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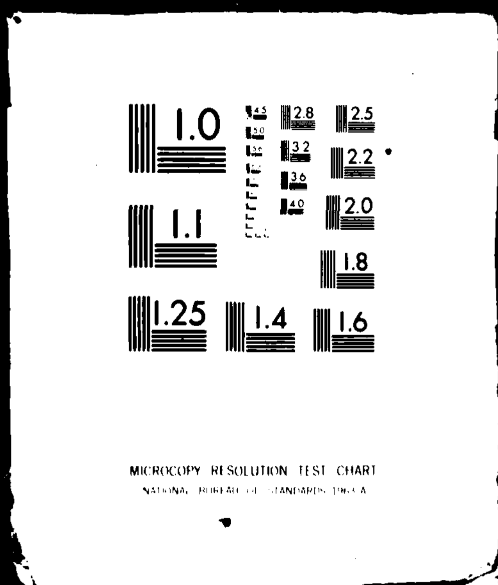

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EVALUATION OF NUMERICAL STORM SURGE MODELS

December 1980

Prepared for the

Office of the Chief of Engineers

by the

Committee on Tidal Hydraulics

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Federal services that minimize loss of life and property due to tropical hurricanes include forecasts and flood warnings by the National Weather Service, design of protective works by the U. S. Army Corps of Engineers, and the establishment of flood insurance rates by the Federal Insurance Administration. Each agency employs mathematical models of hurricane events for simulating impacts. Because of the different concerns of these agencies their models have evolved in different ways and are applied with different input data, and

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20. ABSTRACT (Continued).

apparent disparities have appeared. The Office of the Chief of Engineers expressed concern for this situation and requested that the Committee on Tidal Hydraulics conduct an evaluation of the existing models. OCE specifically requested that the Committee determine the needs for further development of mathematical models by the Corps, the models most suitable for Corps applications, and if the models perform comparably, the most cost-effective models.

Evaluation was accomplished by having each modeling group separately exercise its models for selected past events and by comparing the model outputs with each other and with observed water elevations. The modeling groups were those at the National Weather Service, the Coastal Engineering Research Center, the Waterways Experiment Station, and Tetra-Tech, Inc. Open-coast storm surge models were evaluated, then inland flooding models were evaluated using as input one of the open-coast model results.

Each model tested included features that offered important advantages. Further, the models were continually evolving to include improved descriptions of the land and waters and of storms. No one model's predictions consistently gave better comparisons with observed data, however; and it is unlikely that one will be clearly better than the others for Corps purposes.

It was found that large uncertainties exist in the quality of water-surface elevation observations, large gaps occur in water elevation and meteorological data during the course of storm events, and the few existing observations are not taken at the most desirable locations. This situation is the most serious impediment found during the study to the development of accurate predictive models.

Different procedures for specifying or selecting model input parameters and for calculating storm frequencies can lead to the calculation of widely different return periods for computed surges even when the same hydrodynamic model is used. These procedures are not uniform among the several agencies.

Further improvements of the simulated wind fields are needed, and sensitivity analyses of the models are required in order to extend the usefulness of all of the models to new situations.

Specific recommendations are presented for optimizing the value of mathematical models of storm surge and inland flooding for use by the Corps of Engineers.

CONTENTS

EVALUATION OF NUMERICAL STORM SURGE MODELS

INTRODUCTION

1. Tropical storms approach the Atlantic and Gulf coasts of the United States with sufficient severity and frequency to warrant government programs for preventing or minimizing loss of life and property damage. Two Federal agencies have primary responsibilities in these efforts. The National Weather Service (NWS), of the U. S. National Oceanographic and Atmospheric Administration, Department of Commerce, prepares continually updated forecasts and flood warnings during the landward approach of a tropical storm to facilitate emergency preparation for the storm and evacuation where needed. The U. S. Army Corps of Engineers (USACE), Department of Defense, has primary responsibility for design of coastal protective works and for recommendations, where appropriate, for the management of exposed coastal areas. In addition, the Federal Insurance Administration (FIA), of the Federal Emergency Management Agency (FEMA), is responsible for determining the frequency with which coastal areas are inundated by hurricane surges in order to establish flood insurance rates that are subsidized by the Federal Government.

2. All three agencies have developed and are currently employing mathematical models of hurricane surges that provide means for predicting water-surface elevations resulting from a prescribed storm. However, with development of these models and their subsequent applications, three issues or points of consideration emerged which led the Office of the Chief of Engineers (OCE) to the conclusion that a comparative evaluation of the models was necessary. The first issue concerned the matter of the near-future direction of the Corps' research and development program as it pertains to storm surge analysis; that is, given the available models, should a further research and development effort be directed toward refinement or improvement? The second major point of consideration was the fact that in several known instances, for given geographic locations, significant disparities existed between storm surge-frequency relationships developed by Corps districts having common geographic

boundaries, or between Corps-developed data and similar data generated by other agencies of government. These disparities were often not the result of differences between the numerical models used, but rather differences in study methods and procedures (including storm frequency analysis). This serious problem not only impinges on the Corps' coastal protection mission, but also on other areas such as land-use planning and flood insurance programs. Because of such disparities, it seemed appropriate to identify the model(s) having the characteristics most desirable for Corps applications. The third issue making apparent the need to evaluate the models was the question of which models would be most cost-effective, assuming comparable outputs. It is remarked that these issues and considerations apply to both open-coast models and models of bays and other estuarial waters (inland flooding models).

3. In view of the uncertainties about the application of these various open-coast and inland flooding models, OCE directed that an evaluation of storm surge analysis methods be undertaken through an arrangement whereby the comparable models would be separately exercised by the U. S. Army Coastal Engineering Research Center (CERC), the U. S. Army Engineer Waterways Experiment Station (WES), NWS, and Tetra Tech, Inc. General study management and the responsibility to compare and evaluate the results of the computations were assigned to the Committee on Tidal Hydraulics (CTH), hereinafter referred to as the Committee. An ad hoc committee composed of representatives from OCE, CERC, and WES was charged with responsibility for technical guidance (selection of storms to be considered and the storm parameters to be used) and monitoring the study. The Committee also was charged with the task of providing recommendations to OCE on the need for future development of predictive capabilities that would further assist the Corps in meeting the objectives of its mission as it pertains to coastal flooding.

4. Pursuant to its assignment the Committee, in cooperation with CERC and WES, developed a study plan consisting of two parts. PART I involved an evaluation of three open-coast storm surge models. PART II was an evaluation of three inland flooding models using, as input, the results from one of the open-coast models.

PART I: OPEN-COAST MODELS

5. The purpose of this part of the report is to present the findings of the Committee based on evaluation of three open-coast models. Specifically, the NWS, USACE, and FIA models are referred to herein as the SPLASH, SSURGE, and Tetra Tech models, respectively. The SPLASH model was developed by Dr. C. P. Jelesnianski of NWS (Jelesnianski 1966, 1967, 1972, 1974, 1976), whereas the SSURGE model is principally the work of Dr. J. J. Wanstrath of WES (Wanstrath et al. 1976; Wanstrath 1976, 1977, 1978a, 1978b). The then-current versions of these two models were referred to as the Sheared Coordinate SPLASH model and SSURGE III. The FIA model was developed by Tetra Tech, Inc. (Tetra Tech 1978, 1980; Chen and Divoky 1980; Chen and Yamamoto 1980). In general terms of the present state of knowledge in the numerical simulation of open-coast surge, all three models are acceptable. At the time this phase of the study was initiated, the Tetra Tech model had not been released; therefore it was not included in the first phase of the study. The study reported on in PART I was made by: (a) selecting five hurricanes for which some data on storm characteristics and storm effects were available; (b) furnishing the standard input data (see Appendix A) to the three modeling groups (WES, NWS, and Tetra Tech); and (c) comparing the model predictions with each other and with reported storm surge measurements. In order to keep costs to a reasonable level, the Tetra Tech model was exercised only for two of the five storms. Instructions from the Committee to the modelers at WES and NWS are presented in Appendix B. Similar instructions were contained in the contract with Tetra Tech. No model verification or recalibration was permitted during this part of the study.

6. Computations employing the SSURGE model were performed at WES by the model developer, Dr. Wanstrath. In the case of the SPLASH model, CERC elected to enter into a cooperative agreement with NWS to perform the computations inasmuch as it would have been too time-consuming and costly for CERC to adapt the latest version of the SPLASH model program for use by the CERC computer system. Accordingly, Dr. Jelesnianski, the SPLASH model developer, had an opportunity to actively participate in

the computational effort. Work with the Tetra Tech model was conducted by Tetra Tech, Inc., under contract to CERC.

Model Characteristics

7. It should be noted at the outset that all of the models reviewed are remarkable achievements. They provide information that can be obtained only with the use of two-dimensional numerical models, and the value of that information is very high in terms of human life and property and with respect to the effectiveness of protective measures. However, as mentioned in the introduction, the models were developed for quite different applications. The SPLASH model is a forecasting tool that is in readiness for use at any time a hurricane approaches the open coast between the Mexican-American border in the Gulf of Mexico and the east end of Long Island. The input requirements, simplifications, and mode of reporting for the SPLASH model are designed for effectiveness under these demanding operating conditions. The SSURGE model was developed for use in design of coastal protective works and coastal zone management in order to reduce potential losses from hurricanes; therefore, the absence of emergency model operating conditions permit more detailed input to this model. Moreover, the high costs of protective works or land management actions place a premium on accuracy of the predictions gained through more detailed input rather than a criterion to evacuate people. The Tetra Tech model was designed for assessment of potential storm damage and is therefore operated under conditions similar to those of SSURGE. All three models have undergone considerable improvement since their initial development; in fact, the models were in the process of evolution during the evaluation periods. Since the evaluations, some of desirable features of one model have been incorporated into one or both of the others. Hence, different versions than those tested presently are available for each model.

8. These models use finite-difference techniques for solving two-dimensional (depth-averaged), time-dependent, quasi-linear equations of motion and continuity. These equations include the effects of the atmospheric pressure drop, wind stresses on the water surface, hydrostatic surge pressure, Coriolis acceleration, and bed friction on flow

of water. For the SPLASH and Tetra Tech models, the coastline was assumed to be an unbroken vertical wall, i.e., moving boundaries were not included. The SSURGE model, however, was operated both with and without a finite-height wall that could be overtopped and openings for tidal entrances. The models differ in the methods used to describe water-surface stresses, bed friction, and the coastline boundary.

9. Water-surface stresses are calculated from a wind field and atmospheric pressure gradient that is previously computed in a separate subroutine of each model from the basic storm parameters of atmospheric pressure in the center of the hurricane, the atmospheric pressure outside of the region affected by the hurricane, the radius to the maximum wind, and the velocity of storm translation along the storm track. Because these were the only storm input parameters permitted in this study, it was necessary to replace the wind model subroutine in the SSURGE model, since the original SSURGE wind subroutine also required the maximum wind velocity as an input parameter. Although this information is available in a hindcast study, it is not presently available for a design or predictive study. Therefore, a modified version of the SPH (Standard Project Hurricane) wind model (Hydrometeorological Section 1968) was substituted into SSURGE. Unfortunately, the SPLASH wind subroutine was not available for use in SSURGE in the initial comparison; therefore the initially calculated wind fields were different in these two models. In a later phase of the study, the SSURGE model was operated for the five storms with the SPLASH wind subroutine. When the Tetra Tech model was run, it was operated with its own wind subroutine (a different modification of the SPH wind model) and that of the SPLASH model. The SSURGE calculations using the SPH wind model assumed a constant wind inflow angle relationship which depended on distance from the storm center, the SPLASH computations included a much more variable inflow angle, and the Tetra Tech wind model assumed a constant inflow angle at all radii and related pressure and velocity to radius and the maximum velocity. The resulting SSURGE wind field had lower speeds than the SPLASH wind field out to a radius about five times that of the radius to maximum wind, and higher speeds at larger radii. The Tetra Tech model showed a lower

maximum wind than the SPLASH model and significantly higher winds at radii more than twice the radius of maximum winds. The wind stresses on the water surface are proportional to the square of the wind speed, so that these differences have a significant effect on the model results.

10. The models also differed in the way that the surface shear stress was calculated from the surface winds. The drag coefficient in the SSURGE model is a function of wind speed. The drag coefficient in SSURGE for this study was not recalibrated from the original model verification, even though a different wind model subroutine was used for this study. Tetra Tech also used a variable drag coefficient. The water surface is progressively roughened by increasing winds, and this functional relation can be significant, particularly in that part of the wind field having relatively low wind speeds. Field observations have shown that the drag at short fetches increases with wind speed, so that these differences have a significant effect on the model results.

11. The SPLASH model is completely linear in dealing with all aspects of water motion. The equilibrium depth is used in computing the surface stresses due to the atmospheric pressure gradient and bottom friction. The SSURGE and Tetra Tech models acknowledge the nonlinear nature of the hydrodynamic forces and use the computed total depth of the water at each grid point for each time period. The Tetra Tech model makes an additional correction when the water is shallow. Thus, these models provide a better simulation of the physical processes relating to the wind and bottom stresses than does the SPLASH model.

12. The most apparent difference between the models is the way in which an irregular shoreline boundary is incorporated. The SPLASH model uses a so-called "sheared coordinate" system which nicely accommodates a mildly curved coastline and maintains a uniform grid spacing. In addition, SPLASH is completely automated; that is, a grid has already been developed for the Atlantic and Gulf coasts. The SSURGE model utilizes a conformal mapping procedure with telescoping computing cells which maps a coastline onto a rectilinear solution grid. Such mapping encourages a reduction of the grid spacing nearshore and an increase in the spacing

seaward with the result that the SSURGE model may yield computed results with greater resolution nearshore (but not necessarily with greater accuracy) than do the SPLASH and Tetra Tech models. All three models have the capability to include effects of barriers along a coast such as islands, but this capability was used only in SSURGE. Tetra Tech performed a sensitivity test for Hurricane Camille and decided that use of the barrier option was not warranted. The problem of accommodating irregular boundaries in finite-difference calculations is a difficult one, and the SSURGE and SPLASH approaches are imaginative. The Tetra Tech model uses a uniform rectangular grid. Another numerical computation method, finite-element calculation, is particularly useful for solving problems having complex boundaries; and future model development may include use of this method.

13. None of the models explicitly accounts for short-period gravity waves superimposed on a surge. Prediction of such waves would be valuable for the design of coastal structures. The SPLASH model was originally calibrated by comparing computed water levels with observed hydrographs and maximum high-water marks, which implicitly include the effects of short-period gravity waves on the overall water elevation.

First Model Comparison: SPLASH and SSURGE

14. The preliminary computations and preparation of comparative model results for the SPLASH and SSURGE models were completed at NWS, WES, and CERC in August 1977 and were considered at the 24-25 August 1977 meeting of the Committee. The comparison study report was prepared by Dr. Hubertz of CERC (Hubertz 1977) and furnished to the Committee in advance of the meeting. Details and performances of the two models were presented at the Committee meeting by Drs. Jelesnianski and Wanstrath, and Dr. Hubertz presented the comparisons.

15. The comparison study utilized data from Hurricanes Hazel (1954), Gracie (1959), Eloise (1975), Camille (1969), and Carla (1961). All of these storms made landfall with near normal angles of incidence. Presurge anomalies and calculated astronomical tides were added to the

output of all three models to facilitate comparison with observed data. Results of the predictions are presented in Figures 1-9 (these were duplicated from Figures 11, 18, 19, 26, 27, 34, 35, 42, and 43 of Hubertz 1977). These figures show that:

a. The SPLASH model consistently predicts higher water-surface elevations than does the SSURGE model.

b. The general shape and/or phasing of the hydrographs predicted by both models was grossly different from the observed hydrographs for two of the four cases where a prototype hydrograph was available.

c. Neither model consistently predicted the correct location along the coastline of the maximum high-water mark nor the shape of the high-water-mark profile.

d. Based on a comparison only of the predicted and observed maximum high-water marks, the average error for SPLASH was about 21 percent and that for SSURGE was about 33 percent. The SSURGE was more consistent, however, in that the difference between its two extreme errors was 38 percent, while that for SPLASH was 71 percent.

e. Neither model is consistently more accurate than the other; but taking into consideration all of the comparisons with observations, SSURGE gives results generally closer than does SPLASH to observed data.

It should be noted that the most recent (at that time) improvement to SSURGE was not used in these computations. That feature was the inclusion of a "leaky" shoreline boundary, which permitted overtopping of the beach areas and flow into tidal entrances.

16. The models synthesize a number of factors, so that the causes of the differences are not evident. The wind stress used has a very large effect, and the difference in wind stress calculations undoubtedly is the major factor. As noted above, the winds were calculated for the SSURGE model in ways that produced a lower peak wind speed than for SPLASH. Further, a variable drag coefficient was used in SSURGE that predicts lower stress (at the same wind speed) for wind speeds less than about 106 knots. The SSURGE model also included the updated total water depth in the calculations. All of these factors reduce the calculated surge relative to that calculated by the SPLASH model.

Second Model Comparison:
SPLASH and SSURGE Variations

17. Concurrent with the first model comparisons, Dr. Wanstrath conducted two additional sets of computations incorporating already available improvements to SSURGE and his original wind model (Jelesnianski 1965). Because Dr. Wanstrath had two different wind subroutines readily available (SPH and his original wind model), he conducted additional computations to show directly the influence of different wind fields on surge height computations. Because of limited time, he conducted these additional computations only for Hurricanes Gracie, Camille, and Carla. These additional computations were incorporated into Hubertz (1977) as Appendix II and were presented by Dr. Wanstrath at the August 1977 Committee meeting. Results are shown in Figures 10-15 (duplicated from Figures A2, A3, A5, A6, A8, and A11 of Hubertz 1977). In addition, he presented results of computations using the latest features of SSURGE incorporating a finite-height coastline (instead of a vertical wall) and permitting flow to enter bays or estuaries. In order that the SSURGE/SPLASH model results be as directly comparable as possible, Dr. Wanstrath had elected not to use those features of SSURGE in the basic comparison study. He did conduct additional runs with these features and with the original wind-field model, and these results also are shown in Figures 10-15. From these figures it was seen that:

a. For runs with the original wind model, maximum high-water-mark comparisons between model computations and field observations were greatly improved in two of the cases presented and slightly improved in the other case; and maximum surge elevations during the hydrographs were significantly improved in two of the three cases.

b. For runs including coastal flooding and bay/estuary flow communication, the high-water-mark profiles were essentially unchanged (compared with runs with the original wind field and a vertical wall coastline), but the hydrograph phasing was significantly improved in one case.

Third Model Comparison:
Tetra Tech, SSURGE, and SPLASH

18. Early in 1978, Dr. Wanstrath obtained a copy of the SPLASH wind-field model and adapted it for use with SSURGE in order to compare

directly the results from these two hydrodynamic models being driven with identical meteorological input. Dr. Wanstrath also used the constant wind-stress law from SPLASH. At the time these computations were made, it was determined that the input meteorological parameters previously used for Hurricane Camille did not accurately represent the actual storm conditions. Therefore, the revised input data shown in Appendix C were used for this comparison, and the SPLASH model was rerun with these input data. Results are presented in Hubertz and Wanstrath (1978) and were presented by Dr. Wanstrath at the 11-14 April 1978 meeting of the Committee.

19. The Tetra Tech model exercise was completed two years after the previously reported runs, and direct comparison can be made only with reservations about relative level of development. Nevertheless, it is instructive to review the performance of the Tetra Tech model and to compare the hydrodynamic portions of the models under the same wind field. The application of the Tetra Tech model was performed by Dr. M. H. Chen of Tetra Tech, and the results were submitted to CERC (Chen and Divoky 1980). Comparisons with the previous SSURGE and SPLASH results were compiled by Dr. Herchenroder of CERC and Mr. Herrmann of WES (Herchenroder and Herrmann 1980) and were presented by Dr. Herchenroder at the 26-28 August 1980 meeting of the Committee.

20. The Tetra Tech simulations of Hurricanes Gracie and Camille using the Tetra Tech wind model are presented in Figures 16-19 (duplicated from Figures 6.10, 6.12, 6.28, and 6.31 of Tetra Tech 1980). These figures show that the Tetra Tech model peak water-surface elevations are within 2 to 3 ft of the observed elevations, the time of high water is early by up to 4 hours, and the distribution of high-water elevations along the coast is pretty well represented.

21. In addition to these simulations, Tetra Tech computed the SPLASH wind field and used it to drive the Tetra Tech hydrodynamic model with both a constant wind-stress coefficient (k, as in the SPLASH model) and a variable coefficient (as in the Tetra Tech model). These computations with the constant wind-stress coefficient, together with similar computations by Dr. Wanstrath at WES and the original computations using

the entire SPLASH storm surge model, make possible direct comparison of the hydrodynamic portions of the three models. Results of the computations are presented in Figures 20-23 (duplicated from Figures 2, 3, 6, and 7 of Herchenroder and Herrmann 1980). These figures show that SPLASH water levels tend to be higher and lower at the extremes than the levels predicted by the other models, and that at least for Hurricane Camille, where the phase can be more accurately determined, the SSURGE model most nearly represents the correct phase. Based on this very limited set of comparisons, the distribution of high-water marks along the coast was comparably good (or bad) for all three models.

Evaluation of Models for Corps of Engineers Use

22. The comparison study did not clearly show that one model was superior to the others for Corps use, partly because of constraints placed on model input (wind) data that are part of the operating circumstances. There are, however, several attributes of the SSURGE and Tetra Tech models that make them more appropriate for use in design of protective structures and lowland management. Specifically:

- *a.* The SSURGE and Tetra Tech models explicitly include the variable drag on the water surface and the effect of the changing water depths on bottom friction and atmospheric forces. These features potentially enhance the accuracy of the models and make them more reliable for use in areas where calibration is not possible. Explicit descriptions can be updated easily as new data become available.
- *b.* The SSURGE model may provide the greatest resolution near shore for a given model cost and can accommodate shore barriers and irregular shorelines.
- *c.* The SSURGE and Tetra Tech models are better documented. This means that they can be more readily understood by others and modified to account for special requirements or new technology.

In connection with the above-listed attributes, it is important to bear in mind that design and lowland management studies are free of the urgency that faces storm warning situations, and the refined wind data input can be used to take advantage of the more detailed SSURGE and Tetra Tech calculations.

23. Insofar as could be determined from the discussions of the models, there is no significant difference in the costs of operating the models within the limits of the number of computer runs that could be expected in a normal study, and there are large trade-offs between accuracy and cost in all of the models.

24. As shown by the supplemental results presented by Dr. Wanstrath, surge predictions are significantly improved when an improved simulation of the wind field is incorporated in the computations. It appears that the present procedure for prescribing the SPH are inadequate to provide a good description of actual hurricane wind fields. Unless better wind models can be developed which use only the presently prescribed input parameters, it may be necessary to revise the SPH procedure and develop additional historical statistics with which to specify an additional parameter(s).

25. It is important to note in connection with the available field data that the water-surface observations are not always reliable. A number of the observation points are in bays, channels, and behind bars, thus making model/prototype comparisons questionable with open-coast models. It is not always clear whether short-period wave heights are included, and the qualifications of the observers are quite variable.

PART II: INLAND FLOODING MODELS

Models

26. Inland flooding from hurricane surge is compounded by continuing wind stress as water moves inland and by intense rainfall. The rate of water movement inland, water heights, and the duration of flooding are determined by these factors and by the topography and hydraulic roughness of the land and channels of the nearshore region. All of these factors must be described quantitatively and synthesized in a predictive model. Inland flooding models incorporate these factors in slightly different ways and use various computational techniques to synthesize the descriptions. PART II describes the comparisons of the results of simulations of flooding from Hurricane Carla (1961) in the region of Galveston Bay by models named SURGE II, TWODSRG, and WIFM. Because of cost considerations, the most recent Tetra Tech inland flooding model (Tetra Tech 1980) was not included in this part of the study, although it appears to be as technically sound as the other models.

27. The three models evolved from two separate origins. The SURGE II and TWODSRG models are modifications of the SURGE I model (Reid and Bodine 1968) that permits modeling channels within a computational grid block. The SURGE II model was developed by Reid, Vastano, and Reid (1977) at Texas A&M University under contract to CERC; and TWODSRG was developed at CERC by Herchenroder (1978). A uniform rectangular grid is used to discretize the area to be modeled in SURGE II and TWODSRG, and an explicit finite-difference computational procedure is used in both models. The major differences between these two models are the method of including the subgrid channels and the description of hydraulic friction.

28. Subgrid channels are routed along the top and right edges of SURGE II grid blocks and through the center of TWODSRG/grid blocks. Variable channel reach lengths and variable angles relative to the computation grid are possible with TWODSRG. The TWODSRG model utilizes a Manning's friction term and a surface stress-bottom friction interaction term that facilitates individual descriptions of friction for

submerged blocks. The SURGE II model uses a fixed friction factor for all submerged blocks.

29. The WIFM model was developed by H. L. Butler at WES (Butler 1978a, 1978b, 1978c, 1979) for the computation of tidal circulation, tsunami runup, and storm surge. The WIFM model features variable grid spacing, an implicit computational procedure, and a spatial- and time-dependent friction formulation. The variable grid spacing feature of this model facilitates detailed descriptions in areas of special interest or widely varying topography while maintaining wide spacing in remaining areas. This capability contributes to the cost-effectiveness of WIFM. The implicit computational scheme eliminates concern for computational stability in deeper water areas and permits longer time-steps where precision/economy considerations permit. Comparison of principal features of the three models is shown in Table 1.

