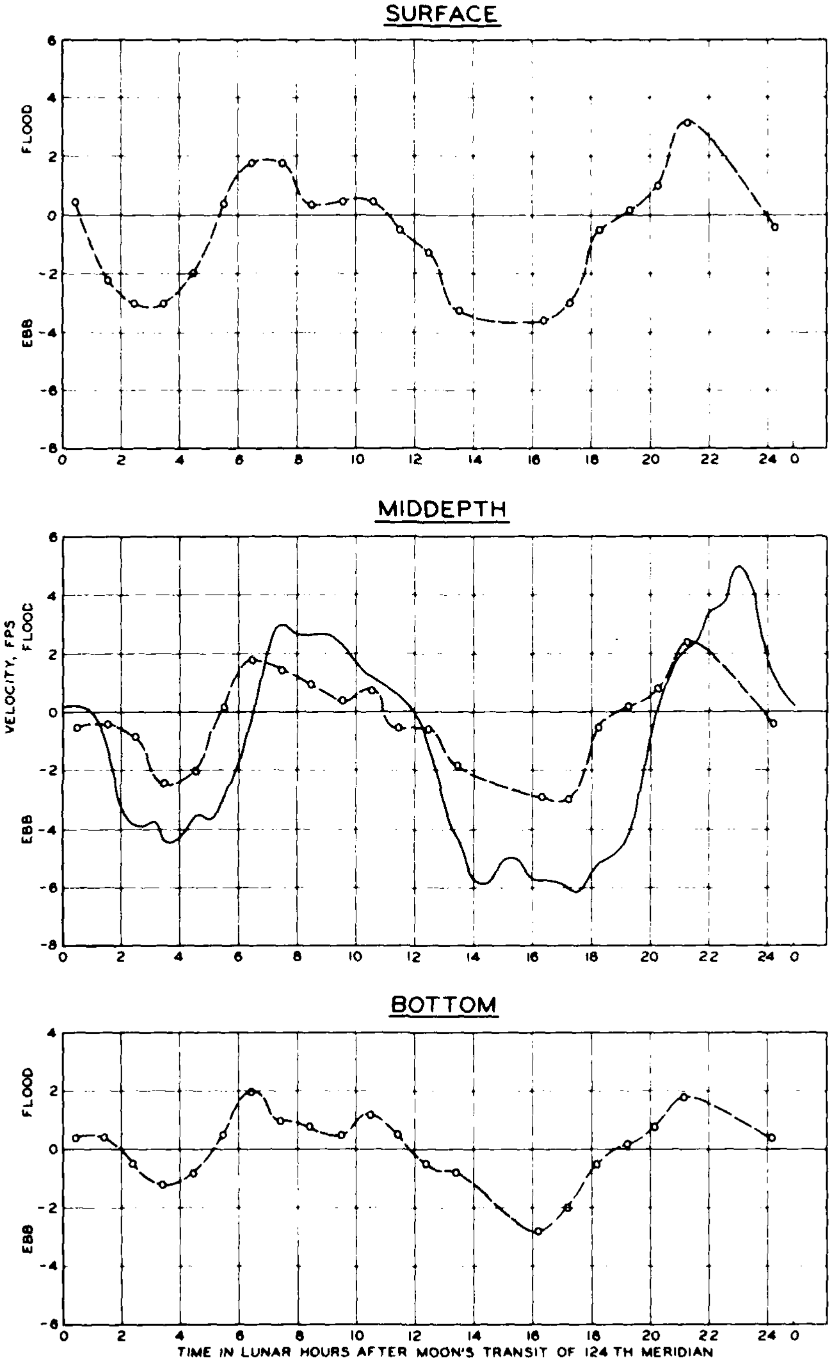
TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 13C



LEGEND

o— — —o PROTOTYPE
——— MODEL

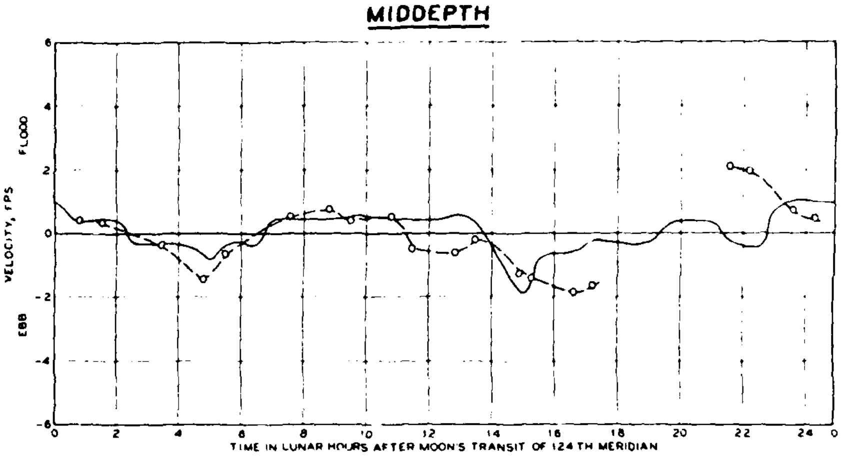
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 12A



LEGEND

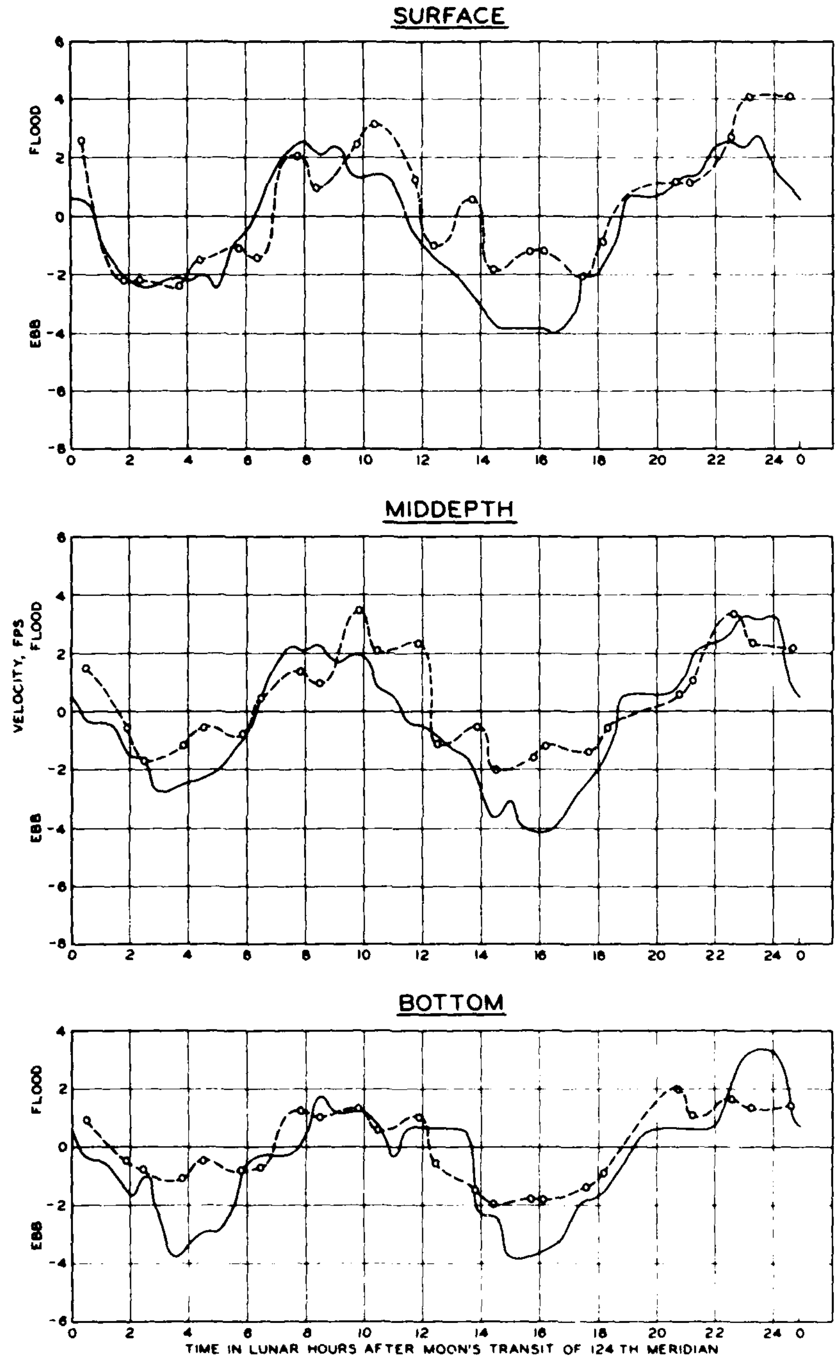
o--o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES
JUNE 1978

STATION 11A



LEGEND

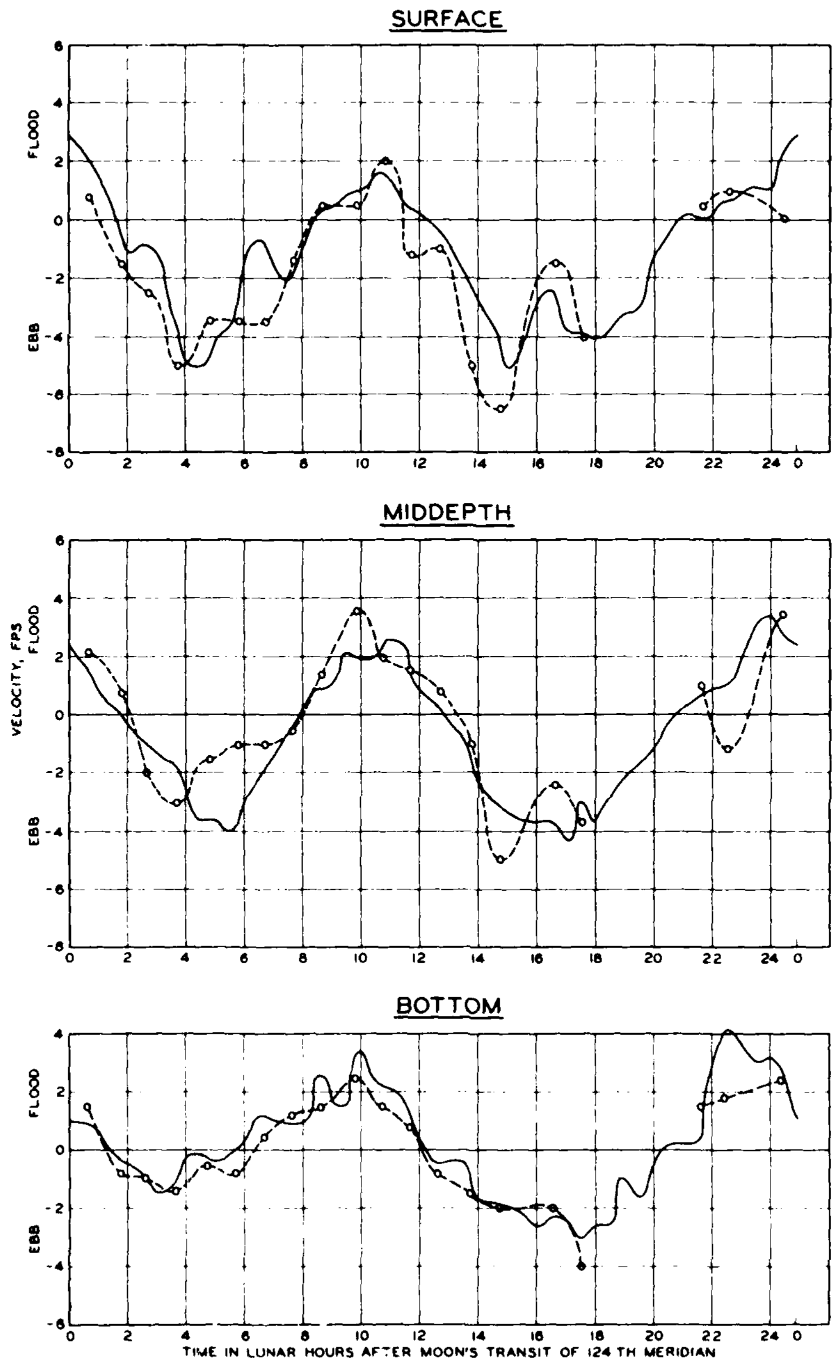
PROTOTYPE
MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 11B



LEGEND

o- - -o PROTOTYPE

——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT

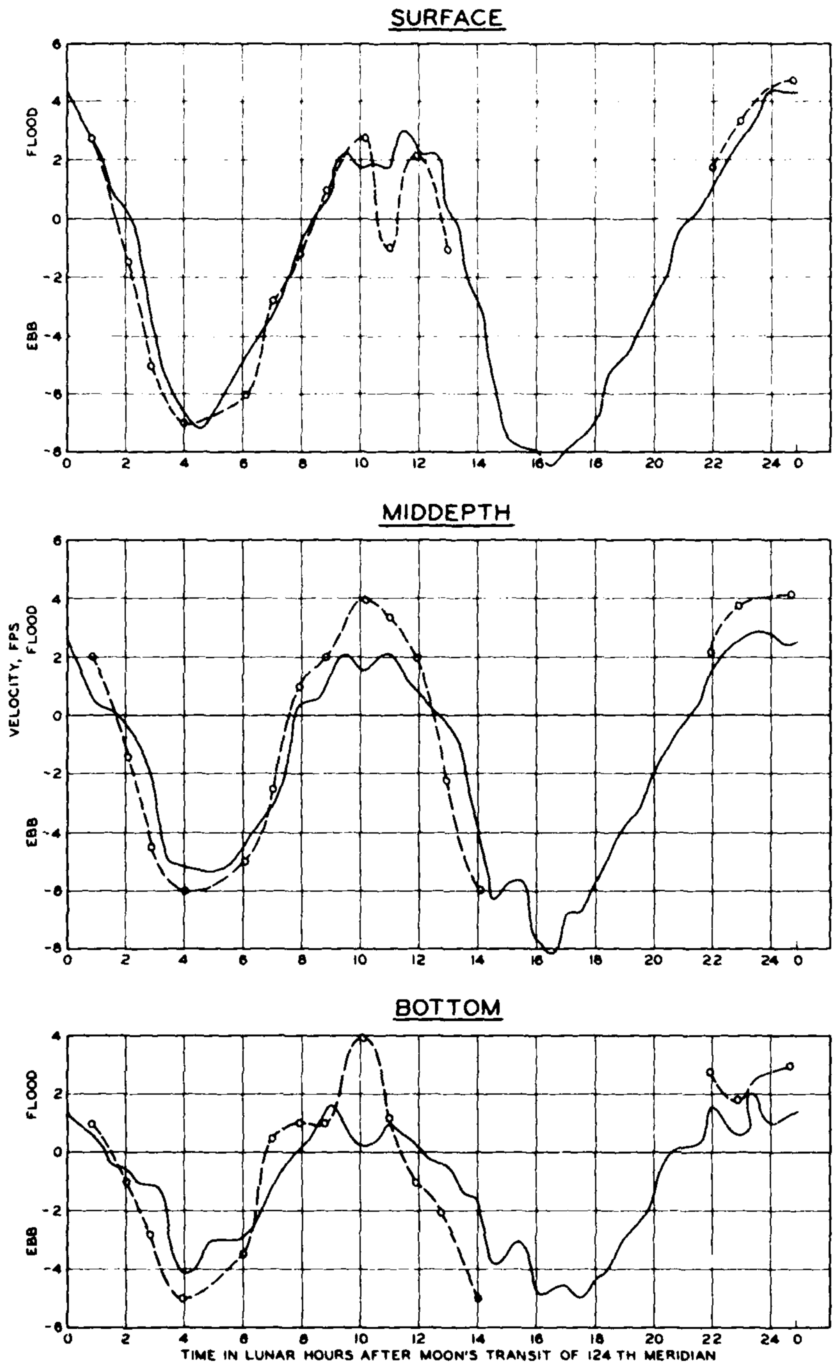
FRESHWATER DISCHARGE 280,000 CFS

SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 1B



LEGEND

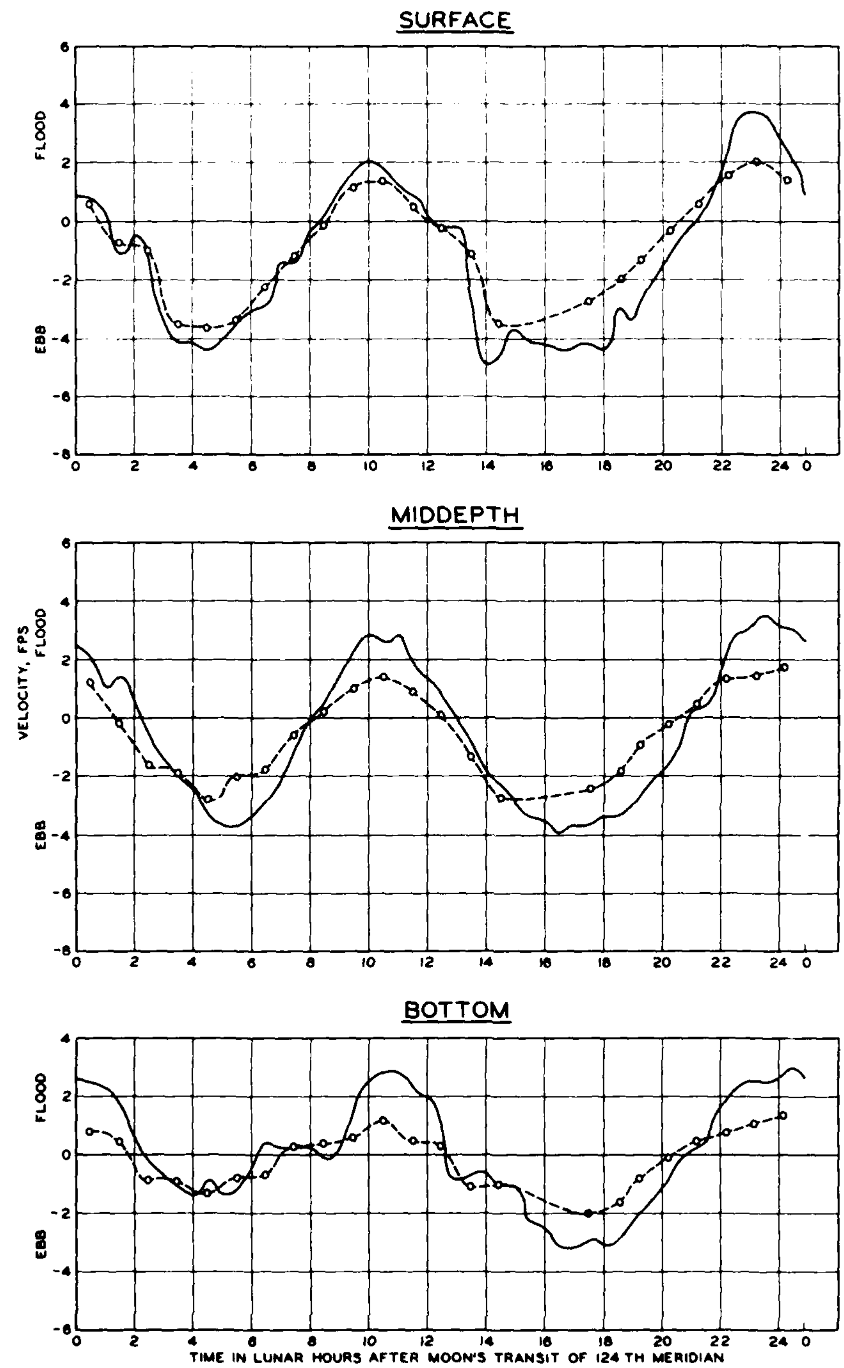
o--o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 1C



LEGEND

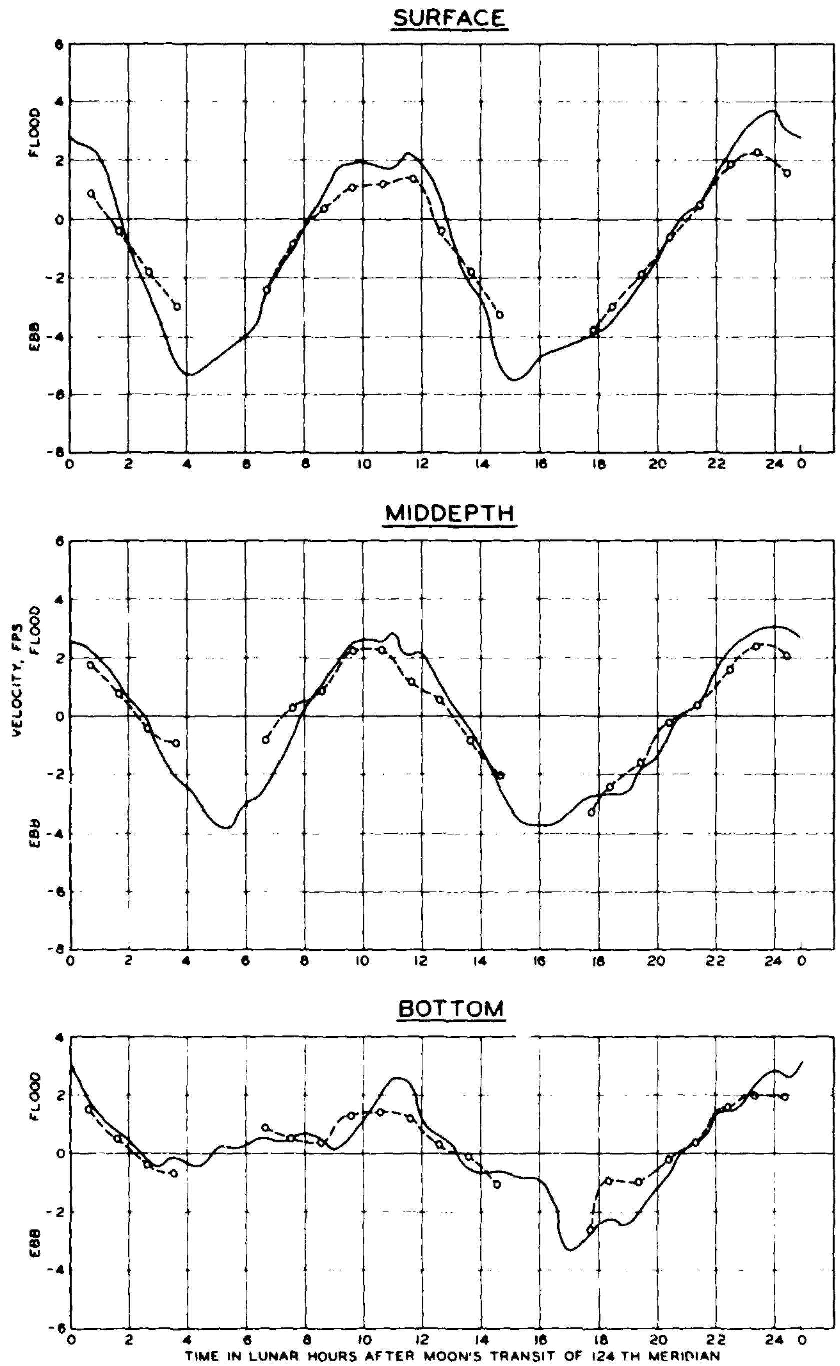
o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES

JUNE 1978
STATION 2D



LEGEND

o- - -o PROTOTYPE
——— MODEL

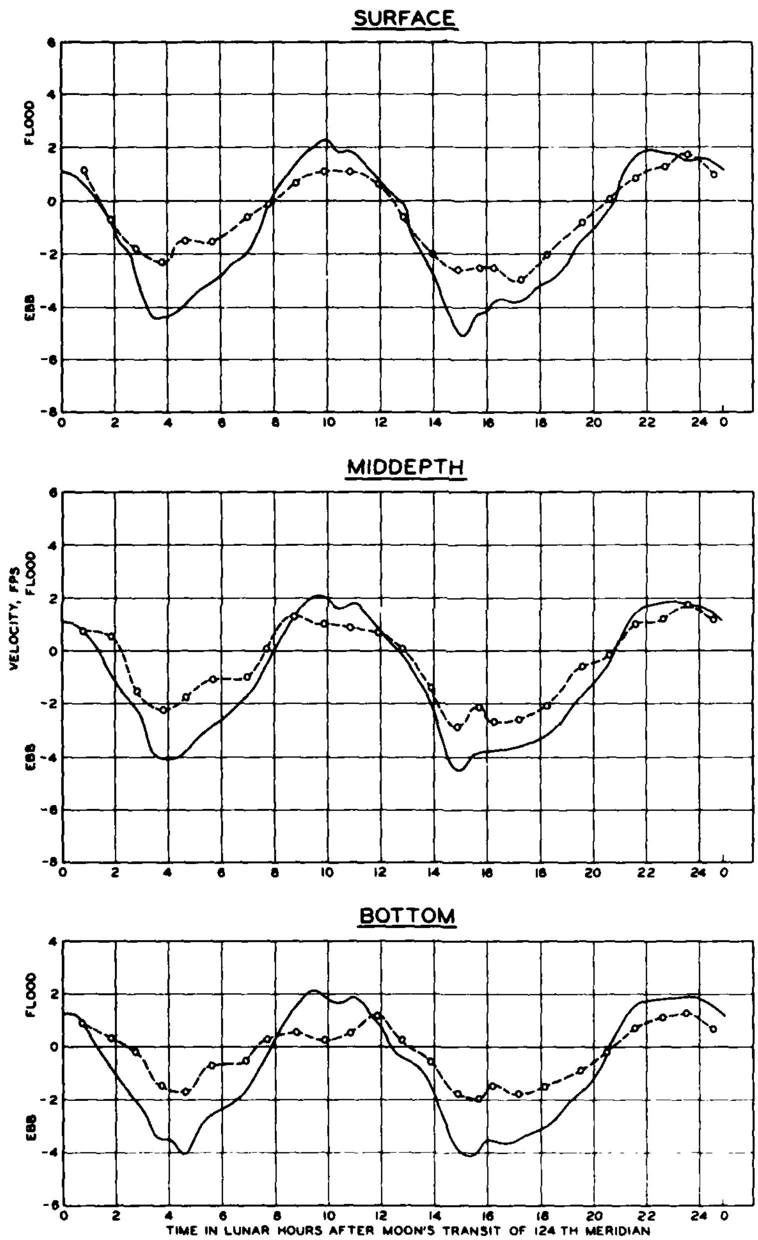
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 2E



LEGEND

o--o PROTOTYPE
—— MODEL

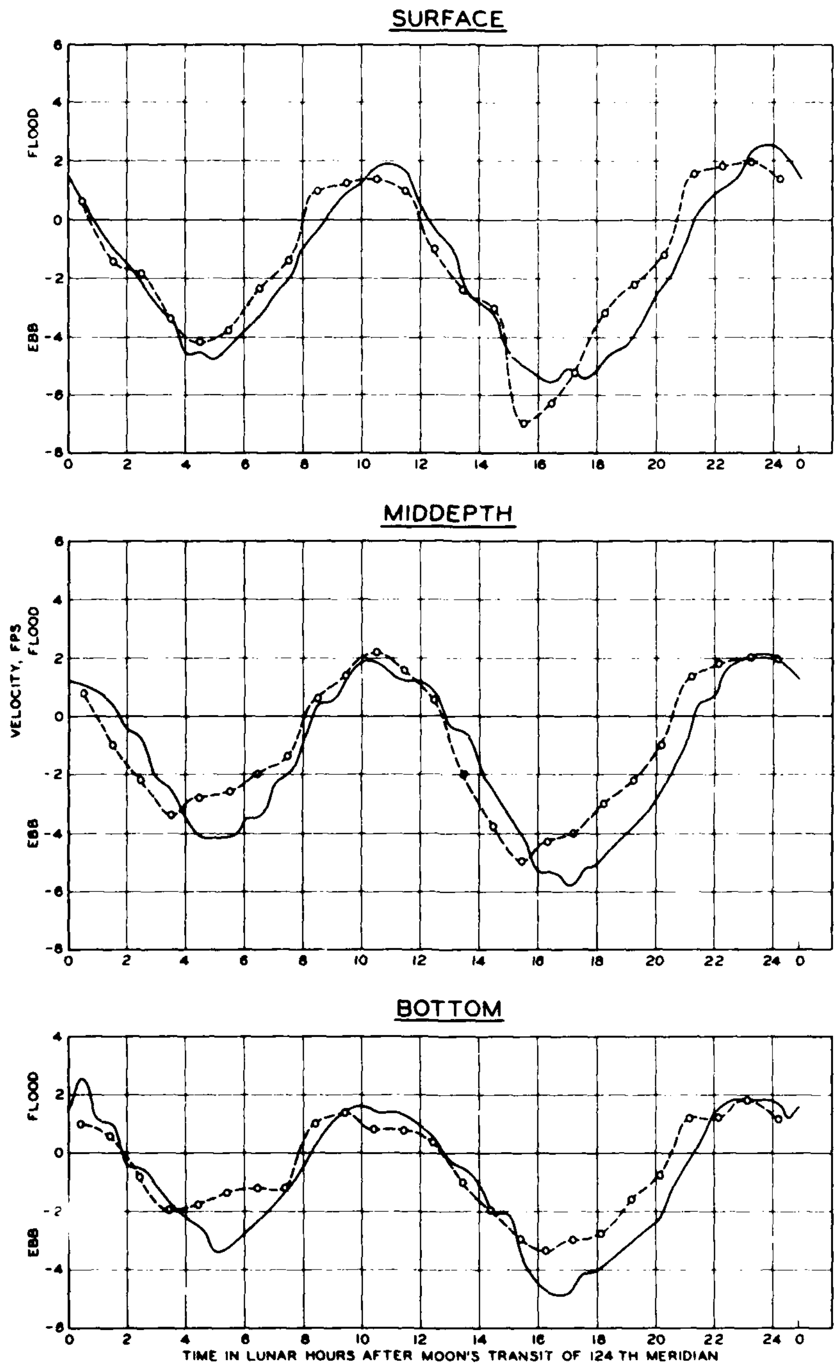
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 2F



LEGEND

o- - -o PROTOTYPE
—— MODEL

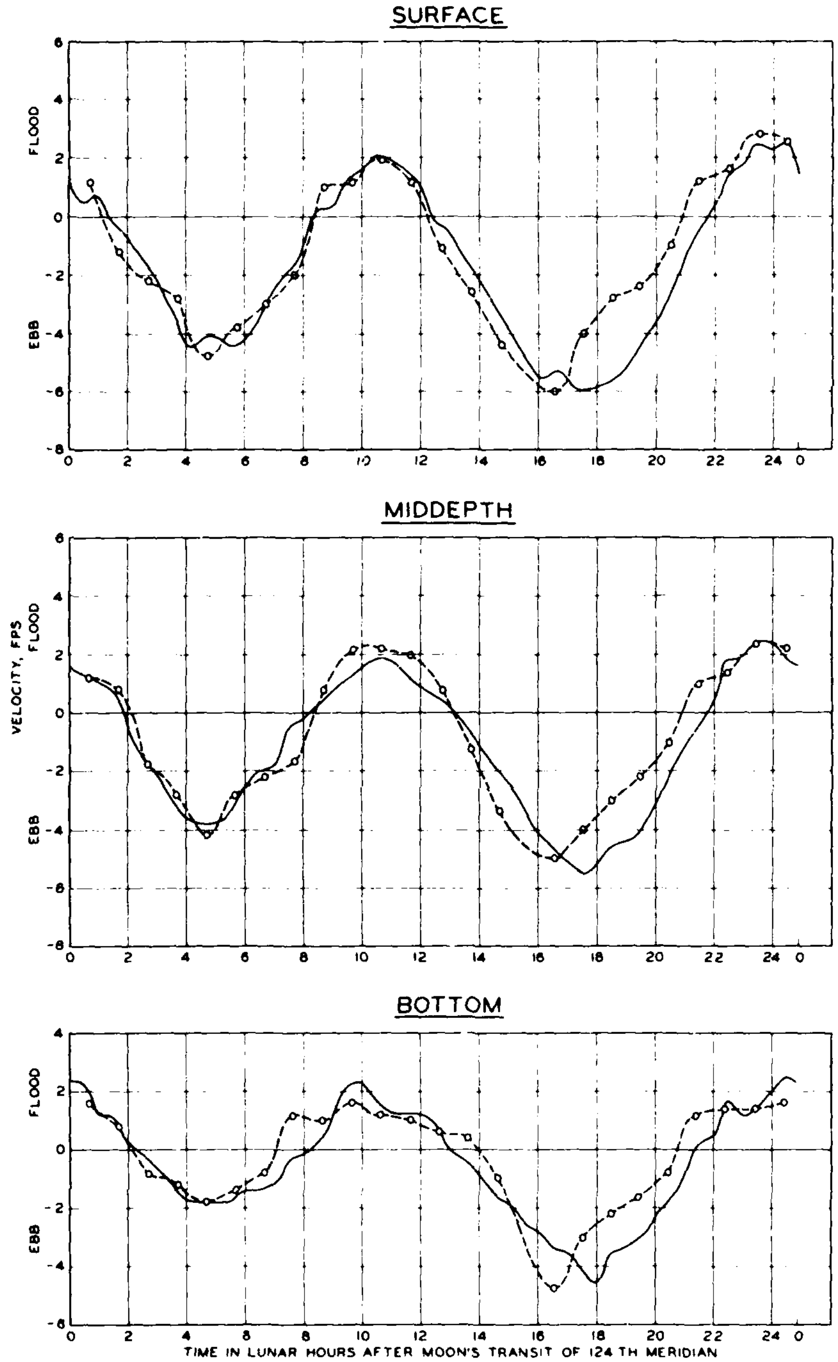
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 3A



LEGEND

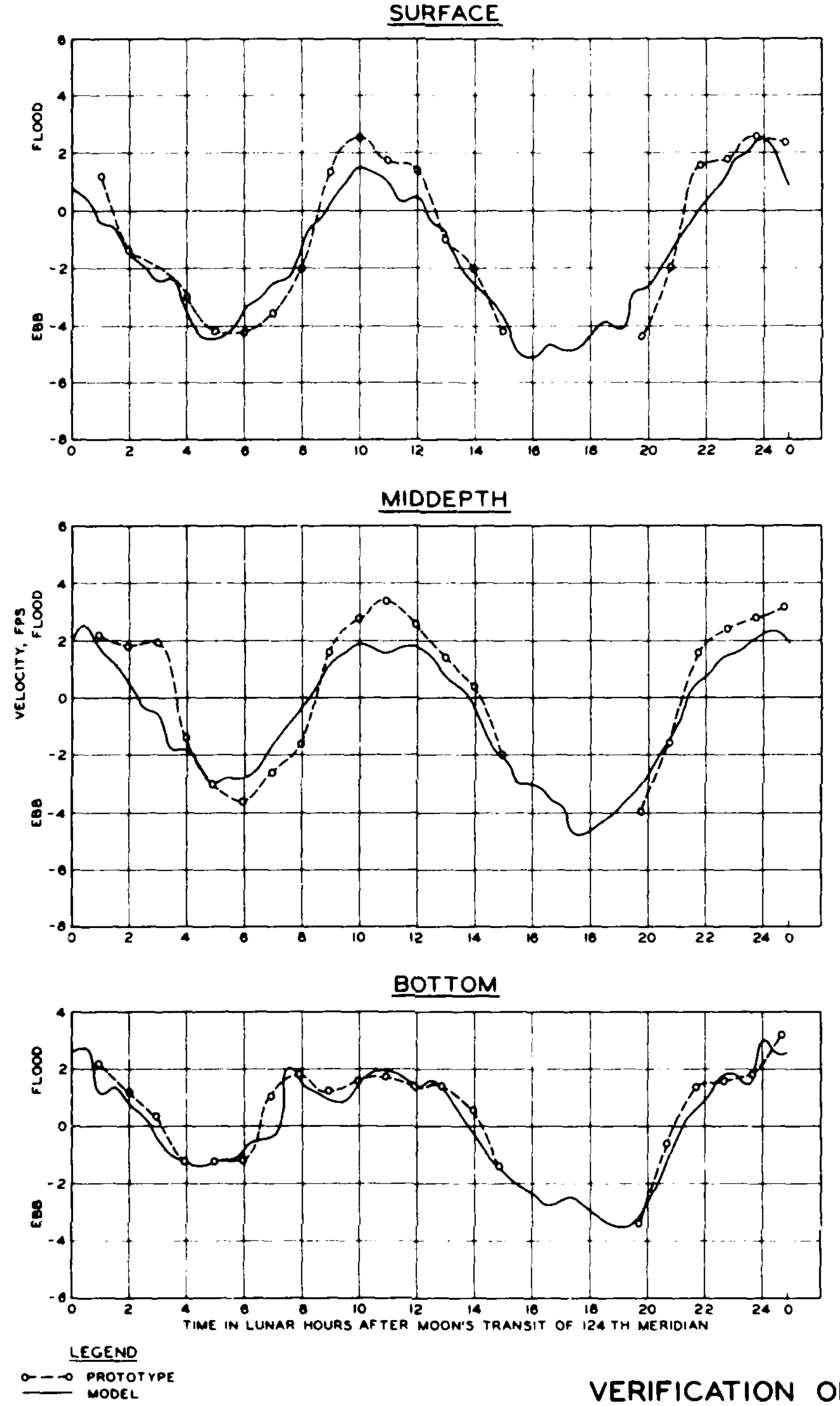
PROTOTYPE
MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 3B



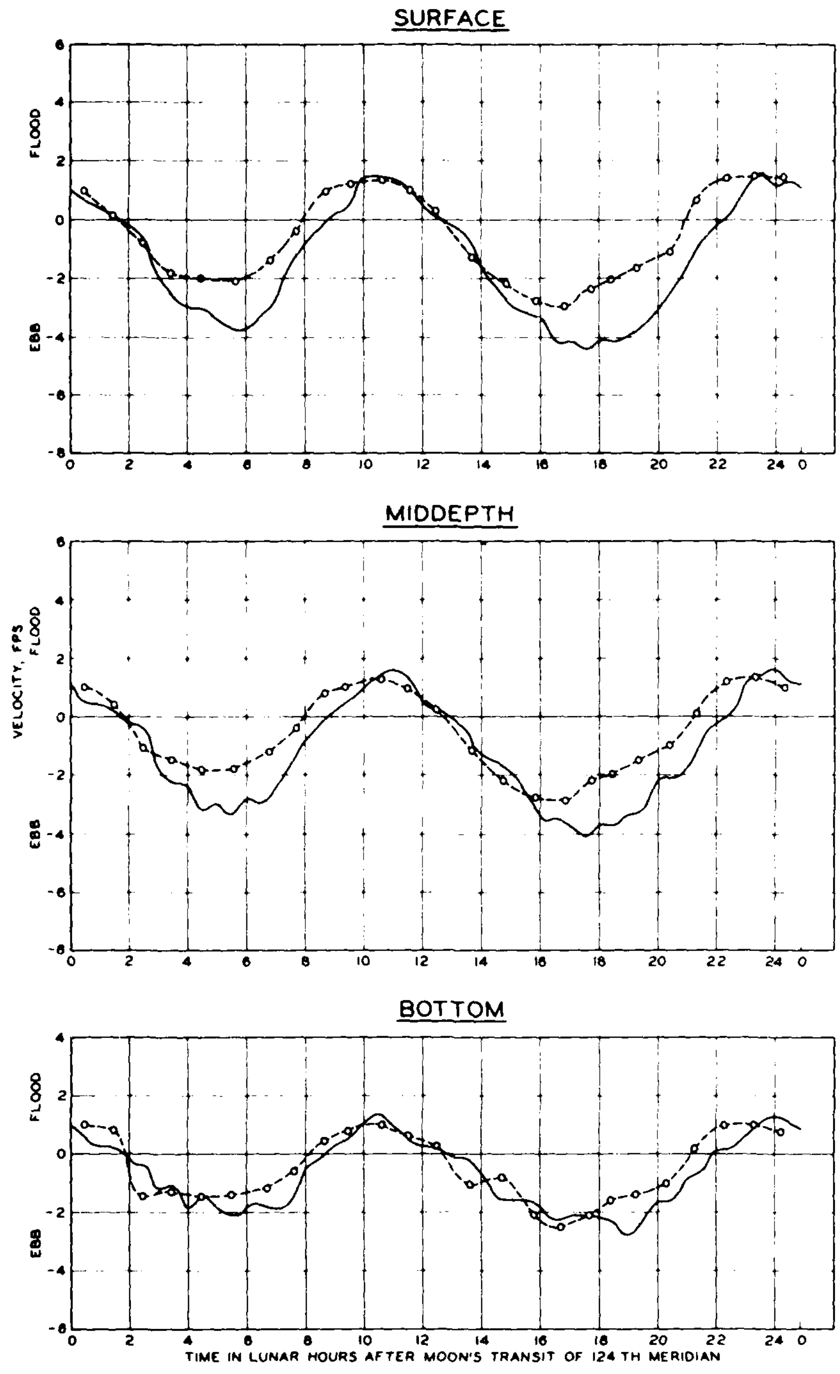
TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 3C



LEGEND

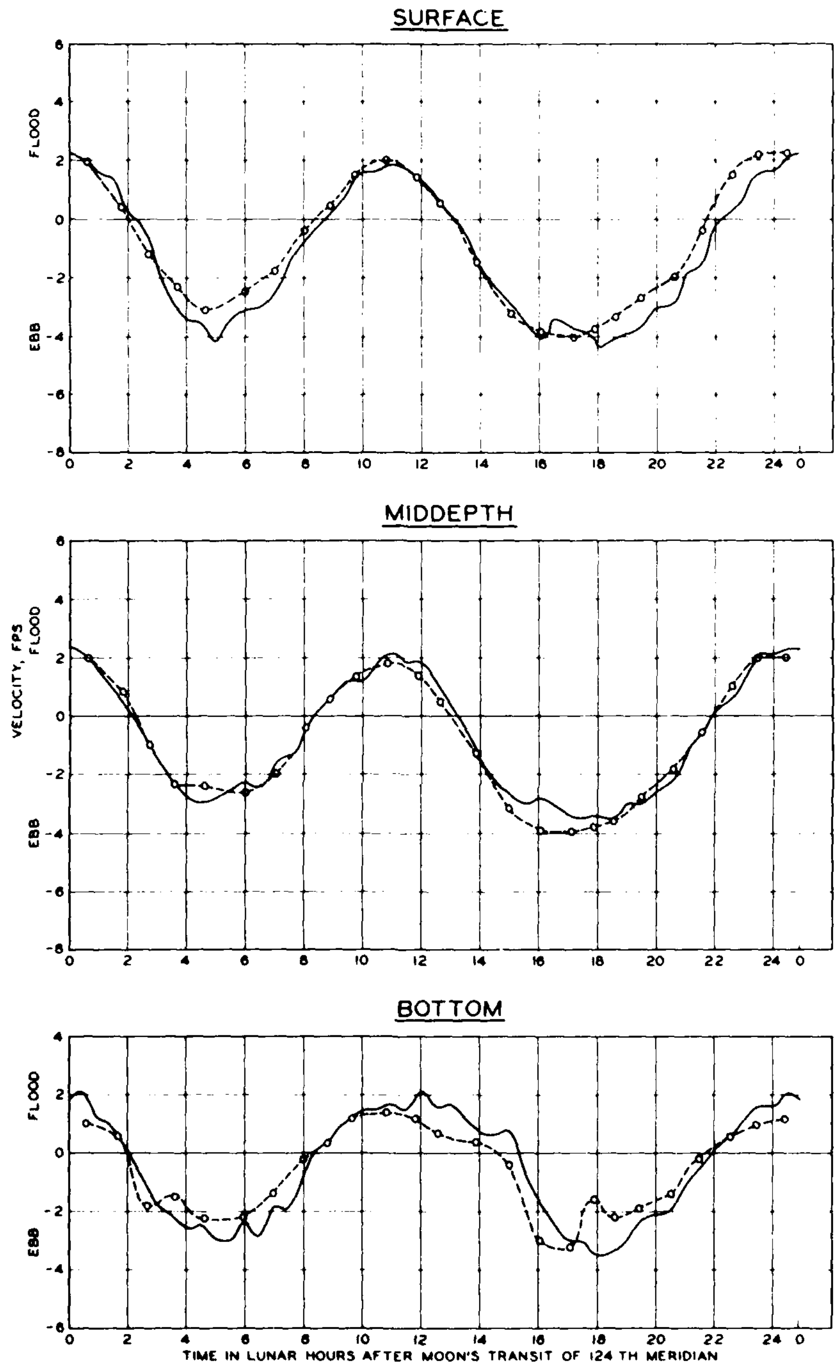
o---o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 6.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES

JUNE 1978
STATION 5A



LEGEND

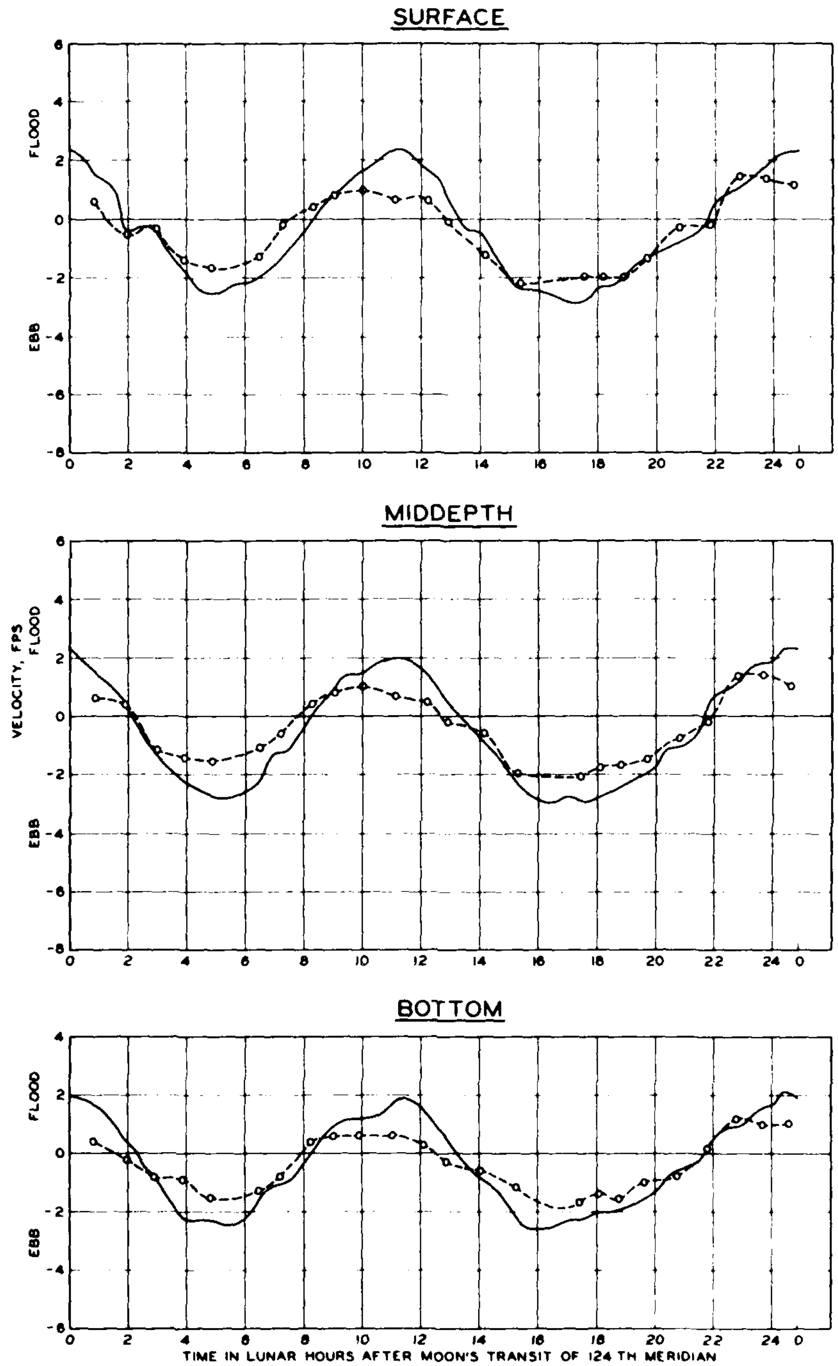
o--o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 5B



