TECHNICAL REPORT HL-90-21

US Army Corps of Engineers

CUMBERLAND SOUND AND KINGS BAY PRE-TRIDENT AND BASIC TRIDENT CHANNEL HYDRODYNAMIC AND SEDIMENT TRANSPORT HYBRID MODELING

VOLUME II

APPENDIX B

by

William H. McAnally, Jr., Mitchell A. Granat

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

April 1991

Final Report

Prepared for Officer in Charge of Construction
TRIDENT
DEPARTMENT OF THE NAVY
Naval Facilities Engineering Command
St. Marys, Georgia 31558-0768

and Naval Submarine Base
Kings Bay, Georgia 31547

HYDRAULICS LABORATORY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1991

3. REPORT TYPE AND DATES COVERED
Final report in 2 vols.

4. TITLE AND SUBTITLE
Cumberland Sound and Kings Bays, Pre-Trident and Basic Trident Channel Hydrodynamic and Sediment Transport Hybrid Modeling; Volume II: Appendix B

5. FUNDING NUMBERS

6. AUTHOR(S)

William H. McAnally, Jr., Mitchell A. Granat

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

USAE Waterways Experiment Station, Hydraulics Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report HL-90-21

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Officer in Charge of Construction, TRIDENT, DEPARTMENT OF THE NAVY, Naval Facilities Engineering Command, St. Marys, GA 31558-0768

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Volume I of this report was previously published under separate cover. Copies of both volumes are available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release: distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A previously verified hybrid modeling system (coupled physical and numerical models) of the Kings Bay/Cumberland Sound estuarine system was used to investigate hydrodynamic and sedimentation variations associated with Trident channel expansion. Although not an explicit objective of the modeling efforts, tidal effects were examined. The tested plan condition was predicted by the models to result in higher high-water and midtide level elevations in both physical and numerical models. Variations were close to, but greater than, model detection limits. Comparison of low-water elevations between the models was inconsistent.

This appendix specifically addresses the issue of tidal changes in a compact format. Pertinent information is compared with field observations and analytical considerations.

Based on the presented information, it is concluded that tide range will probably not change as a result of Trident channel improvements. Mean water

(Continued)

14. SUBJECT TERMS

Analytical treatment
Channel deepening
Cumberland Sound/Kings Bay (Georgia)
Hybrid model
Mean tide level
Water level change

15. NUMBER OF PAGES
77

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

13. (Concluded).

level in Cumberland Sound may increase a small amount, less than the normal annual variation in mean sea level. It will be extremely difficult to detect any change until data have been collected for several years.

APPENDIX B: TIDES IN CUMBERLAND SOUND, GEORGIA, BEFORE AND AFTER ENLARGEMENT OF THE KINGS BAY NAVAL BASE CHANNELS

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

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

Multiply	By	To Obtain
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609347	kilometres
pounds (force)-second per square foot	47.88026	pascals-second
square feet	0.09290304	square metres
square miles	2.589988	square kilometres

APPENDIX B: TIDES IN CUMBERLAND SOUND, GEORGIA, BEFORE AND AFTER ENLARGEMENT OF THE KINGS BAY NAVAL BASE CHANNELS

PART I: INTRODUCTION

1. This report presents information on predicted effects of the Kings Bay Naval Submarine Base, Georgia, on tidal elevations in Cumberland Sound.

2. Preliminary tidal predictions in a hybrid model study by the USAE Waterways Experiment Station (WES) indicated that tidal elevations in Cumberland Sound will be increased after channels and basins of the base are enlarged for passage of Trident class submarines. Concerns expressed by persons interested in the base and Cumberland Sound led to a thorough reevaluation of the test results. Description and analysis of the hybrid model tests and tidal elevation changes are given in two WES reports (Granat et al. 1989 and Granat and Brogdon 1990).

3. The purpose of this appendix is to extract and summarize pertinent information from those reports and to compare that information with field observations and analytical considerations so that the issue of tidal changes can be addressed in a more compact format.

PART II: CUMBERLAND SOUND AND KINGS BAY

4. Cumberland Sound is an estuary near the Georgia-Florida State line with extensive marshes and flats penetrated by numerous channels (Figure B1). Kings Bay, a small embayment within Cumberland Sound, encloses a Navy submarine base. At the south end of Cumberland Sound, the Amelia River extends toward the Nassau Sound and is connected to it and the St. Johns River by the Atlantic Intracoastal Waterway. At the north end of the Sound, the Cumberland River connects to St. Andrew Sound, with some tidal exchange. A tidal node point is located in northern Cumberland Sound.

5. Two main rivers (St. Marys and Crooked Rivers) and the local drainage basin supply the sound with a combined mean freshwater flow of less than 2000 cfs*. Mean tide range at the entrance is about 6 ft. The sound is usually well mixed, with salinity varying during the year from a low of about 26 ppt to a high of about 32 ppt.

6. St. Marys Inlet was about a mile wide and 12 ft deep in 1856. Between 1881 and 1887, north and south jetties were built and subsequently extended or raised several times until 1905, at which time the channel was 19 ft deep (USACE). The present inlet width is about 3000 ft.

7. Dredging of navigation channels in Cumberland Sound has occurred in stages over several decades. A 26-ft-deep (mean low water, mlw) channel was dredged to Fernandina Beach in the 1920's and deepened to 28 ft in 1940. Dredging of the 12- by 90-ft Atlantic Intracoastal Waterway (AIWW) was completed through the sound in 1941.

8. In 1956, channels through Cumberland Sound and in Kings Bay were dredged to an average depth of 32 ft. Maintenance was irregular and dredging records for that channel are sparse, but significant dredging apparently occurred only in 1967-70 and 1973-76.

9. During 1978-79 major channel realignment and some enlargement were performed to permit Poseidon submarines to use the base. After 1979, facility depths ranged from 34 to 40 ft and channel widths ranged from 300 to 400 ft over a 7-nautical-mile reach from the entrance to Kings Bay.

10. Facility enlargement for Trident submarines began in 1982 and

* A table of factors for converting non-SI units of measurement to SI (metric) units is included on page 1.

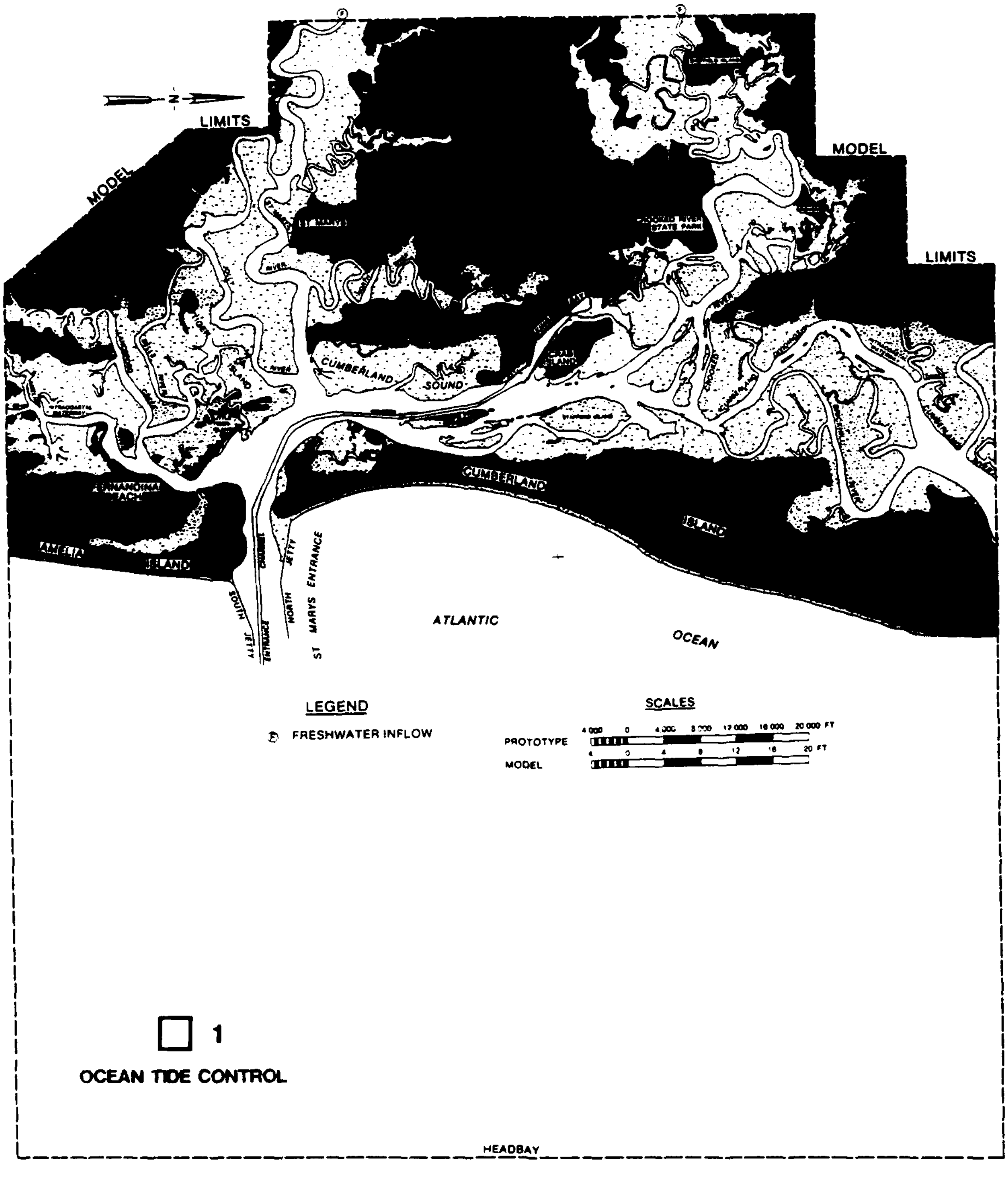


Figure B1. Site map and physical model limits channel dredging was performed from 1984 to 1988, with depths increased, ranging from 46 to 49 ft and channel widths increased to 500 ft. Kings Bay itself was enlarged considerably, with shallows at the north end widened and deepened to 48 ft over a length of about 1 nautical mile. The entrance channel was dredged during the period June 1987 to June 1988. Interior channels were dredged from 1984 to July 1988, with the Crab Island turning basin completed in October 1988.*

* Personal communications with Susan Brinson, USAE District, Savannah, and Bryon Farley, USAE District, Jacksonville.

PART III: HYBRID MODEL STUDY

11. The Officer in Charge of Construction, Kings Bay, commissioned WES in 1982 to perform a hybrid model study of the facility. The purposes of the model study were to:

a. Predict average currents in channels for use in vessel handling studies.

b. Predict long-term average maintenance dredging requirements of the channels and basins.

c. Conduct a fast track study so as to obtain results at the earliest possible date.

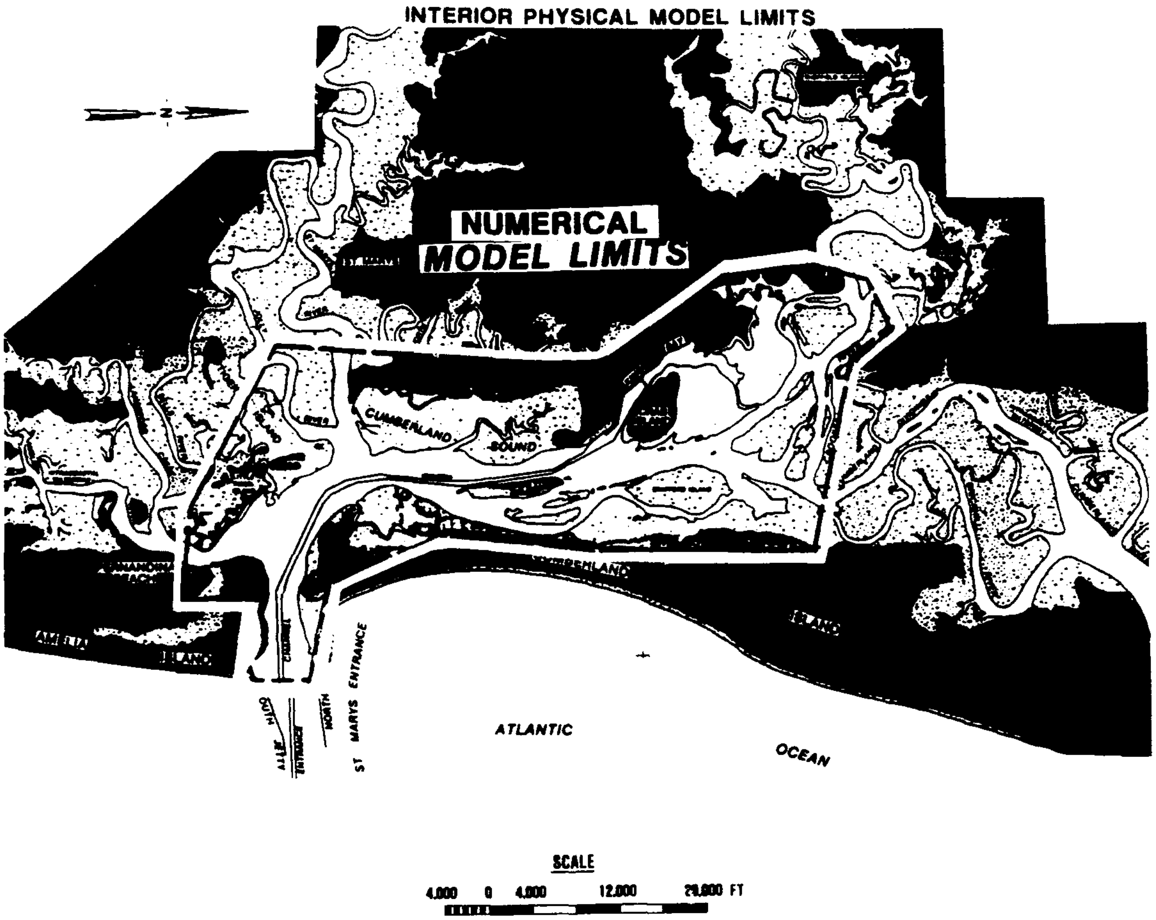
The last objective was strongly emphasized because the facility was being constructed concurrently with modeling and late revisions to channel designs would be extremely costly.

Modeling Approach

12. Modeling was accomplished by a hybrid application of a scaled physical model integrated with a set of two-dimensional depth-integrated numerical models. The physical model, built in concrete to length scales of 1:100 vertical and 1:1000 horizontal, was used to model tides, currents, and salinities in the Sound. The numerical models, from the Corps of Engineers TABS-2 modeling system, were used to interpolate currents and compute sediment transport, deposition and erosion. The TABS-2 models are described in the model study reports cited above and by Thomas and McAnally (1985).

13. Figures B1 and B2 show the models' limits. The numerical model limits were set closer to the area of interest than would be possible in a numerical-only approach. Use of the hybrid technique for sedimentation studies permits the numerical mesh to be that small, but it makes the numerical model very sensitive to, and very dependent on, the boundary forcing conditions derived from the physical model. For that reason, the physical model tidal elevation results will be emphasized here.

14. The physical model was verified to field measurements of tides, velocities, and salinities. The numerical hydrodynamic model was verified to physical model data, and the numerical sediment model was verified to field observations of channel sedimentation, suspended sediment concentrations and bottom characteristics. After some testing, a portion of the physical model



NUMERICAL/HYBRID MODEL A

Figure B2. Numerical model limits

was revised and reverified as described below.

15. The WES has traditionally used midtide level, the average of high water and low water levels, as a measure of the near-mean water level in reporting model results. (That measure was selected because of computational ease in the pre-computer era but is still useful. The reduced rate of water level change near high and low waters makes the midtide level a rather precise measure.) Midtide level (MTL) is not equivalent to mean water level (MWL) or mean sea level (MSL), but serves the same purpose. MWL, computed as the average of all hourly or half-hourly water level measurements, can be appreciably different than MTL, depending on the degree of tidal wave distortion. Base to plan changes in MTL and MWL are very nearly equal except in cases where appreciable changes in tide wave shape occurs. Herein, most model results are reported in terms of MTL and most field data are in terms of MWL. Where a discrepancy can result, both are used.

Test conditions

16. Verifications. Verification and Base tests were conducted with the models reproducing the Poseidon base channels and other areas according to hydrographic charts available in 1982 when the models were constructed. Some data on the available charts were old, dating from the 1930's. A major hurdle in the verification process was establishment of the elevations of the extensive marshes where hydrographic data were not available at all. An initial estimate of elevations based on consultants' knowledge of the area and where various marsh plants thrived was molded in the model and then adjustments to individual marsh areas were made by trial and error. The amount and variety of field data available for verification was sufficient, but was less than optimum.

17. Plan OP-1. A number of variations were tested on two basic plans. The first, Original Plan 1 (OP-1), consisted of channel widening and deepening as contained in the 1983 preliminary facility design, with the entrance channel 500 ft wide by 56 ft deep. That test was completed and results provided in preliminary form to the Navy. Subsequently, the plan design was revised to substantially expand the facility, and Plan OP-1 test results were not published. They are described in a WES Memorandum for Record, Subject: Kings Bay Physical Model, Tests of Preliminary Facility Plan, dated February 1989.

18. Reverification. After Plan OP-1 was tested, a previously recommended task of reverifying the physical model was approved by the Navy but at

a reduced scope and funding level. A small additional field data set was collected in 1985 after construction dredging had begun. Use of that data set and new hydrographic surveys and aerial photographs resulted in revision of the models' geometry and roughness north of Kings Bay. For the reverification, the model reproduced the January 1985 channel depths. The numerical model was reverified to the 1985 channel conditions physical model data.

19. A new physical model base test* should have been conducted after reverification; however, the need for expedited testing of the new basic plan did not permit the schedule to be adjusted for that purpose, and the sedimentation modeling did not demand it. The single, original verification base test was used for subsequent comparison with plan tests. A new numerical model base test was performed but used boundary conditions from the original physical model base test.

20. Plan P4-1. The second basic plan, P4-1, is that described above in paragraph 10, plus rerouting of the AIWW to the east side of Drum Point Island. It was installed and tested after reverification of the models.

21. Comparison with as-built conditions. The Trident facility channels as-built are not identical to the conditions of either Plan OP-1 or Plan P4-1. Plan OP-1 channels were deeper than as-built (56 ft to 49 ft) but enlargement of middle and lower Kings Bay was less extensive than as-built conditions. Plan P4-1 channels were basically the same width and depth as the as-built but did not include a turning basin in lower Kings Bay and turning basin and sediment traps near the ocean inlet. In addition, Plan P4-1 included rerouting of the AIWW from the west to the east side of Drum Point Island, which affected localized sound circulation, but was not constructed in the prototype. These differences may affect model results, as discussed later.

Boundary conditions

22. Physical model. Boundary conditions for the physical model verification tests consisted of a repeating semidiurnal tide at the entrance with ranges of 5.3, 5.8, and 6.2 ft; an empirically derived tide at the Cumberland River boundary; and freshwater flows of 1000 cfs at the St. Marys River

---

* Model tests produce results that are quantitative in an absolute sense, but they are most accurate and reliable when expressed as a change from some other model test. The preferred technique is to conduct one model test with a set of given conditions (often existing geometry, flows, etc) and call that the 'base' test against which all others are compared.

boundary and 100 cfs at the Crooked River boundary. The observed prototype tide at the entrance (South Jetty) was smoothed at the beginning and end of the cycle

23. For the base and all plan tests, the same ocean tide was forced — a 5.7-ft range — and freshwater flows were the same as the verification tests. The Cumberland River tide labyrinth was modified slightly during the 1985 reverification. Tide characteristics at the ocean control are shown below. Water surface elevations at the control were recorded by air capacitance gage to the nearest 0.01 ft (0.00001 ft model), or by point gage to the nearest 0.05 ft, and are considered accurate to at least the nearest 0.1 ft. The additional decimal place is recorded here to facilitate comparisons. Each value is the average of two or three measurements taken concurrently with the sound tide measurements presented later. Within the limits of model accuracy and repeatability, the ocean tide was the same for all three tests.

Physical Model Ocean Control Tides

Test	High Water ft, MLW	Low Water ft, MLW	Range ft	MTL ft	MWL ft
Base	6.24	0.54	5.70	3.39	3.26
Plan OP-1	6.20	0.48	5.72	3.34	3.26
Plan P4-1	6.26	0.52	5.74	3.39	3.24

24. Numerical model. The numerical model tidal tests were conducted with boundary conditions of elevation or flow specified from the physical model measurements. For sensitivity test purposes, the numerical model was also tested with Base and Plan geometry run with Plan and Base physical model boundary conditions, respectively (i.e., crossed geometry and boundary conditions).

