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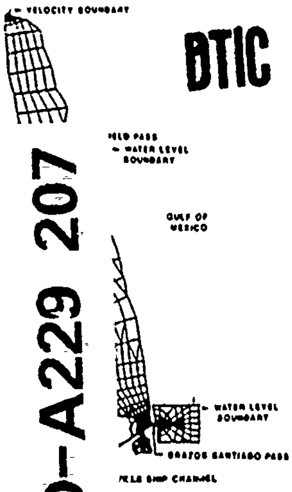
(2)

NUMERICAL MODELING OF HYDRODYNAMICS BRAZOS ISLAND HARBOR PROJECT, TEXAS (BROWNSVILLE SHIP CHANNEL)



by

Larry M. Hauck, Ben Brown, Jr.

Hydraulics Laboratory

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

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The Brazos Island Harbor Project, south Texas, has been authorized for navigation channel improvements, which include deepening of the Brownsville Ship Channel from 38 ft below mean low water (mlw) to 42 ft below mlw and channel widening. The 19-mile-long Brownsville Ship Channel begins in the Gulf of Mexico, transects the Laguna Madre, and continues landlocked to Brownsville, TX.

This study involved the use of the vertically integrated two-dimensional numerical model RMA-2V to simulate the Brownsville Ship Channel and the lower Laguna Madre. RMA-2V was used to produce the hydrodynamics (water levels and velocities) for existing and three alternative channel designs. These hydrodynamic conditions were used in a ship simulator study.

Historical velocity (direction and speed) measurements taken at approximately hourly

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19. ABSTRACT (Continued).

intervals during ~~the~~ period 15-18 July 1980 at several stations were used to verify RMA-2V. Water level measurements from four tide gages were also available for the same period to facilitate model verification. While some difficulties occurred in reproducing measured water level responses in the interior of the Laguna Madre, good numerical model simulation of velocity directions and magnitudes was obtained in the Brazos Island Harbor Project area. Because the Laguna Madre exhibits large response to wind forcing, some of the inaccuracies in water level verification were suspected to be the result of the sparsity of wind speed and direction data in the prototype system for the model verification.

The verified RMA-2V model was operated with a high-amplitude diurnal (spring) tide with a temporally varying southeast wind of 4 to 20 mph. The wind was phased to increase both the ebb and flood velocities. With these tidal and wind conditions, RMA-2V simulated the hydrodynamics for existing and three alternative channel designs. The peak ebb and flood currents for each design were saved as computer files for use in a separate ship simulator study.

Keywords: Mathematical/hydraulic models; Tidal currents; Channels waterways; Computerized simulation (EDC)

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PREFACE

The numerical modeling of hydrodynamic conditions for the Brazos Island Harbor Project, Texas, as documented in this report was performed for the US Army Engineer District, Galveston.

The study was conducted in the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES) during the period September 1989 to February 1990 under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL; R. A. Sager, Assistant Chief, HL; W. H. McAnally, Jr., Chief, Estuaries Division (ED); and J. V. Letter, Jr., Chief, Estuarine Simulation Branch (ESB), ED.

This work was performed and the report prepared by Messrs. Larry M. Hauck and Ben Brown, Jr., ESB. This report was edited by Mrs. Marsha C. Gay, Information Technology Laboratory, WES. Mr. Robert Van Hook was liaison for the Galveston District.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

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

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

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609344	kilometres
pounds (force)-second per square foot	47.88026	pascals-second

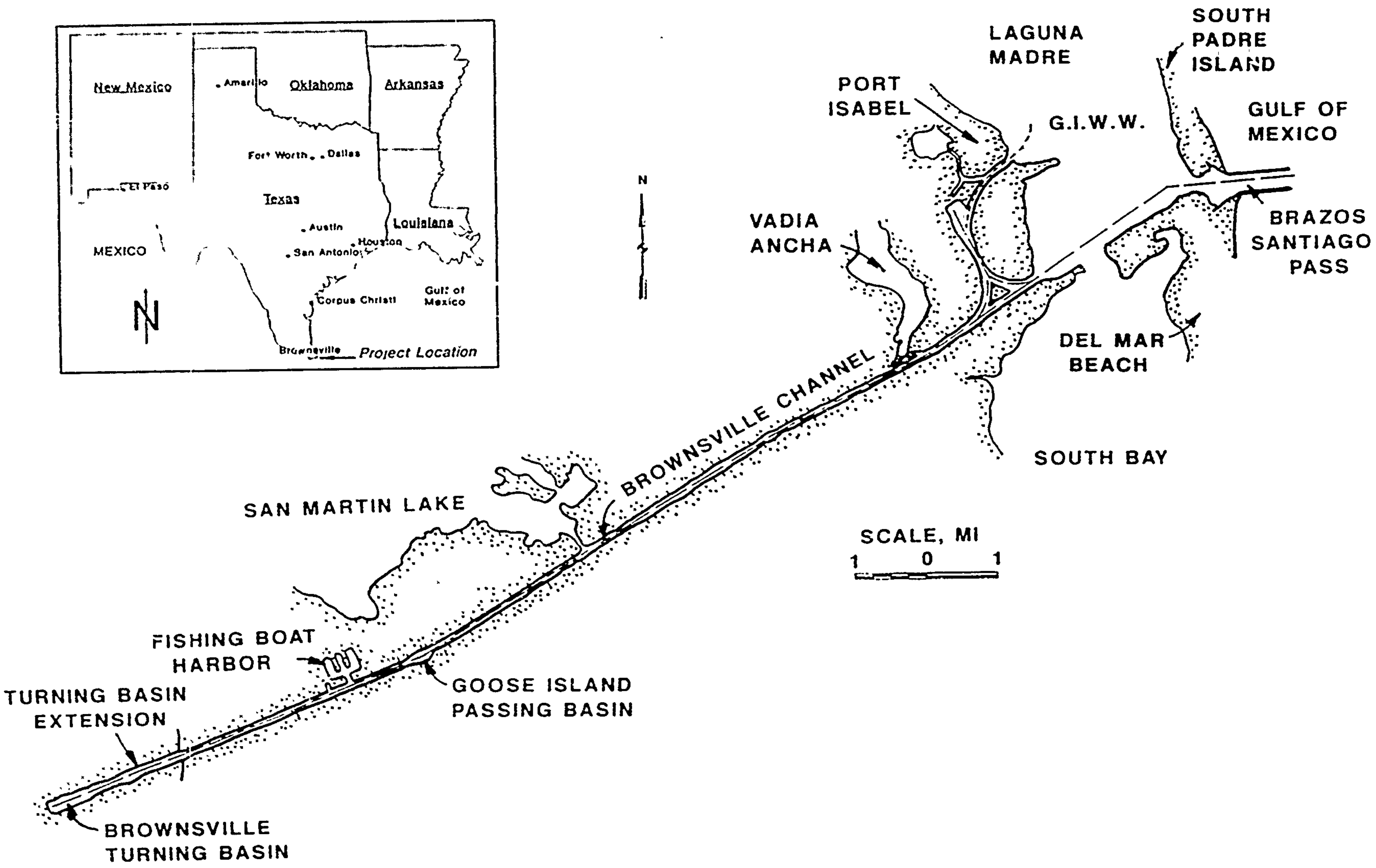

Figure 1. Vicinity map and Brazos Island Harbor Project map

NUMERICAL MODELING OF HYDRODYNAMICS
BRAZOS ISLAND HARBOR PROJECT, TEXAS
(BROWNSVILLE SHIP CHANNEL)

PART I: INTRODUCTION

Background

1. The Brazos Island Harbor Project, southern Texas, which was initially authorized by the River and Harbor Act of 3 July 1930, consists of a 19-mile* deep-draft navigation channel serving Brownsville, Port Isabel, and the Lower Rio Grande Valley region of Texas (Figure 1). The existing project includes a dual-jettied entrance channel 38 ft deep below mean low water (mlw) and 300 ft wide through the Brazos Santiago Pass, a 36-ft-deep by 200-ft-wide channel across the Laguna Madre and the landlocked reach to the former Goose Island Passing Basin, and a 36-ft-deep by 300-ft-wide channel to the terminating turning basin extension (Figures 1 and 2). A commercial fishing harbor is located immediately off the channel near Brownsville, and turning basins are located at Brownsville and Port Isabel.

2. The navigation project transects the southern tip of the lower Laguna Madre estuary (Figure 2). The Laguna Madre is divided into upper (northern) and lower (southern) parts by a natural feature locally referred to as the land bridge. The land bridge, a series of sand dunes and flats some 50 miles north of Port Isabel, effectively separates the upper and lower Laguna Madre except during extreme wind setup events, which raise water levels to inundate the sand flats. Exchange of water between the upper and lower Laguna Madre is normally limited and is confined to the Gulf Intracoastal Waterway (GIWW), which transects the land bridge in roughly a north to south direction.

3. The lower Laguna Madre contains two tidal inlet connections with the Gulf of Mexico, both associated with navigation channels, the Brazos Santiago Pass and the smaller Port Mansfield Channel (Mansfield Pass) (Figure 2). Water depths in the lower Laguna Madre average approximately 4 ft with the

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* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

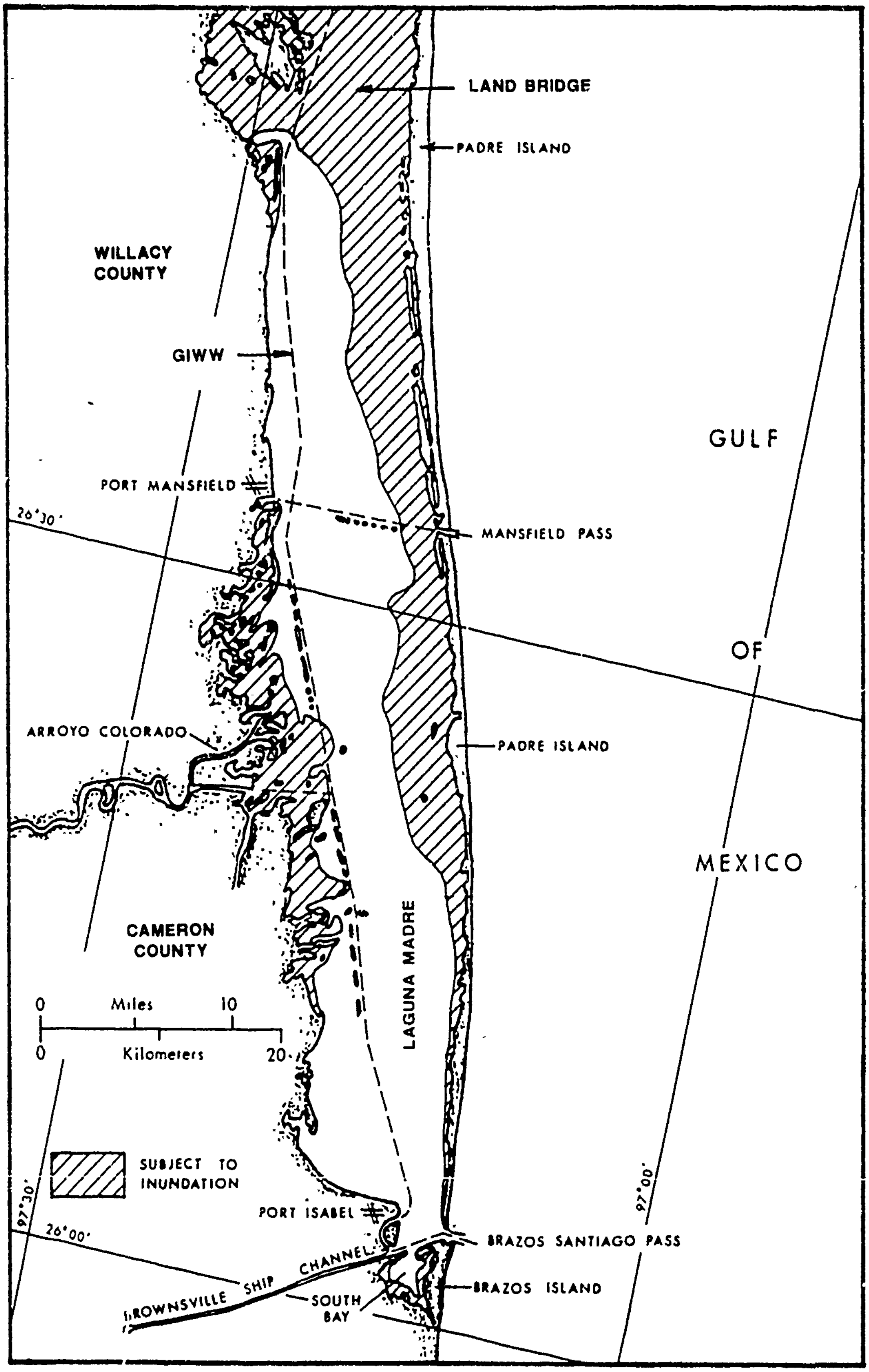

Figure 2. Lower Laguna Madre

greatest depths associated with the three navigation channels: Brownsville Ship Channel, Port Mansfield Channel, and the GIWW.