LEGEND

o- - -o PROTOTYPE
——— MODEL

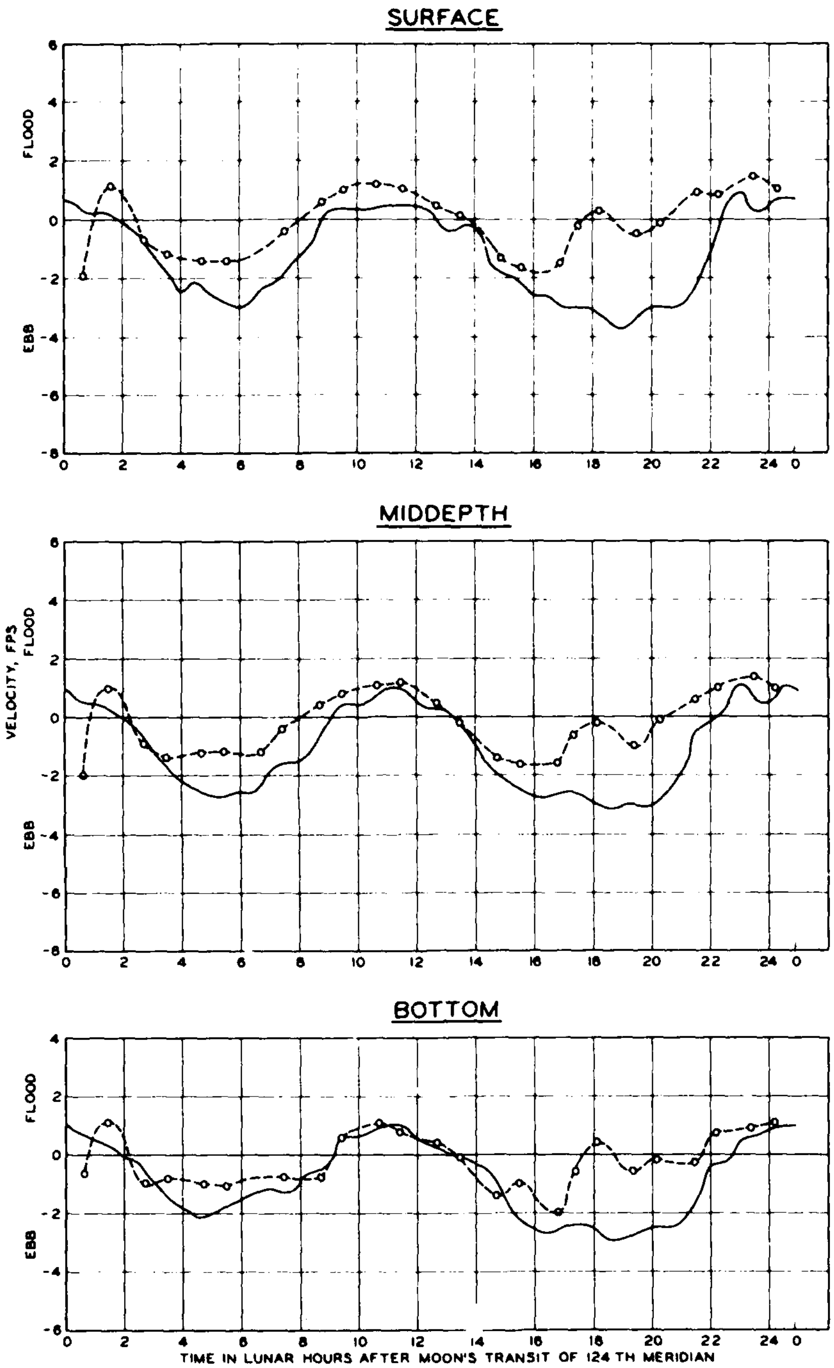
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 5C



LEGEND

o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

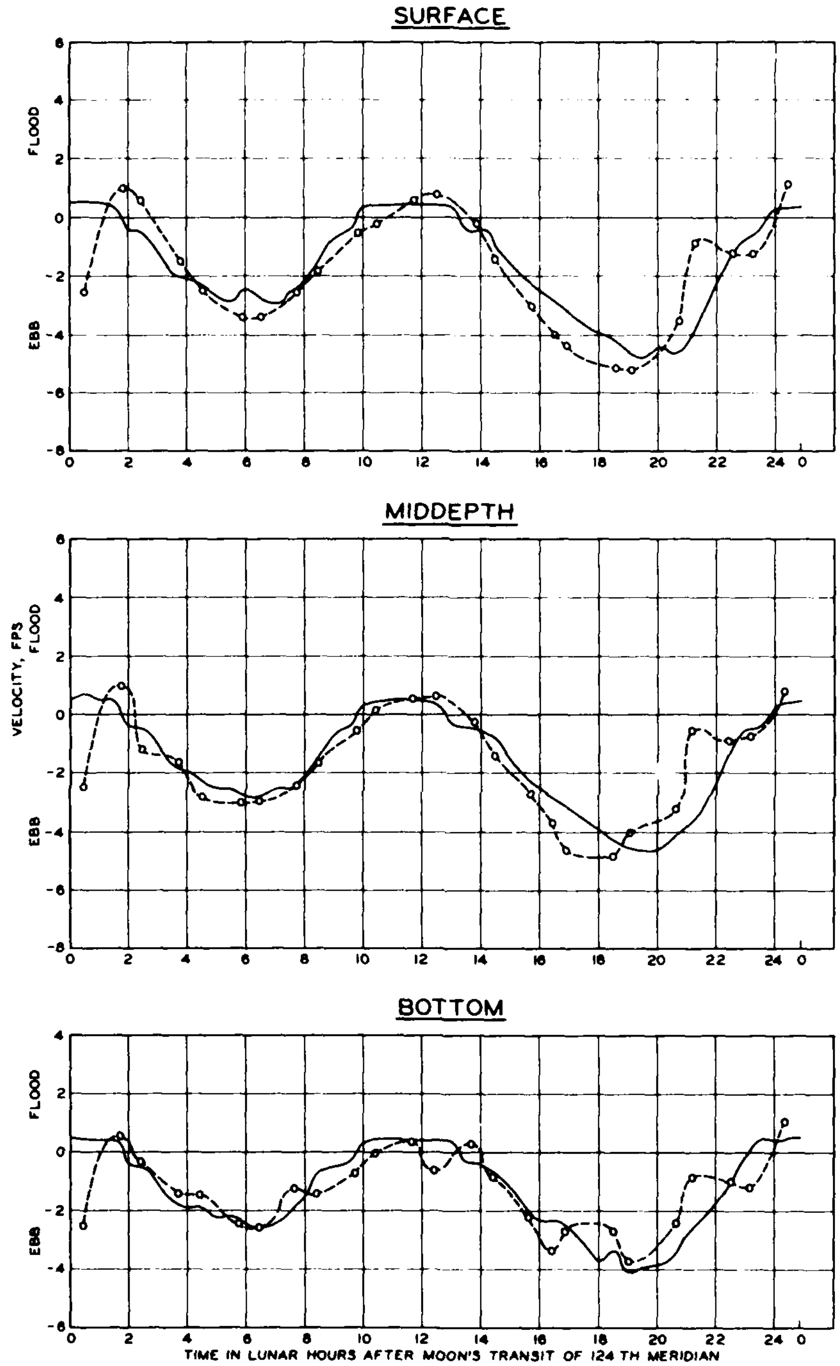
TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 6A

PLATE 50



LEGEND

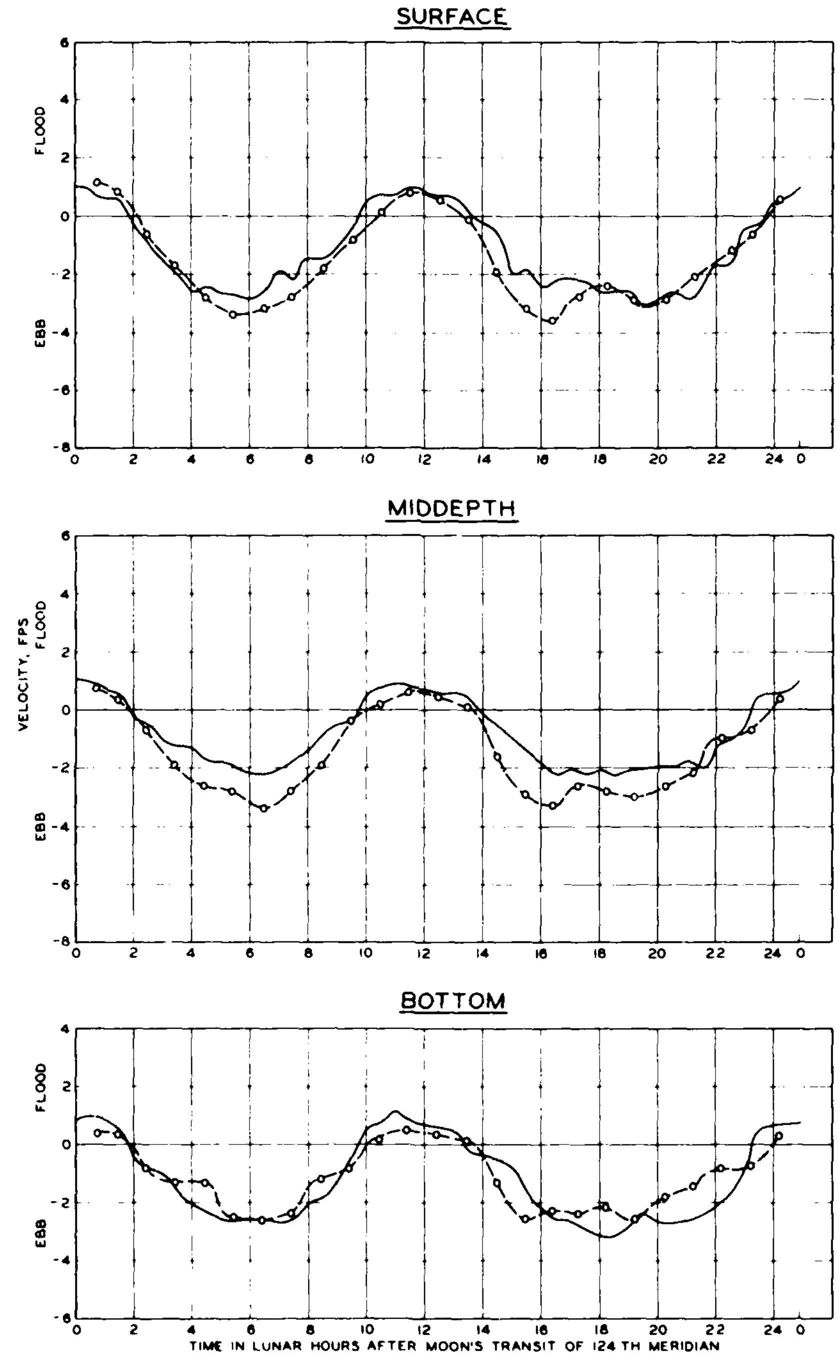
o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 6B



LEGEND

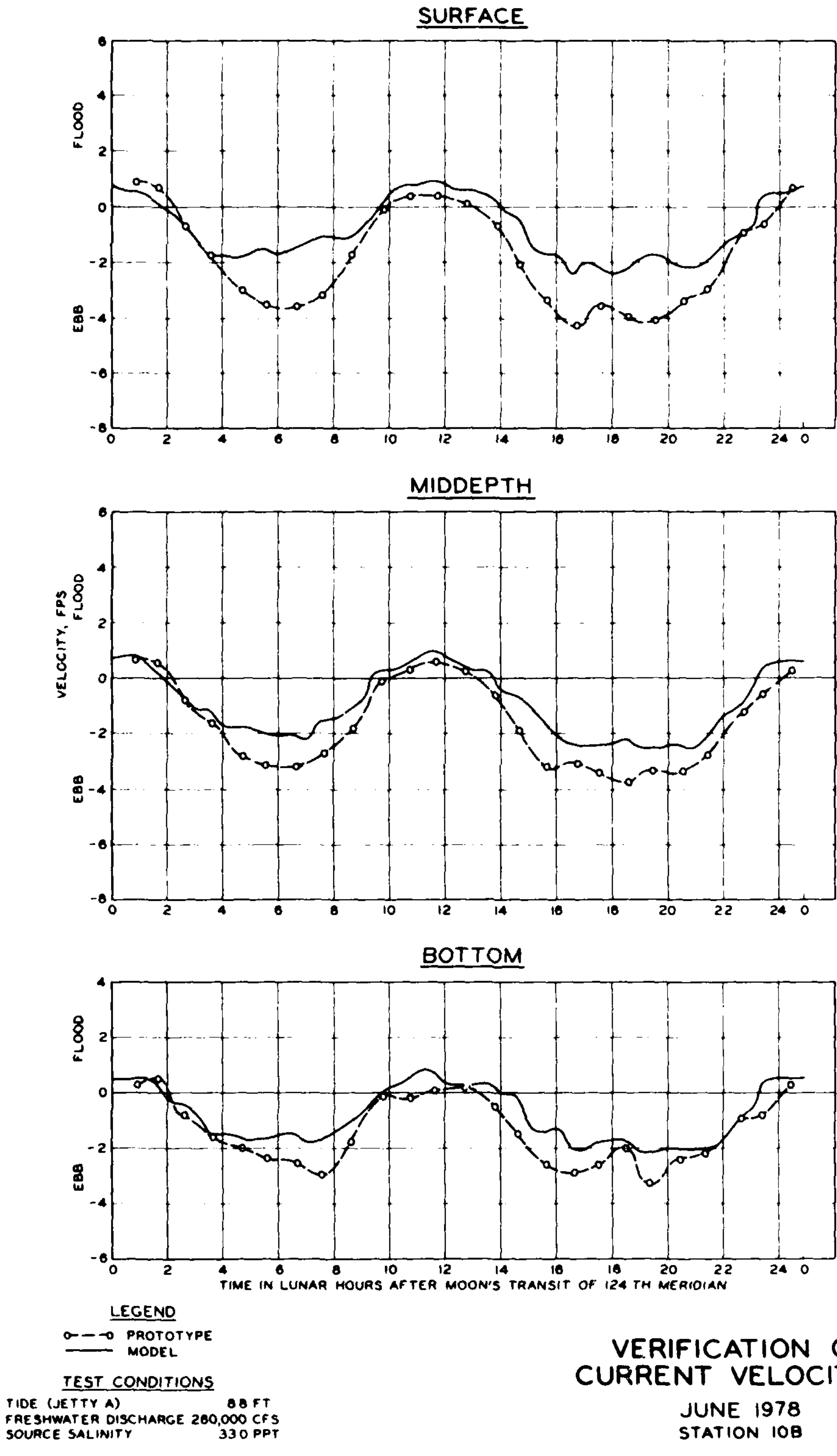
o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

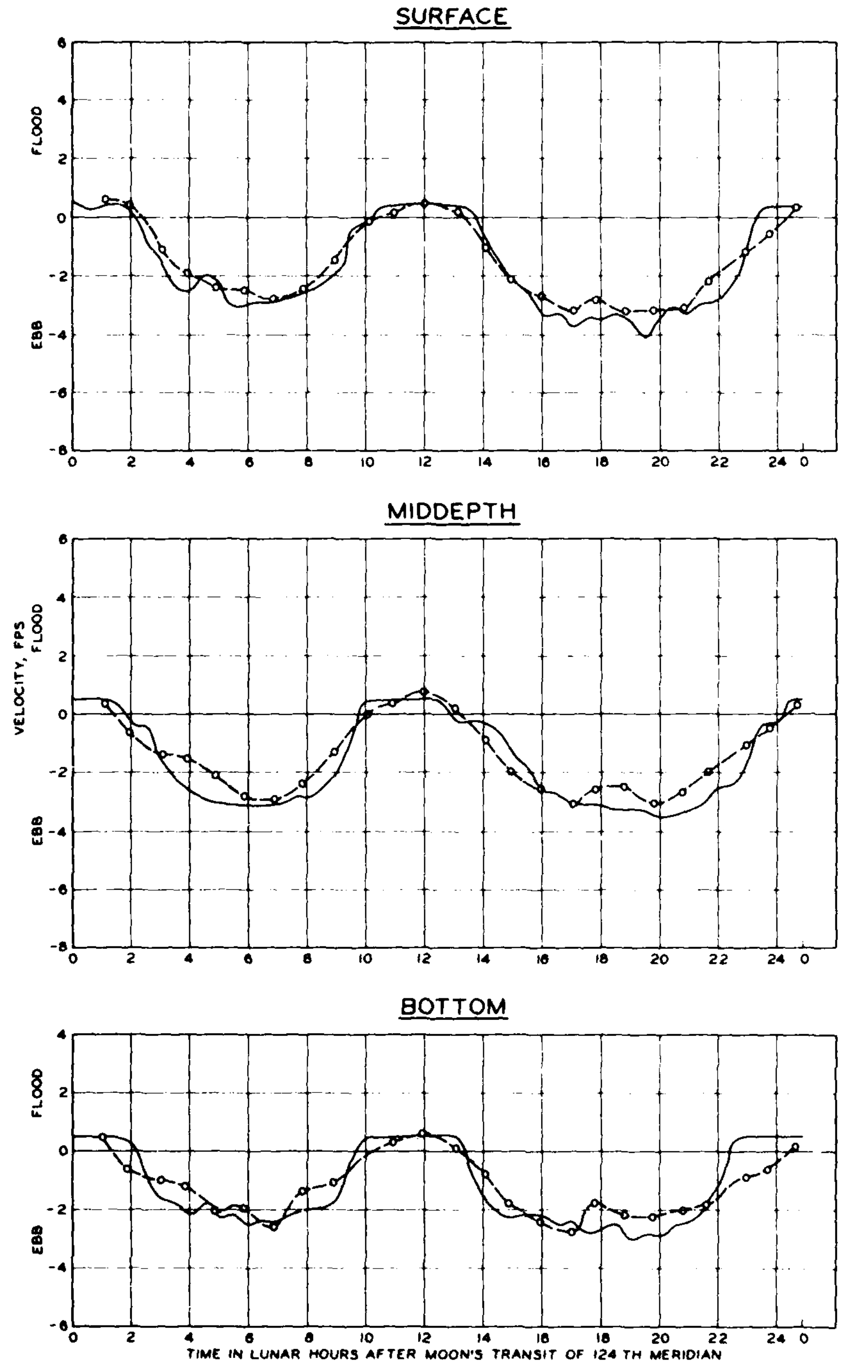
JUNE 1978
STATION 10A



VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 10B



LEGEND

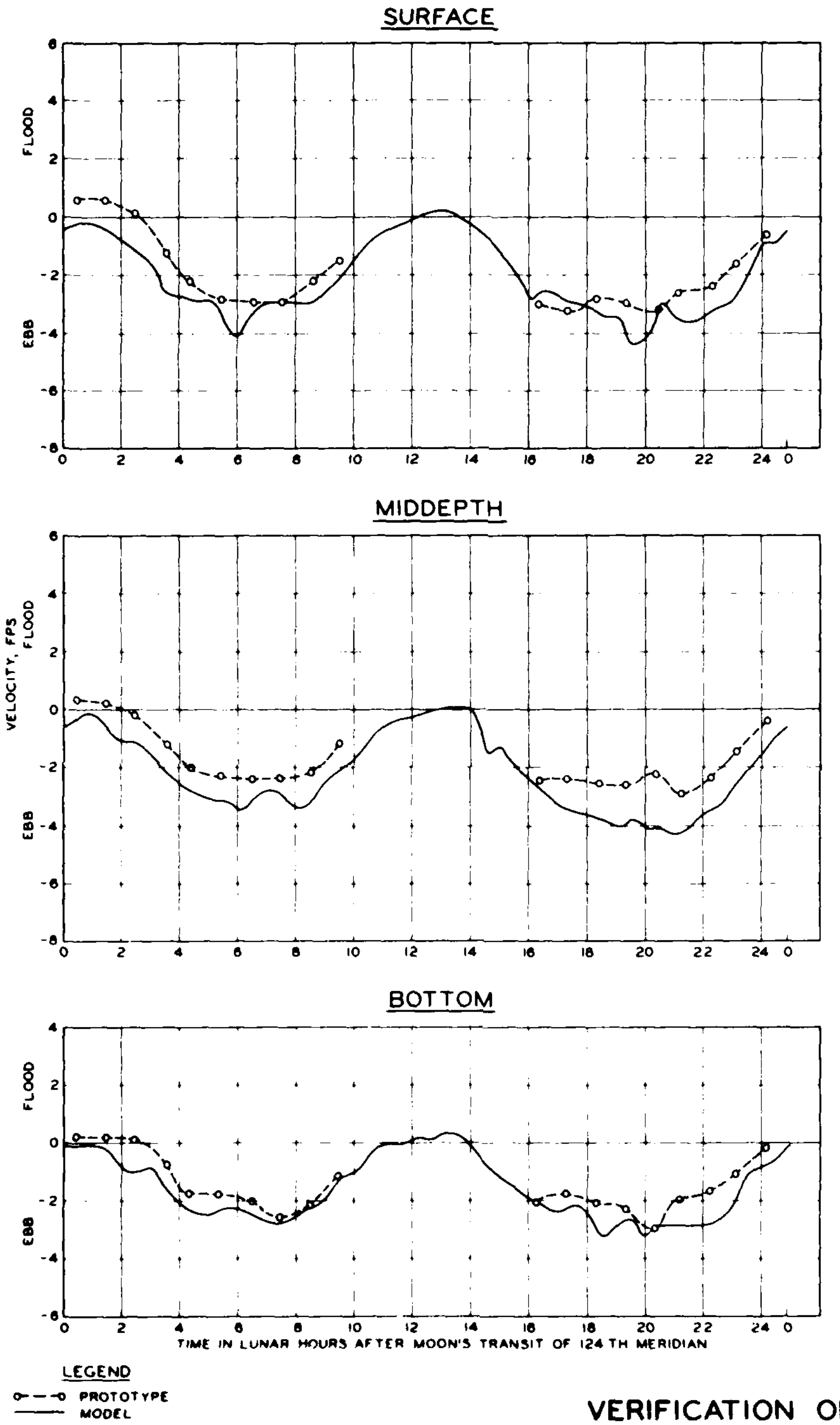
o- — -o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978
STATION 10C

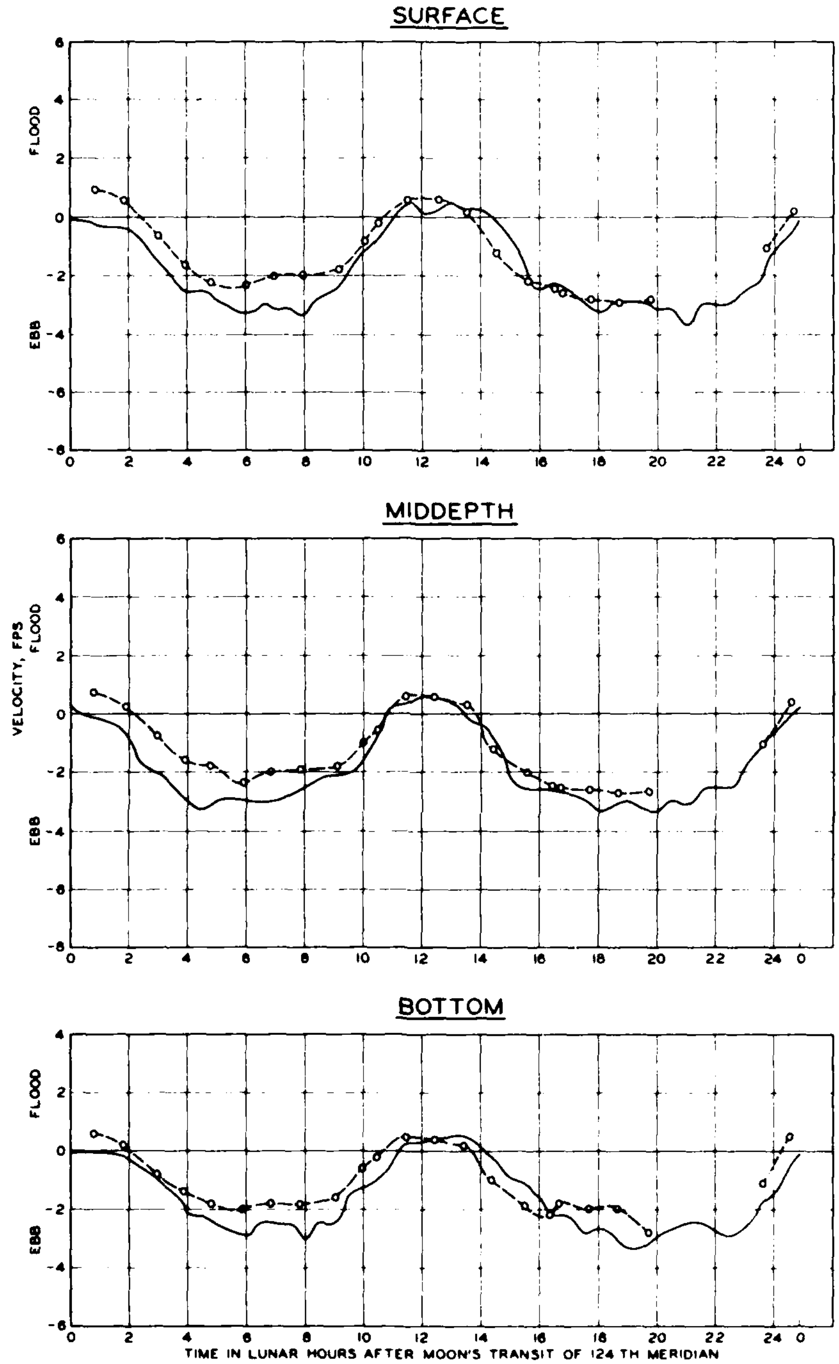


TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF
CURRENT VELOCITIES

JUNE 1978
STATION 8A



LEGEND

o---o PROTOTYPE

—— MODEL

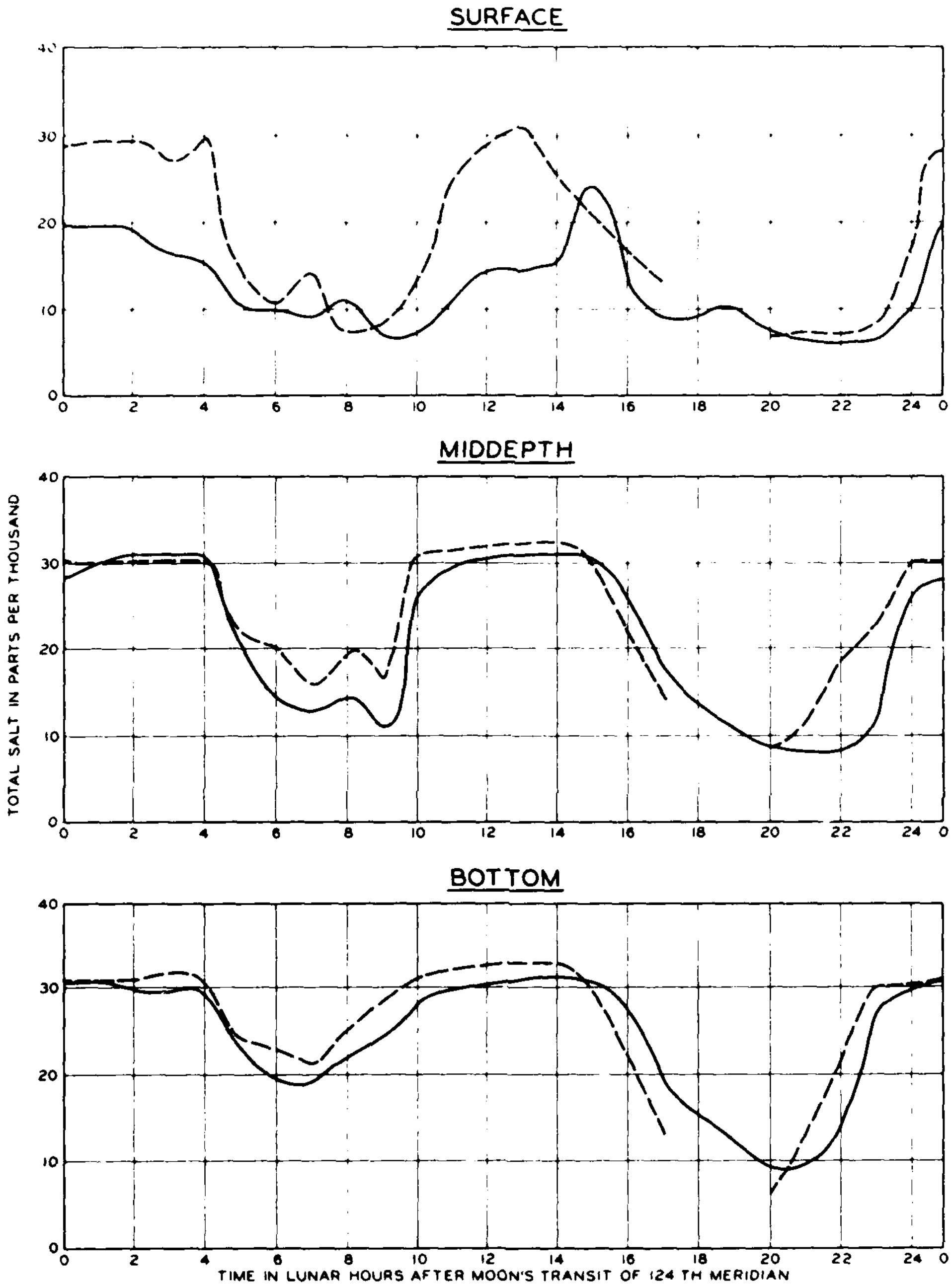
TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF CURRENT VELOCITIES

JUNE 1978

STATION 8B



LEGEND

- – – – PROTOTYPE
- —— MODEL

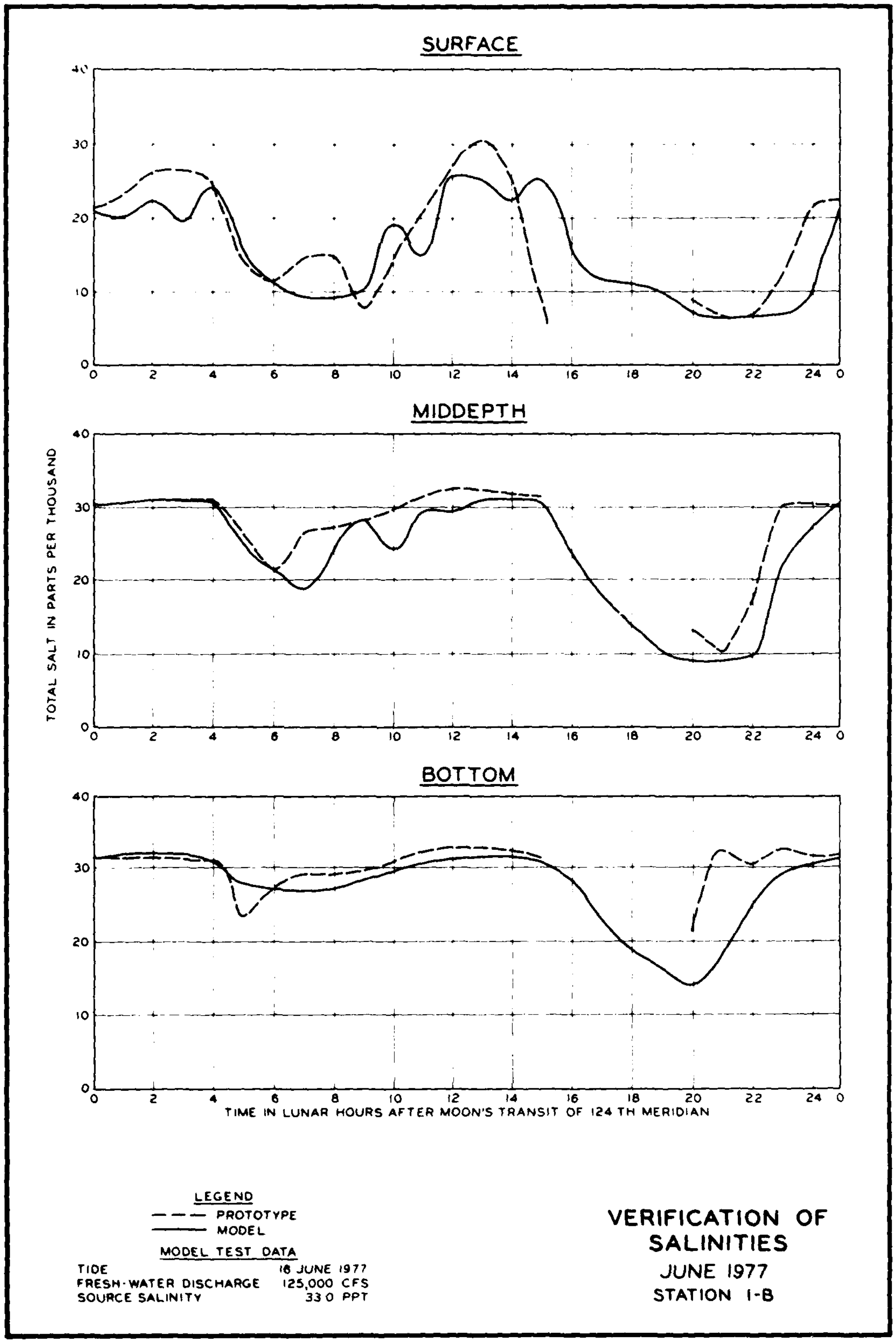
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

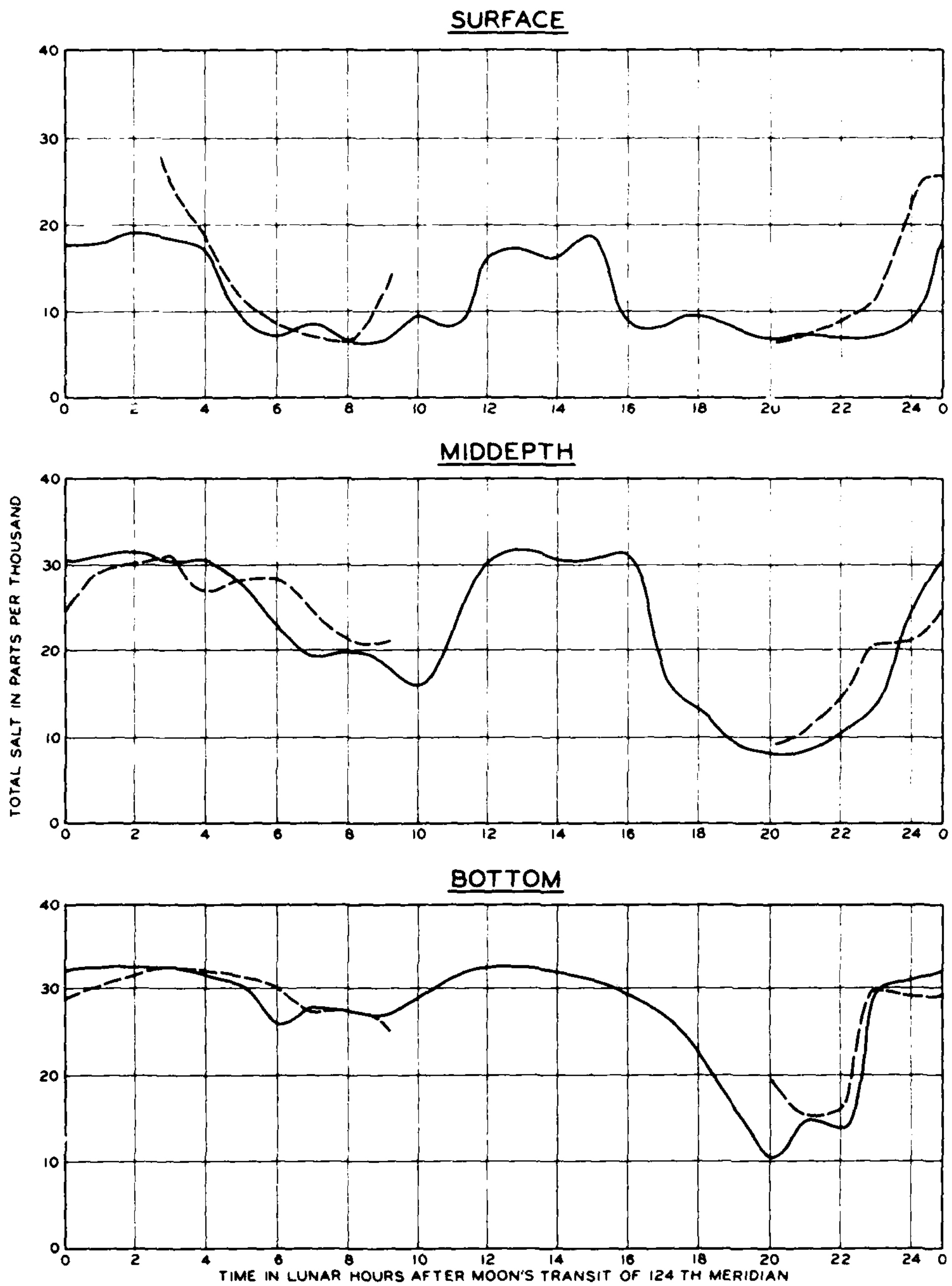
STATION 1-A



VERIFICATION OF SALINITIES

JUNE 1977

STATION 1-B



LEGEND

— — — PROTOTYPE

———— MODEL

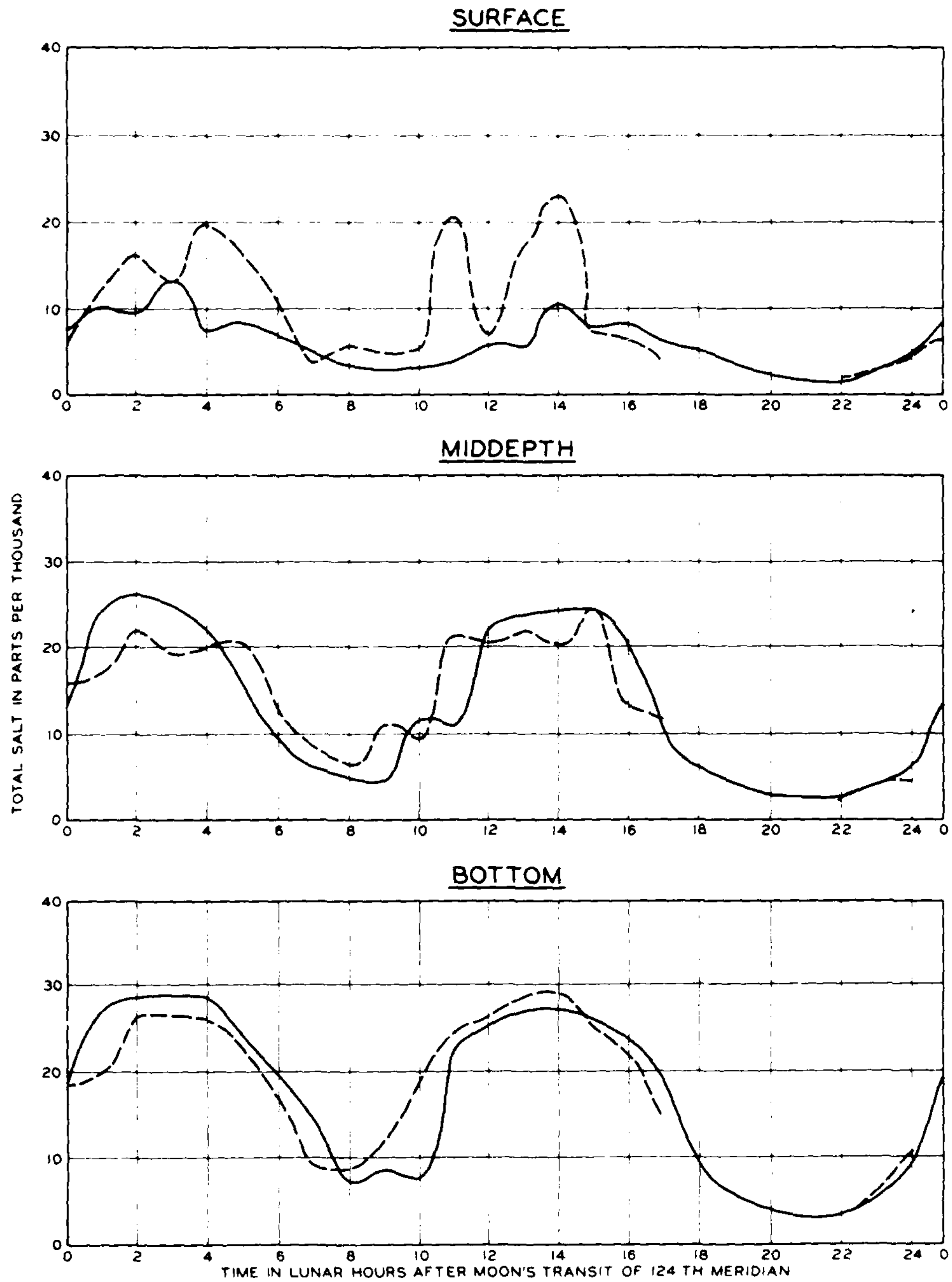
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 1-C



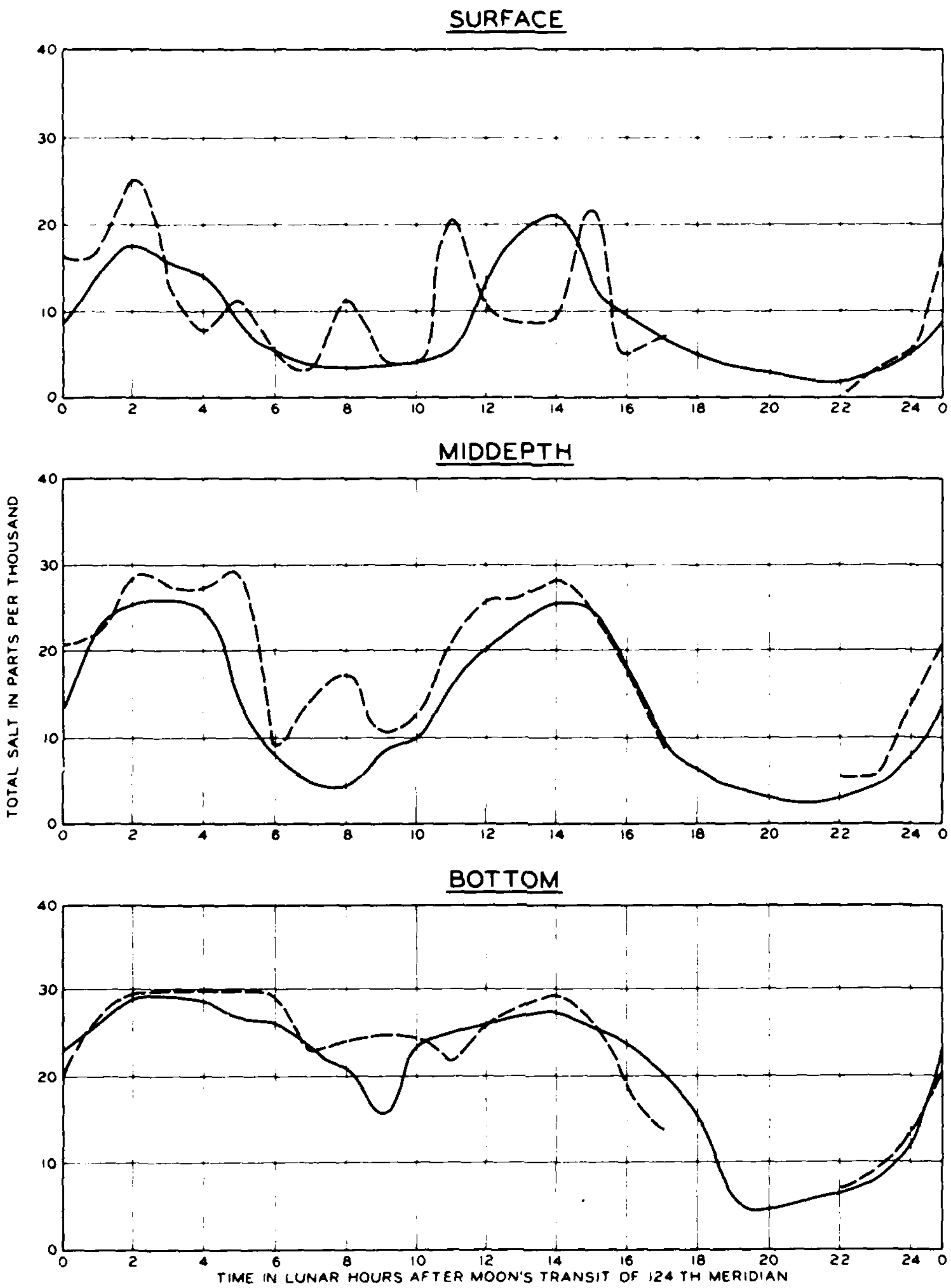
LEGEND
- – – – PROTOTYPE
- ——— MODEL

MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1977
STATION 2-D

PLATE 60



LEGEND

— — — PROTOTYPE
——— MODEL

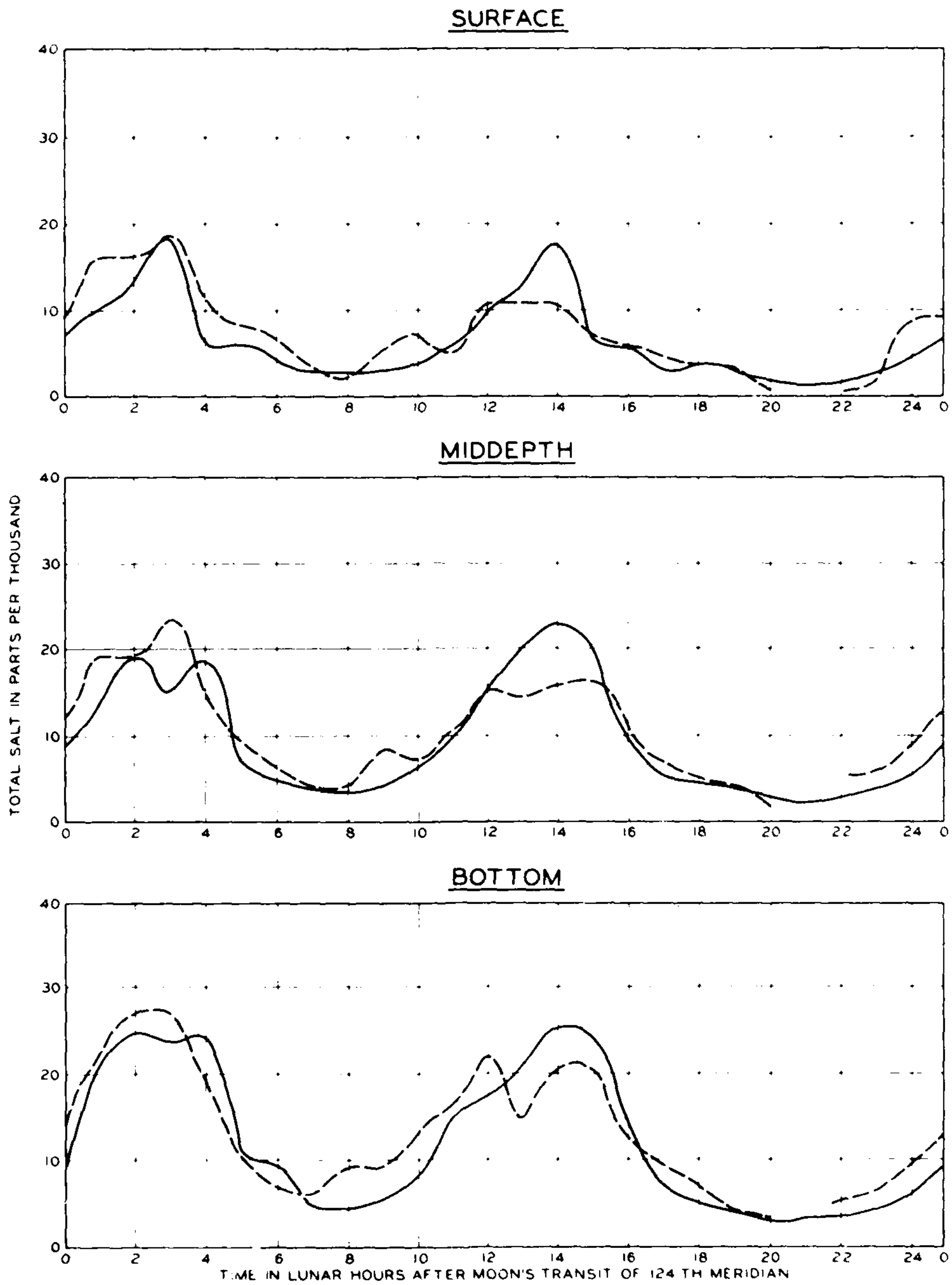
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 2-E