Model Tidal Elevation Results

Physical model

25. Tides were measured in the physical model for each test described above. Two sets of station numbers were used and are shown in Figures B3a (1982 verification) and B3b (Base and Plan tests). Triplicate tide elevations

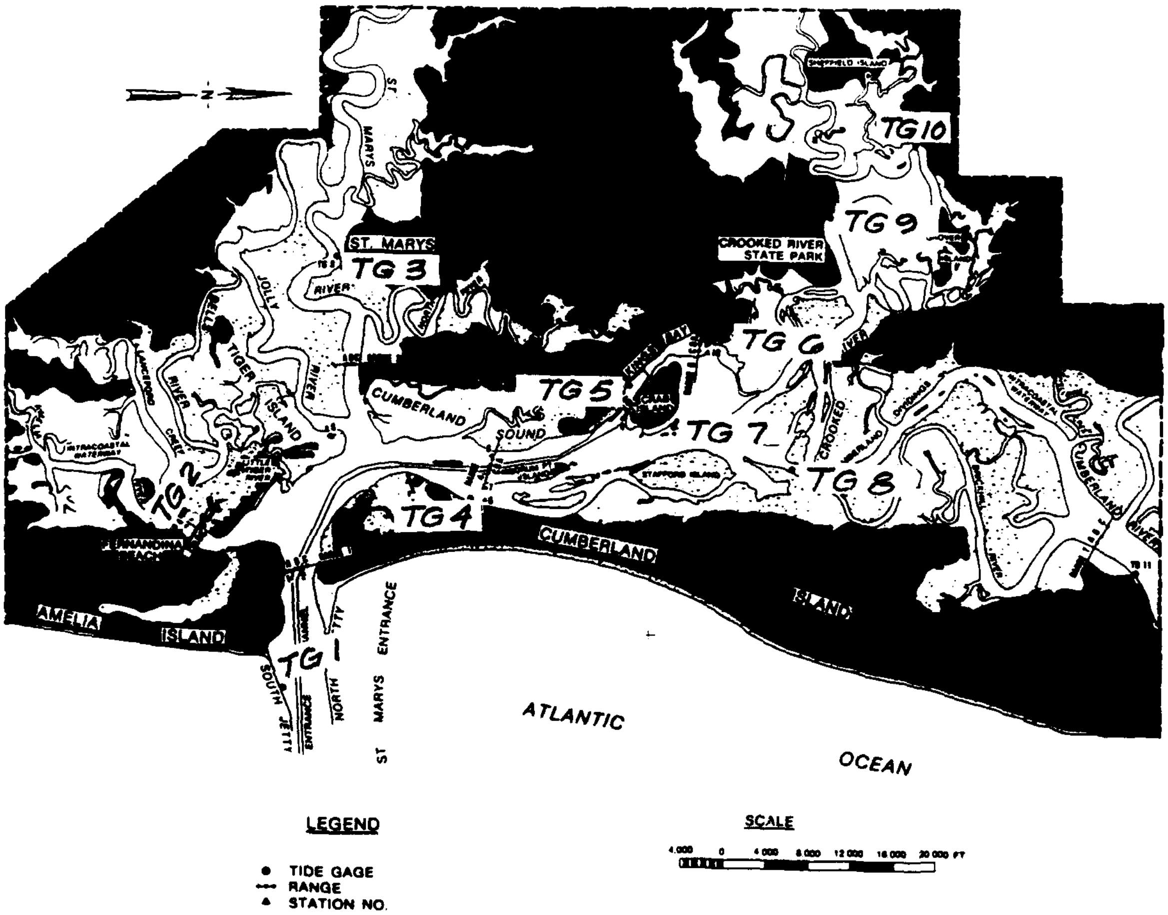


Figure B3a. Station locations, 1982 verification

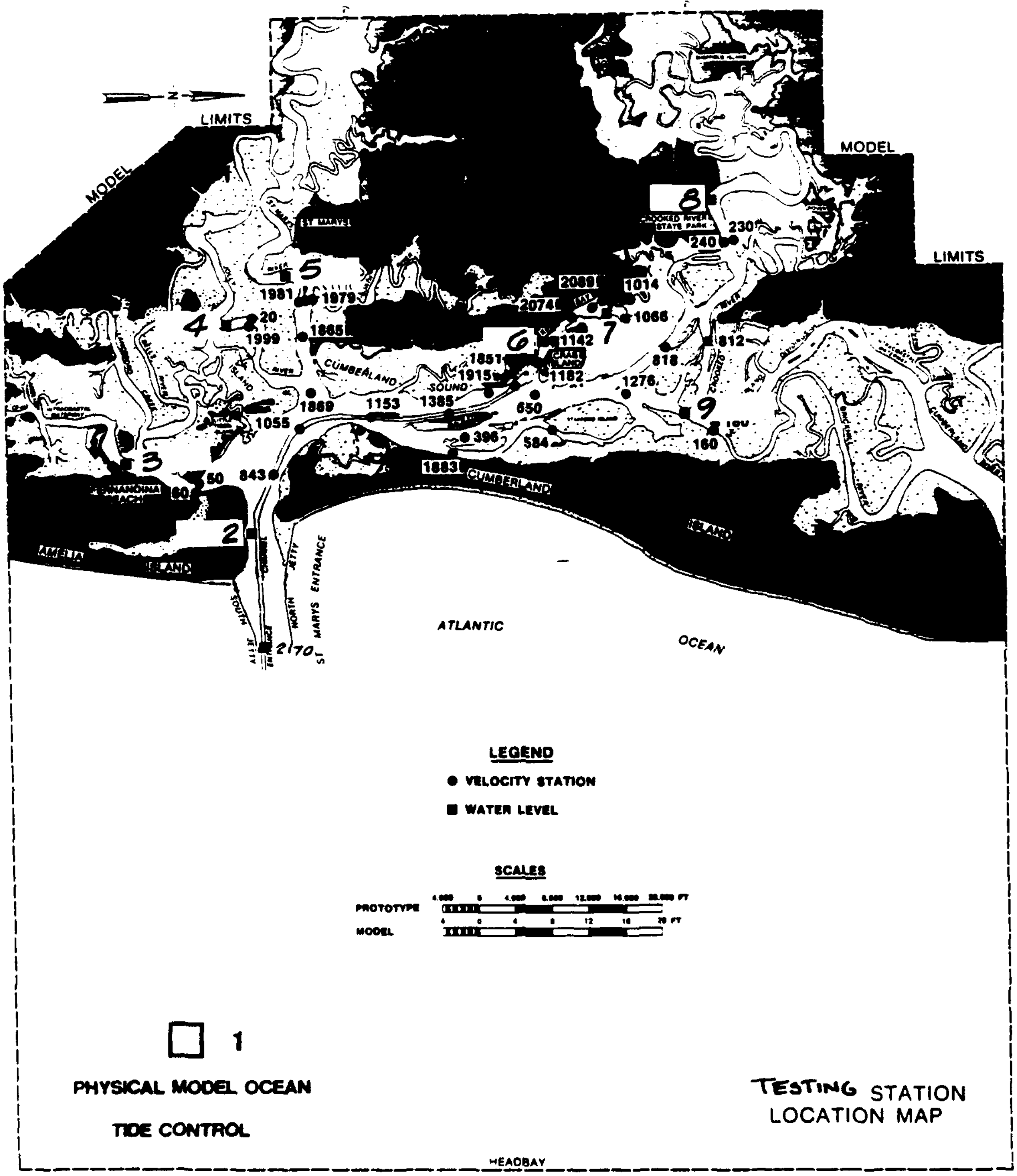


Figure B3b. Station locations, base and plan tests were measured in the sound at 30-min intervals with point gages or air capacitance gages, averaged, and rounded to the nearest 0.1 ft.

26. First verification. The 1982 verification field data set spanned three days, with intensive data collection on 10 and 12 November. Figure B3a shows station locations. Figures B4-B6 illustrate the comparison between prototype and physical model tides. (In these and other physical model data plots, the curves are spline fits that pass through every data point.) The degree of agreement is considered satisfactory, considering the required schedule and that tide predictions were not the objective of the study.

27. Generally, model tidal ranges in the sound (Stations 2, 4, and 5) were the same as prototype, high and low water elevations were within 0.1 ft of prototype, and phases were within 5 minutes of prototype. Greater deviations, up to 0.4 ft in individual elevations were experienced at stations in the tributaries and creeks, where the bathymetric data were most out of date and tide reproduction was worst. In Kings Bay (Station 5), model-prototype elevation differences were less than 0.2 ft and high and low waters were within 0.1 ft. Phase was in good agreement. At Fernandina Beach (Station 2), high and low waters were within 0.1 ft, but some individual elevations were as much as 0.2 ft different from corresponding prototype elevations.

28. Original plan. Plan OP-1 tides for Base and Plan are shown in Figures B7-B9. Station locations (note change in some station numbers) are shown in Figure B3b. Table B1 summarizes changes in tides that were measured. In general, high and low water elevations inside the sound increased up to 0.2 ft and tides arrived sooner by 10 to 15 minutes. Tidal range remained about the same, but the midtide level increased. At Fernandina Beach (Station 3) and Kings Bay (Station 6), both high and low water increased by 0.2 ft and range did not change. For the eight stations, the average increase in midtide level was 0.1 ft.

29. Note that the midtide, high, and low water levels in the sound (Station 3) are lower than the corresponding values of the ocean tide (Station 1). For the plan test, the difference is diminished and sound tide levels approach, but do not reach, ocean tide levels.

30. Reverification. Agreement was about as good as the original verification, although a strong wind during the field data collection period had a pronounced effect on velocities at some locations.