4. Authorized navigation improvements entail a 44-ft-deep by 400-ft-wide channel from the entrance in the Gulf of Mexico to Padre Island, a 42-ft-deep by 300-ft-wide channel from Padre Island to the beginning of the turning basin extension, a 42-ft-deep by 325- to 400-ft-wide turning basin extension, and a 36-ft-deep by 1,200-ft-wide turning basin.

Purpose

5. The purpose of this investigation was to develop the hydrodynamic conditions (currents and water levels) needed for use in a ship simulator study of the Brazos Island Harbor Project. The ship simulator study was performed separately by the Waterways Division of the Hydraulics Laboratory at the US Army Engineer Waterways Experiment Station (USAEWES).

Approach

6. The approach used in this investigation was to obtain available field studies to supply the data for verification of the numerical model. The sole study that met the constraint of synoptic measurements of currents (direction and magnitude) was an intensive inflow study of the Laguna Madre conducted by Espey, Huston and Associates, Inc., in July 1980 for the Texas Department of Water Resources (Ward 1981). Monetary and time constraints prevented conducting a field investigation for this study. While a field investigation designed specifically for providing currents at locations needed for verifying the numerical model would have been preferred, the July 1980 field investigation provided adequate synoptic measurements to allow proper verification of the numerical model.

7. The model was then operated with winds and astronomical tides as boundary conditions to produce reasonable maximum ebb and flood currents in the Brazos Island Harbor Project. Existing conditions in the Brownsville Ship Channel and three alternative channel design conditions, including the authorized plan, were included in the model. The maximum ebb and flood currents predicted by the model for each of the four channel conditions (including existing) were provided to Waterways Division for use in the ship simulator study.

PART II: DESCRIPTION OF HYDRODYNAMIC MODEL

The TABS Modeling System

8. TABS is a modular system composed of distinct computer programs linked together by preprocessors and postprocessors. Each of the major computer programs solves a particular type of problem: hydrodynamics (RMA-2V), sediment transport (STUDH), or water quality (RMA-4). These programs employ the finite element method to solve the two-dimensional vertically averaged governing equations. Only the RMA-2V model was required for this study, and a brief description of RMA-2V appears in Appendix A. The RMA-2V model has been successfully applied in over 50 US Army Corps of Engineers applications to inland and coastal waters.

Two-Dimensional Hydrodynamic Model

9. RMA-2V is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows in two dimensions (vertical averaging). Friction is calculated with Manning's equation, and eddy viscosity coefficients are used to define turbulent exchange characteristics. A velocity form of the basic equation is used with side boundaries treated as either slip (parallel flow) or static (zero flow). The model recognizes computationally wet or dry elements and corrects the mesh accordingly. Boundary conditions may be water-surface elevations, velocities, or discharges and may occur inside the mesh as well as along the outer boundaries.

Numerical Mesh

10. To apply the RMA-2V code to the system, a numerical mesh composed of elements was developed. The mesh developed for the Brazos Island Harbor Project encompassed all of the lower Laguna Madre, the Brownsville Ship Channel, and the immediate Gulf of Mexico (Figure 3). The mesh consisted of 980 elements and 3,118 nodes. Quadrilateral and triangular elements represented all open bay areas and the Gulf of Mexico adjacent to Brazos Santiago Pass. San Martin Lake, Mansfield Pass, the small boat harbor at Port Isabel, and a

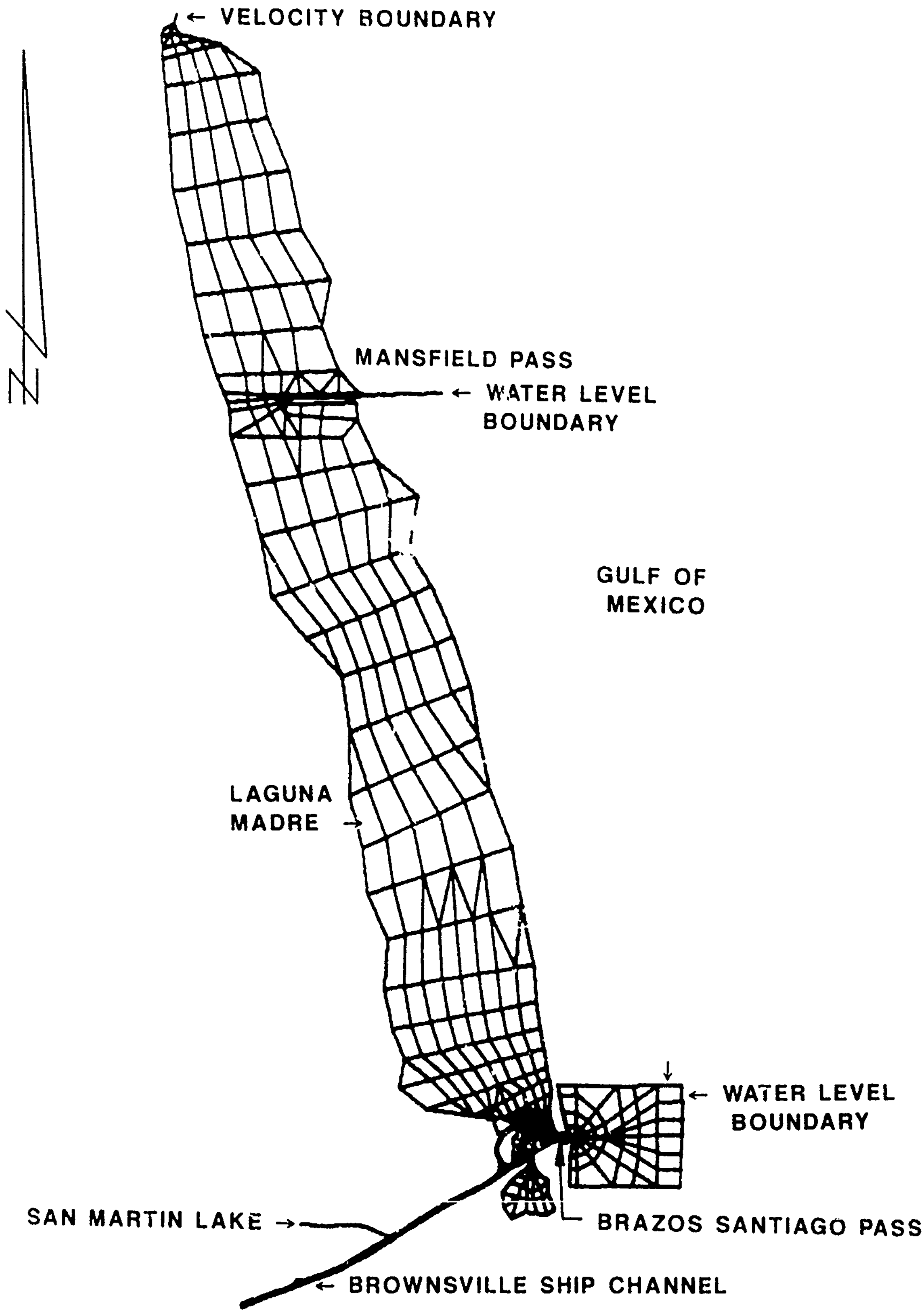

Figure 3. Computational mesh of Brownsville Ship Channel and lower Laguna Madre

segment of the GIWW at the southern extremity of the land bridge were represented by one-dimensional elements.

11. The mesh was generated with high resolution in the Brownsville Ship Channel and the southernmost portions of the lower Laguna Madre. A high level of resolution was required to represent the circulation patterns in sufficient detail to allow accurate representation of currents for the ship simulator study. The resolution provided in the mesh allowed for representation of the alternative channel plans without having to restructure or redevelop the mesh. A second factor allowing development of one mesh is that all planned channel widening was to occur to the southern edge of the existing channel. The exception was an alternative involving a bend widener, which could not be resolved by the existing mesh. (The alternative channel plans will be discussed in detail in Part IV.) A detail of the mesh in the bayward region of Brazos Santiago Pass is presented in Figure 4 to convey the level of model resolution in this area and also to indicate how the resolution provided the flexibility to represent various alternative channel plans. The manner in which the mesh represents the various alternative plans will be further discussed in the section entitled "Bathymetry."

Bathymetry

12 In addition to the horizontal plane representation of the system, the third dimension or depth to the bay bottom (bed elevation) was required to describe the system. Bathymetric information for the bay system and Gulf of Mexico was obtained from the following National Ocean Service/National Oceanic and Atmospheric Administration (NOS/NOAA) nautical charts:

Chart No.	Location	Scale	Date
11302	Stover Point to Port Brownsville	1:40,000	1988
11303	Laguna Madre, Chubby Island to Stover Point	1:40,000	1980
11306	Laguna Madre, Middle Ground to Chubby Island	1:40,000	1982

These charts were used not only to provide the bed elevation (z-coordinate), but also to allow determination of a state coordinate (x- and y-coordinates) for each corner node through use of a digitizer (a corner node is located at every intersection of two or more lines on the mesh). Bed elevations for the

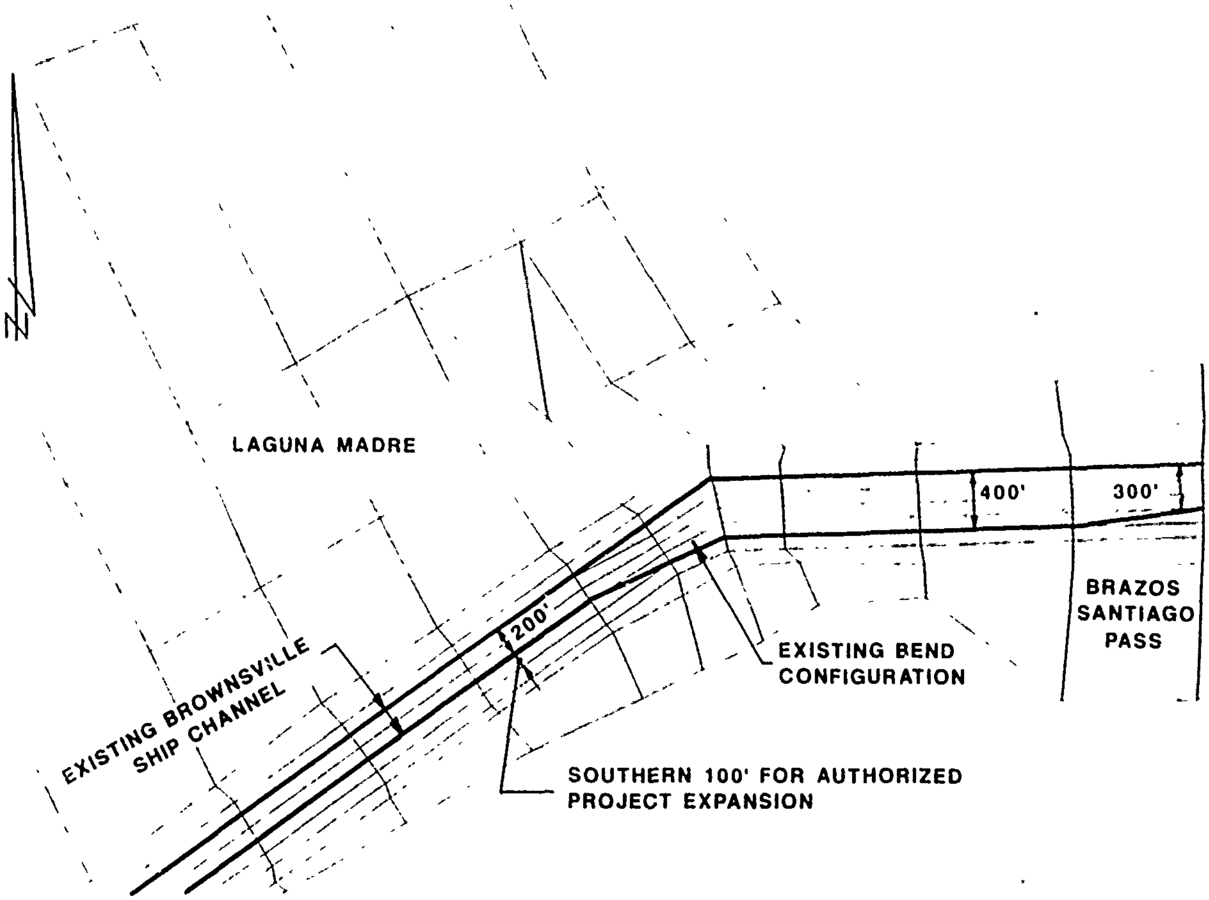

Figure 4. Detail of computational mesh showing segment of Brownsville Ship Channel

nodes composing the Brownsville Ship Channel were determined from the drawings of the Brazos Island Harbor Condition Survey, February 1989, which were provided by the US Army Engineer District, Galveston (van Hook*). For the alternative design plans, the bed elevations of channel nodes were set equal to the design condition channel depth. The reference elevation was mlw (which is interchangeable with Gulf Coast Low Water Datum).