LEGEND

— — — PROTOTYPE
——— MODEL

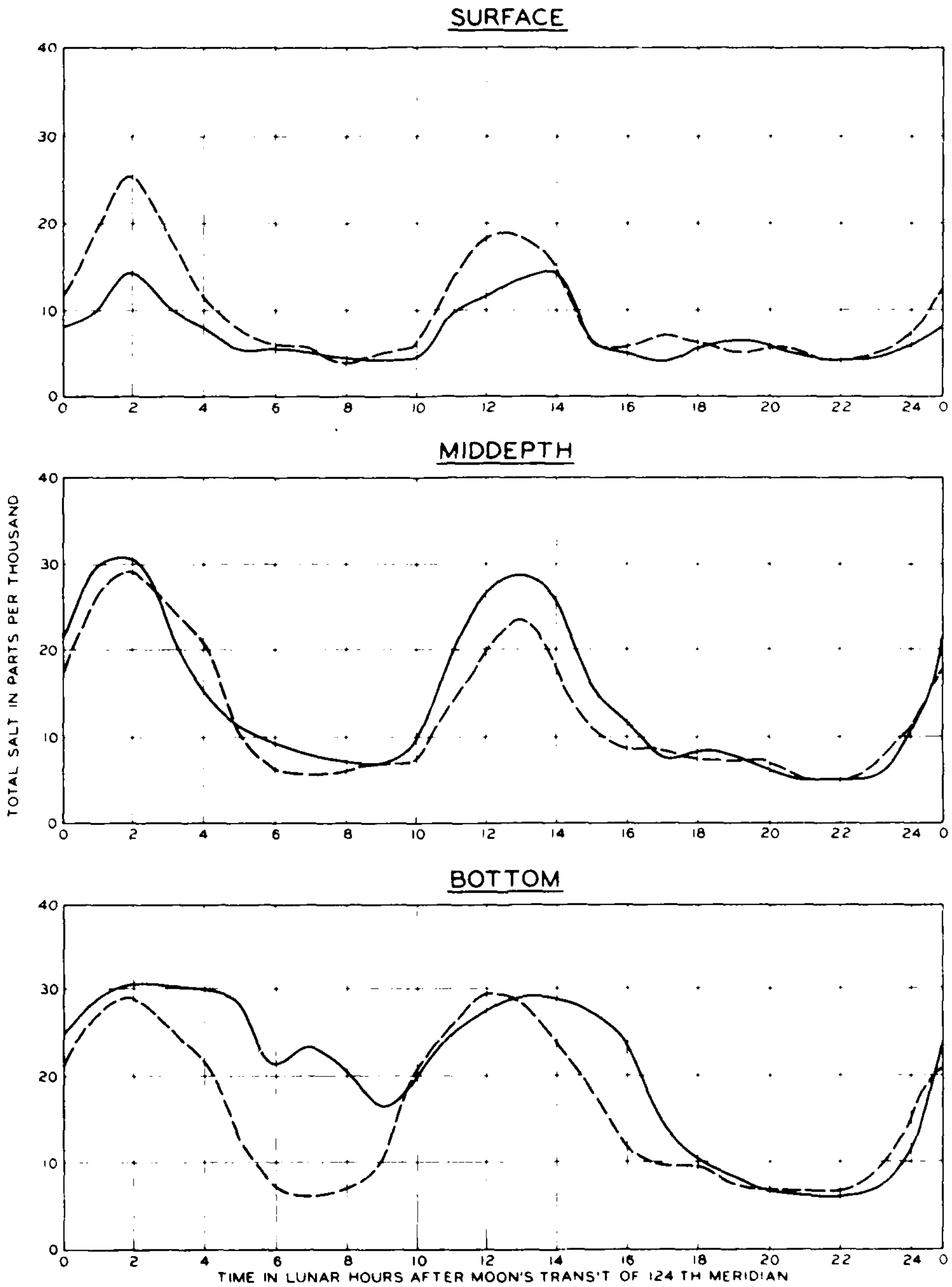
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 2-F



LEGEND

— — — PROTOTYPE
——— MODEL

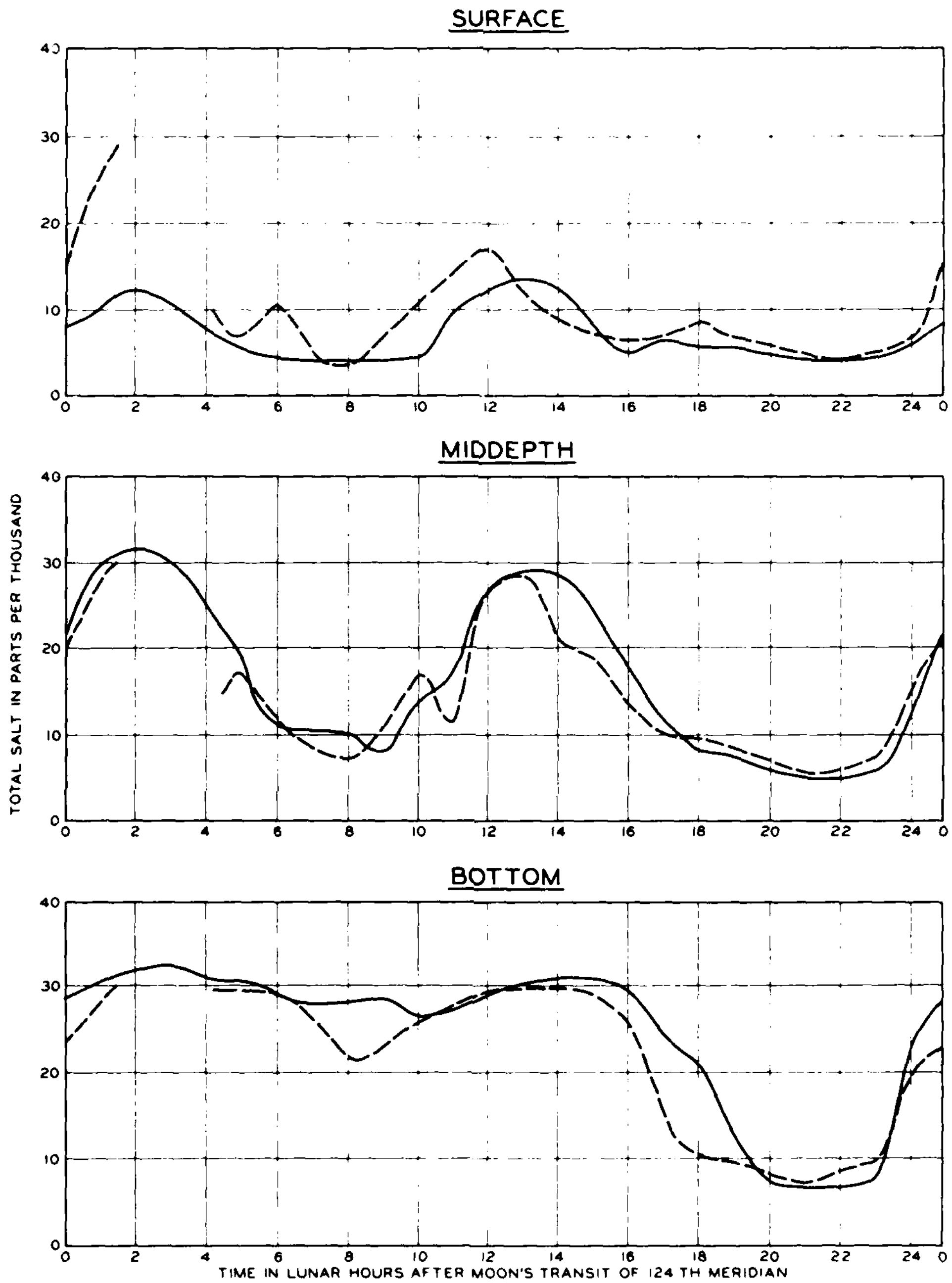
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 3-G



LEGEND

— — — PROTOTYPE

——— MODEL

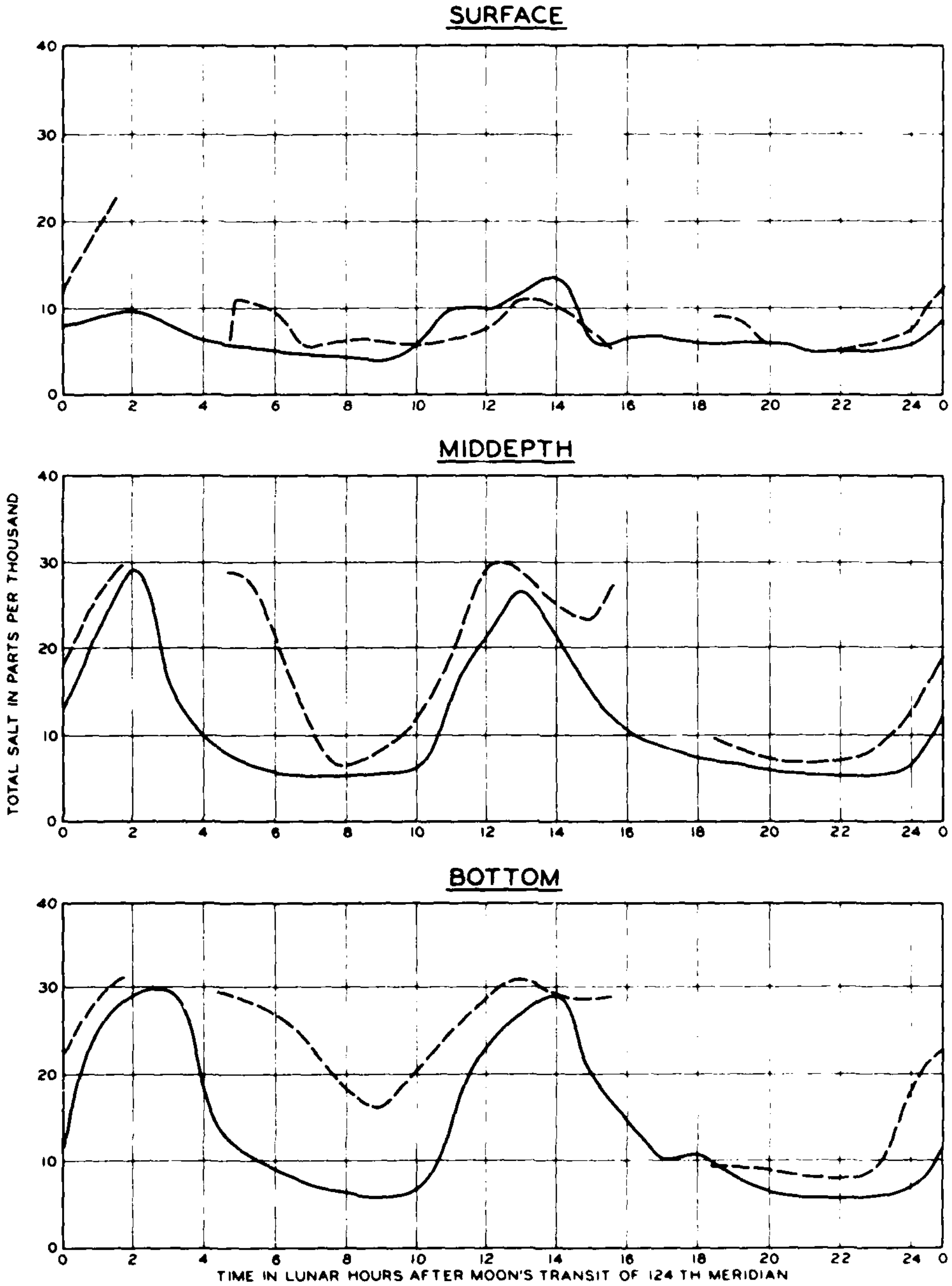
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 3-H



LEGEND

PROTOTYPE

MODEL

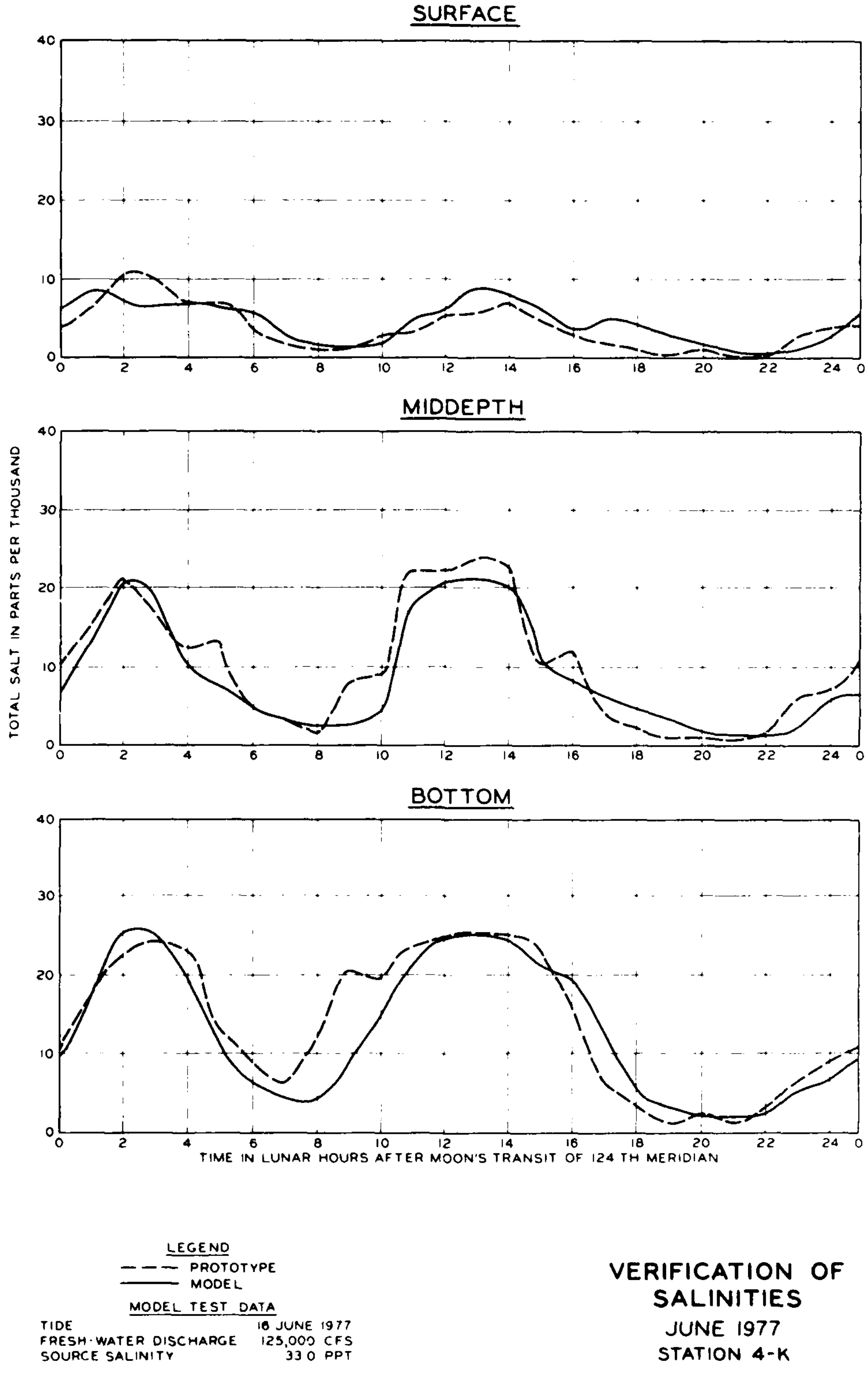
MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

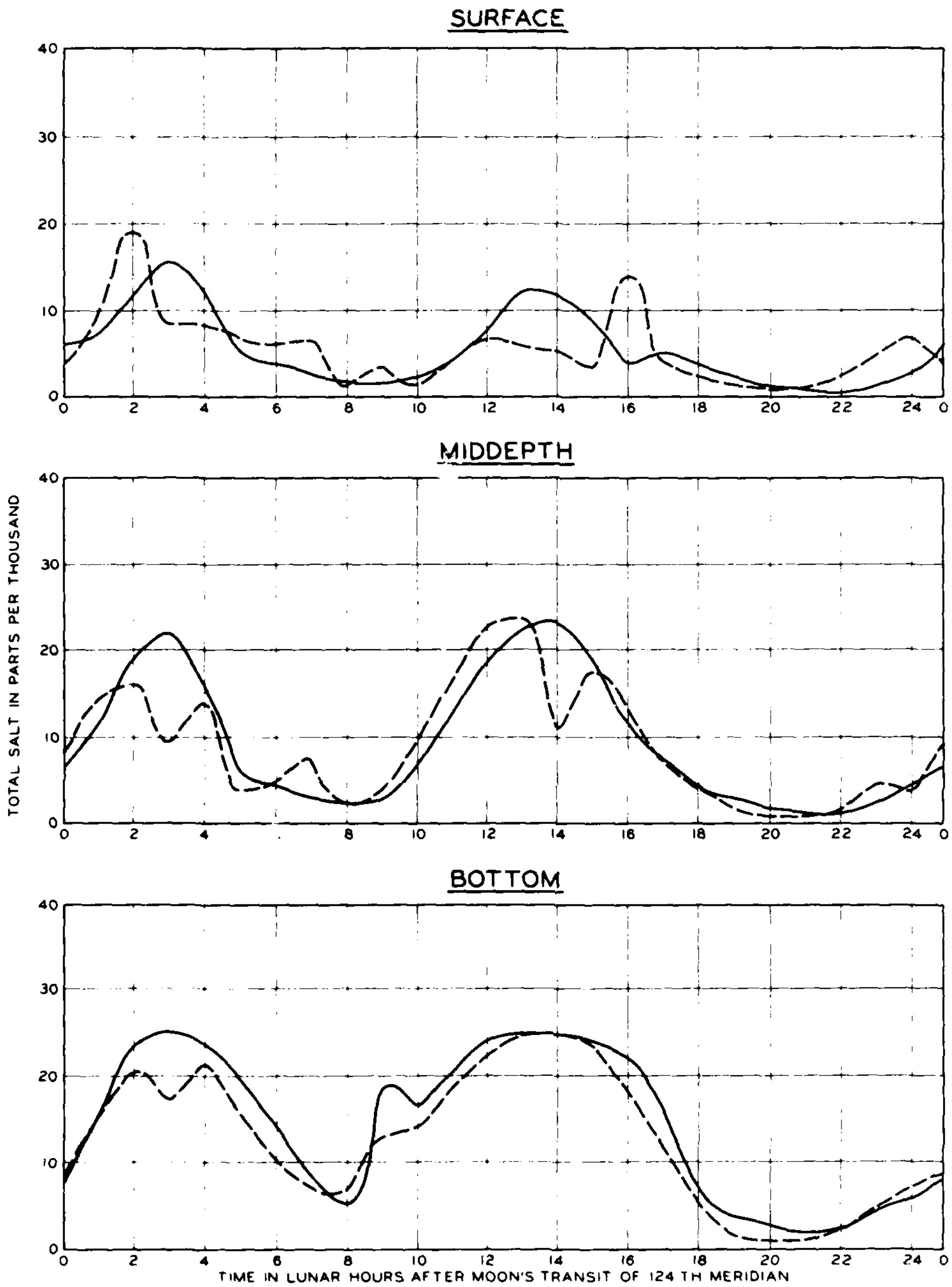
JUNE 1977

STATION 3-J



VERIFICATION OF SALINITIES
JUNE 1977
STATION 4-K

PLATE 66



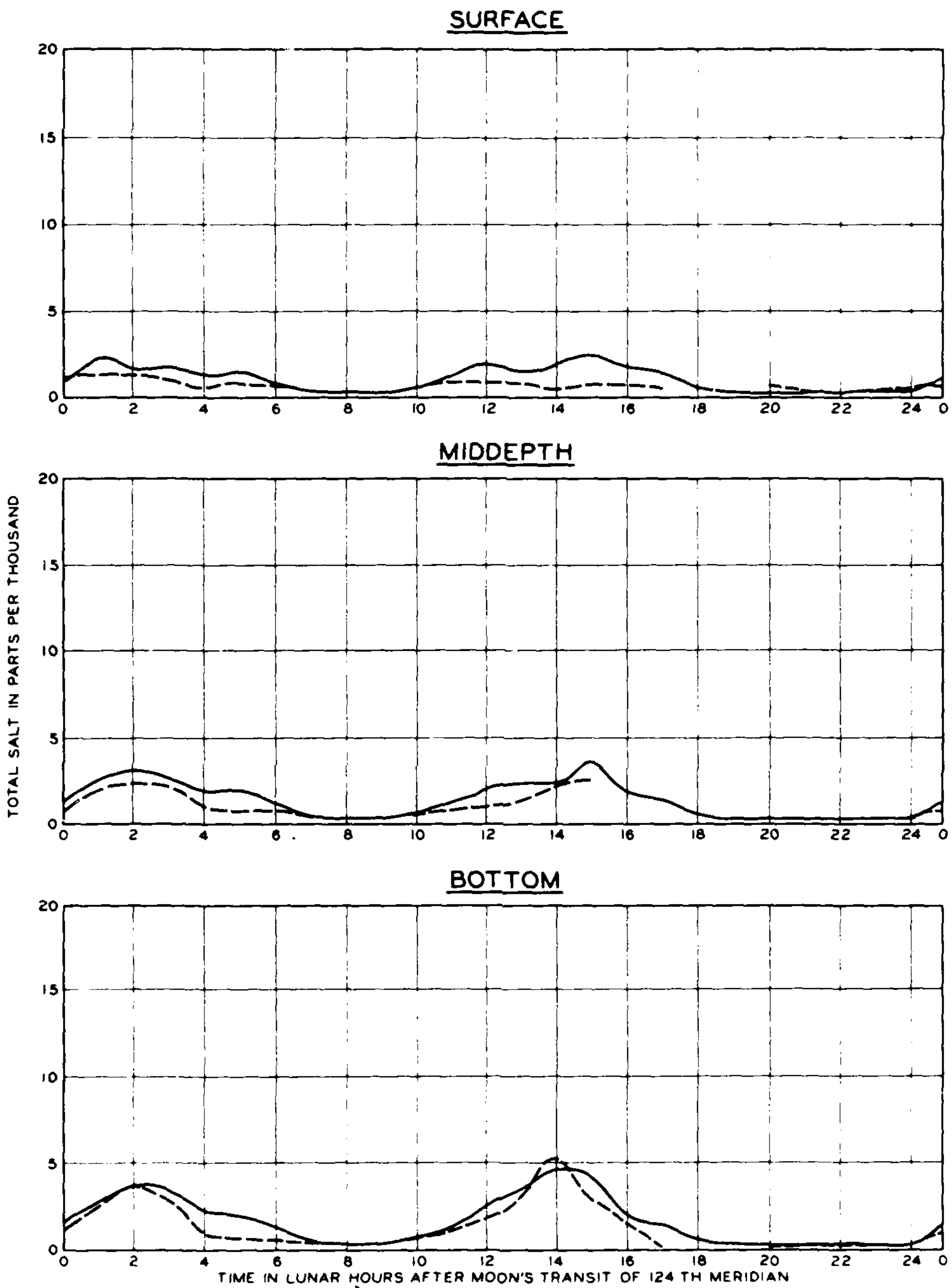
LEGEND

- – – – PROTOTYPE
- ——— MODEL

MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1977
STATION 4-L



LEGEND

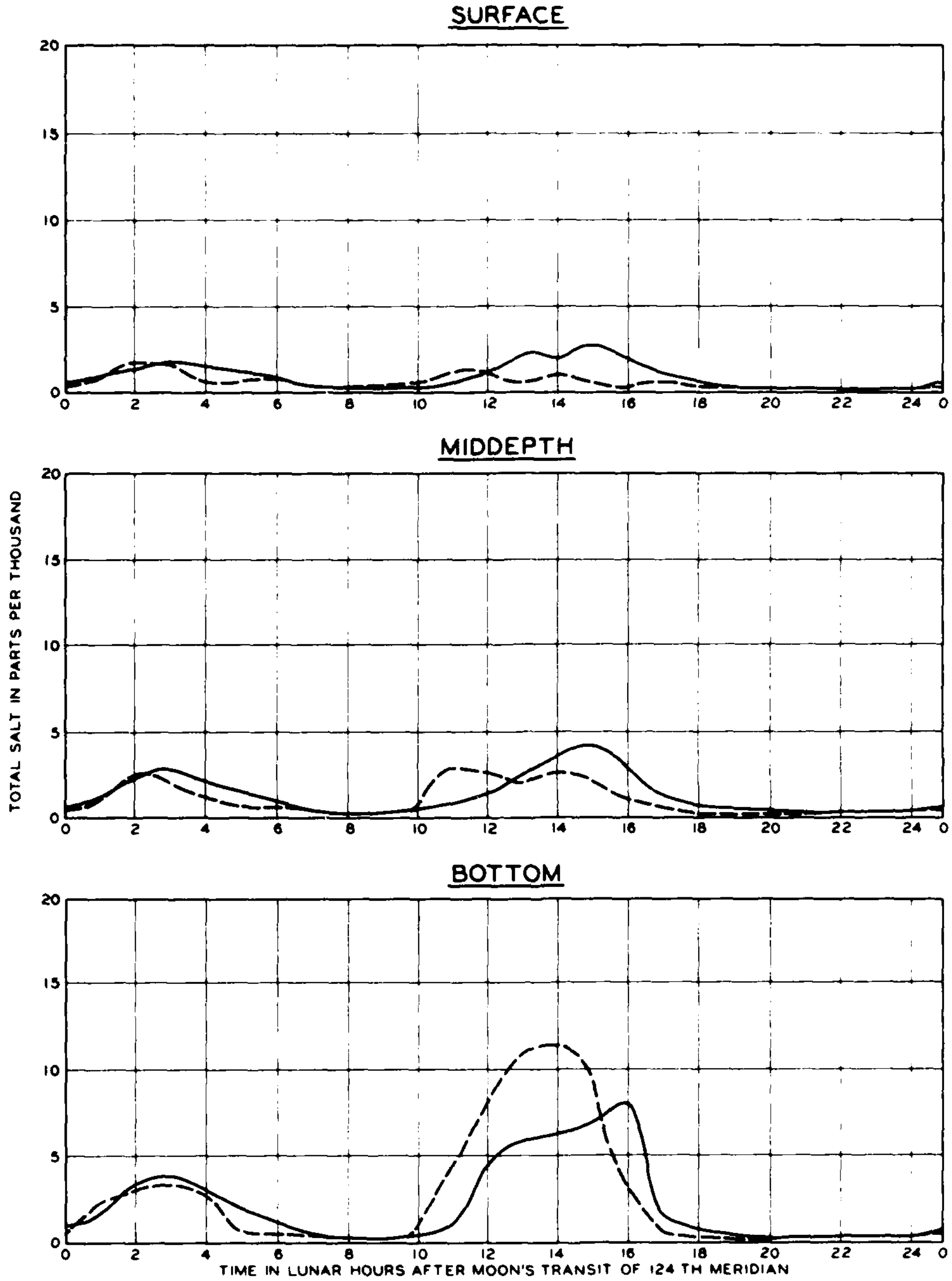
- – – – PROTOTYPE
- ——— MODEL

MODEL TEST DATA

TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1977
STATION 5-M

PLATE 68



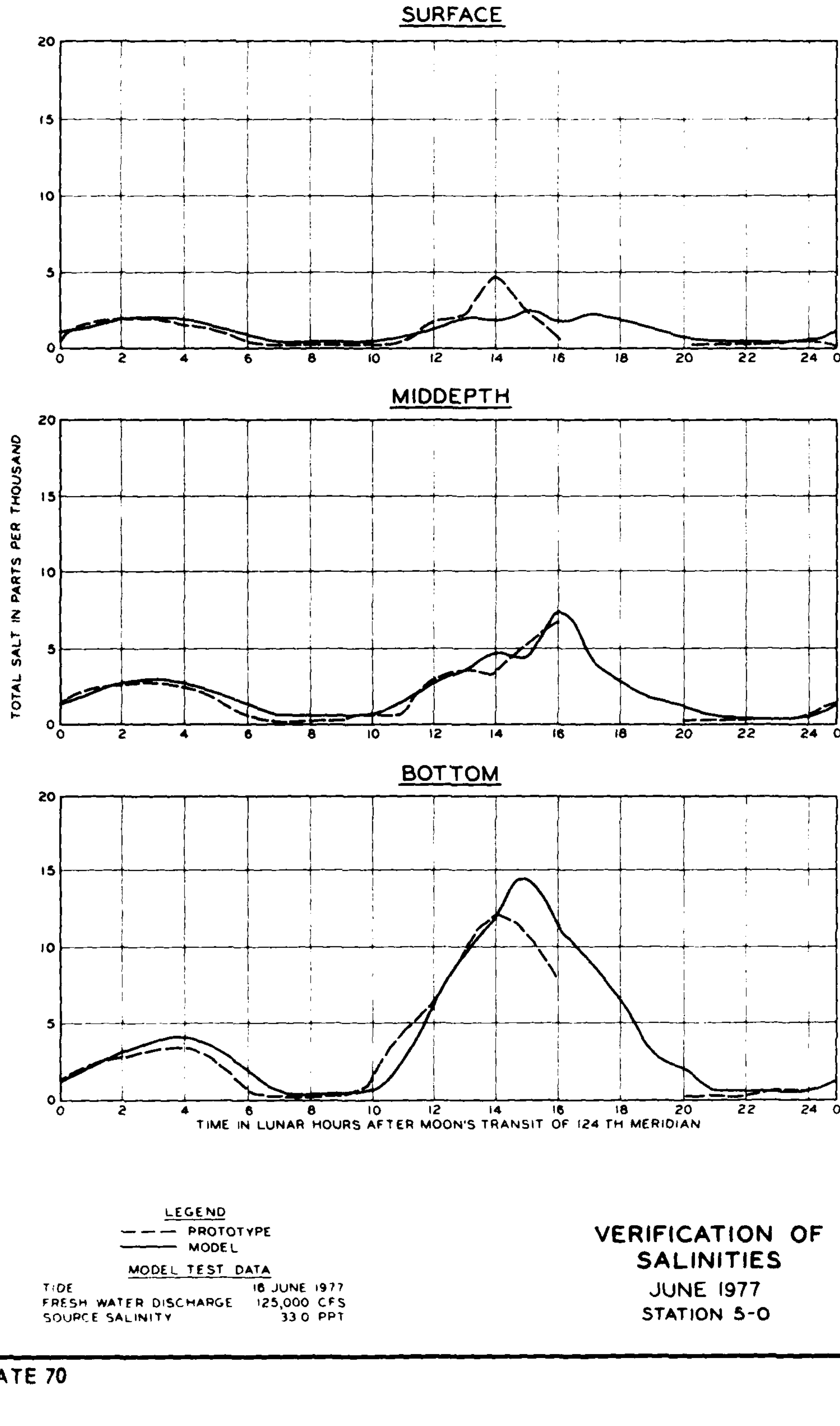
LEGEND

– – – PROTOTYPE
——— MODEL

MODEL TEST DATA

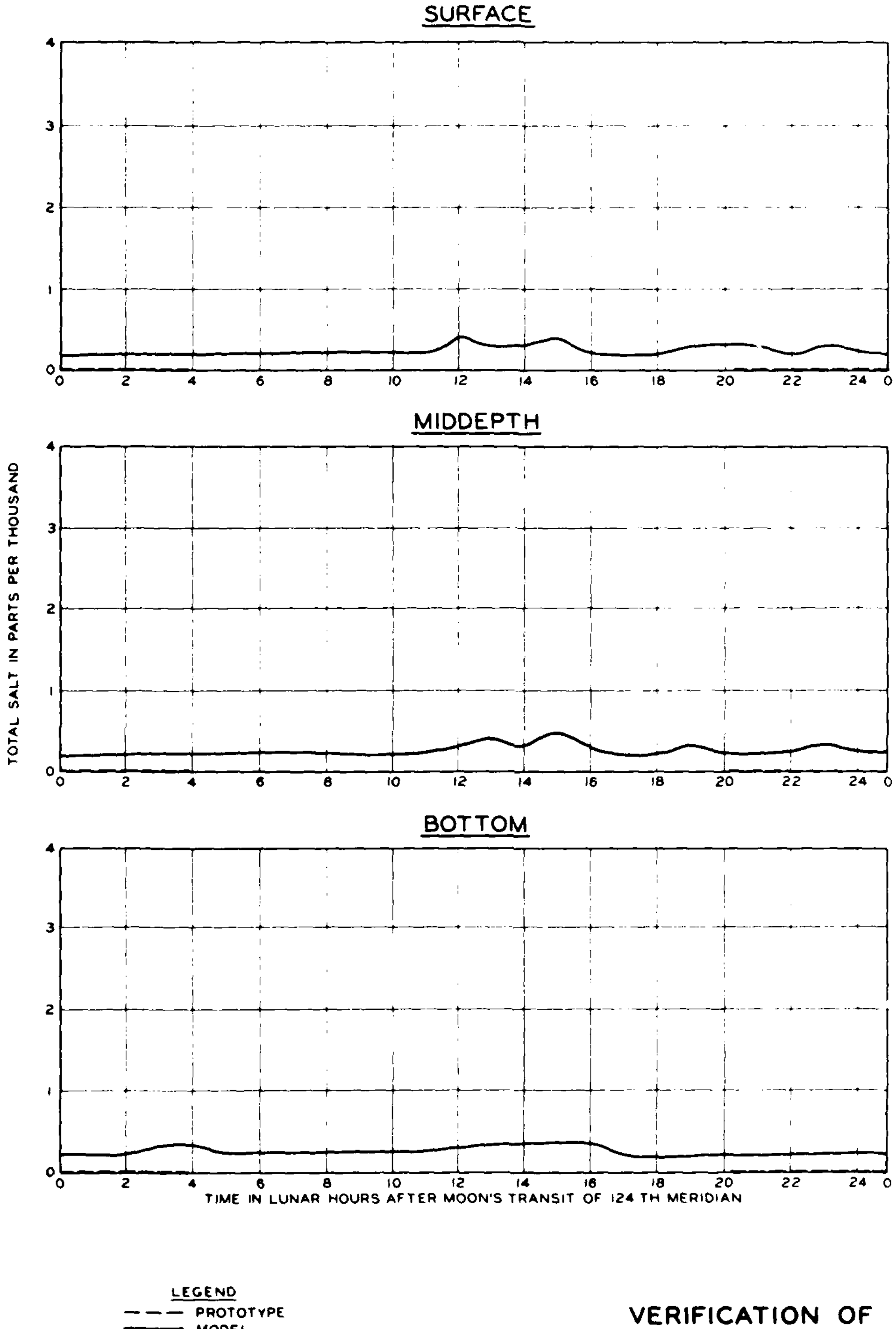
TIDE	18 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1977
STATION 5-N



VERIFICATION OF SALINITIES
JUNE 1977
STATION 5-0

PLATE 70



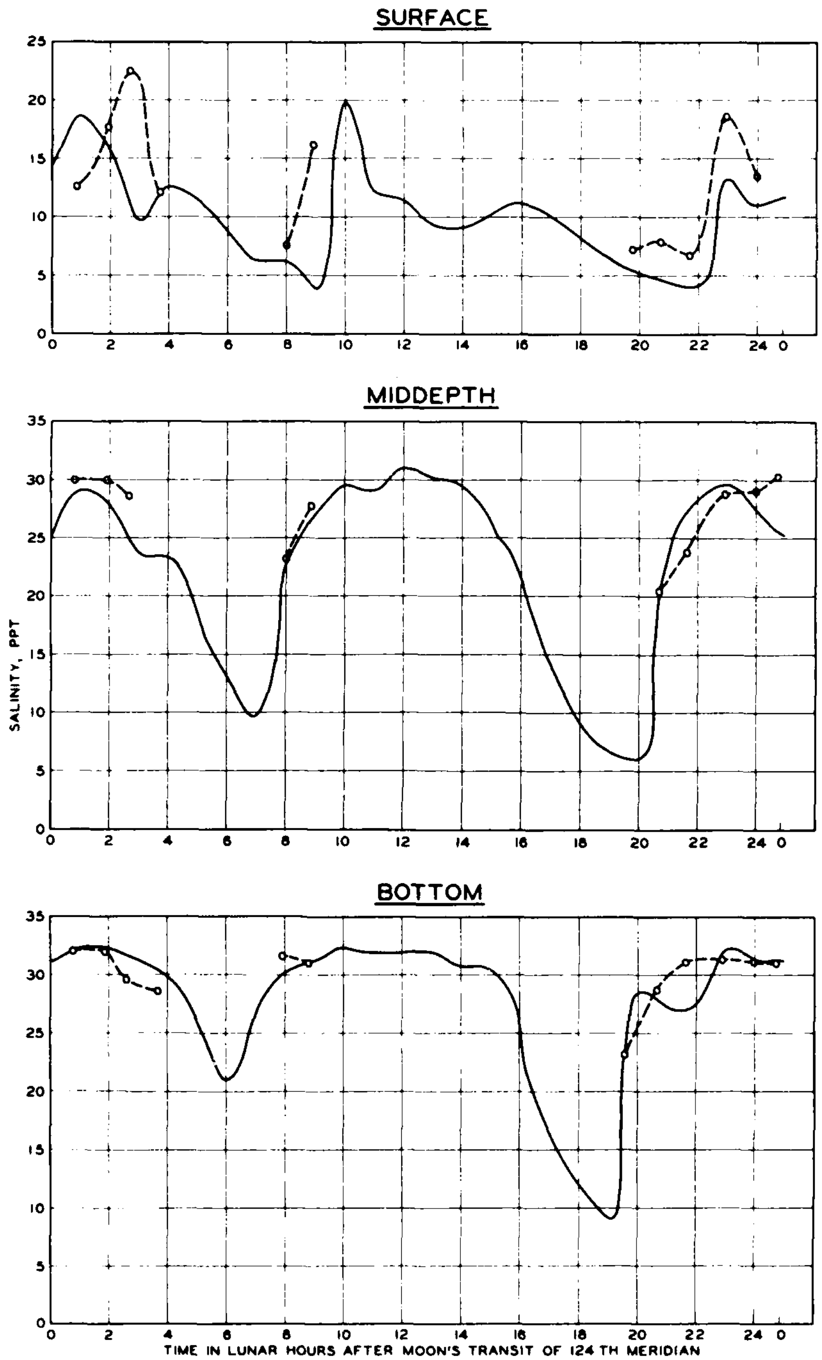
MODEL TEST DATA

TIDE	16 JUNE 1977
FRESH-WATER DISCHARGE	125,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1977

STATION 6-P



LEGEND

o— — —o PROTOTYPE
——— MODEL

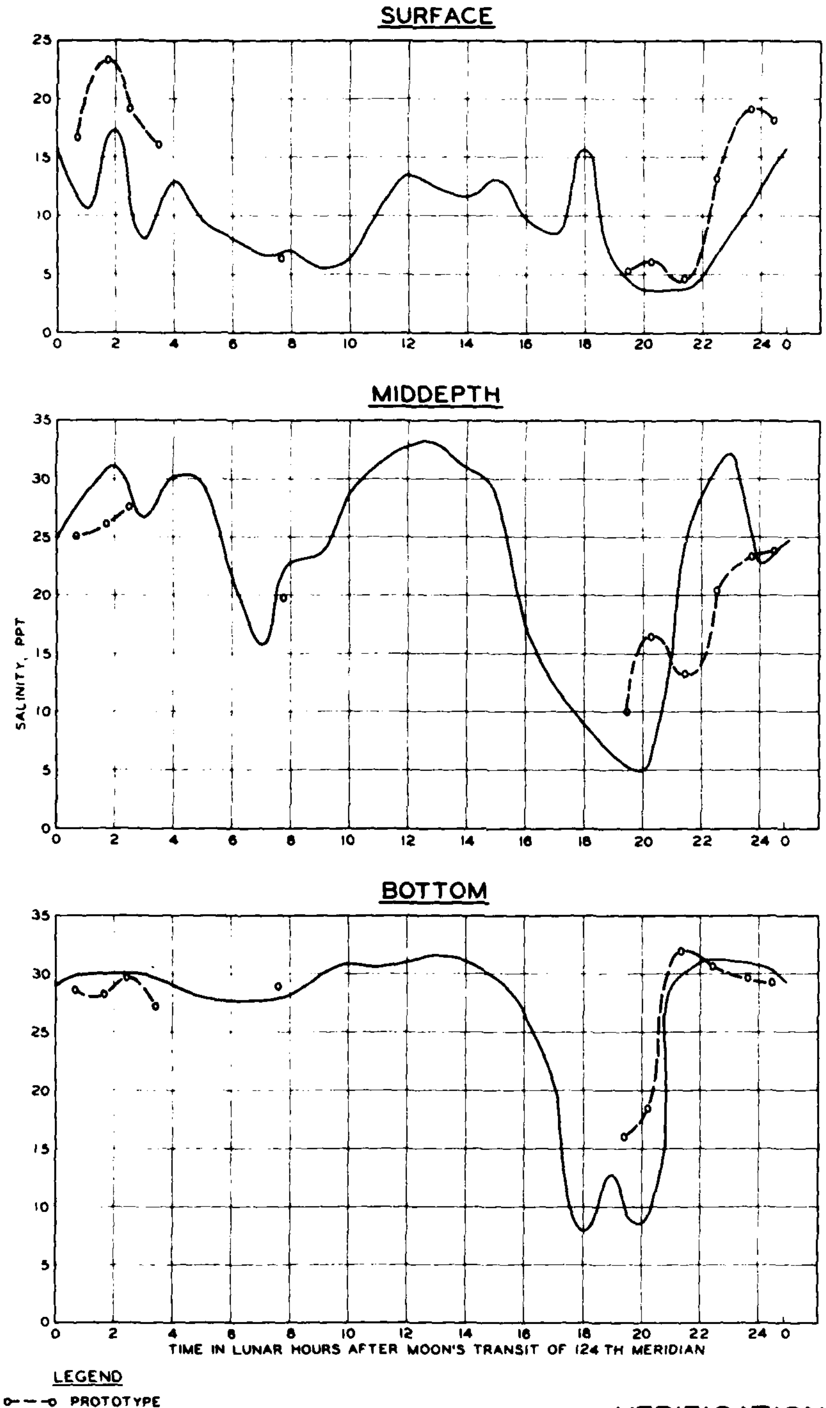
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

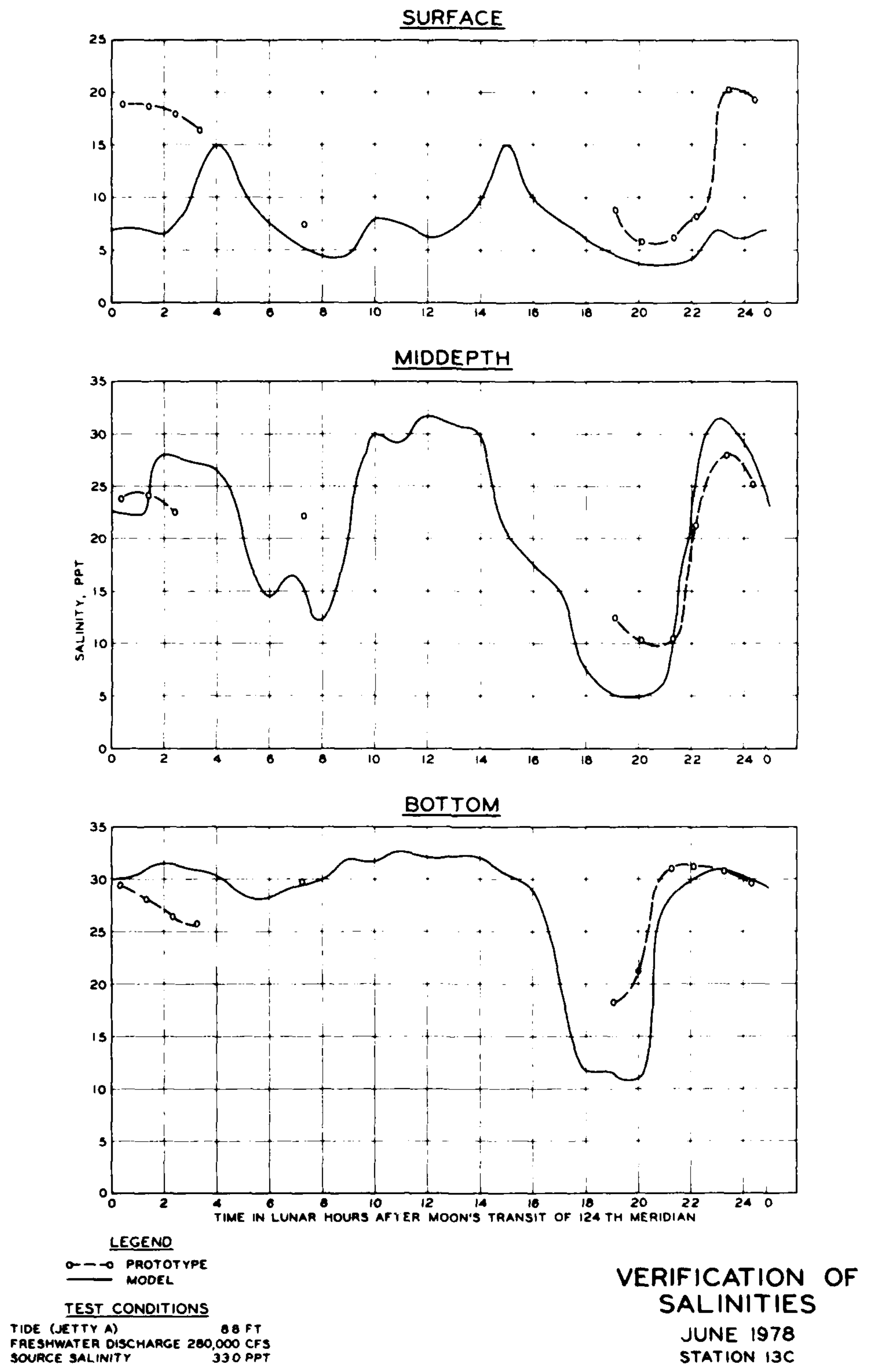
STATION 13A



TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

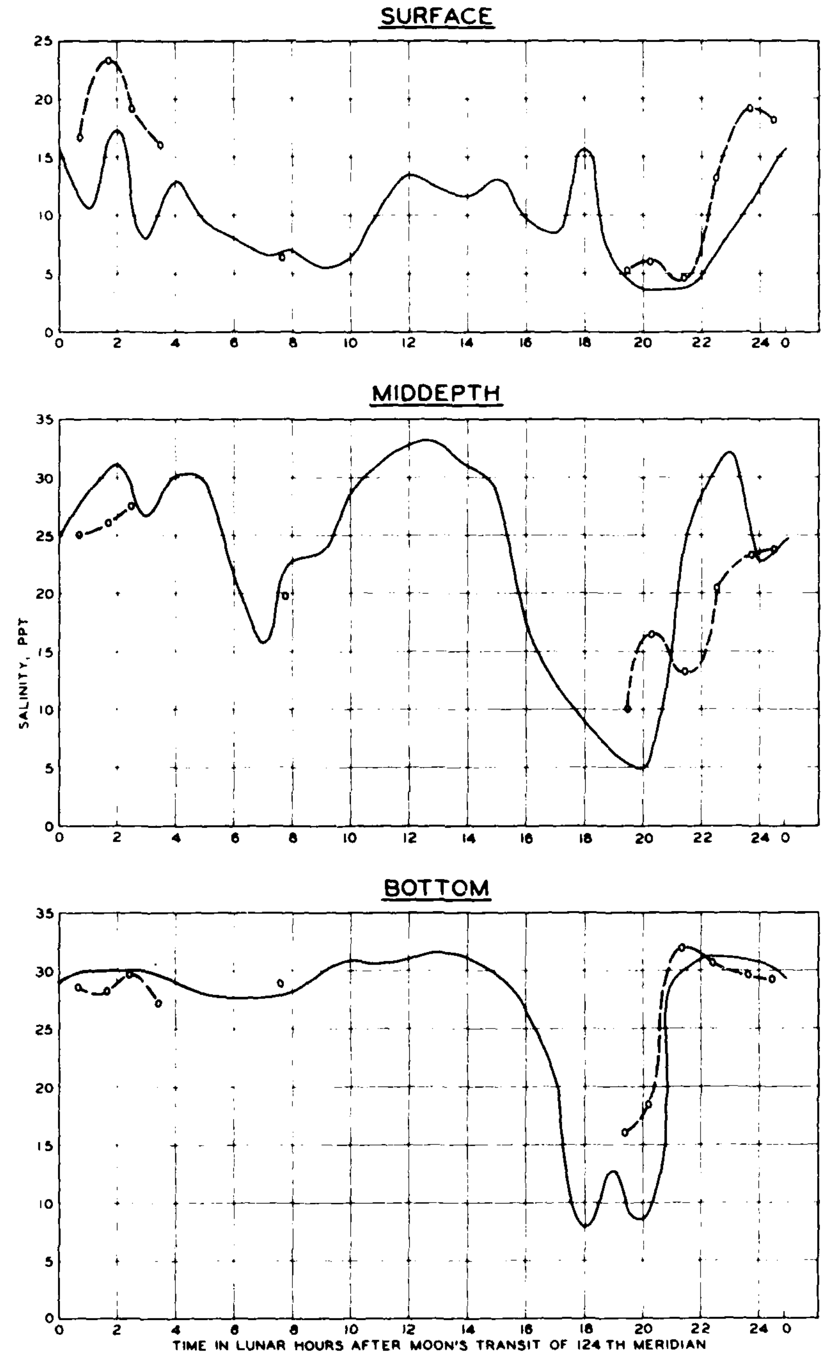
VERIFICATION OF SALINITIES
JUNE 1978
STATION 13B



VERIFICATION OF SALINITIES

JUNE 1978

STATION 13C



LEGEND

o---o PROTOTYPE
—— MODEL

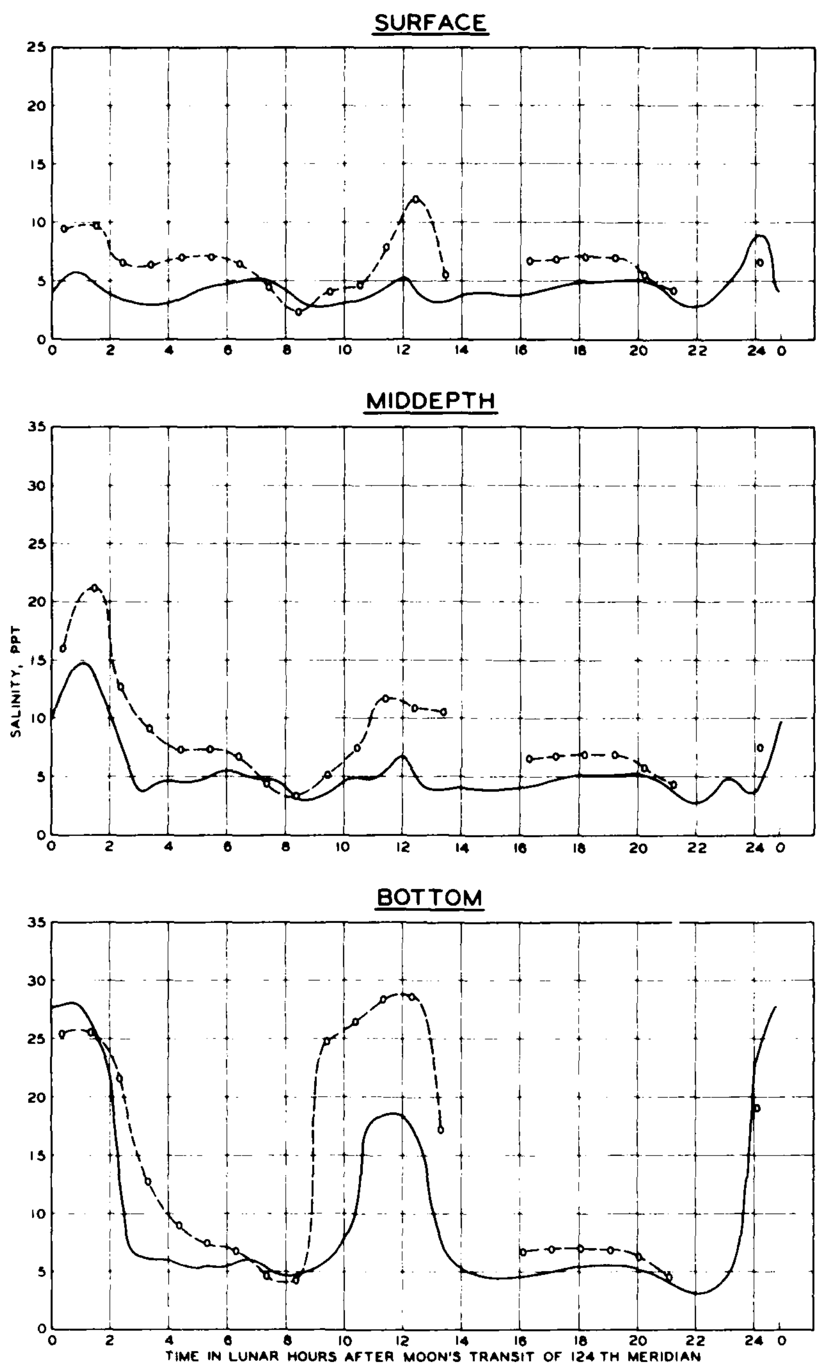
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 138