31. Plan P4-1. Plan P4-1 physical model tides are plotted with Base

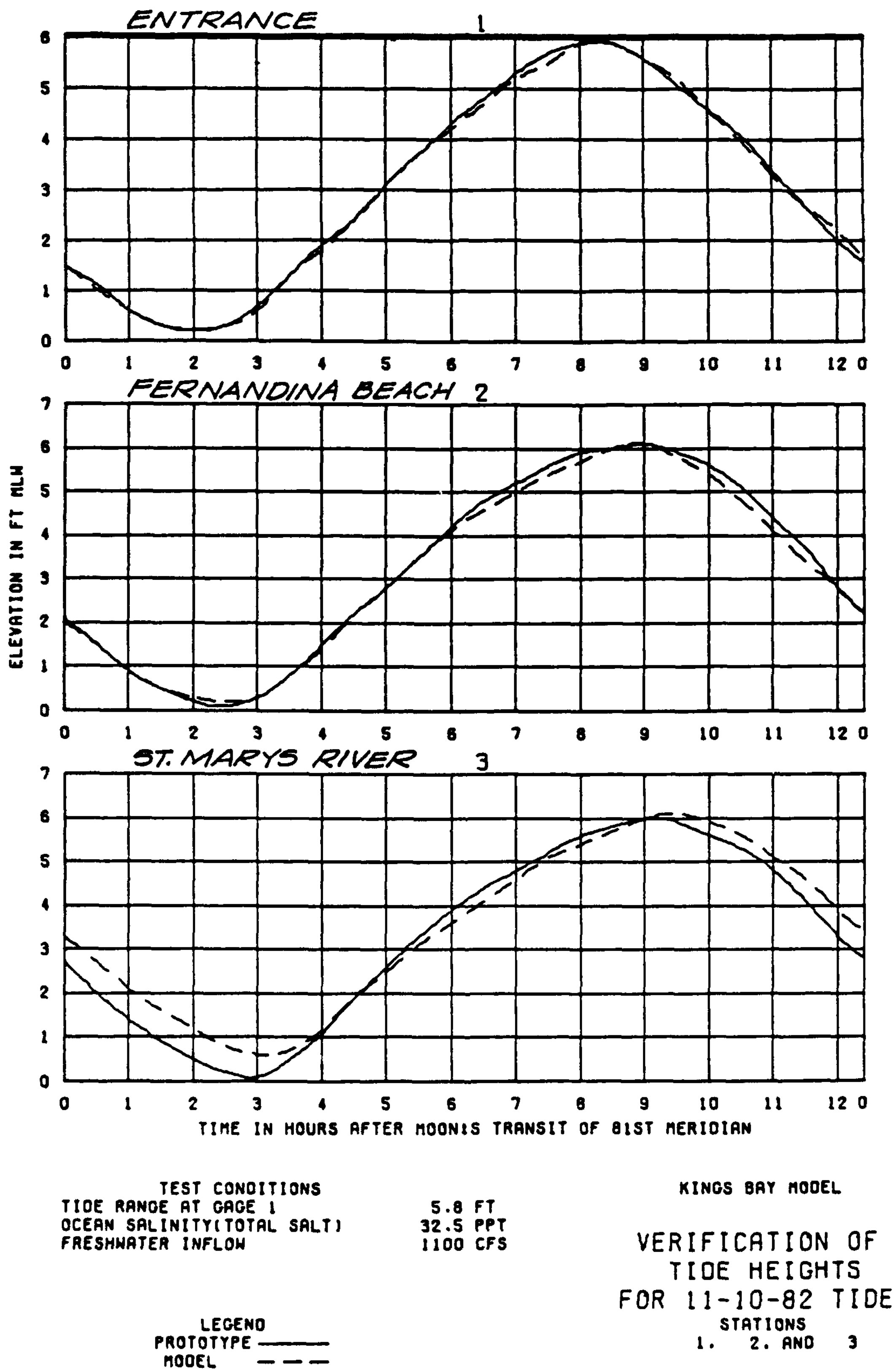


Figure B4. 1982 Physical model verification, tides at Stations 1-3

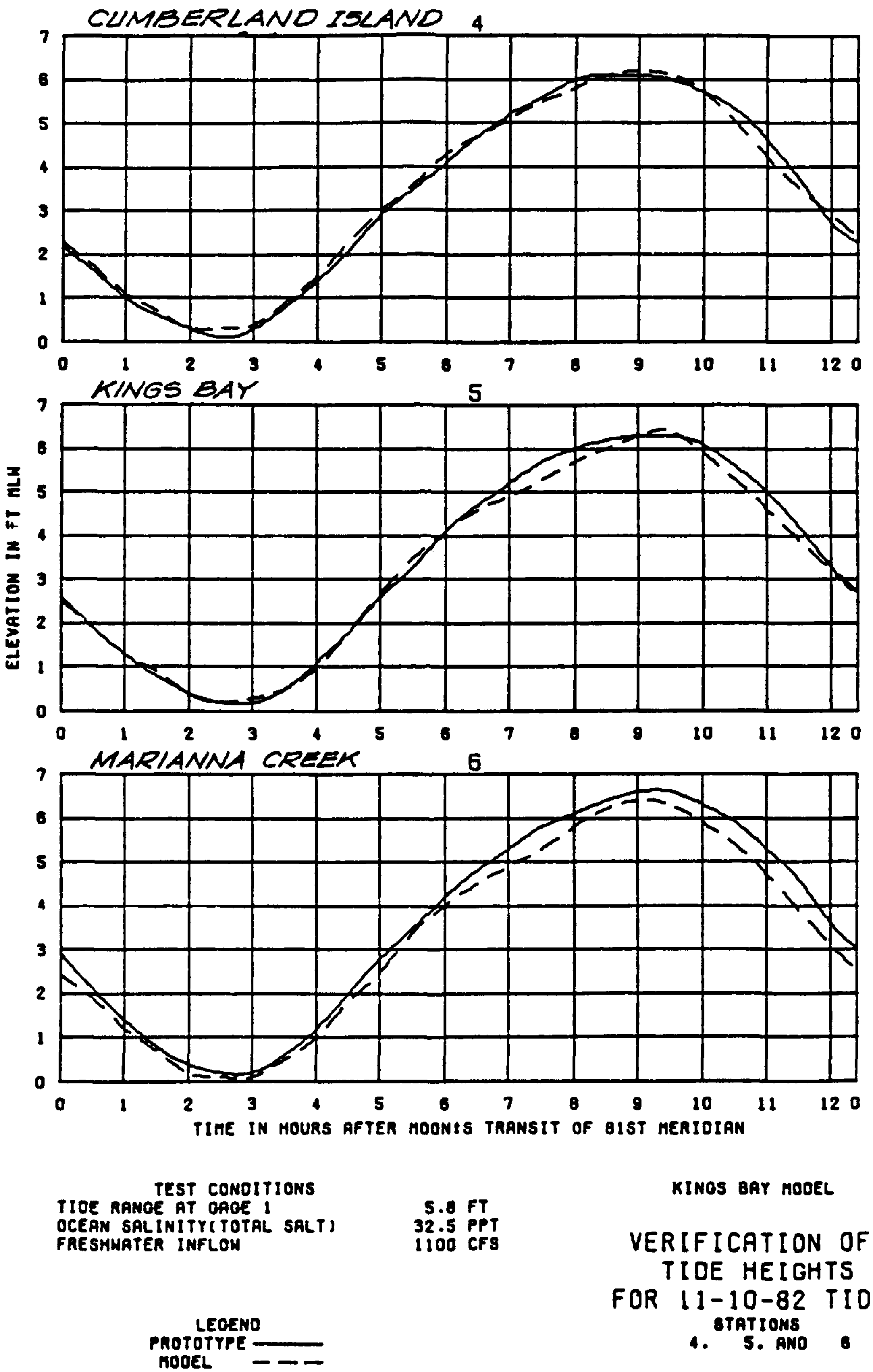


Figure B5. 1982 Physical model verification, tides at Stations 4-6

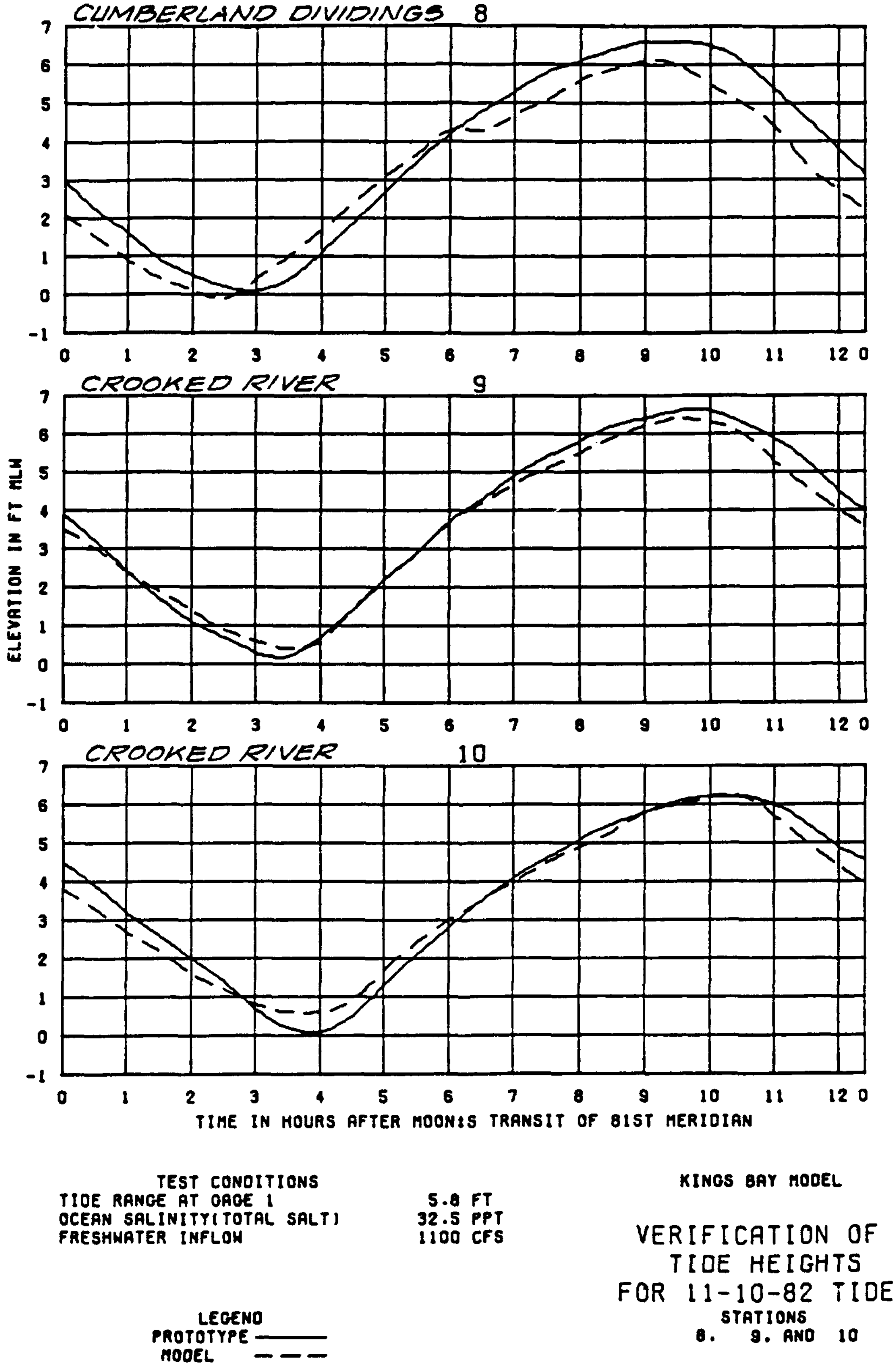


Figure B6. 1982 Physical model verification, tides at Stations 8-10

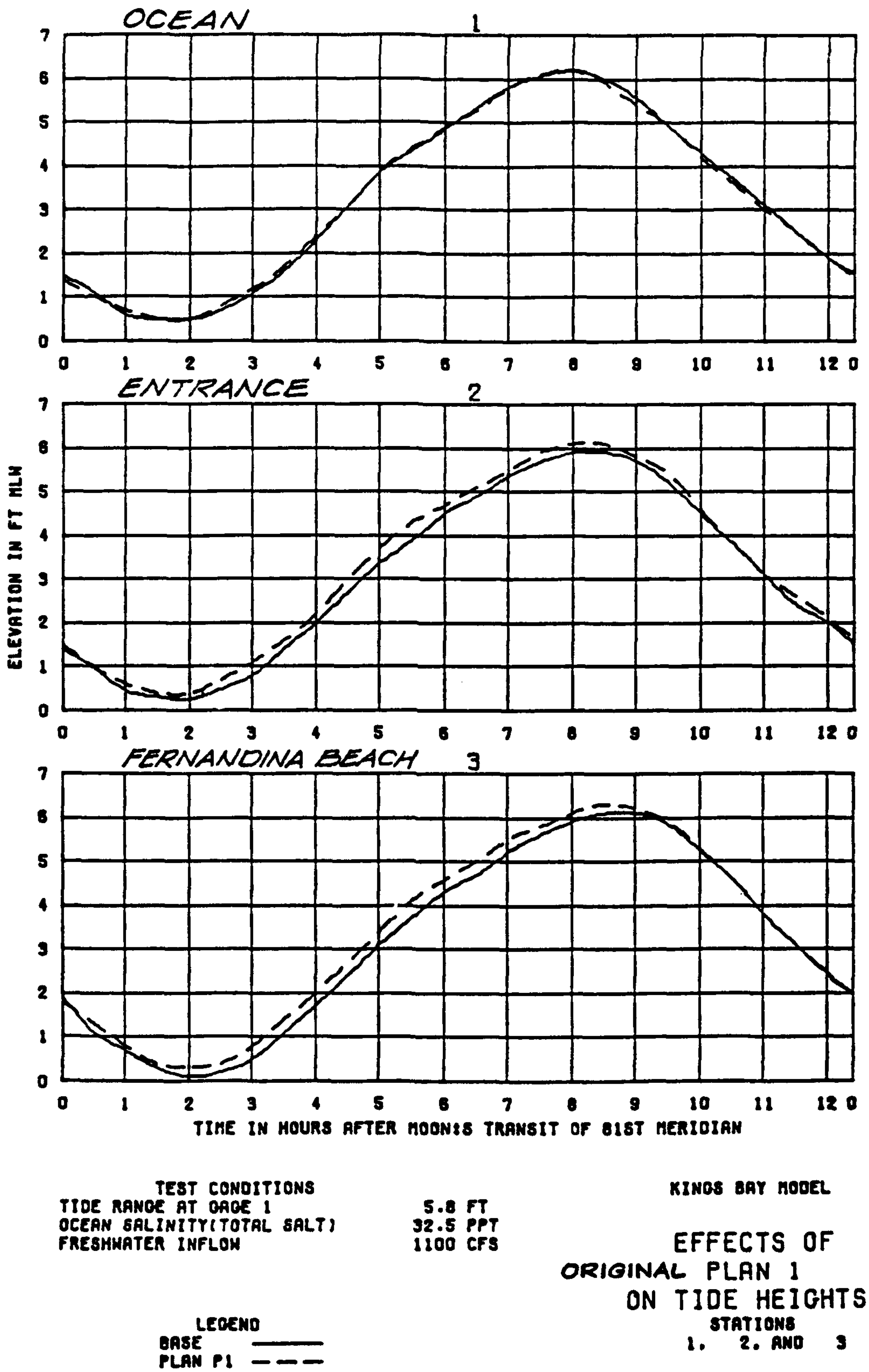


Figure B7. Physical model tidal elevations, Plan OP-1, Stations 1-3

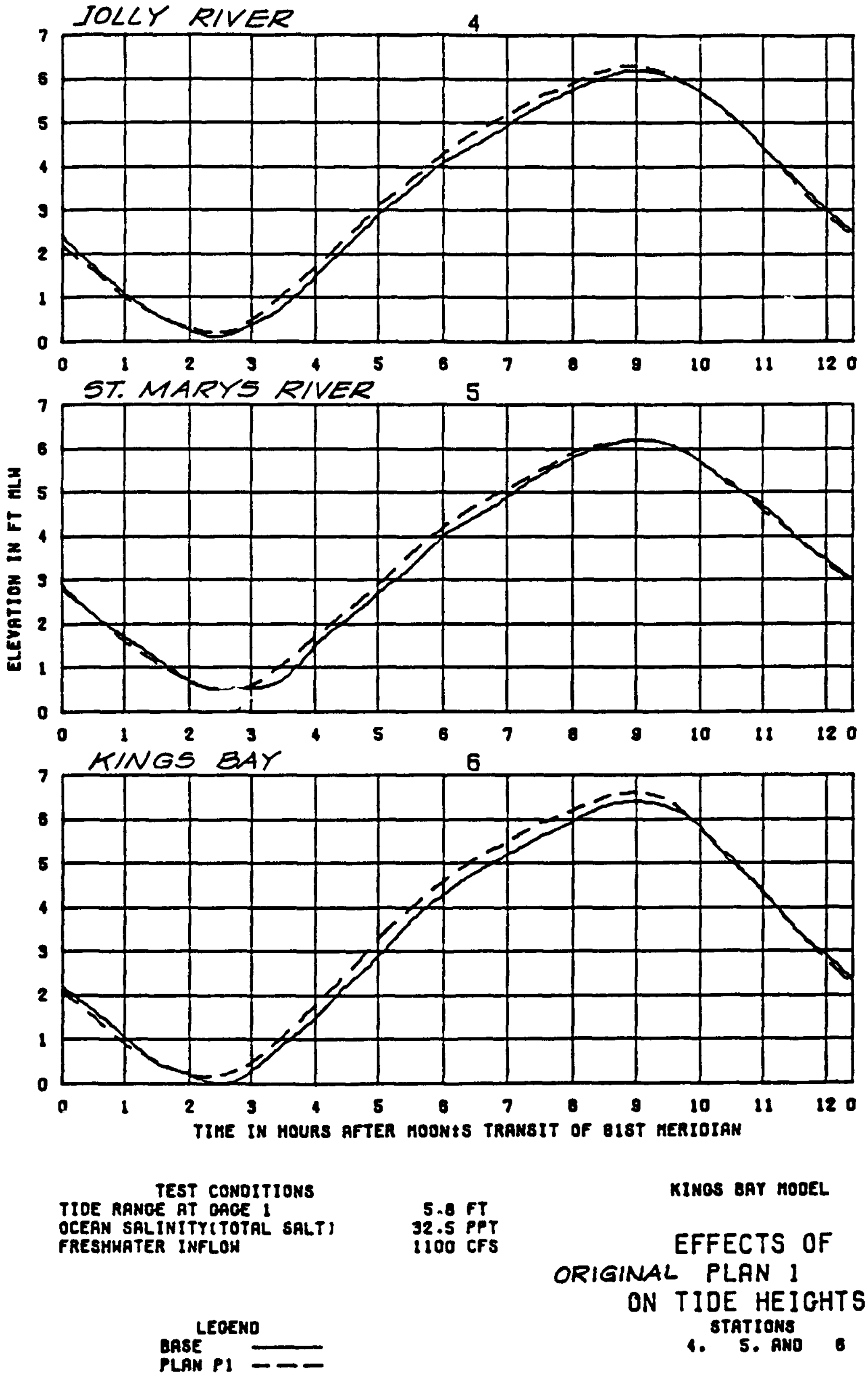


Figure B8. Physical model tidal elevations, Plan OP-1, Stations 4-6

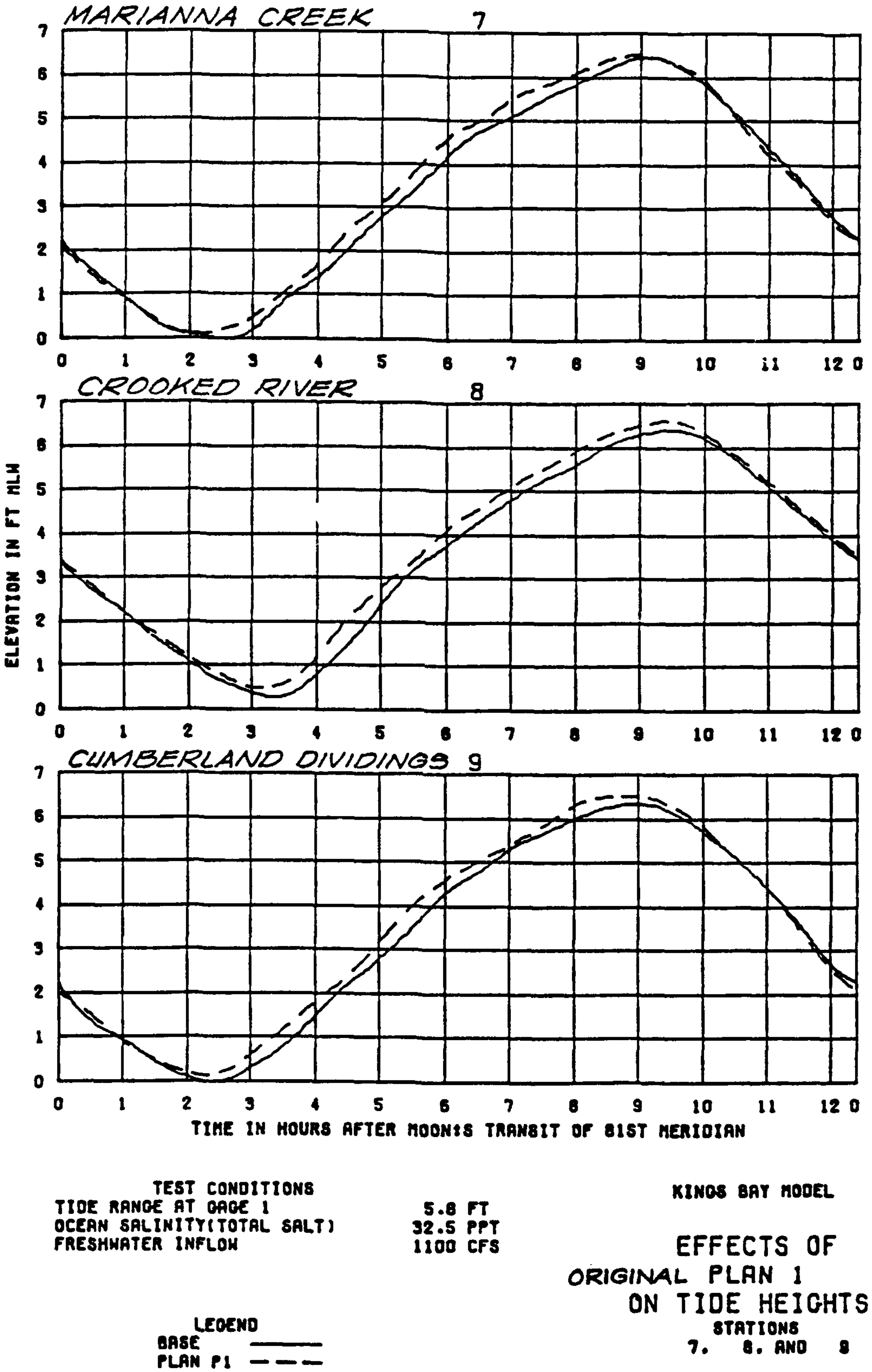


Figure B9. Physical model tidal elevations, Plan OP-1, Stations 7-9

tides in Figures B10-B12. Station locations are shown in Figure B3b. Table B2 summarizes changes in tides for the plan. Low water elevations and high water elevations increased, both by about 0.2 ft, but with slightly greater high water increases such that range increased somewhat. Plan tide phases were slightly later than the base at some stations but not at Fernandina Beach. In Kings Bay (Station 6) low water increased by 0.2 ft and high water by 0.3 ft. At Fernandina Beach (Station 3), low water increased by 0.1 ft and high water by 0.2 ft.

32. Repeatability tests. Repeatability tests were run to define the variability of measurements taken over several tidal cycles and on different days. In three tests, tides were measured for two tidal cycles each. The maximum deviation in individual measurements was 0.2 ft with no readily apparent systematic pattern. Almost systematic deviations of 0.1 ft occurred.

Numerical model

33. Verifications. The numerical model was verified to physical model data for the 1982 condition, the 1985 condition and agreement was considered satisfactory for tides. During the 1985 reverification, the numerical model mesh was revised to reflect new hydrographic information and also to better resolve some areas where prior testing indicated the need for higher resolution. Following reverification, a new base test was run, using original physical model base test data for boundary conditions.

34. Plan P4-1. Plan P4-1 low water elevations remained about the same, while high water elevations increased by up to 0.4 ft over base. Phases were generally unchanged. As stated earlier, numerical model boundaries were located close to the area of interest and inside the zone of channel enlargement, and thus the tide results are highly dependent on the physical model-derived boundary conditions. The fact that the numerical model results demonstrated a trend similar to the physical model provides qualitative support to the physical model finding. The numerical model also offered the opportunity for sensitivity testing.

35. Sensitivity tests. Numerical model sensitivity tests were performed to determine if boundary condition inaccuracies might cause spurious elevations of high waters. The base condition geometry (pre-Trident channels) was run using boundary conditions from physical model Plan P4-1 (base geometry, plan forcing, BGPF). The Trident geometry of Plan P4-1 was run numerically with physical model base boundary conditions (PGBF). Both were compared

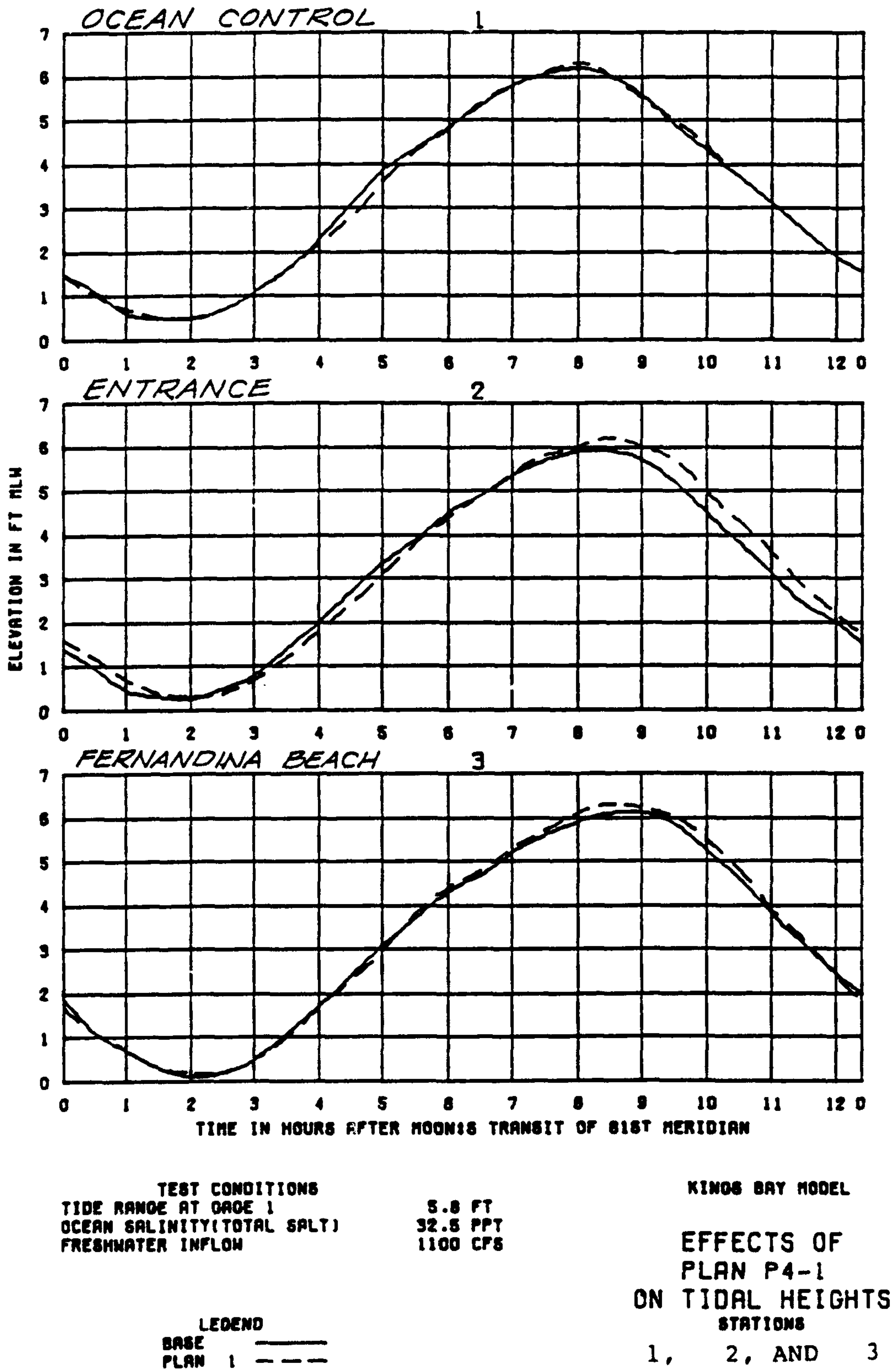


Figure B10. Physical model tidal elevations, Plan P4-1, Stations 1-3

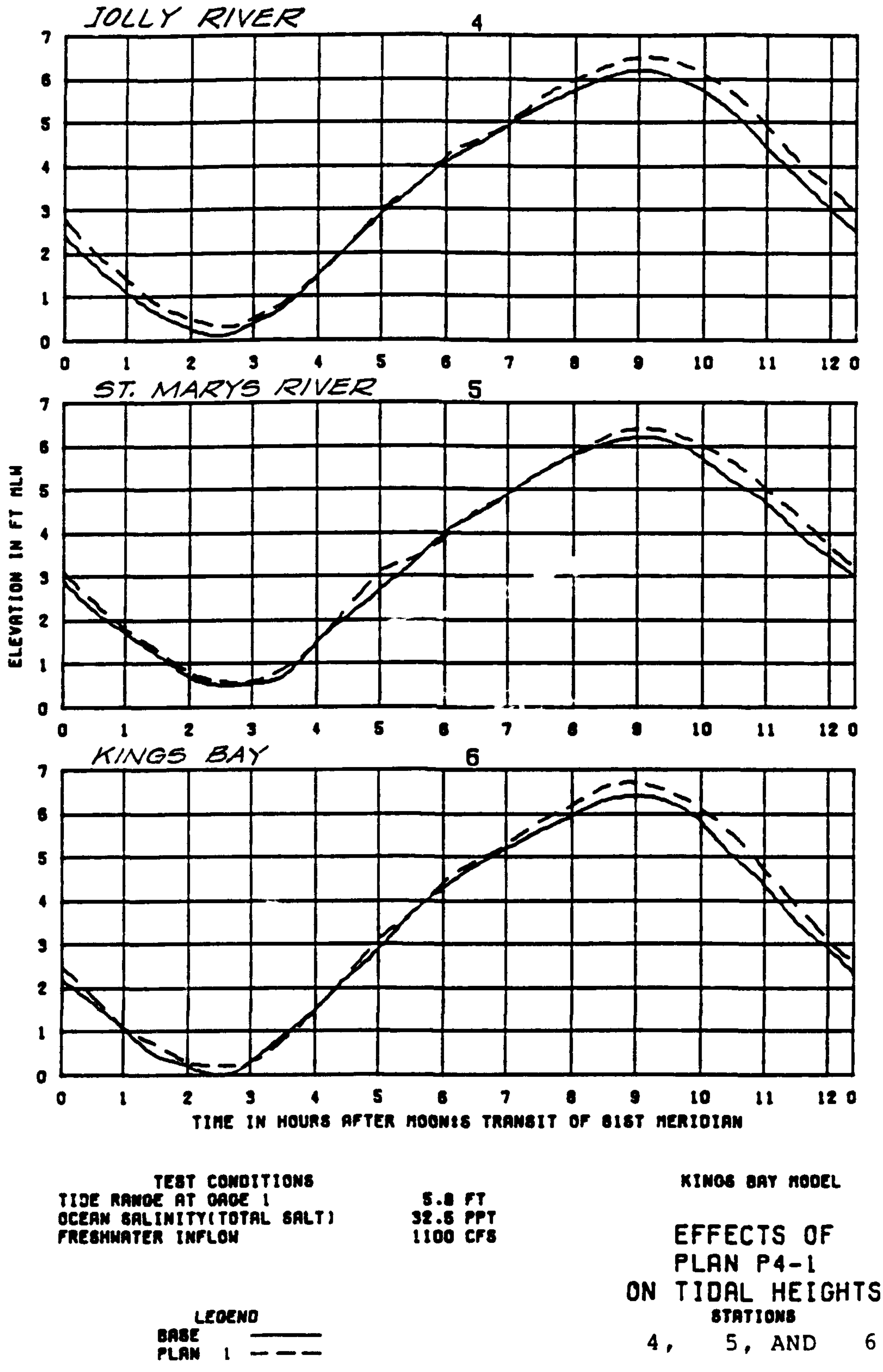


Figure B11. Physical model tidal elevations, Plan P4-1, Stations 4-6

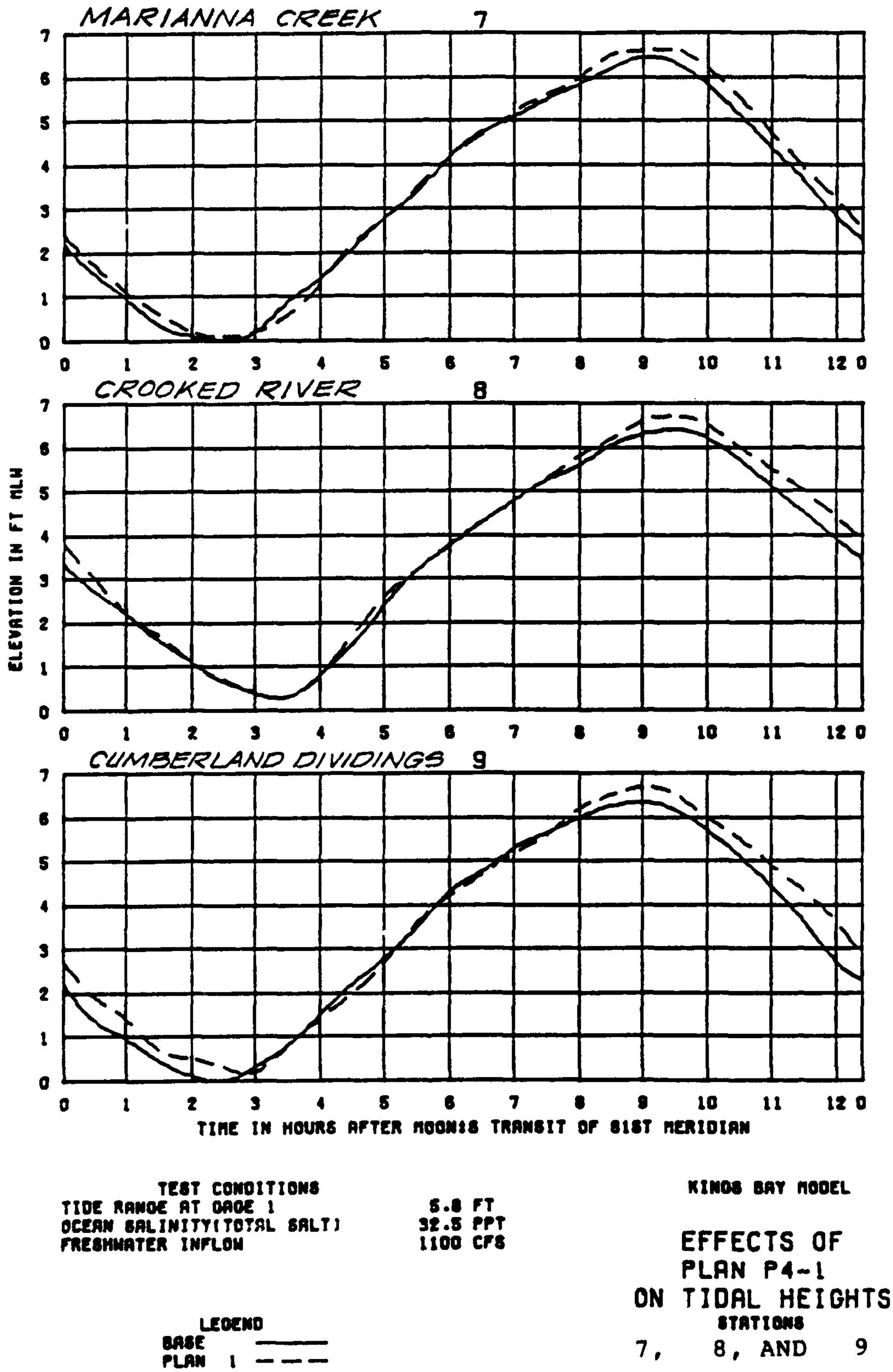


Figure B12. Physical model tidal elevations, Plan P4-1, Stations 7-9

to numerical model base test results (BASE). Figure B13 shows high-water, low-water, and midtide level results for those tests and for regular Plan P4-1 (PL4A) results.

36. The tests showed that changing the boundary conditions to plan, but not the geometry (BGPF), caused about a 0.4-ft increase in high water and a less than 0.1-ft decrease in low water elevations, with midtide levels increasing about 0.2 ft. Changes were close to, but smaller than, Plan P4-1 results.

37. Changing to the plan geometry but leaving the base boundary conditions (PGBF) caused high water to increase slightly over base, but low water remained essentially unchanged. The net effect was to raise midtide level slightly.

38. The numerical sensitivity tests show, as expected, that the numerical model tides are more sensitive to boundary conditions than to geometry; however, they also show that the physical model trends of geometry-induced increases in high water elevations are confirmed for the plan geometry.

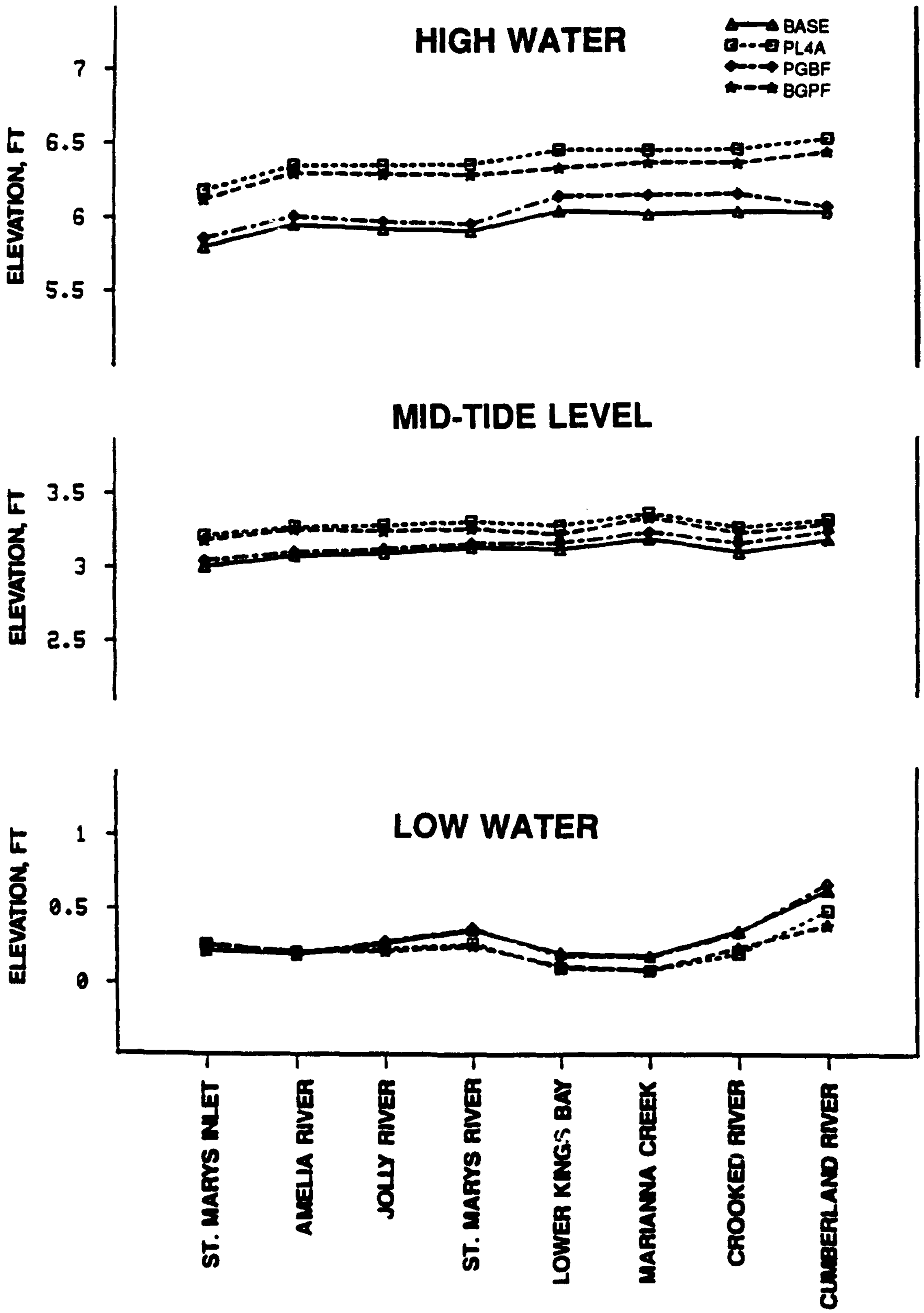


Figure B13. Numerical model tidal sensitivity results

PART IV: HISTORICAL FIELD OBSERVATIONS

39. Historical and recent NOAA tide data from Cumberland Sound were examined to determine if they showed any effect from previous channel enlargements. Historical data from the sound are available only at Fernandina Beach.