Table 1

Features of Inland Flooding Models

WIFM	SURGE II	TWODSRG
Implicit formulation (No stability criterion)	Explicit formulation (Stability requirements limit time-step.)	Explicit formulation (Stability requirements limit time-step.)
Variable grid spacing	Fixed (uniform) grid spacing	Fixed (uniform) grid spacing
Bottom friction varies with space and time	Bottom friction varies with space only	Bottom friction varies with space and time
Subgrid barriers included	Subgrid barriers included	Subgrid barriers included
Subgrid channels not included	One-dimensional (edge) subgrid channels included	One-dimensional interior) subgrid channels included

First Model Comparison

30. Prior to simulating Hurricane Carla, each model was verified to astronomical tide conditions. Model tides were compared with prototype data and with data obtained from a previous physical model. There was no discernible difference in the quality of the tidal verification runs of the three models. Direct comparison of the inland flooding models was accomplished by providing identical inputs and comparing outputs (Appendix D describes CTH instructions to the modeling groups.) The comparison study report was prepared by Dr. Whalin of WES (Whalin 1978). The input values of water levels along the Texas open coast, windfields throughout the modeled areas, and the wind-stress drag coefficient were generated by Wanstrath using the SSURGE III open-coast surge model, including its original wind model as previously developed by Jelesnianski (1965). The simulated wind-velocity histories were very close to winds at Galveston, Deer Park, and Freeport as determined by the Hydrometeorological Section (Hydromet) of NWS, but were about double the Hydromet winds at Houston and roughly 15 percent low in mid-Galveston Bay. Wind directions were accurately represented at all stations. The computed water levels at Pleasure Pier are presented in Figure 24 (duplicated from Figure 14 of Section II in Whalin 1978). Note that the plot in Figure 24 includes adjustments for a presurge anomaly (2.0 ft), for a datum plane correction (1.0 ft), and for astronomical tides. The simulated time-history shown in Figure 24 is reasonably accurate, but the peak value exceeds the observed peak height by approximately 2 ft.

31. The WIFM model was applied under the direction of H. L. Butler at WES, the SURGE II model under the direction of Dr. J. Hubertz at CERC, and TWODSRG under the direction of Dr. B. Herchenroder at CERC. Preliminary comparisons were completed in April 1978 and presented at the 11-14 April 1978 meeting of the Committee. The comparison report (Whalin 1978) was furnished to the Committee prior to the meeting. At the meeting, Mr. Butler presented pertinent information on WIFM, Dr. Hubertz presented information on SURGE II and TWODSRG, and Dr. Whalin presented the comparisons.

32. All model grids were developed from the same bathymetry data.

However, WIFM incorporated a variable-size grid (1980 to 8470 ft), whereas SURGE II and TWODSRG had identical rectangular grids (1.5 X 1.5 miles). In addition, the channels in SURGE II and TWODSRG were represented in different ways as described in paragraph 28. The grids used are shown in Figures 25 and 26 (duplicated from Plates 2 and 3 of Whalin 1978).

33. Time-histories of observed and computed water-surface elevations are presented in Figures 27-33 (duplicated from Plates 45-51 of Whalin 1978). These figures show that WIFM and TWODSRG results vary similarly and that WIFM results are slightly lower than those of TWODSRG. The elevations calculated using SURGE II are significantly lower than those of the other two models. The maximum water-surface elevations were more nearly predicted by SURGE II, however. The difference between the observed elevations at Pleasure Pier and the input values computed by SSURGE III, combined with the uncertainty of the accuracy of "observed" elevations described in PART I, make these data inadequate for recommendation of one model over the others.

34. The model outputs included plots on maps showing the extent of flooding at selected times during the event. Such representations were used to prepare a colored movie of the flooding by the WIFM group (WES), and study of such plots can lead to selection of the most appropriate protective measures.

Second Model Comparison

35. Following a review of the above comparisons by the Committee, a second set of comparisons was undertaken after removal of some of the differences between the models and reduction of the discrepancy between the input surge elevations at the open-coast boundary and the prototype data that become evident from the first set of comparisons. The changes in test conditions included the following:

a. SSURGE III water-surface elevations along the open-coast boundary of the inland flooding models were adjusted in proportion to the adjustment necessary to make SSURGE III output for the Pleasure Pier station coincide with observed water-surface elevations there. It was anticipated that this adjustment in boundary conditions would facilitate a more valid comparison of calculated and observed water levels at interior points. The original wind fields determined by SSURGE III were not changed, however.

b. A revision of the representation of the Galveston Harbor entrance channel was made in SURGE II because it was believed that the limited schematized depth in this area was restricting the water transport through the entrance and causing the relatively low interior water levels shown in the previous comparison.

c. The SURGE II and TWODSRG models were modified to run on the same computer as WIFM to provide a more valid computation cost comparison.

36. The model reruns and revised comparisons were completed in November 1978 and transmitted to the Committee. The revised comparisons were incorporated directly into the previous comparison report (Whalin 1978) and all of the previous data were retained in the report. Dr. Whalin presented the comparisons at the 13-15 December 1978 Committee meeting. Computed results of this revised comparison are presented in Figures 34-40 (duplicated from Plates 74-80 of Whalin 1978).

37. The models all simulate flooding at interior points remarkably well. Examination of the figures shows that WIFM results appear to fall between the slightly higher TWODSRG and lower SURGE II water-surface elevations during the period of rising water levels. The delay in SURGE II suggests that the revised channel representation still might be inhibiting conveyance of flood waters. The differences between model predictions and observed high-water elevations reported are shown in Table 2.

Table 2

Model	Mean Difference (computed) - (observed), ft	Maximum Differences ft	Maximum Differences Location
WIFM	0.73	-2.1	Sea Isle Beach
		+2.9	Baytown
SURGE II	0.98	-3.0	Sea Isle Beach
		+2.7	Lakeside
TWODSRG	0.90	-2.5	Sea Isle Beach
		+3.4	Lakeside

These figures show only a slight (if real) advantage in accuracy for WIFM.

38. Comparison of costs of running the models to simulate Hurricane Carla is shown in Table 3 (duplicated from Table 9 of Whalin 1978). This

Table 3

Model Characteristics

	WIFM	SURGE II*	TWODSRG**
Grid step, ft	Variable Min: 1980 Max: 8470	Fixed 7920	Fixed 7920
Time-step, sec	180 (½ cycle)	120	112.5
Stability limit, sec	Not applicable	128	118
Run duration, time-steps (Program hr: 18-90)	1440	2160	2304
Grid points	3572 (76 X 47)	1800 (60 X 30)	1800 (60 X 30)
Barrier blocks	103	83	148
Channel blocks	Not applicable	74	208
Computer storage (small core)	41,000	36,500	31,000
(CYBER 176) (Large core)	86,000	42,000	42,000
Computer time			
Real time, hr	72	72	72
CPU time, sec	390	292	637
Time/Δt, sec	0.27	0.135	0.276
Cost, $	75	50	122
Application costs, estimated†			
Manpower, man month	3	3	3
Computer, $	400	500	500

* Input boundary values and wind stress defined every 3 hr for SURGE II, every 15 min for WIFM and TWOSRG. Costs and timings reflect a penalty to account for additional computation.

** TWODSRG is composed of 3 separate programs which are run in sequence. Storage reflects maximum core for any one program. Costs and timings include execution of entire package.

† Includes setting up grid, debugging program, and calibration.

table summarizes the operating characteristics and shows the bases for the cost-effectiveness of the models. The WIFM utilized nearly twice as many grid points as the other models, which provides more detail for local conditions, but did not compute flow in subgrid channels which added to the costs of running the SURGE II and TWODSRG models. It is still not possible to determine which model is the most cost-effective, since no sensitivity tests were conducted to optimize the grid spacing and time-step with respect to accuracy of results and computer costs.

Discussion of Comparisons

39. There are three bases for comparing these models: the methods of describing all of the included factors in the computation, model costs, and comparison of model predictions and observations in the prototype. The models incorporate sophisticated descriptions of topography and hydrodynamic factors. Because of its variable grid size, WIFM provides the best representation of topographic detail, except that it does not have the embedded channel feature of TWODSRG and SURGE II. WIFM and TWODSRG have a better representation of hydraulic friction than SURGE II. The variable grid spacing and implicit calculation features of WIFM facilitate economies where some wide spacing and longer time-steps can be used. The combination of good description and economy of WIFM is attractive. Incorporation of subgrid channels will reduce the economy of WIFM somewhat.

40. Comparison of model predictions with prototype data to assess the accuracy of the models leaves significant reservations about the quality of prototype data and particularly concern for the dearth of available data. In view of the costs of protective works, insurance, and the need for accurate warning of impending floods, the lack of accurate, well-placed observations that can be used to develop our predictive capabilities is incredible. Based on the presently available data it can only be concluded that the accuracies of the three models are comparable, and that the models probably are better than the prototype data available for their evaluation.

CONCLUSIONS

41. The exercise and comparison of open-coast surge and inland flooding models described in PARTS I and II provided information that led to the following conclusions:

a. This comparison study did not show that any one of the three open-coast or any one of the three inland flooding models tested gave consistently better comparison with the observed data.

b. Each of the models as tested included features which offer potential technical advantage. For example, the conformal mapping system used by the SSURGE model provides for better accommodation of an irregular coastline than does either of the other two open-coast models. The SPLASH model's use of the "sheared coordinate" system nicely accommodates a widely curved coastline, and hence is better in this regard than the Tetra Tech model with its purely rectangular grid pattern. Both the SSURGE and Tetra Tech open-coast models explicitly include functions describing variable water-surface drag and resistance to flow that depend on water depth, which are not included in the SPLASH model. The SSURGE model also used the capability of overtopping barrier islands. The WIFM inland flooding model uses a variable grid, while SSURGE II and TWODSRG permit embedded channels within a computational grid block. However, new versions of each of these models have now replaced the versions originally tested, and these new versions remove some of these differences.

c. This is a period of dynamic improvement to numerical hydrodynamic modeling. The models which were tested were in fact in the process of evolution during the testing period, and new, improved versions of each now exist. For example, the WIFM inland flooding model has now been adapted to also compute the open-coast surge. The Corps (WES and CERC) has recently acquired the System 21 software package from the Danish Hydraulic Institute, a model widely used in other parts of the world for storm surge modeling. The Committee does not consider it likely that further intercomparison of these improved models would show one clearly better than the others for the needs of the Corps.

d. Large uncertainties exist in the quality of observations of water-surface elevations in areas suffering hurricane surge. These uncertainties in water-surface elevations are made worse by gaps in water-surface elevation histories, absence of wind and rainfall measurements, and less than desirable locations of many of the few observations. This lack of reliable water level and meteorological data is the most serious impediment to the further development of accurate predictive models, since these data are essential for model calibration.

e. The presurge anomaly, especially in the Gulf of Mexico, has a magnitude comparable to the discrepancies between the computed and observed water-surface elevations. The lack of knowledge of the causes of this anomaly detracts from confidence in model predictions.

f. Procedures for specifying or selecting input parameters for surge calculations are not standardized. Additionally, different methods for calculating storm frequencies can lead to determination of widely different return periods for the computed surges even when the same hydrodynamic model is used in the computations.

g. None of the models has had the sensitivity analyses necessary to guide modelers in the application to new areas.

h. Storm wind fields arrived at through the use of methods employing basic storm parameters, as presently prescribed, fail to adequately simulate real wind fields. This situation results in difficulties when attempts are made to hindcast storm surge levels and can easily result in improper model calibration.

RECOMMENDATIONS

42. The preceding conclusions lead directly to the following recommendations:

- a. The Committee does not recommend that any one model should be designated as the primary storm surge model for Corps purposes. It is our belief that accuracy of predictions is more valuable to the Corps' missions than is uniformity of predictions. In view of the dynamic character of storm surge model development, this is best attained by use of the state-of-the-art model most applicable to each particular case rather than a single, standardized model.
- b. Accuracy of storm surge modeling depends upon a number of factors in addition to the particular form of the model to be used. These include the description of the wind field, the choice of the size of the area to be modeled, and the grid size and time-steps to be used. These factors should be selected to be appropriate for the particular area that is to be modeled, and such selection requires professional competence. It is recommended, therefore, that storm surge models be either run by or approved by a working group of expert modelers within the Corps who maintain state-of-the-art competence and who are charged with determining the model appropriate to the particular project.
- c. A program for obtaining accurate measurements of winds over sea and land, wave heights and periods, and water-surface elevations over land in areas subject to hurricane surge should have a high priority. The Committee recognizes that some such efforts are in progress.
- d. The major research efforts by the Corps in the field of hurricane surge prediction should be concentrated in the area of improving wind models and storm frequency analysis. However, funding for sensitivity analysis of existing models and for testing of improvements in the treatment of surface and bottom stresses should be provided.
- e. A uniform procedure should be established for calculating the frequency of storm surge occurrences along the coast.
- f. Studies of the causes of the presurge anomaly should be initiated immediately. A model study of the gulf, using a coarse grid, could provide the needed insight.
- g. Model sensitivity tests should be conducted with each application to assure adequate evaluation of boundary and initial conditions.
- h. It is recommended that OCE initiate a dialog with NWS on

the matter of wind-field models for the purpose of reviewing and improving the present mathematical descriptions.

i. Models used for analyses and design of projects should be documented adequately for the evaluation of the model results.

43. A model is the synthesis of mathematical descriptions of natural processes. Improved descriptions of wind stress, bottom friction, nonlinear waves, etc., can be incorporated as knowledge advances. Opportunities for advancing such knowledge often appear when additional field data can be obtained at modest cost, or when field data can be analyzed beyond immediate needs of a project. Corps personnel should be alert to these opportunities and should be encouraged to propose appropriate studies. Such efforts can pay handsome returns.

44. The capabilities of predicting hydraulic flows and water-surface elevations in coastal and estuarial regions is vital to the missions of the Corps. A hurricane surge is only one of the kinds of events for which mathematical hydraulic models are used, and such models should be considered as only one of the facilities used in studies of coastal waters. The continuing development of proficiency and versatility of Corps personnel in modeling of coastal and inland waters should be given continuing support.

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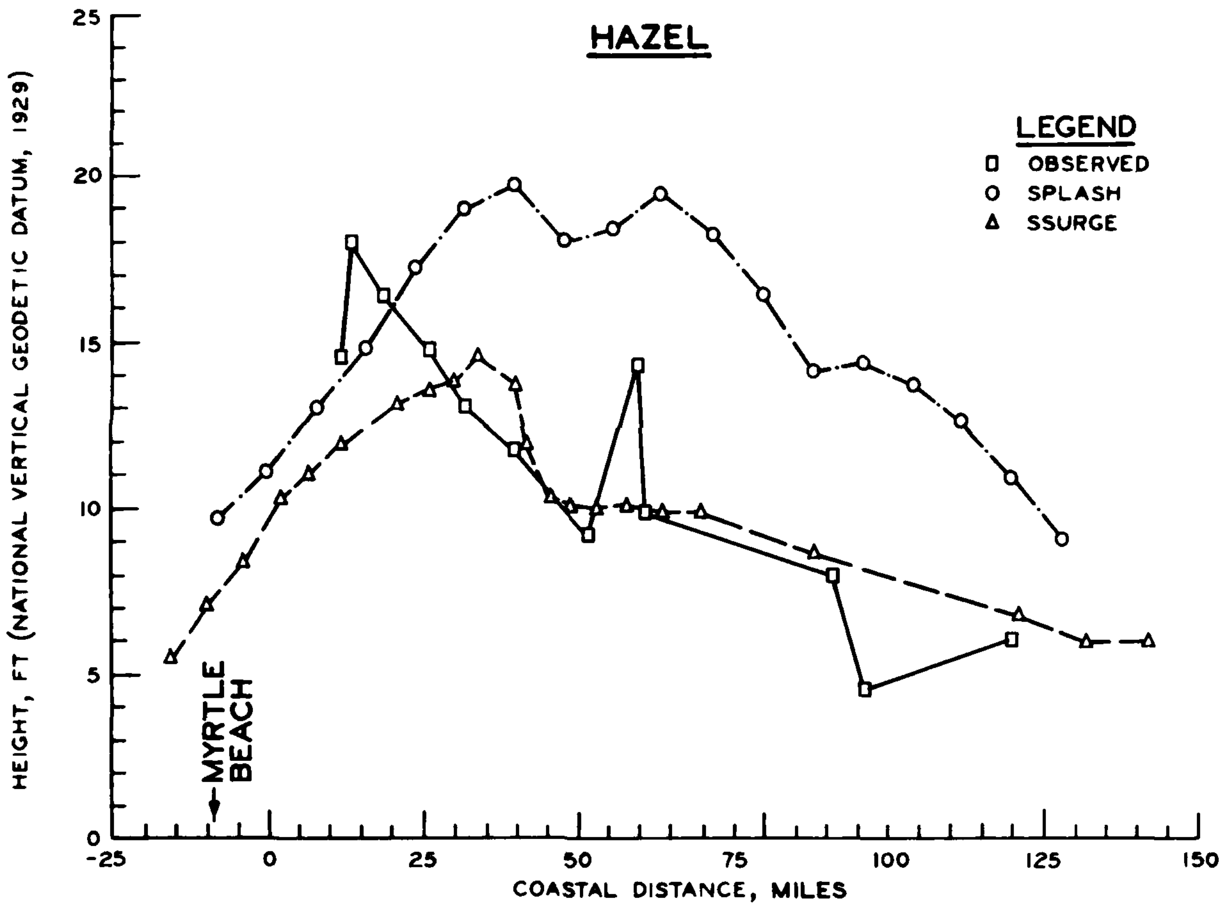

Figure 1. Observed and computed high-water marks for Hurricane Hazel

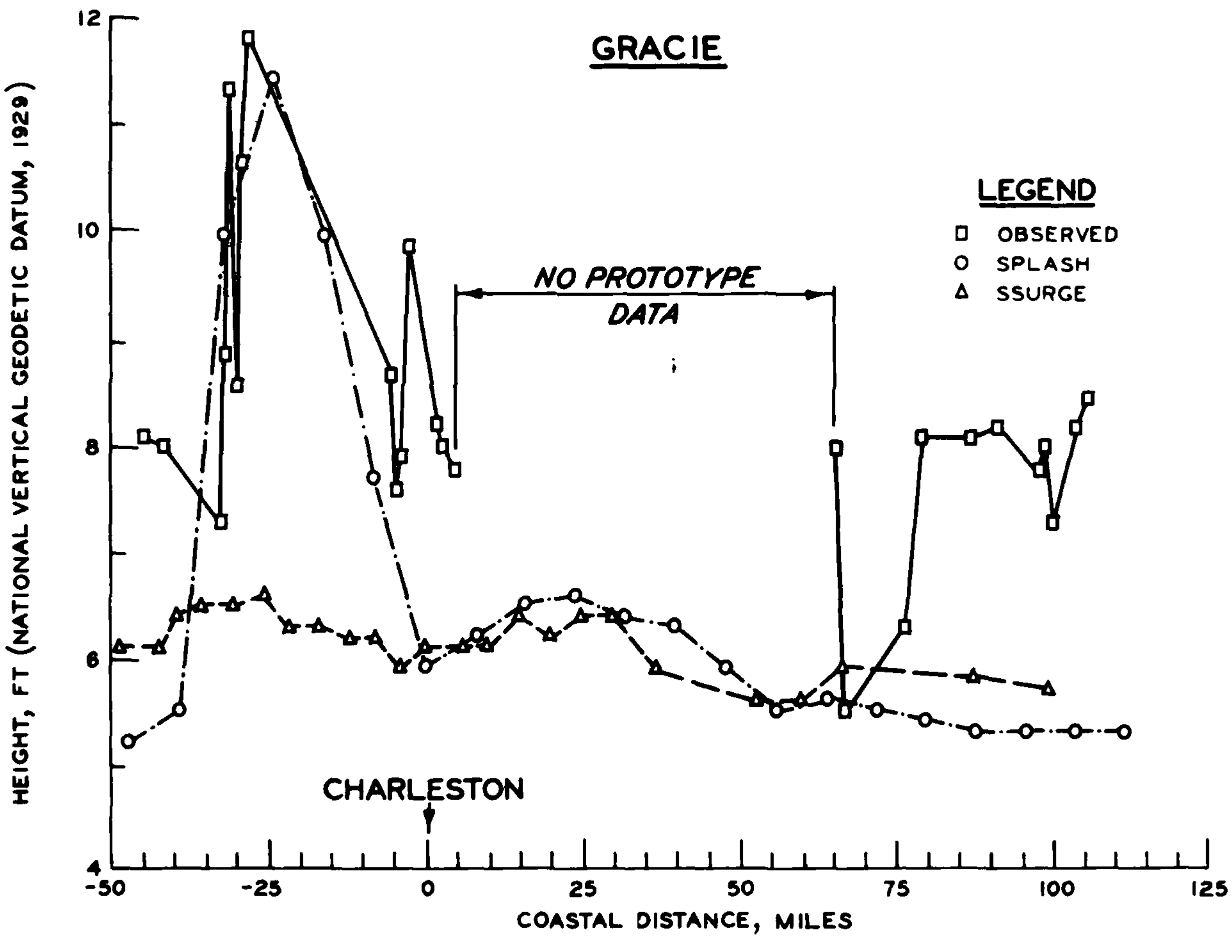

Figure 2. Observed and computed high-water marks for Hurricane Gracie

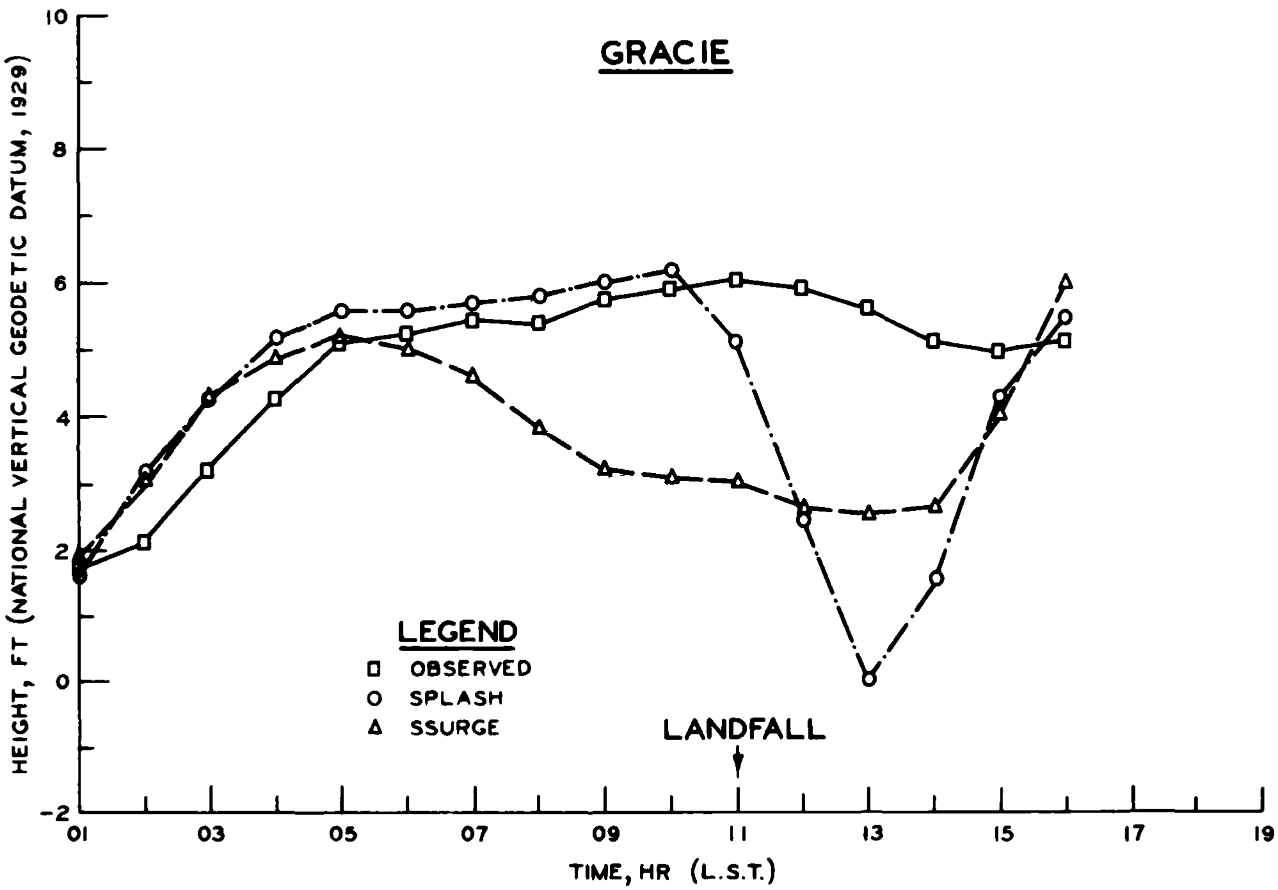

Figure 3. Observed and computed water levels at Charleston, S. C., before and after landfall of Hurricane Gracie