LEGEND

PROTOTYPE

MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT

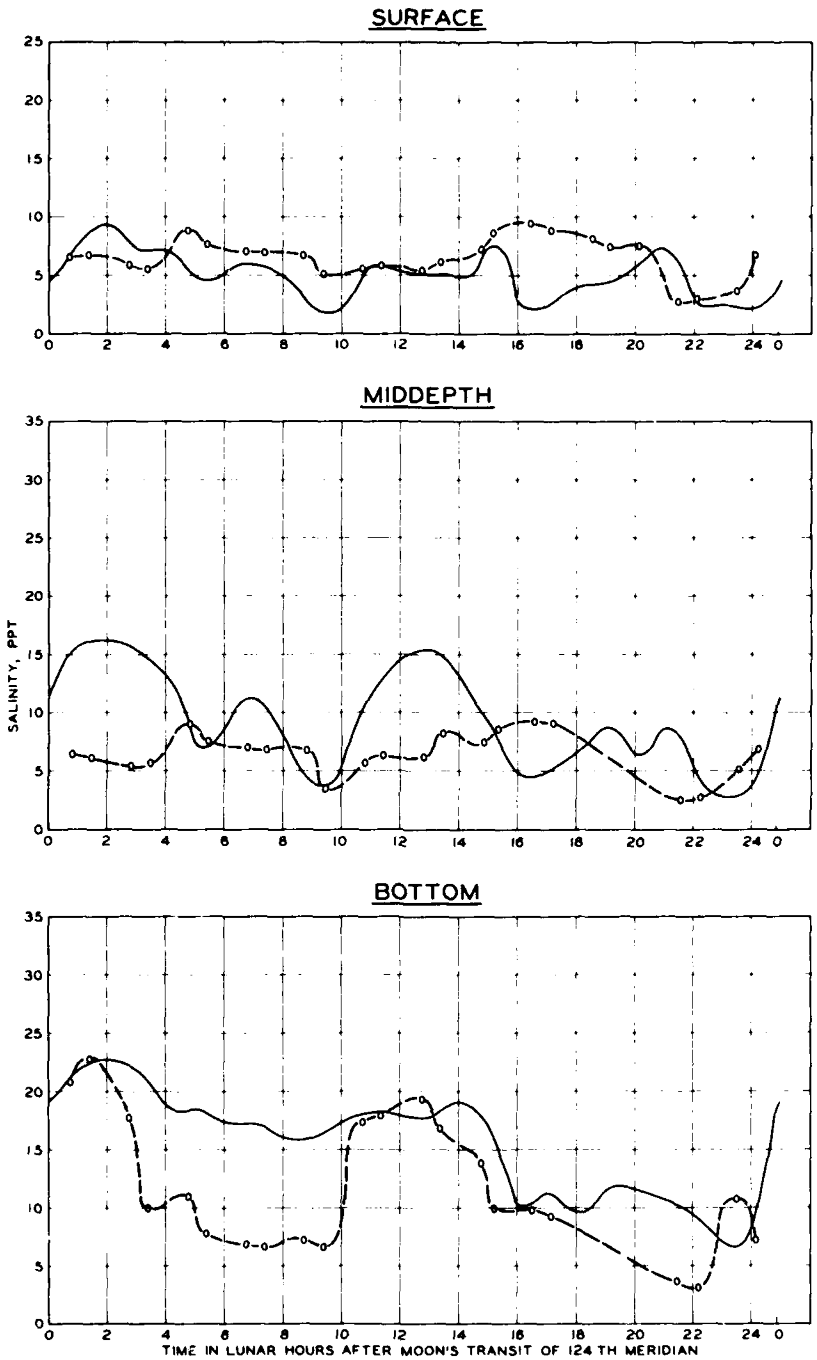
FRESHWATER DISCHARGE 280,000 CFS

SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 12A



LEGEND

o- - -o PROTOTYPE
—— MODEL

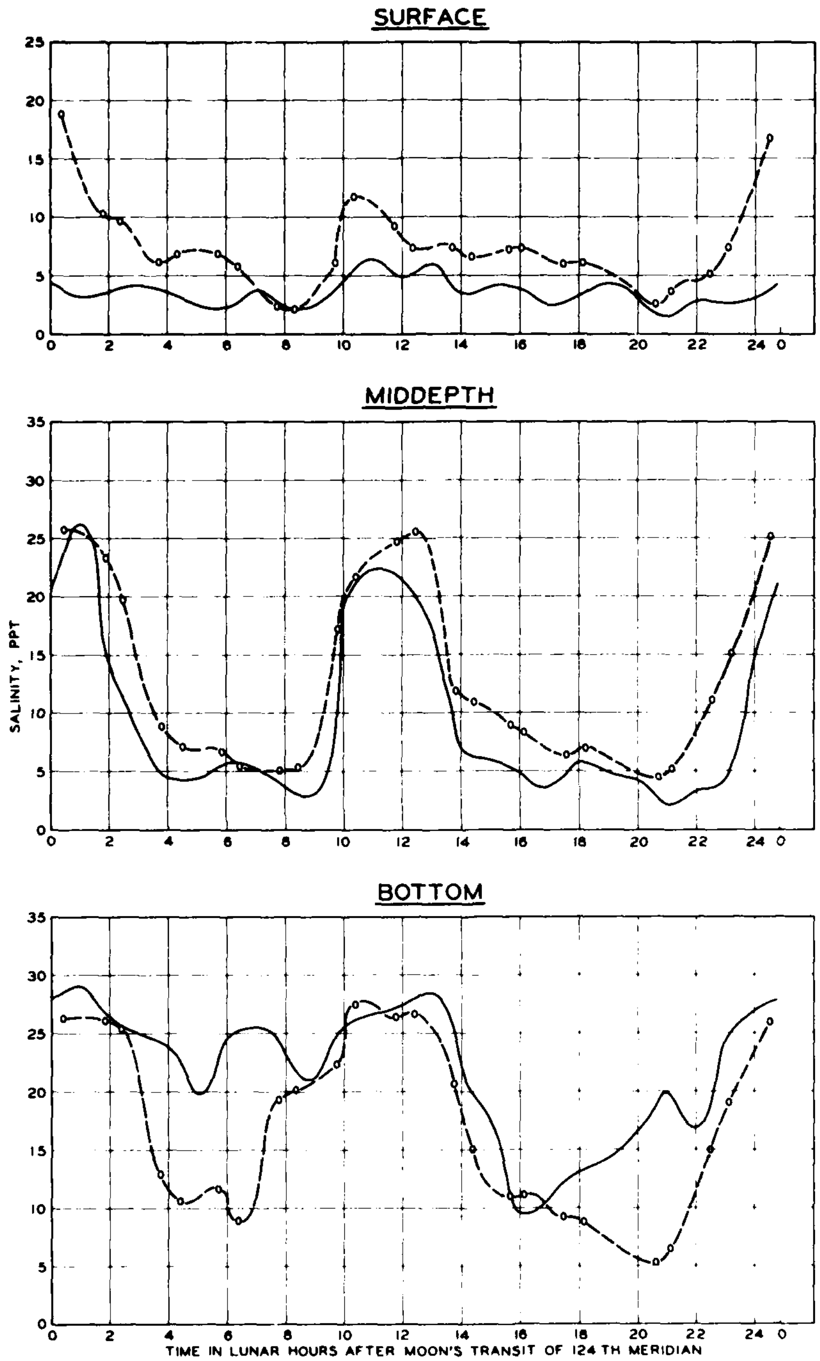
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 11A



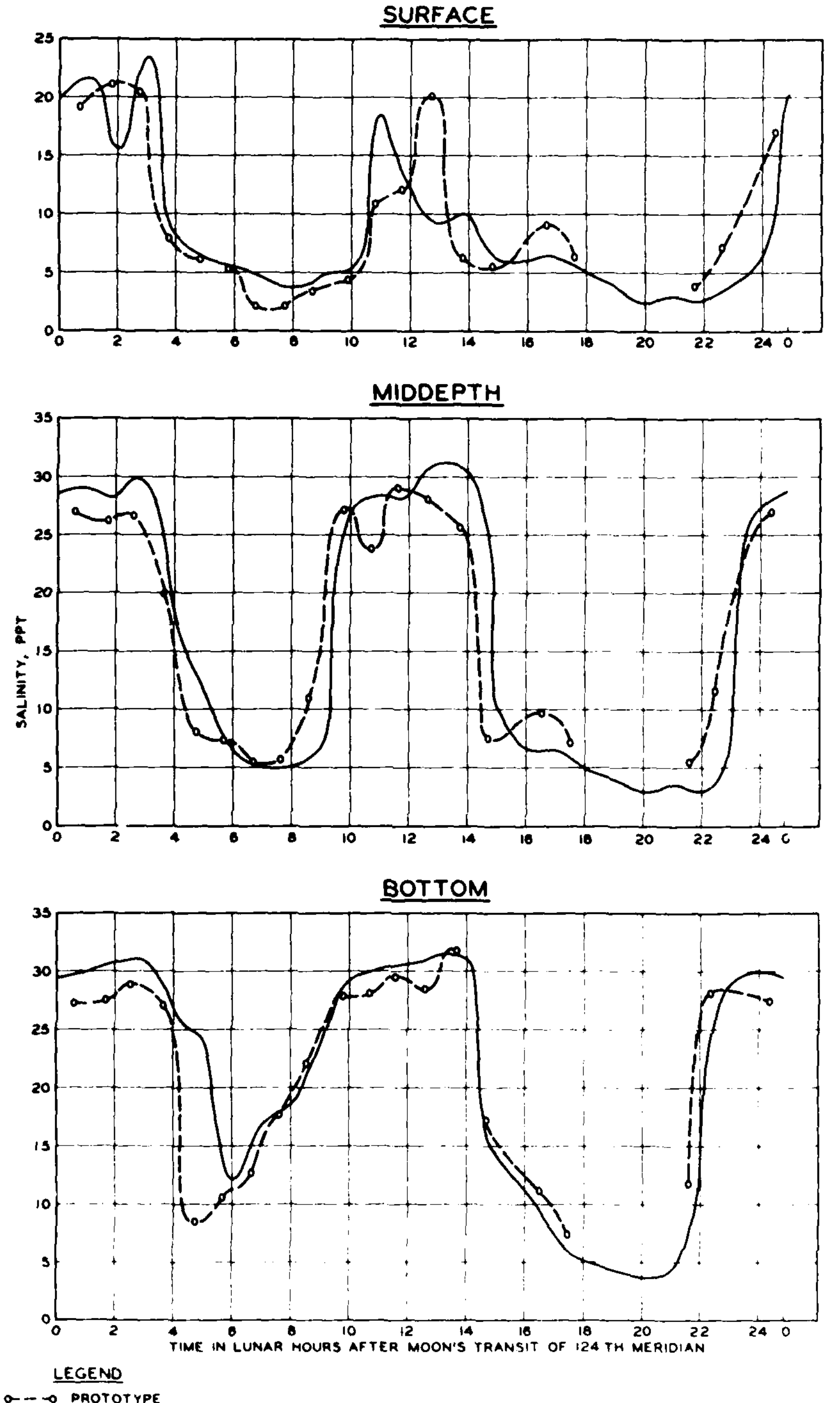
LEGEND

o---o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1978
STATION 11B



TEST CONDITIONS

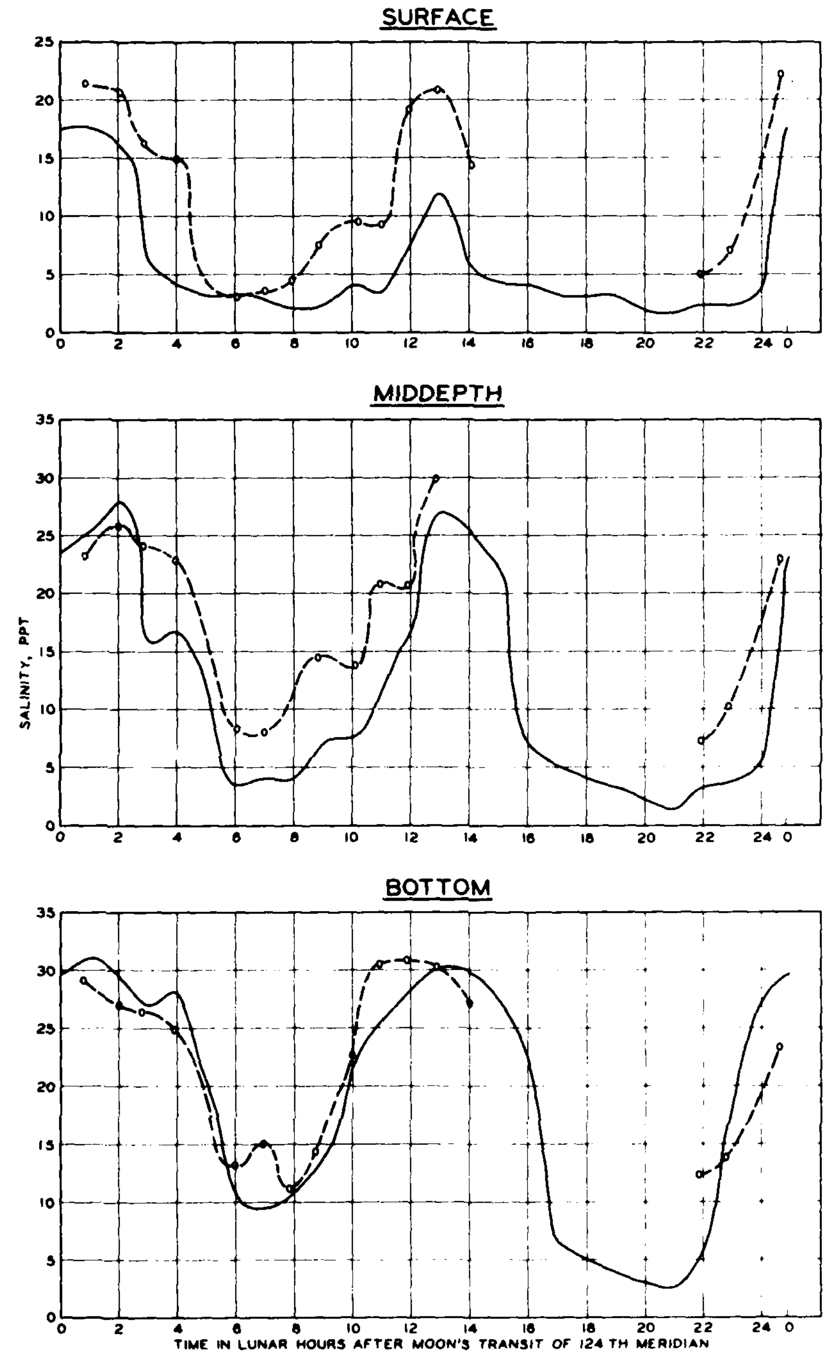
TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 1B

PLATE 78



LEGEND

o--o PROTOTYPE
—— MODEL

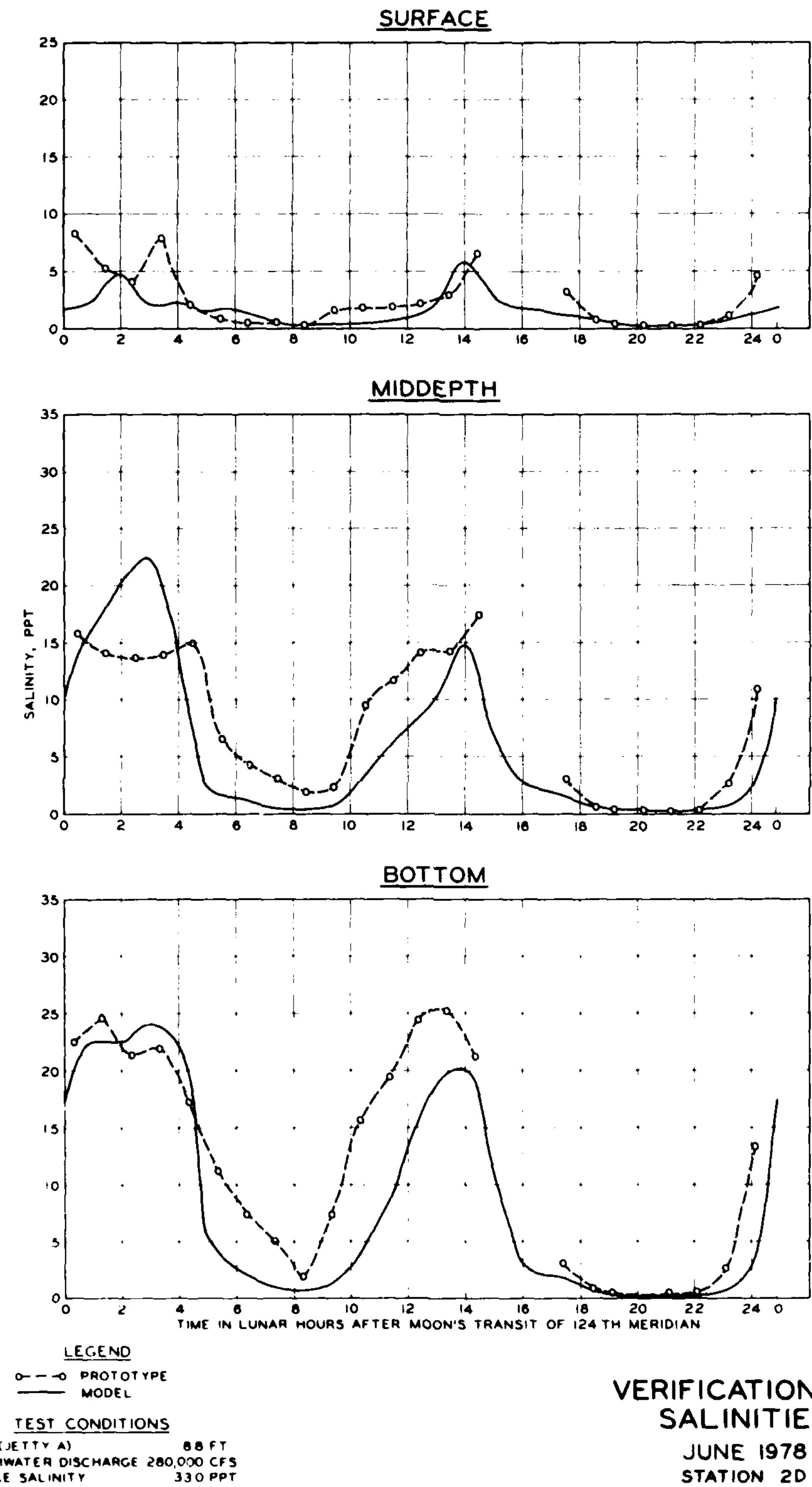
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

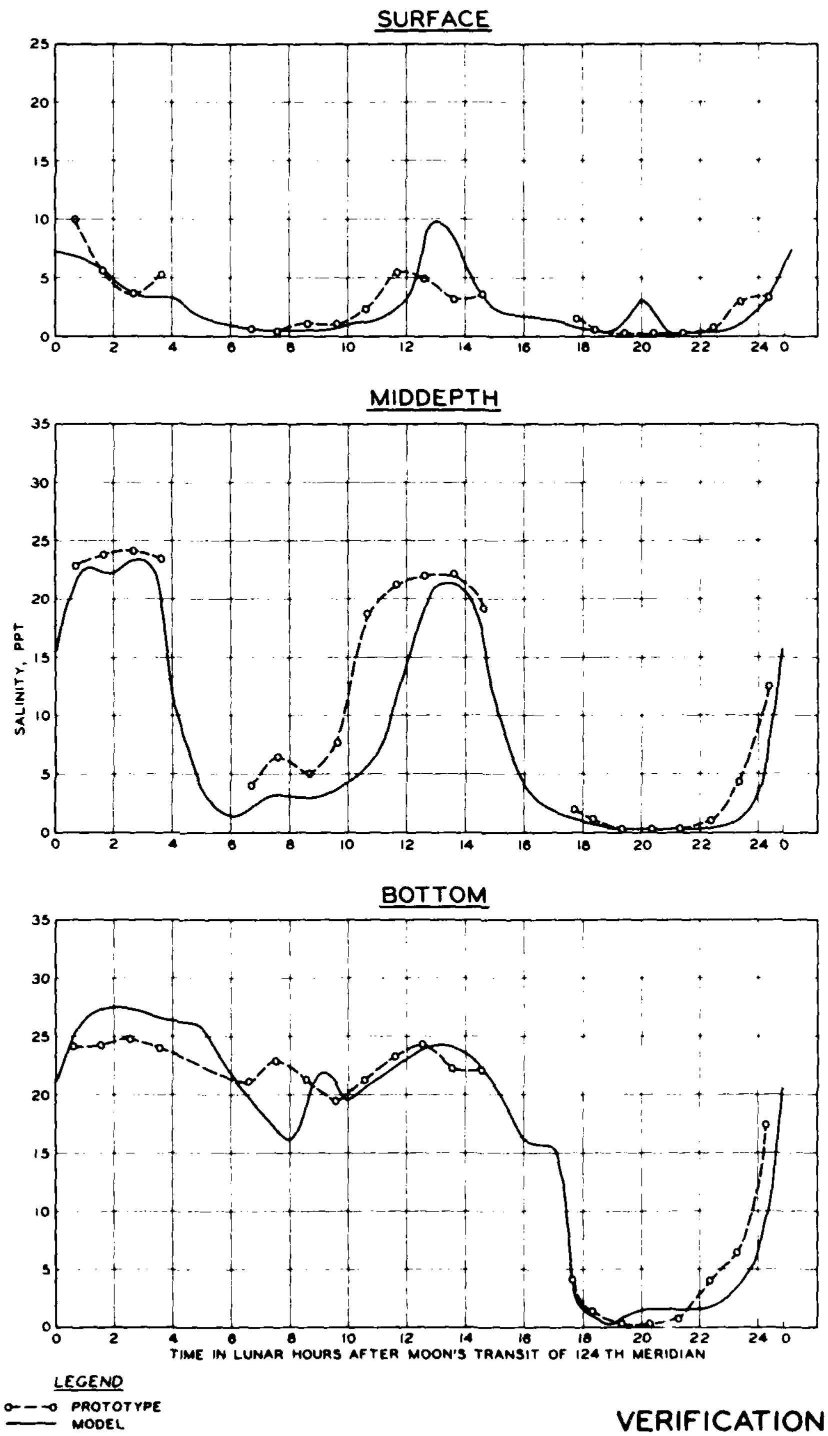
VERIFICATION OF SALINITIES

JUNE 1978

STATION 1C



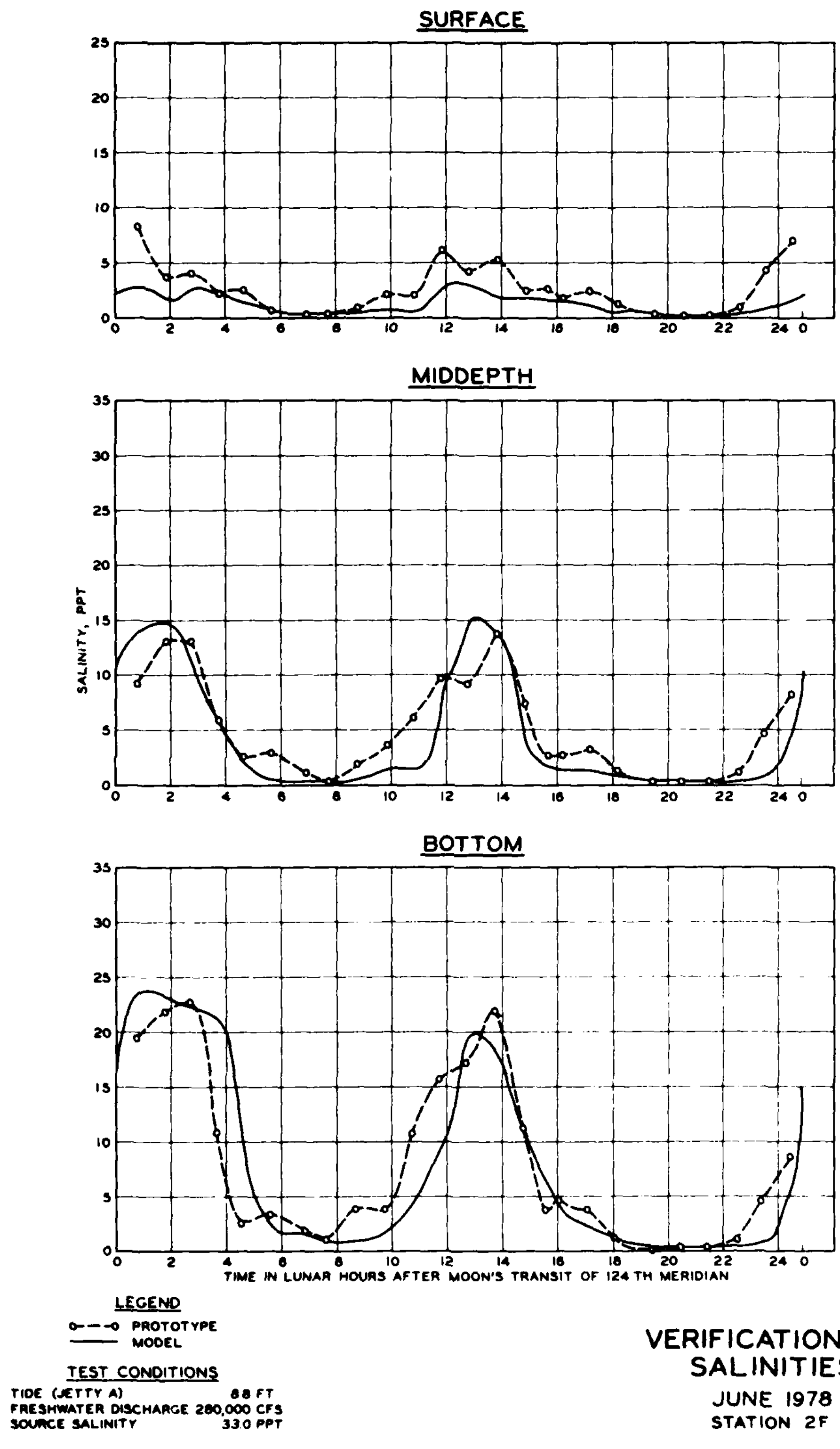
VERIFICATION OF SALINITIES
JUNE 1978
STATION 2D



TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

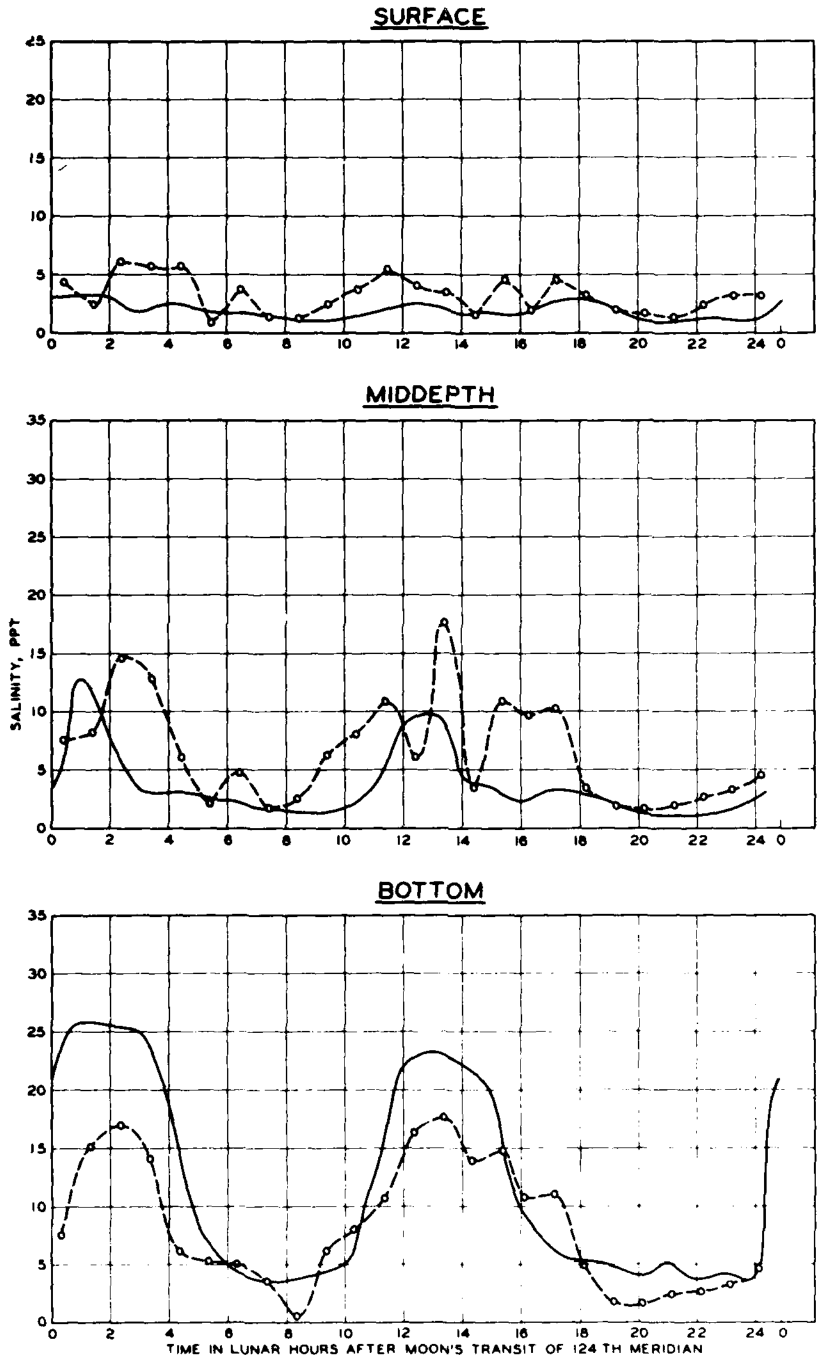
VERIFICATION OF SALINITIES
JUNE 1978
STATION 2E



VERIFICATION OF SALINITIES

JUNE 1978

STATION 2F



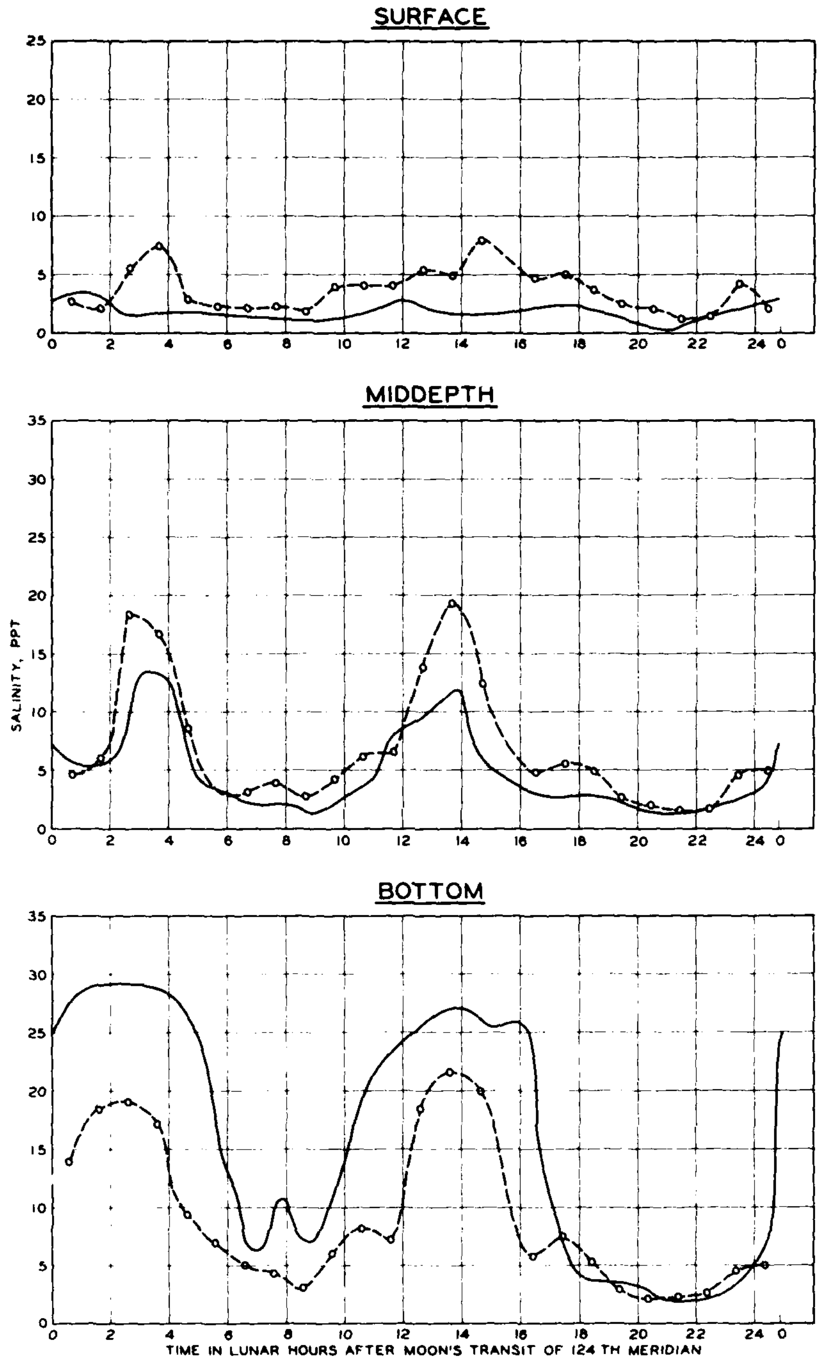
LEGEND

o— —o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1978
STATION 3A



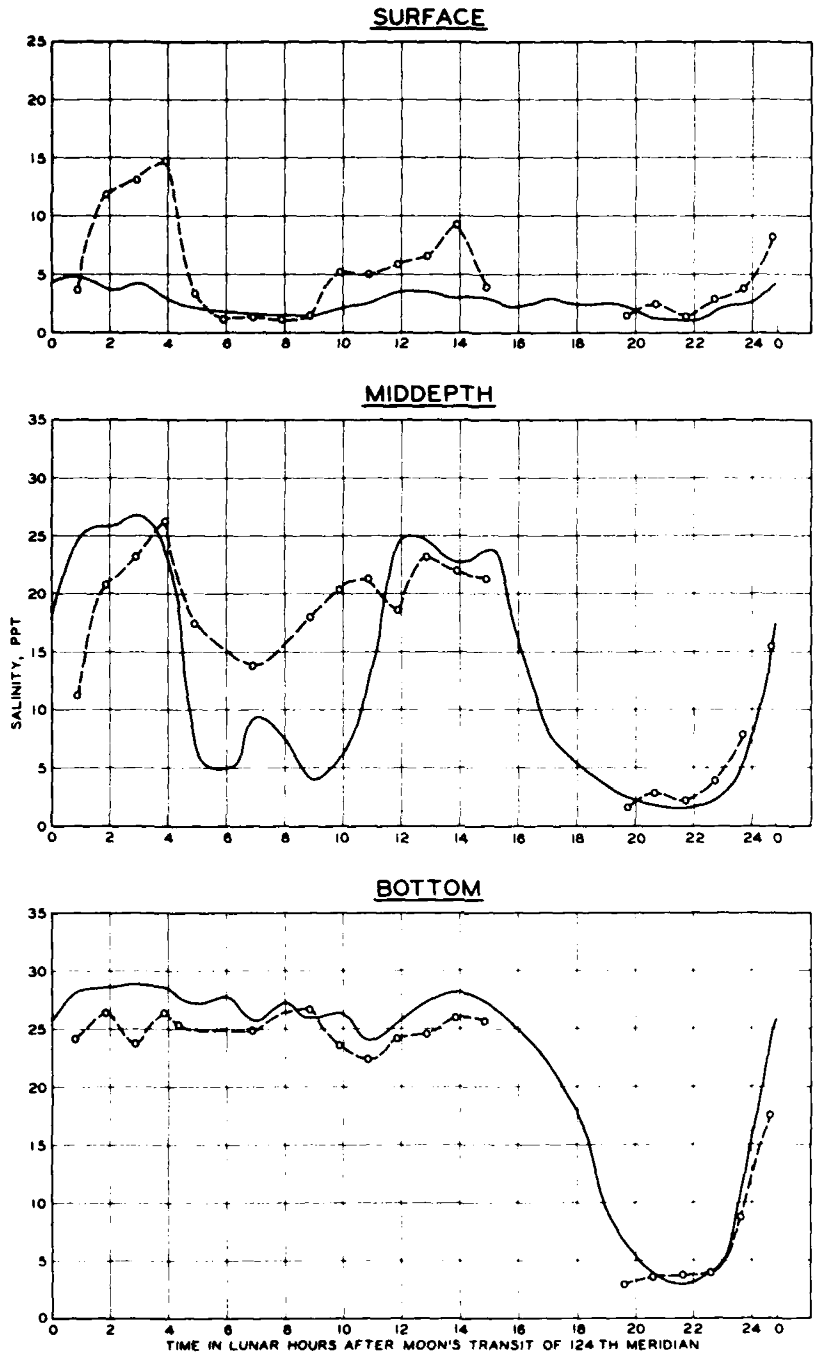
LEGEND

o- - -o PROTOTYPE
——— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES
JUNE 1978
STATION 3B



LEGEND

- PROTOTYPE
- MODEL

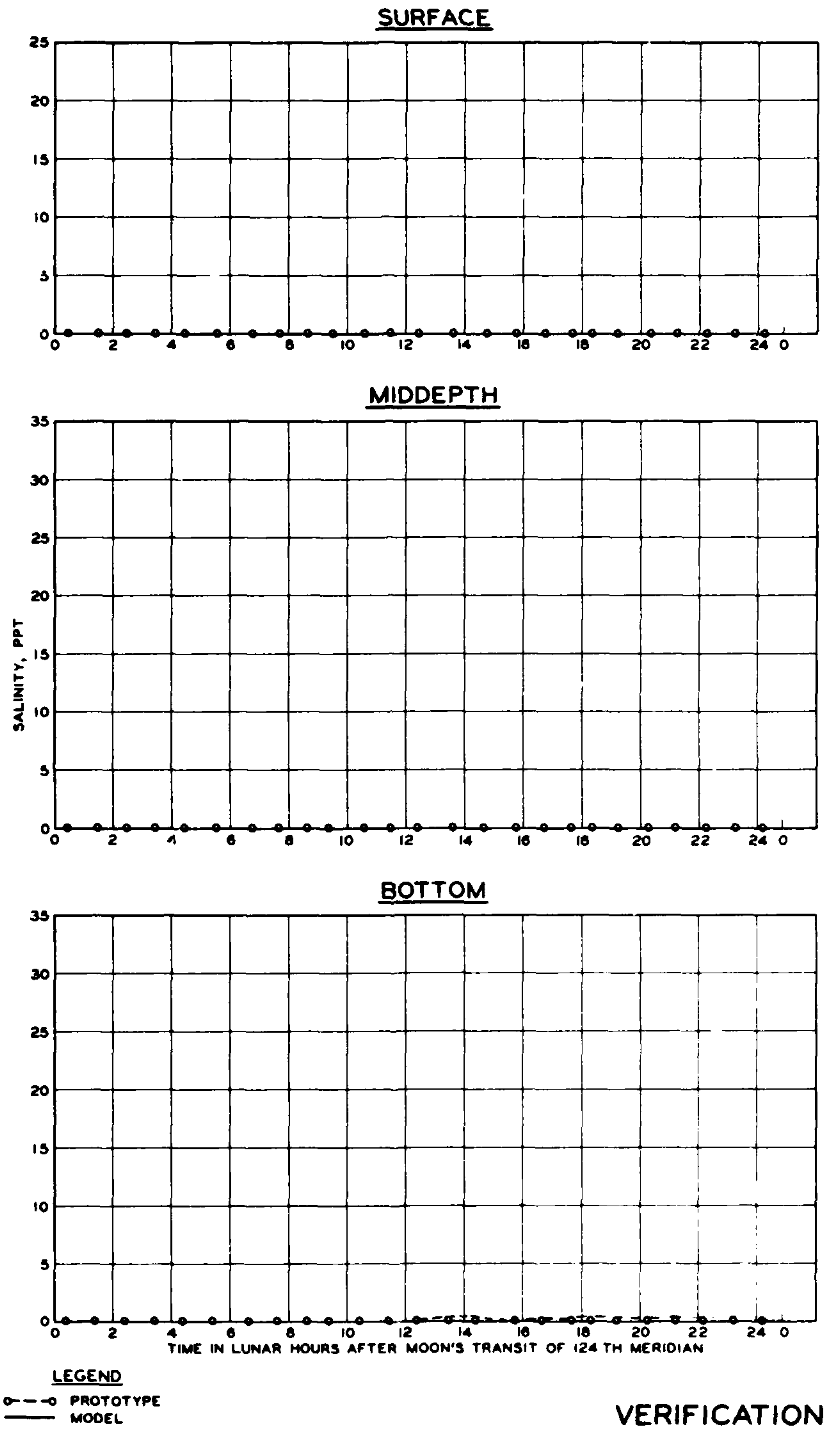
TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 3C