40. Figures B14-B16 show historical mean water levels, high and low water elevations, and tide ranges at the NOAA Fernandina Beach gage (near Station 3 on Figure B3b, just inside the entrance). These data are annual averages calculated by NOAA from hourly water level measurements.

41. Figure B14 presents 1898-1986 annual averages of monthly mean water levels as calculated by NOAA. (No data are available for 1924-1937.) The second curve on Figure B14 is a 5-year running average of the annual values. Across the bottom are shown the major dredging events for the inlet and sound. A significant trend of incrementally increasing mean water level (from about 0 to 0.6 ft NGVD) with temporary plateaus can be observed, as can substantial year-to-year variation (up to 0.25 ft).

42. The dredging events shown were derived from the annual reports of the Corps of Engineers (USACE). The information available consists of volume of new work and maintenance material dredged each year and dates when projects were completed. It does not tell the actual channel size, since the amount of maintenance depends on funds available as well as the need. Major maintenance dredging events where the volumes were significantly higher than normal have been identified, since that may reflect the end of a period when channel depths were not fully maintained. The channel enlargements have been dated to their completion, and the initiation will have been 1 to 3 years earlier.

43. The discontinuous nature of the mean level increases indicates that the effect may be either human-induced or related to some episodic or intermittent natural process (e.g., eustatic sea level rise or land downwarping). While every channel enlargement was followed by an increase in level, some rises were much less rapid than others. This could indicate that some or all of the rises were due to other processes, or that the channel size effect is either nonlinear or partially dependent on cyclic changes in mean range. It should be noted that the 34-ft channel was apparently not well maintained, so the actual depth from 1955 to 1965 is not known. The 5-year average curve shows that the 1956 deepening was followed by a modest increase in mean water level, then a plateau until the late 1960's when maintenance was resumed.

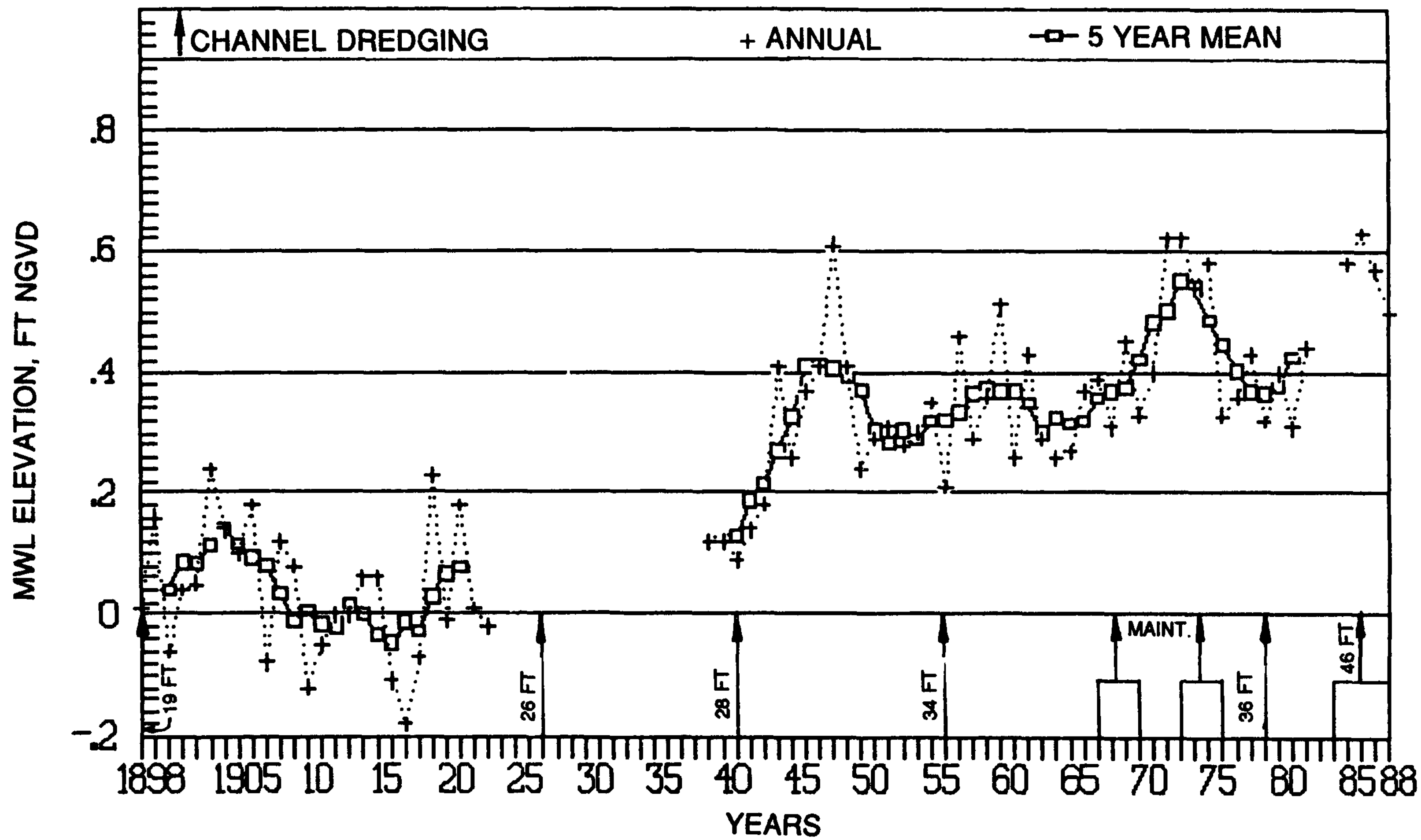


Figure B14. Fernandina Beach with dredging events

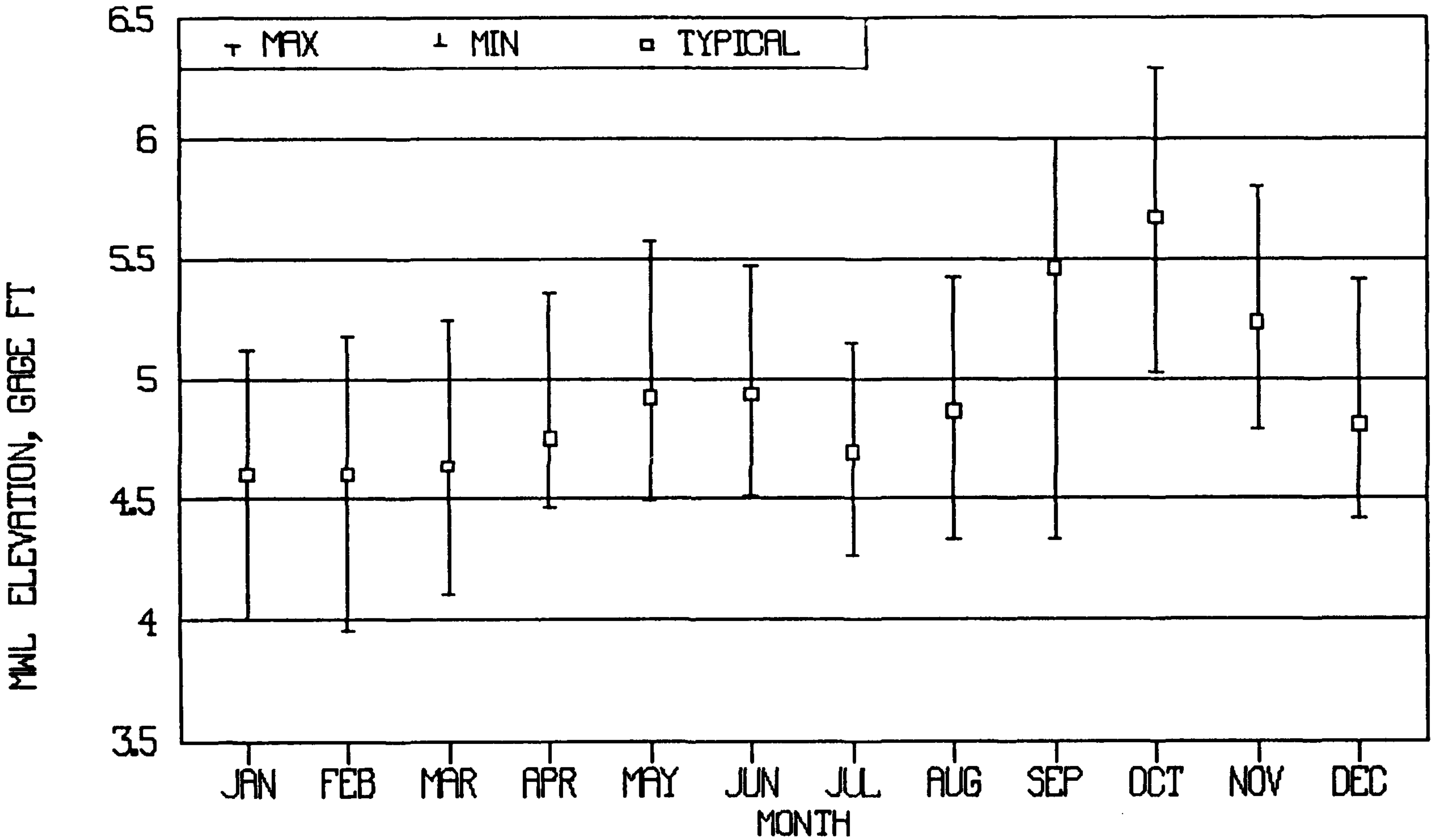


Figure B15. Typical monthly variation in mean water level at Fernandina Beach

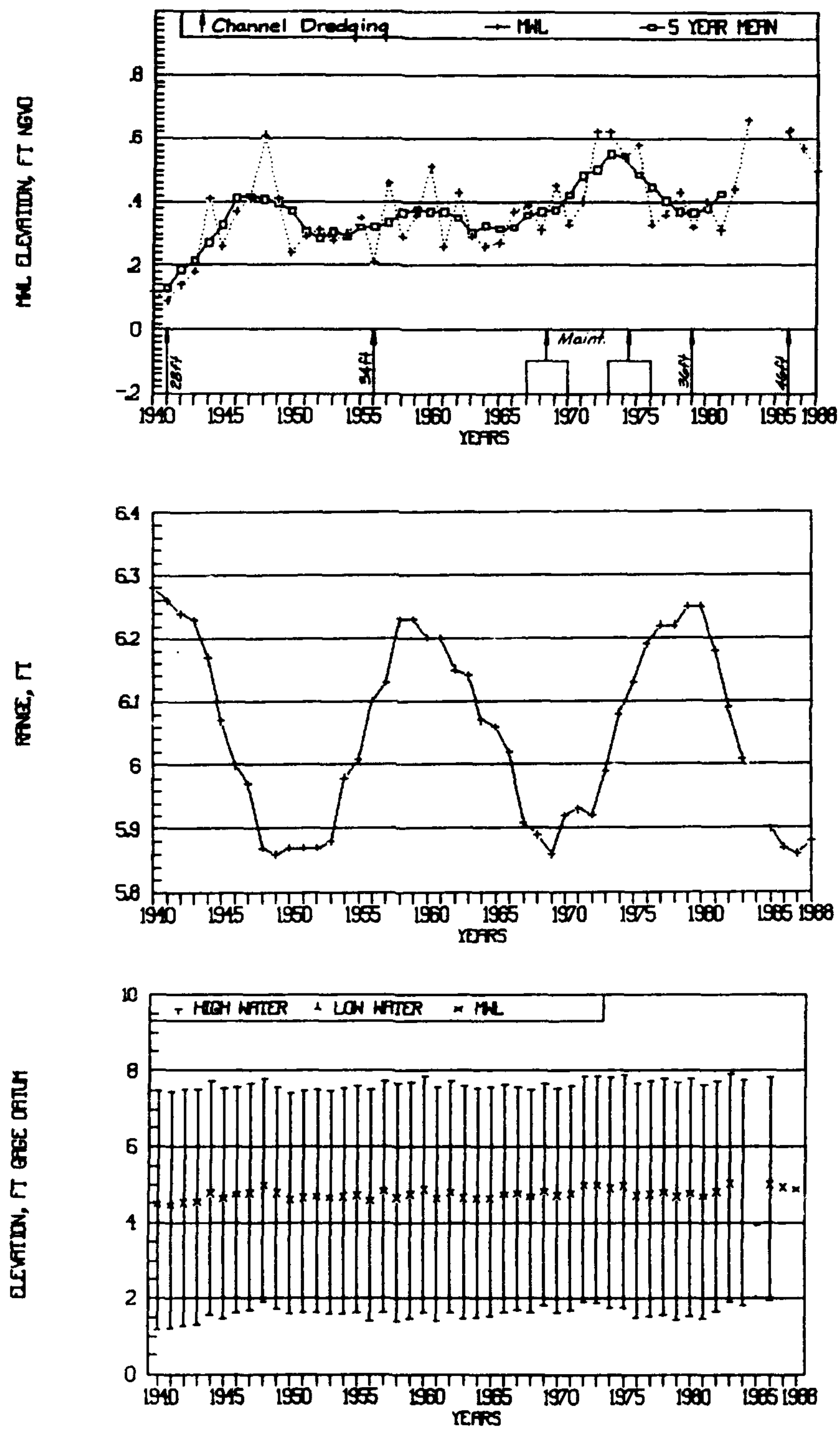


Figure B16. MWL, range, and tides at Fernandina Beach

44. These water level and dredging data suggest, but do not prove, a cause and effect linkage between channel size and mean water level at Fernandina Beach. Further information and analysis are needed.

45. Figure B15 shows the typical variation of MWL within the year, with extreme and average monthly average levels since 1898. (The values shown are those for years since 1898 for which a full 12 months of data are available. Partial years were excluded from the averaging. The absolute monthly values were normalized by the annual MWL for the corresponding year, then averaged by month over all years. The average normalized monthly means were then multiplied by the annual mean of 1987 to put them back into consistent units of feet.)

46. Monthly typical water levels vary from about 4.6 (in January) to about 5.7 ft (in October) above gage datum (gage datum is 4.37 ft below NGVD), and extreme values for each month may be more than half a foot higher or lower than its long-term average value.

47. Figure B16 shows three representations of Fernandina Beach tides in parallel — annual mean water levels, annual mean tide range, and annual mean high and low waters. At the bottom, annual mean high and low water elevations at Fernandina Beach are plotted with the midpoint between the two. A trend of increase with time can be seen for high and low waters and mean water levels.

48. As shown in Figure B16, the annual mean tide range at Fernandina Beach displays a typical 18.6-year cycle with minima near 5.9 ft and maxima near 6.3 ft and no discernible trend in range. Note that the late 1980's is near a minimum mean annual range, and an increase in range should be expected for the next several years because of the natural cycle.

49. Table B3 shows harmonic constituent amplitudes calculated from 1-year records at several intervals as calculated by NOAA. The results are plotted in Figure B17. (Note that the time scale is not uniform.) The component amplitudes have exhibited changes over the period, but no overall trend of increase or decrease is observed. The 1977 data display an anomaly in amplitude of the diurnal (K_1 and O_1) components that may be an error. A cursory examination of compound and overtides other than M_4 revealed no obvious trends in amplitude.

50. Tidal component phases are shown in Table B3 and Figure B18. The diurnal phases declined slightly over time. The higher frequency components' phase angles decreased through 1974, then all but the S_2 increased in 1977.

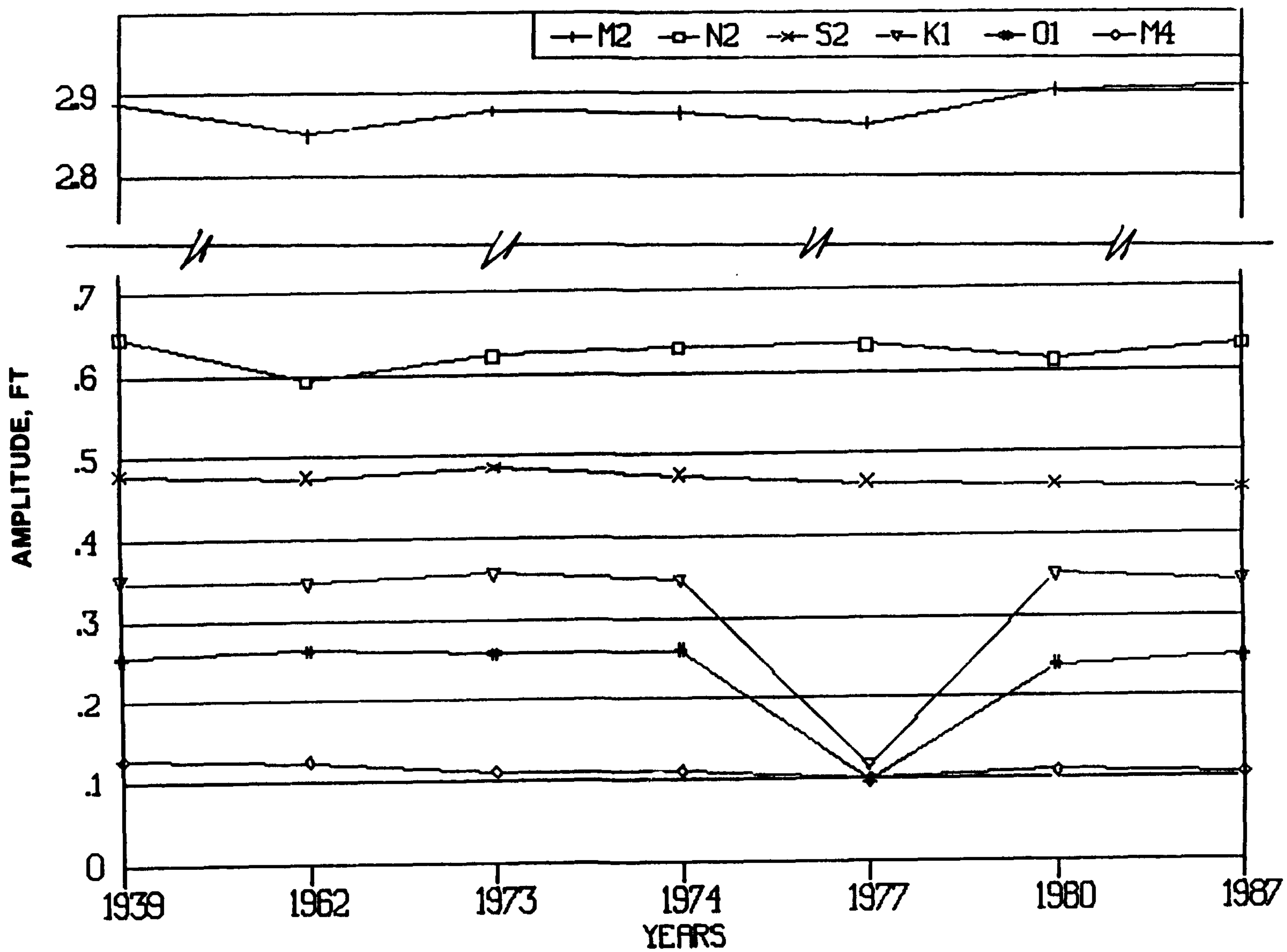


Figure B17. Tidal constituent ranges at Fernandina Beach

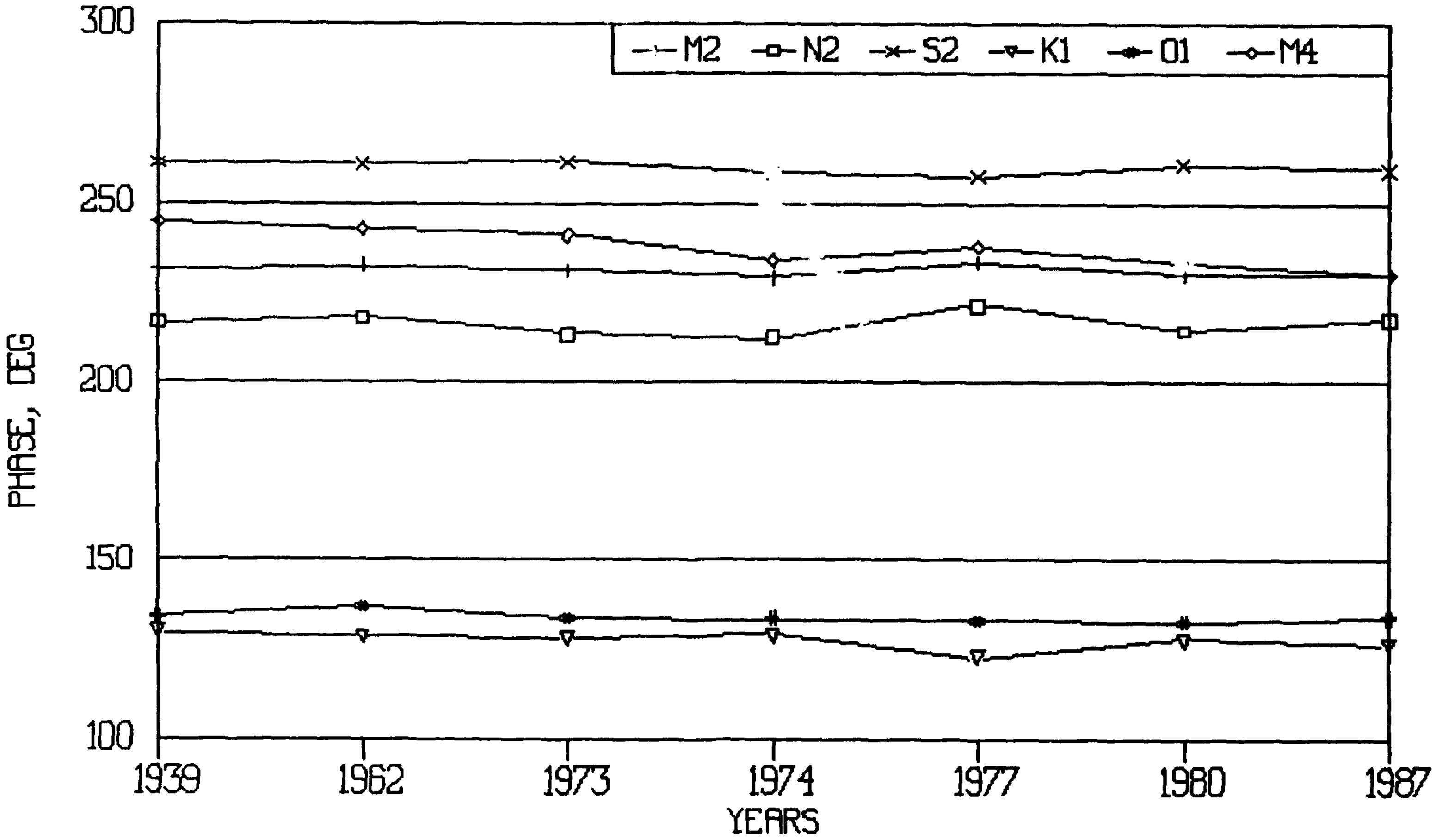


Figure B18. Tidal constituent phases at Fernandina Beach

The apparently spurious 1977 component amplitudes makes the phase rebound suspect. Reductions in phase angles were 2 to 14 deg (4 to 14 min). These suggest that earlier arrival times may be occurring in response to channel deepening as predicted by Plan OP-1 tests.