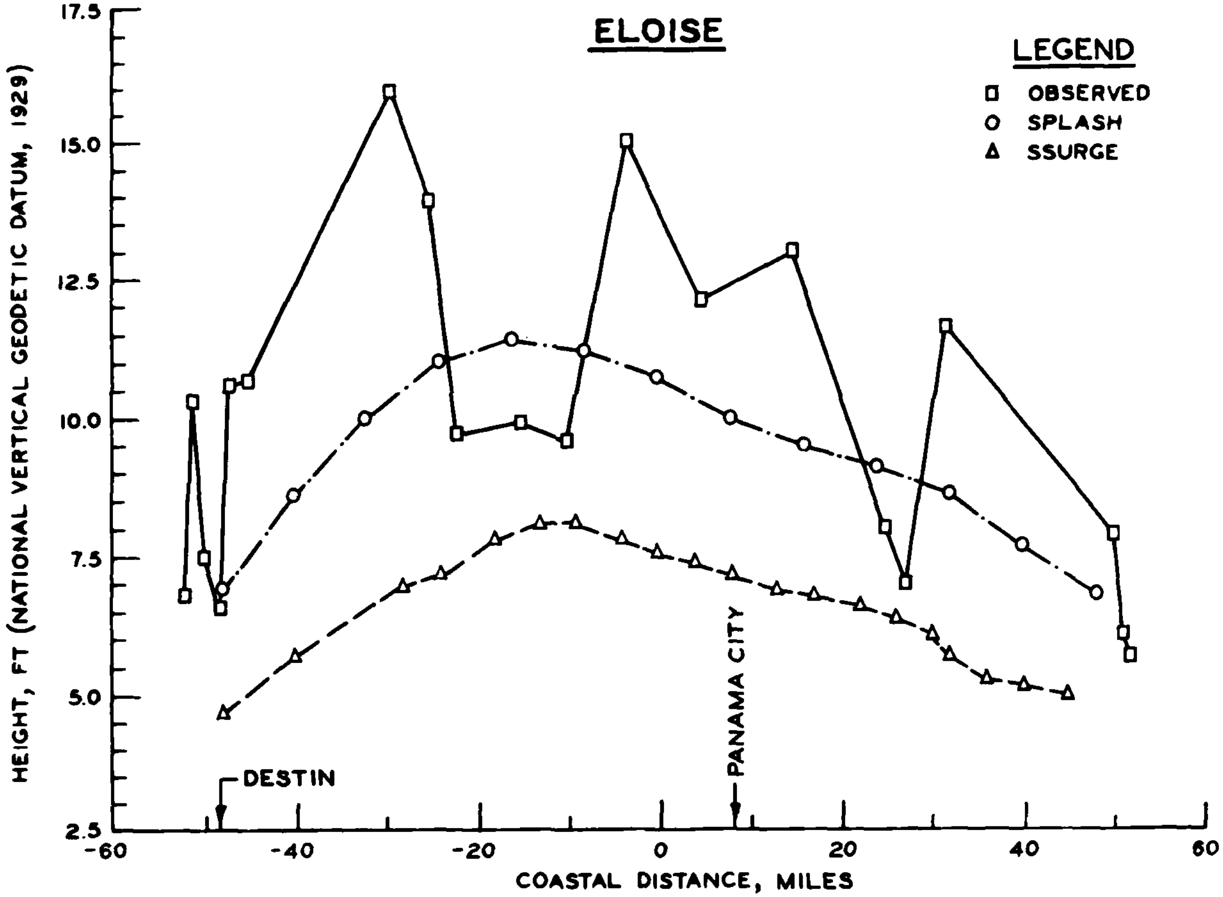

Figure 4. Observed and computed high-water marks for Hurricane Eloise

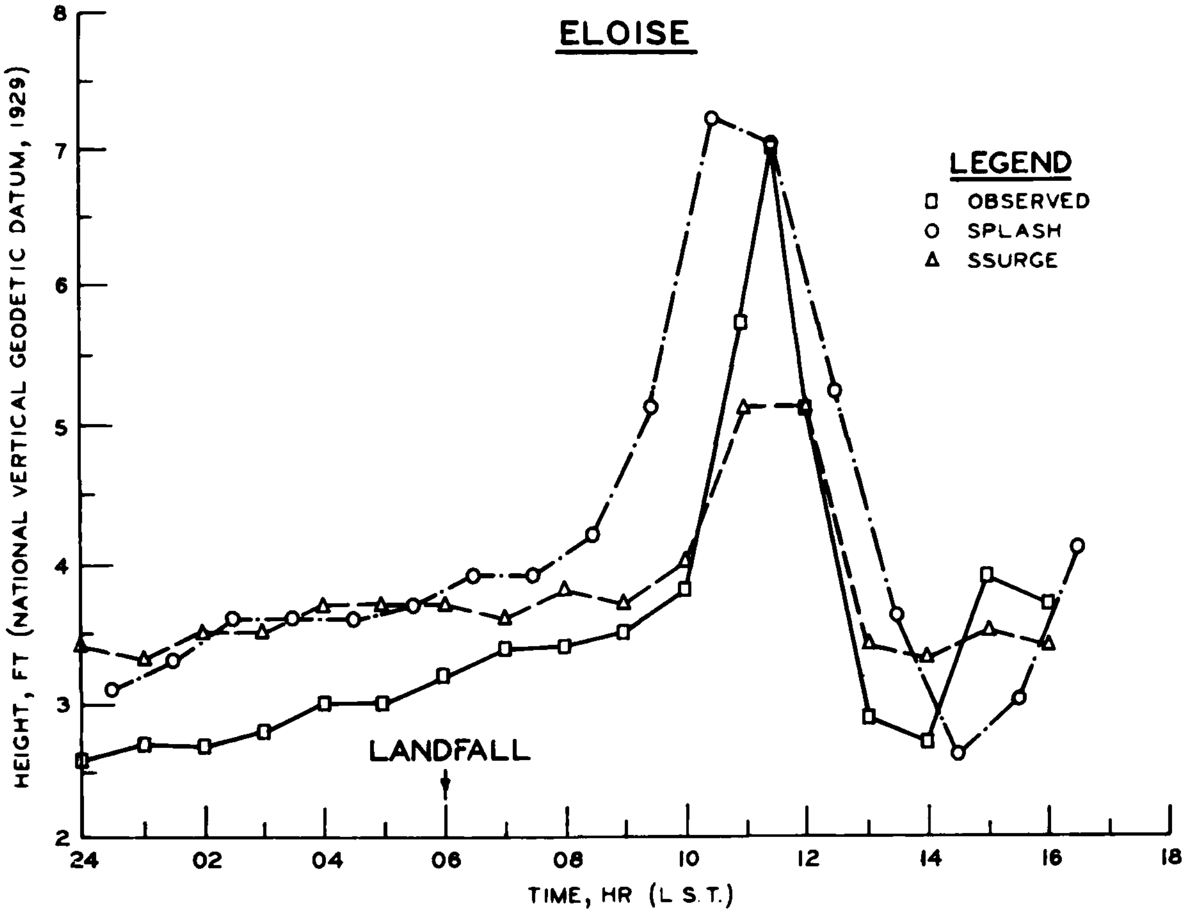

Figure 5. Observed and computed water levels at Destin, Fla., before and after landfall of Hurricane Eloise

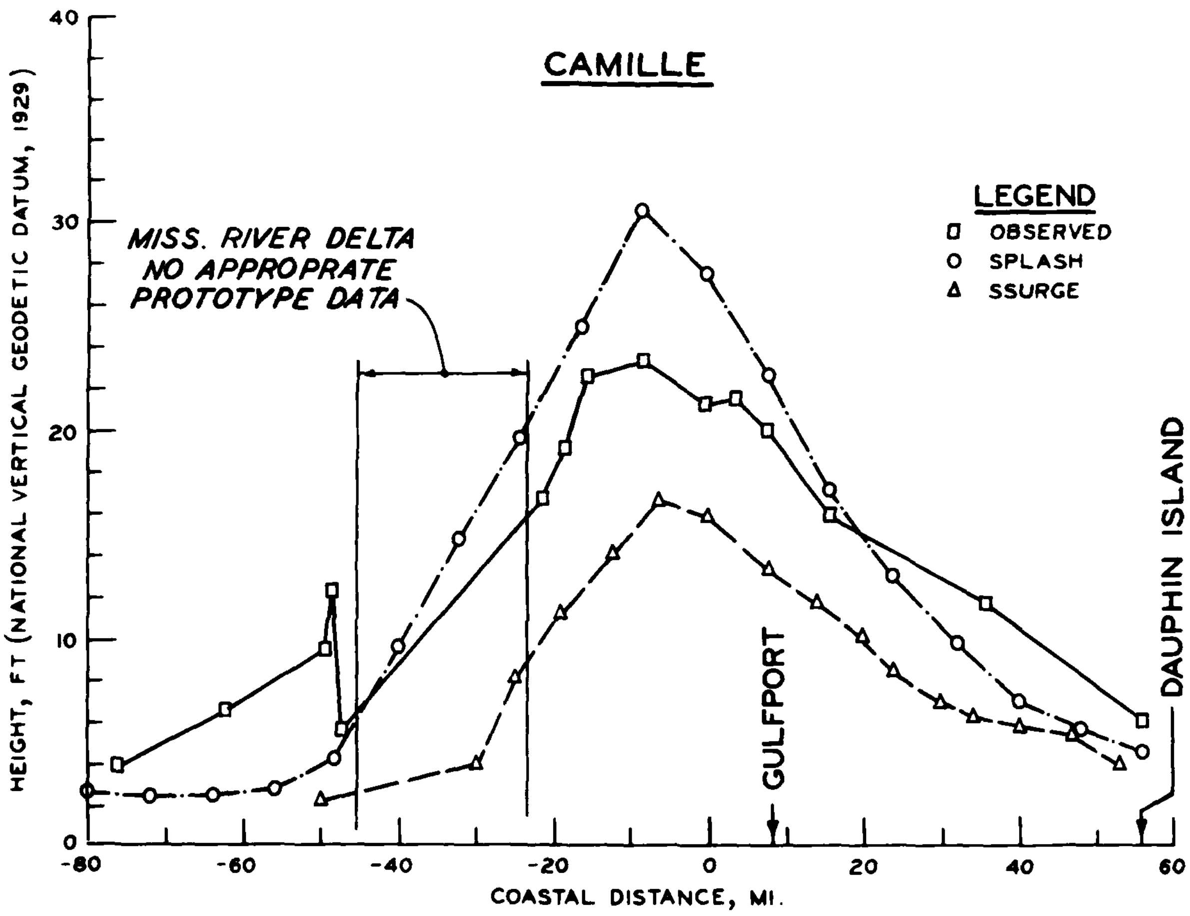

Figure 6. Observed and computed high-water marks for Hurricane Camille

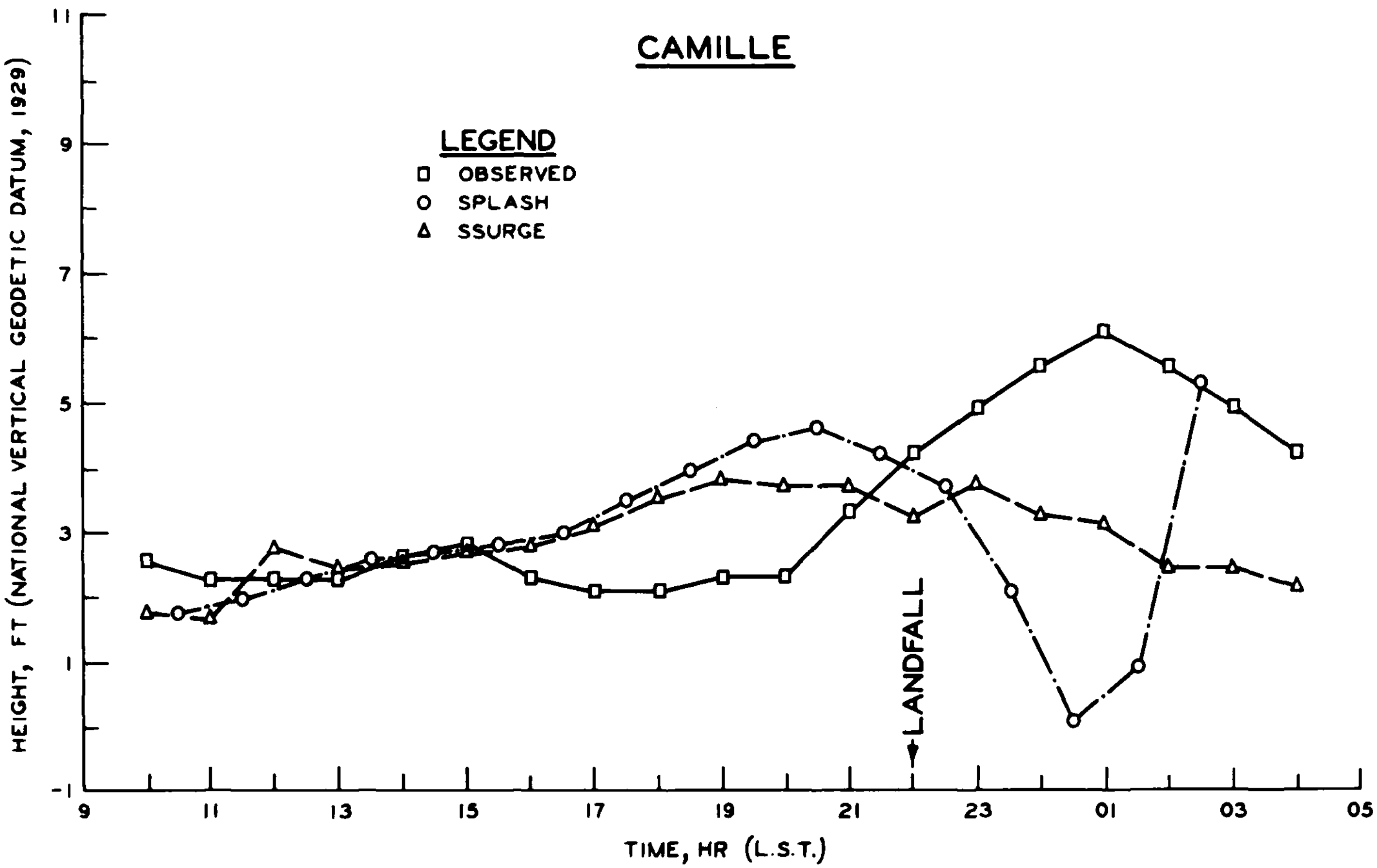

Figure 7. Observed and computed water levels at Dauphin Island, Ala., before and after landfall of Hurricane Camille

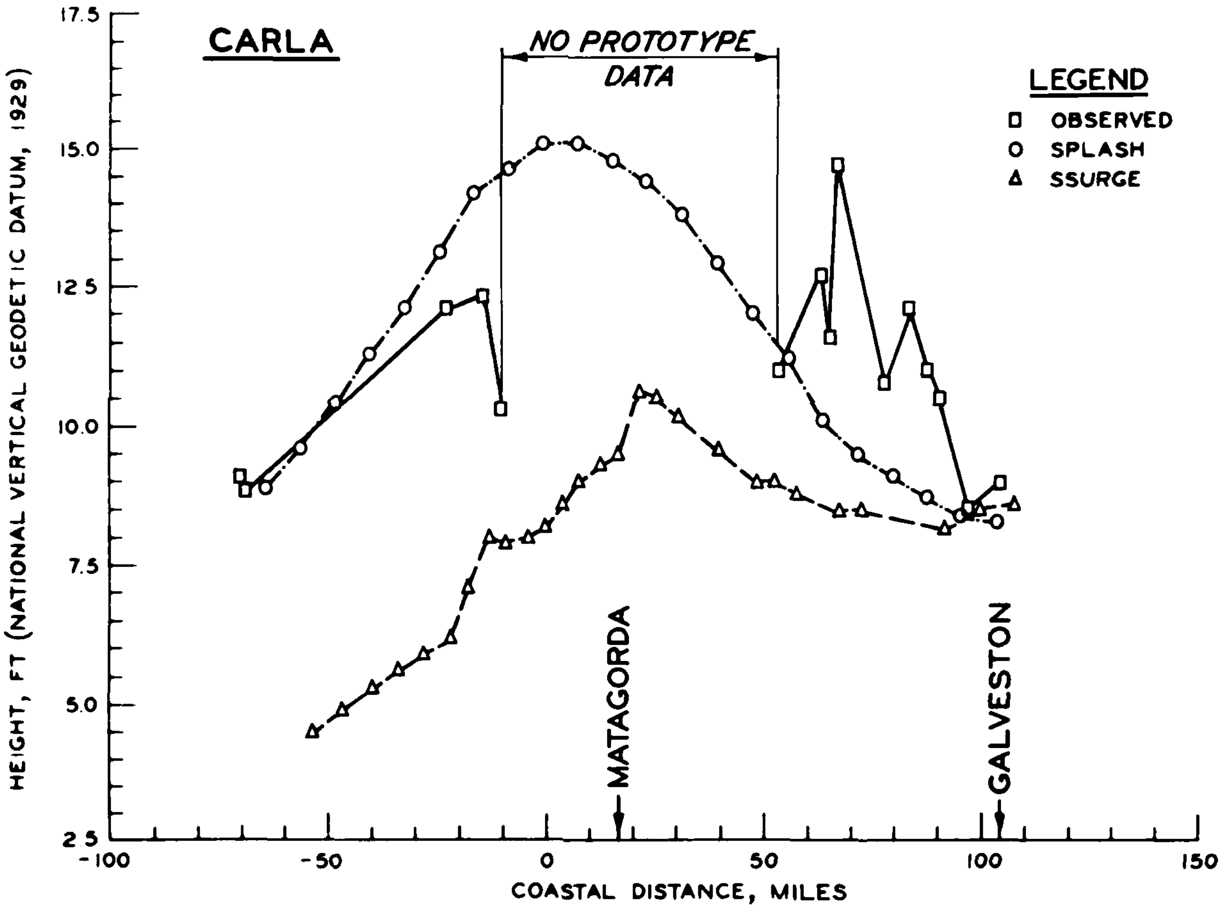

Figure 8. Observed and computed high-water marks for Hurricane Carla

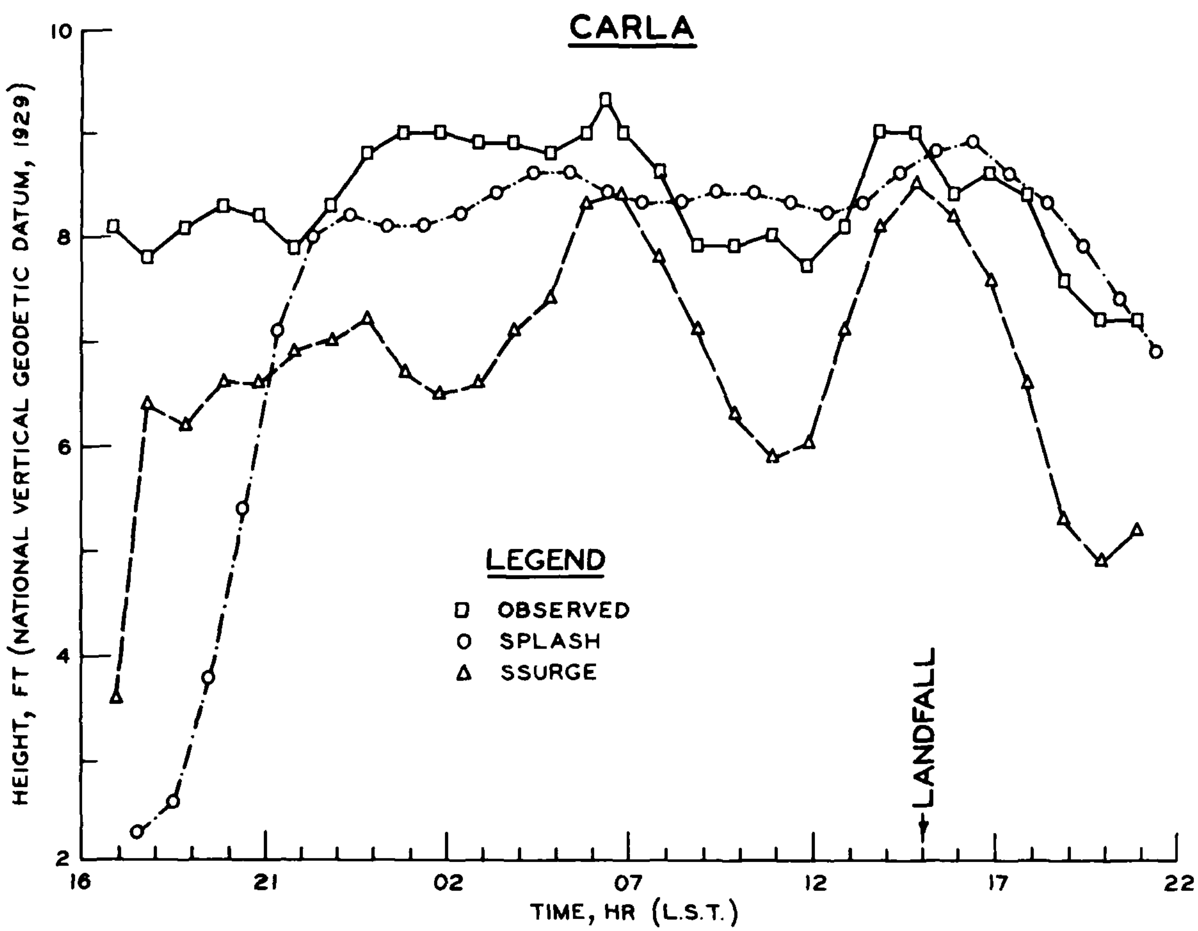

Figure 9. Observed and computed water levels at Galveston, Tex. (Pleasure Pier), before and after landfall of Hurricane Carla

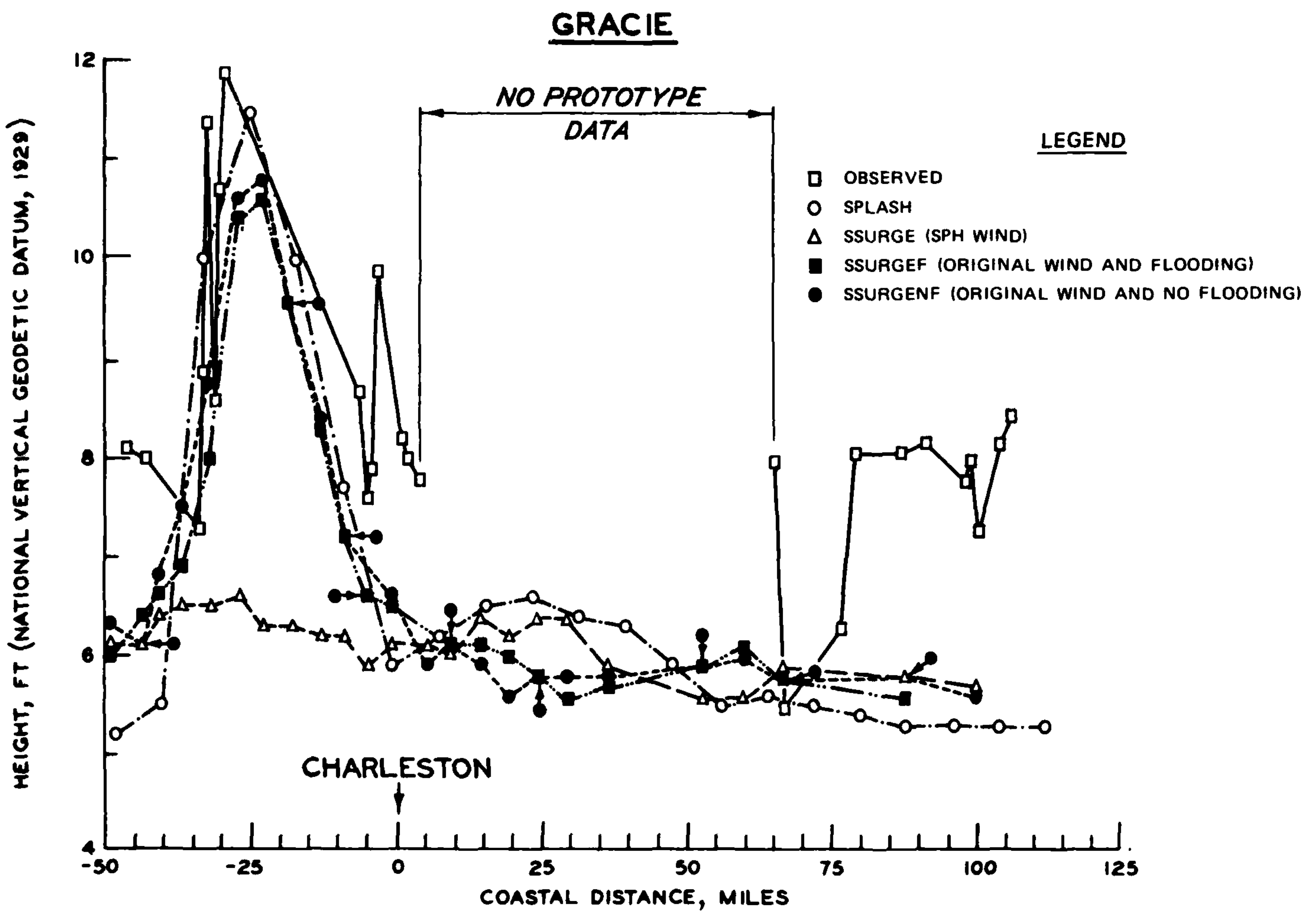

Figure 10. Observed and computed high-water marks for Hurricane Gracie (additional computer runs)