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* Personal Communication from R. van Hook, 1989, US Army Engineer District, Galveston, Galveston, TX.

PART III: HYDRODYNAMIC MODEL VERIFICATION

13. The RMA-2V model was verified to water levels and currents measured during the period of 15-18 July 1980 (Ward 1981; Miertscl ıd Ward 1982). The field measurements from this July 1980 investigation were the only available detailed and synoptic data of currents for the Brownsville Ship Channel and lower Laguna Madre.

14. The process of verification of RMA-2V required adjustment of eddy viscosity coefficients, which control momentum exchange due to velocity gradients; Manning's n values, which determine bed friction; and wind shear stress formulation, which controls wind stress on the water surface. In addition, accurate boundary conditions must be supplied at the open water edges (or boundaries) of the numerical mesh. Boundary conditions were specified in the Gulf of Mexico near Brazos Santiago Pass and Mansfield Pass and at the GIWW transect of the land bridge at the northern extremity of the mesh (Figure 3).

Model Coefficients

15. The process of model verification resulted in one final set of model coefficients representing Manning's n values, eddy viscosity, and wind stress. These coefficients were selected by adjustment within the range of realistic values until the optimum comparison of RMA-2V-predicted water levels and currents to field-measured values was obtained.

Eddy viscosity and Manning's n

16. The following is a tabulation of eddy viscosity coefficients and Manning's n values used in this study:

Location	Eddy Viscosity $lb\text{-}sec/ft^2$	Manning's n
Laguna Madre, Port Isabel area	75	0.021-0.025
Laguna Madre, north of Port Isabel	200	0.030
Laguna Madre, sparse sea grass	200	0.035
Laguna Madre, dense sea grass	200	0.050
Gulf of Mexico	300	0.027
Brownsville Ship Channel, deep	50	0.016
Brownsville Ship Channel, side areas	75-100	0.019-0.030

Large element areas in the northern portion of the Laguna Madre and in the Gulf of Mexico necessitated the larger eddy viscosities in these areas. (The eddy viscosity coefficient is directly proportional to both element size and velocity.) The Manning's n values reflected expected differences in bottom roughness and a slight inverse relationship of n value to water depth, which ranged from over 40 ft in the channels to approximately 3 or 4 ft in much of the Laguna Madre. The relatively high n value in the Gulf of Mexico was selected because of the higher occurrence of large-grained (sands) material in the Gulf as compared to a predominance of fine-grained (clays) material in the Brownsville Ship Channel. Because the Laguna Madre contains extensive sea grass beds, n values were increased in these areas to reflect the increased roughness due to the vegetation. Sea grass bed locations were obtained from Chin (1977), Merkord (1978), and White et al. (1984).

Wind stress formulation

17. Researchers have developed a number of relationships of stress on the water surface as a function of wind velocity. These formulas generally take the following form:

$$\tau = \rho_a C W^2 \tag{1}$$

where

τ = horizontal stress

ρ_a = density of air

C = nondimensional drag coefficient

W = wind speed, generally measured at a height of 10 m

The results of numerous researchers indicated that C is a function of wind speed, atmospheric stability, fetch, wind duration, water depth, and surface film (e.g., oil) condition. The interested reader is directed to any number of references on the subject, including van Dorn (1953), Wu (1969, 1980), Smith and Banke (1975), Garratt (1977), and Smith (1980). Wind stress is often an important factor influencing water levels and circulation in the Laguna Madre because of the relatively feeble Gulf of Mexico astronomical tides, the alignment of the Laguna Madre with the prevailing southeast winds, and the small tidal inlets at Brazos Santiago Pass and Mansfield Pass relative to the surface area of the Laguna Madre.

18. While somewhat surprising agreement exists between researchers on

the value of C , a moderate range of values is found in the literature. As an example, the formula presented in Wu (1969) gives a C value of 0.0015 at a wind of 9 m/sec (20 mph), while the formulas presented by Smith (1980) give a C value of 0.0012 at the same wind speed. These two formulas represented the extremes of predicted C from the literature reviewed for this study.

19. Among several other wind stress formulation options, the RMA-2V model contained the Wu (1969) formula for the drag coefficient, C :

$$C = 0.0005\ W^{0.5} \tag{2}$$

where W is the wind speed in metres per second measured at a height of 10 m. Use of this option in the verification process resulted in excessive wind setup of water levels in the northern extremity of the Laguna Madre from the strong southeast winds occurring each afternoon of the 15-18 July 1980 verification period. During this period, winds typically peaked at approximately 20 mph for several hours each afternoon and diminished to 5 mph by early morning. As previously discussed, this Wu wind stress formulation provides a high C value. Optimum model verification occurred when the C was calculated as one-half the Wu formula:

$$C = 0.00025\ W^{0.5} \tag{3}$$

This C formulation provided lower values than any formulations found in the literature. For a wind speed of 9 m/sec, a C value of 0.00075 was calculated. However, this formulation was not justified solely by verification results, but by consideration of conditions present in the Laguna Madre that were contrary to assumptions in most formulations of C . The following factors contribute to justification of the C formulation (Equation 3):

a. The shallow depths of the Laguna Madre reduce the development of waves. (Waves are important in the transfer of momentum from wind to water.) For example, with a wind speed of 20 mph and a fetch of 30 miles, the fully developed wave height is 1.2 ft for a water depth of 5 ft and the comparable wave height is 3.7 ft for deep water (see nomographs in USAEWES 1984).

b. The extensive sea grass beds would act further to damp wave development to a degree difficult to determine quantitatively.

c. Temporal variation in wind direction, to some extent, and wind speed, to a much greater extent, resulted in consistent wind speed and direction being of relatively short duration. From

USAEWES (1984), a duration of 3 hr is required for waves to become fully developed for a 20-mph wind and a 30-mile fetch. Typically, the maximum daily winds were sustained only for 3-4 hr.

d. Spatial variation in wind direction and speed is expected to occur over the Laguna Madre. The wind data from the Brownsville National Weather Service (NWS), Corpus Christi NWS, and a station at Leo Kaufer Memorial Park near Baffin Bay (immediately north of study area) indicated general agreement of wind speed and direction, though pronounced differences occurred at times. The RMA-2V model is presently formulated to allow a spatially uniform wind field, though temporal variations were specified.

e. Dredged material disposal islands and extremely shallow areas adjacent to the GIWW, which transects the entire length of the Laguna Madre, would act to reduce fetch lengths, winds, and wind stress in a manner difficult to quantify.

These factors in conjunction with the fact that nearly all wind stress research has been conducted in open oceans with large fetches and deep waters supported the wind stress formulation used in this study.

Boundary Conditions

20. RMA-2V was operated with boundary conditions at all external water edges to the mesh, i.e., the Gulf of Mexico and GIWW in the land bridge. Along the Gulf of Mexico boundary, a time-dependent water-surface elevation was specified at all external boundary nodes to represent tidal elevation fluctuations (Figure 3). The boundary water-surface elevations were adjusted such that the model reproduced the water levels recorded at the tide gage location between the jetties in Brazos Santiago Pass as indicated in Figure 5. Since no site-specific information existed for the Gulf tide in the Mansfield Pass area, the same water levels were used at both the Mansfield Pass and Brazos Santiago Pass locations. While water level fluctuations or tidal range would be expected to be very similar at both locations, some small phasing difference might be expected. Comparisons of water-level strip chart records at tide gage locations between the jetties in both Brazos Santiago Pass and Mansfield Pass for 1972 indicated little or no time differences and similar water levels. (The Mansfield Pass tide gage operated briefly before it was destroyed by gunfire, and 1972 was a period when both tide gage records were available.)

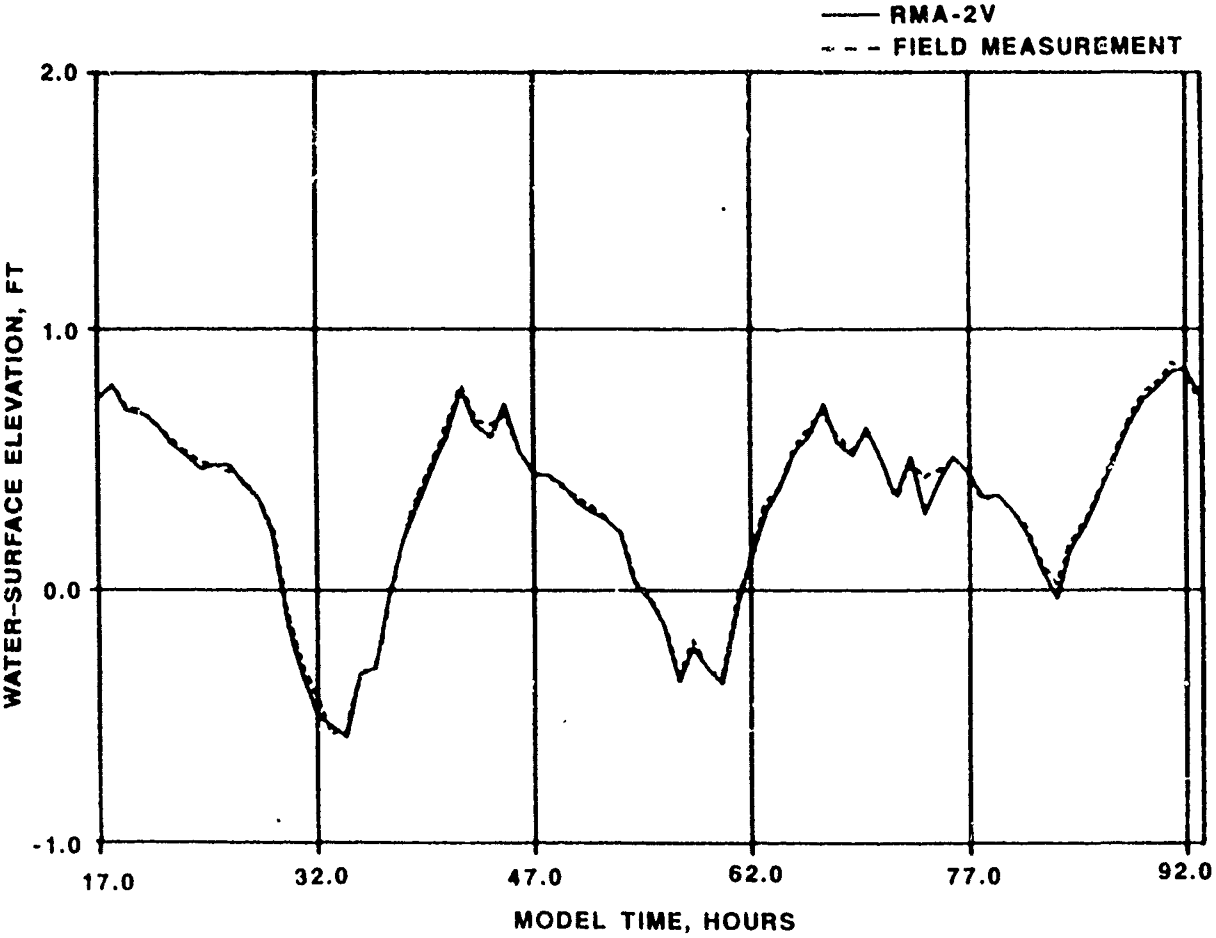


Figure 5. RMA-2V-predicted water level in Brazos Santiago Pass, 15-18 July 1980

21. The boundary condition at the northern boundary of the mesh at the GIWW was described as a constant velocity northward of 1.0 fps. Measurements at this location during the July 1980 field investigation ranged from 0.5 to 1.6 fps with an average of approximately 1.0 fps. Velocity direction was toward the north with no reversal of current direction occurring during the investigation period. While the measured time-dependent currents could have been specified for the verification case, the problem of how to specify this boundary condition for the production simulations would still remain. By specifying a constant velocity boundary condition, the total volume of water directed northward through the land bridge was accounted for even though it was overestimated at times and underestimated at other times. For the production simulations the boundary was also specified as 1.0 fps northward. The insensitivity of the Brazos Island Harbor Project area to the GIWW boundary condition is demonstrated in Figure 6. In the figure are depicted the