Responses in Other Estuaries

51. Tidal responses both similar to and different from those predicted for Cumberland Sound have been observed in other studies. Some examples are given below.

Charleston Harbor, SC

52. In physical model tests of deepening the channel from 35 to 40 ft, mixed results were observed. For a tide range of 5.4 ft and freshwater discharge of 15,600 cfs, midtide levels decreased very slightly at the Customs House gage in Charleston and at mile 18.5. They increased or remained the same at locations further up the river. In Back River Reservoir high, low, and midtide levels increased by about 0.2 ft. In the Ashley and Wando Rivers, which were not deepened, no significant change occurred. At 3500-cfs discharge, tide level changes at the Customs House were negligible and levels fell slightly in Back River Reservoir (Benson 1976). That channel deepening has not been accomplished in the prototype.

53. Mean prototype tides at the NOAA Customs House gage are shown in Figure B19. In addition to the 18.6-year cycle, a trend of increase in mean range can be seen. Mean water levels exhibit a pattern of increases and plateaus, like Fernandina Beach, that may or may not be related to channel enlargement. Linkage of the two is not apparent from the plot. The 35-ft channel was a huge dredging burden after the Santee-Cooper diversion in 1942, and the mid 1960's were a period of intense maintenance dredging in which the channel may not have been fully maintained.

54. A possible link between dredging events and water level increases at Charleston is not suggested as strongly as at Fernandina Beach, although it may still exist. That is consistent with the physical model results cited above, but undermines any argument for detecting a historical relationship at Fernandina Beach, as discussed in a subsequent section.

Georgetown Harbor, SC

55. In physical model tests, both high water levels and low water

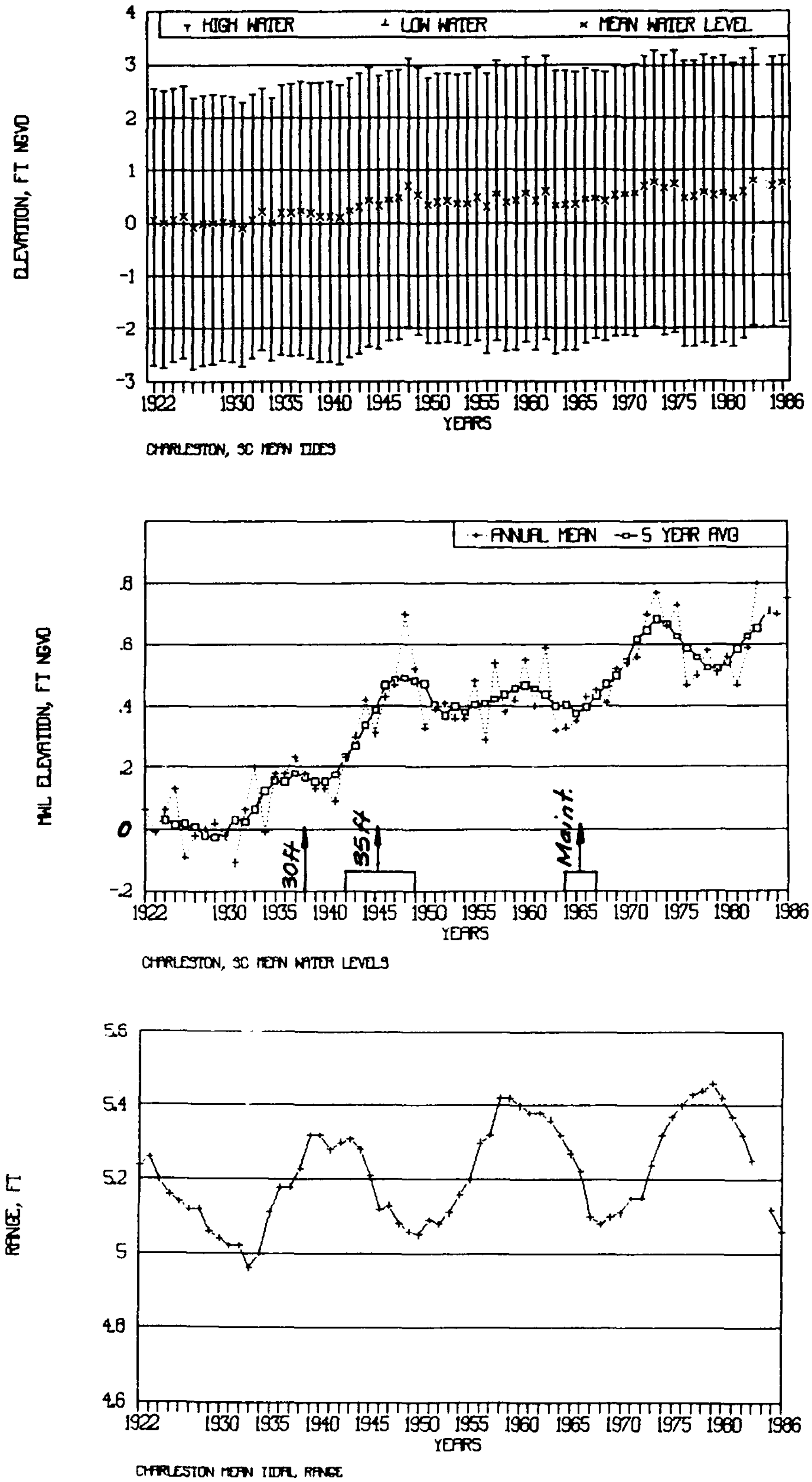


Figure B19. Tides at Charleston, SC

levels were increased about 0.2 ft in Winyah Bay and Georgetown Harbor after deepening the channel from 27 to 35 ft mlw (Trawle and Boland 1979).

Mobile Bay, AL

56. High water elevations decreased 0.3 ft at State Docks in the upper bay when the navigation channel was enlarged in the physical model from 40 ft by 400 ft wide to 50 ft by 500 ft wide. At Fowl River near mid-bay both high and low waters fell by about 0.2 ft (Berger and Boland, 1979).

Columbia River, OR

57. Physical model tests showed that high water elevations increased up to 0.4 ft after the channel was deepened from 48 ft to 60 ft mllw (McAnally et al. 1984).

Hampton Roads and Wilmington

58. Figures B20 and B21 show NOAA averages of tides at two locations — Hampton Roads, VA, and Wilmington, NC. The data show an increase in MWL at both locations, and a dramatic increase in tide range at Wilmington during a period of increasing channel depths. Channel enlargement periods are shown as given by USACE annual reports.

59. These two locations' records could be interpreted as showing a relationship between channel enlargement and water level, but they are not as suggestive as Fernandina Beach. In fact, some of the Wilmington enlargements (e.g., 1958) were followed by falling water level, although that may be attributable to other effects. The patterns are so similar that it seems unlikely that the major rises are solely related to channel enlargement, as discussed below. The effect on tide range at Wilmington seems more clearly related to channel enlargement, although again the evidence is not conclusive.

Elbe River, Germany

60. Tide levels have been measured on the Elbe River at St. Pauli (Hamburg), Germany, continuously since the 1850's. Until about 1900, the tide range tended to increase in consequence of a (and attendant fall in mean tide level) slowly falling mean low water. In about 1900, coincident with deepening of the navigation channel, the rate of low water fall sharply increased. In the 1940's, mean high water began to increase. Further channel deepening occurred in the later 1960's, 1970's, and 1980's, and high and low waters diverged even more during that period. From 1900 to 1988, tide range

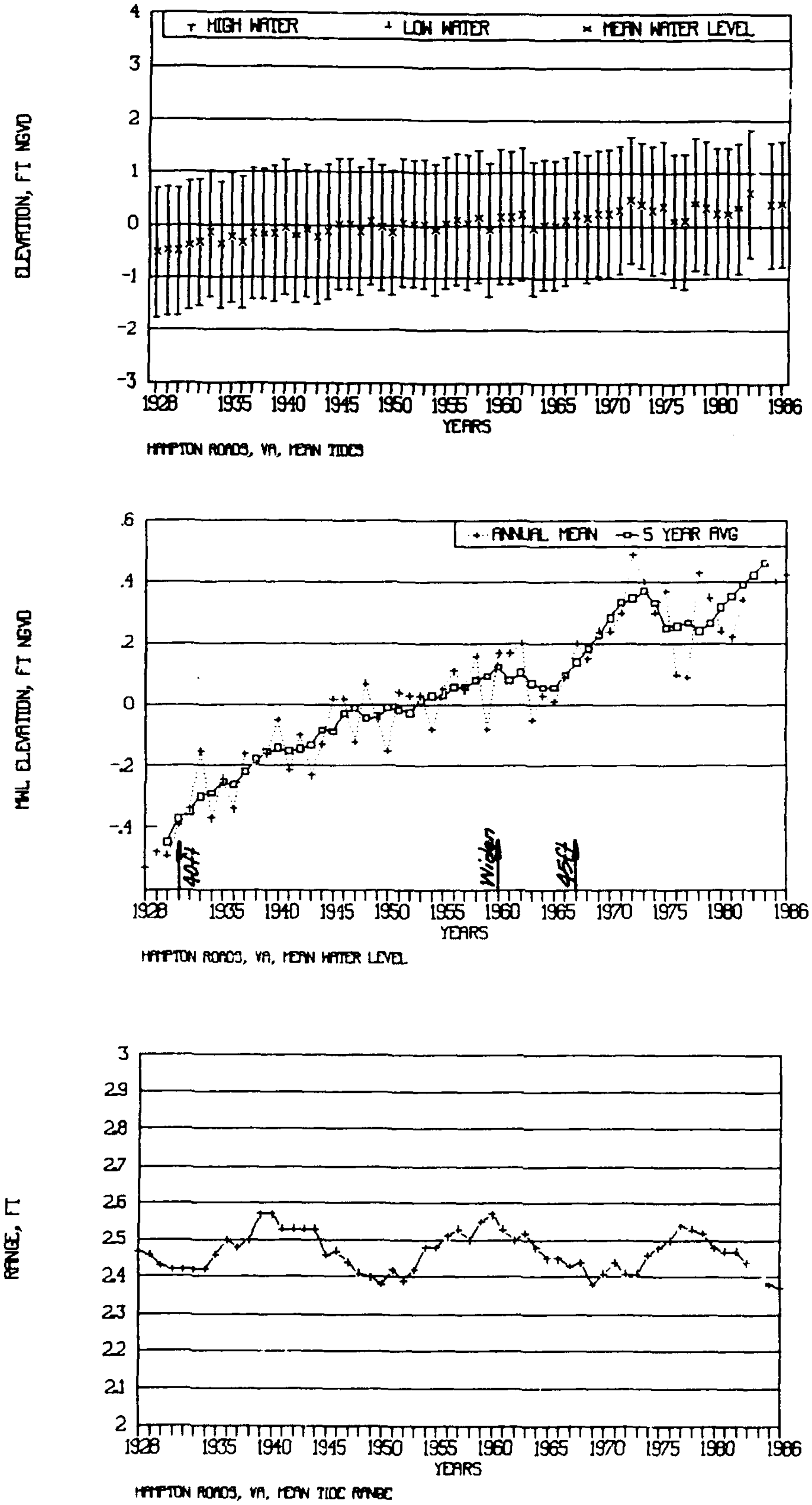


Figure B20. Tides at Hampton Roads, VA

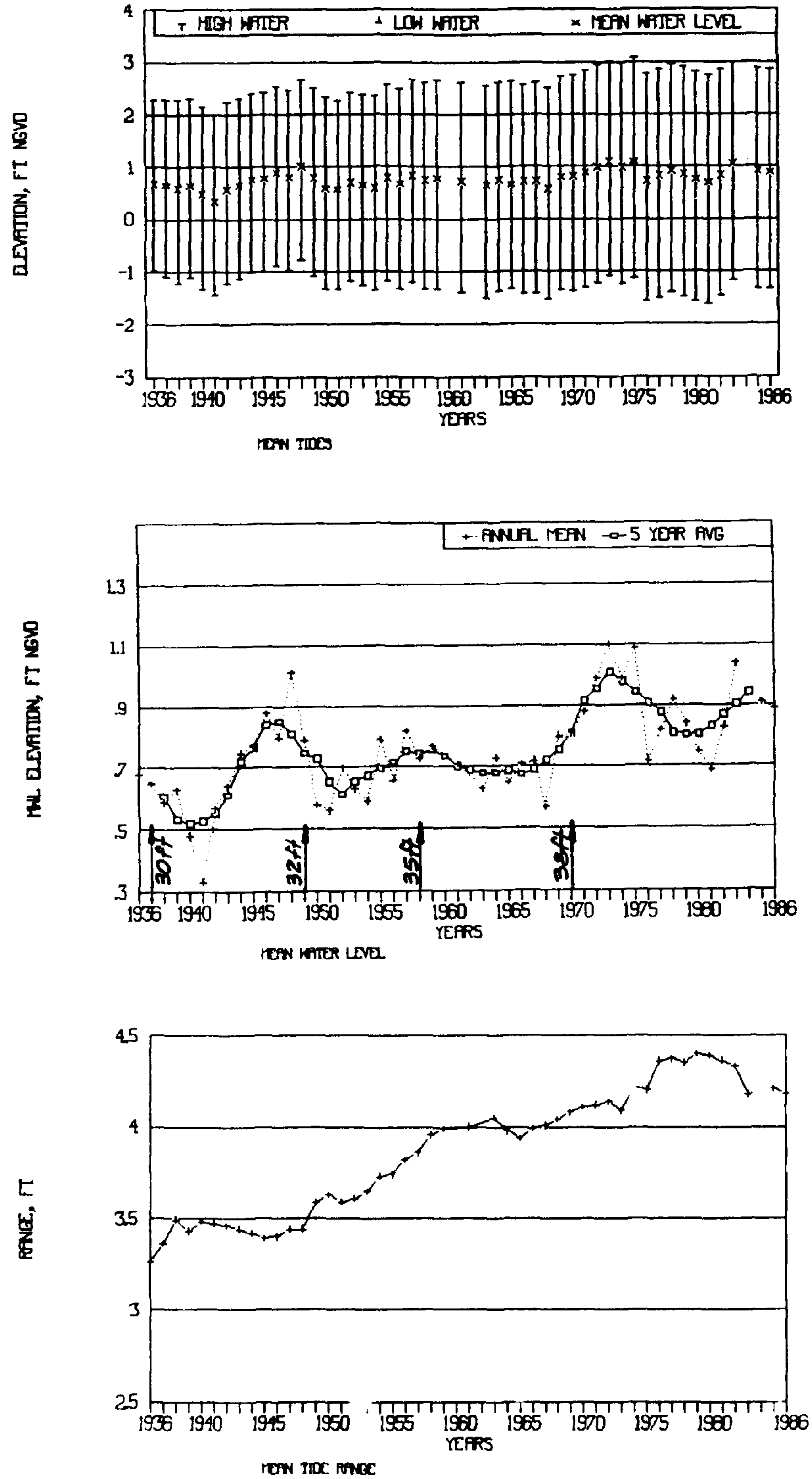


Figure B21. Tides at Wilmington, NC

increased by 4.8 ft (78%) and MTL fell by 0.9 ft (5%)*.

Possible Historical Relationships Between Channel Size and Water Levels at Several Sites

61. For the reasons given in the discussion of Fernandina Beach prototype tides, channel enlargement records may not reflect actual channel size over time, so that even if they are the cause of water level increases, the relationship may not be obvious. Furthermore, other processes, including eustatic sea level rise and geologic downwarping, may be occurring simultaneously, obscuring the relationship. The noisiness of the annual levels, as reflected in Figures B16 and B19-B21, makes it necessary to examine several years' data when performing analysis.

62. If such a cause and effect relationship exists, it will most certainly involve a complex set of interacting processes, including initial hydrodynamic response, slow morphological response, and subsequent hydrodynamic adjustment, all simultaneously interacting with the cyclic tidal variations (at time scales of weeks to decades) and episodic events (storms and floods). In light of these complexities, an obvious link between channel enlargement and mean water level changes — an immediate jump the same year as the enlargement — is too much to expect.

63. It is noted that the pattern of mwl rises seems similar in all four locations for which field data are presented; therefore, they are presented together with two more sites near Cumberland Sound in Figure B22.

64. Figure B22 shows the changes since 1941 in annual mean water levels at Fernandina Beach, Mayport, Savannah, Charleston, Hampton Roads, and Wilmington as 5-year running averages. The similarity of patterns among the six locations is striking. Peaks and troughs tend to occur in the same years and are of the same general magnitude. The most noticeable differences are: Hampton Roads rose more slowly in the 1940's; Mayport declined more than the others in the 1950's and 1970's; and Wilmington steadily declined in the 1960's. The latter may be explained by the fact that Wilmington is located in a zone of land rise (Stewart, 1975), which could cause water level to appear to fall. The similarity in patterns suggests that a phenomenon other than channel enlargement is responsible for the major trends seen in the plots.

---

* Personal communication with H. Christiansen, Port of Hamburg.

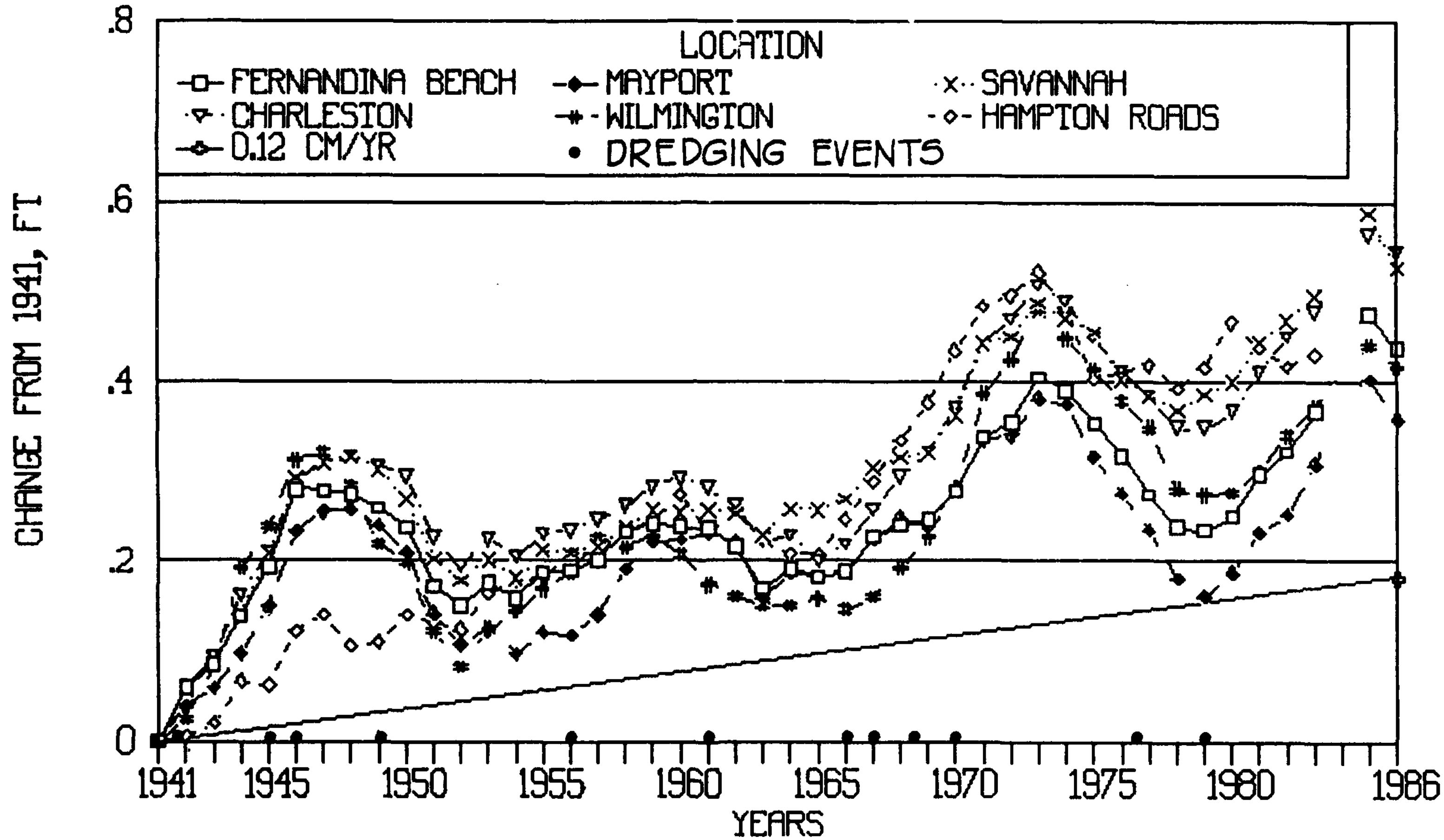


Figure B22. MWL 5-year average variation at six locations since 1941

65. Dredging events for all six sites are shown as dots across the plot bottom. Dredging was clustered in the early 1940's and again in the late 1960's, both periods of steepest rise in mean water level. Dredging, both channel enlargement and full maintenance, does occur in spurts corresponding to Federal budget variations and commercial traffic demands. That could lead to similar patterns among the various ports. Of particular interest is the steep increase beginning in the middle 1960's. Charleston and Hampton Roads began their ascent in 1965; whereas Wilmington and Fernandina Beach began in 1967 and 1969, respectively. All were about the same time as significant channel enlargements.

66. While Figure B22 can be argued to provide circumstantial evidence that the major water level rises are related to channel enlargement, we consider it too great a coincidence that the major rises and falls occurred both at about the same time and were of about the same magnitude at all six locations. Our interpretation of Figure B22 is that the major rises (the primary water level signal) illustrated were of geologic and/or oceanographic origin and not caused by navigation channel enlargements. However, secondary signals are obviously present that could have been channel induced. The interpretation of the major signal does not preclude the presence of a secondary channel enlargement effect, it simply fails to conclusively confirm or disprove it.