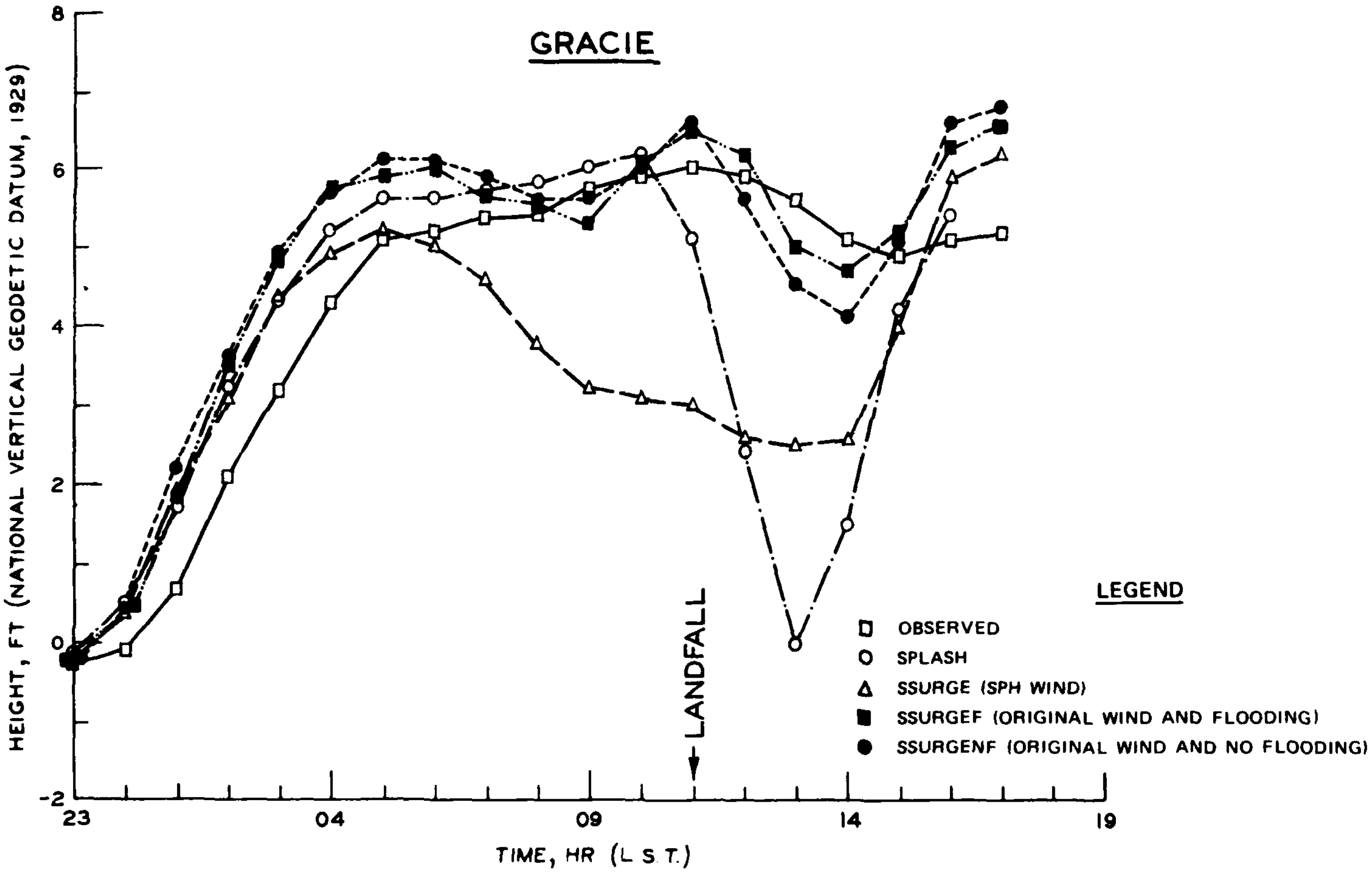

Figure 11. Observed and computed water levels at Charleston, S. C., before and after landfall for Hurricane Gracie (additional computer runs)

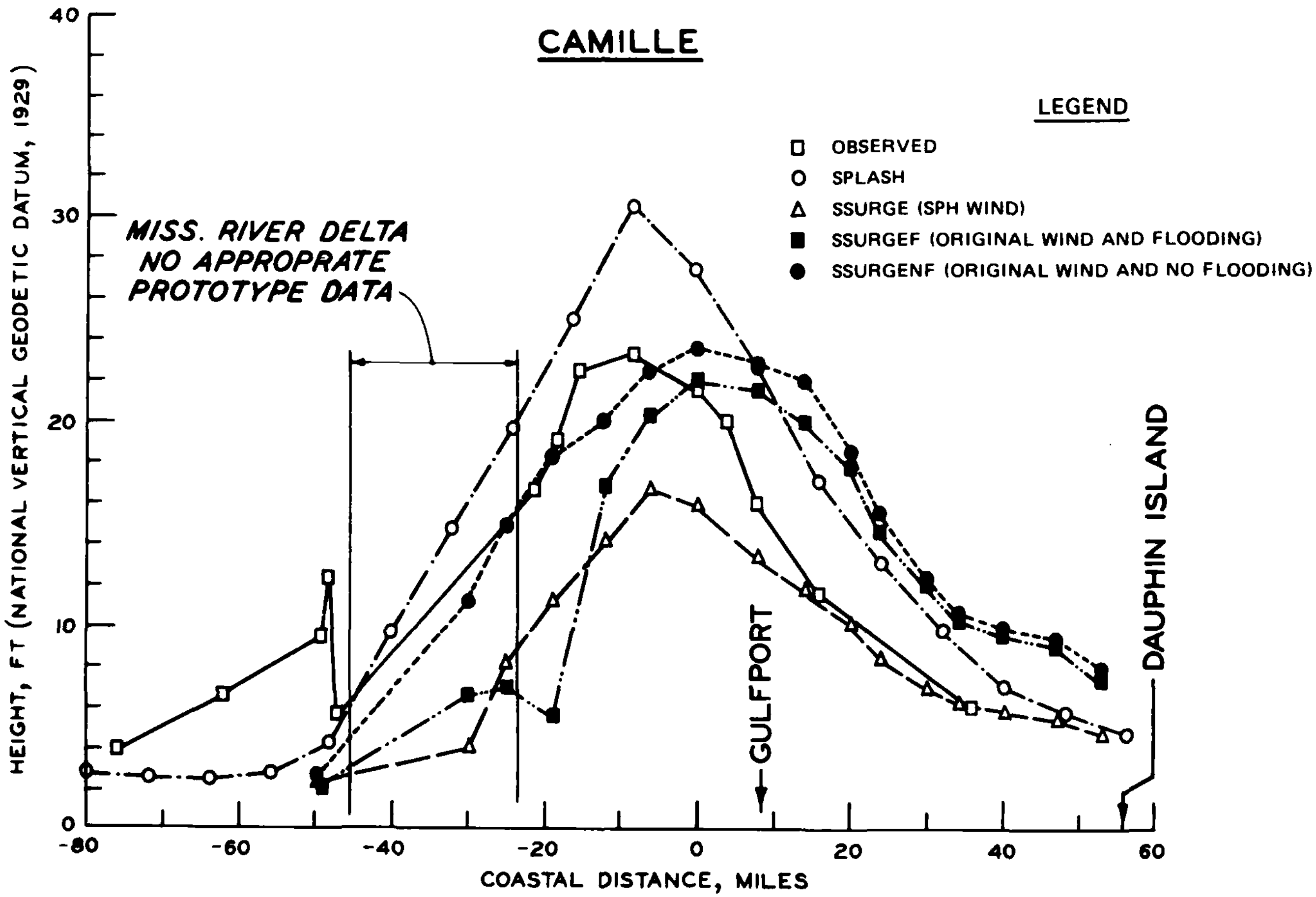

Figure 12. Observed and computed high-water marks for Hurricane Camille (additional computer runs)

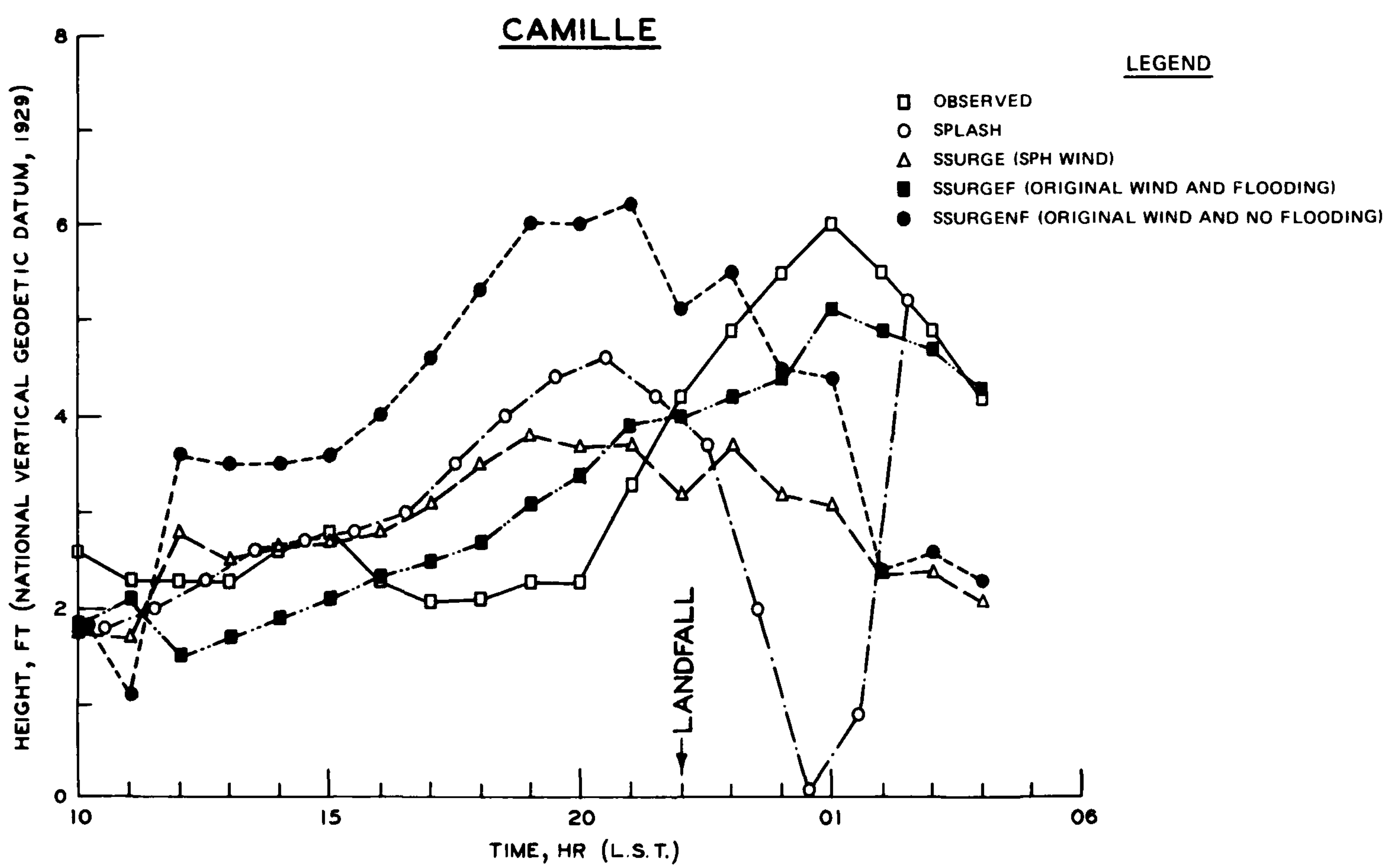

Figure 13. Observed and computed water levels at Dauphin Island, Ala., before and after landfall of Hurricane Camille (additional computer runs)

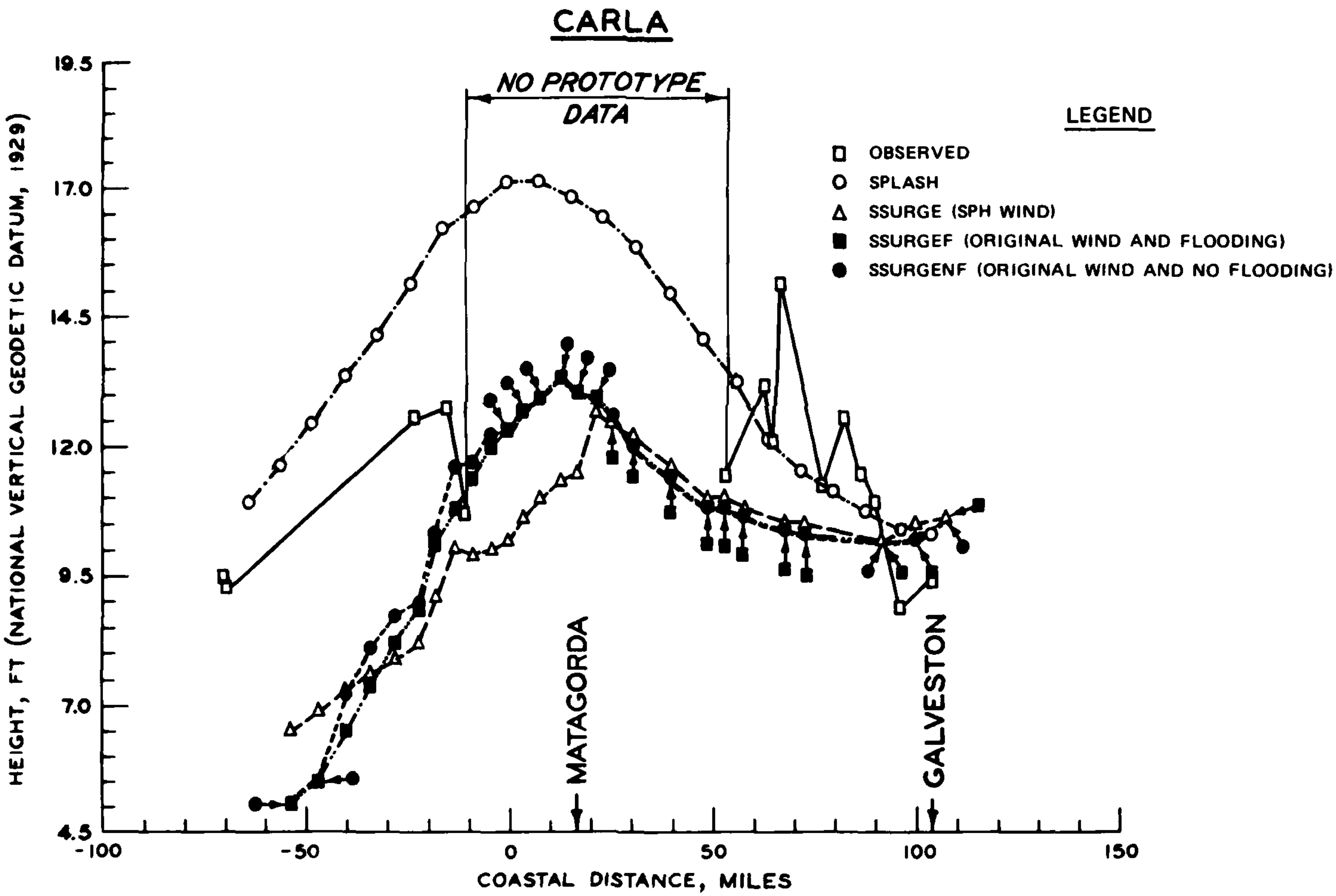

Figure 14. Observed and computed high-water marks for Hurricane Carla (additional computer runs)

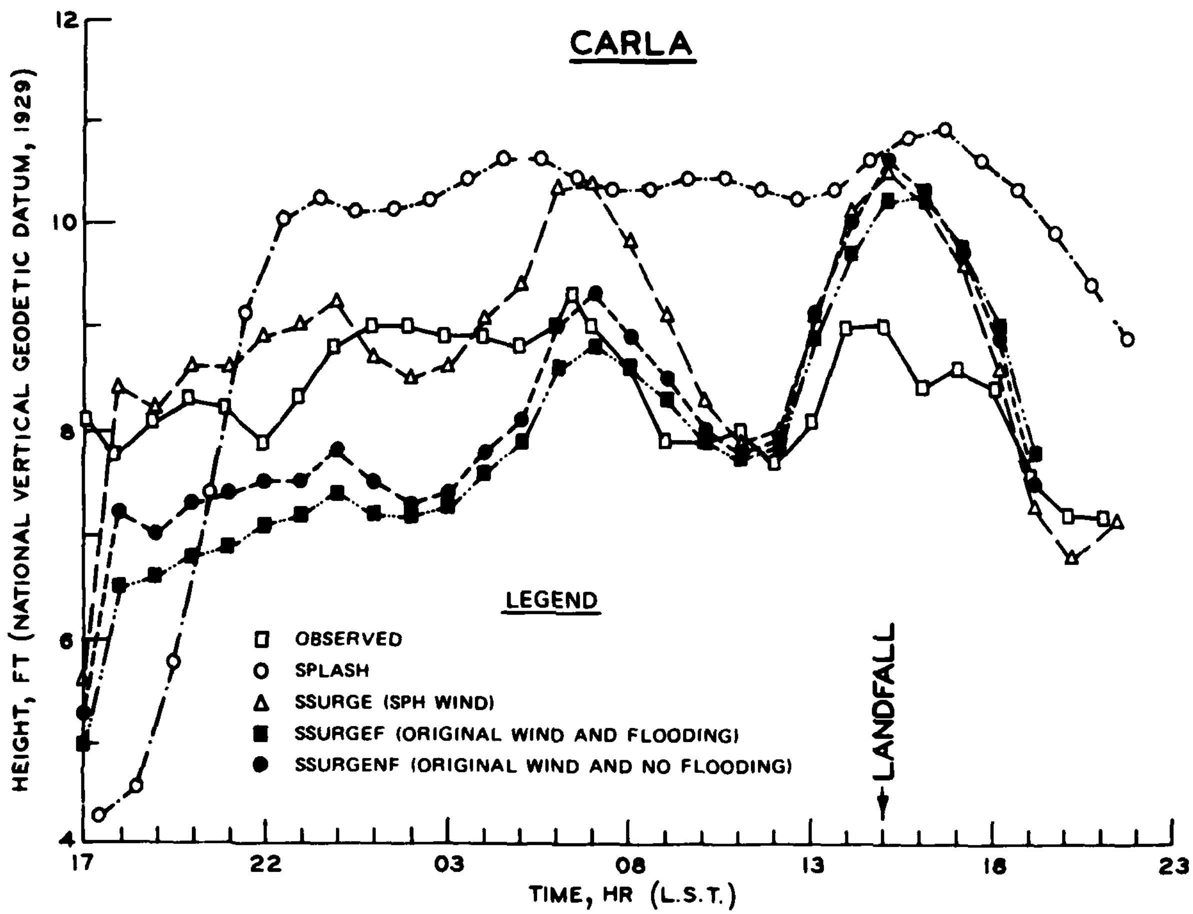

Figure 15. Observed and computed water levels at Galveston, Tex. (Pleasure Pier), before and after landfall of Hurricane Carla (additional computer runs)

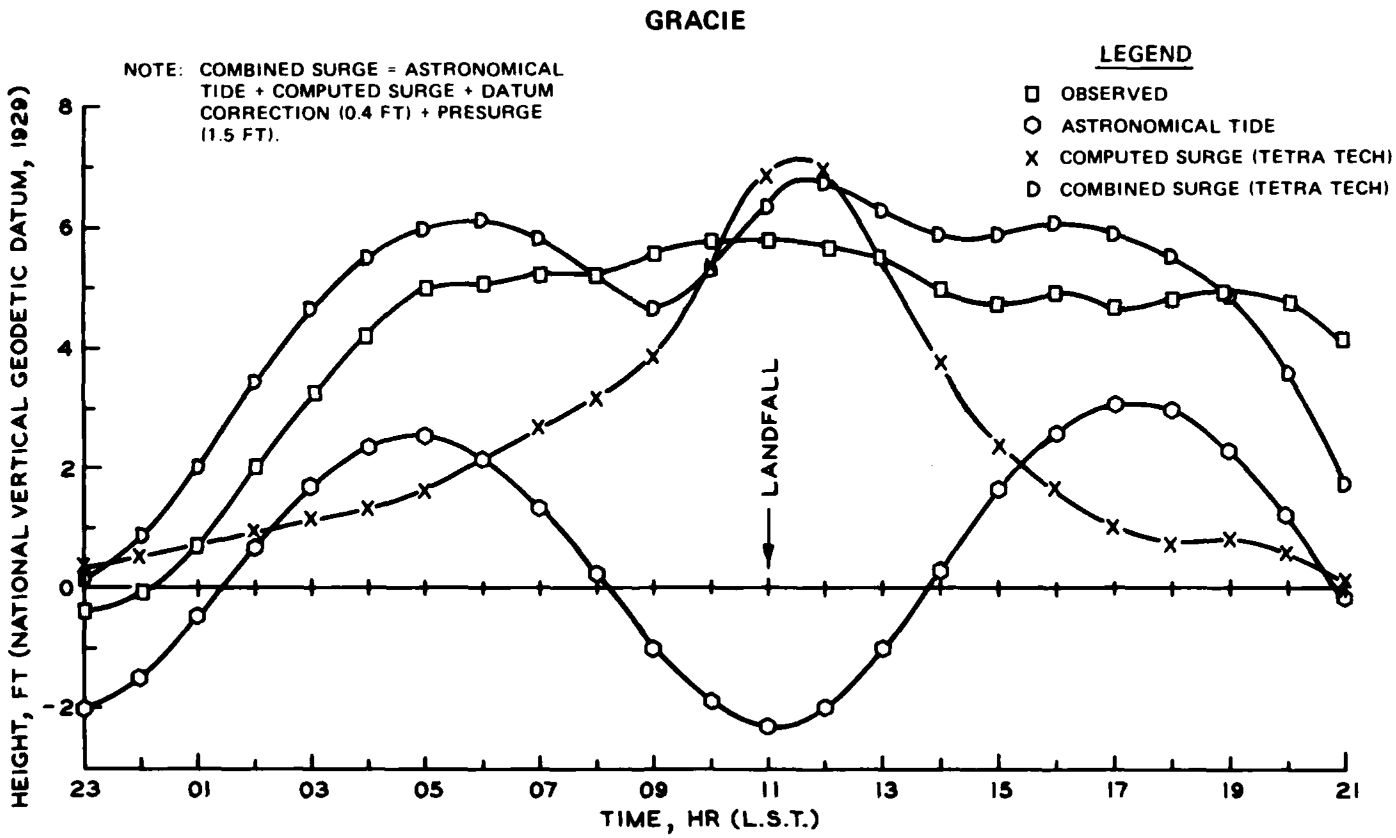

Figure 16. Computed surge, predicted astronomical tide, and their combination at Charleston, S. C., before and after landfall of Hurricane Gracie using the Tetra Tech wind model with variable k

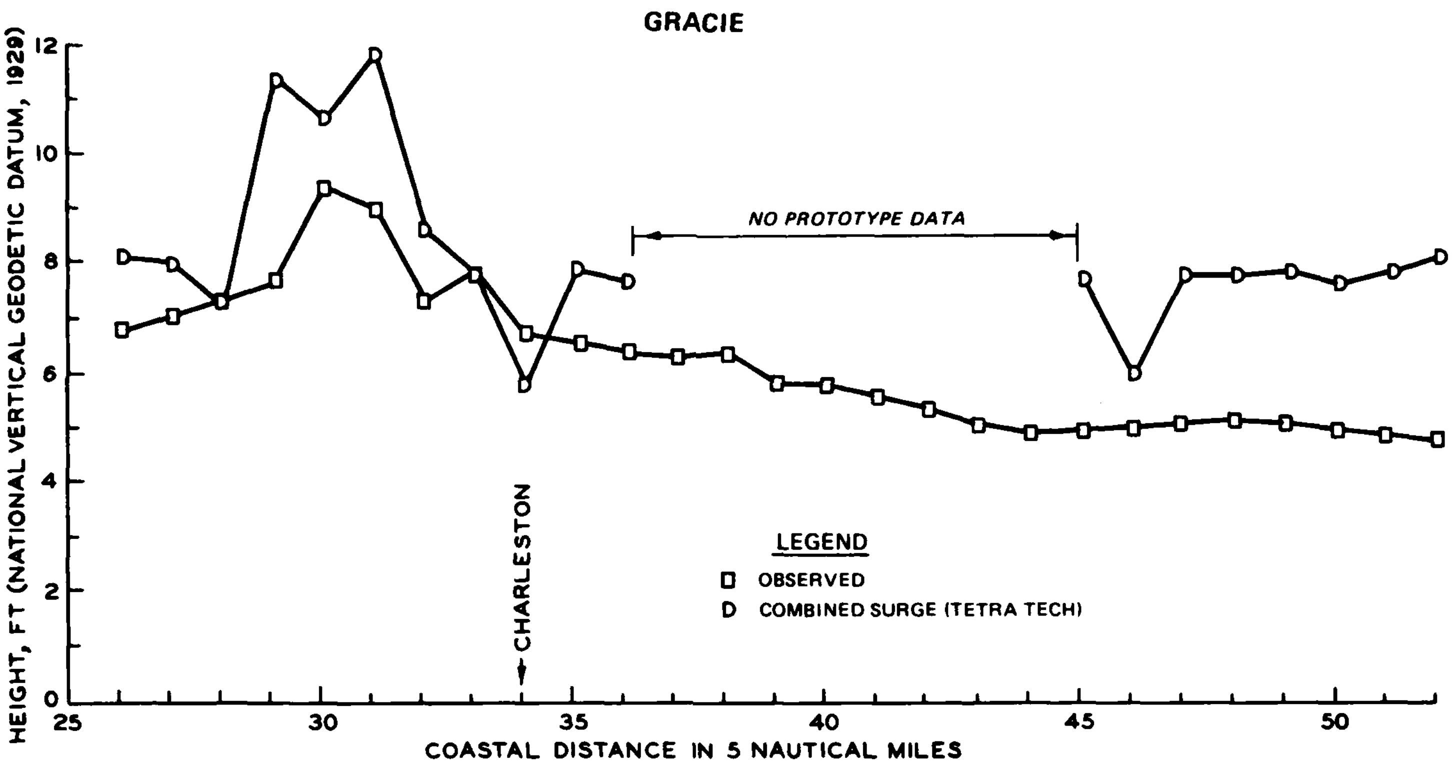

Figure 17. Observed and computed high-water marks for Hurricane Gracie using the Tetra Tech wind model with variable k