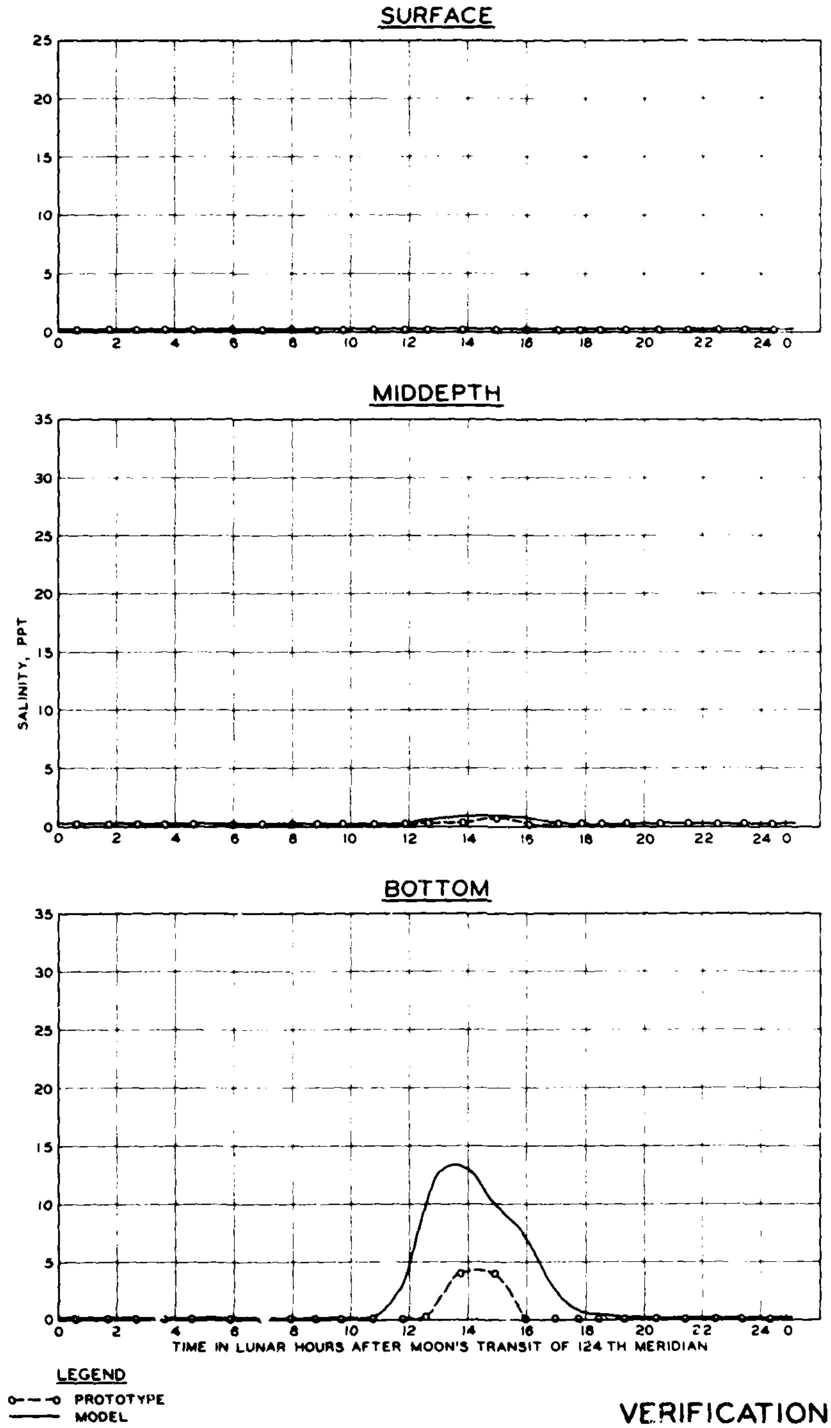
TEST CONDITIONS

TIDE (JETTY A)	8.8 FT
FRESHWATER DISCHARGE	280,000 CFS
SOURCE SALINITY	33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 5A



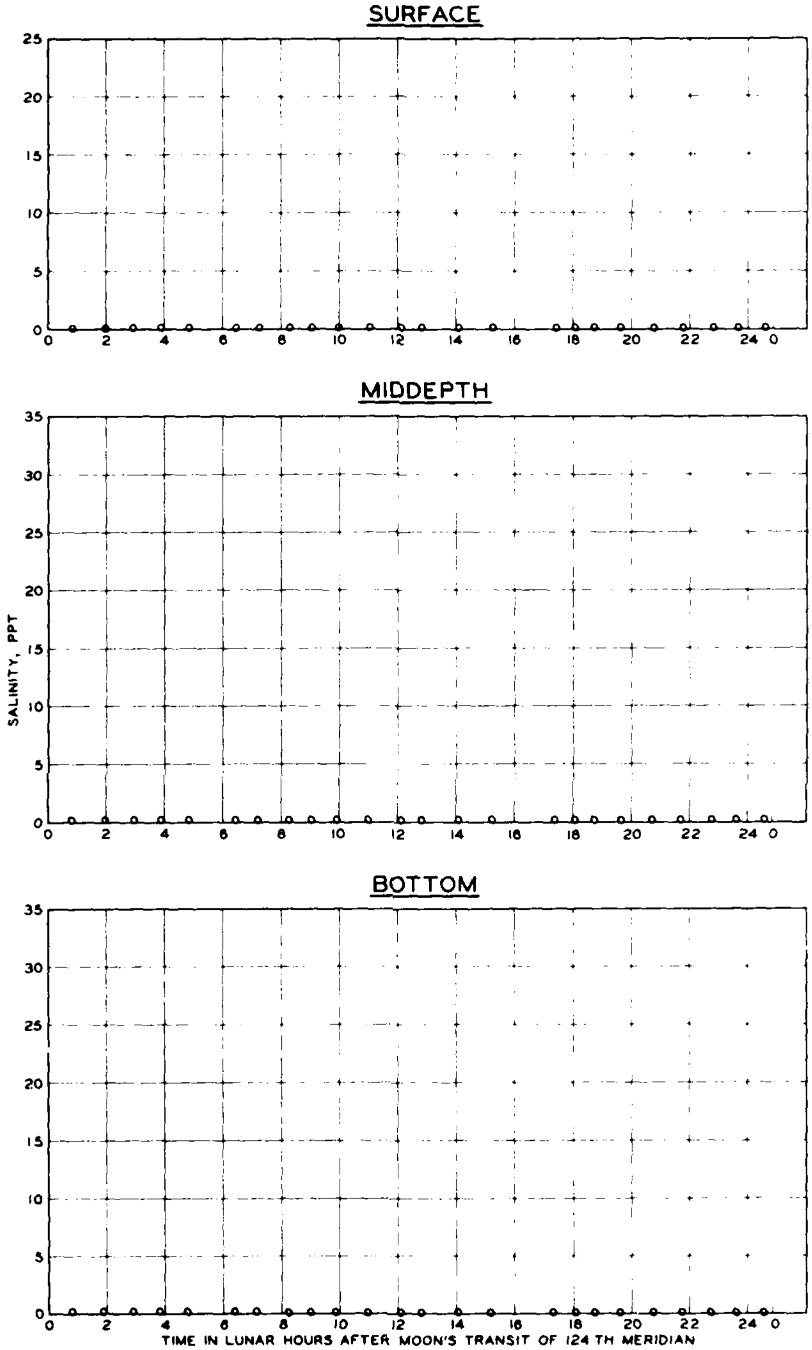
TEST CONDITIONS

TIDE (JETTY A) 6.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 5B



LEGEND

o- - -o PROTOTYPE
——— MODEL

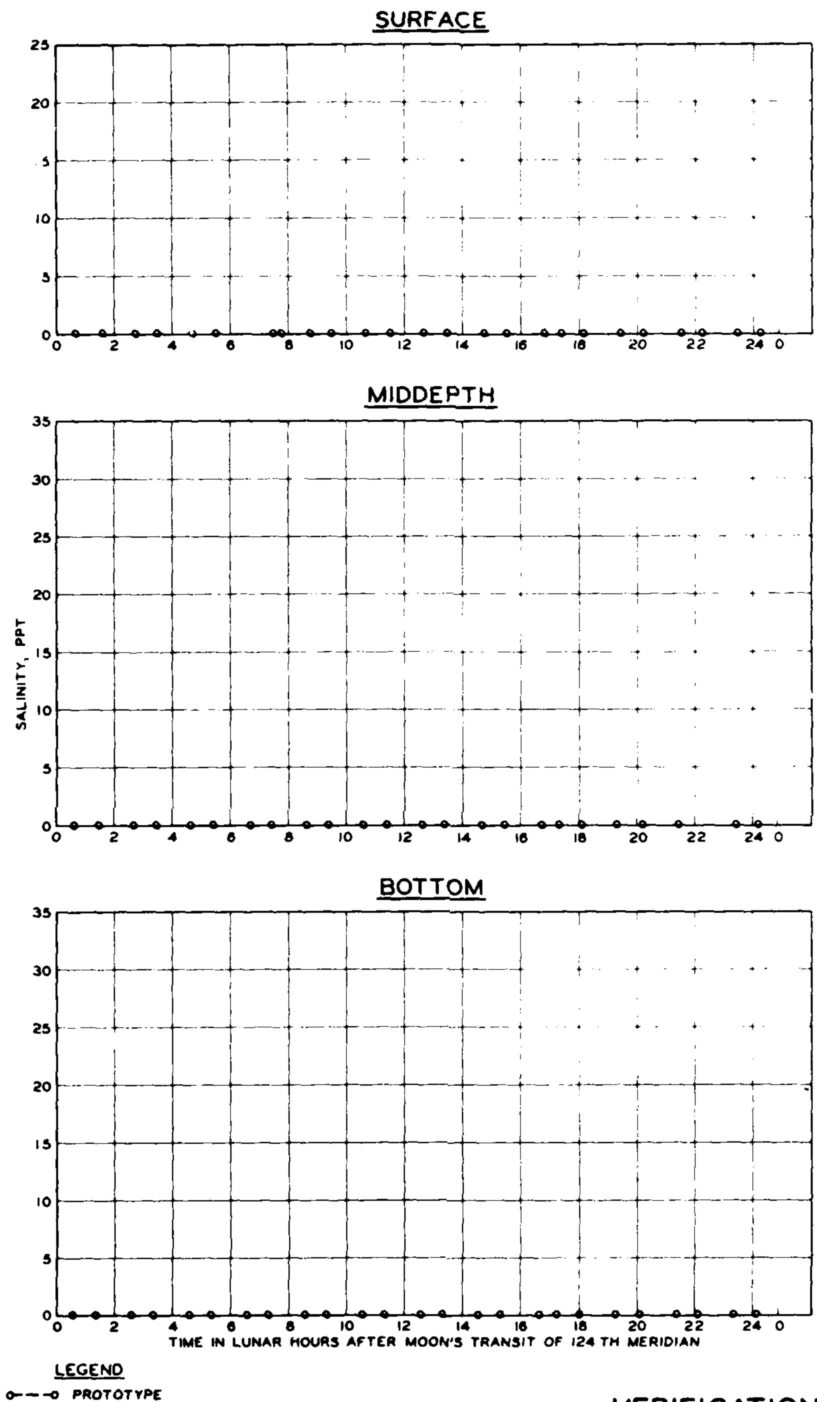
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 5C



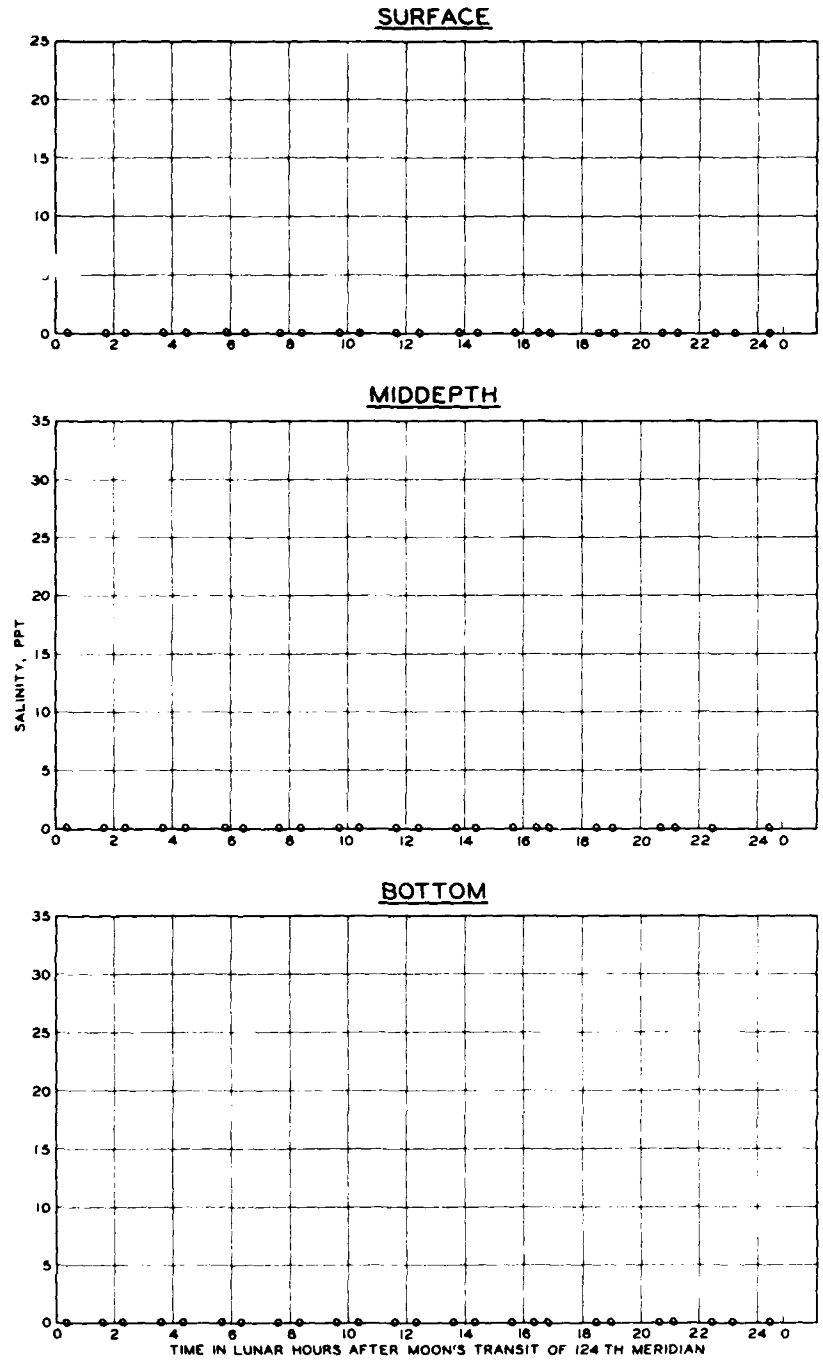
TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 6A



LEGEND

o---o PROTOTYPE
—— MODEL

TEST CONDITIONS

TIDE (JETTY A) 8.8 FT
FRESHWATER DISCHARGE 280,000 CFS
SOURCE SALINITY 33.0 PPT

VERIFICATION OF SALINITIES

JUNE 1978

STATION 6B

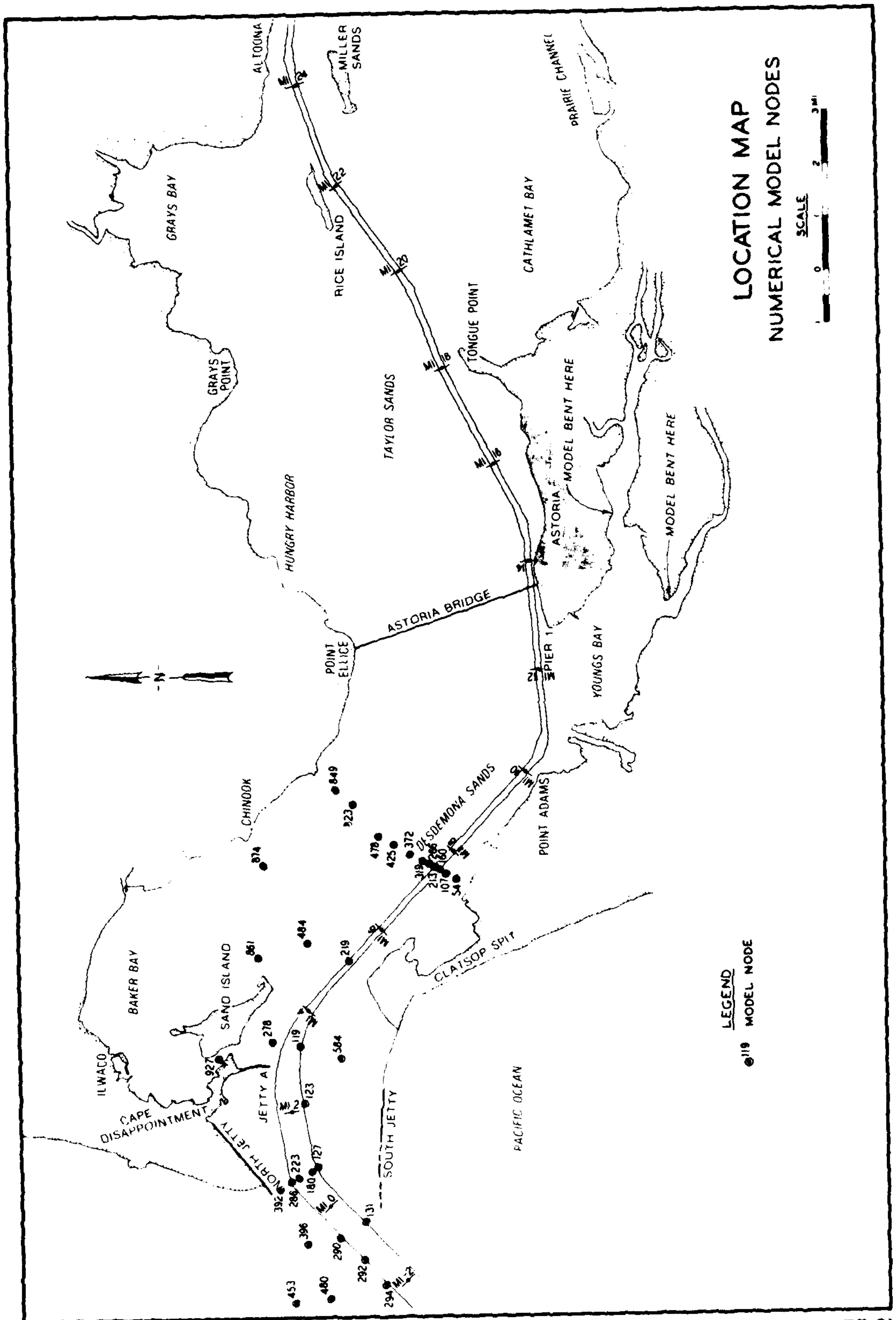
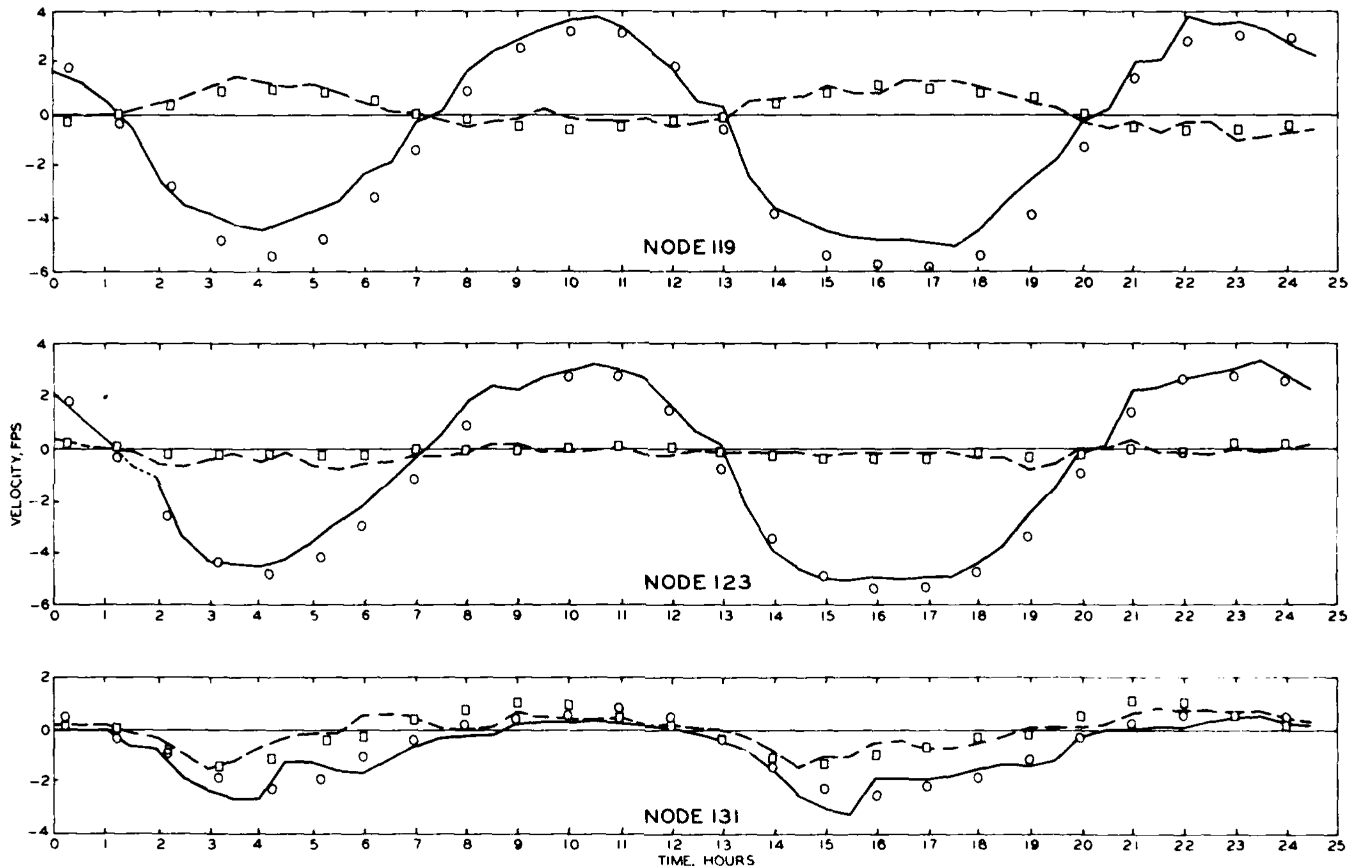

LOCATION MAP
NUMERICAL MODEL NODES
SCALE
0
1
2
3 MI
LEGEND
119 MODEL NODE
ALTOONA
MILLER SANDS
PRAIRIE CHANNEL
GRAYS BAY
RICE ISLAND
CATHLAMET BAY
TONGUE POINT
GRAYS POINT
TAYLOR SANDS
MODEL BENT HERE
MODEL BENT HERE
ASTORIA
HUNGRY HARBOR
ASTORIA BRIDGE
POINT ELLICE
PIER 1
YOUNGS BAY
N
CHINOOK
DESDEMONA SANDS
POINT ADAMS
CLATSOP SPIT
BAKER BAY
SAND ISLAND
ILWACO
CAPE DISAPPOINTMENT
JETTY A
NORTH JETTY
SOUTH JETTY
PACIFIC OCEAN
MI 24
MI 22
MI 20
MI 18
MI 16
MI 12
MI 0
MI 2
MI -2
849
923
874
478
425
372
319
286
213
160
107
54
484
861
219
278
119
584
927
123
127
223
180
286
392
131
396
290
292
453
480
294

PLATE 91



LEGEND

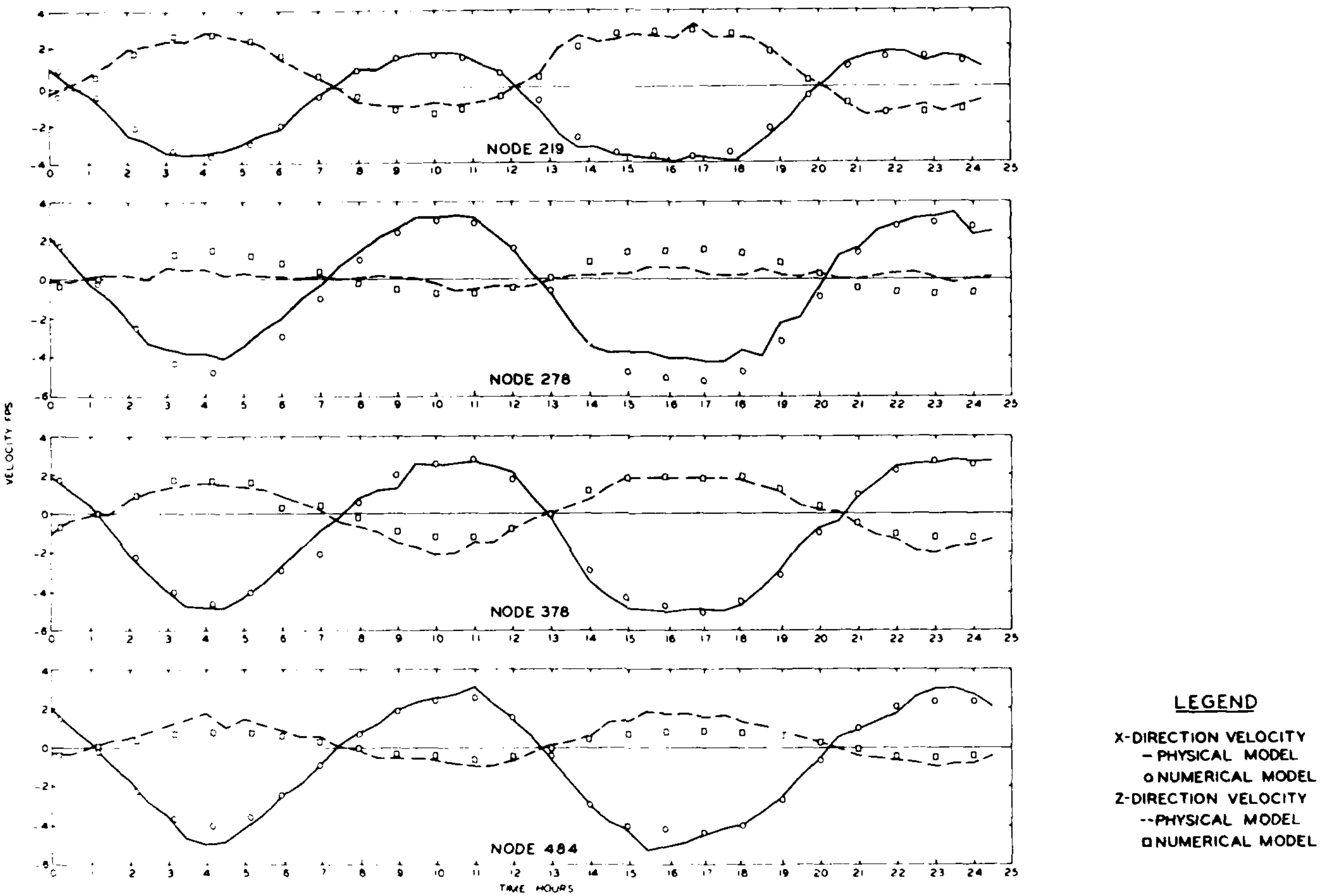
X-DIRECTION VELOCITY { — PHYSICAL MODEL; O NUMERICAL MODEL

Z-DIRECTION VELOCITY { -- PHYSICAL MODEL; □ NUMERICAL MODEL

NOTE: POSITIVE IS NORTHWARD (Z) AND EASTWARD IS (X)

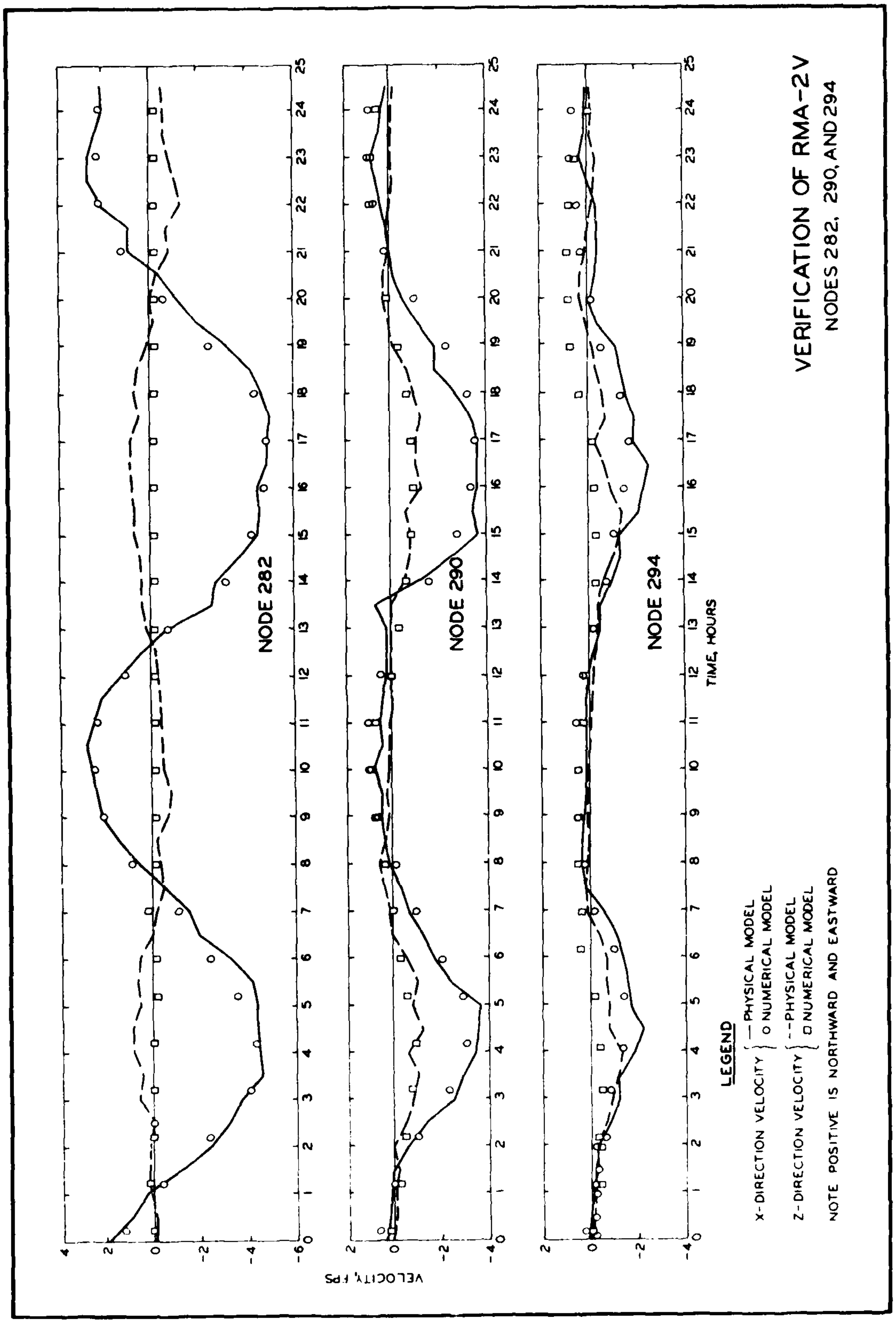
TEST CONDITIONS	
TIDE RANGE	7.2 FT
DISCHARGE	300,000 CFS

VERIFICATION OF RMA-2V
NODES 119, 123, AND 131



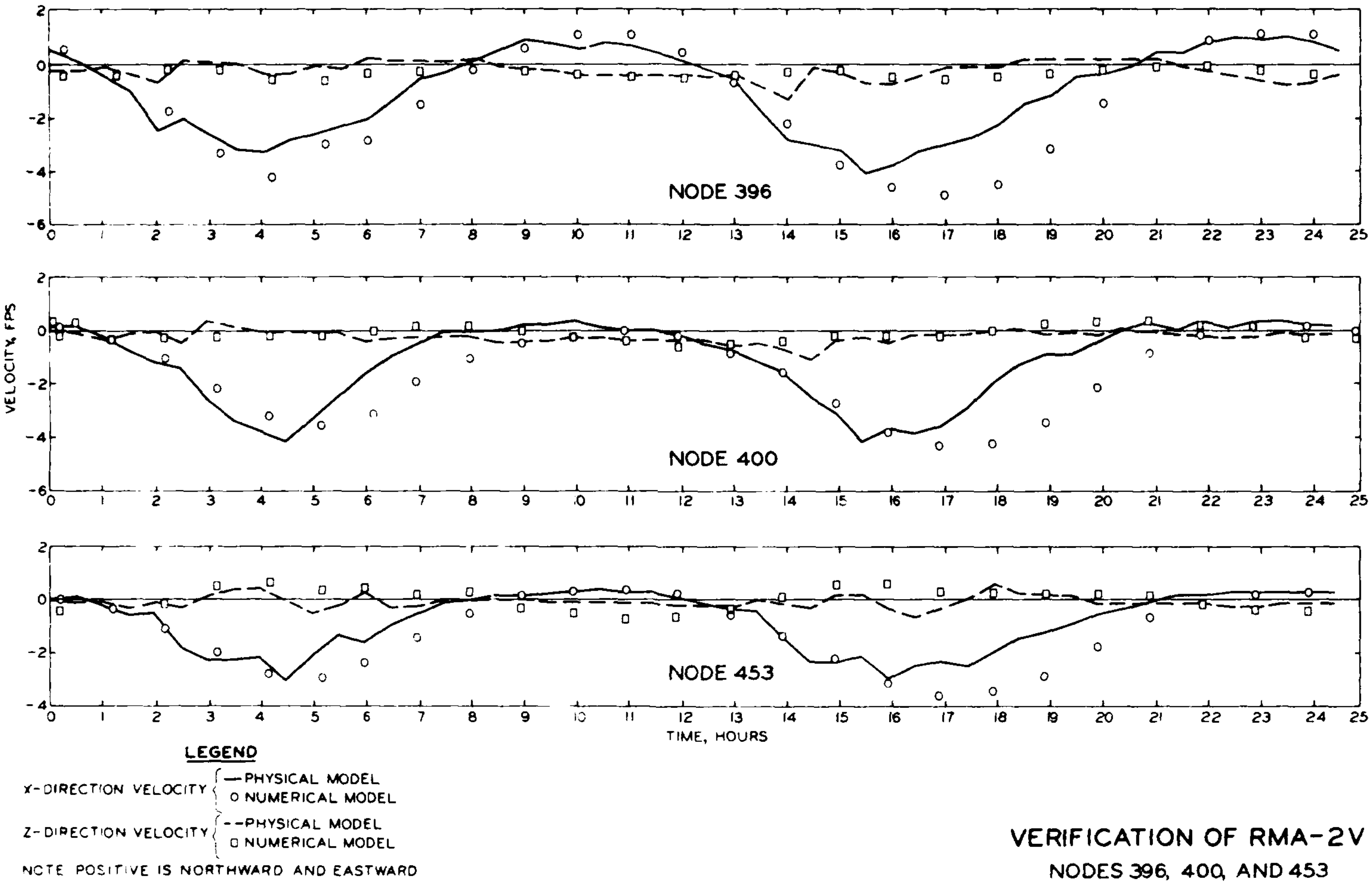
NOTE POSITIVE IS NORTHWARD AND EASTWARD

VERIFICATION OF RMA-2V
NODES 219, 278, 378 AND 484



VERIFICATION OF RMA-2V
NODES 282, 290, AND 294
NODE 282
NODE 290
NODE 294
VELOCITY, FPS
TIME, HOURS
LEGEND
X-DIRECTION VELOCITY — PHYSICAL MODEL
○ NUMERICAL MODEL
Z-DIRECTION VELOCITY - - PHYSICAL MODEL
□ NUMERICAL MODEL
NOTE POSITIVE IS NORTHWARD AND EASTWARD

PLATE 94



VERIFICATION OF RMA-2V
NODES 396, 400, AND 453

APPENDIX A: BIBLIOGRAPHY AND KEYWORD INDEX FOR THE COLUMBIA RIVER ESTUARY

1. This bibliography was originally compiled in 1976-1977 to serve as a resource for the model studies listed in the PART I: INTRODUCTION. As such, most of its entries relate to the physical characteristics of the estuary.

2. As the bibliography grew larger, a keyword index was added to permit rapid location of desired information. Most items were assigned keywords based on the authors' review of the documents. Those entries which could not be acquired were assigned keywords inferred from their titles and are so noted at the end of the keyword list.

3. Since 1977 no organized effort has been made to keep the bibliography up to date. New entries have been added only as they have come to our attention; therefore coverage since 1977 is much less complete than that prior to that time.

KEYWORD INDEX, COLUMBIA RIVER BIBLIOGRAPHY

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Category/Keyword	References Described By Keyword
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AD-A134 978 COLUMBIA RIVER ESTUARY HYBRID MODEL STUDIES REPORT 1 VERIFICATION OF HYBR..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS HYDRA.. 3/3

UNCLASSIFIED W H MCANALLY ET AL. SEP 83 WES/TR/HL-83-16 F/G 13/2 NL

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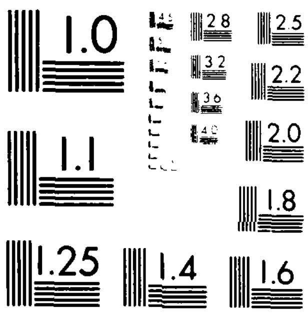
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2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

BIBLIOGRAPHY

1. Anderson, G.C. 1963. "Columbia River Effluent in the Northeast Pacific Ocean, 1961, 1962: Selected Aspects of Phytoplankton Distribution and Production," Technical Report No. 96, Dec., University of Washington, Seattle, WA.

2. Anderson, G.C. 1964. "The Seasonal and Geographic Distribution of Primary Productivity Off the Washington and Oregon Coasts," Limnology and Oceanography, Vol. 9, 1964.

3. Anderson, G.C., et al. 1961. "The Columbia River Discharge Area of the NE Pacific Ocean - A Literature Survey," REF M61-25, Jul., University of Washington, Department of Oceanography, Seattle, WA.

4. Anderson, G.C., et al. 1962. "Summary of 1961 Research Program Under Columbia River Effects in the Northeast Pacific," University of Washington, Department of Oceanography, Seattle, WA.

5. Andrews, R.S. 1965. "Modern Sediments of Willapa Bay, Washington, A Coastal Plain Estuary," Technical Report No. 118, REF M65-8, May, University of Washington, Department of Oceanography, Seattle, WA.

6. Ballard, R.L. 1964. "Distribution of Beach Sediments near the Columbia River," Technical Report No. 98, University of Washington, Department of Oceanography, Seattle, WA.

7. Barnes, C.A. 1957. "Circulation near the Washington Coast," Proceedings, Pacific Science Congress, 8th Meeting, Quezon City, 1953, Vol. 10, Pacific Science Association.

8. Barnes, C.A., Duxbury, S.C., and Morse, B.A. 1972. "Circulation and Selected Properties of the Columbia River Effluent at Sea," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

9. Barnes, C.A., and Gross, M.G. 1966. "Distribution at Sea of Columbia River Water and Its Load of Radionuclides," Proceedings, Symposium on Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters, Vienna, 16-20 May 1966, International Atomic Energy Agency, Vienna.

10. Battelle Pacific Northwest Laboratories. 1974. "Columbia River and Tributaries, Environmental Assessment Manual," May, Richland, WA.

11. Berg, J.W., King, J.M., and Carlson, P.R. 1966. "Seismic Reflection Studies of Buried Channels off the Columbia River," Ore Bin, Vol. 28, Aug.

12. Boone, C.G., Granat, M.A., Farrell, M.P. 1978. "Aquatic Disposal Field Investigations, Columbia River Disposal Site, Oregon, Evaluative Summary," Technical Report D-77-30, U.S.A.E. Waterways Experiment Statio-, CE, Vicksburg, MS.

13. Borgeld, J.C., et al. 1978. "A Geological Investigation of the Sedimentary Environment at Sites E, G, and H, near the Mouth of the Columbia River," University of Washington, Department of Oceanography, Seattle, WA.

14. Bourke, R.H., Glenne, B., and Adams, B.W. 1971. "The Nearshore Physical Oceanographic Environment of the Pacific Northwest Coast," Ref 71-45, Feb., Oregon State University, Corvallis, OR.

15. Budinger, T.F., Coachman, L.K., and Barnes, C.A. 1963. "Description of the Columbia River Plume and Certain Aspects of the Mixing of River Water in the Sea," Transactions, American Geophysical Union, Vol. 44, Mar. (Abstract).

16. Budinger, T.F., Coachman, L.K., and Barnes, C.A. 1964. "Columbia River Effluent in the Northeast Pacific Ocean, 1961,1962: Selected Aspects of Physical Oceanography," Technical Report No. 99, University of Washington, Department of Oceanography, Seattle, WA.

17. Burt, W.V. 1956. "Hydrography of Oregon Estuaries Prior to June 1956: Data Report No. 1," Oregon State College (now Oregon State University), Corvallis, OR.

18. Burt, W.V., and McAllister, W.B. 1958. "Hydrography of Oregon Estuaries June 1956 to September 1958," Data Report No. 3, Ref 58-6, Oct., Oregon State University, Department of Oceanography, Corvallis, OR.

19. Burt, W.V., and McAllister, W.B. 1959. "Recent Studies in the Hydrography of Oregon Estuaries," Technical Report No. 9, Ref 59-2, Aug., Oregon State University, Department of Oceanography, Corvallis, OR.

20. Burt, W.V., and McAllister, W.B. 1962. "Hydrographic Data from Oregon Coastal Waters June 1960 through May 1965," Data Report No. 7, Ref 62-6, Apr., Oregon State University, Department of Oceanography, Corvallis, OR.

21. Burt, W.V., and Wyatt, B. 1964. "Drift Bottle Observations of the Davidson Current off Oregon," Studies on Oceanography.

22. Byrne, J.V. 1963. "Coastal Erosion, Northern Oregon," Essays in Marine Geology in Honor of K.O. Emory.

23. Byrne, J.V. 1964. "An Erosional Classification for the Northern Oregon Coast," Annals of the Association of American Geographies, Vol. 54, No. 3, Sept.

24. Callaway, R.J. 1961. U.S.A.E. Portland District. "U.S. Public Health Service, Water Supply and Pollution Control Program Region IX," Portland, OR, 2 parts.

25. Callaway, R.J. 1971. "Applications of Some Numerical Models to Pacific Northwest Estuaries," Proceedings, 1971 Conference on Estuaries of the Pacific Northwest, Circular No. 42, Engineering Experiment Station, Oregon State University, Corvallis, OR.

26. Callaway, R.J., and Byram, K.V. 1970. "Mathematical Model of the Pacific

Ocean to Bonneville Dam, Part II, Input-Output and Initial Verification Procedures," Dec., Pacific Northwest Water Lab., Environmental Protection Agency, Corvallis, OR.

27. Callaway, R.J., Byram, K.V., and Ditsworth, G.R. 1969. "Mathematical Model of the Columbia River from the Pacific Ocean to Bonneville Dam, Part I, Theory, Program Notes and Programs," Nov., Pacific Northwest Water Lab., Federal Water Pollution Control Administration, Corvallis, OR.

28. Canadian Joint Committee on Oceanography. 1955. "Physical Chemical and Plankton Data Record Project NORPAC, 26 July to 1 September 1955," Prepared By Pacific Oceanographic Group, Nanimo, B.C.

29. Cissell, M.C. 1969. "Chemical Features of the Columbia River Plume off Oregon," Thesis, Oregon State University, Corvallis, OR.

30. Clairain, E.J., et al. 1978. "Habitat Development Field Investigations, Miller Sands Marsh and Upland Habitat Development Site, Columbia River, Oregon, Summary Report," Technical Report D-77-38, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

31. Clark, S.M., and Snyder, G.R. 1969. "Timing and Extent of a Flow Reversal in the Lower Columbia River," Limnology and Oceanography, Vol. 14, No. 6, Nov.

32. Clarke, T.W. 1924. "The Composition of the River and Lake Waters of the U.S.," Professional Paper 135, U.S. Geological Survey.

33. Collins, E.E. 1969. "RV Thomas G. Thompson Cruise 20: Coastal and Offshore Survey 15 to 31 July 1969," Preliminary Report, Nov., Ref. M68-70, University of Washington, Department of Oceanography, Seattle, WA.

34. Collins, C.A. 1964. "Structure and Kinematics of the Permanent Oceanic Front off the Oregon Coast." Thesis, Jun., Oregon State University, Corvallis, OR.

35. Columbia Basin Inter-Agency Committee. 1965. "Bibliography of Published Climatological Data, Columbia Basin States," Meteorology Subcommittee, Portland, OR.

36. Conomos, T.J. 1966. "Processes Affecting Suspended Particulate Matter in the Columbia River Effluent System, Summer, 1965," Ph.D. Thesis, University of Washington, Seattle, WA.

37. Conomos, T.J., and Gross, M.G. 1968. "Mixing of Columbia River and Ocean Waters in Summer," Journal of the Sanitary Engineering Division, Proceedings, American Society of Civil Engineers, Oct., Vol. 94, SA5.

38. Conomos, T.J., and Gross, M.G. 1972. "River-Ocean Suspended Particulate Matter Relations in Summer," The Columbia River Estuary And Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

39. Cooper, W.S. 1958. "Coastal Sand Dunes of Oregon and Washington," Memoir 72, Jun., Geological Society of America, Boulder, CO.

40. Curtis, W.F., Culbertson, J.K., and Chase, E.B. 1973. "Fluvial-Sediment Discharge to the Oceans from the Coterminous United States," Circular 670, U.S. Geological Survey, Washington, DC.

41. Cushing, C.E., and Watson, D.G. 1966. "Accumulation and Transport of Radionuclides by Columbia River Biota," Proceeding, Symposium on Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters," Vienna, International Atomic Energy Agency.

42. Cutshall, N.G., and Johnson, V.G. 1977. "Habitat Development Field Investigations, Miller Sands Marsh and Upland Habitat Development Site, Columbia River, Oregon, Appendix A: Inventory and Assessment of Predisposal Physical and Chemical Conditions," Technical Report D-77-38, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

43. Cutshall, N.G., Johnson, V., and Osterberg, C. 1966. "Chromium-51 in Sea Water: Chemistry," Science, Vol. 152, No. 3719.

44. Cutshall, N.G., and Osterberg, C. 1964. "Radioactive Particle in Sediment from the Columbia River," Science, Vol. 144, No. 3618.

45. Daniels, D.G., Sonnichsen, J.C., and Jaske, R.T. 1970. "The Estuarine Version of the Colheat Digital Simulation Model," BNWL-1342, Battelle Pacific Northwest Laboratory, Richland, WA.

46. Denner, W. 1963. "Sea Water Temperature and Salinity Characteristics at Oregon Stations in 1961," M.S. Thesis, Oregon State University Department of Oceanography, Corvallis, OR.

47. Dent, E.J. 1935. "Layout of Outer Protective Works, Maintenance of Depths in Harbors on Sandy Shores and Before Mouths of Estuaries," Paper No. 69, XVI International Congress of Navigation, Brussels, Permanent International Association of Navigation Congresses.

48. Ditsworth, G.R. 1967. "Index to Research on Coastal and Estuarine Waters in the United States," Pacific Northwest Water Laboratory, Federal Water Pollution Control Administration, Corvallis, OR.

49. Ditsworth, G.R. 1966. "Environmental Factors in Coastal and Estuarine Waters, Bibliographic Series - Vol. I, Coast of Oregon," Pacific Northwest Water Laboratory, Federal Water Pollution Control Administration, Corvallis, OR.

50. Ditsworth, G.R. 1968. "Environmental Factors in Coastal and Estuarine Waters Bibliographic Series-Vol. II, Coast of Washington," Pacific Northwest Water Laboratory, Federal Water Pollution Control Administration, Corvallis, OR.

51. Dodge, R.O. 1976. "Construction of the 40-ft Channel in Columbia River," Rivers 76, Proceedings, 3rd Annual Symposium for Navigation, Flood Control and Water Diversions, Aug., American Society of Civil Engineers, New York.

52. Dodge, R.O. 1971. "Design of Columbia Pile Dikes," Journal of Waterways and Harbors Division, Vol. 97, No. WW2, American Society of Civil Engineers, New York.

53. Duxbury, A.C. 1975. "The Union of the Columbia River and the Pacific Ocean, General Features," Ocean Science and Engineering, Transactions, 1st Conference of the Marine Technology Society, Washington, DC, Jun., Vol. 2.

54. Duxbury, A.C. 1967. "Currents at the Columbia River Mouth," Photogrammetric Engineering, Vol. 33, No. 3, Mar.

55. Duxbury, A.C. 1979. "Coastal Zone Processes and Their Influence on Esutarine Conditions," Proceedings of Northwest Estuarine and Coastal Zone Symposium, Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior, Portland, OR.

56. Duxbury, A.C. 1972. "Variability of Salinity and Nutrients off the Columbia River Mouth," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

57. Duxbury, A.C., and McGary, N.B. 1967. "Tidal Period Oscillations of an Isohaline Surface off the Mouth of the Columbia River," International Journal of Oceanology and Limnology, Vol. 1, No. 2, Apr.

58. Duxbury, A.C., and McGary, N.B. 1968. "Local Changes of Salinity and Nutrients off the Mouth of the Columbia River," Limnology and Oceanography, Vol. 13, No. 4.

59. Duxbury, A.C., Morse, B.A., and McGary, N.B. 1966. "The Columbia River Effluent and Its Distribution at Sea, 1961-1963," Technical Report No. 156, University of Washington, Department of Oceanography, Seattle, WA.

60. Environmental Protection Agency. 1971. Columbia River Thermal Effects Study: Temperature Predictions, Vol. 2, Seattle, WA.

61. Evans, R.H., and Pattulo, J.G. 1970. "Structure and Movements of the Columbia River Plume During a Two Week Period in Early August of 1969," (Abstract) American Society of Limnology and Oceanography, Ref. 22-24, Jun., Berkeley, CA.