Analysis of Recent Field Data

67. Recent NOAA field observations of mean water levels at Fernandina Beach, Savannah, and Mayport were examined for evidence for or against a Trident-channel induced rise. Figure B23 shows annual MWL at all three locations since 1940. Monthly mean water levels determined by NOAA were averaged to obtain annual means, which were used to calculate the year-to-year change at each location. The following notation is adopted: CWL, change in water level, for year N, at Fernandina Beach (F), Savannah (S), and Mayport (M), respectively, is shown thus,

$$CWL(F,N) = MWL(F,N) - MWL(F,N-1)$$
$$CWL(S,N) = MWL(S,N) - MWL(S,N-1)$$
$$CWL(M,N) = MWL(M,N) - MWL(M,N-1)$$

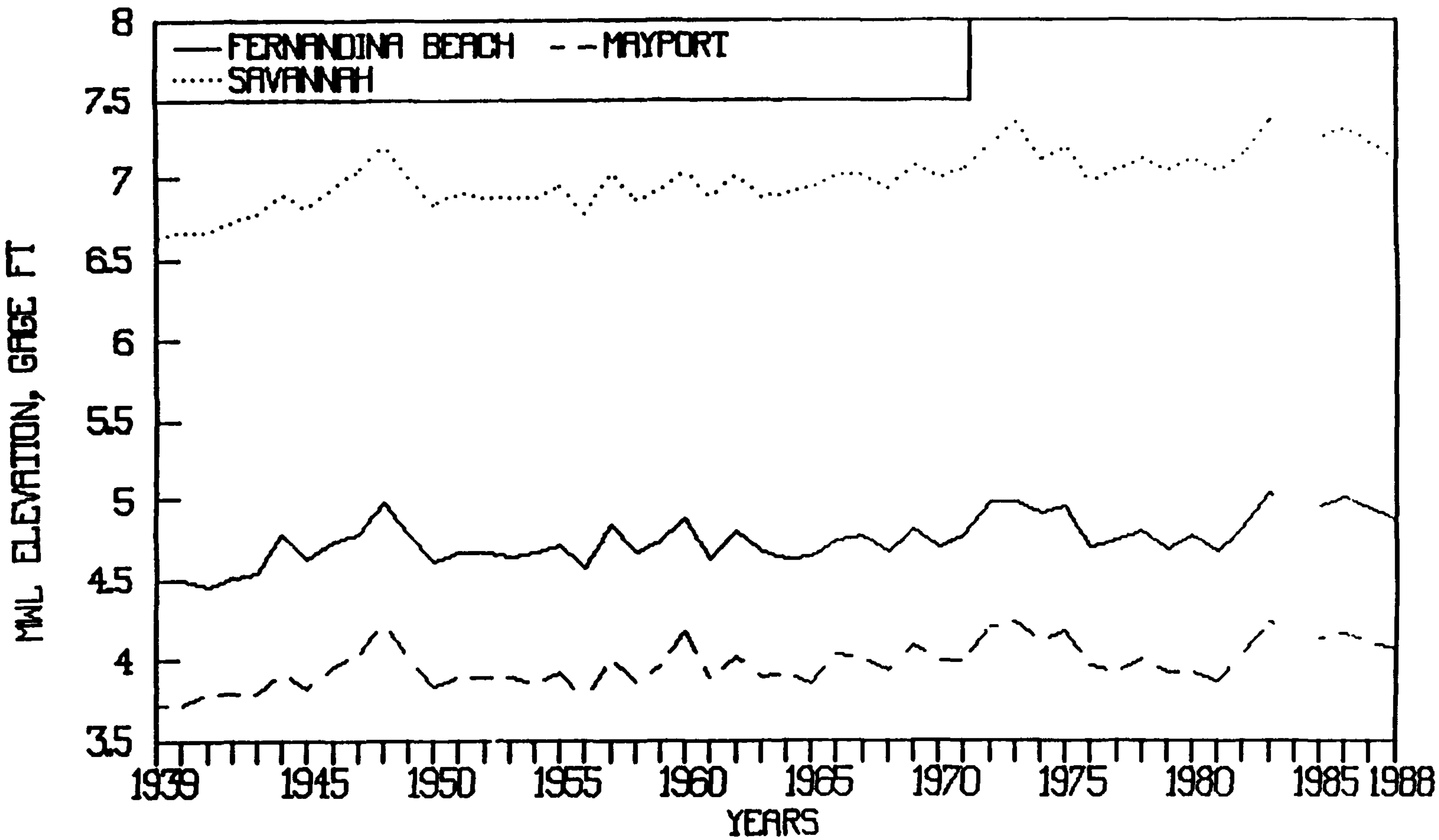


Figure B23. MWL annual variation at three locations

This calculation removes the datum planes from the data. For some years, one or more months' data were missing at the stations. In those cases, more than one CWL change was computed, so that the changes would be truly comparable. For example, in 1988, June was missing from the Savannah data, and April was missing from the Mayport data; so a 10-month MWL (both April and June omitted) was calculated for both stations for comparison with each other. These special calculations were required for 1988 and 1984. In 1977 the Savannah record had 7 months missing, so no changes were computed at that location in that year.

68. If the annual changes were due only to a uniform sea level rise or fall, the CWL would be equal at all three locations. CWL for 1940-1988 is plotted in Figures B24a and B24b (Fernandina vs. Savannah and Fernandina vs. Mayport). A high degree of correlation is evident in both. The R-squared correlation coefficient is 0.91 for Fernandina-Savannah and 0.88 for Fernandina-Mayport, and the standard error in estimating Fernandina CWL from Savannah and Mayport CWLs using a linear curve least-squares fit is 0.04 ft for both.

69. The degree of correlation is striking, though water levels at Fernandina and Mayport may not be truly independent. The connection between Cumberland Sound and the St. Johns River via the AIWW could cause some degree of linkage between tides at those two gages, though the statistics given above do not suggest it. Figure 24 does show that CWL at Mayport and Savannah can be used to evaluate CWL at Fernandina to a higher degree of confidence than from Fernandina records only.

<u>Single-year changes in MWL</u>

70. Since MWL changes at the three locations are highly correlated, a dramatic and unique 1-year change in MWL at any of them should be identifiable as a difference in the annual CWL values, provided that it is larger than the natural noise of the data. The notation is extended to the difference in CWL as

$$DCWL(FS,N) = CWL(F,N) - CWL(S,N)$$
$$DCWL(FM,N) = CWL(F,N) - CWL(M.N)$$

with FS indicating Fernandina to Savannah and FM indicating Fernandina to Mayport. A positive DCWL value indicates that Fernandina Beach MWL rose more,

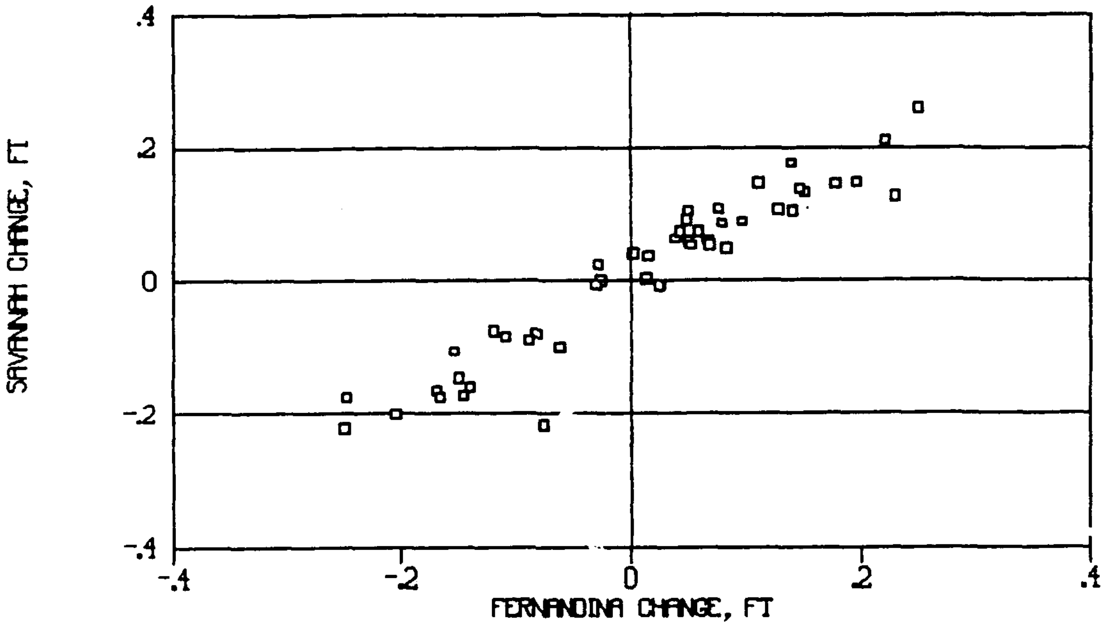


Figure B24a. One-year change in annual MWL at Fernandina vs Savannah

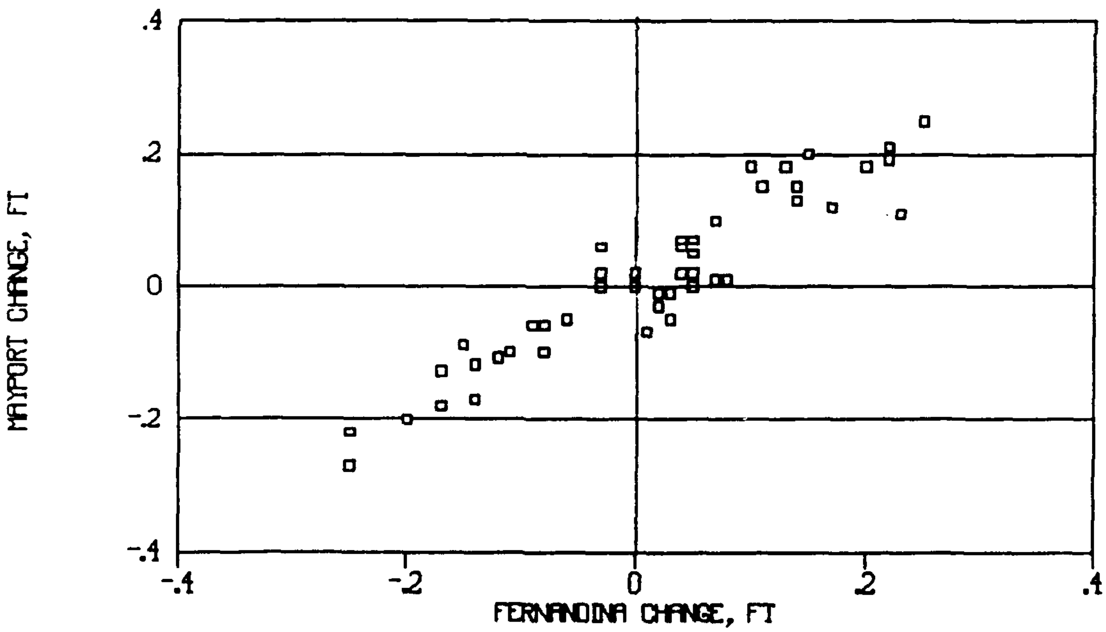


Figure B24b. One-year change in annual MWL at Fernandina vs Mayport or fell less, than that at the other location, thus it reflects a relative rise at Fernandina Beach.

71. Figures B25a and B25b show DCWL combinations plotted for 1940-1988. Dredging events are again shown across the bottom. Maximum DCWL values of about ±0.1 ft have occurred during the period of record and the standard deviation of the calculated result is about 0.04 ft. The single year differences of about 0.1 ft are quite noticeable, as for example, the 1974 rise of 0.14 ft at Fernandina relative to Savannah.

72. For the Trident dredging period of 1984-1988, the maximum positive Fernandina DCWL was 0.04 ft with respect to both Savannah and Mayport. Thus we can conclude that the maximum possible Trident-induced 1-year rise is between 0 and 0.08 ft (0.04 ft ±0.04 ft) for that period. The maximum may also not have occurred yet but will be detectable in 1989 or after.

Multiple-year rises in MWL

73. The plots of Figure B25 limit 1-year rises to about 0.04 ft or less, but they do not exclude the possibility of a larger gradual rise spread over several years. To examine that possibility, a cumulative DCWL was calculated and plotted. In terms of the previous notation, the cumulative DCWL is

$$SUM\_DCWL(FS,N) = DCWL(FS,1) + DCWL(FS,2) + \ldots + DCWL(FS,N).$$

74. SUM_DCWL for Fernandina vs. Savannah is plotted in Figure B26 along with the dredging periods. They show a trend of decreasing difference, or that Fernandina was rising more slowly than Savannah MWL until the abrupt 1974 rise, after which the relative fall continued until about 1980. Since 1980, the trend has reversed with an almost steady climb through 1988. To better quantify the changes, the linear trend was removed from the data (a linear least squares fit was subtracted from the values) and they were replotted in Figure B27, along with a 5-year running average.

75. Figure B27 shows the post-1980 cumulative difference climbing, with the 5-year average increasing monotonically to 1986. At that point it is 0.06 ft, about 1.5 times the standard deviation, above the trend line and a 50-year-high value.

76. Figure B28 shows the cumulative difference for Fernandina minus Mayport. As with the Savannah comparison, there has been a relative Fernandina rise since about 1980 (following Poseidon channel enlargement), and by