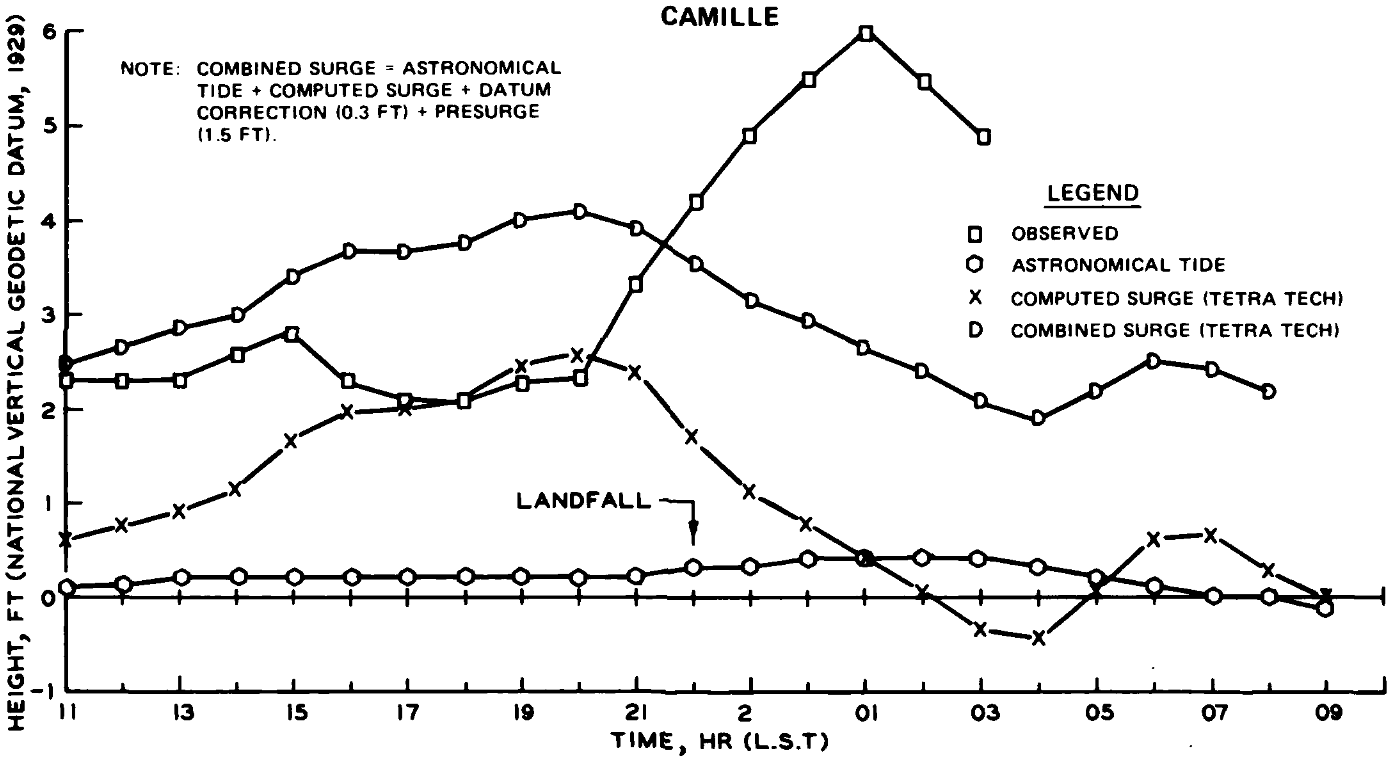

Figure 18. Computed surge, predicted astronomical tide, and their combination at Dauphin Island, Ala., before and after landfall of Hurricane Camille using the SPLASH wind model with constant k

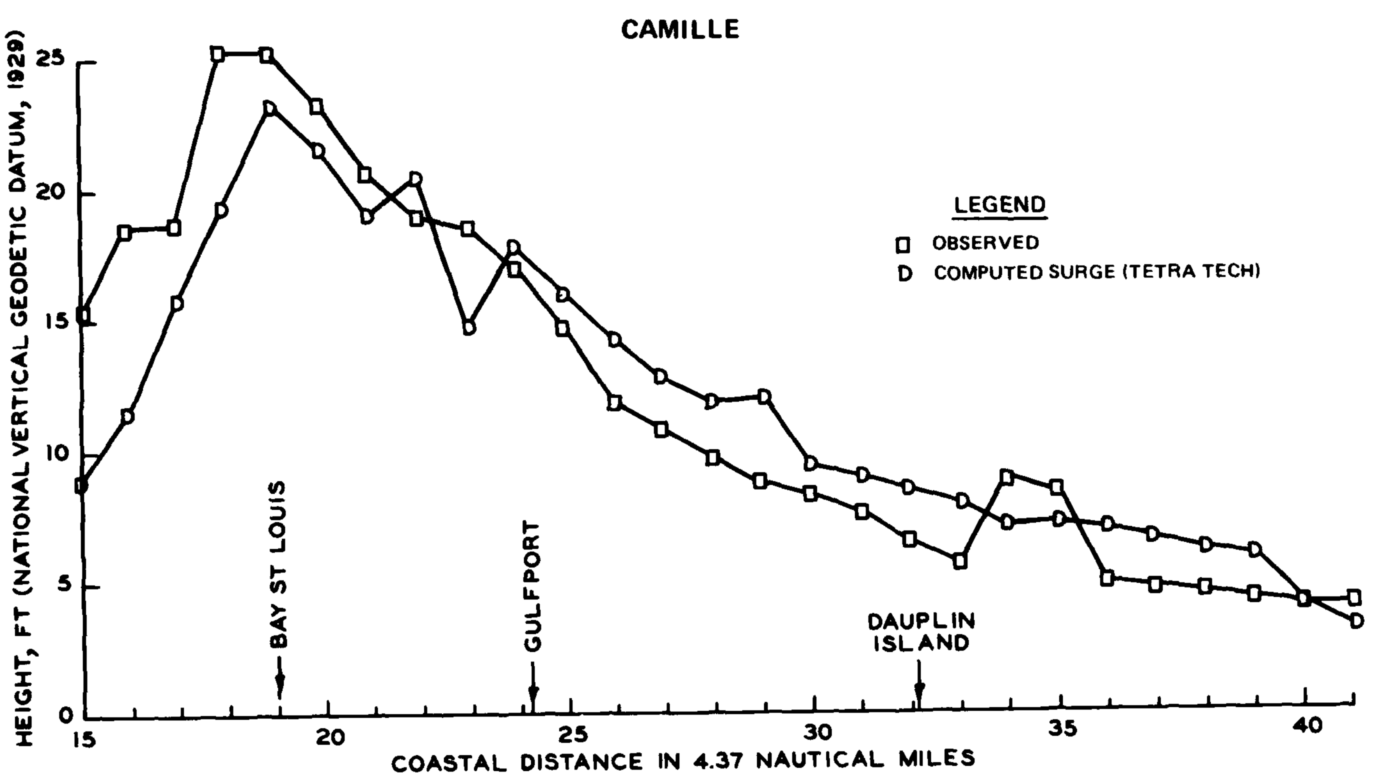

Figure 19. Observed and computed high-water marks for Hurricane Camille using the Tetra Tech wind model with variable k

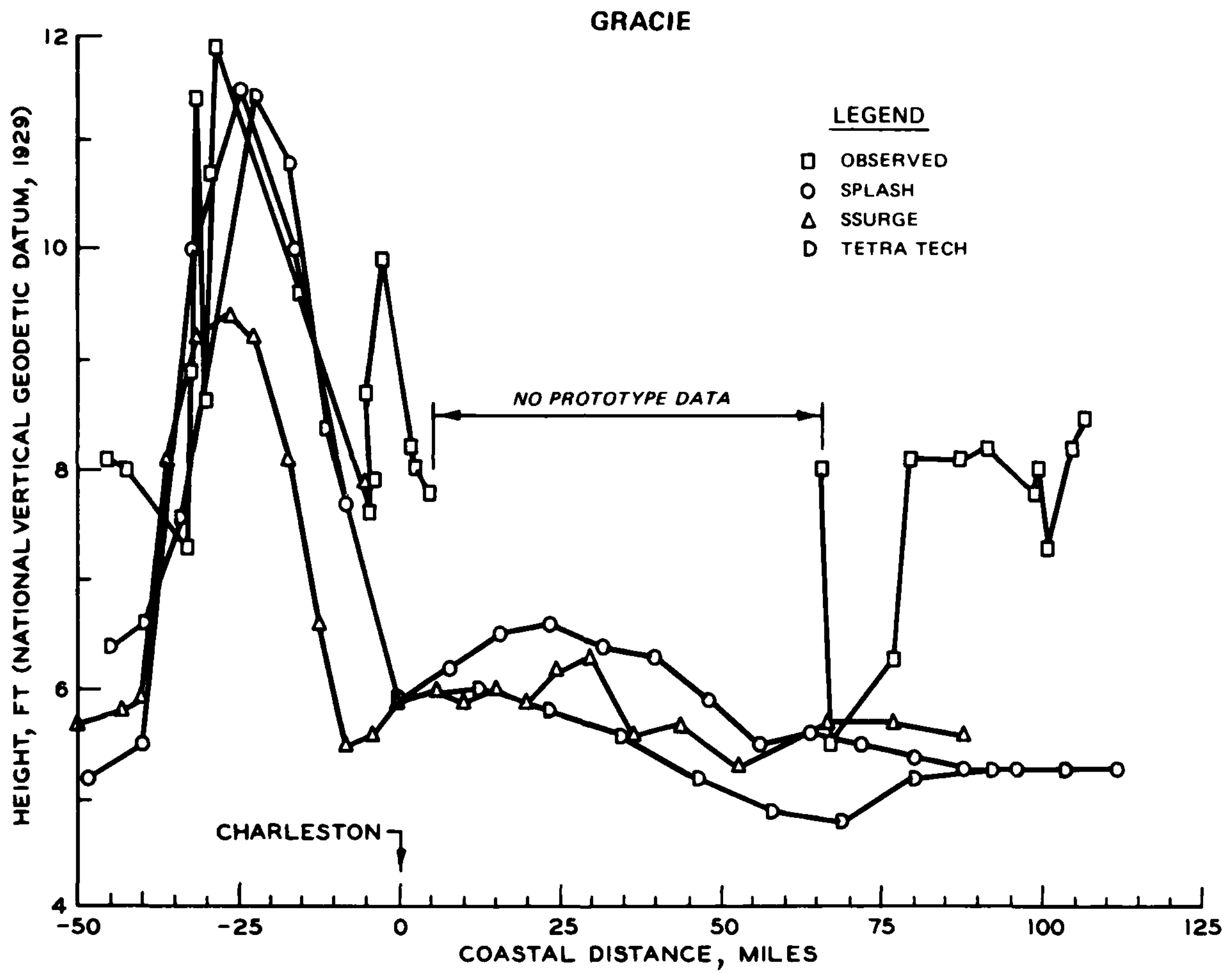

Figure 20. Observed and computed high-water marks for Hurricane Gracie with all models using the SPLASH wind model and constant k

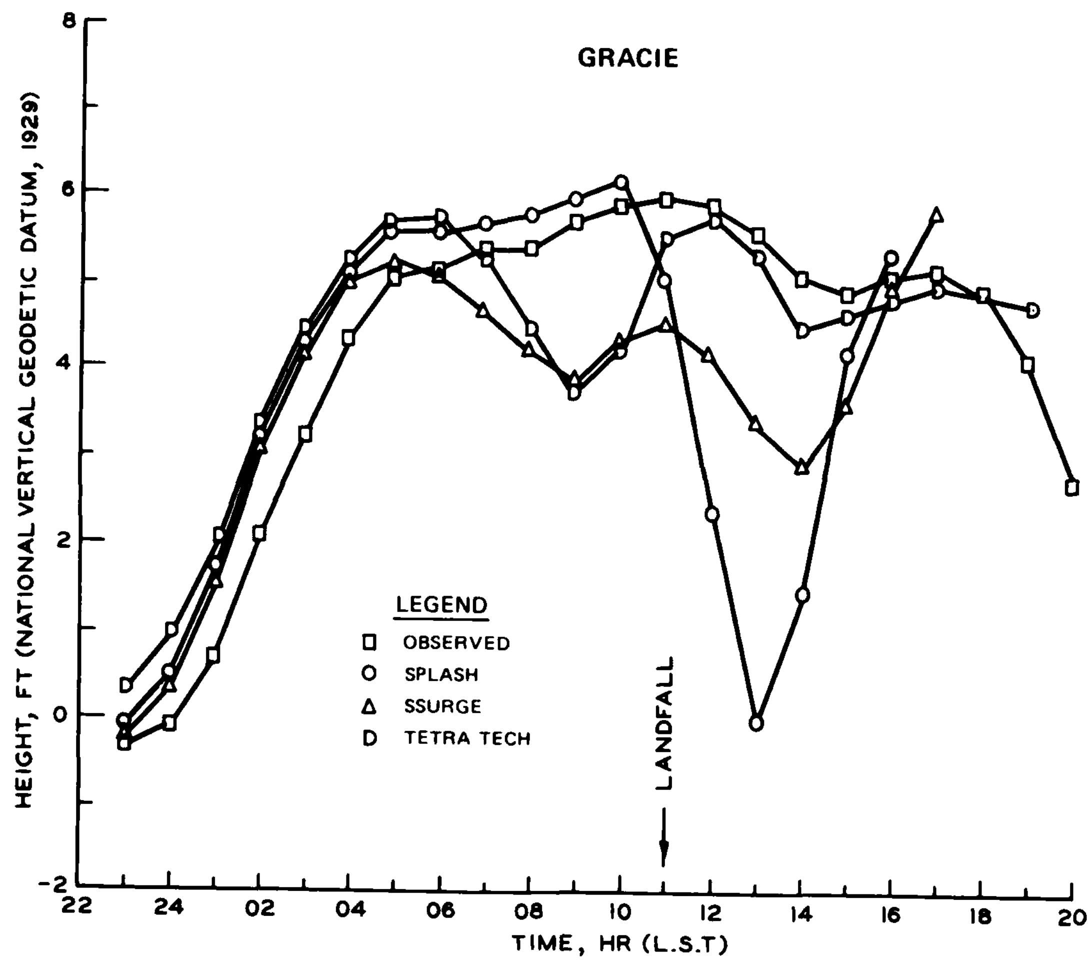

Figure 21. Observed and computed water levels at Charleston, S. C., before and after landfall of Hurricane Gracie with all models using the SPLASH wind model and constant k

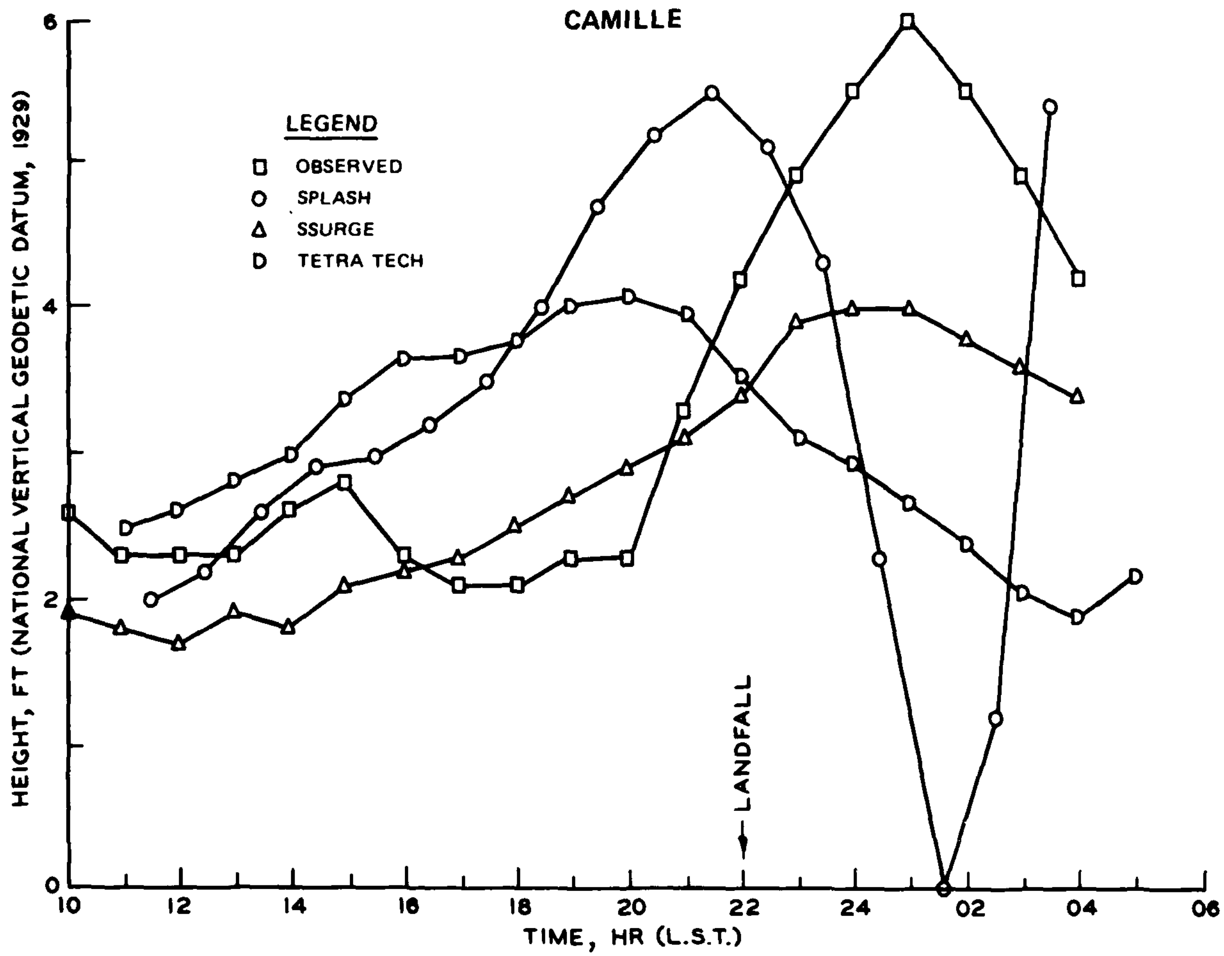

Figure 22. Observed and computed water levels at Dauphin Island, Ala., before and after landfall of Hurricane Camille with all models using the SPLASH wind model and constant k

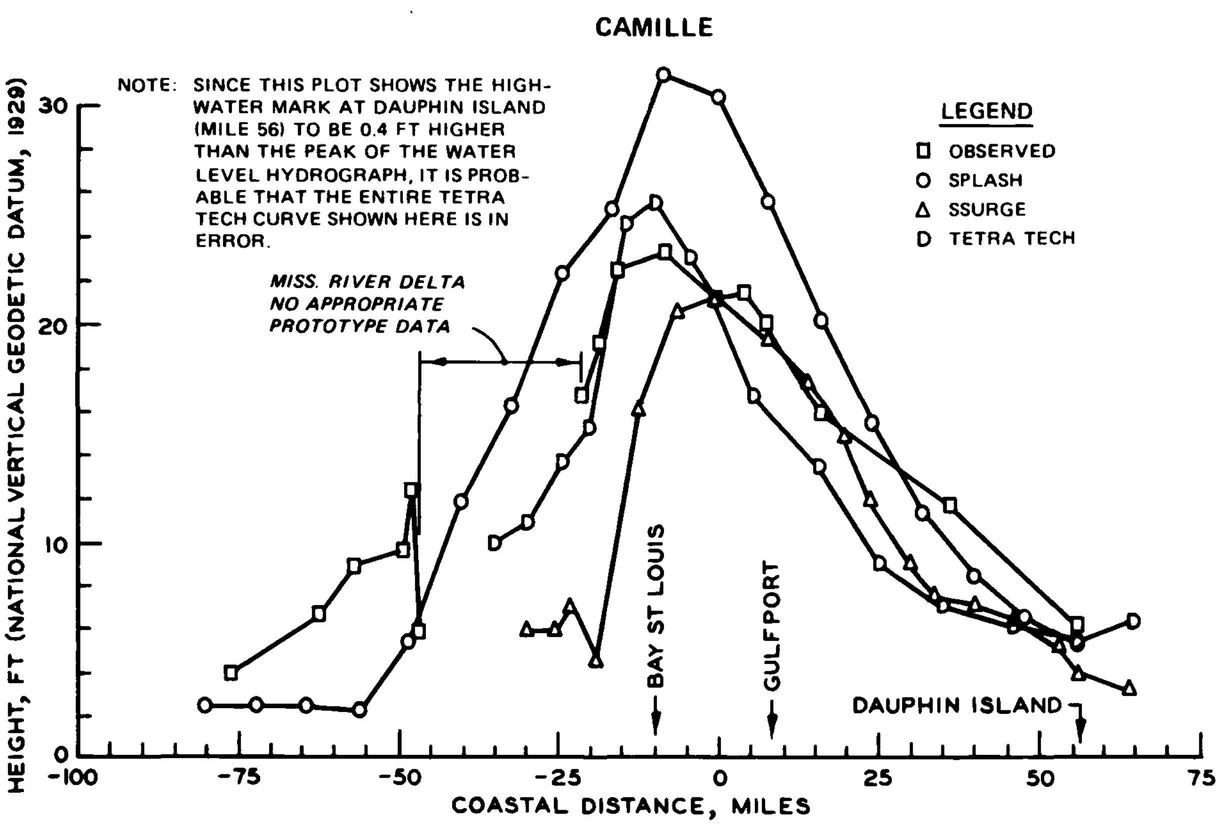

Figure 23. Observed and computed high-water marks for Hurricane Camille with all models using the SPLASH wind model and constant k

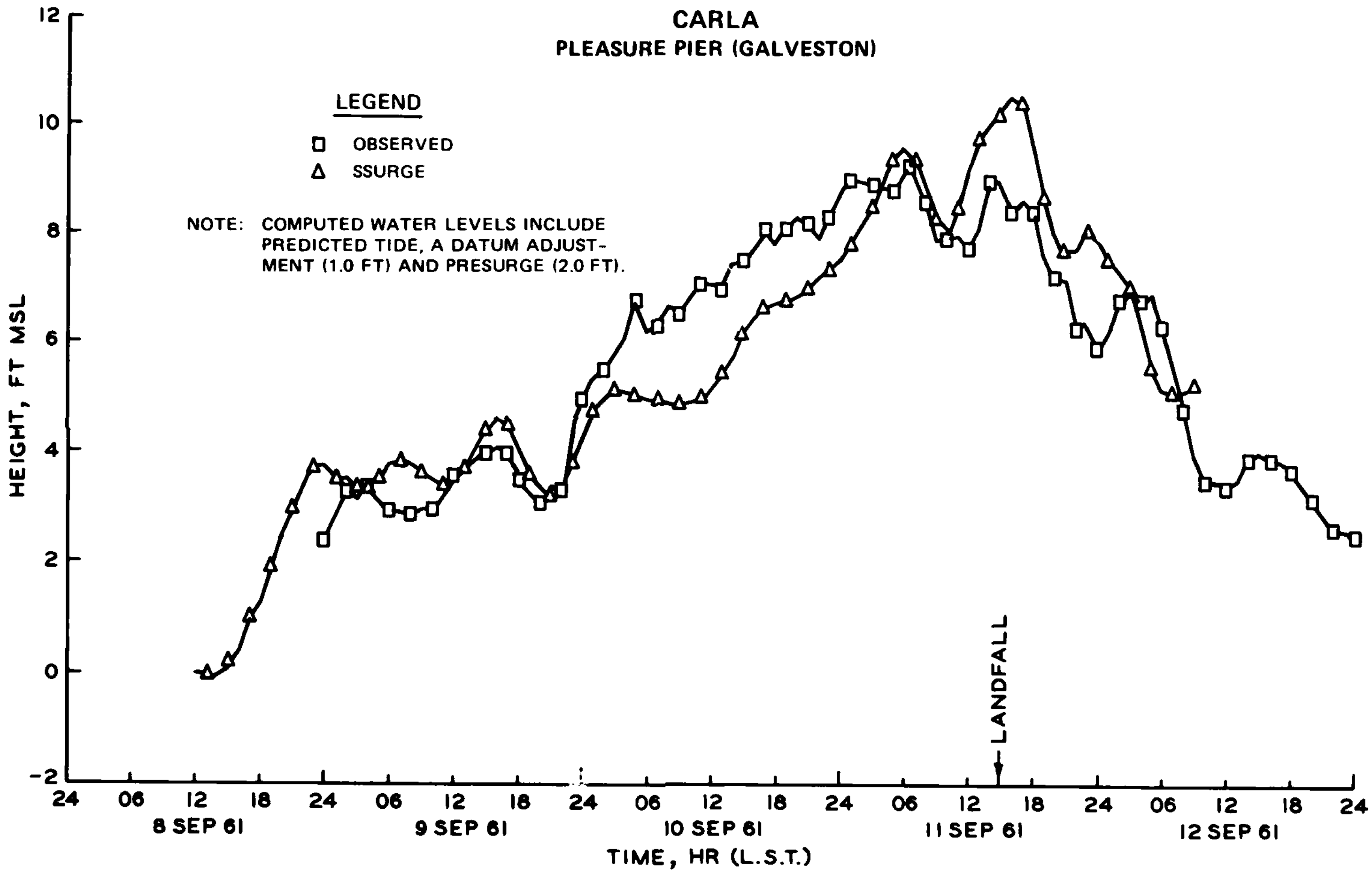

Figure 24. Observed water levels at Galveston, Tex., before and after landfall of Hurricane Carla and those computed by the SSURGE model to generate ocean boundary input data for the inland flooding models