62. Forster, W.O. 1972. "Radioactive and Stable Nuclides in the Columbia River and Adjacent Northwest Pacific Ocean," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

63. Forster, W.O. 1972. "Radionuclide Distribution in Columbia River and Adjacent Pacific Shelf Sediments," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

64. Foster, R.F. 1972. The History of Hanford and Its Contribution of Radionuclides to the Columbia River," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

65. Fredrick, L.C. 1967. "Dispersion of the Columbia River Plume Based on Radioactivity Measurements," Ph.D. Thesis, Oregon State University, Corvallis, OR.

66. Gilbert, W., and Wyatt, B. 1968. "Surface Temperatures and Salinity Observation at Shore Stations on the Oregon Coast 1967," Data Report 28, Ref 68-1, Jan., Oregon State University, Corvallis, OR.

67. Gilbert, W., and Wyatt, B. 1969. "Surface Temperature and Salinity Observations at Pacific Northwest Shore Stations for 1968," Data Report 37, Jun., Oregon State University, Department of Oceanography, Corvallis, OR.

68. Glenn, J.L. 1973. "Relations Among Radionuclide Content and Physical, Chemical, and Mineral Characteristics of Columbia River Sediments," Professional Paper 433-M, U.S. Geological Survey.

69. Goodwin, C.R., Emmett, E.W., and Glenne, B. 1970. "Tidal Study of Three Oregon Estuaries," Bulletin No. 45, May, Engineering Experiment Station, Oregon State University, Corvallis, OR.

70. Griggs, G.B., and Lulm, L.O. 1969. "Glacial Marine Sediments from the Northeast Pacific," Journal of Sedimentary Petrology, Vol. 39, No. 3, Sept.

71. Gross, M.G. 1966. "Distribution of Radioactive Marine Sediment Derived from the Columbia River," Journal of Geophysical Research, Vol. 71, No. 8, Apr.

72. Gross, M.G. 1972. "Sediment-Associated Radionuclides from the Columbia River," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

73. Gross, M.G., Barnes, C.A., and Riel, G.K. 1965. "Radioactivity of the Columbia River Effluent," Science, Vol. 149, No. 3688.

74. Gross, M.G., McManus, D.A., and Creager, J.S. 1963. "Preliminary Report on the Sediments and Radioactivity in the Vicinty of the Columbia River Effluent," Technical Report 84, University of Washington, Department of Oceanography, Corvallis, WA.

75. Gross, M.G., McManus, D.A., and Ling, H. 1967. "Continental Shelf Sediment near the Columbia River, NW U.S.," Collected Reprints of the 7th International Sedimentological Congress.

76. Gross, M.G., and Nelson, J.L. 1966. "Sediment Movement of the Continental Shelf near Washington and Oregon," Science, Vol. 154, No. 3750.

77. Grover, M.C., and Parker, G.L. "Summary of Records of Surface Waters in Washington," Water Supply Paper 870, U.S. Geological Survey.

78. Haertel, L., and Osterberg, C. 1967. "Ecology of Zooplankton, Benthos, and Fishes in the Columbia River Estuary," Ecology, Vol. 48, No. 3.

79. Hansen, D.V. 1965. "Currents and Mixing in the Columbia River Estuary," Transactions of the Joint Conference and Exhibit, Marine Technology Society.

80. Hanson, P.J. 1967. "Vertical Distribution of Radioactivity in the Columbia River Estuary," M.S. Thesis, Oregon State University, Corvallis, OR.

81. Hanson, P.J., and Forster, W.O. 1969. "Measurement of Columbia River Flow Time from Hanford Reactors to Astoria, Oregon - Summer 1966," Water Resources Research, Vol. 5, No. 5.

82. Harmon, R.A. 1972. "The Distribution of Microbiogenic Sediment near the Mouth of the Columbia," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle WA.

83. Haushild, W.L., Stevens, H.H.,Jr., and Nelson, J.L. 1971. "Radionuclides in Transport in the Columbia River from Pasco to Vancouver, Washington," Open File Report, U.S. Geological Survey, Water Resources Division, Portland, OR.

84. Heineman, A.J. 1977. "Corps Dredges Help Maintain West Coast Channels," Sep., World Dredging and Marine Construction.

85. Herrmann, F.A.,Jr. 1965. "Model Tests of Enlarged Navigation Channel at Miller Sands Bar, Columbia River Estuary," Misc. Paper No. 2-765, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

86. Herrmann, F.A.,Jr., and Simmons, H.B. 1966. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 2, Entrance Studies, Section 2, Fixed-Bed Studies of North Jetty Rehabilitation," Technical Report 2-735, No. 2-2, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

87. Herrmann, F.A.,Jr., and Simmons, H.B. 1966. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 2, Entrance Studies, Section 1, Fixed-Bed Studies of South Jetty Rehabilitation," Technical Report 2-735, No. 2-1, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

88. Herrmann, F.A.,Jr. 1968. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 1, Hydraulic and Salinity Verification," Technical Report 2-735, No. 1, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

89. Herrmann, F.A.,Jr. 1970. "Tidal Prism Measurements at Mouth of Columbia River," Misc. Paper H-70-3, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

90. Herrmann, F.A.,Jr. 1971. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 3, 40-ft Channel Studies, Section 1, Wauna-Lower Westport Bar," Technical Report 2-735, No. 3-1, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

91. Herrmann, F.A.,Jr. 1971. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 2, Entrance Studies, Section 3, Fixed-Bed Studies of Disposal Areas C & D," Technical Report 2-735, No. 2-3, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

92. Herrmann, F.A.,Jr. 1974. "Model Studies of Navigation Improvements, Columbia River Estuary, Report 2, Entrance Studies, Section, Jetty Rehabilitation, Jetty B, and Outer Bar Channel Relocation," Technical

Report 2-735, No. 2-4. U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

93. Hickey, B.M. 1979. "The California Current System Hypotheses and Facts," Progressive Oceanographer, Vol. 8.

94. Hickson, R.E. 1930. "Shoaling on the Lower Columbia River," The Military Engineer, Vol. XXII, No. 123, May-Jun.

95. Hickson, R.E. 1933. "Jetty Maintenance at the Mouth of the Columbia," The Military Engineer, Vol. XXV, No. 143, Sept.-Oct.

96. Hickson, R.E. 1937. "Columbia River South Jetty Terminal," The Military Engineer, Vol. XXIX, No. 164, Mar.-Apr.

97. Hickson, R.E., and Rofolf, F.W. 1950. "History of Columbia River Jetties," Proceedings, First Conference on Coastal Engineering, The Engineering Foundation.

98. Hickson, R.E. 1960. "Columbia River Open River Channel Improvement," Portland, OR.

99. Hickson, R.E. 1965. "Columbia River Stabilization and Improvement for Navigation," Chapter 4 of Symposium on Channel Stabilization Problems, Committee on Channel Stabilization, U.S. Army Corps of Engineers, Technical Report 1, Vol. 3.

100. Hickson, R.E. 1961. "Columbia River Ship Channel Improvement and Maintenance," Journal of the Waterways and Harbors Division, Proceedings, American Society of Civil Engineers, Vol. 87, WW3.

101. Higley, D.L., Holton, R.L., and Komar, P.D. 1976. "Analysis of Benthic Infauna Communities and Sedimentation Patterns of a Proposed Fill Site and Nearby Regions in the Columbia River Estuary," Final Report to Port of Astoria, Astoria, OR, Oregon State University, Corvallis, OR.

102. Hines, W.G., et al. 1978. River Quality Conditions of the Lower Columbia River-A Preliminary Assessment, Seattle, WA, IRS Company.

103. Hobson, L.A. 1961. "Some Influence of the Columbia River Effluent on Marine Phytoplankton During January 1961," Masters Thesis, University of Washington, Seattle, WA.

104. Hodge, E.T. 1934. "The Geology of the Beach and the Petrography of Its Sands," Report to the U.S.A.E. District, Portland.

105. Holton, R.L., et al. 1978. "Aquatic Disposal Field Investigations, Columbia River Disposal Site, Oregon, Appendix B: Water Column, Primary Productivity and Sediment Studies," Technical Report D-77-30, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

106. Honstead, J.T. 1957. "Dispersion of Dissolved Material in the Columbia River," HW-49008, Hanford Atomic Products Operation, Richland, WA.

107. Hopkins, T.S. 1971. "Velocity, Temperature, and Pressure Observations from Moored Meters on the Shelf near the Columbia River Mouth, 1967-1969," Special Report No. 45, University of Washington, Department of Oceanography, Seattle, WA.

108. Hubbell, D.W., and Glenn, J.L. 1973. "Distribution of Radionuclides in Bottom Sediments of the Columbia River Estuary," Professional Paper 433-L, U.S. Geological Survey.

109. Hubbell, D.W., Glenn, J.L., and Stevens, H.H.,Jr. 1971. "Studies of Sediment Transport in the Columbia River Estuary," Proceedings, 1971 Conference on Estuaries of the Pacific N.W., Circular No. 42, Engineering Experiment Station, Oregon State University, Corvallis, OR.

110. Hughes, F.W. 1968. "Salt Flux and Mixing Processes in the Columbia River Estuary During High Discharge," University of Washington, Seattle, WA.

111. Hughes, F.W., and Rattray, M.,Jr. 1980. "Salt Flux and Mixing in the Columbia River Estuary," Estuarine and Coastal Marine Research, Vol. 10.

112. Hulsing, H., and Kallio, N.A. 1964. "Magnitude and Frequency of Floods in the United States, Part 14: Pacific Slope Basins in Oregon and Lower Columbia River Basin," Water Supply Paper 1689, U.S. Geological Survey.

113. Huyer, A., 1972. "A Comparison Between the Wind and Current Observations over the Continental Shelf off Oregon, Summer 1969." Journal of Geophysical Research, Vol. 77.

114. Hyde, G.E., and Beeman, O. 1963. "Improvement of the Navigability of the Columbia River by Dredging and Construction Works," Misc. Pub. 970, Federal Interagency Sedimentation Conference of the Subcommittee on Sedimentation, Jackson, MS, U.S. Department of Agriculture.

115. Jaske, R.T. 1972. "Potential Thermal Effects of an Expanding Power Industry: Columbia River Basin," BNWL-1646/UC-70, Battelle Pacific Northwest Laboratories, Water and Land Resources Department, Richland, WA.

116. Jennings, C.D. 1966. "Radioactivity of Sediments in the Columbia River Estuary," Masters Thesis, Oregon State University, Corvallis, OR.

117. Jennings, C.D., and Osterberg, C. "Sediment Radioactivity in the Columbia River Estuary," Proceedings, Second National Symposium on Radioecology, U.S. Atomic Energy Commission.

118. Johnson, J.W. 1948. Model Studies at the University of California River and Harbor Laboratory, Transactions, American Geophysical Union.

119. Jones, K.R., et al. 1951. "An Investigation of Pollution in the Lower Columbia River," Technical Bulletin 12, Washington Pollution Control Commission.

120. Johnson, V.G., and Cutshall, N.H. 1975. "Geochemical Baseline Data, Youngs Bay, Oregon, 1974," Ref 75-7, Oregon State University, Department of Oceanography, Corvallis, OR.

121. Johnson, V.G., Cutshall, N.H., and Osterberg, C. 1967. "Retention of Zinc-65 by Columbia River Sediment," Water Resources Research, Vol. 3, No. 1.

122. Judson, S., and Ritter, D.F. 1961. "Rates of Denudation in the U.S.," Journal of Geophysical Research, Vol. 69, No. 16.

123. Kelley, J.C., and Whetten, J.T. 1969. "Quantitative Statistical Analyses of Columbia River Sediment Samples," Journal of Sedimentary Petrology, Vol. 39, No. 3.

124. Kelly, J.V. 1947. "Columbia River Magnetite Sands, Clatsop County, OR, and Pacific County, WA, Hammond and McGowan Deposits," Report of Investgations 4011, U.S. Bureau of Mines.

125. Kidby, H.A. 1965. "Columbia and Lower Willamette Rivers, 40-by 600-foot Project," Chapter III of Symposium on Channel Stabilization, Commission and Channel Stabilization, Technical Report 1, Vol. 3, U.S. Army Corps of Engineers.

126. Kidby, H.A., and Oliver, J.G. 1965. "Erosion and Accretion Along Clatsop Spit," Proceedings, Coastal Engineering Conference, Santa Barbara, American Society of Civil Engineers, New York.

127. Knebel, H.J., Kelly, J.C., and Whetten, J.T. 1968. "Clay Minerals of the Columbia River: A Quantitative, and Statistical Evaluation," Journal of Sedimentary Petrology, Vol. 38, No. 2.

128. Kuentz, O.O. 1933. "The Lower Columbia River Project," The Military Engineer, Vol. XXV, No. 139.

129. Kujala, N., and Wyatt, B. 1961. "Surface Temperature and Salinity Observations at Shore Stations on the Oregon Coast," Data Report No. 6, Ref 61-4, Oregon State University, Department of Oceanography, Corvallis, OR.

130. Leifeste, D.K. 1974. "Dissolved-Solids Discharge to the Oceans from the Coterminous United States," Circular 685, U.S. Geological Survey.

131. Lister, C.R.B., Whetten, J.T., and Bates, M. 1967. "Sonar Reflection Profiling on the Columbia River and in Lake Washington," Northwest Science, Vol. 41, No. 4, Apr.

132. Lockett, J.B. 1959. "Interim Consideration of the Columbia River Entrance," Journal of the Hydraulics Division, Proceedings, American Society of Civil Engineers, Vol. 85, No. HY1.

133. Lockett, J.B., and Kidby, H.A. 1961. "Prototype Measurements of the Columbia River Estuary," Journal of the Hydraulics Division, Proceedings, American Society of Civil Engineers, Vol. 87, No. HY1.

134. Lockett, J.B. 1963. "Phenomena Affecting Improvement of the Lower Columbia Estuary and Entrance," Misc. Pub. 970, Federal Interagency Sedimentation Conference of the Subcommittee on Sedimentation, Jackson, MS, U. S. Department of Agriculture.

135. Lockett, J.B. 1965. "Some Indications of Sediment Transport in the Vicinity of the Columbia Estuary and Entrance, Oregon and Washington," Transactions of the XI Congress, International Association for Hydraulic Research, Leningrad.

136. Lockett, J.B. 1967. "Sediment Transport and Diffusion: Columbia Estuary and Entrance," Journal of the Waterways and Harbors Division, Proceedings, American Society of Civil Engineers.

137. Lutz, G.A., Hubbell, D.W., and Stevens, H.H.,Jr. 1975. "Discharge and Flow Distribution, Columbia River Estuary," Professional Paper 433-P, U.S. Geological Survey.

138. Mathematical Sciences Northwest, Inc. 1980. "Columbia River Estuary Data Development Program, Literature Review, Task B-1.1, Circulation Studies," Bellevue, WA.

139. McCauley, J.E., ed. 1969. "Ecological Studies of Radioactivity in the Columbia River Estuary and Adjacent Pacific Ocean, Progress Report, 1 Jul 1968 through 30 June 1969," Oregon State University, Department of Oceanography, Corvallis, OR.

140. McConnell,R.J., et al. 1979. "Concentration Extent and Duration of Salinity Intrusion into the Columbia River Estuary September-October 1977-1978," National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, WA.

141. McDonald, C.C., and Riggs, H.C. 1948. "Annual Runoff in Columbia River Basin in Percent of the Mean, 1928-45," Circular 36, U.S. Geological Survey.

142. McManus, D.A. 1972. "Bottom Topography and Sediment Texture near the Columbia River Mouth," Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

143. Moore. A.M. 1968. "Water Temperatures in the Lower Columbia River," Circular 551, U.S. Geological Survey, Washington, DC.

144. Morse, B.A., Gross, M.G., and Barnes, C.A. 1968. "Movement of Seabed Drifters near the Columbia River,' Journal of the Waterways and Harbors Division, Proceedings, American Society of Civil Engineers.

145. Morse, B.A., and McGary, N.B. 1975. "Graphic Representation of the Salinity Distribution near the Columbia River Mouth," Transactions, Joint Conference and Exhibit, 14-17 Jun, Marine Technology Society.

146. Mundorff, M.J. "Progress Report on Ground Water in the Columbia Basin Project, Washington," Open File Report, U.S. Geological Survey.

147. Naidu, J.R., and Cutshall, N.H. 1971. "Radioactive Zinc (Zinc-65), Zinc, Cadmium, and Mercury in the Pacific Hake MERLUCCIUS PRODUCTUS (Ayres) off the West Coast of the United States: A Data Report," Data Report 60, Ref 74-9, Oregon State University, Corvallis, OR.

148. National Marine Consultants, Inc., 1961. "Wave Statistics for Twelve Most Severe Storms Affecting Three Selected Stations off the Coast of Washington and Oregon During the Period 1950-1960," Santa Barbara, CA.

149. National Marine Consultants, Inc., 1961. "Oceanographic Study for Columbia River Entrance," Santa Barbara, CA.

150. National Marine Consultants, Inc., 1961. "Wave Statistics for Three Deep Water Stations Along the Oregon-Washington Coast," Santa Barbara, CA.

151. National Ocean Survey. 1977. "Tidal Current Tables 1977," Annual Publication, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

152. National Ocean Survey. 1977. "Tide Tables, 1977, West Coast of North and South America," Annual Publication, National Oceanic and Atmospheric Admn., U.S. Department of Commerce.

153. Neal, V.T. 1965. "A Calculation of Flushing Times and Pollution Distribution for the Columbia River Estuary," Ph.D. Thesis, Oregon State University, Corvallis, OR.

154. Neal, V.T. 1963. "Physical Aspects of the Columbia Estuary," Oregon State University, Department of Oceanography, Corvallis, OR.

155. Neal, V.T. 1970. "Predicted Flushing Times and Pollution Distribution in the Columbia River Estuary," Coastal Engineering Conference Proceedings, American Society of Civil Engineers, New York.

156. Neal, V.T. 1972. "Physical Aspects of the Columbia River and Its Estuary," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

157. Nelson, J.L., and Cutshall, N.J. 1964. "Studies of the Mechanism of Retention of Radionuclides in Columbia River Sediments," Scientific Research and Development, Annual Report for 1964, BNWL-36, Battelle Pacific Northwest Laboratories, Richland, WA.

158. Nelson, J.L., and Haushild, W.L. 1970. "Accumulation of Radionuclides in Bed Sediments of the Columbia River Beween the Hanford Reactors and McNary Dam," Water Resources Research, Vol. 6, No. 1.

159. Nelson, J.L., Perkins, R.W., and Haushild, W.L. 1966. "Determination of Columbia River Flow Times Downstream from PAsco, Washington, Using Radioactive Tracers Introduced by the Hanford Reactors," Water Resources Research, Vol. 2, No. 1, First Quarter 1966.

160. Nelson, J.L., Perkins, R.W., and Nielson, J.M. 1964. "Progress in Studies of Radionuclides in Columbia River Sediments, A Summary of Hanford Achievements in the Program Under General Electric, 1963-1964," HW-83614, Hanford Atomic Products Operation, Richland, WA.

161. Nelson, J.L., Perkins, R.W., Nielson, J.M., and Haushild, W.L. 1966. "Reactions of Radionuclides from the Hanford Reactors with Columbia River

Sedments," Proceedings of a Symposium on Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters, International Atomic Energy, Vienna.

162. Nielson, J.M. 1963. "Behavior of Radionuclides in the Columbia River," Transport of Radionuclides in Fresh Water Systems, T10-7664, U.S. Atomic Energy Commission, Washington, DC.

163. Norgaard, R.B. 1967. "Streamflow and Deposition on the Lower Columbia River: A Partial Physical Production Function with an Economic Application," M.S. Thesis, Oregon State University, Corvallis, OR.

164. O'Brien, M.P. 1935. "Report on Experiments July 1933 to May 1935, Mouth of the Columbia River, Beach Erosion Investigations," Technical Memorandum No. 7, on file U.S.A.E. District, Portland, OR.

165. O'Brien, M.P. 1935. "Models of Estuaries," Transactions, American Geophysical Union.

166. O'Brien, M.P. "Mouth of Columbia River Beach Erosion Investigation," Technical Memo 20, U.S. Tidal Model Lab, University of California, Berkeley, CA.

167. O'Brien, M.P. 1951. "Wave Measurements at the Columbia River Light Vessel, 1933-1936," Transactions, American Geophysical Union, Vol. 32, No. 6.

168. O'Brien, M.P. 1971. "Field and Laboratory Studies, Navigation Channels of the Columbia River Estuary," HEL 24-4, University of California, Berkeley, CA.

169. O'Brien, M.P. 1948. "Wave Action and Salinity Currents at the Mouth of the Columbia River," Memorandum HE-116-59, University of California, Fluid Mechanics Laboratory, Berkeley, CA.

170. Oliphant, M., Wyatt, N., and Kajala, N.F. 1962. "Surface Temperature and Salinity at Oregon Shore Stations," Data Report No. 8, Ref 62-11, Oregon State University, Department of Oceanography, Corvallis, OR.

171. Onishi, Y., Johanson, D.A., Baca, R.G., and Hilty, E.L. 1976. "Annual Report, Studies of Columbia River Water Quality," Report to U.S. Energy Research and Development Adminstration, BNWL-B452, Battelle Pacific Northwest Laboratories, Richland, WA.

172. Oregon Department of Environmental Quality. 1974. "Estuarine Water Quality Data (Computerized Summary of Water Quality Observations in Oregon's Estuaries)," Portland, OR.

173. Oregon State University. 1962. "Hydrographic Data from Oregon Waters, June 1960 Through May 1961," Data Report 7, Corvallis, OR. First of a series of reports with same primary title, various authors.

174. Oregon State University. 1975. "Physical Characteristics of the Young's Bay Estuarine Environs," Final Report to Alumax Pacific Aluminum Corporation. School of Engineering, Corvallis, OR.

175. Oregon State Water Resources Board. 1961. "North Coast Basin," State of Oregon, Salem, OR.

176. Orem, H.M. 1968. "Discharge in the Lower Columbia River Basin, 1928-1965," Circular 550, U.S. Geological Survey, Washington, DC.

177. Orem, H.M. 1961. "Computation of Total Flow of the Columbia River at the Mouth," Short Papers in the Geologic and Hydrologic Sciences, Professional Paper 424-C, U.S. Geological Survey.

178. Osterberg, C. 1965. "Radioactivity from the Columbia River," Transactions, Oceanographic Science and Oceanographic Engineering Symposium, Vol.2.

179. Osterberg, C., Cutshall, N., and Cronin, J. "Chromium-51 as a Radioactive Tracer of Columbia River Water at Sea," Science, Vol. 150, No. 3703.

180. Osterberg, C.L., et al. 1966. "Some Non-Biological Aspects of Columbia River Radioactivity," Proceedings of a Symposium on Disposal of Radioactive Waste into Seas, Oceans, and Surface Water, International Atomic Energy Agency, Vienna.

181. Osterberg, C.L., Kulm, L.D., and Byrne, J.V. 1963. "Gamma Emitters in Marine Sediments near the Columbia River," Science, Vol. 139, No. 3558.

182. Osterberg, C.L., Pattullo, J.G., and Pearcy, W. 1964. "Zinc-65 in Euphausiids as Related to Columbia River Water off the Oregon Coast," Limnology and Oceanography, Vol. 9, No. 2.

183. Osterberg, C.L., and Perkins, R.W. 1972. "Methods for the Measurement of Hanford-Induced Gamma Radioactivity in the Ocean," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

184. Overland, J.E. 1979. Waves at the Columbia River Entrance, U.S. Department of Commerce, Environmental Research Laboratories, Boulder, CO.

185. Pacific Northwest River Basins Commission Meteorology Committee. 1969. "Climatological Handbook-Columbia River States," 3 Vol., Columbia Basin Inter-Agency Committee, Vancouver, WA.

186. Pak, H. 1970. "The Columbia River as a Source of Marine Light Scattering Particles," Ph.D. Thesis, Oregon State University, Corvallis, OR.

187. Pak, H., Beardsley, G.F.,Jr., and Park, P.K. 1970. "The Columbia River as a Source of Marine Light Scattering Particles, " Journal of Geophysical Research, Vol. 75, No. 24.

188. Park, P.K. 1966. "Columbia River Plume Identification by Specific Alkalinity," Limnology and Oceanography, Vol. 11, No. 1.

189. Park, P.K., Catalfomo, M., Webster, G.R., and Reid, B.H. 1970. "Nutrients and Carbon Dioxide in the Columbia River." Limnology and Oceanography, Vol. 15, No. 1.

190. Park, P.K., et al. 1965. "Strontiom-70 and Cesium-137 in Columbia River Plume," Nature, Vol. 208, No. 5015.

191. Park, P.K., Osterberg, C.L., and Forster, W.O. 1972. "Chemical Budget of the Columbia River," The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

192. Park, P.K., Webster, G.R., and Yamanoto, R. 1969. "Alkalinity Budget of the Columbia River," Limnology and Oceanography, Vol. 14, No. 4.

193. Pattullo, J.G., and Burt, W.V. 1962. "The Pacific Ocean," Technical Report No. 11, Ref 62-2, Oregon State University, Department of Oceanography, Corvallis, OR.

194. Pattulo, P.D.W. 1965. "Processes Affecting Seawater Characteristics Along the Oregon Coast," Limnology and Oceanography, Vol. 10, No. 3.

195. Paulson, C.C. 1949. "Floods of May-June 1948 in the Columbia River Basin," Water-Supply Paper No. 1080, U.S. Geological Survey, Washington, DC.

196. Pearcy, W.G., and Mueller, J.L. 1970. "Upwelling, Columbia River Plume and Albacore Tuna," 6th International Symposium Remote Sensing of the Environment.

197. Percy, K.L., et al. 1974. "Descriptions and Information Sources for Oregon Estuaries," Sea Grant College Program, Oregon State University, Corvallis, OR.

198. Perkins, R.W. 1963. "Columbia River Sediment and Transport Studies," Hanford Radiological Sciences Research Development Annual Report, AEC Report No. HW-81746.

199. Perkins, R.W., Nelson, J.L., and Haushild, W.L. 1966. "Behavior and Transport of Radionuclides in the Columbia River Between Hanford and Vancouver, Washington," Limnology and Oceanography, Vol. 11, No. 2.

200. Peterson, D.R. 1960. "Water Quality-Lower Columbia River," Water Quality in the Columbia River Basin, Proceedings, Water Quality Conference, Pullman, WA.

201. Pruter, A.T., and Alverson, D.L., editors. 1972. The Columbia River Estuary and Adjacent Ocean Waters, University of Washington Press, Seattle, WA.

202. Prych, E.A., Hubbell, D.W., and Glenn, J.L. 1965. "Measurement Equipment and Techniques Used in Studying Radionuclide Movement in the Columbia River Estuary," Coastal Engineering Conference Proceedings, American Society of Civil Engineers, New York.

203. Quinn, W.H., and Enfield, D.B. "The Development of Forecast Techniques for Wave and Surf Conditions over the Bars in the Columbia River Mouth and at the Entrance to Yaquina Bay," Oregon State University, Department of Oceanography, Corvallis, OR.

204. Rantz, S.E., and Moore, A.M. 1965. "Floods of December 1964 in the Far Western States," Open File Report, U.S. Geological Survey.

205. Richards, F.A., and Stefansson, U. "Silicate-Salinity Relationship in the Columbia River Effluent," Transactions, American Geophysical Union (Abstract), Vol. 44, No. 1.

206. Robe, R.Q. 1968. Salt Flux in and Classification of the Columbia River Estuary During High and Low Discharge, University of Washington, Department of Oceanography, Seattle, WA.

207. Robeck, G.G., Henderson, C., and Palange, R.C. 1954. "Water Quality Studies on the Columbia River," U.S. Public Health Service, Taft Sanitary Engineering Center, Cincinnati, OH.

208. Roberson, John A. 1980. "Baker Bay Circulation by Mathematical Modeling," American Society of Civil Engineers, Portland, OR.

209. Rockwood, D.M. 1958. "Columbia Basin Streamflow Routing By Computer," Journal of the Waterways and Harbors Division, Proceedings, American Society of Civil Engineers, Vol. 84, WW5.

210. Roden, G.I. 1967. "On River Discharge into the NE Pacific Ocean and the Bering Sea," Journal of Geophysical Research, Vol. 72, No. 22.

211. Royse, C.F.,Jr. 1964. "Sediments of Willapa Submarine Canyon," Technical Report 111, Ref M64-60, University of Washington, Department of Oceanography, Seattle, WA.

212. Santos, J.F. 1965. "Quality of Surface Waters in the Lower Columbia River Basin," Water-Supply Paper 1784, U.S. Geological Survey.

213. Savini, J., and Bodhaine, G.L. 1971. "Analysis of Current-Meter Data at Columbia River Gaging Stations, Washington and Oregon," Water Supply Paper 1869-F, U.S. Geological Survey.

214. Sayre, W.W., Guy, H.P., and Chamberlain, A.R. 1963. "Uptake and Transport of Radionuclides by Stream Sediments," Professional Paper 433A, U.S. Geological Survey.

215. Schultz, E.A., and Simmons, H.B. 1957. "Fresh Water-Salt Water Density Currents, A Major Cause of Siltation in Estuaries," Technical Bulletin No. 2, U.S. Army Corps of Engineers, Committee on Tidal Hydraulics, Vicksburg, MS.

216. Scripps Institute of Oceanography, 1960. "Surface Water Temperatures at Shore Stations, United States West Coast and Baja, California 1956-1959," Data Report 68-27, University of California.

217. Seaman, M.H., ed. 1978. "Columbia River Estuary Inventory of Physical, Biological and Cultural Characteristics," Columbia River Estuary Task Force, Astoria, OR.

218. Seymour, A.H., and Lewis, G.B. 1964. "Radionuclides of Columbia River Origin in Marine Organisms, Sediments, and Water Collected from the Coastal and Offshore Waters of Washington and Oregon, 1961-1963," Report No. UWFL-86, University of Washington, Laboratory of Radiation Biology, Seattle, WA.

219. Simmons, H.B. 1971. "The Potential of Physical Models to Investigate Estuarine Water Quality Problems," Proceedings, 1971 Conference on Estuaries of the Pacific Northwest, Circular No. 42, Engineering Experiment Station, Oregon State University, Corvallis, OR.

220. Smith, J.D., and Hopkins, T.S. 1972. "Sediment Transport on the Continental Shelf off of Washington and Oregon in Light of Recent Current Measurements," Shelf Sediment Transport: Process and Pattern, D.J.P. Swift, D.B. Dvane, and O.H. Pilkey, eds., Dowen, Hutchinson, and Ross, Stroudsburg, PA.

221. Speers, D.D. 1976. "Simulation of Future River Fluctuations," Rivers 76, Proceedings, 3rd Annual Symposium of Inland Waterways for Navigation, Flood Control, and Water Diversions, American Society of Civil Engineers, New York.

222. Stefansson, U., and Richards, F.A. 1963. "Processes Contributing to the Nutrient Distributions off the Columbia River and Strait of Juan De Fuca," Limnology and Oceanography, Vol. 8, Oct.

223. Sternberg, R.W., et al. 1977. "Aquatic Disposal Field Investigations, Columbia River Disposal Site, Oregon, Appendix A, An Investigation of the Hydraulic Regime and Physical Nature of Bottom Sedimentation at the Columbia River Dump Site," Technical Report D-77-30, U.S.A.E. Waterways Experiment Station, CE, Vicksburg, MS.

224. Sternberg, R.W., and McManus, D.A. 1972. "Implications of Sediment Dispersal from Long-Term, Bottom-Current Measurements on the Continental Shelf of Washington," Shelf Sediment Transport, Stroudsburg, PA.

225. Still, R., Wyatt, B., and Kujala, N. 1963. "Surface Temperature and Salinity Observations at Shore Stations on the Oregon Coast for 1962," Data Report 11, Ref 63-27, Oregon State University, Department of Oceanography, Corvallis, OR.

226. Sylvester, R.O., and Carlson, D.A. 1961. "Lower Columbia River Basin Water Quality Data Analysis for the Year 1960," University of Washington, Department of Civil Engineering, Seattle, WA.

227. Tsivoglou, E.C., and Lamnering, M.W. 1961. "A Report by the Columbia River Advisory Group of an Evaluation of the Pollutional Effects of Effluents from Hanford Works," Division of Water Supply and Pollution Control, Robert A. Taft Sanitary Engineering Center U.S. Public Health Service, Cincinnati, OH.

228. Twenhofel, W.H. 1946. "Mineralogical and Physical Composition of the Sands of the Oregon Coast from Coos Bay to the Mouth of the Columbia River,"

Bulletin 30, Oregon State Department of Geology and Mineral Industries, Portland, OR.

229. U.S. Army Corps of Engineers, Commitee on Tidal Hydraulics. 1960. "Present and Potential Channel Maintenance Problems in Lower Columbia Estuary," Vicksburg, MS.

230. U.S. Army Corps of Engineers, Committee on Tidal Hydraulics, 1967. "Intracoastal Waterway, Columbia River to Puget Sound, Washington," Vicksburg, MS.

231. U. S. Army Corps of Engineers, Committee on Tidal Hydraulics, 1971. "Columbia River Estuary, Oregon and Washington," Technical Bulletin 17, Estuarine Navigation Projects, Vicksburg, MS.

232. U.S.A.E. District, Portland. 1932. "Mouth of Columbia River Current Survey, 1932," on file U.S.A.E. District, Portland, OR.

233. U.S.A.E. District, Portland. 1953. "Salinity Observations Columbia River in 1936," Memorandum dated 10 Apr 1953.

234. U.S.A.E. District, Portland. 1938. "Mouth of the Columbia River Oregon and Washington."

235. U.S.A.E. District, Portland. 1941. "Navigation on the Columbia River."

236. U.S.A.E. Portland District. 1949. "Columbia River and Tributaries Below Yakima River, Report on Flood of May-June, 1948."

237. U.S.A.E. District, Portland. 1953. "Columbia River at the Mouth, Oregon and Washington," House Document No. 249, 83rd Congress, 2nd Session, GPO, Washington, DC.

238. U.S.A.E. District, Portland. 1959. "Columbia River at the Mouth, Oregon and Washington, South Jetty Repair, General Design Memorandum."

239. U.S.A.E. District, Portland. 1971. "Runoff Evaluation and Streamflow Simulation by Computer."

240. U.S.A.E. District, Portland. 1960. "Interim Report on 1959 Current Measurement Program, Columbia River at Mouth, Oregon and Washington," 4 Vols.

241. U.S.A.E. District, Portland. 1960. "Summary of Interim Report on 1959 Current Measurement Program, Columbia River at Mouth, Oregon and Washington."

242. U.S.A.E. District, Portland. 1961. "Sedimentation Investigation, Lower Columbia and Lower Willamette River, July 1959-August 1960."

243. U.S.A.E. District, Portland. 1961. "Results of a Preliminary Study of the Long-Term Scour and Shoal Trend at the Mouth of the Columbia River."

244. U.S.A.E. District, Portland. 1976. "Columbia River Maintenance Disposal Plan," Draft.

245. U.S.A.E. Portland District. 1979. "Propeller Wash Agitation Dredging, Chinook Channel, Washington, P1, Evaluation of Propeller Wash Dredging at Chinook Channel," Navigation Division, Research and Evaluation Report No. 2-79.

246. U.S.A.E. Seattle District. 1967. "Study Program of the Columbia River to Puget Sound Intracoastal Waterway," Presentation to Committee on Tidal Hydraulics.

247. U.S.A.E. Division, North Pacific. 1933. "Columbia River and Tributaries," in Congressional Documents 73rd Congress, 1st and 2nd Sessions, 1933-1934, House Document No. 103, 2 Vols.

248. U.S.A.E. Division, North Pacific. 1950. "Columbia River and Tributaries, North Western United States," in Congressional Document 81st Congress, 2nd Session, House Document No. 531, 8 Vols.

249. U.S.A.E. Division, North Pacific. 1971. "National Shoreline Study, Inventory Report, Columbia-North Pacific Region, Washington and Oregon."

250. U.S.A.E. Division, North Pacific. 1972. "Columbia River and Tributaries Review Study, CRT-11, Power Pondage Studies."

251. U.S.A.E. Division, North Pacific. 1971. "Columbia River and Tributaries Review Study, CRT-12, Examples of Actual Hourly Project Operations, 1970-71," Portland, OR.

252. U.S.A.E. Division, North Pacific. 1973. "Columbia River and Tributaries Review Study, CRT-14, Water Surface Fluctuation Studies, Bonneville and McNary Projects 1974-75 Conditions."

253. U.S.A.E. Division, North Pacific. 1976. "Development and Application of the SSARR Model, Summaries of Technical Reports" (Revised Sep. 1976).

254. U.S.A.E. Division, North Pacific. 1976. "Columbia River and Tributaries Review Study, CRT-30, Power Pondage Studies, Hourly-Daily-Weekly Mid 1980 Conditions."

255. U.S.A.E. Division, North Pacific. 1977. "Columbia River and Tributaries Review Study, CRT-231, Water Surface Fluctuation Studies, Mid 1980 Conditions."

256. U.S. Board of Engineers for Rivers and Harbors. Report of the Board of Engineers, 13 Oct 1882, U.S. Senate Executive Document No. 13, 47th Congress, 2nd Session.

257. U.S. Department of Commerce. 1975. "Local Climatological Data: Annual Summary with Comparative Data, Astoria, Oregon," National Oceanic and Atmospheric Administration, Environmental Data Service, Boulder, CO.

258. U.S. Department of the Interior. 1947. "The Columbia River: A Comprehensive Report on the Development of the Water Resources of the Columbia River Basin for Irrigation, Power Production, and Other Beneficial Uses in Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming."

259. U.S. Geological Survey. 1960. "Slope Basins in Oregon and Lower Columbia Basin 1943 to 1959," Water Resources Division.

260. U.S. Geological Survey. 1965. "Water Resources Data For Washington Part 2: Water Quality Records 1965," Tacoma, WA.

261. U.S. Geological Survey. 1967. "Water Resources Data For Washington Part 1: Surface Water Records 1966," Tacoma, WA.

262. U.S. Geological Survey. 1971. "Water Resources Data for Oregon, Part 1: Surface Water Records, 1971," Tacoma, WA.

263. U.S. Geological Survey. "Water Resources Data for Oregon, Part 2: Water Quality Records, 1972," Tacoma, WA.

264. U.S. Geological Survey. 1975. "Surface Water Supply of the United States, 1966-70, Part 12, Pacific Slope Basins in Washington, Vol. 2, Upper Columbia River Basin," Water Supply Paper 2133.

265. U.S. Geological Survey. 1972. "Surface Water Supply of the United States, 1966-70, Part 14, Pacific Slope Basins in O.. gon and Lower Columbia River Basin," Water Supply Paper 2135.

266. U.S. Navy Hydrographic Office. 1960. "Inshore Survey Results Columbia River Approaches Winter 1958," Oceanographic Survey Branch, Division of Oceanography, Washington, DC.

267. U.S. Naval Weather Service Command. 1970. "Summary of Synoptic Meteorological Observations, North American Coastal Marine Areas," Volumes 9 and 10.

268. U.S. Tidal Model Lab. 1936. "Final Report on Field and Laboratory Studies of the Navigation Channel in the Estuary of the Columbia River," Technical Memorandum No. 21, University of California, Berkeley, CA.

269. Van Winkle, W. 1914. "Quality of the Surface Waters of Washington," Water Supply Paper 339, U.S. Geological Survey, Washington, DC.

270. Walsh, O.E. 1954. "Slackwater Improvement of the Columbia River," Paper No. 2663, V119, Transactions, American Society of Civil Engineers, New York.

271. Wang, S., et al. 1979. "Columbia River Entrance Channel Deep-Draft Vessel Motion Study, Final Report-Phase 1, Tetra Tech Report No. TC-3925.

272. Washington, University of. 1963. "Physical, Chemical, and Biological Data from the Northeast Pacific Ocean, Columbia River Effluent Area, January-June 1961," Technical Report 86, Ref M63-13 (First of a series with the same primary title and nonconsecutive report ..umbers), University of Washington, Seattle, WA.

273. Waters, A.C. 1933. "Terraces and Coulees Along the Columbia River near Lake Chelan, Washington," Bulletin of the Geophysical Society of America, Vol. 55, No. 4.

274. Whetten, F.T. 1976. "Sediments from the Columbia River and the Origin of Graywacke," Science, Vol. 152, May.

275. Whetten, J.T., and Fullam, T.J. 1967. "Columbia River Bed Forms," Proceedings, 12th Congress of the International Association for Hydraulic Research.

276. Whetten, J.T., Kelley, J.C., and Hansom, L.G. 1969. "Characteristics of Columbia River Sediment and Sediment Transport," Journal of Sedimentary Petrology, Vol. 39, No. 3.

277. White, S.M. 1970. "Mineralogy and Geochemistry of Continental Shelf Sediments off the Washington and Oregon Coast," Journal of Sedimentary Petrology, Vol. 40, No. 1.

278. Wildung, R.E., Rouston, R.C., and Schmidt, R.L. 1972. "Seasonal Changes in Particle Size Distribution, Composition and Strontium Exchange Capacity of Particulate Matter Suspended in the Columbia River," BNWL 1638, Battelle Pacific Northwest Laboratories, Richland, WA.

279. Williams, C.F. 1933. "Mouth of Columbia River Current Survey 1932-33," War Department Office of the District Engineer, Part 1, Portland, OR.

280. Wyatt, B., et al. 1971. "Drift Bottle Recoveries and Releases off the Oregon Coast 1961 through 1970," Data Report 50, Ref 71-36, Oregon State University, Department of Oceanography, Corvallis, OR.

281. Wyatt, B., and Gilbert, W. 1967. "Surface Temperature and Salinity Offshore at Oregon Shore Stations for 1965 and 1966," Data Report 25, Ref 67-8, Oregon State University, Department of Oceanography, Corvallis, OR.

282. Wyatt, B., and Gilbert, W. 1971. "Surface Temperature and Salinity Observations at Pacific NW Shore Stations During 1970," Data Report No. 47, Ref 71-8, Oregon State University, Department of Oceanography, Corvallis, OR.

283. Wyatt, B., and Gilbert, W. 1972. "Surface Temperature and Salinity Observations at Oregon Shore Stations from 1971," Data Report 51, Ref 72-2, Oregon State University, Department of Oceanography, Corvallis, OR.

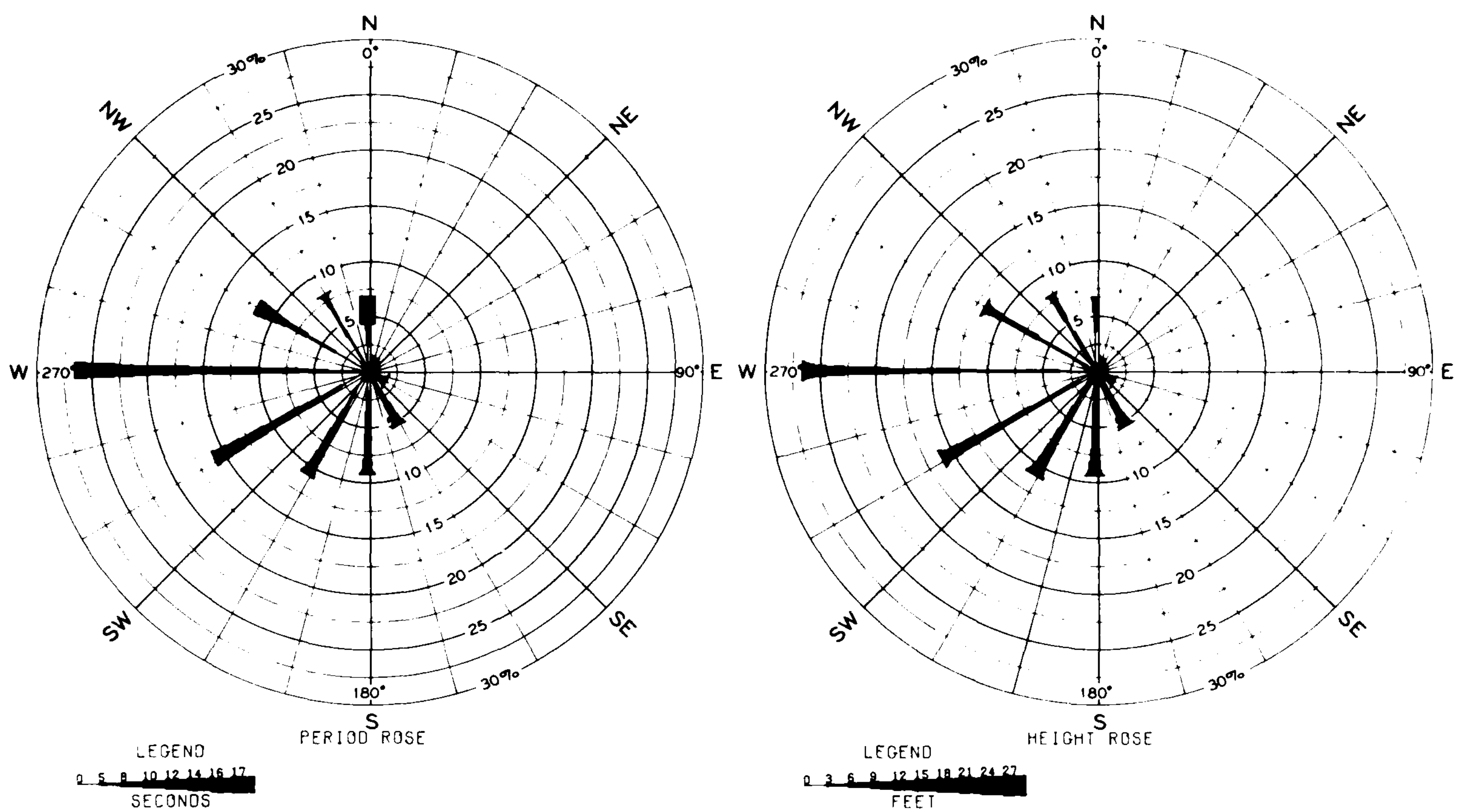
284. Wyatt, B., and Kujala, N.F. 1961. "Physical Oceanographic Data Offshore from Newport and Astoria, Oregon for July 1959-June 1960," Data Report No. 5, Ref 61-3, Oregon State University, Department of Oceanography, Corvallis, OR.

285. Wyatt, B., Still, R., and Haag, C. 1965. "Surface Temperature and Salinity Observations at Oregon Shore Stations," Data Report 21, Ref 65-20, Oct., Oregon State University, Department of Oceanography, Corvallis, OR.

286. Zopf, D.O., Creech, H.C., and Quinn, W.H. 1976. "The Wavemeter: A Land-Based System for Measuring Nearshore Ocean Waves," Journal of the Marine Technology Society, Vol. 10, No. 4.