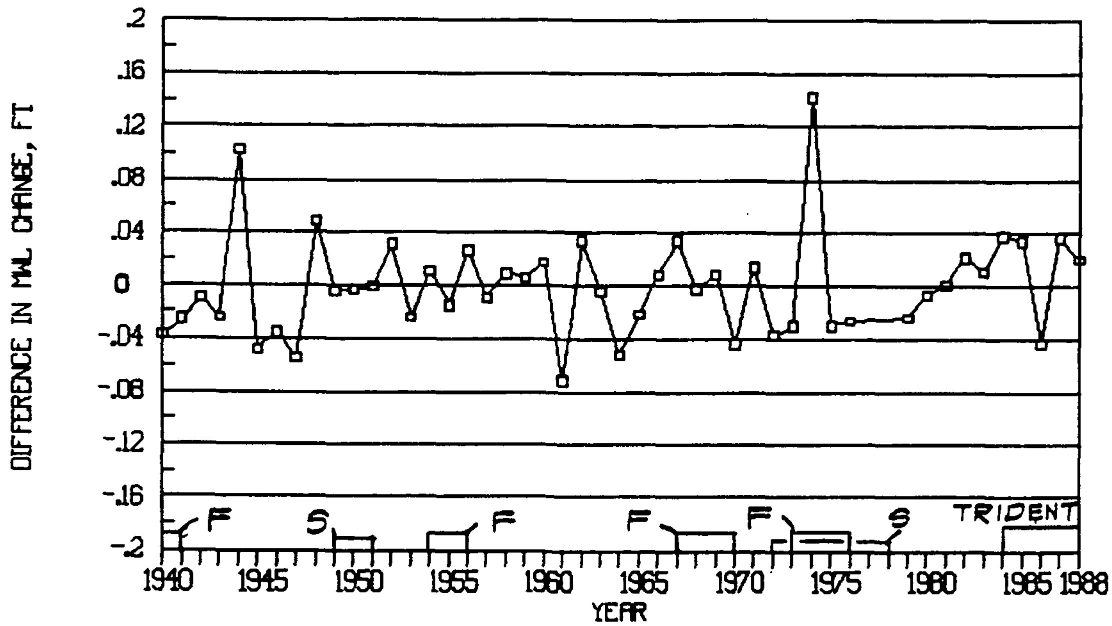


Figure B25a. DCWL, difference in MWL changes, Fernandina - Savannah

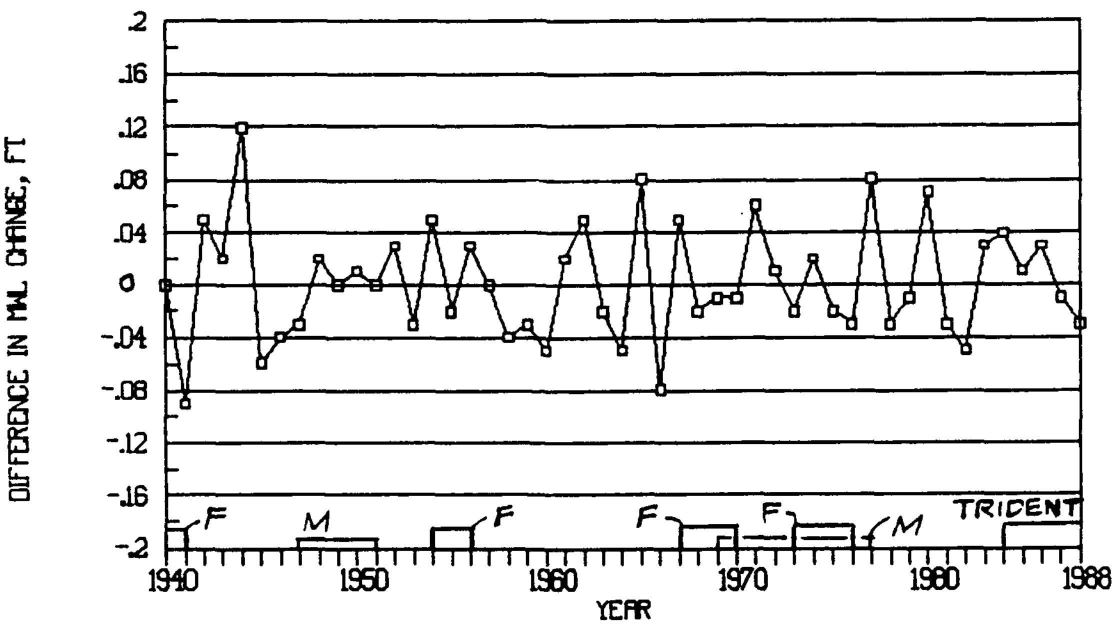


Figure B25b. DCWL, difference in MWL changes, Fernandina - Mayport

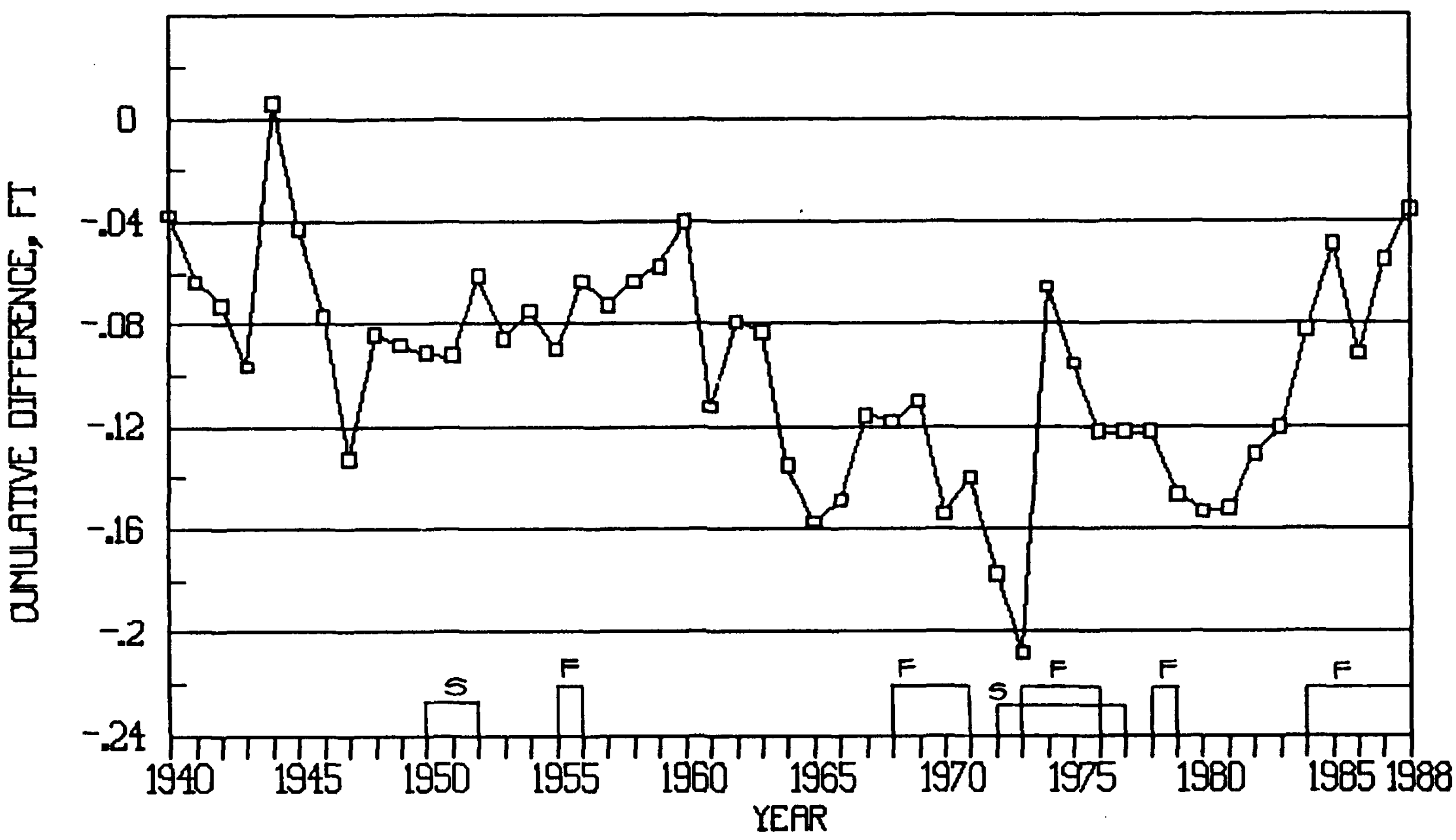


Figure B26. Cumulative MWL changes, Fernandina vs. Savannah

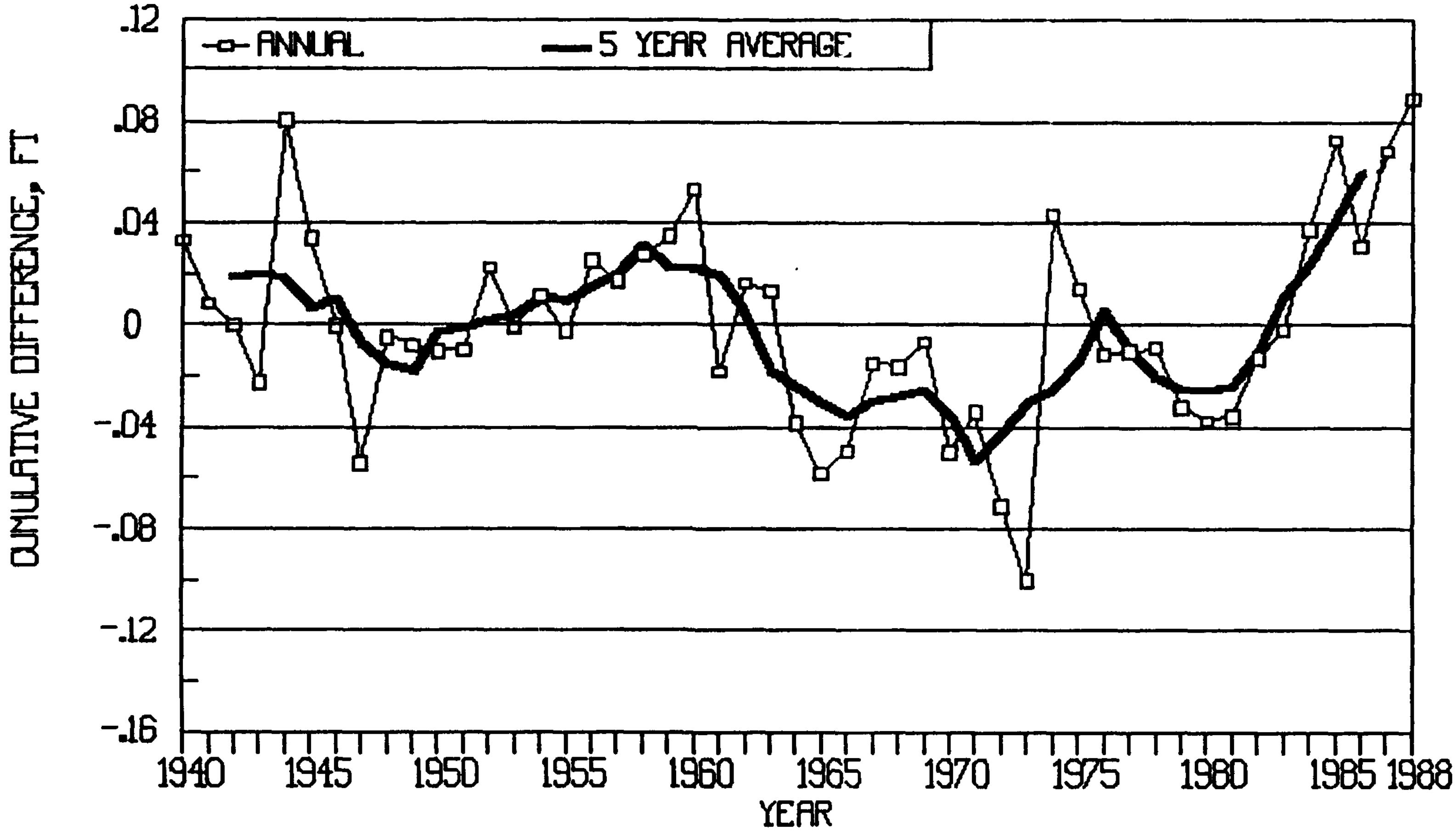


Figure B27. Cumulative MWL changes, Fernandina vs. Savannah, with trend removed

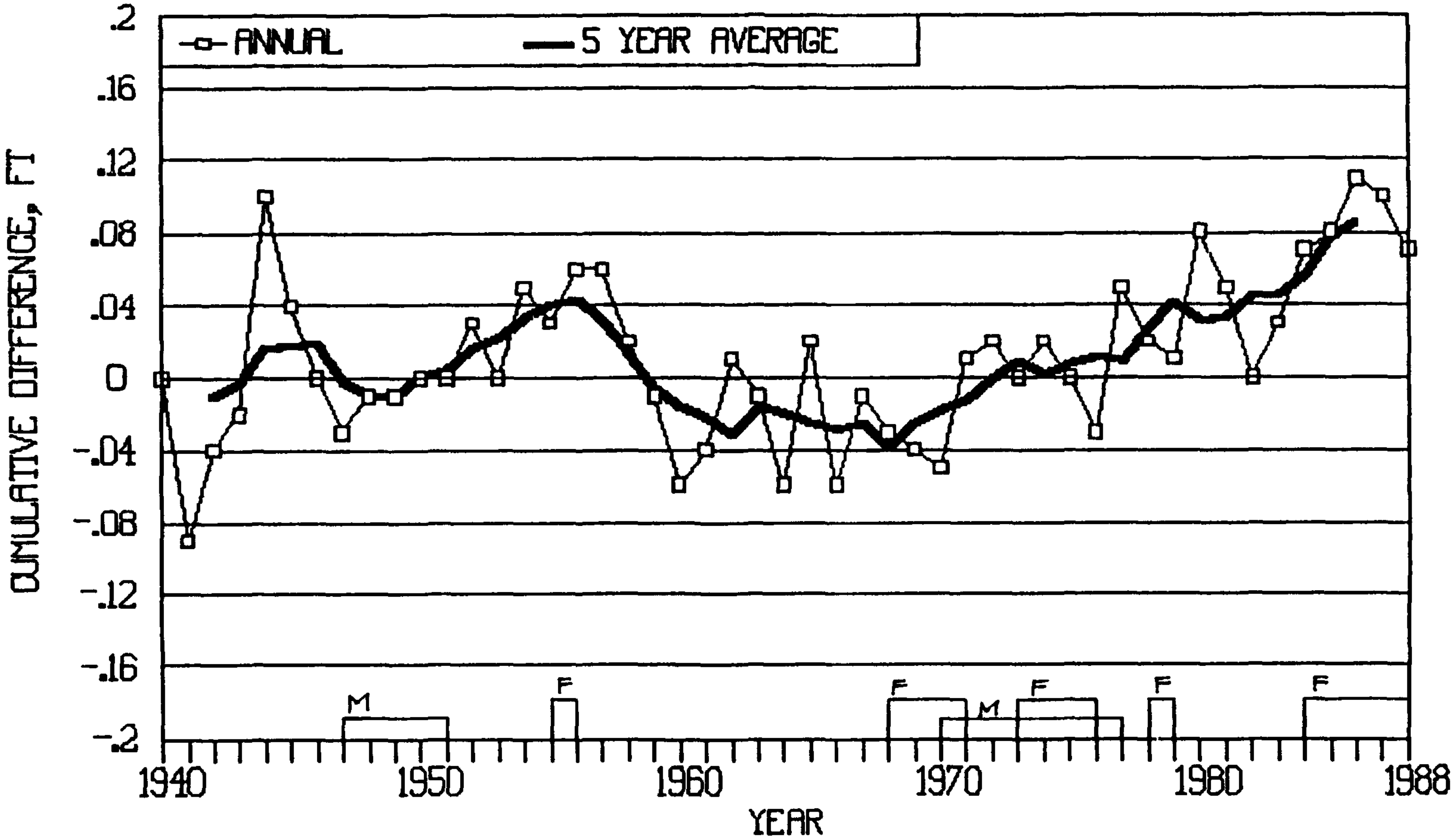


Figure B28. Cumulative annual mwl changes, Fernandina vs. Mayport

1988 it was about 0.08 ft, two standard deviations above the long-term mean of 0.01 ft. Like Fernandina minus Savannah, that is the highest cumulative difference in the 50 year record.

77. These results support the possibility that the predicted Trident-induced MWL rise has been occurring gradually over several years, but they do not prove it. (In fact, they may prove only that data can be decomposed to the point of absurdity.) The change is still small with respect to the noisiness of the data, and several more years' water level data will be required to confirm or disprove the effect. If it is occurring, the best present estimate of the possible magnitude of the rise based on this analysis is 0 to 0.08 ft through 1988.

78. Since tide data were missing for at least half of 1984 (in the midst of dredging) at all three locations, we were concerned that using a partial year CWL might introduce a misleading error in the SUM_DCWL. Therefore we constructed an MWL data set consisting of only July-December average monthly water levels for Fernandina and Mayport and repeated the above analyses for that data set. The resulting SUM_DCWL is shown in Figure B29. It can be seen that the 5-year average in 1986 is about 0.06 ft above the long-term average. That is close enough to the annual results (0.08 ft) to show that they are not seriously distorted by the 1984 partial year.

79. One further examination of the data was performed. Since there is a large annual variation in monthly MWL, we thought the response may vary during the year. The Fernandina-Mayport SUM_DCWL was calculated for February, the month of lowest MWL, and October, the month of highest MWL (see Figure B15). Results are plotted in Figure B30*. Both months display a post-1980 Fernandina cumulative rise above the long-term mean value. October is 0.10 ft above the long term mean; whereas, February SUM_DCWL is only 0.04 ft above the long term mean. If we assume that a post-1980 channel-induced rise has occurred, these results suggest that it is weighted to periods when mean water levels are naturally higher than usual. i.e., autumn. Thus, if sea level were to fall slightly for a few years (as it has in the past), the

---

* Note that in these figures only, 1989 data are used. Data for that year were obtained after preparation of this document, but monthly mean water levels were not available for 3 of the 12 months. The annual average mean water level thus could not be used with confidence.

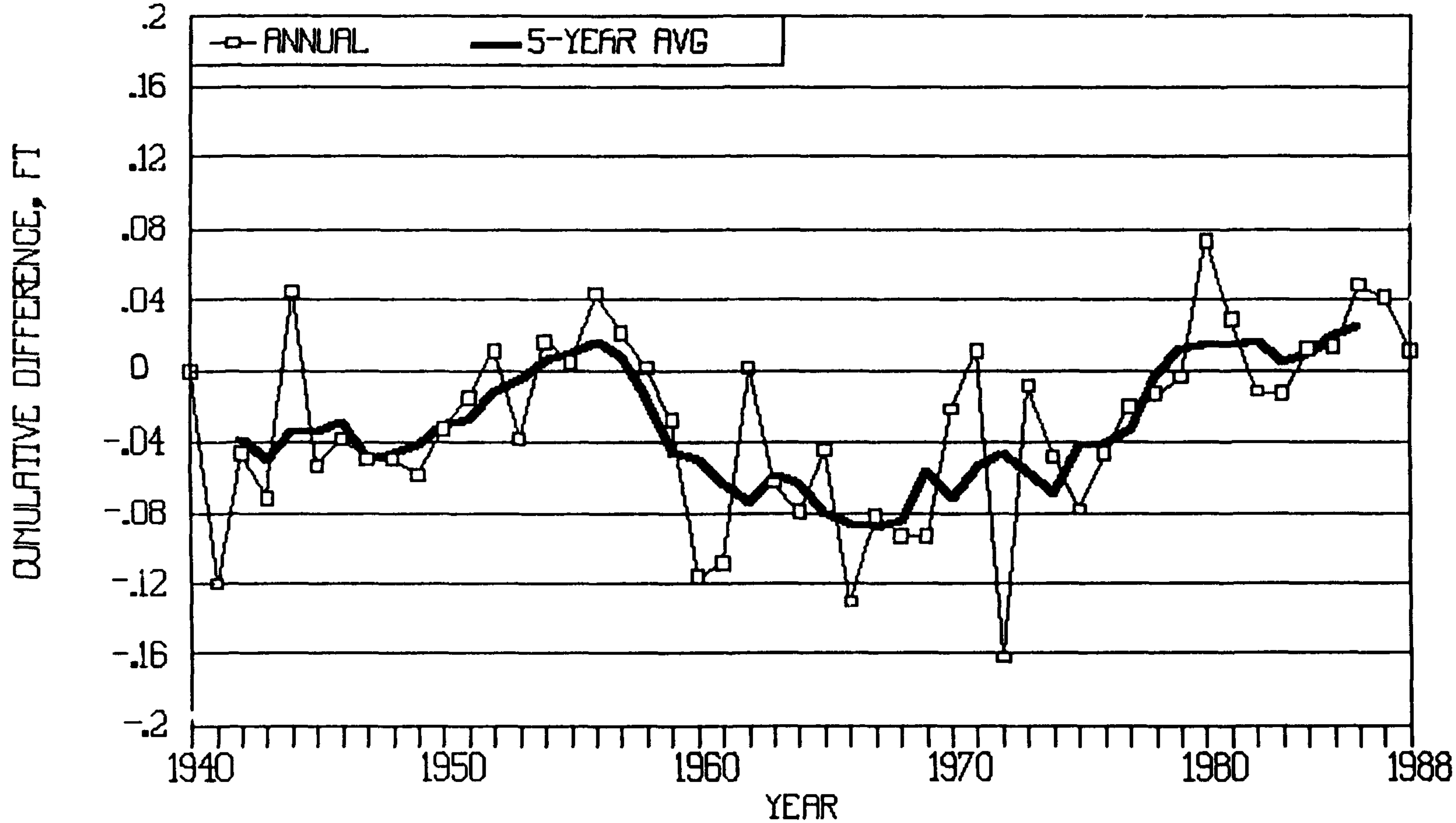


Figure B29. Cumulative July-December MWL changes, Fernandina vs. Mayport

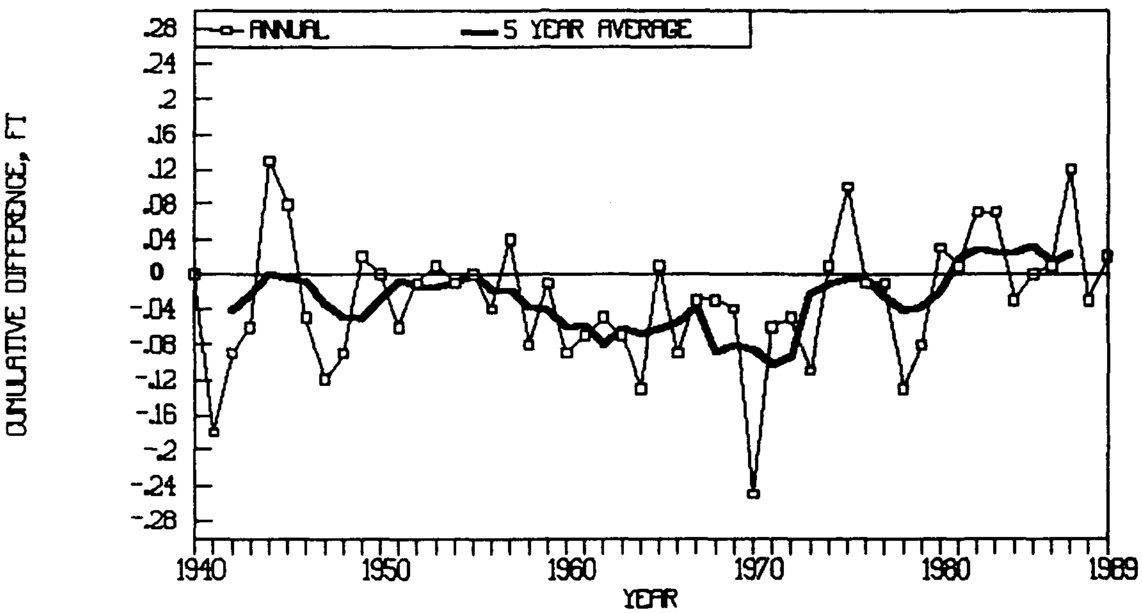


Figure B30a. Cumulative February MWL changes, Fernandina-Mayport

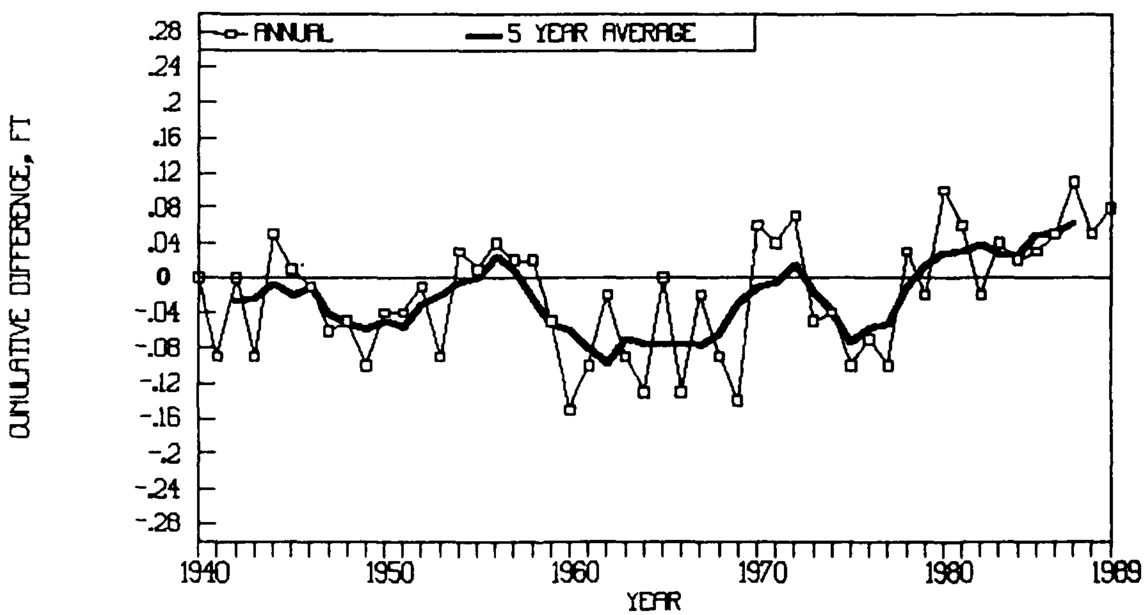


Figure B30b. Cumulative October MWL changes, Fernandina-Mayport effect would diminish, and if sea level were to rise the effect would increase.

A Possible Physical Explanation

80. A heuristic explanation of the increase in Cumberland Sound water levels can be constructed. It has been noted (e.g. Noye 1974 and Cross 1968) that a tide well connected to the sea by an orifice responds nonlinearly to waves, and water level set-down within the well can result. We do not have long-term field tide data in the ocean at St. Marys Inlet*, but the physical model clearly showed that a set-down existed for the base condition and that it diminished for the plan tests. If we assume a nonlinear mean tide level relationship induced by the constricted inlet and open sound, then increasing the inlet cross-sectional area would diminish the effect, raising water levels within the sound.

King's model

81. King (1974) followed Keulegan (1967) in developing a bay response model from the one-dimensional conservation of mass and momentum equations. Using major assumptions of:

- a. Size of the system is small compared to the tide wave length.
- b. Inlet depth is large compared to tide range, but inlet volume is very small compared to bay volume.
- c. Freshwater flow and stratification are negligble.
- d. Temporal acceleration can be neglected.
- e. Inlet cross-sectional area and bay surface area vary linearly from low tide level to high tide level.
- f. Water level in the inlet can be described as the average of ocean and bay water levels.

Assumption e. is the weakest of these, since the intertidal marsh areas tend to be quite flat. The other assumptions, while significant simplifications, are reasonably descriptive of the Cumberland Sound System.

---

* A NOAA tide gage was operated briefly outside the sound on the Fernandina Beach Pier. During January 1954, when both gages were simultaneously in operation, MTL at the inside gage averaged 0.07 ft below that of the outside gage.

The equation below is derived

$$\frac{\partial \eta_b}{\partial \theta} = \pm \frac{\bar{A}_c T}{\bar{A}_b a_o} \frac{\left[1 + N_1 \left[\frac{\eta_o + \eta_b}{2}\right]\right]}{\left[1 + N_2 \frac{a_o}{a_b} \left(\eta_b - \Delta\right)\right]} \left[\frac{2ga_o}{1 + \frac{f\ell}{4R}}\right]^{1/2} \left|\eta_o - \eta_b\right|^{1/2} \tag{B4}$$

where

η_b = Bay water level divided by a_o

a_o = Ocean tide amplitude

θ = Time divided by tidal period

η_o = Ocean water level divided by a_o

a_b = Bay tide amplitude

Δ = Bay mean water level setup (over ocean mean water level) divided by a_o

T = Tidal period

A_c = Cross-sectional area of inlet

A_b = Surface area of bay

g = Accelleration of gravity

f = Darcy friction factor

ℓ = Inlet length

$$N_1 = \frac{A_{cmax} - A_{cmin}}{2\bar{A}_c} \tag{B5}$$

$$N_2 = \frac{A_{bmax} - A_{bmin}}{2\bar{A}_b} \tag{B5}$$

$$R = \bar{d} + a_o\left(\frac{\eta_o + \eta_b}{2}\right) \tag{B7}$$

where

$\bar{d}$ = Inlet mean water depth

The overbar indicates mean value over the tidal cycle, and subscripts max and min indicate values at high water and low water, respectively. (Note: King omitted inlet and exit losses in his equation, showing that they were small for his cases of interest. We have left them in as the "1" in the second term of Equation B4, following Keulegan).

82. King applied the model to Siletz Bay, Oregon, with satisfactory results. He then performed calculations over a range of representative values for the geometry variables. He found that bay superelevation increased with increasing values of N_1 and decreasing $\bar{d}/a_o$. Superelevation decreased with increasing N_2 and sometimes became negative, the setdown phenomenon of interest here.

83. We solved Equation B4 by means of a fourth order Runge-Kutta scheme. King's results were replicated, then the equation was altered by restoring the entrance and exit loss term before solving for the Cumberland Sound case.

84. St. Marys Inlet cross-sectional areas and Cumberland Sound surface areas were measured by planimetering cross-section plots and sound maps, respectively. Of these measurements, the maximum (high water) surface area of the sound was the most difficult to accurately obtain since vegetation often obscures the high water line in aerial photos used for mapping. Inlet depth and length were measured from the same maps, and roughness coefficients were estimated based on values used in numerical modeling of the inlet. Table B4 shows the best estimate of each of the input parameters for the base and plan condition plus high and low estimates for the base condition.

85. Shown in Table B5 are results of solving Equation B4 for the listed input parameters. Under base conditions (Poseidon channels), the equation yields a best estimate that the sound will experience an MTL setdown of 0.11 ft below that of the ocean and an MWL setdown of 0.04 ft. These values are qualitatively similar to the physical model values but about half as large.

86. Table B5 shows that the best estimates for plan condition MTL and MWL are, to two significant digits, equal to those of the base. Including a third significant digit shows the plan setdown values to be slightly smaller than those of the base. Thus the change is in the same direction as the physical model tests, but two orders of magnitude smaller.

87. The Low Estimate and High Estimate columns in Table B4 were used in a number of calculations to determine sensitivity of the results to the input data. Over the range of values shown in the table, Cumberland Sound MTL ranged from 0.004 ft below mean ocean level to as much as 0.2 ft below mean

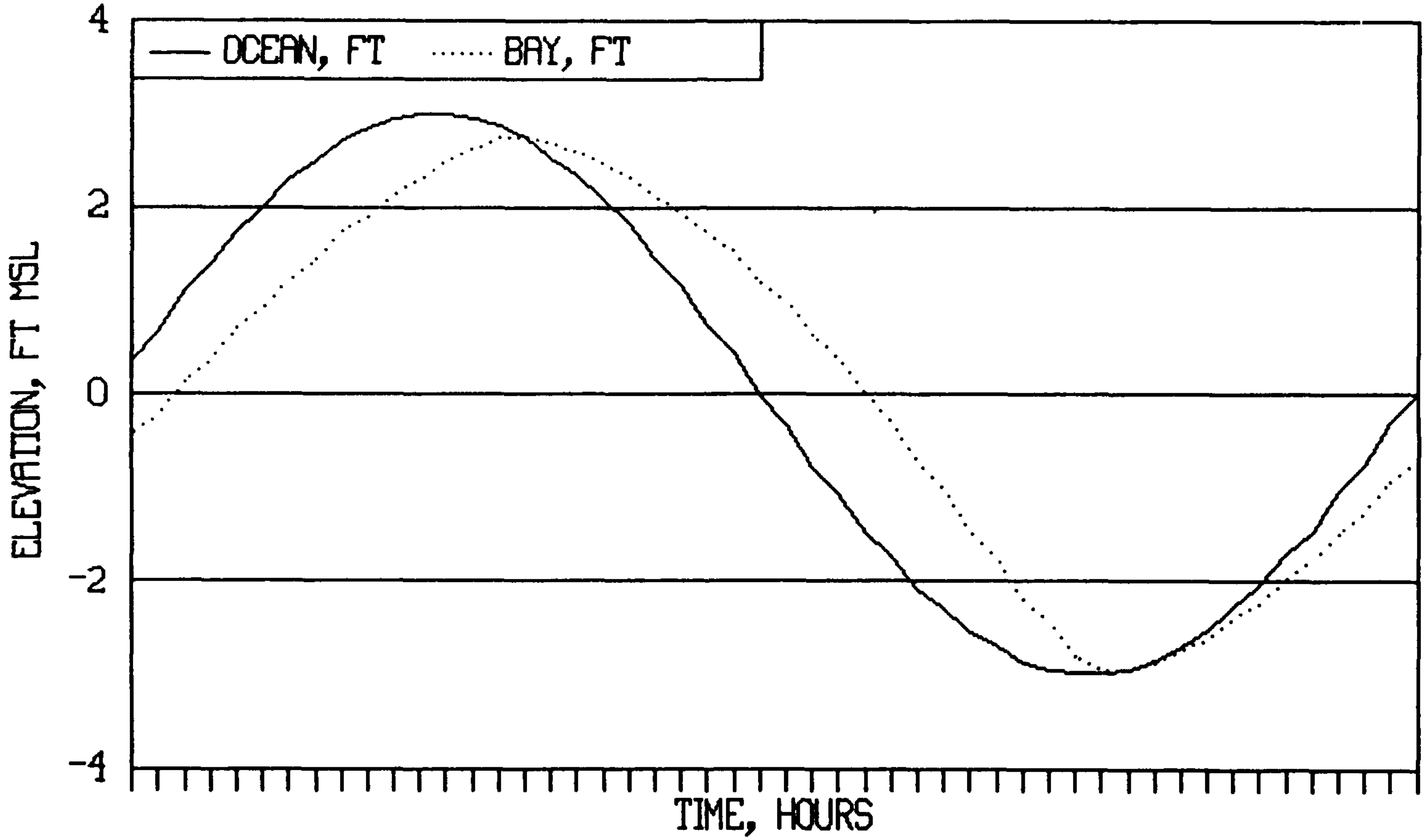


Figure B31. Tides calculated by King's Solution for the best estimate of base condition parameters ocean level. MWL setdown varied from 0.005 to 0.05 ft. In general, a smaller inlet and a larger high water surface area in the sound led to larger setdown values.