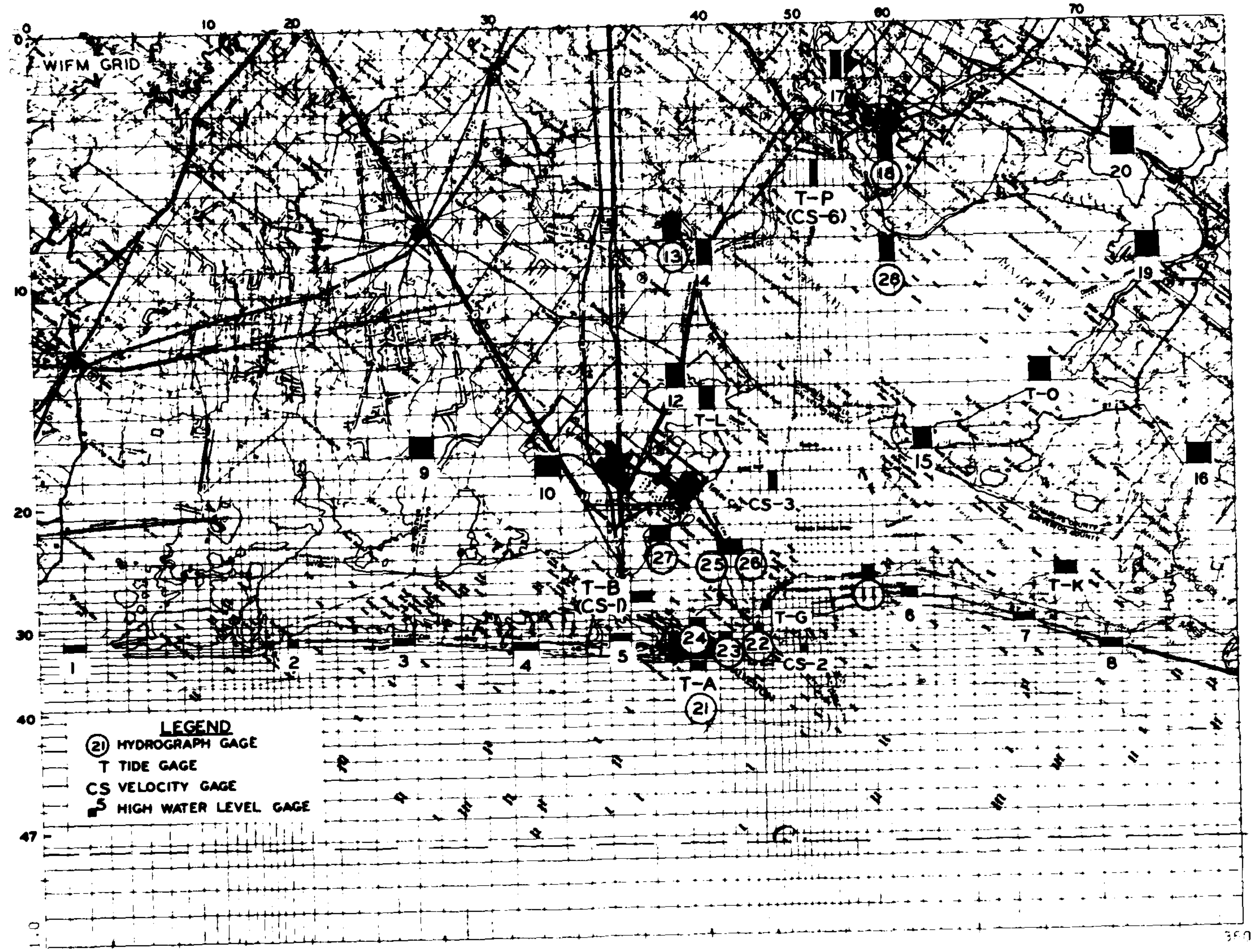

Figure 25. Location of data points, WIFM grid

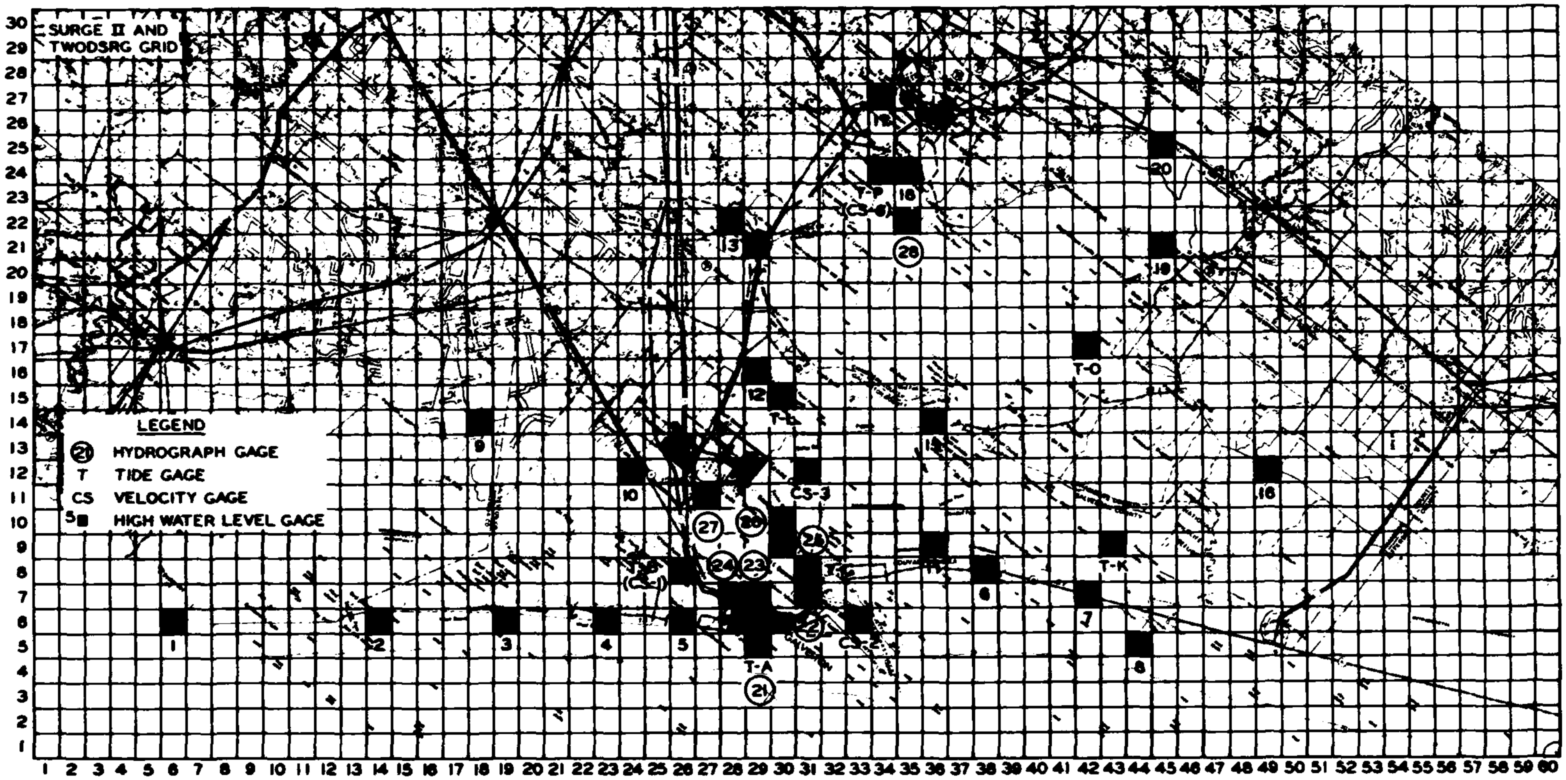

Figure 26. Location of data points, SURGE II and TWODSRG grid

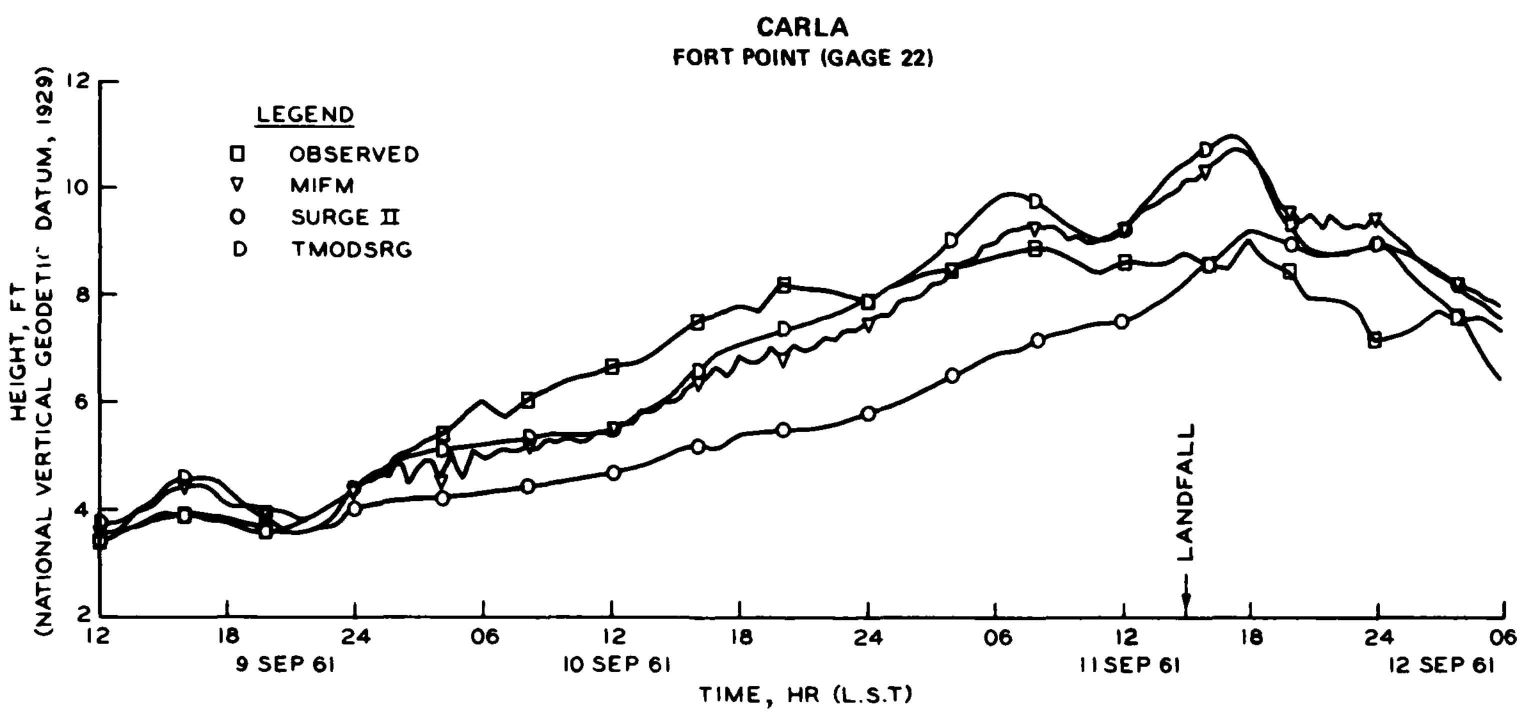

Figure 27. Observed and computed water levels at Fort Point (gage 22) before and after landfall of Hurricane Carla

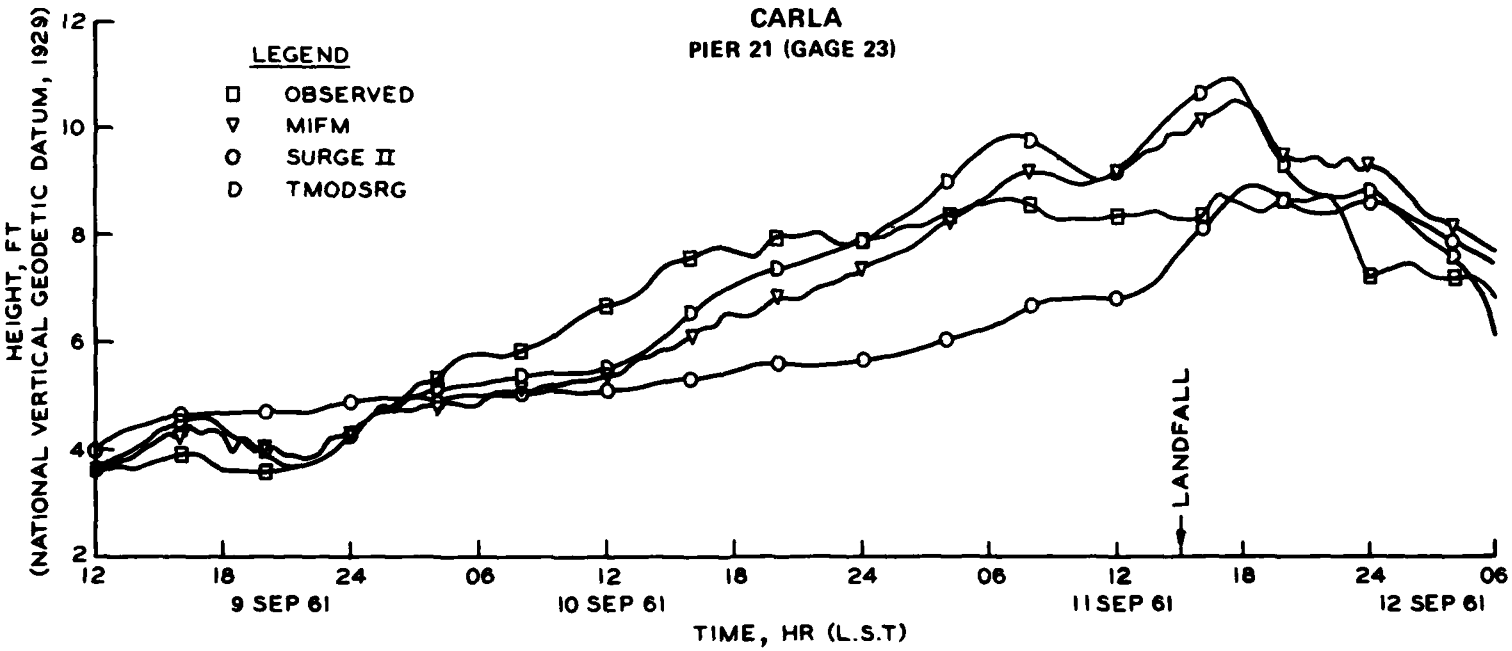

Figure 28. Observed and computed water levels at Pier 21 (gage 23) before and after landfall of Hurricane Carla

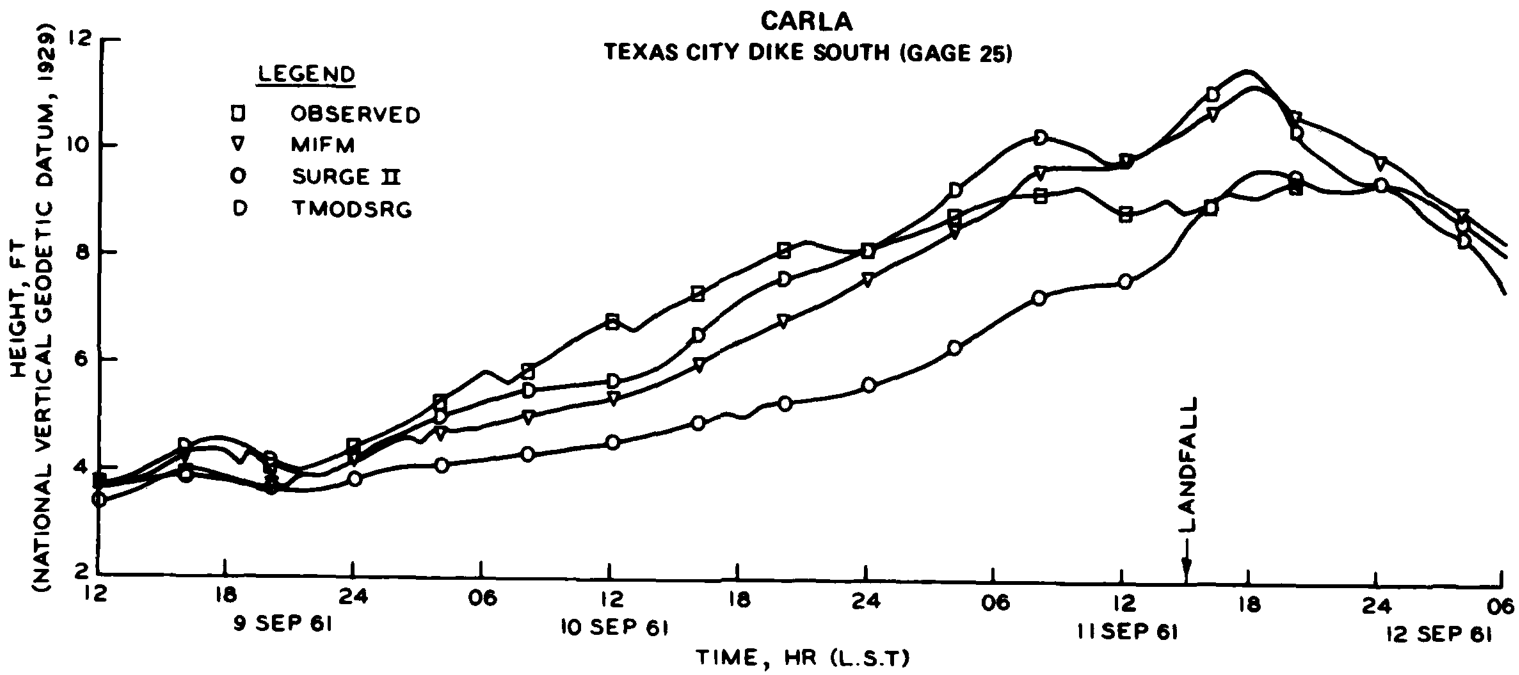

Figure 29. Observed and computed water levels at Pelican Bridge (gage 24) before and after landfall of Hurricane Carla

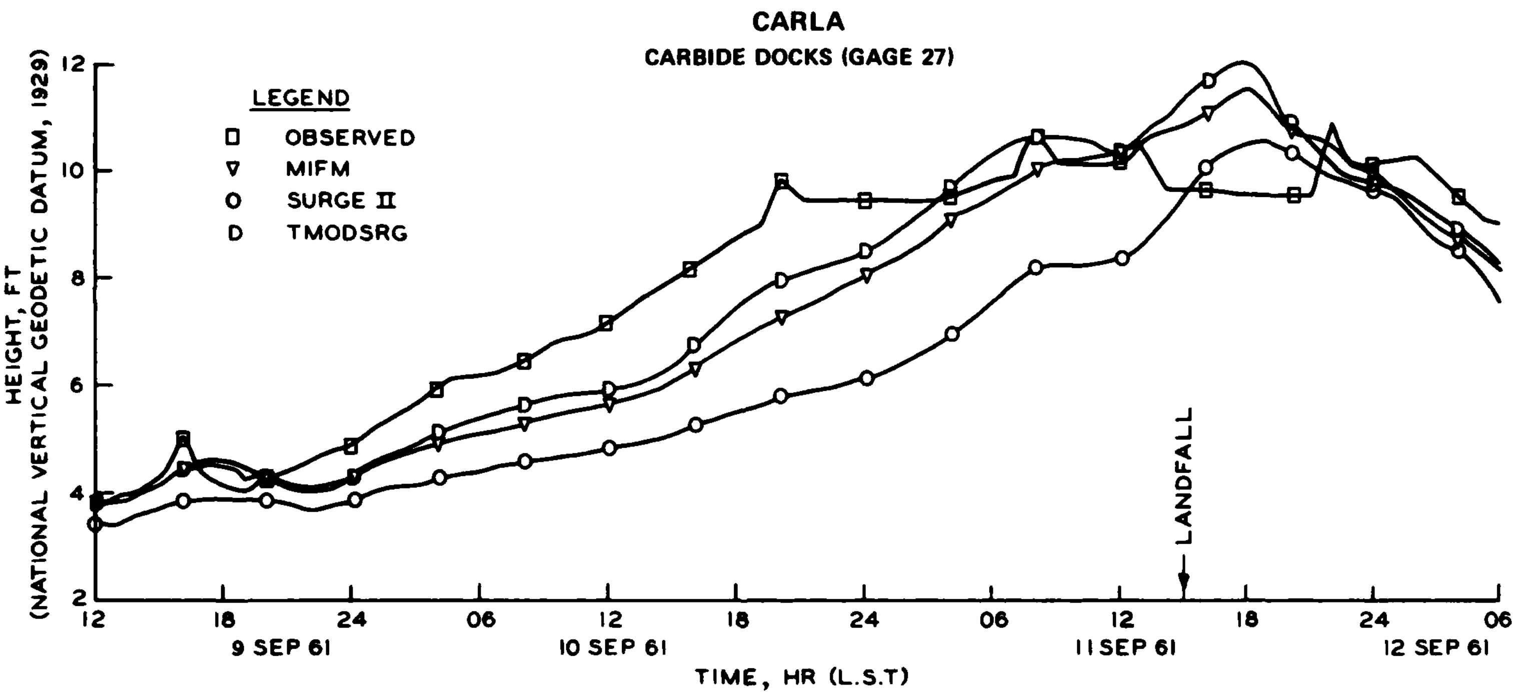

Figure 30. Observed and computed water levels at Carbide Docks (gage 27) before and after landfall of Hurricane Carla

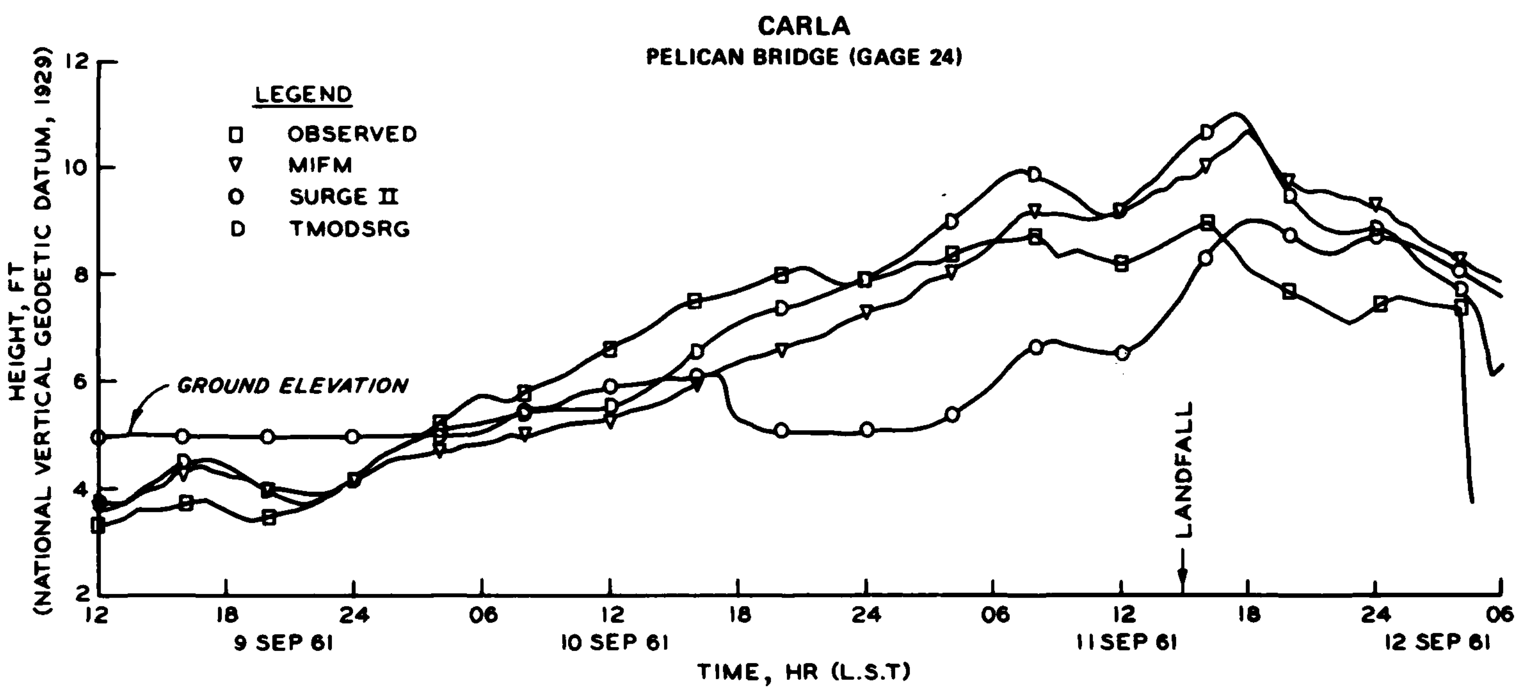

Figure 31. Observed and computed water levels at Texas City Dike South (gage 25) before and after landfall of Hurricane Carla

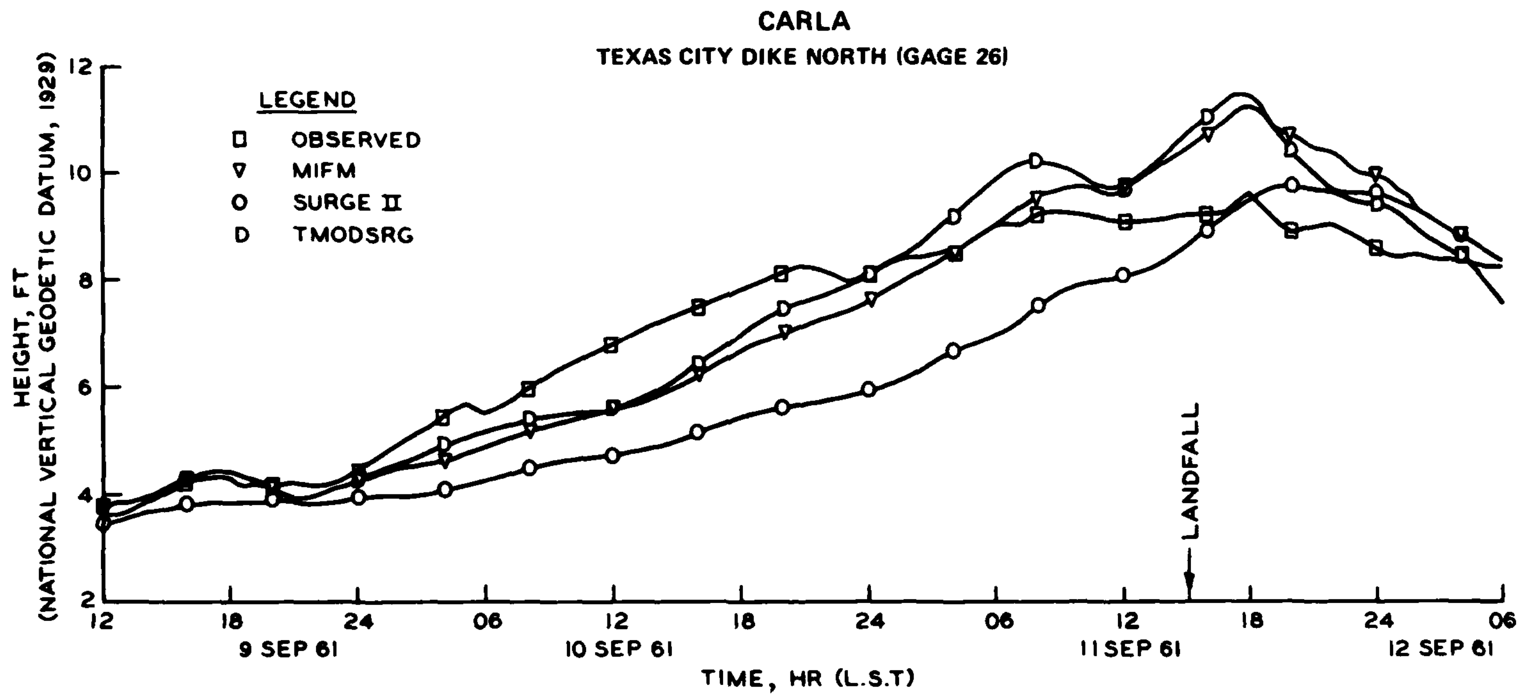

Figure 32. Observed and computed water levels at Texas City Dike North (gage 26) before and after landfall of Hurricane Carla