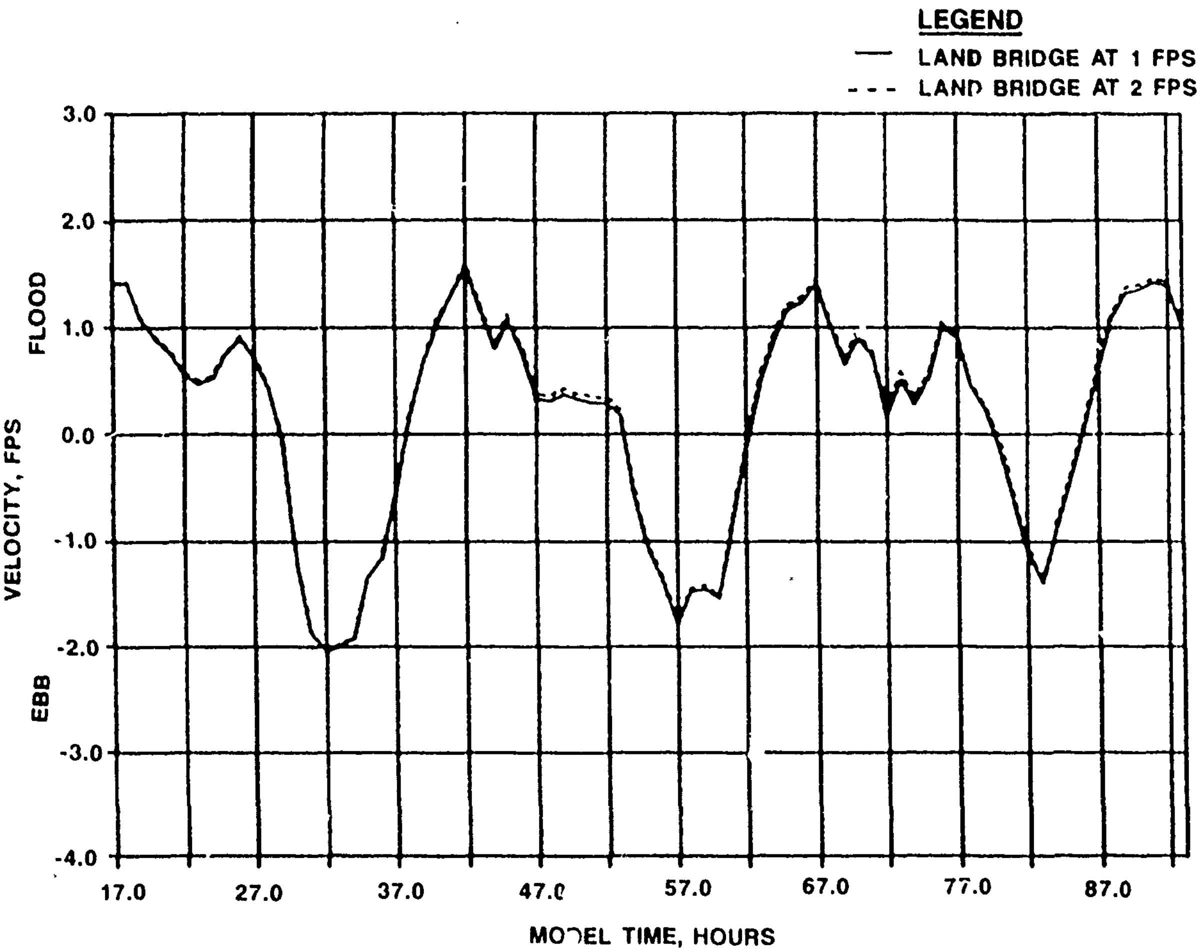


Figure 6. Sensitivity of Brazos Santiago Pass (node 1199) to velocity boundary specification at land bridge

velocities at center channel between the jetties of Brazos Santiago Pass during the field investigation for boundary-specified velocities of 1.0 and 2.0 fps at the land bridge.

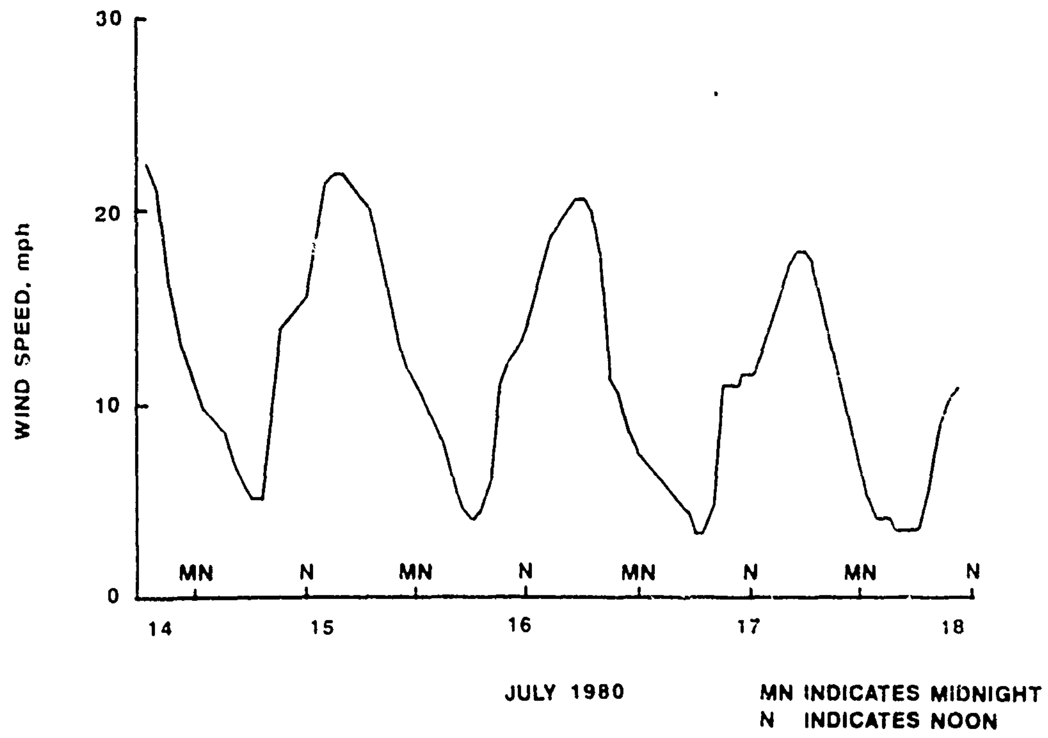
22. Freshwater inflow boundary conditions were considered to be insignificant to the hydrodynamic considerations of this study. The Brownsville NWS station had reported a cumulative rainfall of 4.99 in. from January 1980 through the time of the July survey, and only 0.13 in. for the 2 months prior to the survey. Under average conditions, freshwater inflow to the lower Laguna Madre is approximately 400 cfs (Espey, Huston and Associates, Inc., 1977). This average inflow represented less than 1 percent of the peak ebb and flood discharges determined during the July 1980 survey through Brazos Santiago Pass (Ward 1981). Even smaller freshwater inflows would have occurred under the less-than-normal rainfall prior to the field survey.

23. The air-water interface boundary condition has been previously discussed under "Wind Stress Formulation." The wind speed and direction during the July survey are depicted in Figure 7. Peak wind speeds of approximately 20 mph from the southeast occurred approximately midafternoon each day with a more southerly direction becoming established as the wind decreased to a minimum prior to sunrise. The wind speed and direction used in the model were the average of the Brownsville NWS record and that from Leo Kaufer Memorial Park.

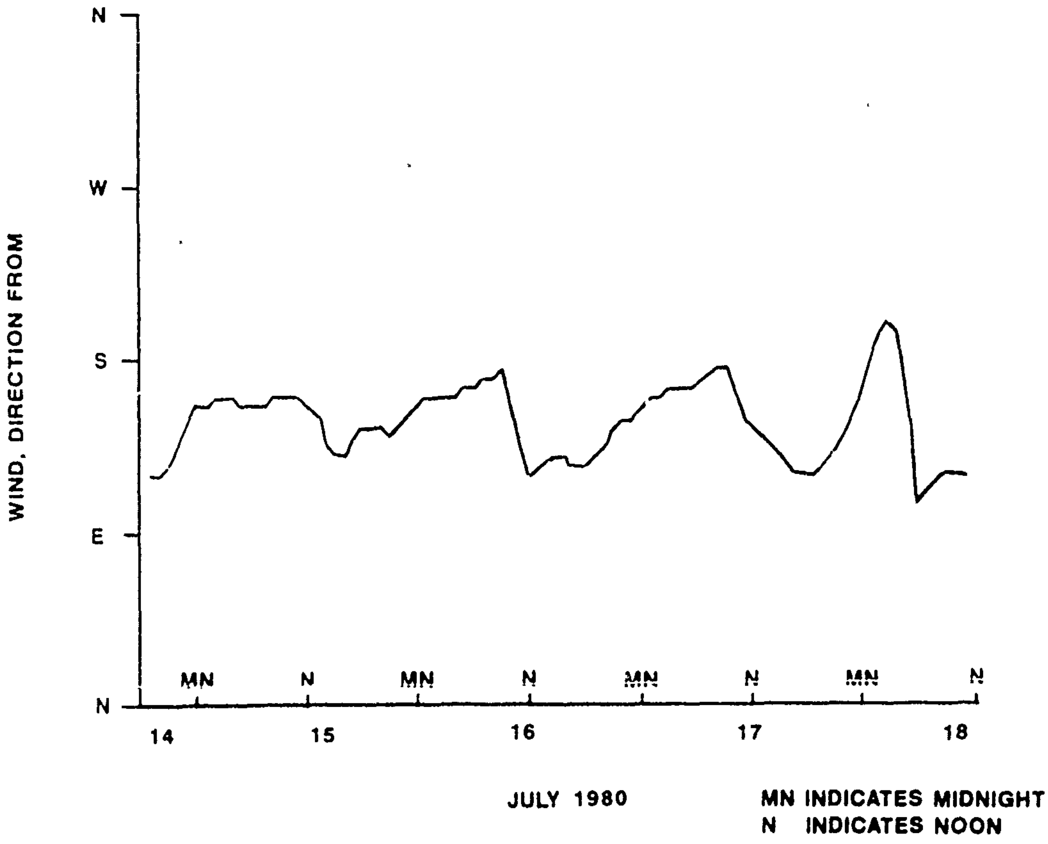
Comparison to July 1980 Field Measurements

24. RMA-2V was operated for the July 1980 verification period with the eddy viscosities, Manning's n values, wind stress formulation, wind speed and direction, water-level boundary conditions, and velocity boundary condition previously discussed. The water level and currents predicted with RMA-2V were compared to the field measurements, which were taken at the stations depicted in Figure 8. RMA-2V was operated with a 1-hr time-step, which has proven to be acceptable for several studies with RMA-2V along the Gulf of Mexico. A 17-hr initial period was specified to allow the transients induced by initialization of RMA-2V to dissipate and for the model solution to respond correctly to the imposed boundary conditions. Limited testing indicated essentially no difference in results predicted by RMA-2V in the Brazos Island Harbor Project area with either a 17-hr or 24-hr initialization (spin-up) period.