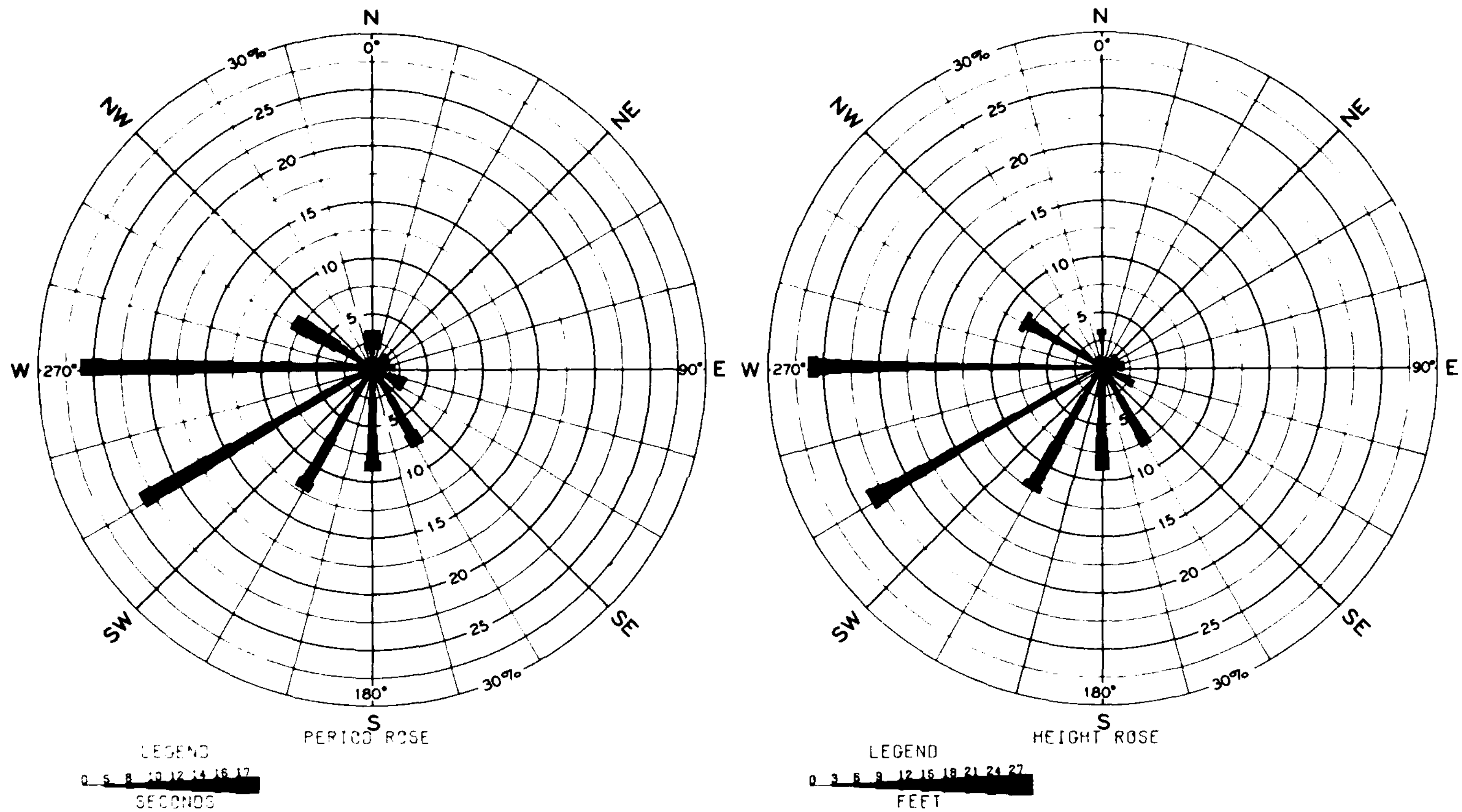
APPENDIX B: WAVE FREQUENCY ROSES

Daily wave hindcasts by the U. S. Navy Fleet Numerical Weather Center were collected for the Oregon coast by the Portland District. Data for the period January 1969-December 1976 at sta 2 (latitude 47°N, longitude 127°W) and sta 4 (latitude 44°N, longitude 127°W) were converted to punched card format and subjected to statistical analyses of height, period, and direction. Plate B1 shows annual wave frequencies at sta 2 and Plates B2-B13 show monthly frequencies for sta 2. Sta 4 frequencies are illustrated in Plates B14-B26.



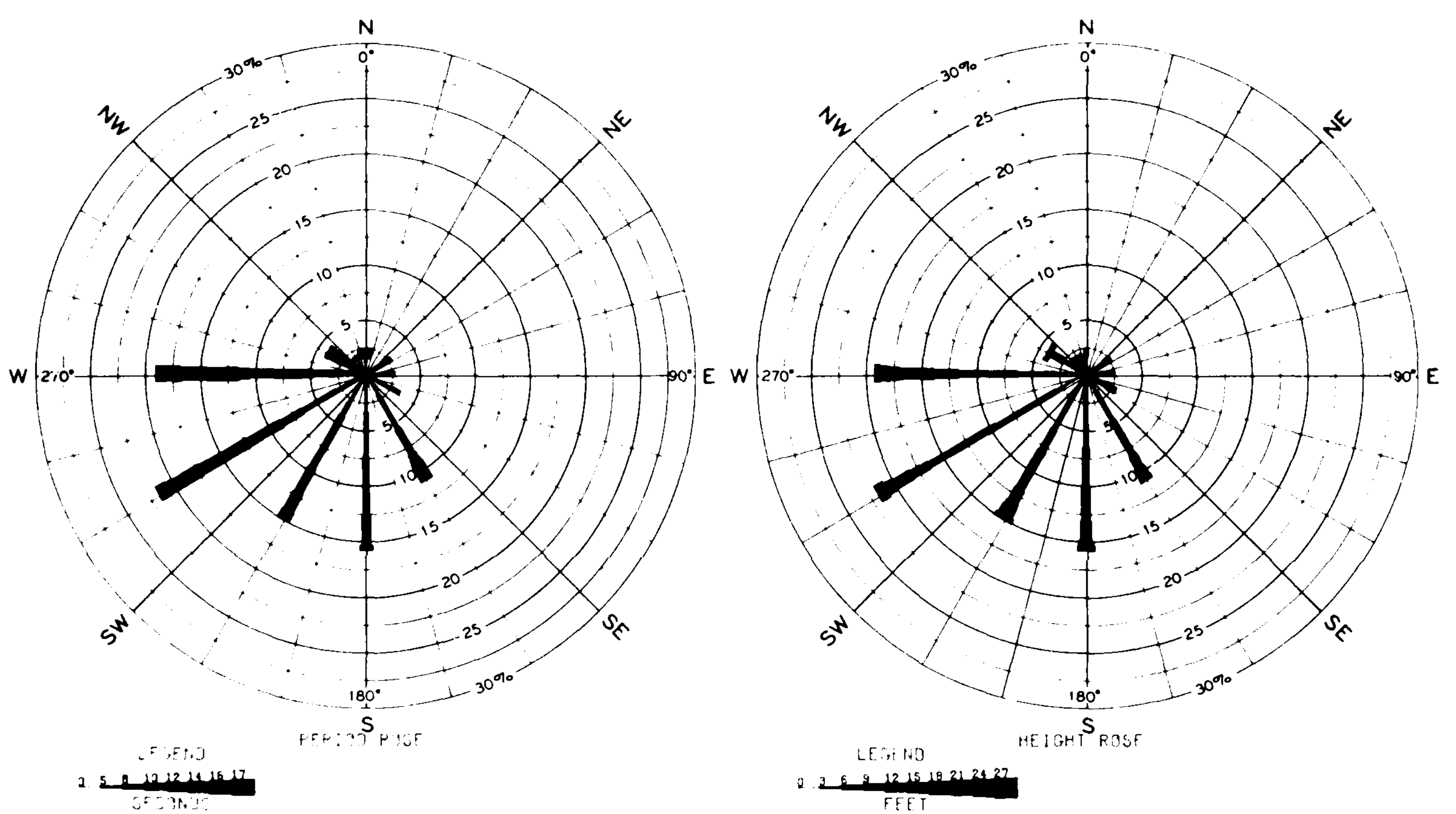
WAVE FREQUENCIES
STATION 2
ANNUAL

PLATE B1



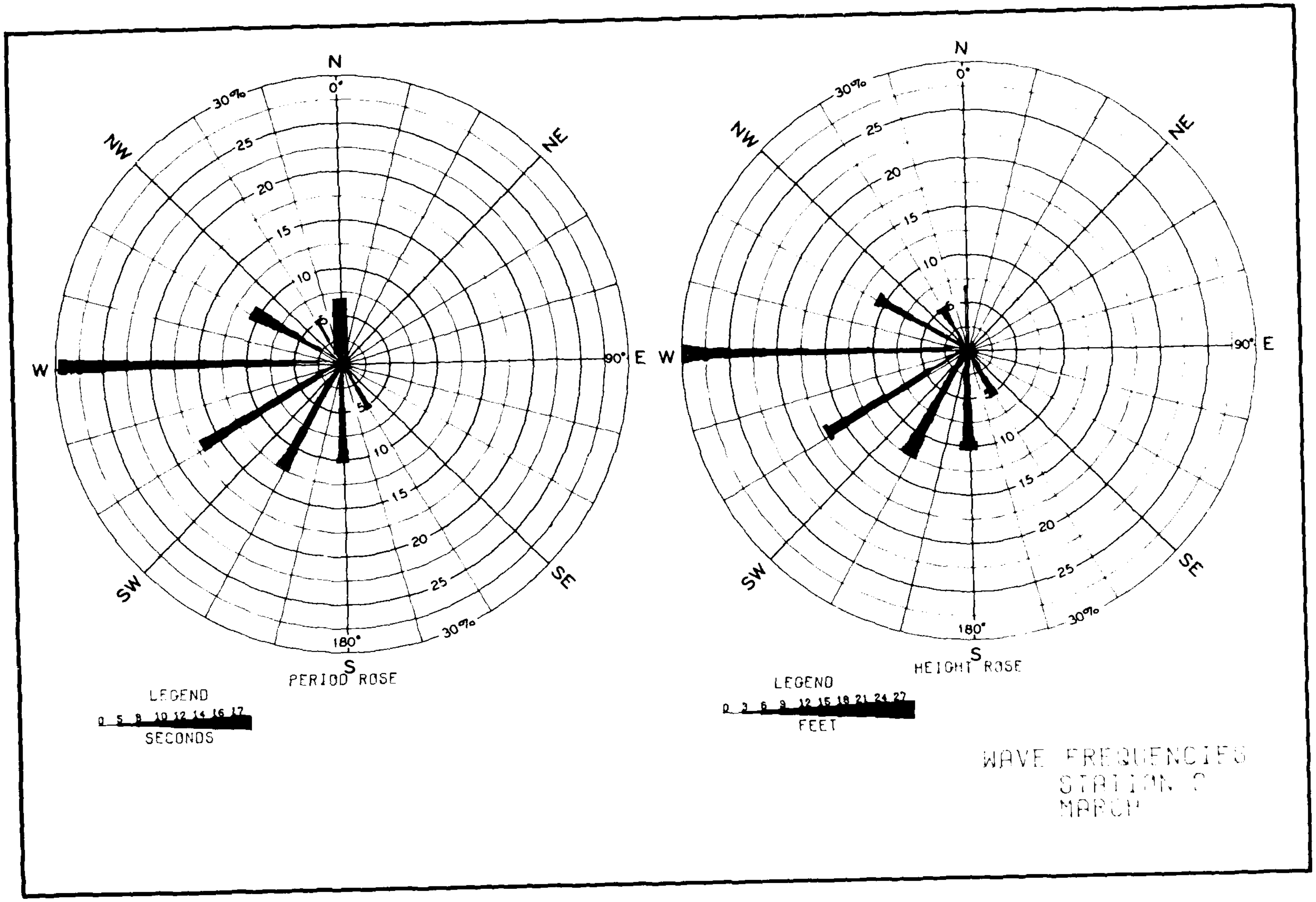
WAVE FREQUENCIES
STATION 2
JANUARY

PLATE B2



WAVE FREQUENCIES
STATION 2
FEBRUARY

PLATE B3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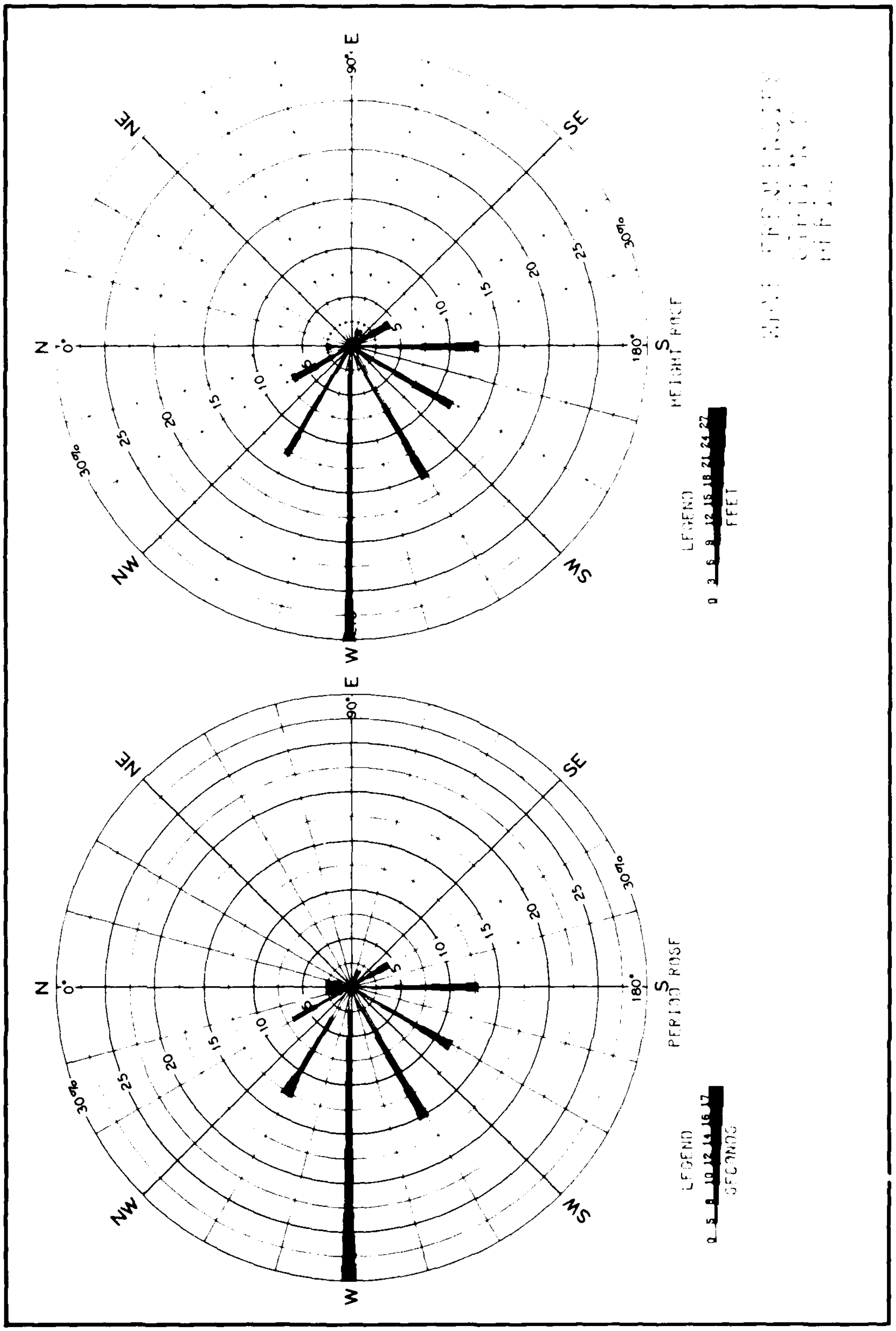
WAVE FREQUENCIES
STATION
MARCH

PLATE B4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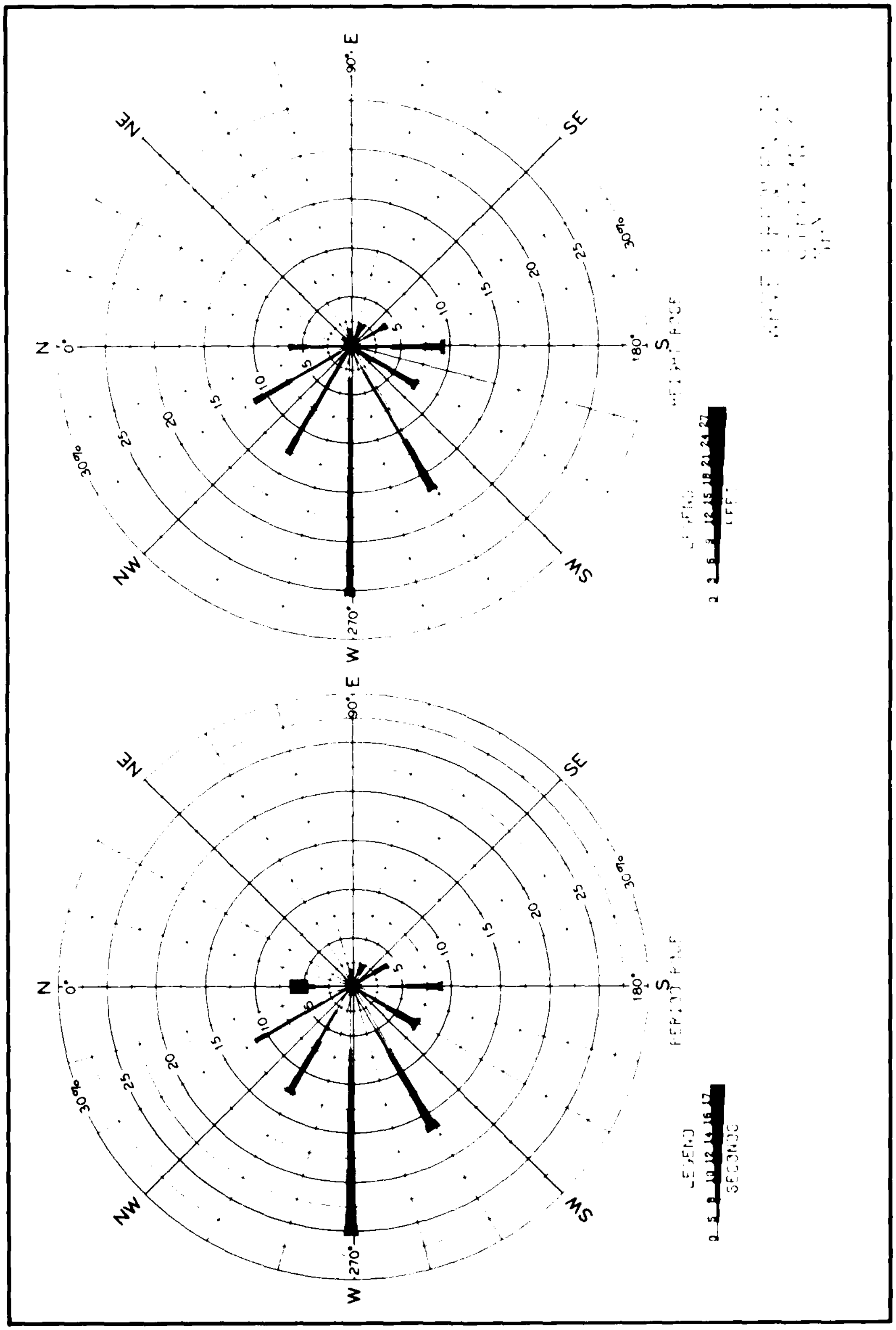

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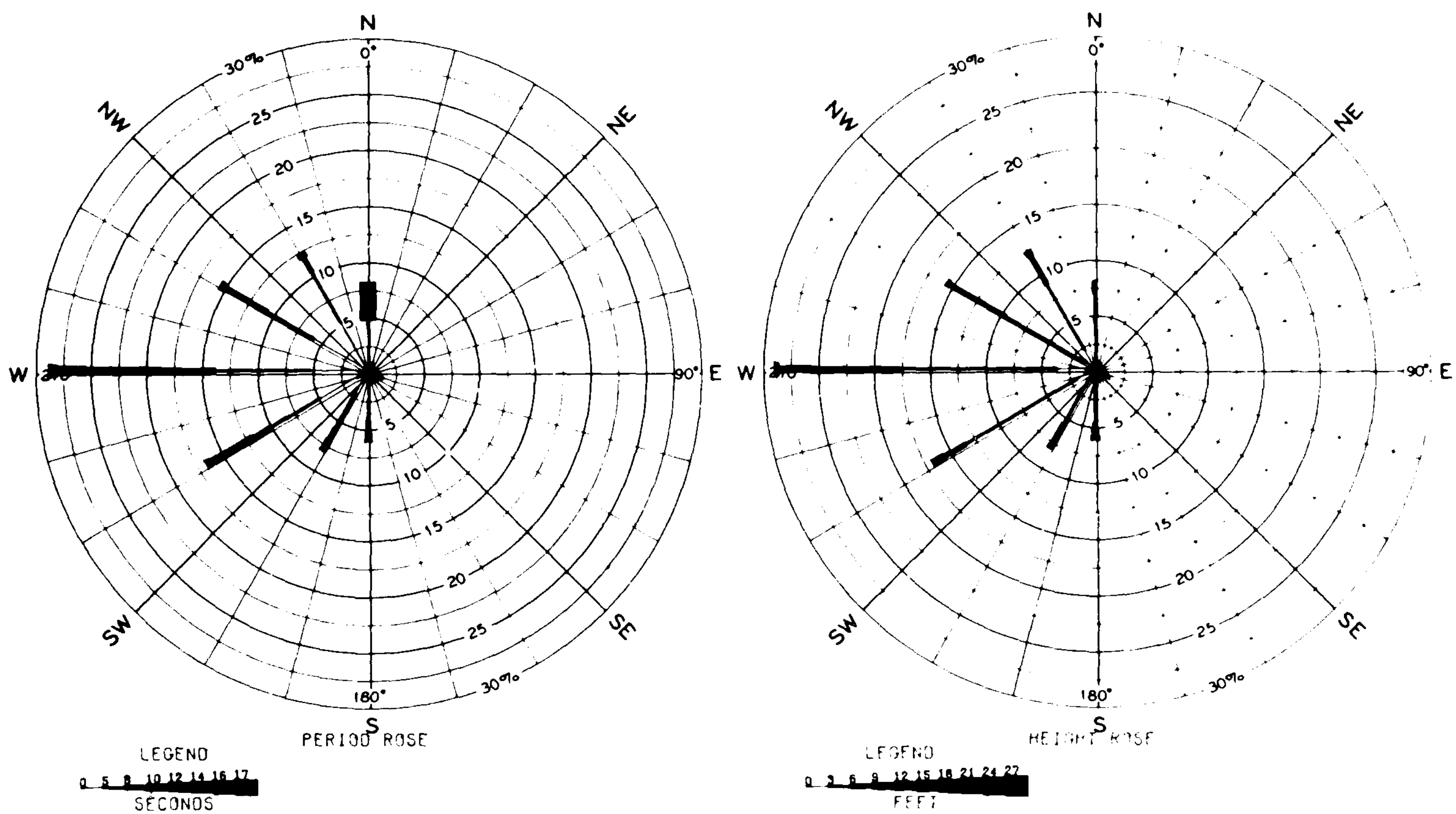
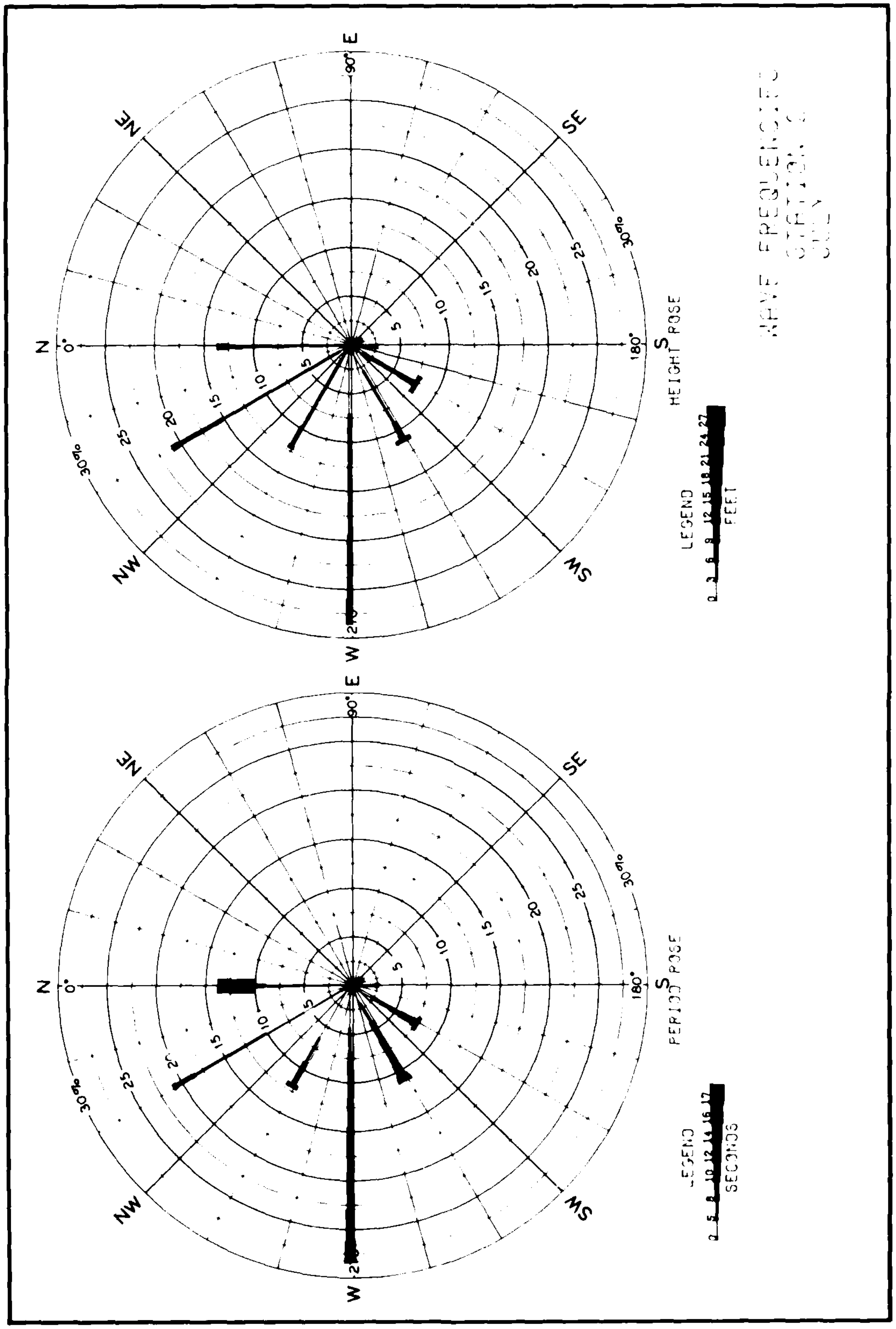
PLATE B6



WAVE FREQUENCIES
STATION
JUNE

PLATE B7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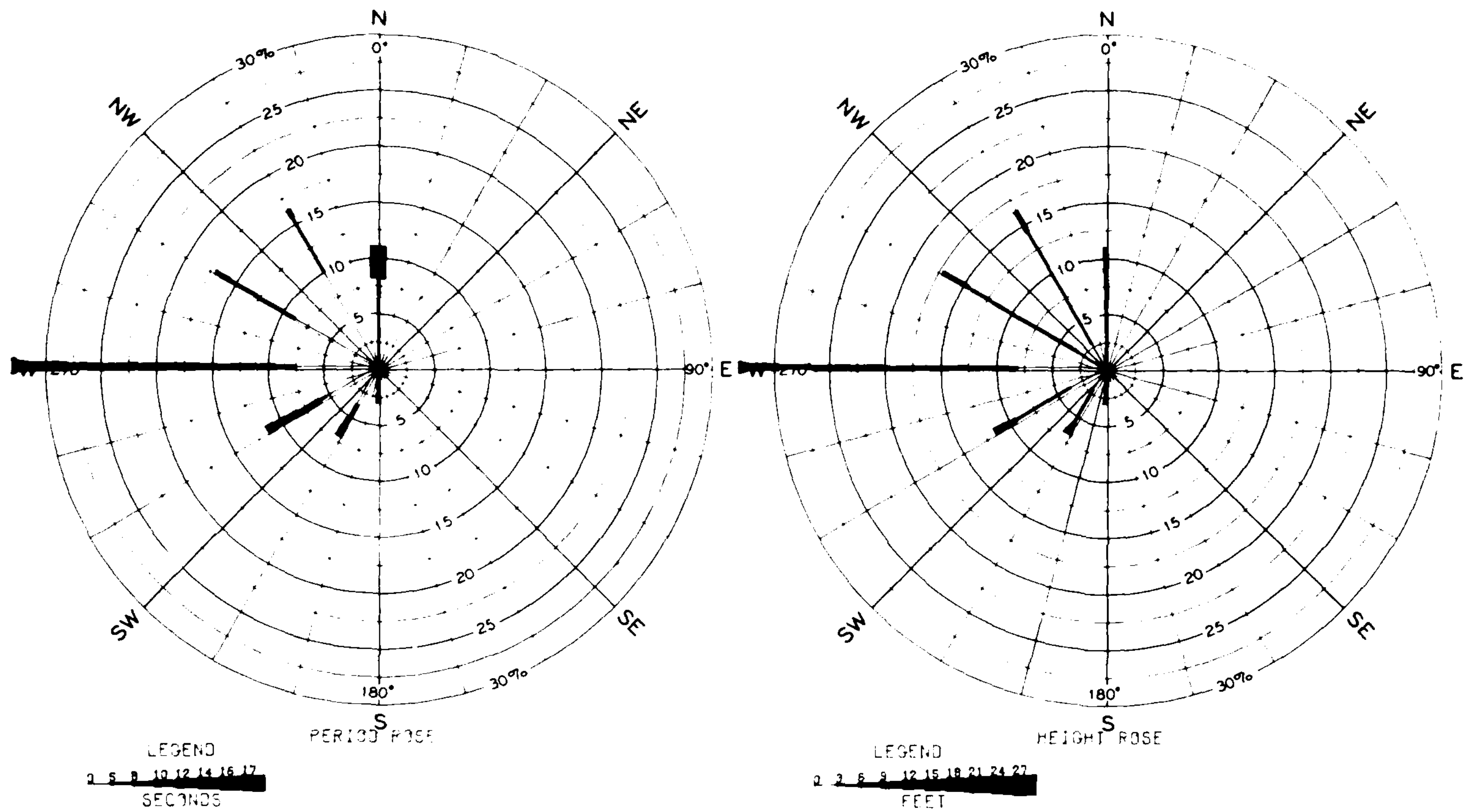
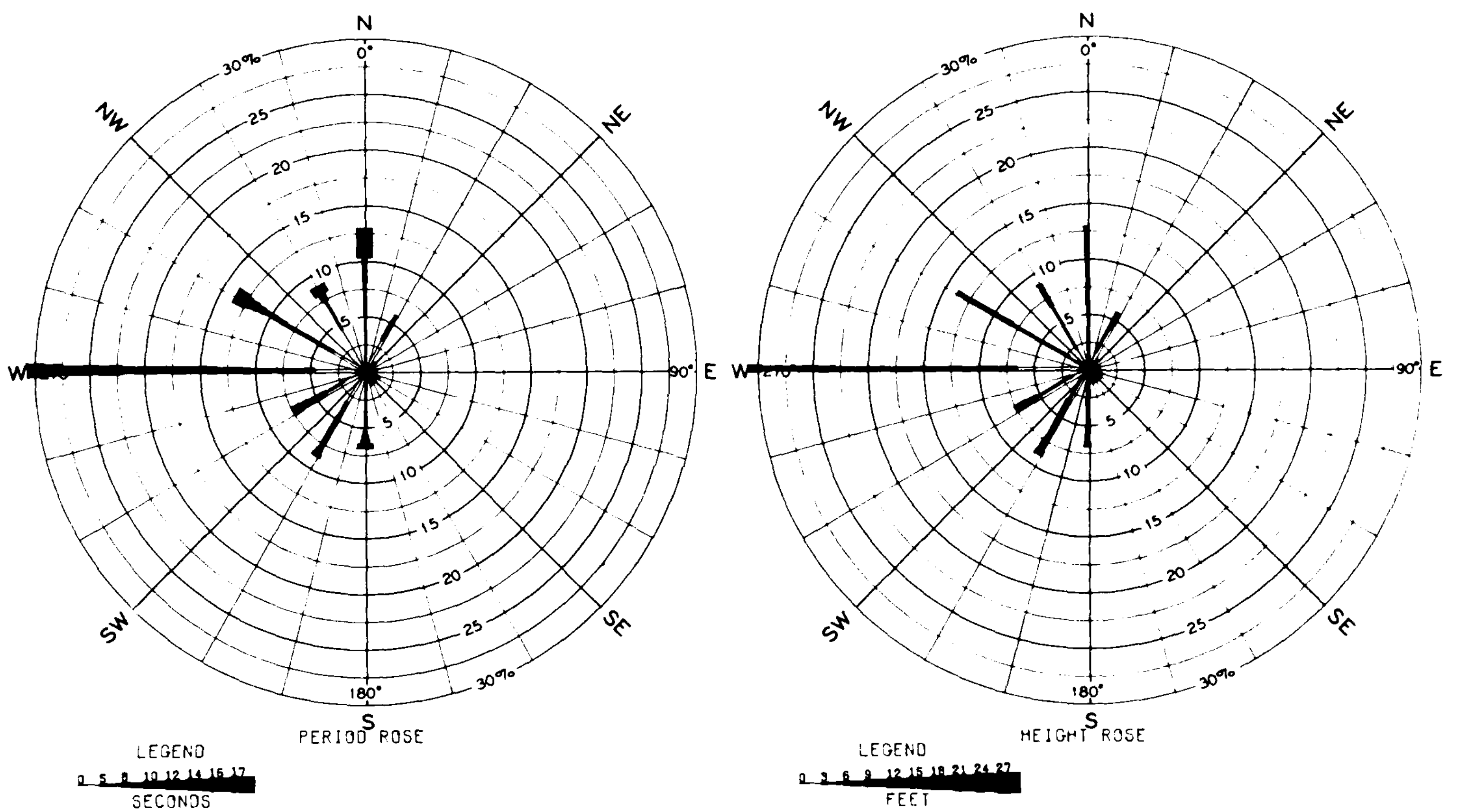
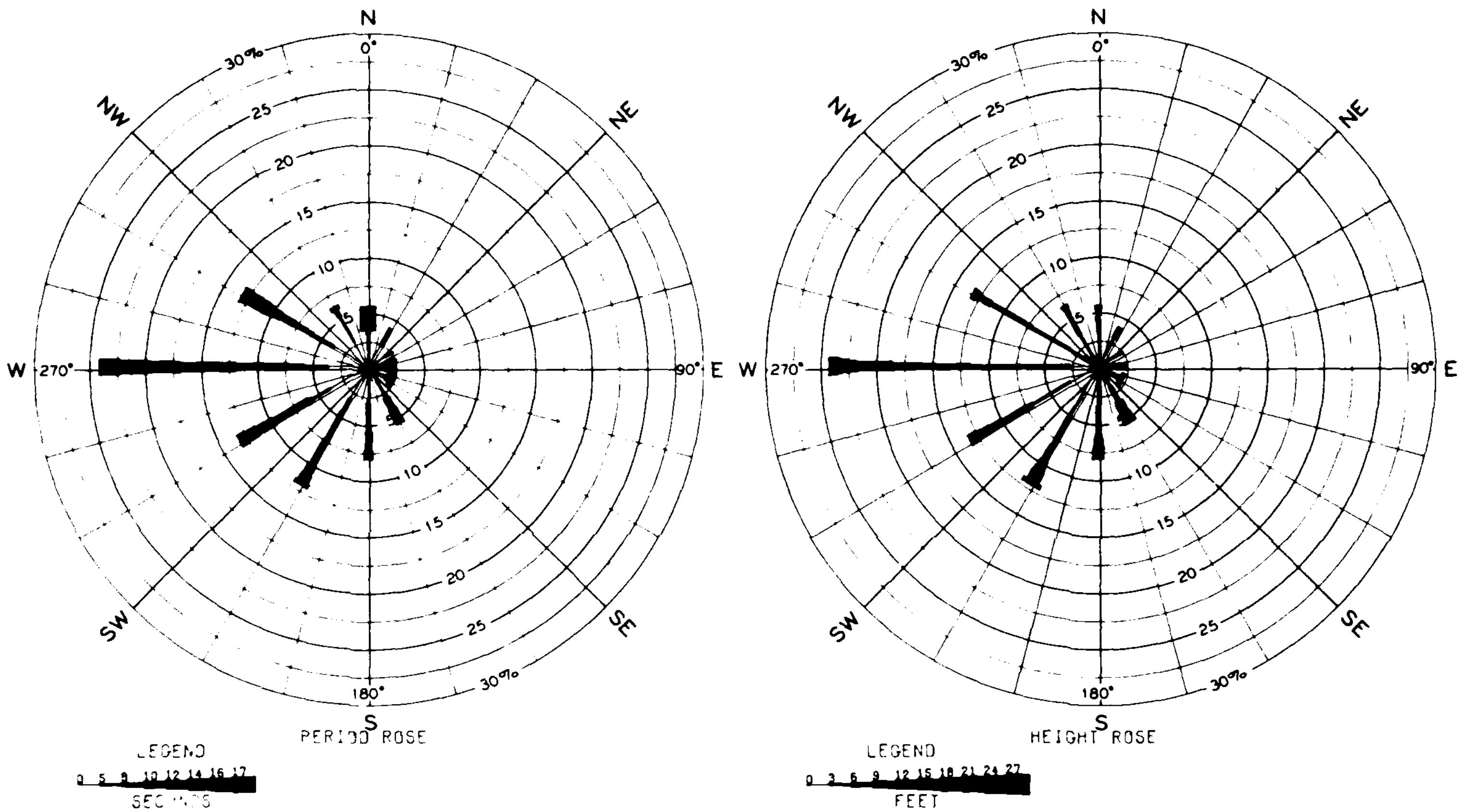


WAVE FREQUENCIES
STATION 2
AUGUST

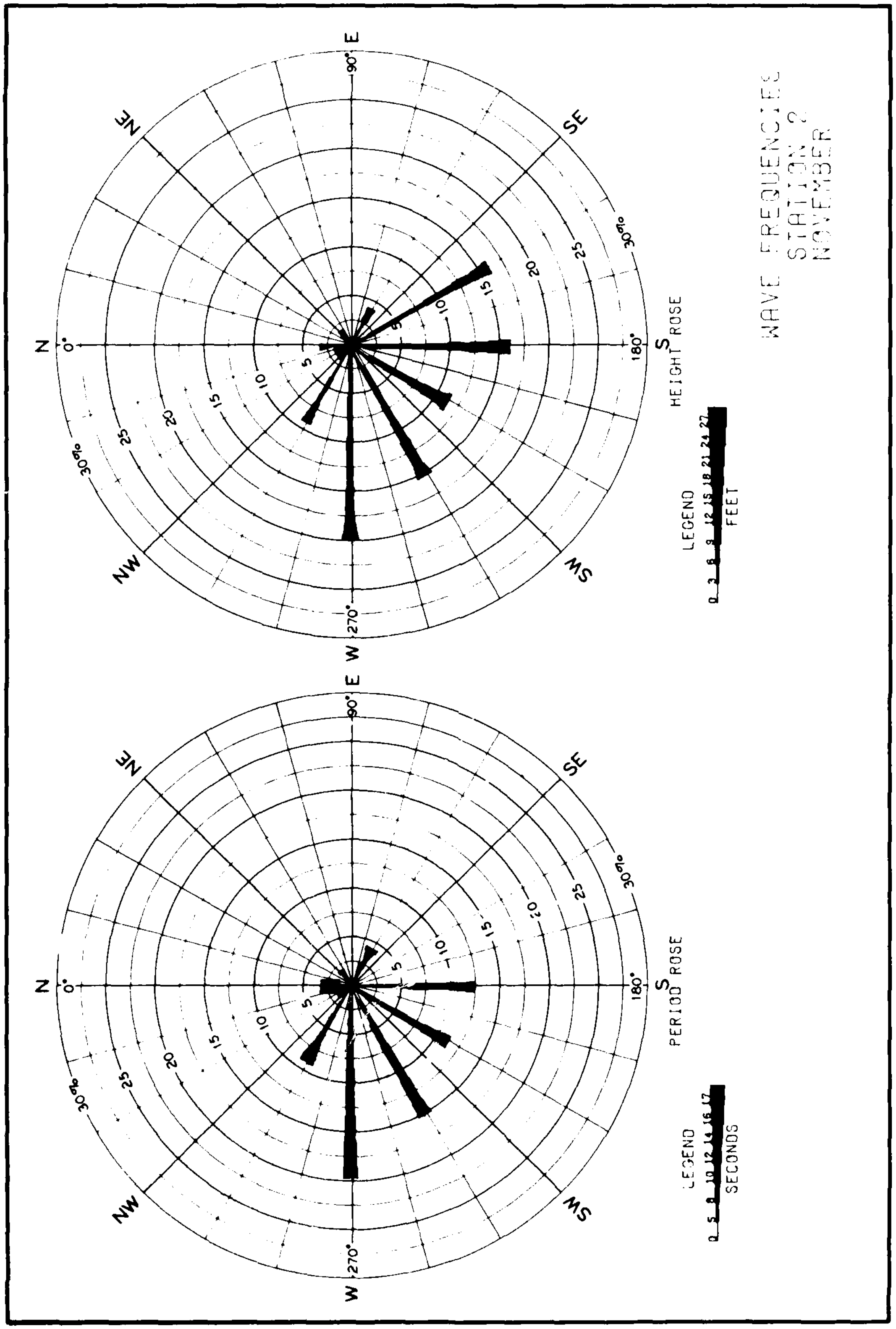


WAVE FREQUENCIES
STATION 2
SEPTEMBER

PLATE B10



WAVE FREQUENCIES
STATION 2
OCTOBER



WAVE FREQUENCIES
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PLATE B12

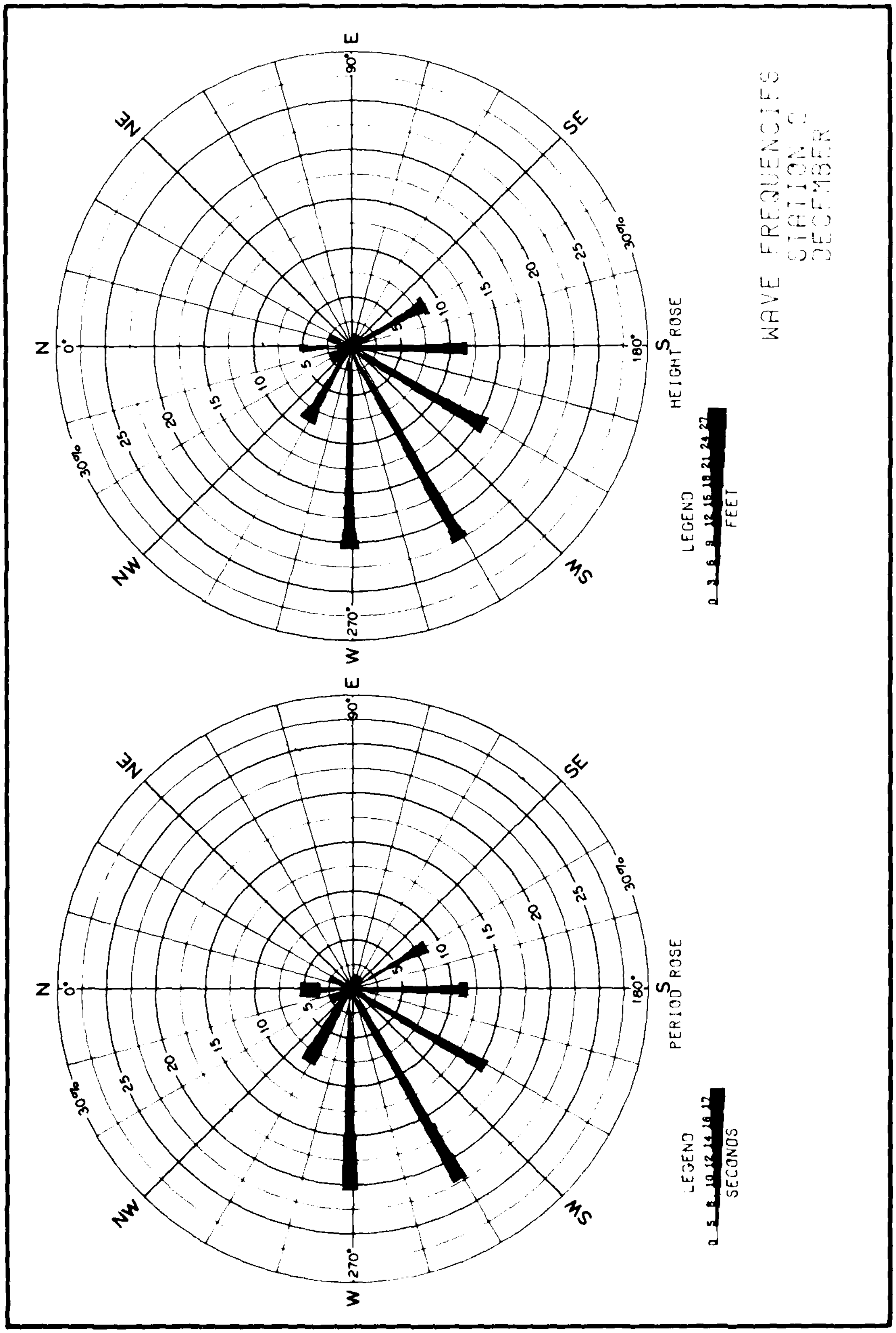
WAVE FREQUENCIES
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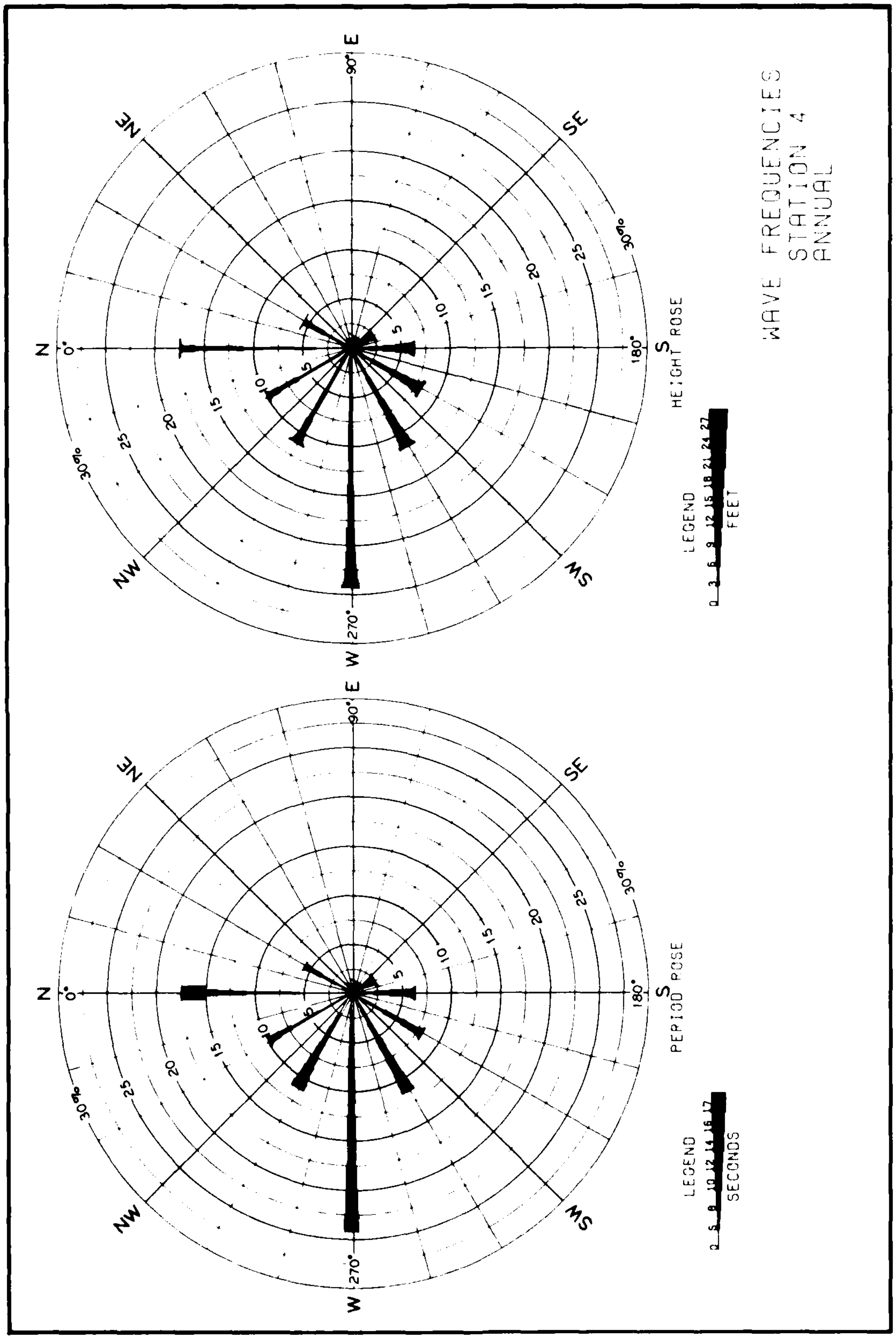
PLATE B13