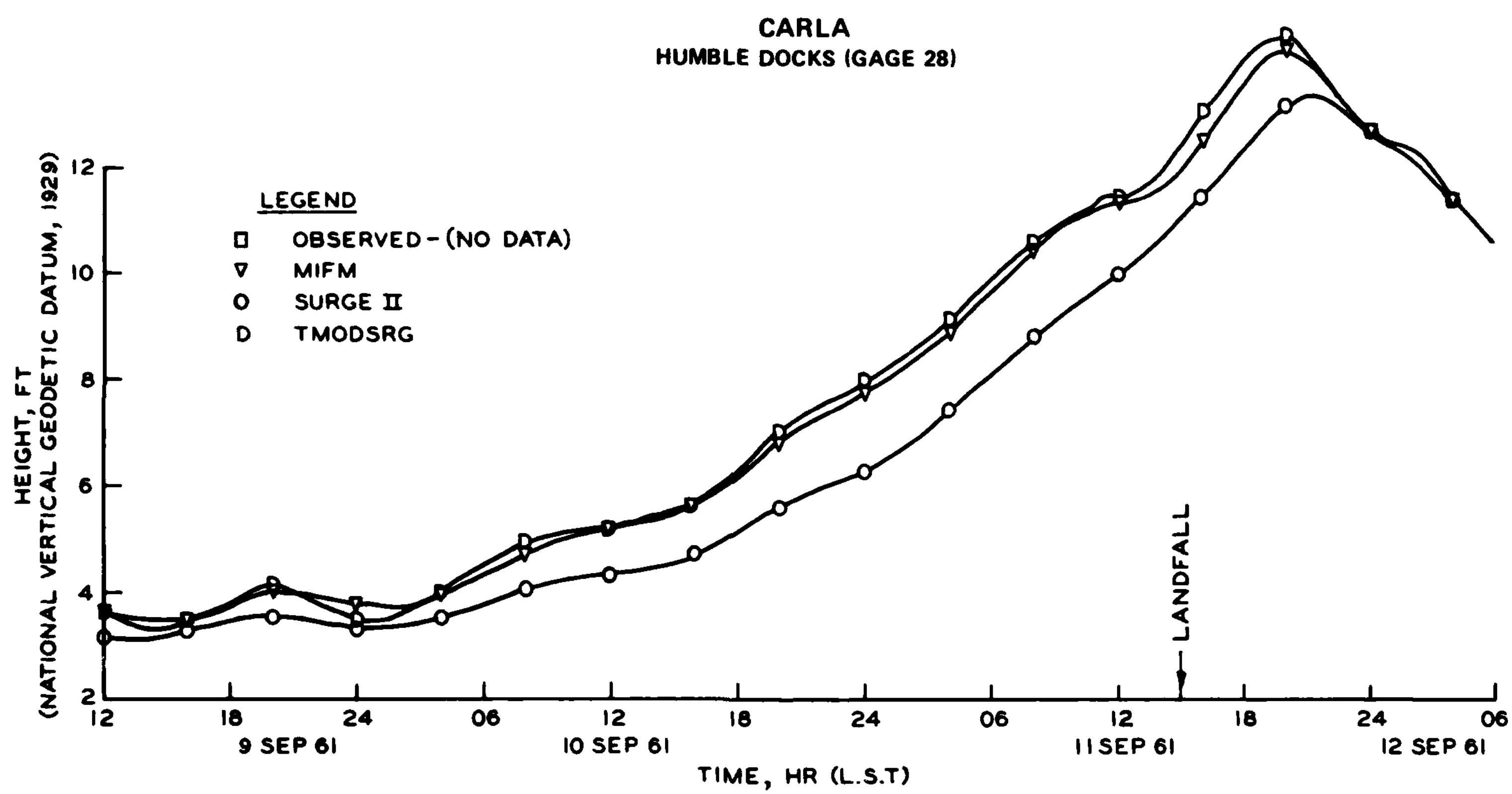

Figure 33. Observed and computed water levels at Humble Docks (gage 28) before and after landfall of Hurricane Carla

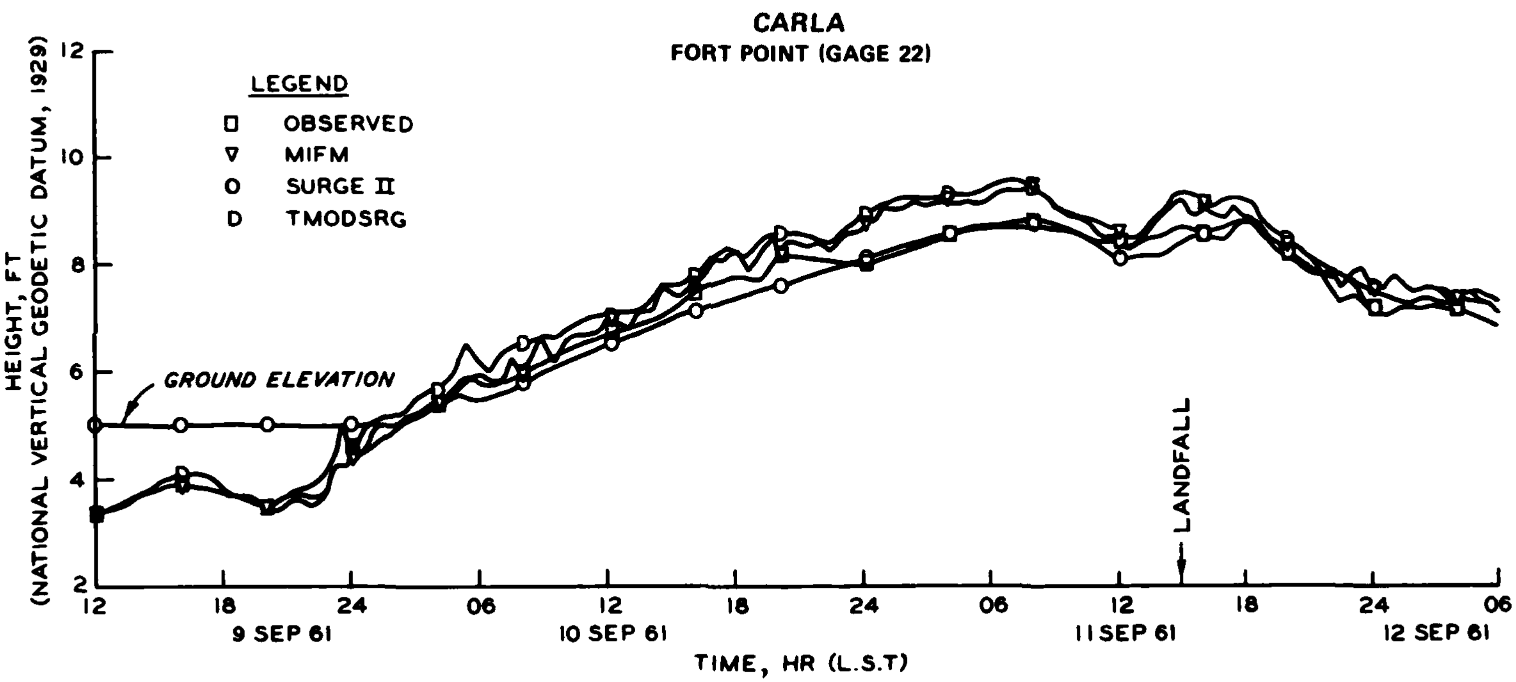

Figure 34. Observed and computed water levels at Fort Point (gage 22) before and after landfall of Hurricane Carla using improved ocean boundary input data

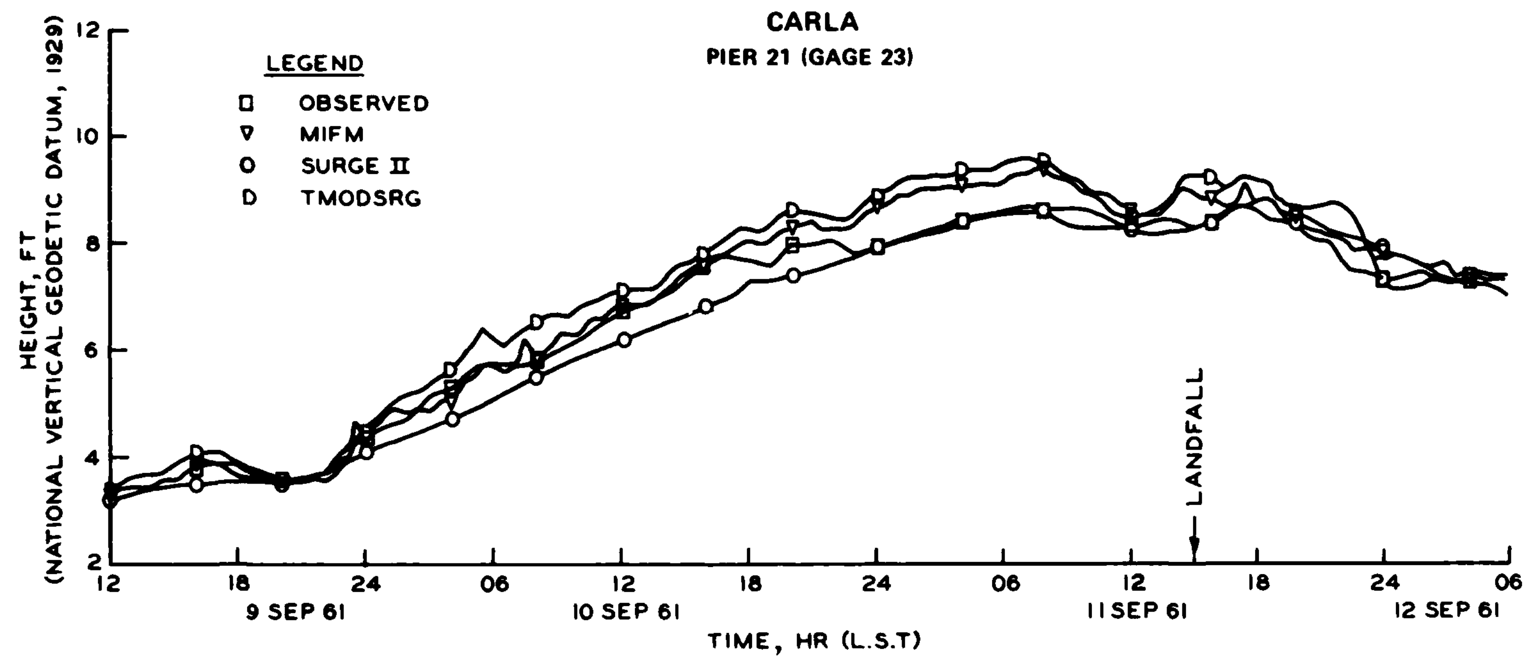

Figure 35. Observed and computed water levels at Pier 21 (gage 23) before and after landfall of Hurricane Carla using improved ocean boundary input data

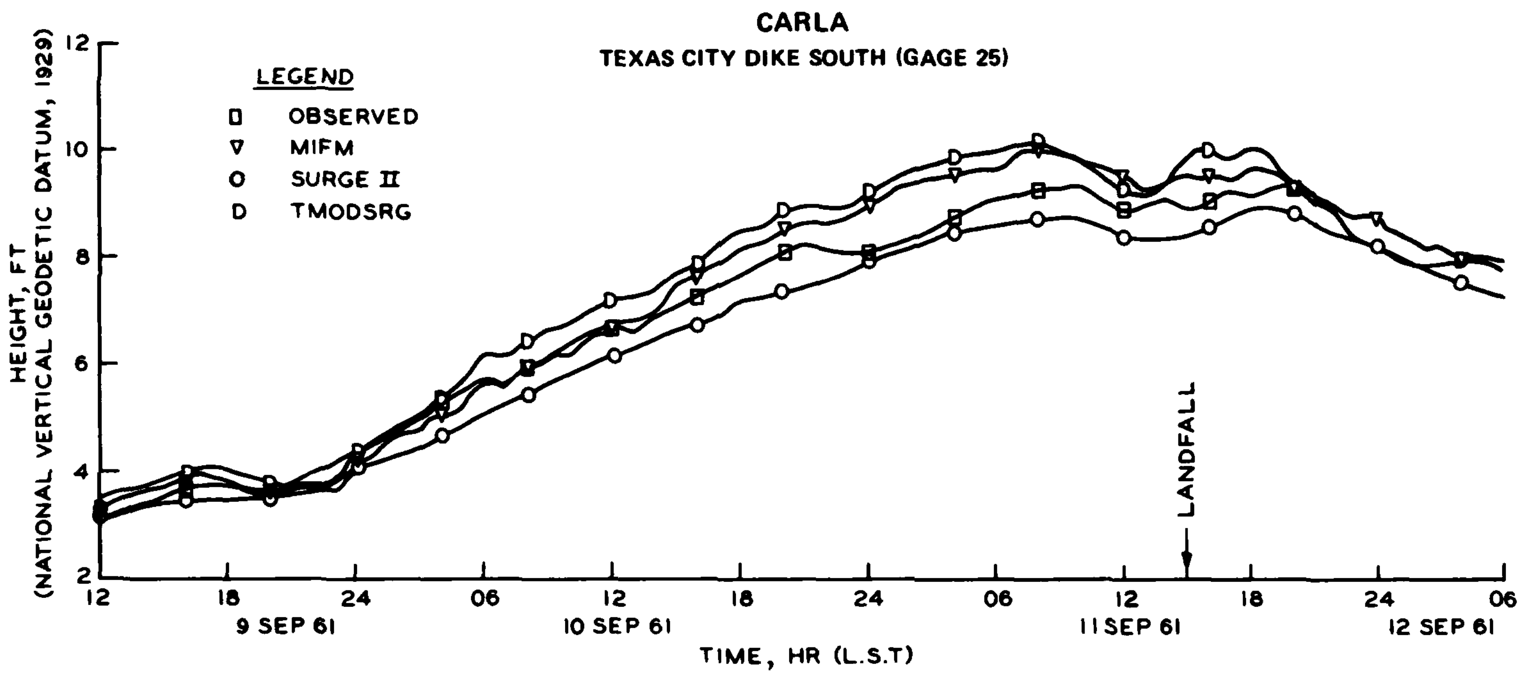

Figure 36. Observed and computed water levels at Pelican Bridge (gage 24) before and after landfall of Hurricane Carla using improved ocean boundary input data

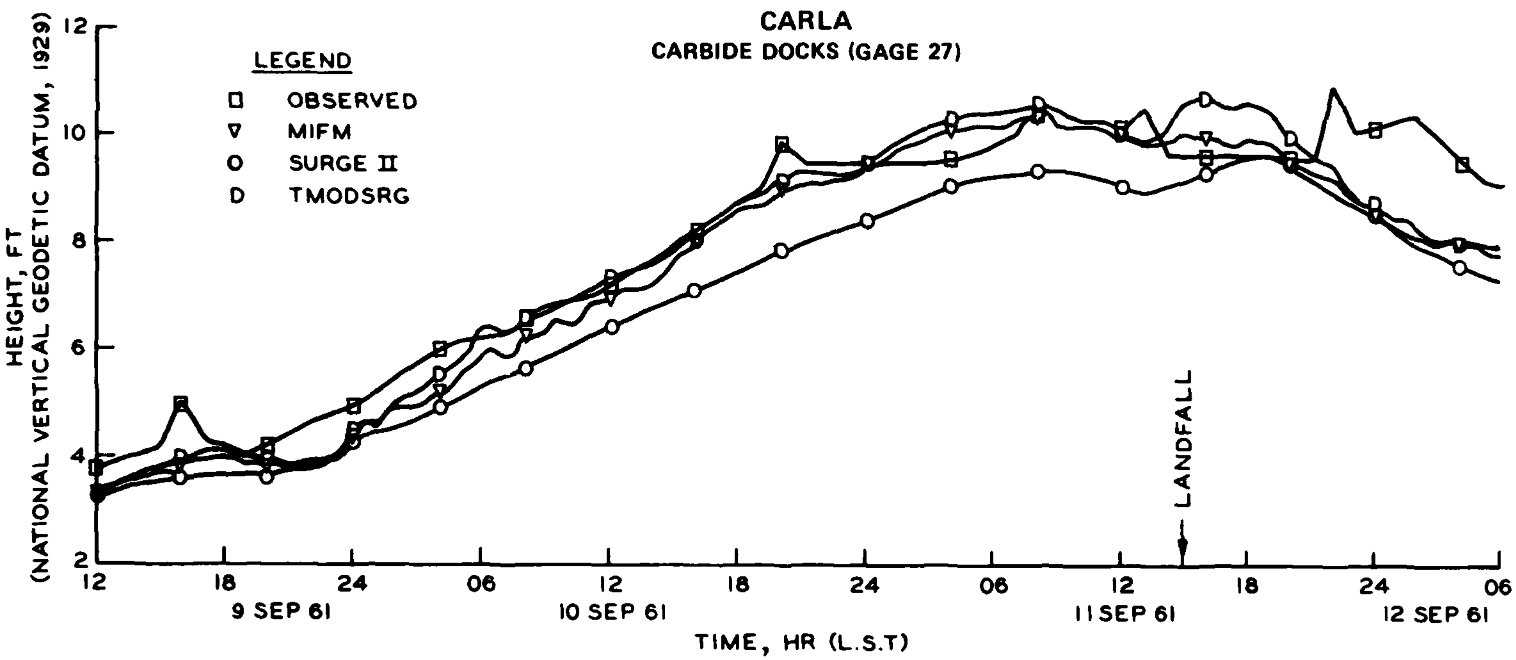

Figure 37. Observed and computed water levels at Carbide Docks (gage 27) before and after landfall of Hurricane Carla using improved ocean boundary input data

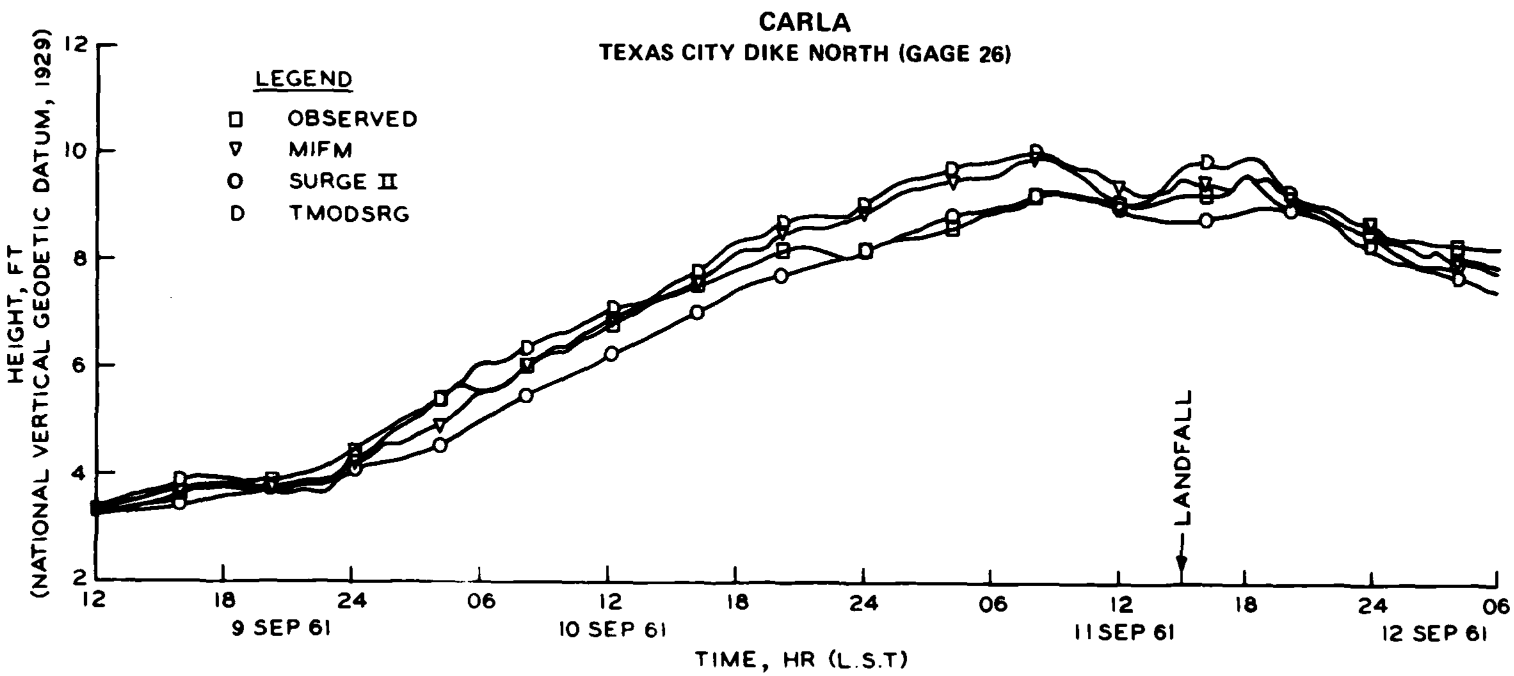

Figure 38. Observed and computed water levels at Texas City Dike North (gage 26) before and after landfall of Hurricane Carla using improved ocean boundary input data

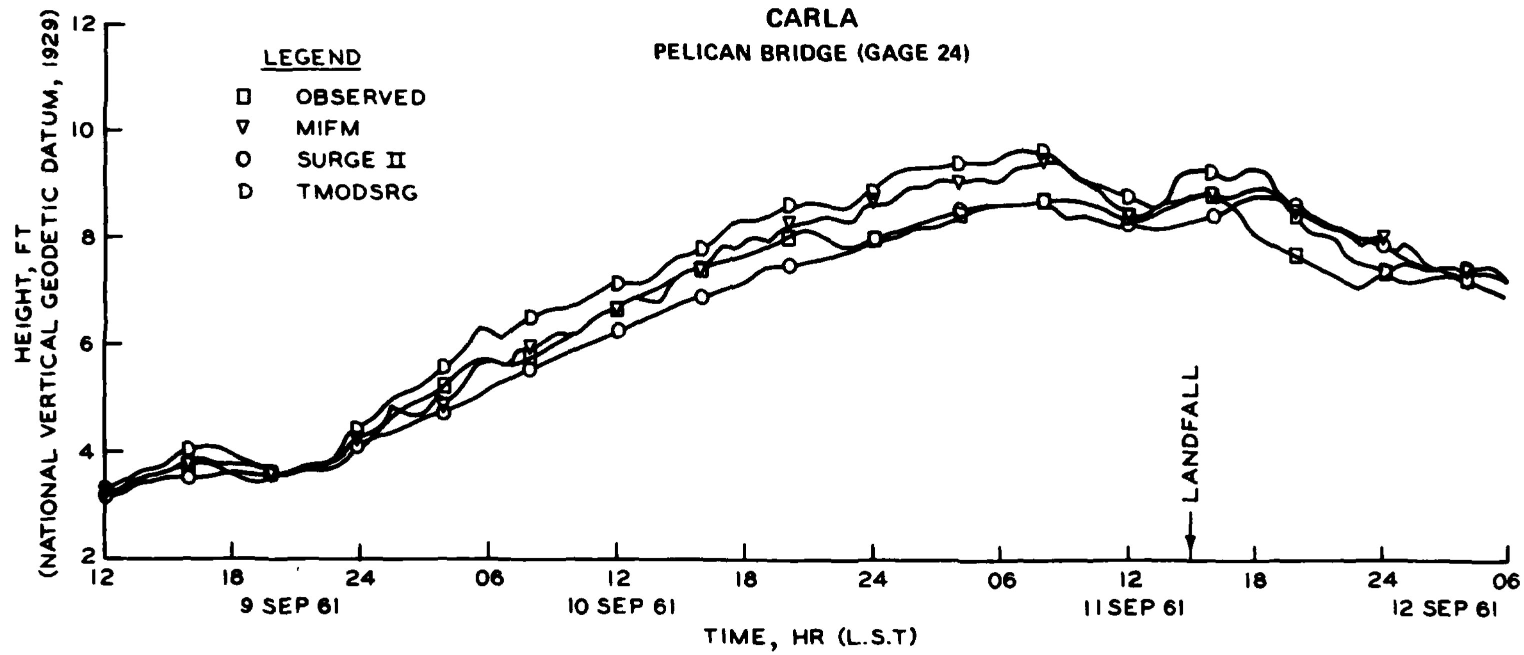

Figure 39. Observed and computed water levels at Texas City Dike South (gage 25) before and after landfall of Hurricane Carla using improved ocean boundary input data