25. Comparisons of water levels predicted by RMA-2V to tide gage records are provided in Plate 1. The water level comparisons indicated general agreement between model results and field measurements. However, model results were less satisfactory than typically experienced in other Gulf Coast estuaries. The phasing was good but model water level variations were slightly damped at tide gage T2, the Small Boat Harbor. For tide gage T3, GIWW marker 73, the phasing was again good; however, model water level variations were extremely damped. At tide gate T4, GIWW marker 225, the phasing and amplitude were both in error. As will be shown in the section, "Sensitivity Testing," indications existed that some of the poor response of the model in predicting interior bay water levels was caused by unknowns regarding wind speeds and directions over the study area.



a. Speed



b. Direction

Figure 7. Wind speed and direction used in model verification

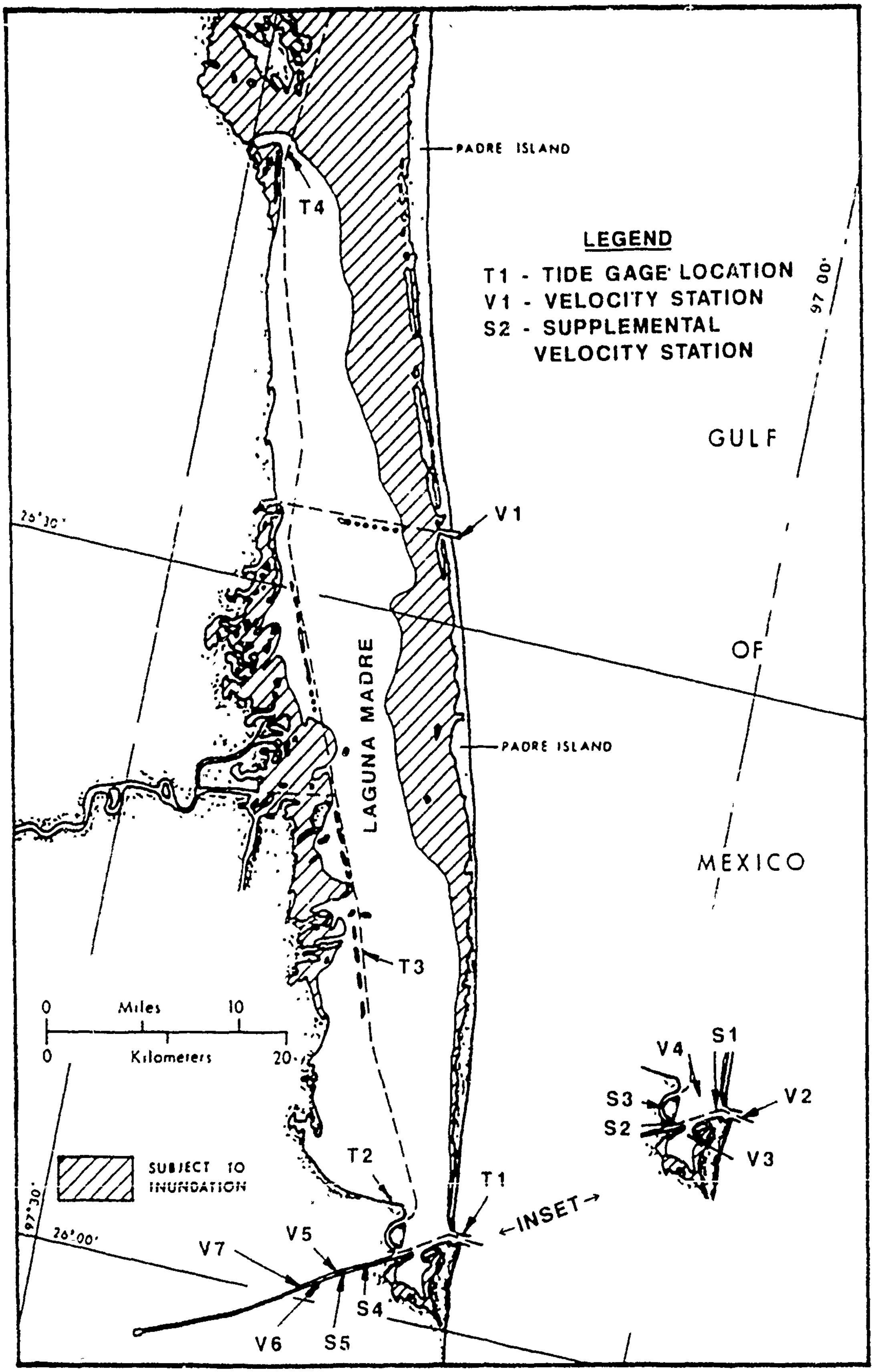


Figure 8. Field station locations for 15-18 July 1980 study

26. Comparisons of velocities predicted by RMA-2V to field-measured values are provided in Plates 2-4. RMA-2V-predicted velocities generally compared very favorably with the vertically averaged field measurements. At all survey stations, the vertical depth profile from the field survey was averaged to obtain a single value for comparison with the vertically integrated RMA-2V results. Good comparisons occurred at sta V1, Port Mansfield Channel jetties, except during the strong winds of 15 July (model hours 20-25). Good comparisons also occurred at sta V2, Brazos Santiago Pass jetties, though peak ebb velocities were slightly overpredicted and peak flood velocities were slightly underpredicted.

27. The RMA-2V results at sta V3, the inlet between South Bay and Laguna Madre, compared favorably with the measured velocities. At sta V3 the measured velocities did not indicate a pronounced tidal response, but rather more of a response to local wind forcing. In fact, it can be observed that the RMA-2V results fairly represented the period of model hours 20-30 when the inlet was ebbing while the Brazos Santiago was flooding (anticorrelated flow period) and the period of hours 70-80 when field measurements indicated rapid flow reversals and the model results replicated several of these reversals.

28. At sta V4, the center of the old causeway, the model results somewhat underpredicted velocities for the first 30 hr of the survey, but accurately predicted velocities for the remaining 40 hr ot the survey. At sta V7, the inlet between the Brownsville Ship Channel and San Martin Lake, good replication of measured velocities was obtained with RMA-2V. The ebb flow dominance at this station was the result of a cooling water return from Union Carbide of approximately 300 cfs into San Martin Lake, which was included in the model.

29. The poorest comparison of model results to measured values occurred in the landlocked portion of the Brownsville Ship Channel, sta V5 and V6. While always an easy excuse for the numerical modeler, the validity of the measurements at these locations are highly suspect. Inconsistencies exist between sta V5 and V6; for example, compare the measured velocity directions at the stations for hours 32-40 and 70-85. Velocity measurements at these two stations were made with Price meters. For the low velocities measured in the channel, the Price meter was operated for 30-120 sec, which would occur simultaneously with the survey boat swinging at anchor under the influence of the strong winds during the survey. Not so coincidentally, the maximum and often

most erratic velocity measurements occurred with maximum daily winds, model hours 22-30, 47-54, and 72-78. A second explanation of these high velocities could be vertical circulation patterns induced by the winds, a phenomenon not reproduced in the depth-integrated model. However, this cannot be determined from the velocity data, since a Price meter does not provide a current direction. Current direction at these stations was determined from a surface drogue.

30. Supplemental field measurements at stations infrequently monitored using a Bendix Model Q-9 Current Meter, which contains a Savonius rotor and directional sensor, provided limited data. These data generally confirmed the lower velocities predicted in the landlocked channel by RMA-2V, as shown in supplemental station comparison plots for S2, S4, and S5 (Plate 4). These limited supplemental stations also confirmed the accuracy of model velocities in the channel's transect of the Laguna Madre, sta S1, and the cutoff channel by Long Island, sta S3.

31. The verification process indicated that RMA-2V could accurately reproduce velocities in the Brazos Island Harbor Project area. The inability of RMA-2V to reproduce water levels accurately in the interior of the Laguna Madre remained a significant question. The question was made more complicated by the fact that not only were the velocities in the channel of Brazos Santiago Pass accurately reproduced, but the tidal exchange or discharge through the Brazos Santiago Pass also seemed to be reasonably replicated. Model-predicted discharges are compared to the discharges determined from the rating curve developed at velocity station V2 and the velocities measured at V2 (Ward 1981) in Figure 9. The relatively good agreement in Figure 9 indicated the approximate correct tidal volume exchange through Brazos Santiago Pass, which gave some indication that the water level response at the interior bay tide gages was not entirely related to the astronomical Gulf tidal exchange. (A similar discharge comparison could not be made at Mansfield Pass, since the field survey monitoring mistakenly occurred at a much wider portion of the channel than where the rating curve was developed.)

32. Since the emphasis of this study was to provide currents for ship simulator studies, the verification process indicated the acceptability of RMA-2V to predict accurate currents in the Brazos Island Harbor Project area. While the model's inability to replicate water levels removed from the study

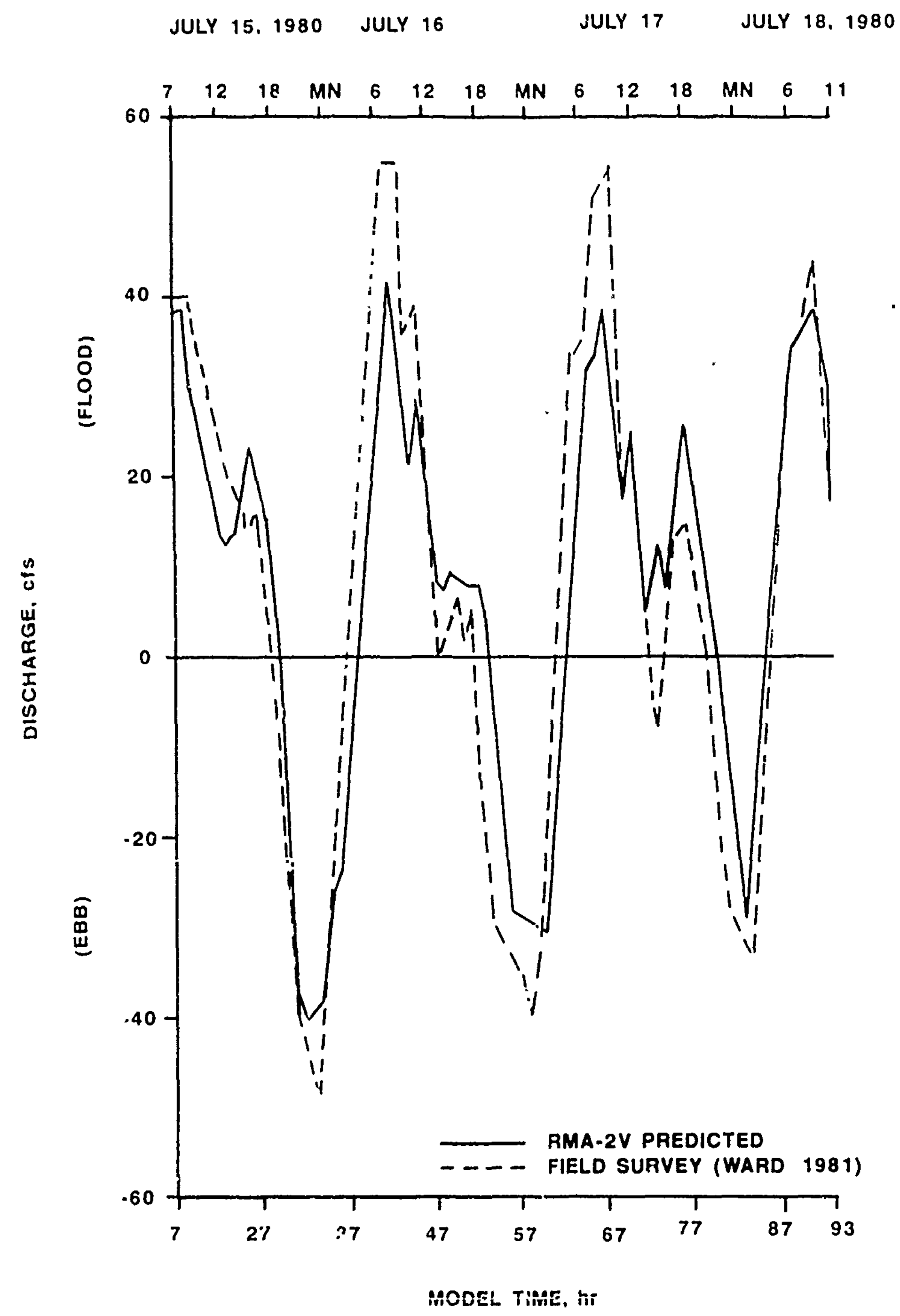


Figure 9. Comparison of RMA-2V-predicted and field-measured discharge through Brazos Santiago Pass. (Source of field survey discharge: Ward (1981), Figure 5-16.)

area remained a concern, model results indicated that confidence could be placed in the velocities in the study area.