88. Figure B31 shows the calculated time histories for ocean and sound tides for the base conditions, best estimate input values. It can be seen that the setdown effect was the result of calculated sound high water levels being depressed more than low waters, producing a tide with a broader, flat peak and a narrower, sharper trough than the ocean sinusoidal tide. This effect can be conceptually justified by reasoning that a parcel of water entering or leaving the bay at low water more effectively alters the water level than does a parcel entering or leaving near high water since a unit volume will be distributed over a larger surface area at high water. Thus a sinusoidal ocean tide will produce a flatter high water peak on the bay tide. Such a distorted tide has been identified in other numerical studies of estuaries with extensive tidal flats (Speer and Aubrey 1985).

89. These results show that a sound setdown relative to the ocean is a theoretical possibility. They differ from the physical model results in that high water and low water are affected differently instead of uniformly. Refinements of the estimates for input parameters (such as sound surface area) are not expected to shed additional light on the situation because differences between real systems and the idealized inlet-bay system prevent subtle discrimination of such features.

<u>DiLorenzo's model</u>

90. DiLorenzo (1986), like King, began with the one-dimensional equations of motion for a simple ocean-bay system. He also used the same major assumptions and added assumptions that the first overtide component (for example, the shallow water lunar constituent, M_4) is an order of magnitude smaller than the fundamental tidal component (e.g., the lunar semi-diurnal component, M_2) and that higher harmonics do not contribute significantly to the bay tide.

91. By the method of harmonic balance, DiLorenzo selected the solution:

$$\eta_b = \frac{\Delta}{2} + \frac{a_1}{2i} \exp\left[i\left(\alpha\tau - \epsilon_1\right)\right] + \frac{a_2}{2i} \exp\left[i\left(2\alpha\tau - \epsilon_2\right)\right] + \text{c.c.} \qquad \text{(B8)}$$

where

$\tau = \Omega_h t$

$\alpha = \frac{1}{\Omega_h T}$

$\Omega_h = \left[\frac{g \bar{A}_c}{\ell \bar{A}_b} \right]^{1/2}$

Δ = bay mean water level setup divided by a_o

a_o = ocean tide amplitude

a_1 = amplitude of the fundamental tide constituent (e.g., M_2) in the bay, divided by a_o

a_2 = amplitude of the first overtide (e.g., M_4) in the bay, divided by a_o

$i = \sqrt{-1}$

ϵ_1 = phase difference of fundamental tide component between the ocean and bay

ϵ_2 = phase difference of first overtide between ocean and bay

t = time

T = period of the fundamental tide

Ω = Helmholtz frequency

$\bar{A}_c$ = Inlet average cross-sectional area

$\bar{A}_b$ = Bay average surface area

ℓ = Inlet length

c.c. = complex conjugate terms

Substituting Equation B8 into the equation of motion and assuming that inlet and bay area are constant produces these solutions for the bay tidal response.

$$\Delta = -\frac{3}{5} \nu a_1 a_2 \cos(\epsilon_2 - 2\epsilon_1) \qquad \text{(B9)}$$

$$a_1 = \frac{\left[(1-\alpha^2)^4 + \nu \right]^{1/2} - (1-\alpha^2)^2}{\frac{1}{2} \nu^2} \qquad \text{(B10)}$$

$$\epsilon_1 = \tan^{-1} \left[\frac{5\nu a_1 - 2\nu a_2}{10(1-\alpha^2)} \right] \qquad \text{(B11)}$$

$$a_2 = \frac{\xi}{\left[(1 - 4\alpha^2)^2 + \frac{64}{25}\nu^2 a_1{}^2\right]^{1/2}} \quad \text{(B12)}$$

$$\gamma + \epsilon_2 = \tan^{-1}\left[\frac{8\nu a_1}{5(1 - 4\alpha^2)}\right] \quad \text{(B13)}$$

where

$$\nu = \frac{16\alpha^2\beta}{3\pi}$$

$$\beta = \frac{F\, a_o\, \bar{A}_b}{\ell\, \bar{A}_c}$$

$$F = k_{en} + k_{ex} + \frac{f\, \ell\, (b + 2\bar{d})}{\bar{A}_c}$$

ξ = ratio of first ocean overtide component amplitude to ocean fundamental tide component

γ = phase difference between first ocean overtide and ocean fundamental tidal component

k_{en} = entrance loss coefficient

k_{ex} = exit loss coefficient

b = inlet width

$\bar{d}$ = average inlet depth.

Equations B9-B13 permit general bay tidal responses to be examined as functions of the readily determined Helmholtz frequency and the damping coefficient β .

92. Bay setup defined by equation B9 varies in sign as a periodic function on $\epsilon_2 - 2\epsilon_1$, producing a setup or setdown as the phasing between the fundamental and first overtide components changes.

93. Equations B9-B13 constitute a set of five simultaneous equations with five unknowns, provided that the ocean tide fundamental and first overtide components' amplitude and phase are known. In the case of Cumberland Sound, we do know a_1 and a_2 (see Table B3) but do not have the ocean tide component information so there are six unknowns and the equations cannot be solved.

94. The amplitude part of Equation B9 (the maximum MWL setdown) can be calculated from the geometric information in Table B4 and the M_2 and M_4 component amplitudes from Table B3. The best estimate values for the physical characteristics give values of ±0.01 ft for a 6-ft ocean tide range. That is the same order of magnitude as that calculated by King's equation.

95. DiLorenzo expands his analysis conceptually to the case of variable inlet and bay areas, noting that variable inlet cross-sectional area favors flood-dominant (peak flood velocities higher than peak ebb velocities) conditions and possible bay setdown. In contrast, he asserts that a variable bay surface area tends to make the system ebb-dominant with a possible bay setup.

PART V: DISCUSSION AND SUMMARY

Model Results

96. The degree of physical model verification to tides was fair overall and good at Fernandina Beach and Kings Bay. This degree was satisfactory for the intended purposes, but is less than desirable for the precise prediction of tides. An examination of boundary tides for the physical model tests, self consistency of the results, and the physical and numerical test data leads us to conclude that the Plan OP-1 test results are valid for that plan condition and indicate an expected increase in midtide levels under similar conditions. Plan P4-1 results are suggestive of an increase in range at some locations, but the reverification and associated model revisions between Base and Plan diminishes the usefulness of those quantitative tide results.

97. The model results clearly indicate an increase of midtide level in Cumberland Sound as a result of Trident channel enlargement. Both plans (OP-1 and P4-1) and both physical and numerical model tests of one plan (P4-1) indicate an increase in midtide level. However, the model results are for plans that differ from as-built and are for only one tide condition -- a mean range. Different plans and neap and spring tides may cause a different response, but the data suggest that the overall effect on midtide level is in the direction indicated by the models, so the difference should be in degree of change only. The implication for annual mean water level is that changes may be greater or less than the predicted amount.

98. Absolute values (as opposed to relative changes between base and plan) of physical model high and low waters for Plan OP-1 at Fernandina Beach and Kings Bay are considered accurate to within about 0.2-ft elevation and 15 minutes in phase based on verification results and repeatability tests. At Kings Bay they may be slightly less accurate, because the geometry change for Kings Bay is substantial for the plans, and that can strain the verification. At other locations the accuracy is considerably less and absolute errors of up to 0.5 ft are possible in individual elevations. Base to plan changes in water levels are considered more accurate than absolute elevations, about ±0.2 ft for individual elevations (other than high and low water) and ±0.1 ft for high water, low water, and midtide level. The increase in accuracy level is due to the well-established model practice of accepting small errors in

absolute values because relative changes in the carefully controlled lab environment are more reliably indicative of prototype response (Letter and McAnally 1981). High and low water accuracy improvements are also due to the slower rate of change at those times and the way those values are obtained. For Plan P4-1, the potential error is larger because of the partial reverification.

99. Physical model results for Plan OP-1 appear to be most indicative of the quantitative impact on tide elevations, since the only difference in base and plan tests was the plan itself. Those results may overstate or understate the effect since the plan channels were different from as-built. Plan OP-1 showed effects on high water and low water elevation ranging from none (St. Marys River) to 0.2 ft higher (Fernandina Beach and Kings Bay). Minor decreases in range for the Cumberland River and Marianna Creek and a slight increase of range at Crooked River were shown. Tide elevations occurred about 10 to 15 minutes earlier at all internal tide stations.

100. These results are near the expected degree of accuracy of the model for midtide level changes but are large enough to justify a prediction of change. Without other information, we would interpret the results to indicate that midtide levels of mean range tides in the sound would increase by as little as 0.1 ft to as much as 0.3 ft as a result of the Plan OP-1 deepening. We expect tidal phases to shift backward (earlier arrival) by a few minutes for any similar plan.

101. While the tests were valid, there is a possibility that the observed set-down of water level in the sound and its rebound for the plans was an artifact of the model itself. The relationship between ocean and sound tides was not verifiable and could be dependent on the finite physical model limits. There is no evidence to suggest such an effect; in fact, seeing similar trends in the numerical model reduces its probability, but the possibility must still be noted.

102. Tide results for Plan P4-1 show an increase in tide range; however, reverification and model revision between Base and Plan tests reduces confidence in those results, as does the lack of a historical change in range at Fernandina Beach. A prediction of project-induced tide range change cannot be made with the available results.

103. If a nonlinear effect is responsible for the midtide level set-down, then the system may well respond differently for tides with MWL or tidal

range different than the one tested. It would be imprudent to extrapolate the quantitative results to spring or neap tides, but it is reasonable to extend the qualitative trend to all tide conditions.

Field Data

104. NOAA tide data from Fernandina Beach and other Atlantic coast locations show almost simultaneous intermittent sharp increases in mean water level since 1940. It is conceivable, but unlikely, that the similar patterns of rise and plateau have channel dredging origins. We do not believe that the major rises observed have been related to channel enlargements.

105. Water levels at Fernandina Beach have declined in recent years, but the decrease is within the normal variability of the data, and follows a trend that is observed at Savannah and Mayport also.

106. Detailed examination of Fernandina Beach water levels with respect to those of Savannah and Mayport shows that small (0.04 ft or less) relative increases in annual MWL have occurred at Fernandina Beach, leading to 1988 water levels 0 to 0.08 ft higher than would be expected from the 1940-1988 record. The timing of these increases, following the Poseidon and during the Trident deepening, suggests that the model-predicted MWL increase may have occurred, albeit at a to-date smaller magnitude than suggested by the model results.

107. A simple examination of variation of MWL at Fernandina relative to Savannah and Mayport for March and October shows that the observed increases are most noticeable in months when MWL is naturally higher in Cumberland Sound. The cumulative difference puts Fernandina Beach MWL about 0.1 ft higher than would be expected for the month of October. Since the model was verified to data collected during November, another month of higher-than-average MWL, the findings are consistent. That suggests that the model results may be slightly exaggerated because of the prototype tides used for verification, base, and plan tests.

108. Historical data suggests that tide range at Fernandina Beach has not increased noticeably when the channel was enlarged. Increased range has been observed in other estuaries, including the Cape Fear River (Wilmington). The observed Fernandina Beach tide range since 1982 has bottomed out and increased slightly by 1988, but that behavior is expected because of the

natural 18.6-year tidal period. If a Trident channel-induced increase in range has occurred, it may require up to 20 years more observations to define.

109. Observed Fernandina tide components have shown a trend toward earlier arrival in later years. That could be a response to deeper water brought on by naturally increasing sea level or to the channel deepenings. It is appropriate to conclude that the model predictions of earlier arrival are correct.

110. All of these observations are tentative, in that noisiness of the tidal data record tends to obscure any potential changes except in longer term averages and that the analyses performed here have probably strained the limits of useful interpretation for these data. At least 3 to 4 more years of post-Trident water level data are needed to reach defendable conclusions about the observed tidal changes.

Other Sites

111. Physical models of other sites have shown that tide elevations can either increase or decrease as a result of channel enlargement. These examples do not prove that the Kings Bay model predictions are correct, but they do demonstrate that the phenomenon is not unique.

112. The examples clearly show that the Cumberland Sound results should not be generalized to other sites until the processes are more fully understood.

Simple Numerics

113. The one-dimensional numerical solutions of King (1974) and DiLorenzo (1986) are exceptionally useful in that they provide insight into the probable mechanisms by which setdown or setup might occur.

114. The calculations (Table B5) uniformly support the motion of a sound setdown, though they suggest a magnitude of -0.1 ft rather than the physical model's -0.2 ft. They tend to refute the physical model result of the plan reducing sound setdown, in that the calculated plan changes are very small relative to that seen in the model.

115. Our interpretation of these calculations is that they demonstrate

the plausibility of the physical model test results, but do not confirm either the direction or magnitude of the results.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

116. It is concluded that:

a. TRIDENT channel plans tested in the model were different from the channel constructed, and thus the prototype's response will be somewhat different.

b. Kings Bay numerical tide results are less useful than physical model results.

c. Examination of all model results leads to the following interpretations:

(1) Tide range will probably not change as a result of the TRIDENT project.

(2) A small phase shift in tides will probably occur.

(3) Mean water level in Cumberland Sound may increase by a small amount.

d. Prototype data for 1982-1988 show no unexpected increase in mean tide range.

e. Annual mean sea level at Fernandina Beach was 0.16 ft lower at the end of dredging (1988) than it was at the beginning (1982) with the difference falling well within the normal variability of sea level.

f. Mean sea levels at Fernandina Beach are highly correlated with those at Charleston, SC; Savannah, GA; and Mayport, FL.

g. During final dredging (1986-1988), mean sea level at Fernandina Beach decreased less than at Charleston and Savannah, and more than at Mayport. Single year changes were within the natural variability of the data.

h. Due to natural causes, mean annual tide range will increase for the next 8 years (from about 5.87 ft to about 6.27 ft) at Fernandina Beach. Also, mean sea level will probably rise in 1989, since two consecutive years of drop have occurred only once since 1940.

i. Relative sea level will continue its historic long-term rise with the usual year-to-year variations significantly exceeding the magnitude of the average annual long-term rise.

j. If mean sea level changes in Kings Bay due to the TRIDENT project, it will be less than the normal yearly variation in mean sea level; and as such, it will be extremely difficult to detect until several years of data are available.

Recommendations

117. The following recommendations are made:

a. Continue monitoring and analysis of tide data at Fernandina Beach.

b. Continue the existing monitoring program.

c. Continue to hold semi-annual or annual reviews of progress with the Monitoring Program Technical Committee.

d. No increase or acceleration of the monitoring program appears justified.

Acknowledgements

118. We thank M. L. Rutstein and S. K. Gill of the National Ocean Survey, NOAA, for rapid responses to our data requests. We also gratefully acknowledge fruitful discussions with D. W. Pritchard, R. B. Krone, H. B. Simmons, and A. J. Mehta on this subject. C. R. Berger performed the numerical calculations to solve King's equation, J. M. Savage performed harmonic analysis of tide data for use in DiLorenzo's equations, and J. W. Parman performed the area measurements for these two analyses.

REFERENCES

Benson, H. A. 1976 (May). "Effects of 40-Foot Charleston Harbor Project on Tides, Currents, and Salinities," Miscellaneous Paper H-76-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Berger, R. C., Jr., and Boland, R. A., Jr. 1979 (Mar). "Mobile Bay Model Study, Report 2, Effects of Enlarged Navigation Channel on Tides, Currents, Salinities, and Dye Dispersion, Mobile Bay, Alabama," US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cross, R. H. 1968. "Tide Gauge Frequency Response," Journal of the Waterways and Harbors Division, American Society of Civil Engineers, pp 317-329.

DiLorenzo, J. L. 1986 (Aug). "The Overtides and Filtering Response of Inlet-Bay Systems," Ph.D. dissertation, State University of New York, Stony Brook, NY.

Granat, M. A., Brogdon, N. J., Cartwright, J. T., and McAnally, W. H., Jr. 1989. "Verification of the Hydrodynamic and Sediment Transport Hybrid Modeling System for Cumberland Sound and Kings Bay Navigation Channel, Georgia," Technical Report HL-89-14, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Granat, M. A., and Brogdon, N. J. 1990 (Dec). "Cumberland Sound and Kings Bay Pre-Trident and Basic Trident Channel Hydrodynamic and Sediment Transport Hybrid Modeling," Technical Report HL-90-21, Volume 1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

King, D. B. 1974. "The Dynamics of Inlets and Bays," Technical Report No. 22, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville.

McAnally, W. H., Jr., Brogdon, N. J., and Stewart, J. P. 1983 (Sep). "Columbia River Estuary Hybrid Model Studies, Report 4, Entrance Channel Tests," Technical Report HL-83-16, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Noye, B. J. 1974 (Jan). "Tide-well Systems I: Some Non-Linear Effects of the Conventional Tide Well," Journal of Marine Research.

Speer, P. E. and Aubrey, D. G. 1985. "A Study of Nonlinear Tidal Propogation in Shallow Inlet/Estuarine Systems, Part II: Theory," Estuarine and Coastal Shelf Science, Vol 21.

Stewart, D. M. 1975. "Possible Precursors of a Major Earthquake Centered Near Wilmington-Southport, North Carolina," Earthquake Notes, Vol 46, No. 4, Oct-Dec.

Thomas, W. A., and McAnally, W. H., Jr. 1985 (Aug). "User's Manual for the Generalized Computer Program System, Open-Channel Flow and Sedimentation, TABS-2," Instruction Report HL-85-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Trawle, M. J., and Boland, R. A. 1979 (May). "Georgetown Harbor, South Carolina, Report 2, Effects of Various Channel Schemes on Tides, Currents, and Shoaling," US Army Engineer Waterways Experiment Station, Vicksburg, MS.

USACE. Multiple years. "Annual Report of the Chief of Engineers on Civil Works Activities," Headquarters, US Army Corps of Engineers, Washington, DC.

Table B1

Effect of Plan OP-1 on Tides, Physical Model-1 on Tides, Physical Model

Station		High Water, ft mlw			Low Water, ft mlw			Range, f			MID-Tide Level, ft		
No.	Station	Base	Plan	Diff.	Base	Plan	Diff.	Base	Plan	Diff.	Base	Plan	Diff.
2	Entrance	5.9	6.1	0.2	0.3	0.4	0.1	5.6	5.7	0.1	3.1	3.3	0.2
3	Fernandina	6.1	6.3	0.2	0.1	0.3	0.2	6.0	6.0	0.0	3.1	3.3	0.2
4	Jolly River	6.2	6.3	0.1	0.1	0.2	0.1	6.1	6.1	0.0	3.2	3.3	0.1
5	St. Marys River	6.2	6.2	0.0	0.5	0.5	0.0	5.7	5.7	0.0	3.4	3.4	0.0
6	Kings Bay	6.4	6.6	0.2	0.0	0.2	0.2	6.4	6.4	0.0	3.2	3.4	0.2
7	Marianna Creek	6.5	6.5	0.0	0.0	0.1	0.1	6.5	6.4	-0.1	3.3	3.3	0.1
8	Crooked River	6.4	6.6	0.2	0.3	0.5	0.2	6.1	6.1	0.0	3.4	3.6	0.2
9	Cumberland River	6.4	6.5	0.1	0.0	0.2	0.2	6.4	6.3	-0.1	3.2	3.4	0.2
	Average			0.13			0.14			-0.01			0.13

Table B2

Effect of Plan P4-1 on Tides, Physical Model

Station		High Water, ft mlw			Low Water, ft mlw			Range, f			MID-Tide Level, ft		
No.	Station	Base	Plan	Diff.	Base	Plan	Diff.	Base	Plan	Diff.	Base	Plan	Diff.
2	Entrance	5.9	6.2	0.3	0.3	0.3	0.0	5.6	5.9	0.3	3.1	3.3	0.2
3	Fernandina	6.1	6.3	0.2	0.1	0.2	0.1	6.0	6.1	0.1	3.1	3.3	0.2
4	Jolly River	6.2	6.5	0.3	0.1	0.3	0.2	6.1	6.2	0.1	3.2	3.4	0.3
5	St. Marys River	6.2	6.4	0.2	0.5	0.6	0.1	5.7	5.8	0.1	3.4	3.5	0.2
6	Kings Bay	6.4	6.7	0.3	0.0	0.2	0.2	6.4	6.5	0.1	3.2	3.5	0.3
7	Marianna Creek	6.5	6.6	0.1	0.0	0.1	0.1	6.5	6.5	0.0	3.3	3.4	0.1
8	Crooked River	6.4	6.7	0.3	0.3	0.3	0.0	6.1	6.4	0.3	3.4	3.5	0.2
9	Cumberland River	6.4	6.7	0.3	0.0	0.2	0.2	6.4	6.5	0.1	3.2	3.5	0.3
	Average			0.25			0.11			0.14			0.18

Table B3

Selected Fernandina Beach Tidal Constituents from NOAA

Component	1939	1962	1973	1974	1977	1980	1987
				Amplitude, ft			
M2	2.889	2.850	2.879	2.877	2.863	2.905	2.910
N2	0.647	0.593	0.622	0.631	0.632	0.612	0.631
S2	0.479	0.474	0.485	0.474	0.464	0.461	0.455
K1	0.348	0.345	0.355	0.346	0.116	0.350	0.342
O1	0.254	0.263	0.258	0.260	0.097	0.240	0.249
M4	0.127	0.124	0.111	0.110	0.098	0.108	0.105
				Phase, degrees			
M2	231.8	232.4	231.3	229.1	233.3	230.0	230.2
N2	216.3	218.0	213.3	212.2	221.5	214.3	217.6
S2	261.0	260.9	261.3	258.3	257.5	260.4	259.3
K1	129.7	128.6	128.1	128.9	122.8	127.6	126.5
O1	134.2	136.8	133.7	133.5	133.1	132.8	133.8
M4	244.6	242.8	241.0	234.0	238.0	233.6	230.0

Table B4

Sound Physical Characteristics and Computed Parameters

Parameter	Base (Poseidon) Condition Best Estimate	Base (Poseidon) Condition Low Estimate	Base (Poseidon) Condition High Estimate	Plan Condition Best Estimate
Ocean tide amplitude, ft	3.0	3.0	3.0	3.0
Max sound surface area, $10^9 ft^2$	2.87	1.40	4.5	2.87
Min sound surface area, $10^9 ft^2$	0.91	0.86	0.96	0.91
Max inlet cross-section, $10^5 ft^2$	1.49	1.44	1.52	1.50
Min inlet cross-section, $10^5 ft^2$	1.29	1.21	1.35	1.31
Inlet average depth, ft	37	29	46	38
Mannings n coefficient	0.0250	0.0200	0.0350	0.0250
Darcy f coefficient	0.0219	0.0152	0.0398	0.0217
Inlet length	16,500	16,500	16,500	16,500
Inlet width	3,800	3,100	4,500	3,800

Table B5

Sound Tide Characteristics Calculated by Kings (1979) and Dilorenzo's (1986) Methods*

Parameter	Base Condition Best Estimate	Base Condition Range	Plan Condition Best Estimate
King's Solution			
High Water Elevation, ft	2.75	2.32 to 2.99	2.77
Low Water Elevation, ft	-2.97	-2.72 to -3.00	-2.98
Mid Tide Level, ft**	-0.114	-.004 to -0.20	-0.108
Mean Water Level, ft**	-0.040	-.005 to -0.05	-0.035
Dilorenzo's solution			
Mean Water Level, ft	-0.01	--	--

* Calculations based on 6 ft ocean tide range. All elevations relative to mean ocean level.

** Extra decimal places shown for demonstration of small changes.