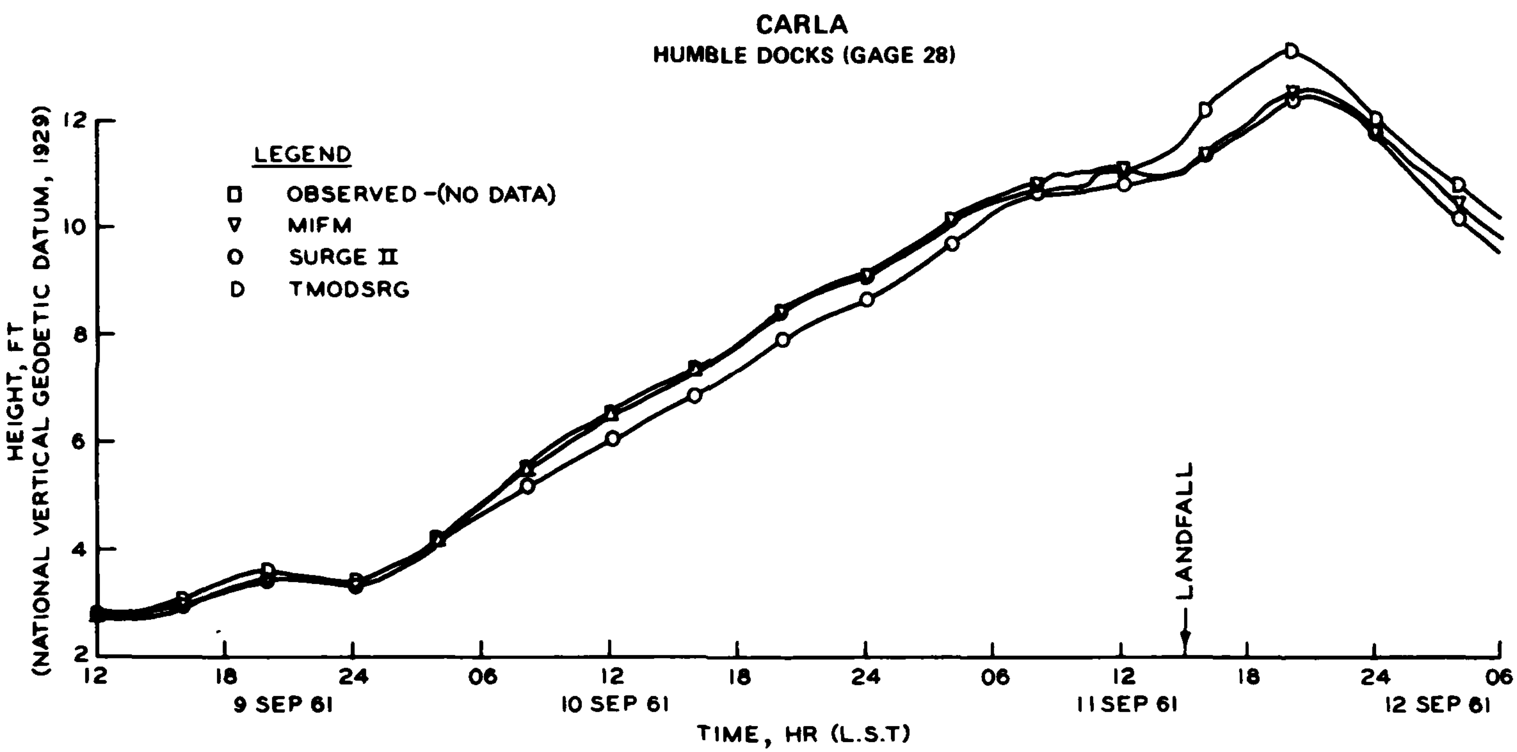

Figure 40. Observed and computed water levels at Humble Docks (gage 28) before and after landfall of Hurricane Carla using improved ocean boundary input data

APPENDIX A

STANDARD INPUT DATA

Table 1 - Characteristics of the Historical Storms used in the Open Coast Model Comparison*

	STORM	DATE	TIME (LST)	LAT. (°N)	LONG. (°W)	P_o (mb)	P_n (mb)	R (mi)
EST	Hazel	14 Oct.1954	2100	29.2	77.0	937	1012	23
		15 Oct.	0300	31.2	78.1	937	1012	23
			0900	33.8	78.5	937	1012	23
			1500	37.0	77.8	937	1012	23
			2100	44.0	77.0	937	1012	23
EST	Gracie	28 Sep. 1959	2300	30.4	78.8	950	1012	12
		29 Sep.	0500	31.4	79.5	950	1012	12
			1100	32.4	80.4	950	1012	12
			1700	33.3	81.0	950	1012	12
			2300	34.2	81.4	950	1012	12
CST	Eloise	22 Sep. 1975	1800	27.4	88.5	968	1012	22
		23 Sep.	0000	28.4	87.3	958	1012	22
			0600	30.2	86.3	955	1012	22
			1200	33.0	85.7	982	1012	22
			1800	35.5	84.3	999	1012	22
CST	Camille	17 Aug.1969	1000	27.9	88.6	905	1012	10
			1600	29.1	89.0	905	1012	10
			2200	30.2	89.4	910	1012	10
		18 Aug.	0400	31.6	89.9	920	1012	10
			1000	33.2	90.2	931	1012	10
CST	Carla	10 Sep. 1961	1500	26.9	94.7	936	1019	53
			2100	27.2	95.3	936	1014	46
		11 Sep.	0300	27.5	95.7	936	1015	45
			0900	27.6	96.2	937	1015	47
			1500	28.4	96.5	938	1015	43
			2100	29.0	97.0	939	1014	43
		12 Sep.	0300	30.0	97.4	942	1014	43

* Taken from Hubertz 1977

APPENDIX B

INSTRUCTIONS FROM THE COMMITTEE TO THE MODELERS AT WES AND NWS FOR PART I

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS
COMMITTEE ON TIDAL HYDRAULICS

IN REPLY REFER TO:

THE CHAIRMAN
c/o WATERWAYS EXPERIMENT STATION
P. O. BOX 631
VICKSBURG, MISSISSIPPI

WESHV 22 April 1977

SUBJECT: Format for Open Coast Hurricane Surge Model Comparison

Commander and Director
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631
Vicksburg, MS 39180

1. Reference the following:

a. DAEN-RDZ-A letter dated 27 January 1977, subject: Comparison of Hurricane Surge Models.

b. DAEN-CWE-H letter dated 7 February 1977, subject: Comparison of Hurricane Surge Models.

By references a and b, CERC and WES were directed to perform hurricane surge hindcasts with the Reid-Bodine, Butler, Splash II, and Wanstrath-Reid numerical models, and CTH was directed to compare and evaluate the results. In reference b, CTH was further directed to provide the necessary formats for the numerical model outputs.

2. It is the feeling of CTH that the most current (and fully developed) versions of the Splash II and Wanstrath-Reid open coast surge models should be used for this comparison study. It is our understanding that the current version of Splash II is referred to as the Sheared Coordinate model, and the current version of the Wanstrath-Reid model is referred to as the SSURGE III model.

3. The computational grids for both models should be displayed. Points at which prototype data are available should also be shown in order to see how close they are to the nearest computational points. It would also be informative if the depths and friction factors assigned to each grid cell could be tabulated. It is recognized, however, that tabulation of friction factors for the sheared coordinate model is not likely to be feasible.

4. Each model should provide the time history (tabulated and plotted) at all grid points nearest the coast, within about 30-40 miles of the storm center. If the computation grid points are not at the shoreline, an explanation should be provided of how the computed values are interpolated or extrapolated to the shoreline. The datum plane of reference should be specified (preferably the mean sea level plane), and computations should be made at a time interval of one hour or less.

5. Astronomical tides should be computed by the procedure used by NOS, with the same time interval and nearshore locations used in computing the storm surge. The datum for these predictions should be specified (preferably the mean sea level plane). The amplitude of the predictions should be modified by the ratio of the mean tide range at the nearest point for which tidal corrections are published and the mean tide range at the reference station. The tide should be lagged by the amounts listed in the table of corrections for tide phase as published in the TIDE TABLES. The constant required to bring the storm surge calculations plus the astronomical tide predictions to the National Vertical Geodetic Datum of 1929 should be added. The combination of storm surge and astronomical tide should be plotted for comparison with all available observed hydrographs. The maximum values of the sum of storm surge plus astronomical tide should be computed for all available high water marks.

6. The display of hydrographs used in the comparison should take the form of a graph showing the observed and predicted hydrographs. Root-mean-square values for the differences between computed and predicted hydrographs should be computed. The display of high water mark comparisons should be in the form of a map showing the observation sites and a table showing observed and computed values. Root-mean-square differences should be computed.

7. In addition to the computed water levels and the grid, information on the costs associated with operating the model should be provided. Such information should include the costs of preparing the model for a site specific application, running time, and analyzing the output. It is realized that the costs will vary according to the computer used for the computations; therefore, it would be preferable that the models be run on computer systems that would be readily available for Corps use now and within the near future. If the models are not applicable to all locations along the Atlantic and Gulf coasts, an indication should be provided of the level of effort required to modify the model for a specific site.

8. Since there is a very definite possibility that different wind fields will be generated by the two models and since this could influence the surge computations, information on the wind fields should be provided. The methodology used in deriving the wind fields should be explained, and if feasible, time-history plots of the wind fields should be provided.

9. Written documentation of the models should be provided in sufficient detail for CTH to study and understand assumptions, methods, approximations, applications, and limitations. Pertinent references should be attached. This material should be in sufficient detail so that only minor questions should arise after study by CTH members and consultants.

H. B. SIMMONS
Chairman
Committee on Tidal Hydraulics

CF:
Members & Consultants, CTH
Mr. Neill E. Parker, HQDA (DAEN-CWE-H)

APPENDIX C

REVISED INPUT DATA FOR HURRICANE CAMILLE

Revised Storm Parameters for Hurricane Camille*

Date	Time LST	P_o mb	R mile	P_o mb	R mile
17 Aug 69	1000	910	12	905	10
	1600	910	12	905	10
	2200	915	12	915	10
18 Aug 69	0400	925	12	920	10
	1000	931	12	931	10

Note: It was not necessary to revise the other storm parameters (pressure outside the region of the storm and velocity of storm translation along the storm track).

* Taken from Hubertz and Wanstrath 1978.

APPENDIX D

INSTRUCTIONS FROM THE COMMITTEE TO THE MODELERS AT WES AND CERC FOR PART II

DEPARTMENT OF THE ARM
CORPS OF ENGINEERS
COMMITTEE ON TIDAL HYDRAULICS

IN REPLY REFER TO:
THE CHAIRMAN
c/o WATERWAYS EXPERIMENT STATION
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

WESHV

22 December 1977

SUBJECT: Format for Inland Flooding Hurricane Surge Model Comparison

Commander and Director
U. S. Army Coastal Engineering
Research Center
Kingman Building
Ft. Belvoir, Virginia 22060

1. At the 24-25 August 1977 Committee on Tidal Hydraulics (CTH) Meeting, it was decided that the SSURGE III, Wanstrath (unpublished), open coast hurricane surge model would be used to provide input conditions for the inland flooding hurricane surge model comparison. The wind model of SSURGE I will be used to provide the windfield input to the inland models and the SSURGE III model. All models will employ the same wind stress drag coefficient. Since this wind model requires more input information than the standard parameters and will contain the SPM land effects routine, modified to give the best fit to observed data, the computer program deck, data deck and documentation of the algorithm to compute the wind stress as a function of space and time will be provided to the inland flooding modelers by Dr. Wanstrath.

2. The SSURGE III model will be run at WES to provide the necessary ocean boundary surge conditions to drive the inland flooding models. The grid spacing and location of the ocean boundary used in the SSURGE III model has been agreed upon by WES and CERC. Since different spatial resolutions and grid orientation will be used by the inland models, SSURGE III time histories of water elevations will be provided in tabular and punched card form at regular station locations along the respective ocean boundaries of the two inland flooding models. For this purpose, it will be necessary for each inland modeler to specify the latitude and longitude of his ocean boundary grid points and provide this information to Dr. Wanstrath. Time-histories also should be provided from SSURGE III at selected ocean locations within the limits of the inland flooding models. This information will provide the basis for comparing surge histories generated by the open coast and inland flooding models to ensure that the models have been coupled

properly. WES and CERC have selected the ocean locations for this purpose. Similarly, open coast and inland stations have been selected for comparison of time-histories of wind velocity and direction.

3. The comparison of the inland flooding models will consist of simulating the effects of Hurricane Carla in the Galveston Bay area. Following a CTH review of the Galveston Bay results, an additional hurricane may be selected for further study. Prior to conducting the surge study, each inland model will be verified by simulating tidal conditions in each of the study areas. Sufficient model and prototype data are available for this purpose from previous physical model studies performed at WES of the Galveston region. Following verification, the water level for the storm period under study will be predicted using an open sea driving function determined from the predicted tide at a NOS reference station and the surge predicted with the SSURGE model. The predicted tide at the NOS station will be backed out to the SSURGE ocean boundary and specified as part of that boundary condition so the input to the inland models will be the sum of tide and computed surge.

4. The computational grids for the inland models should be displayed on a reduced NOS chart. Points at which prototype data are available also should be shown, as should the input points from the open coast model. It would be informative if the depths and friction factors assigned to each grid cell could be tabulated.

5. SSURGE III will be run for a prototype duration of about 72 hours, which will be sufficient to reproduce the rise and fall of the storm surge. The inland flooding models will be started at 1200 hr, 9 September 1961 and run to 0000 hr, 12 September 1961. These models will be spun up during a 6-hr period prior to 1200 hr, 9 September using a uniform water level of +3.0 ft msl as the initial condition.

6. The results from the inland flooding models should be presented as follows:

a. Plot of tide at the NOS reference station as computed by the SSURGE III model to illustrate that it reproduces the predicted tide at the reference station. (This will be provided by Dr. Wanstrath.)

b. Time plots of model and prototype water levels and velocities for tidal verification. Tides will be shown for tide gages T-A, B, G, K, P, O, and L (see Incl 1) and velocities will be shown for stations CS-1, CS-2, CS-3, and CS-6 (see Incl 1).

c. A descriptive plot (magnitude and direction) of the wind fields (model and prototype) at 6-hour intervals to demonstrate that the wind program supplied by Dr. Wanstrath has been properly implemented in each model. Dr. Wanstrath will select the location for this plot and will establish the format for the plot.

d. Time plots of water level at all locations for which prototype time histories are available and at about six other locations to be selected by WES and CERC.

e. Tabulation of model and prototype high-water marks. Location of high-water mark points should be identified clearly on the NOS chart used to display the numerical grid. The locations of about 20 points for high-water marks will be selected by WES and CERC. Maximum water level (including tide) should be tabulated for each point without regard to time of occurrence.

f. Contour plots of numerical displays of water surface levels to indicate the extent of flooding. Such figures should be provided at intervals to be selected by WES and CERC. It is anticipated that about five such plots will be prepared. These plots will be made at a scale such that they can be overlaid on map number NH 15-7, U. S. Geological Survey, Houston, Texas, 1956. One of the intervals should coincide with the time of maximum water level within the estuary.

7. The following model information will be provided:

a. The size of the space steps employed, the maximum and minimum spatial step increments, and physical constraints of these.

b. The size of the time step employed and the limiting time step as a function of the space step.

c. The number of time steps used and the number of grid points used.

d. The computer storage requirements for the model.

e. The duration of the run in real time and in CPU time.

f. The computer cost algorithm which is appropriate to the model and computer being employed. The numerical value and significance of each parameter in this algorithm will be stated. Other cost related information to be provided should include estimates of the manpower required in preparing the model for each application, the type of application and estimates of total computer costs.

WESHV 21 December 1977

SUBJECT: CERC Revision of WES Format for Inland Flooding Hurricane Surge Model Comparison

8. Written documentation of the models should be provided in sufficient detail for CTH to study and understand assumptions, methods, approximations, applications, and limitations. Pertinent references should be attached. This material should be in sufficient detail so that only minor questions should arise after study by CTH members and consultants. This material, the information indicated in para 6, and the computational results specified in para 6b, d, c, and f, should be assembled and mailed to WES in order that comparisons between the models and their results can be assembled to facilitate interpretation and analysis by CTH members. Computational results are to be output on cards so that WES may automate the plotting of the comparisons. Values will be given for every half hour in a card format of 12F6.2. Water surface elevations will be given in feet msl and velocities in ft/sec. Flood velocity should be recorded as positive and ebb velocity as negative. Absolute direction will not be plotted; rather, velocity will be plotted only as ebb or flood.

1 Incl
as

H. B. SIMMONS
Chairman
Committee on Tidal Hydraulics

CF:
Members and Consultants, CTH
HQDA (DAEN-CWE-HY/Dr. Ming Tseng)
Identical letter to WES/CERC

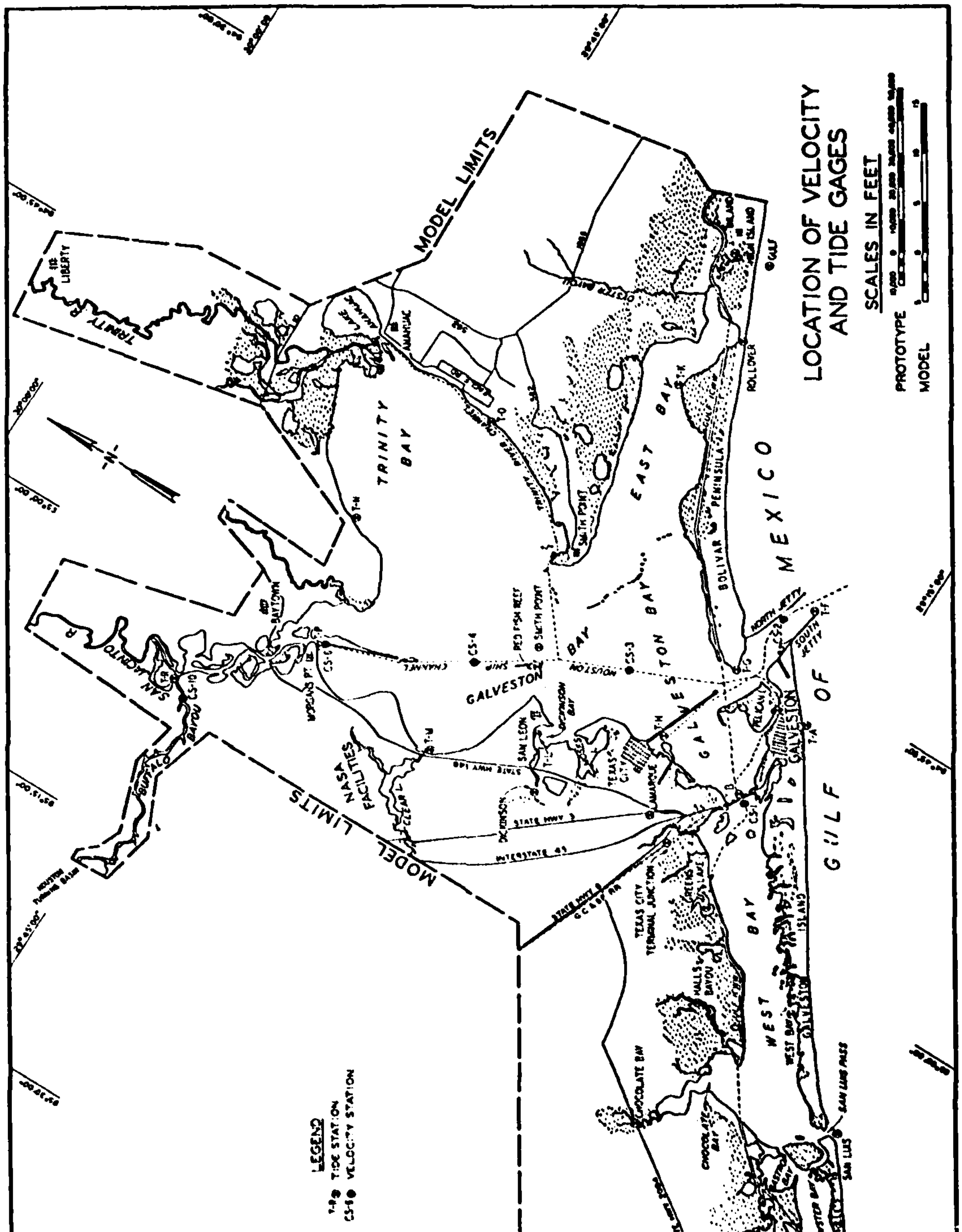
LOCATION OF VELOCITY AND TIDE GAGES
SCALES IN FEET
PROTOTYPE
MODEL
LEGEND
T-8 ■ TIDE STATION
CS-1 ● VELOCITY STATION
MODEL LIMITS
MODEL LIMITS
TRINITY BAY
EAST BAY
GALVESTON BAY
WEST BAY
GULF OF MEXICO
TRINITY R
SAN JACINTO R
BUFFALO BAYOU
NASA FACILITIES
BAYTOWN
MORGANS PT.
SMITH POINT
RED FISH REEF
BOLIVAR PENINSULA
ROLLOVER
GALVESTON
PELICAN
NORTH JETTY
SOUTH JETTY
TEXAS CITY
SAN LEON
DICKINSON BAY
CHOCOLATE BAY
SAN LUIS PASS
FREEPORT
LIBERTY
INTERSTATE 45
HOUSTON SHIP CHANNEL

PLATE 2

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Committee on Tidal Hydraulics
  Evaluation of numerical storm surge models / by Committee on Tidal Hydraulics. Vicksburg, Miss. : U. S. Waterways Experiment Station, 1980.
  25, [56] p. : ill. ; 27 cm. (Committee on Tidal Hydraulics Technical Bulletin No. 21)
  Prepared for Office, Chief of Engineers.
  References: p. 24-26.

1. Comparison. 2. Evaluation. 3. Hurricanes. 4. Mathematical models. 5. Numerical simulation. 6. Storm surges.
I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Committee on Tidal Hydraulics Technical Bulletin No. 21.
GC303 C6t no. 21

REPORTS OF COMMITTEE ON TIDAL HYDRAULICS

Report No.	Title	Date
1	Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena	Feb 1950
2	Bibliography on Tidal Hydraulics	Feb 1954
	Supplement No. 1, Material Compiled Through May 1955	Jun 1955
	Supplement No. 2, Material Compiled from May 1955 to May 1957	May 1957
	Supplement No. 3, Material Compiled from May 1957 to May 1959	May 1959
	Supplement No. 4, Material Compiled from May 1959 to May 1965	May 1965
	Supplement No. 5, Material Compiled from May 1965 to May 1968	Aug 1968
	Supplement No. 6, Material Compiled from May 1968 to May 1971	Jul 1971
	Supplement No. 7, Material Compiled from May 1971 to May 1974	Jun 1975
3	Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena (revised edition of Report No. 1)	May 1965

Technical Bulletin No.	Title	Date
1	Sediment Discharge Measurements in Tidal Waterways	May 1954
2	Fresh Water-Salt Water Density Currents, A Major Cause of Siltation in Estuaries	Apr 1957
3	Tidal Flow in Entrances	Jan 1960
4	Soil as a Factor in Shoaling Processes, A Literature Review	Jun 1960
5	One-Dimensional Analysis of Salinity Intrusion in Estuaries	Jun 1961
6	Typical Major Tidal Hydraulic Problems in United States and Research Sponsored by the Corps of Engineers Committee on Tidal Hydraulics	Jun 1963
7	A Study of Rheologic Properties of Estuarial Sediments	Sep 1963
8	Channel Depth as a Factor in Estuarine Sedimentation	Mar 1965
9	A Comparison of an Estuary Tide Calculation by Hydraulic Model and Computer	Jun 1965
10	Significance of Clay Minerals in Shoaling Problems	Sep 1966
11	Extracts from The Manual of Tides	Sep 1966
12	Unpublished Consultation Reports on Corps of Engineers Tidal Projects	Dec 1966
13	Two-Dimensional Aspects of Salinity Intrusion in Estuaries: Analysis of Salinity and Velocity Distributions	Jun 1967
14	Tidal Flow in Entrances; Water-Level Fluctuations of Basins in Communication with Seas	Jul 1967
15	Special Analytic Study of Methods for Estuarine Water Resources Planning	Mar 1969
16	The Computation of Tides and Currents in Estuaries and Canal	Sep 1969
	Appendix A: A User's Manual	Jun 1973
17	Estuarine Navigation Projects	Jan 1971
18	History of the Corps of Engineers Committee on Tidal Hydraulics	Jun 1972
19	A Field Study of Flocculation as a Factor in Estuarial Shoaling Processes	Jun 1972
20	Unsteady Salinity Intrusion in Estuaries	
	Part I: One-Dimensional, Transient Salinity Intrusion with Varying Freshwater Inflow	Jul 1974
	Part II: Two-Dimensional Analysis of Time-Averaged Salinity and Velocity Profiles	Jul 1974
21	Evaluation of Numerical Storm Surge Models	Dec 1980

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SUPPLEMENTARY

INFORMATION

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESHA

March 9, 1981

Errata Sheet

No. 1

EVALUATION OF NUMERICAL
STORM SURGE MODELS

Technical Bulletin No. 21

December 1980

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PREFACE

Because of the Corps of Engineers mission to provide flood protection from hurricane surges, the Office, Chief of Engineers (OCE), has had a continuing interest in the state-of-the-art of numerical modeling of hurricane surges. By letter dated 7 February 1977, OCE directed the Committee on Tidal Hydraulics to ascertain present modeling capabilities with regard to both open-coast and inland flooding models, determine which model(s) would best meet Corps of Engineers needs, and determine what additional research, if any, is needed. A task committee was established by OCE to select the specific storms and locations to be studied and to establish general guidelines for conducting the study. The task committee was composed of representatives of OCE, the Coastal Engineering Research Center (CERC), and the Waterways Experiment Station (WES). The numerical modeling efforts for the study were assigned to CERC and WES.

In addition to the modeling efforts conducted directly at CERC and WES, models developed by the National Weather Service and Tetra Tech, Inc., were exercised by those organizations as part of this study. Both of these outside modeling efforts were coordinated by CERC.

Results from the various modeling efforts were presented to the Committee at its 83rd, 84th, 86th, 87th, and 88th Meetings during the period August 1977-August 1980. This report contains the Committee's evaluation of those modeling efforts and its recommendations based thereon.