Sensitivity Testing

33. Sensitivity testing was performed on RMA-2V to determine the model's response to changes in Manning's n value, wind stress, and the velocity boundary condition at the GIWW (land bridge). This process was especially important in attempts to understand the less than desirable prediction of interior bay water levels with RMA-2V. In the sensitivity testing, all parameters were kept at the verified values, except the parameter being studied.

34. Since RMA-2V was underpredicting water level response in the Laguna Madre, the model was operated with the n values in the Laguna Madre all set to 0.020 or less to see if tidal damping would be reduced. (In the verified model, n values as high as 0.050 were set for dense sea grass areas.) The response of the peak velocities in Brazos Santiago Pass, sta V2, during the July 1980 verification case to reduced n values was minor. Peak ebb and flood velocities were increased 5 percent or less (Plate 5). The most pronounced differences occurred during the high wind periods of approximately hours 27, 52, and 77, when the lowered bottom roughness allowed a more pronounced effect from wind stress. A similar response to that at V2 was indicated at sta V4 at the old causeway. The water level sensitivity to the reduced n values at tide gage sta T3 and T4 are also depicted in Plate 5. The differences between water levels at T3 were small. Because of the increased wind stress response with the lowered n values, a more pronounced wind setup occurred at T4 with the reduced n values. Reduction in n values did not appreciably increase peak velocities in the study area, though response to wind stress was exacerbated. Water levels immediately north of the study area, sta T3, showed little response to reduced n values, while at sta T4, excessive wind setup resulted from the reduced n values. Overall, reduced n values exaggerated wind stress response in the model, but had slight effects on predicted peak velocities.

35. The response of RMA-2V to various wind drag coefficients is presented in Plate 6. Each plot depicts response to a drag coefficient determined by the Wu formulas (Equation 2), the drag coefficient used in the verified model (Equation 3), and essentially a zero drag coefficient. The

sensitivity of results to the drag coefficient formulation is amply demonstrated in Plate 6.

36. The response of RMA-2V model results to a doubling of the velocity specified in the GIWW at the land bridge from 1.0 to 2.0 fps is depicted in Figure 6. As expected, the velocities predicted in the study area showed little sensitivity to a reasonable range of velocity specification at the land bridge. Since the land bridge velocity boundary was the greatest unknown for the future condition simulations, the insensitivity of the velocities in the Brazos Island Harbor Project area to this boundary increased confidence in those future condition simulations for the ship simulator study.

PART IV: SHIP SIMULATOR HYDRODYNAMICS DEVELOPMENT

37. The development of hydrodynamic conditions for the ship simulator study required use of the verified Brownsville Ship Channel/lower Laguna Madre mesh. This mesh was modified to include the bathymetry of three alternative project designs. Also, conditions to produce reasonable maximum ebb and flood currents were generated. (Typically, ship simulation studies analyze reasonably severe current conditions to ensure that the project design ships can be safely navigated through the channel under these adverse conditions.)

Alternative Project Configurations

38. Including the existing condition, three alternative project configurations were evaluated. These configurations included the authorized design and two proposed alternatives obtained from the Waterways Division, USAEWES, which performed the simulator studies. The following channel configurations were evaluated with RMA-2V:

a. Existing channel: 38 ft below mlw by 300 ft wide from Gulf of Mexico to Padre Island, 36 ft below mlw by 200 ft wide from Padre Island to Goose Island, 36 ft below mlw by 300 ft wide to the turning basin extension, 36 ft below mlw by 400-500 ft wide for turning basin extension, and 36 ft below mlw by 900 ft wide at the turning basin.

b. Alternative design 1: 44 ft below mlw by 300 ft wide from Gulf of Mexico to Padre Island, 42 ft below mlw by 200 ft wide from Padre Island to turning basin extension, 42 ft below mlw by 325-400 ft wide for turning basin extension, and 36 ft below mlw by 1,200 ft wide for turning basin.

c. Alternative design 2 (authorized project): same project depths as alternative design 1. A 400-ft width from Gulf of Mexico to Padre Island, 300-ft width from Padre Island to turning basin extension, and 1,200-ft width at turning basin.

d. Alternative design 3: same project depths as alternative design 1. A 300-ft width from Gulf of Mexico to South Padre Island, bend widener reconfigured (Figure 10), 250-ft width from Padre Island to turning basin extension, and same configuration as alternative design 1 for turning basin extension and turning basin.

Design Conditions

39. The reasonable worst-case currents were assumed to occur with the

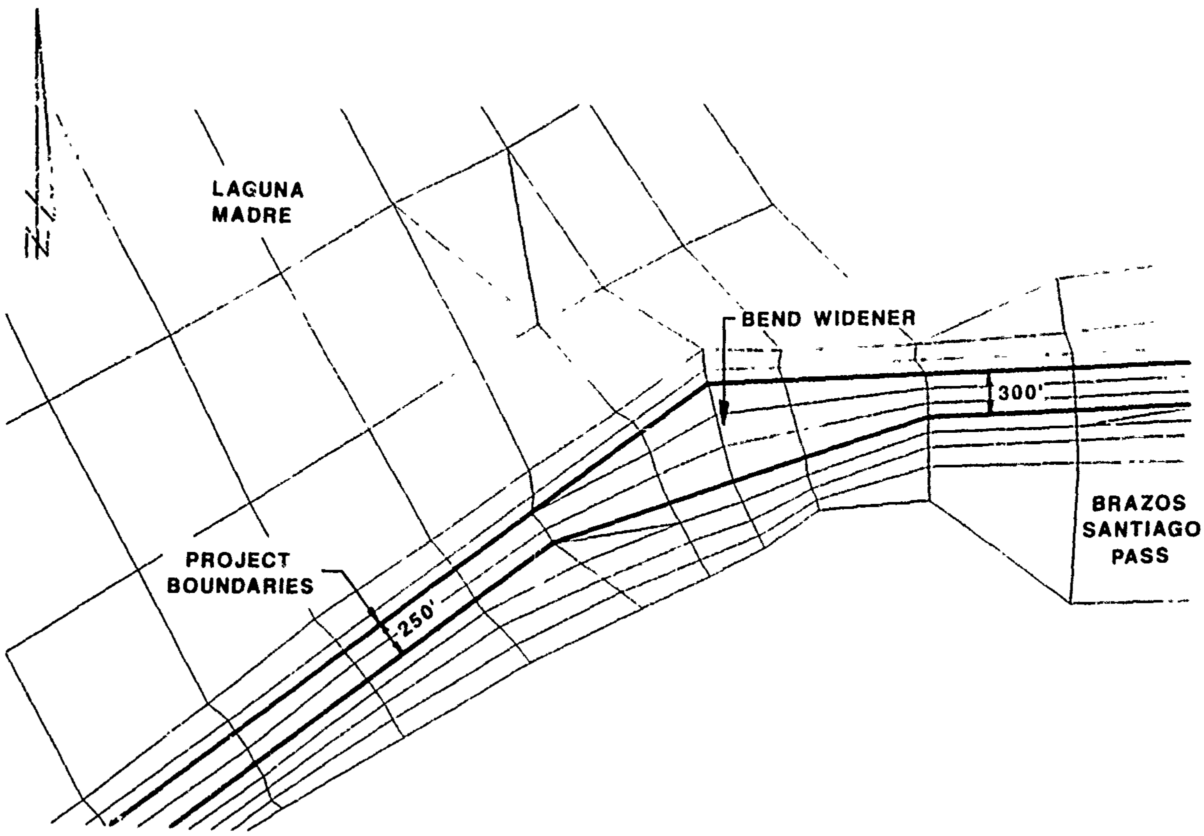


Figure 10. Detail of mesh configuration for alternative design 3 bend widener

high-amplitude diurnal tide (often called a spring tide) with a 20-mph southeast wind during flood tide with the typical daily reduction to 4 mph coinciding with ebb tide. Figure 11 shows the phasing of the design astronomical tide and wind speed. The selected period for the astronomical tide was 0800 on 2 June 1989 to 0100 on 3 June 1989. The amplitude of the astronomical tide during this period was equaled on only two other days of 1989 and was not exceeded during the year. The tide for this period was reconstructed from the major diurnal and semidiurnal constituents as obtained from NOS/NOAA.* The 14 most important harmonic constituents (K_1, O_1, P_1, Q_1, J_1, M_1, M_2, S_2, N_2, K_2, ν_2, $(2Q)_1$, $(OO)_1$, and ρ_1) from the standard harmonic analysis for the Padre Island (south end), Texas Station No. 8779750, were used to reconstruct the tide. The prevailing direction of the wind on the south Texas coast is from the southeast, and 20 mph was selected as a reasonable maximum wind

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* Personal communication from J. Culp, 1990, National Ocean Service, National Oceanic and Atmospheric Administration, Rockville, MD.

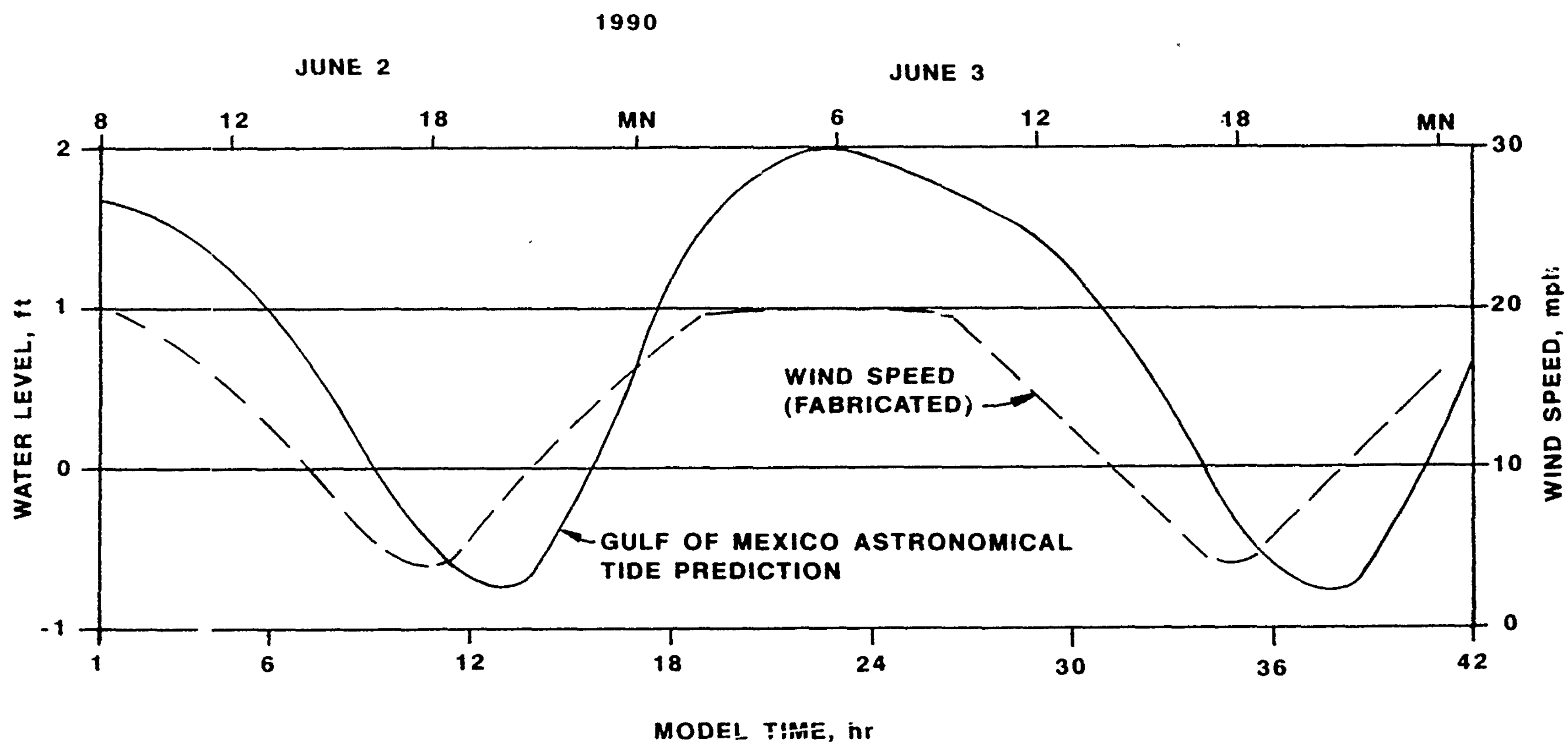

Figure 11. Phasing of astronomical tide and variable wind speed used as design condition

speed. Based on wind speeds and directions at the Brownsville NWS, winds from the south, southeast, or east occur approximately 70 percent of the time and winds from the southeast occur approximately 40 percent of the time. Winds of 20 mph or greater occur less than 5 percent of the time, considering the cumulative for all compass directions.