WAVE FREQUENCIES
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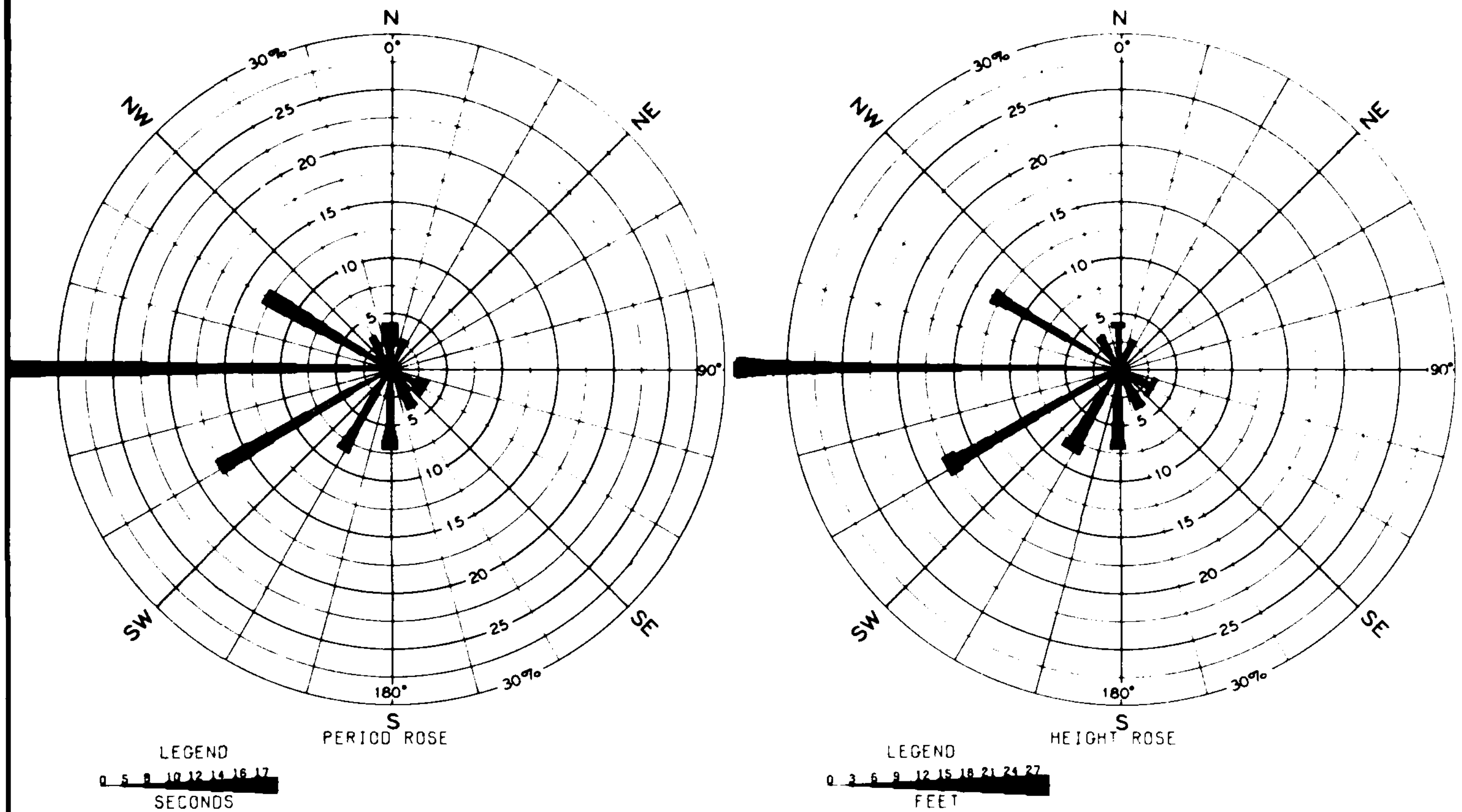
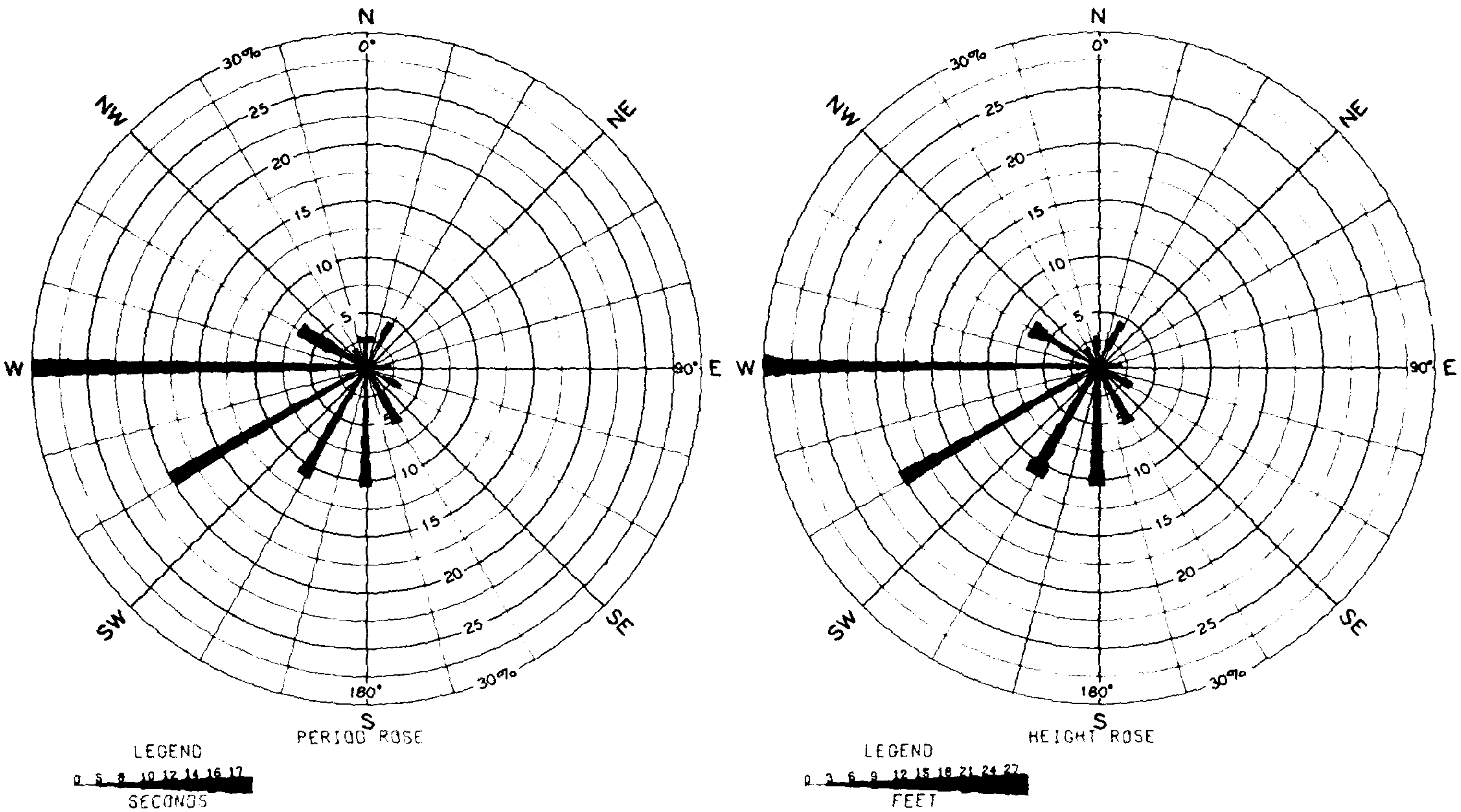
30%

PLATE B14

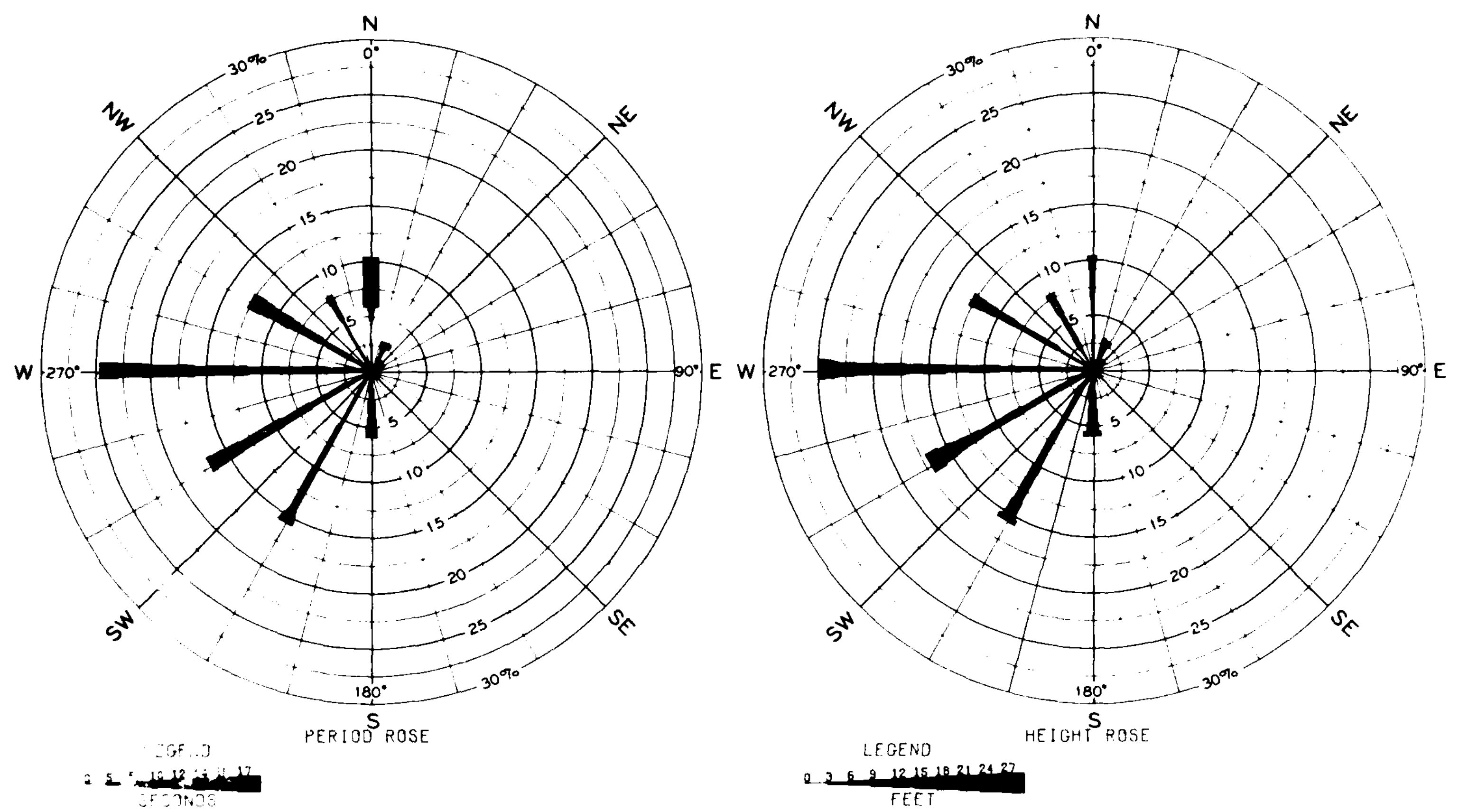


WAVE FREQUENCIES
STATION 4
JANUARY



WAVE FREQUENCIES
STATION 4
FEBRUARY

PLATE B16



WAVE FREQUENCIES
STATION 4
MARCH

PLATE B17

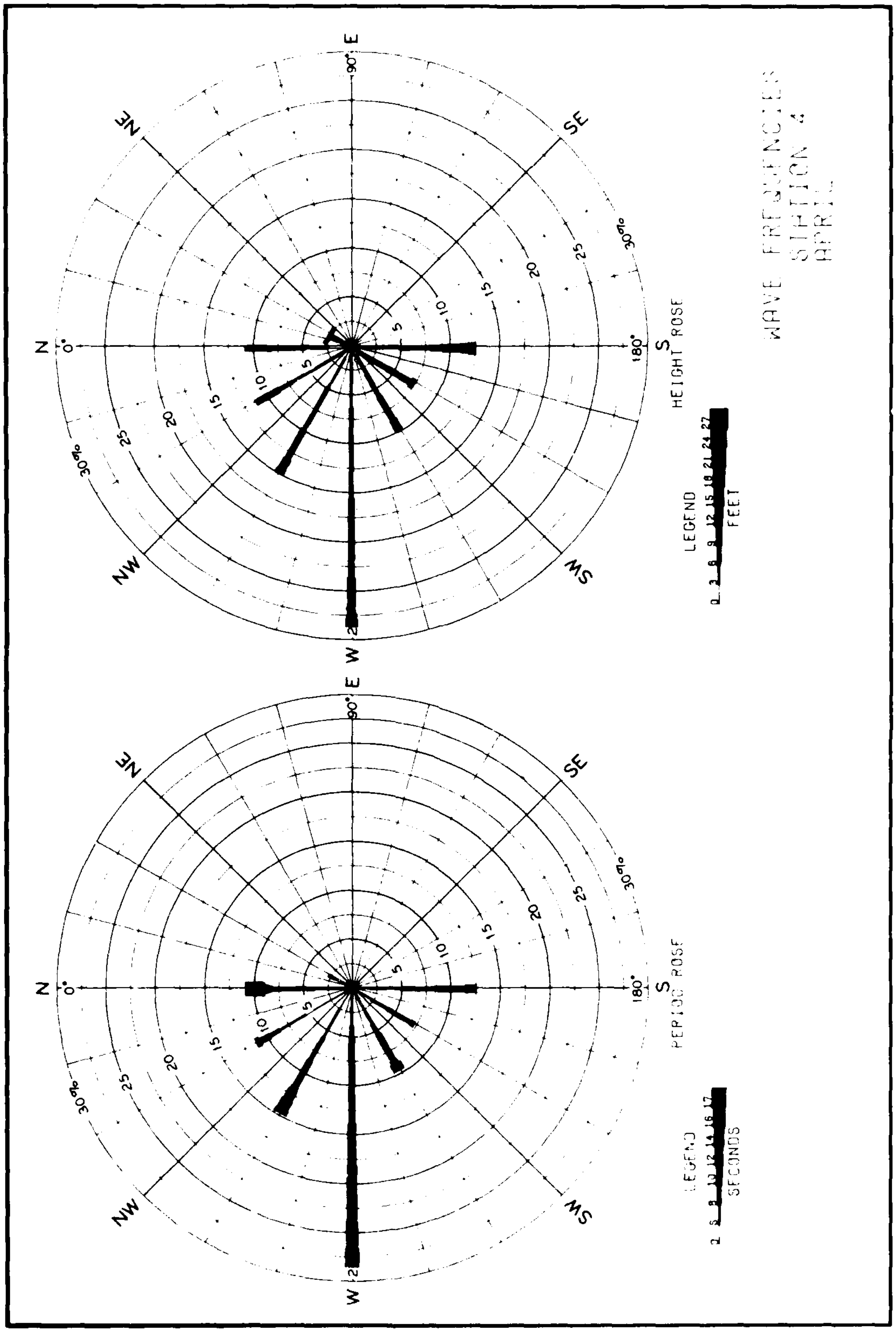
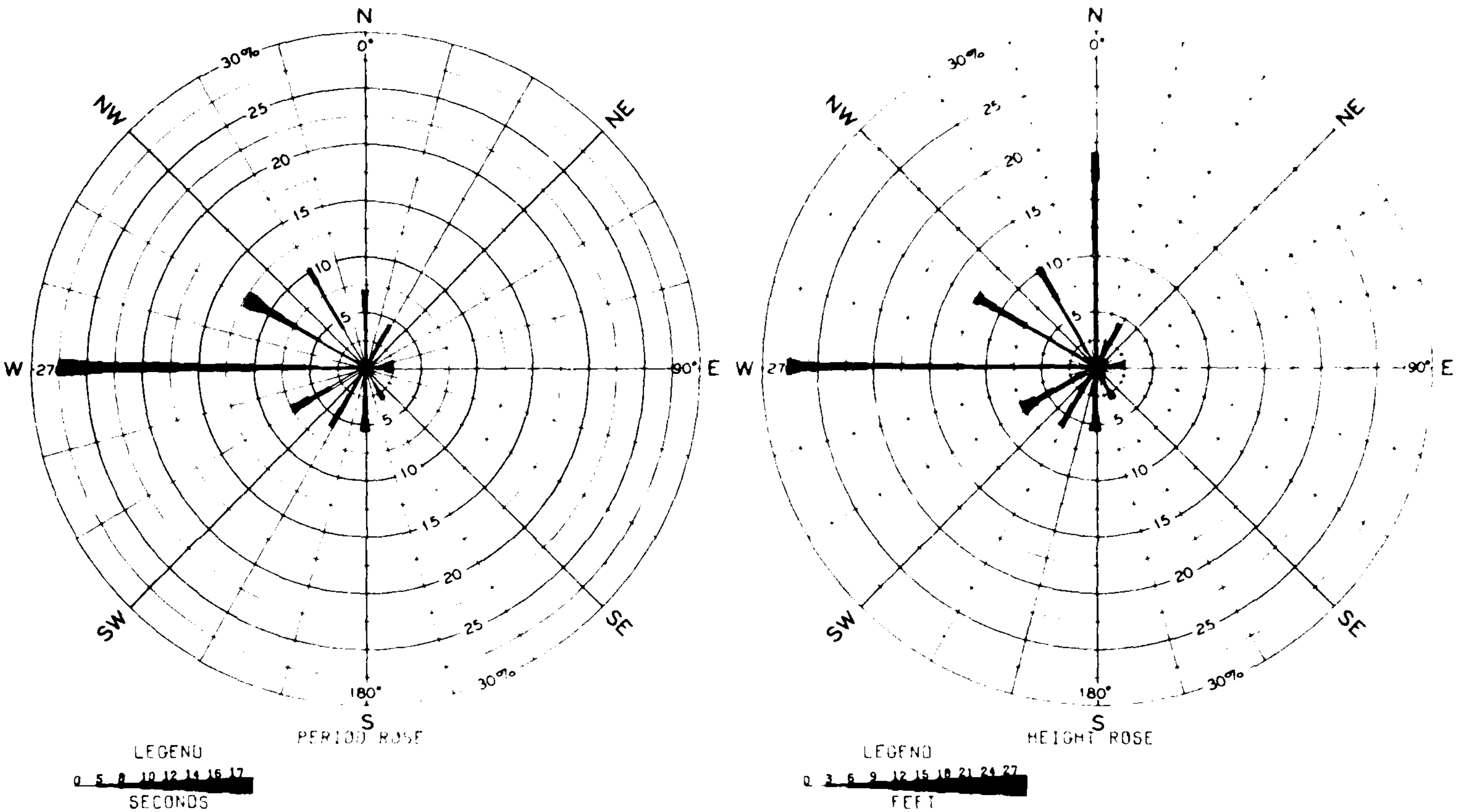

WAVE FREQUENCIES
STATION 4
APRIL
HEIGHT ROSE
LEGEND
0 2 6 9 12 15 18 21 24 27
FEET
PERIOD ROSE
LEGEND
SECONDS
N
NE
E
SE
S
SW
W
NW

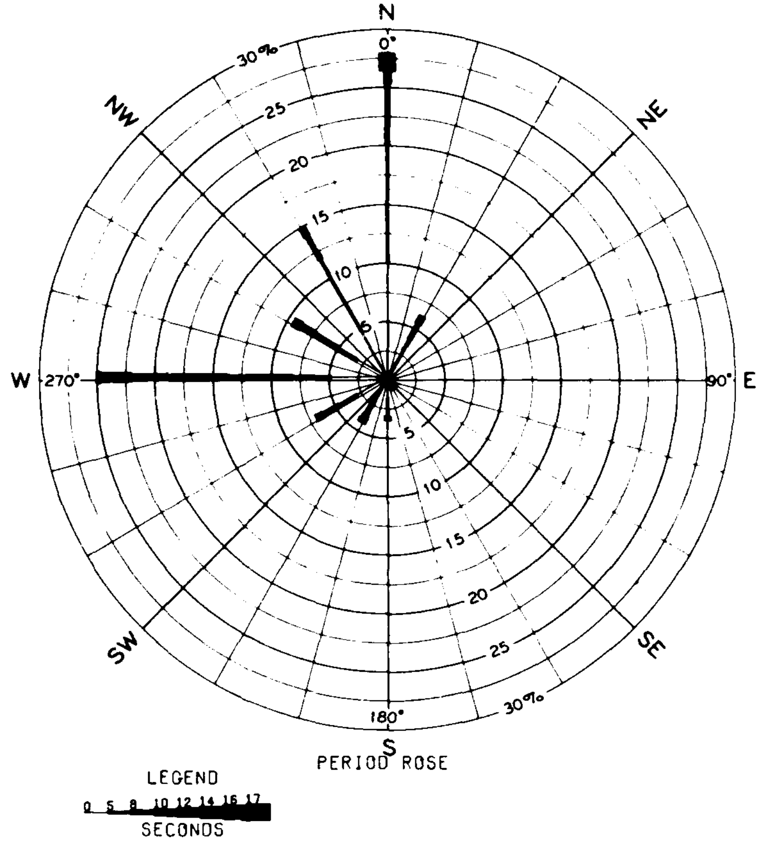
PLATE B18

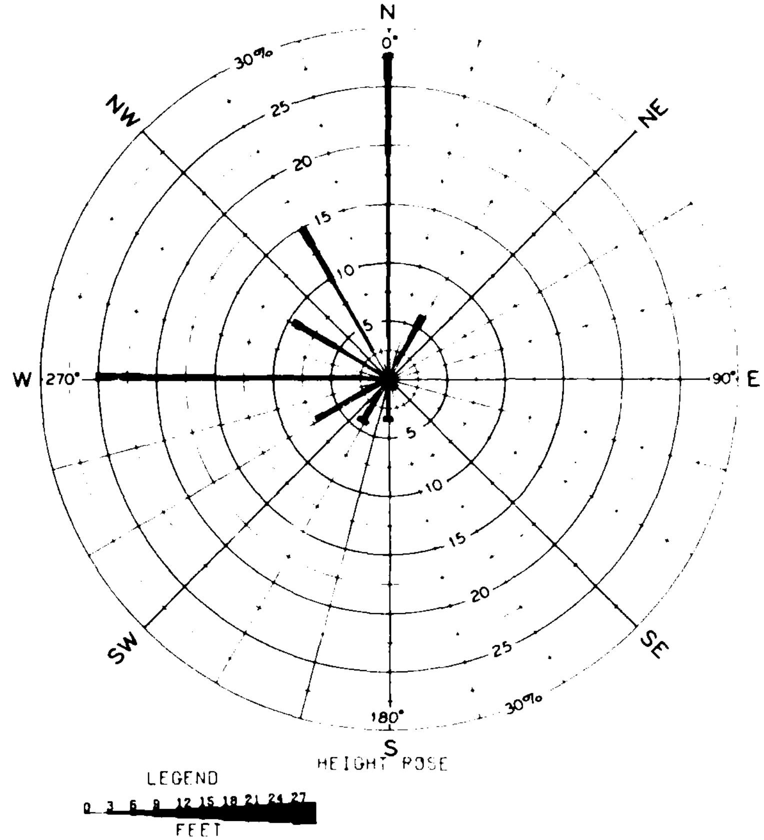


WAVE FREQUENCIES
STATION 4
MAY

PLATE B19

PLATE B20





WAVE FREQUENCIES
STATION 4
JUNE

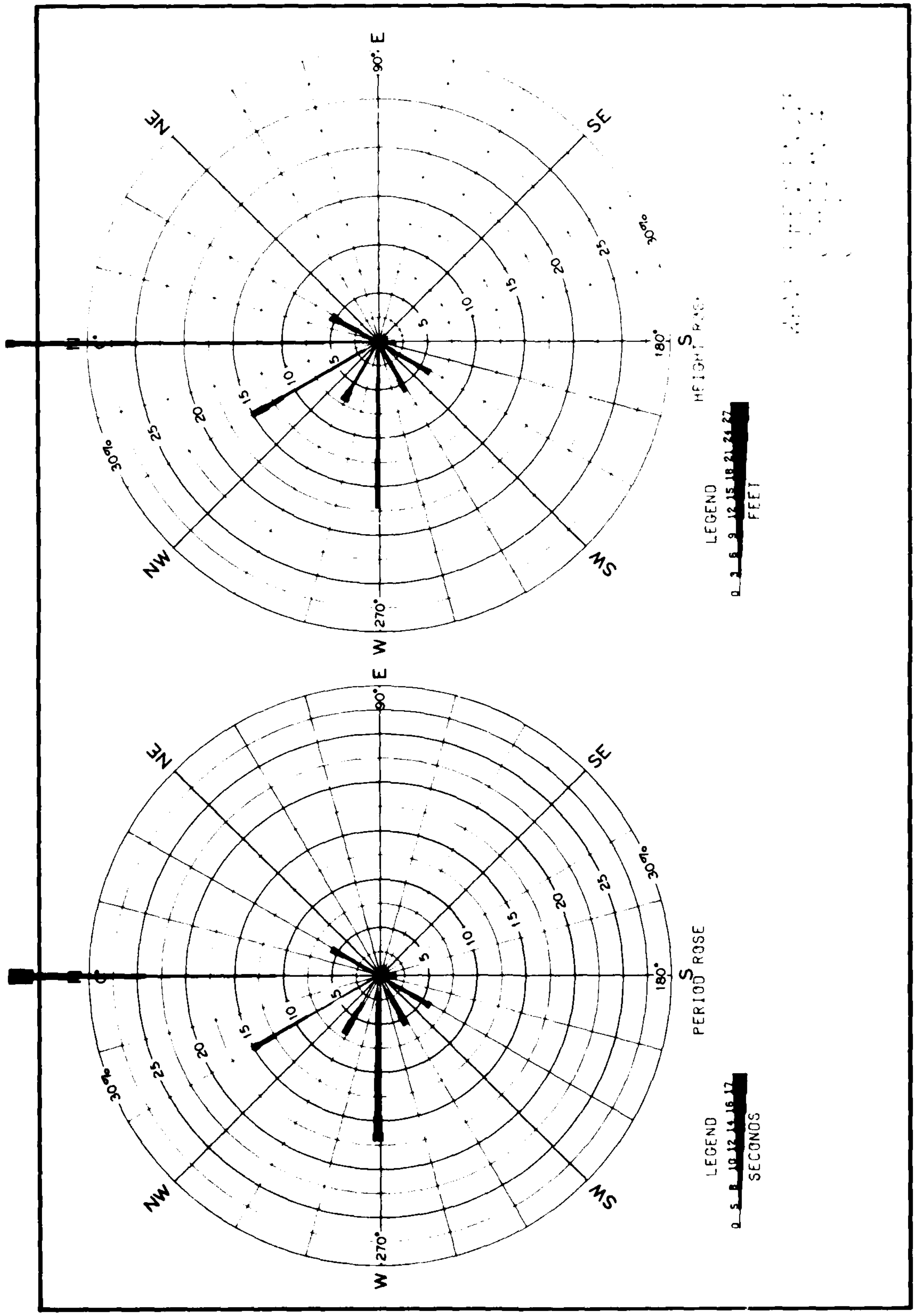
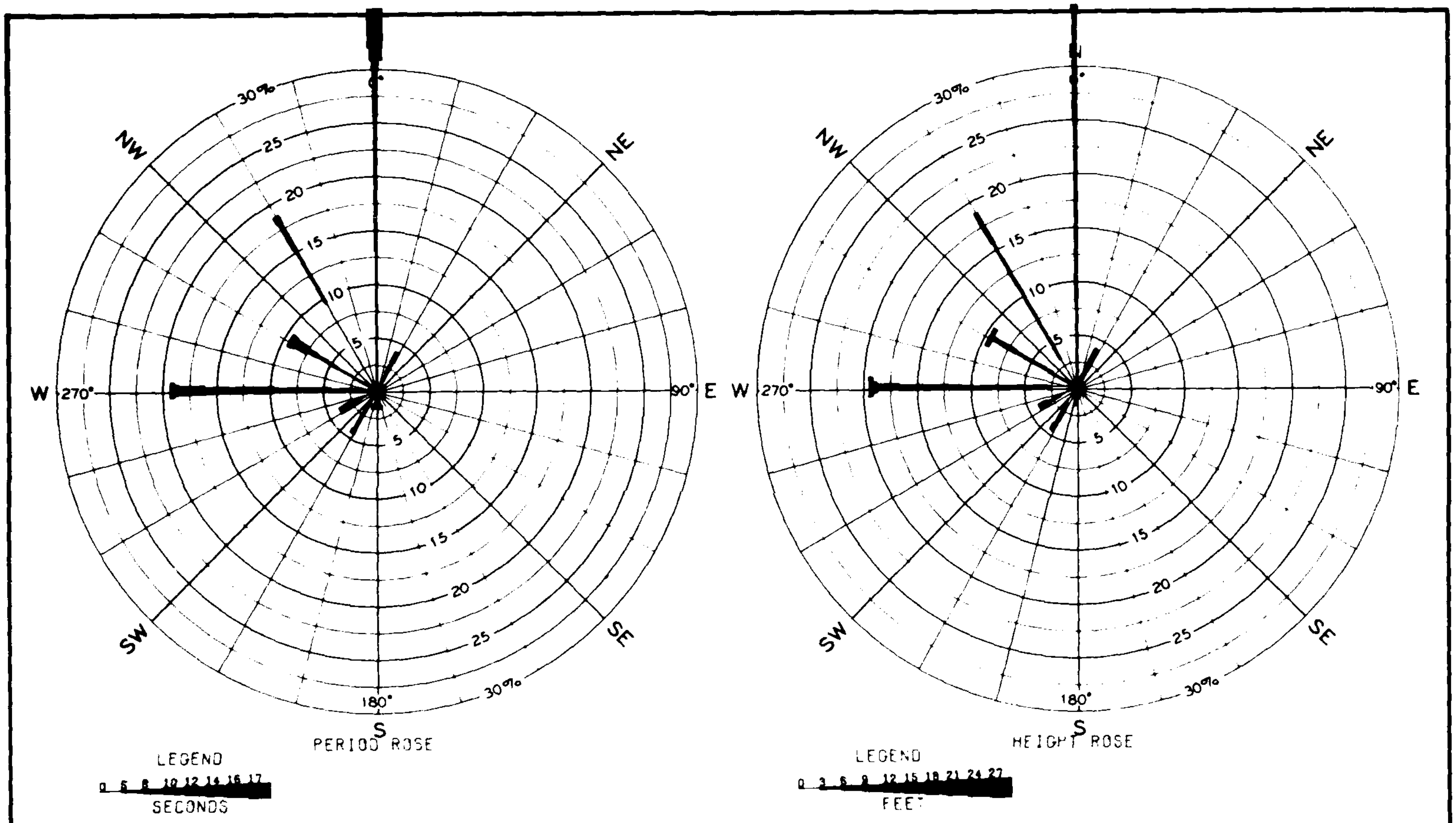
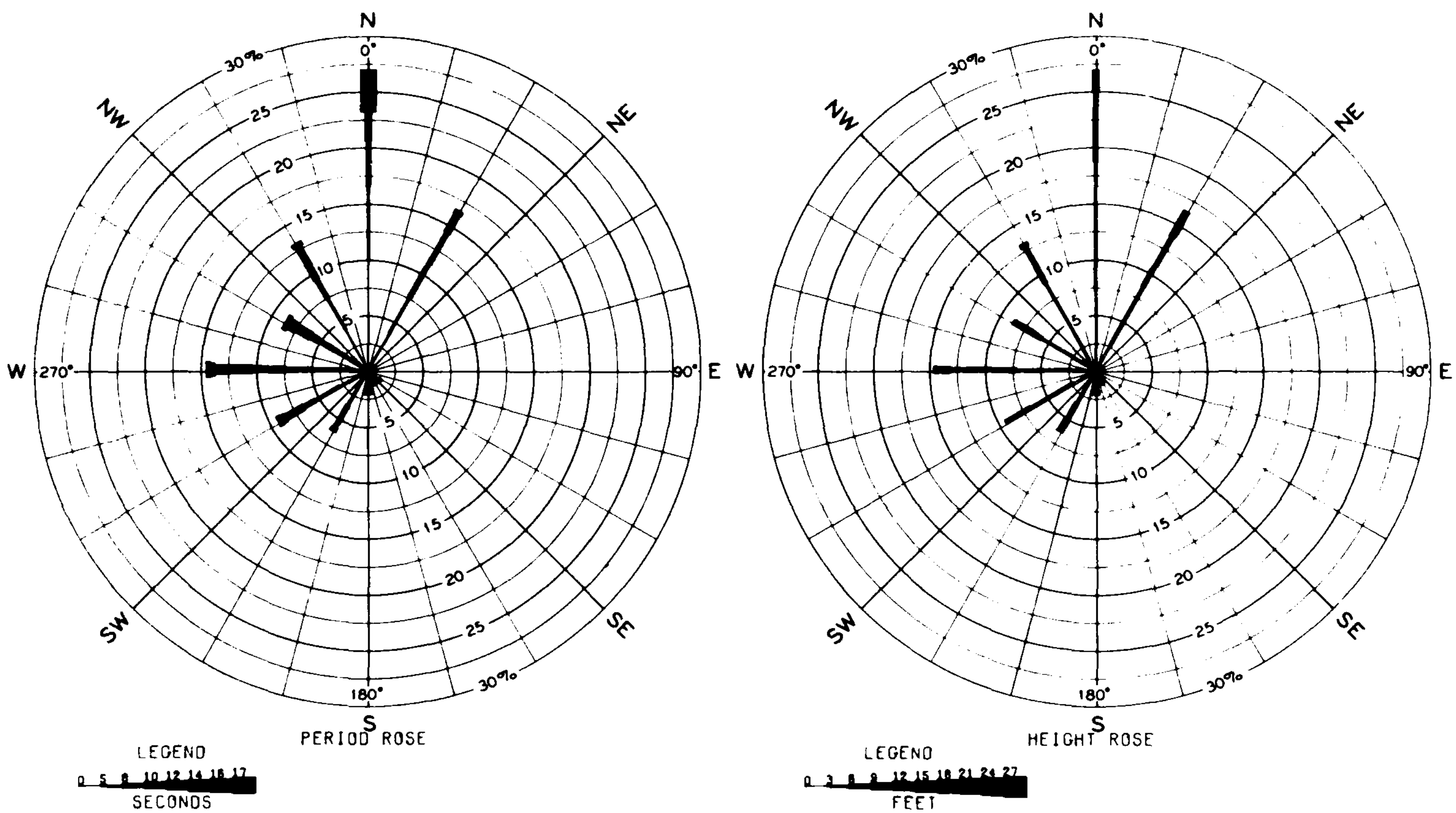

HEIGHT ROSE
LEGEND
0 3 6 9 12 15 18 21 24 27
FEET
PERIOD ROSE
LEGEND
0 5 8 10 12 14 16 17
SECONDS
NE
SE
SW
NW
90° E
180° S
270° W

PLATE B21

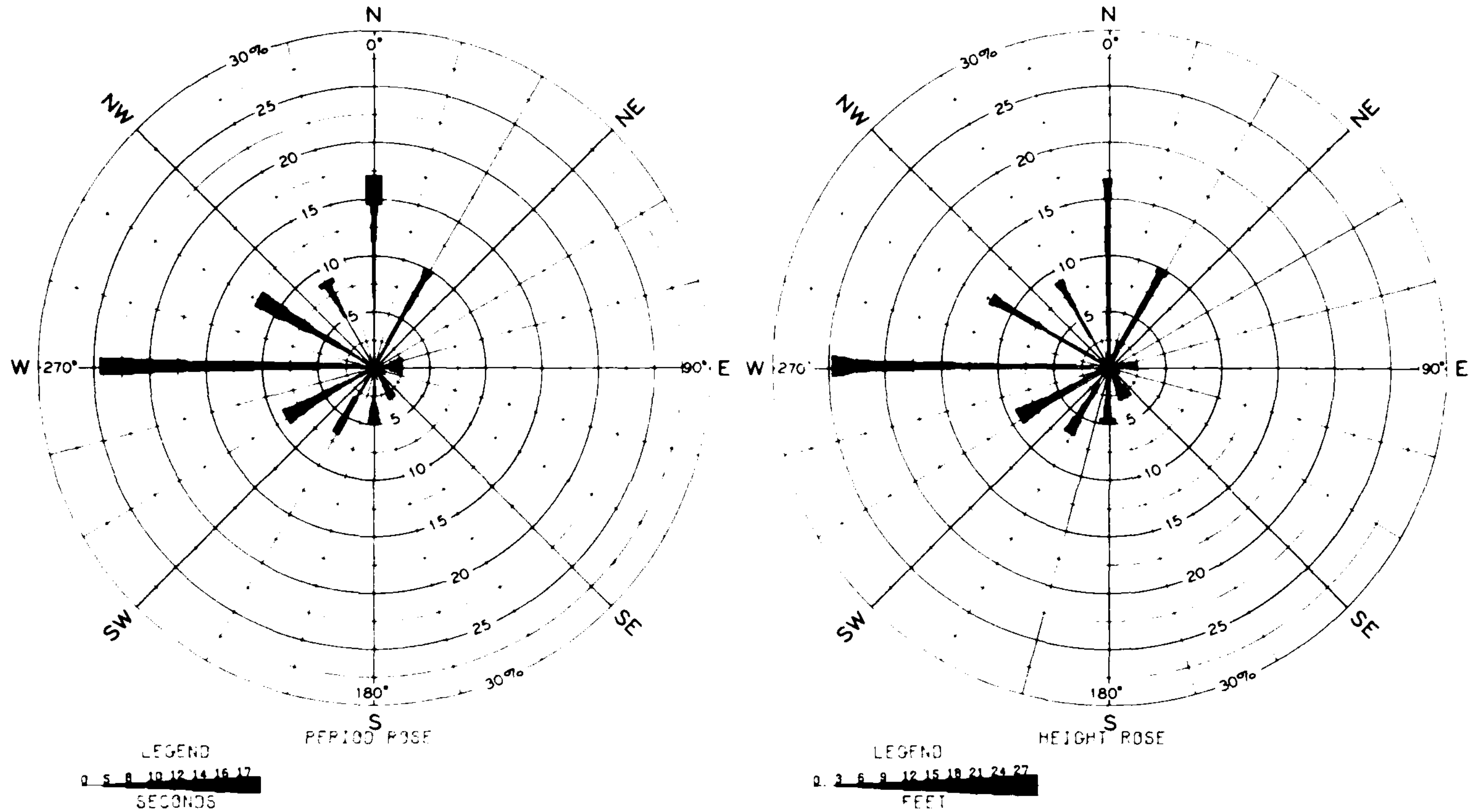


WAVE FREQUENCIES
STATION 4
AUGUST

PLATE B22

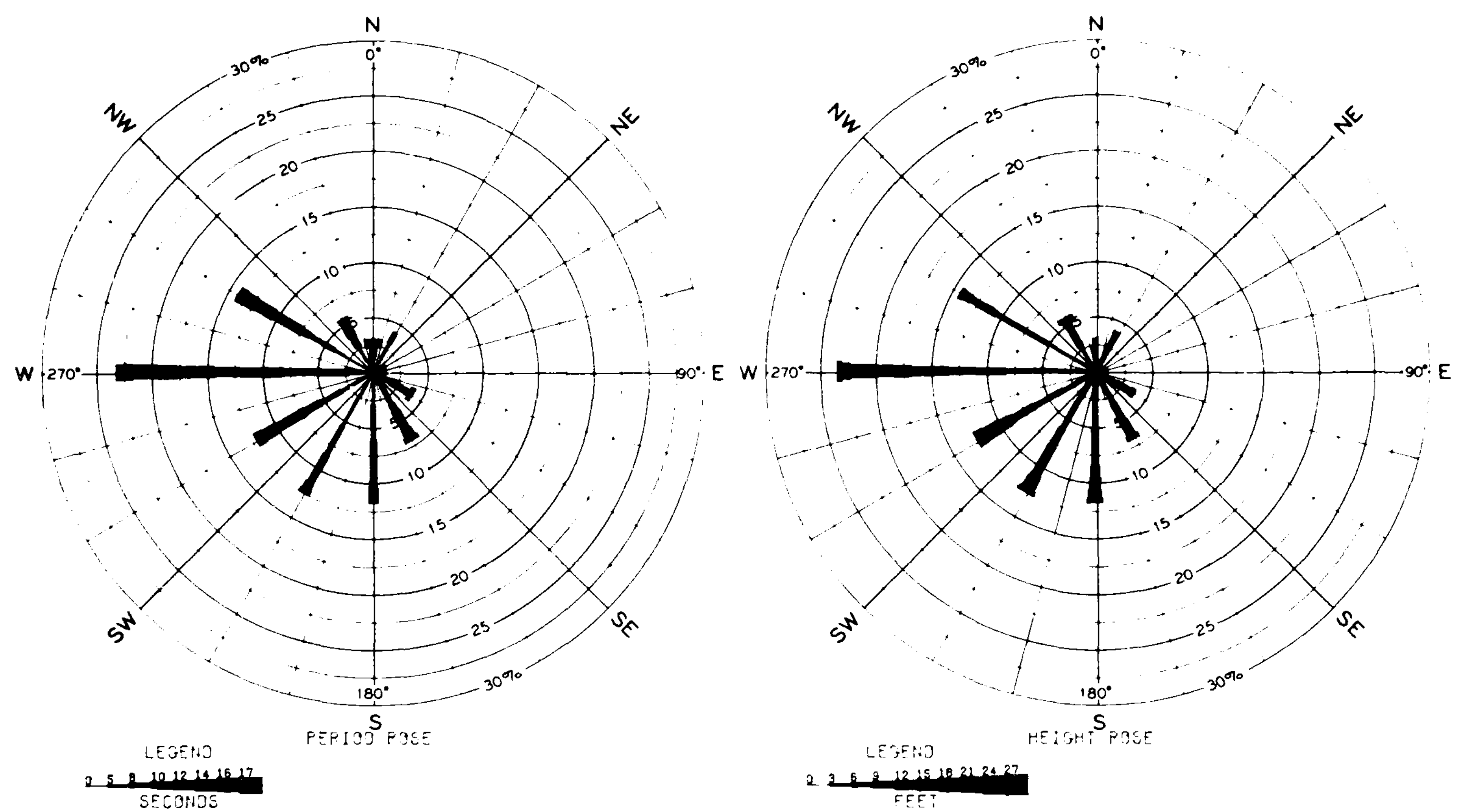


WAVE FREQUENCIES
STATION 4
SEPTEMBER



WAVE FREQUENCIES
STATION 4
OCTOBER

PLATE B24



WAVE FREQUENCIES
STATION 4
NOVEMBER

PLATE B25

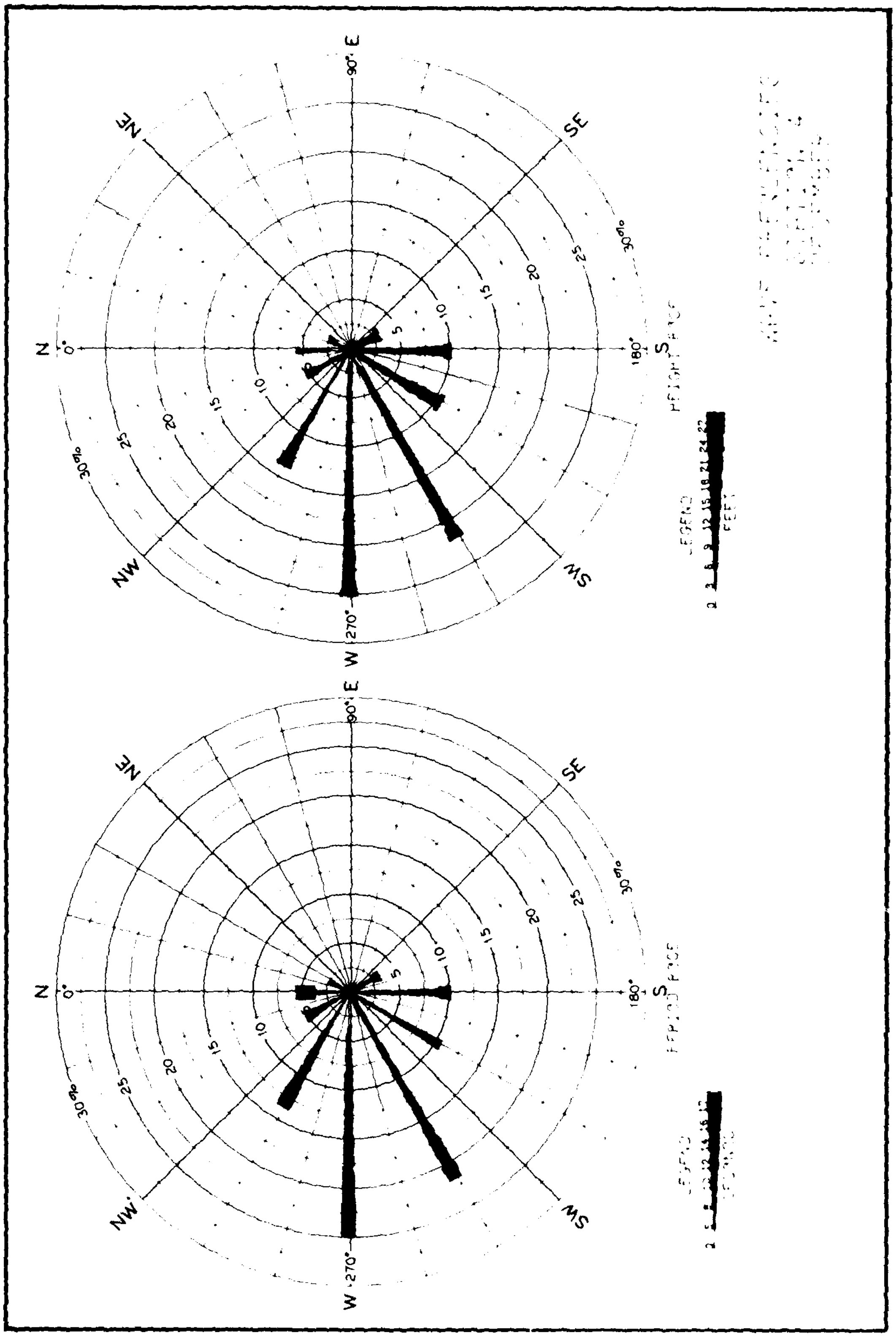


PLATE B26

APPENDIX C: NOTATION

a	An arbitrary constant
a_o	Elevation of the bottom
A	Sediment motion threshold factor
A_o	Wave orbital excursion length
b	An arbitrary constant
c	An arbitrary constant
C	Chezy roughness coefficient; concentration of sediment
C_{Ld}	Response time coefficient for deposition
C_{Le}	Response time coefficient for erosion
D	Sediment particle diameter
D_{gr}	Dimensionless grain size
D_x	Dispersion coefficient in x direction
D_z	Dispersion coefficient in z direction
E	Energy
f	Wave frequency
f_c	Shear stress coefficient for currents
fm	Maximum wave frequency
f_w	Shear stress coefficient for waves
F_{gr}	Sediment mobility factor
g	Acceleration due to gravity
G_p	Sediment transport rate expressed as an effective concentration
h	Water depth
H	Wave height
L	Wavelength
m	Factor in Ackers-White transport function
n	A coefficient expressing the relative importance of bed-load and suspended-load transport
R	Rate of sediment deposition or erosion
s	Specific gravity of the sediment
t	Time
t_c	Time constant
T	Wave period
u	Horizontal flow velocity in the x direction
u_{om}	Maximum wave orbital velocity near the bed

U	Average flow velocity; current speed
v	Velocity
vh	Unit discharge
V_a	Wind velocity
V_s	Sediment settling velocity
w	Horizontal flow velocity in the z direction
x	Distance in the x direction (longitudinal)
z	Distance in the z direction (lateral)
α	Phillip's equilibrium coefficient ($\approx 7.4 \times 10^{-3}$)
α_1	Coefficient of concentration dependent source/sink term
α_2	Coefficient of source/sink term
ε_{xx}	Normal turbulent exchange coefficient in the x direction
ε_{xz}	Tangential turbulent exchange coefficient in the x direction
ε_{zx}	Tangential turbulent exchange coefficient in the z direction
ε_{zz}	Normal turbulent exchange coefficient in the z direction
Δt	Computational time-step
ν	Kinematic viscosity
ω	Angular rate of earth's rotation
ϕ	Latitude
ψ	Angle between wind direction and x axis
ρ	Fluid density
τ	Total boundary shear stress
τ'	Bottom boundary shear stress corresponding to a plane bed
τ'_{wc}	Combined shear stress due to combined waves and currents over a plane bed
θ	Wave direction
θ_o	Mean direction via ray tracing
ξ	Coefficient relating wind speed to stress exerted on the fluid

LMED

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