40. The wind speed was phased with the astronomical tide to enhance movement of water into the Laguna Madre on the flood currents, and then to diminish with ebb currents to allow enhanced movement of water through Brazos Santiago Pass into the Gulf. The wind variation used increased maximum ebb currents in Brazos Santiago Pass approximately 0.5 fps as compared to a constant 20 mph for the entire simulation period. However, the wind variation did not change the maximum flood currents.

41. The velocity boundary for the GIWW at the land bridge was set at a constant 1.0 fps toward the north. This specification assumed a similar response at the land bridge boundary as occurred during the July 1980 verification period. The validity of this assumption cannot be evaluated; however, the relative insensitivity of the velocities in the Brazos Harbor Island Project area to this extreme northern boundary was previously demonstrated (Figure 6).

Hydrodynamic Simulations

42. The four channel configurations were represented through changes in depths to the numerical mesh to reflect the depth and width of each configuration. Only alternative design 3 with the modified bend widener east of Padre Island required some minor changes in the actual horizontal configuration of the mesh.

43. The time-history of velocities at four representative stations (V2, S1, S2, and V5 in Figure 8) in the Brownsville Ship Channel are presented for the three alternative designs in Plates 7-9 with the existing condition as the common basis of comparison. (The 250-ft channel width for design 3 was not extended into the landlocked portion of the ship channel, sta S2 and V5, so plots are omitted for these two stations in Plate 9.) As expected, all three alternative designs result in reduced velocities because of increased channel depths and, for alternative designs 2 and 3, increased channel widths.

44. For all four simulations and designs, the peak flood velocity in the

project area occurred at approximately model hour 21 and the peak ebb velocity occurred at approximately model hour 36. A vector plot of currents for the existing condition at hours 21 and 36 are provided in Plates 10 and 11, respectively. The vector plots for the three alternative designs would be very similar, though channel velocities would be slightly less.

PART V: CONCLUSIONS AND RECOMMENDATIONS

45. The RMA-2V model was successfully verified to limited field measurements from a synoptic field survey in the lower Laguna Madre and Brownsville Ship Channel for the period 15-18 July 1980. The comparison of RMA-2V-predicted velocities to approximately hourly measurements of velocity at several stations in the Brazos Island Harbor Project area was good. At some stations, corruption of field measurements from strong wind and waves seemed a distinct possibility. Water level comparisons at locations removed from the project area were not as good as those for velocities in the study area. Some of the model error was suspected to be the result of difficulties in properly representing the dynamic and very pronounced wind forcing on the lower Laguna Madre, primarily because of the lack of accurate prototype wind data.

46. Including existing conditions, four channel configurations of the Brazos Island Harbor Project were evaluated during conditions of a high-amplitude diurnal tide with temporally variable wind speeds of 4 to 20 mph from the southeast. The astronomical tide and variable wind were phased to enhance both the ebb and flood currents in the project area. These conditions produced reasonable maximum ebb and flood currents for each channel configuration.

47. The peak ebb and flood currents for all four channel configurations were to be used as hydrodynamic conditions in a ship simulator study conducted at USAEWES.

48. If further refinement of currents in the project area becomes necessary, then further field investigations are recommended. The field investigation should be conducted during high-amplitude diurnal tides. Tide gages should be positioned in the Laguna Madre concurrent with the field measurement of velocities to help resolve wind setup conditions in the bay. The measurement of wind speed and direction is an essential part of any field investigation of this system.

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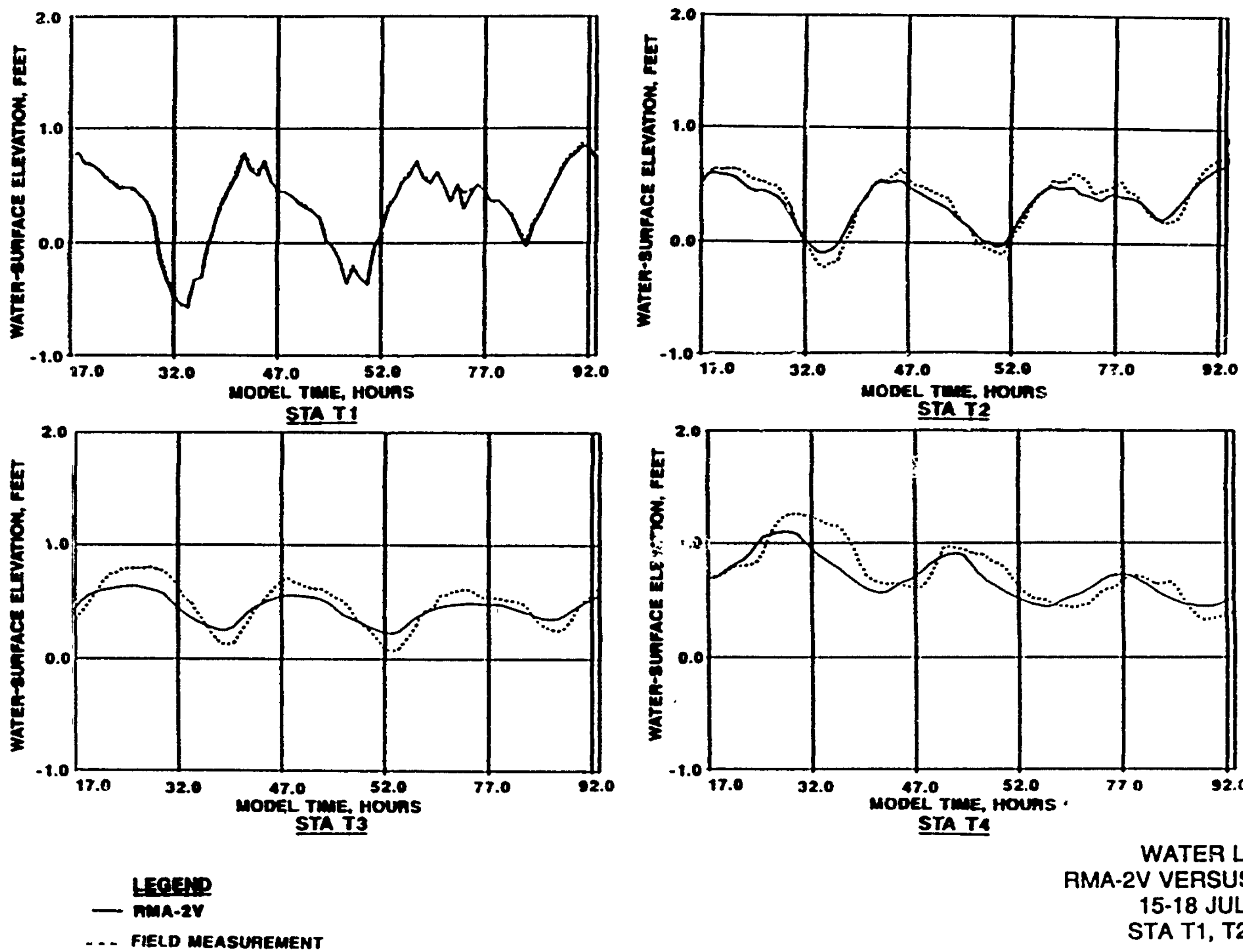
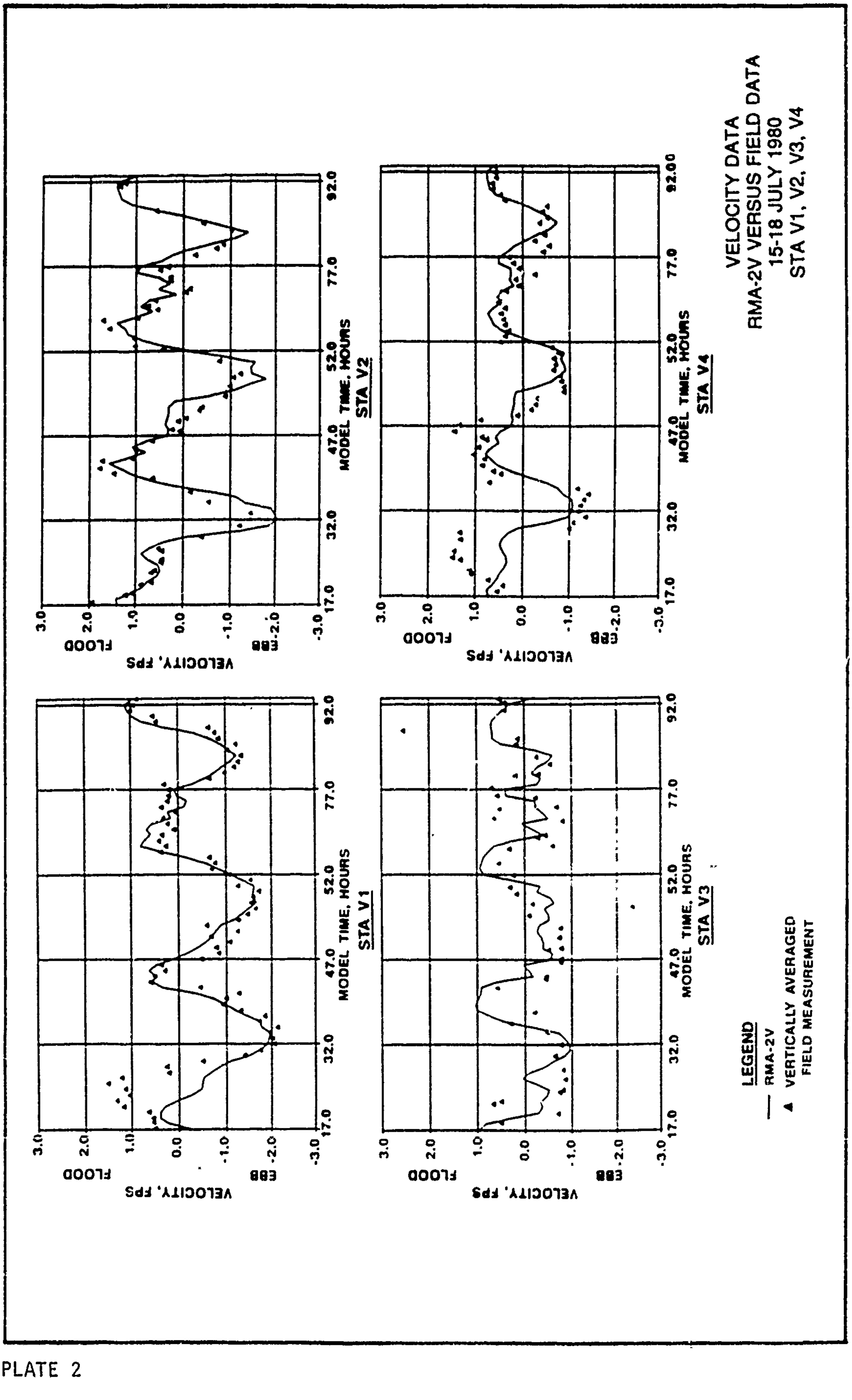
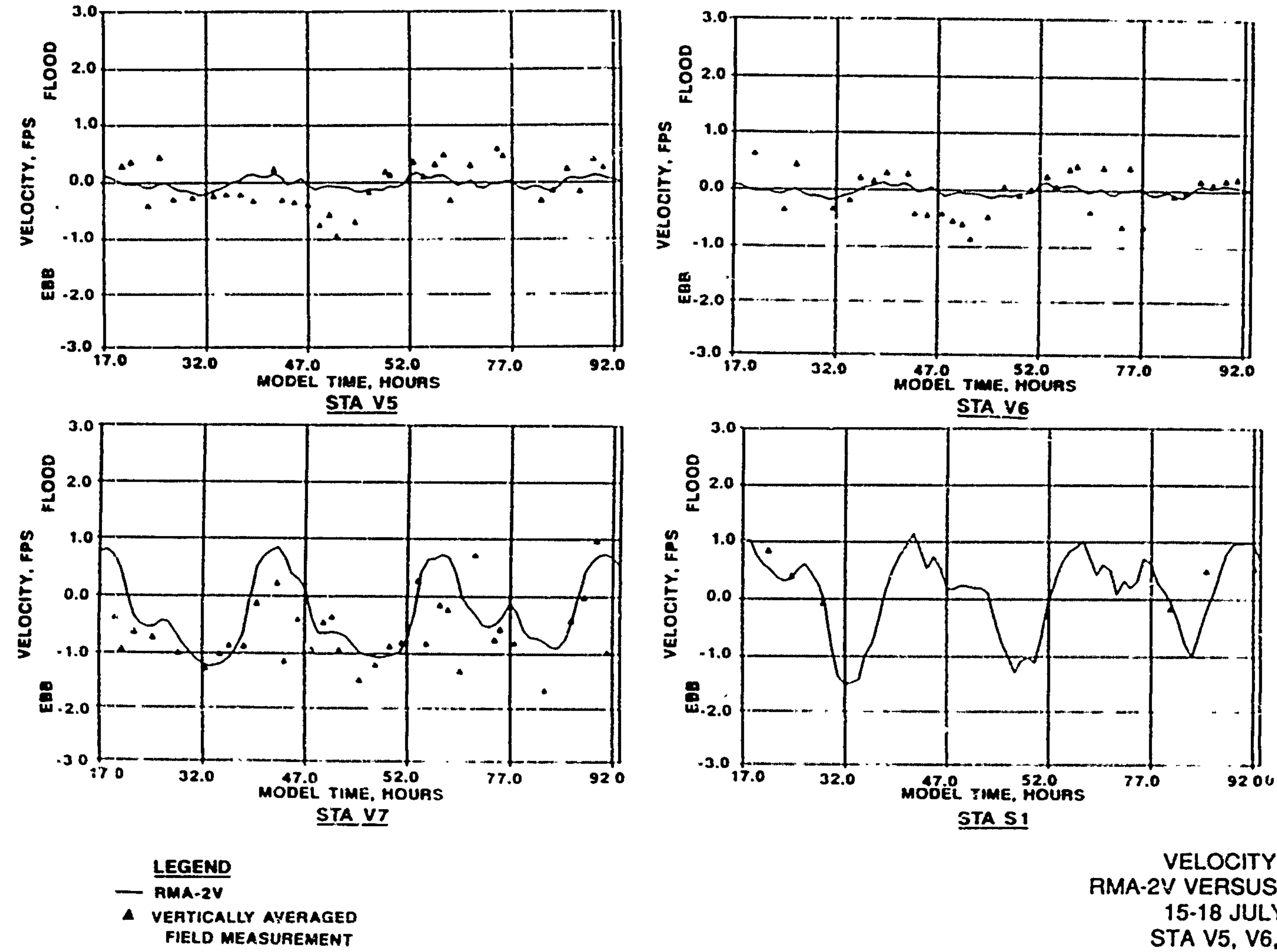


WATER LEVELS
RMA-2V VERSUS FIELD DATA
15-18 JULY 1980
STA T1, T2, T3, T4

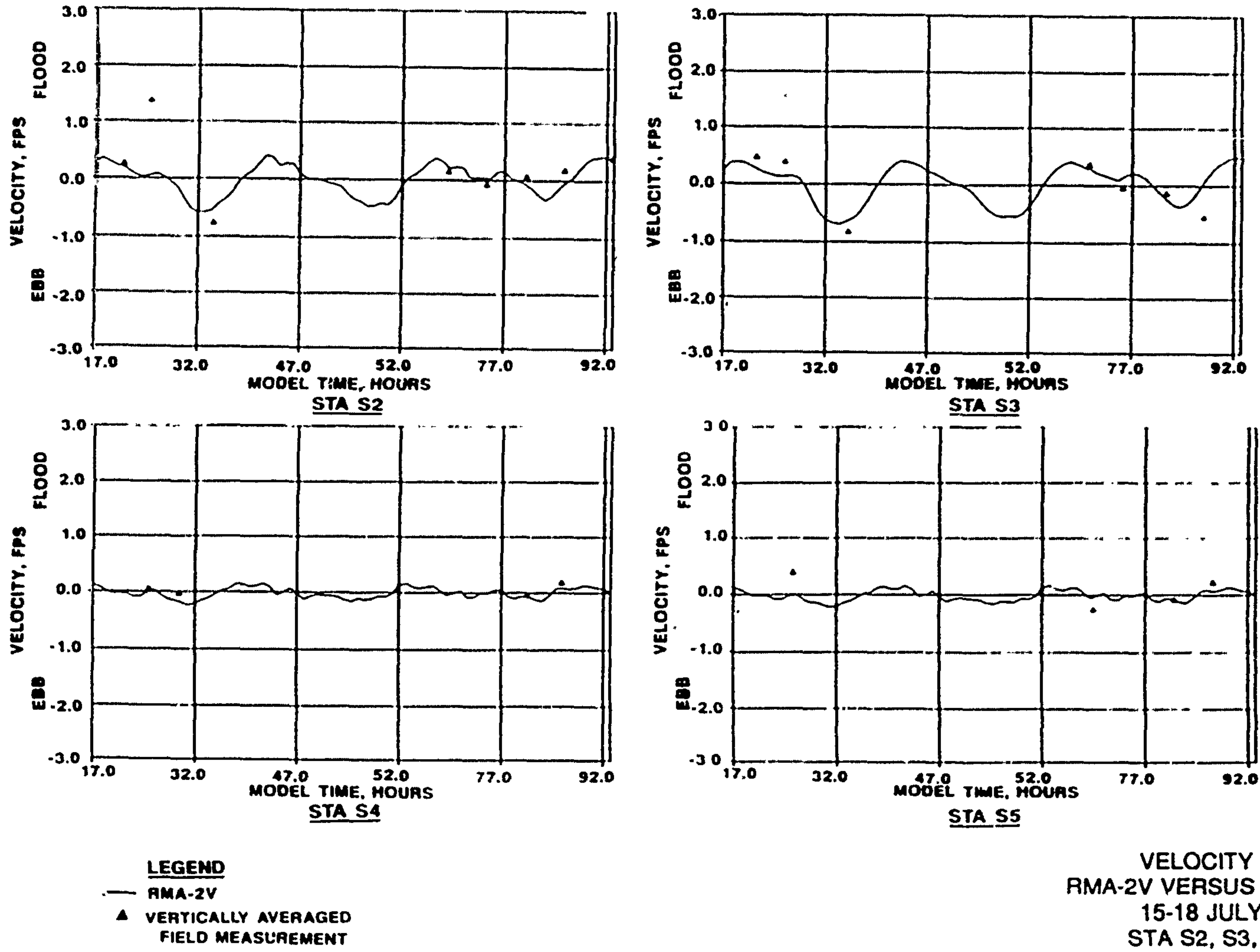


VELOCITY DATA
RMA-2V VERSUS FIELD DATA
15-18 JULY 1980
STA V1, V2, V3, V4

PLATE 2

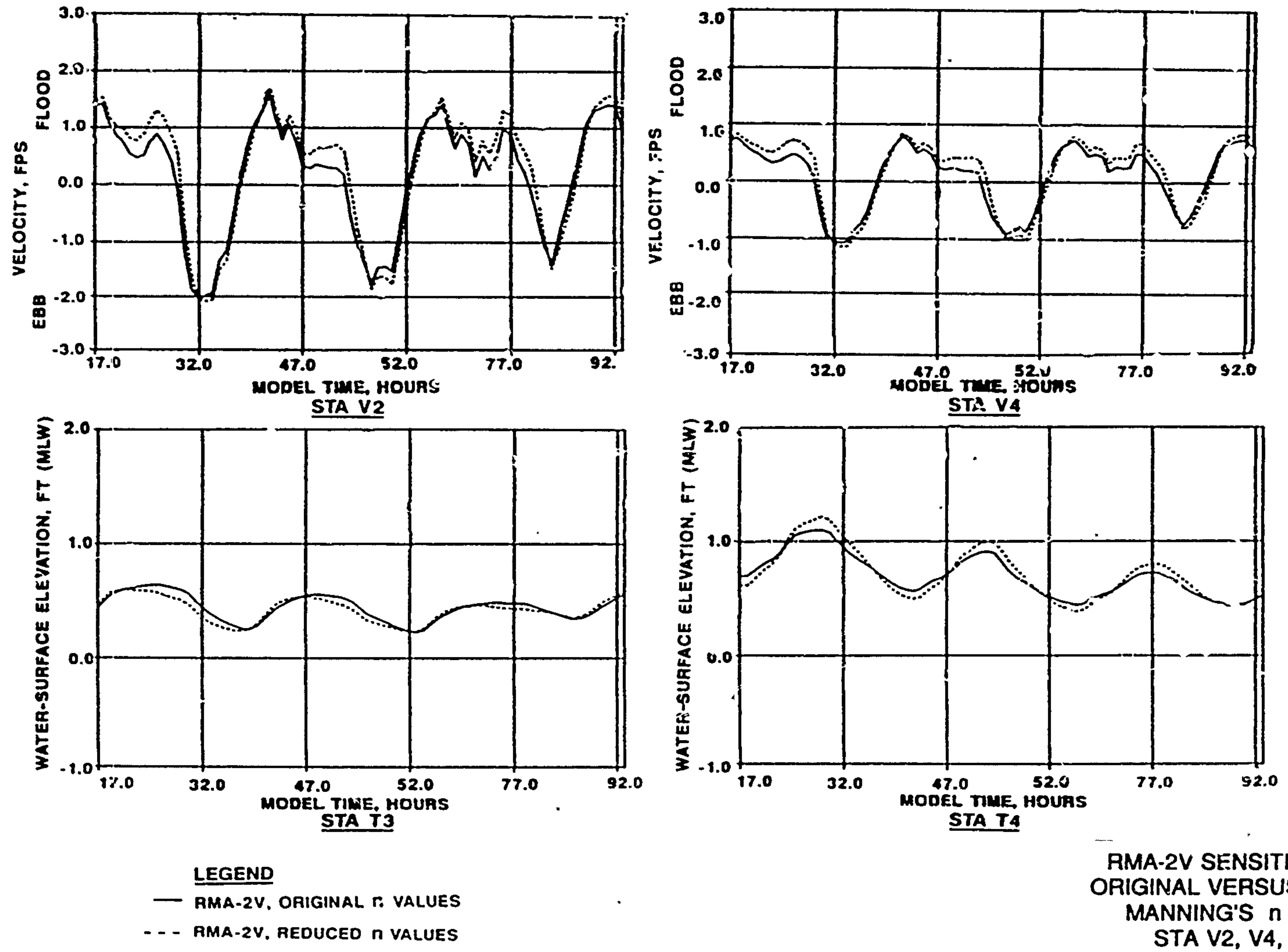


VELOCITY DATA
RMA-2V VERSUS FIELD DATA
15-18 JULY 1980
STA V5, V6, V7, S1

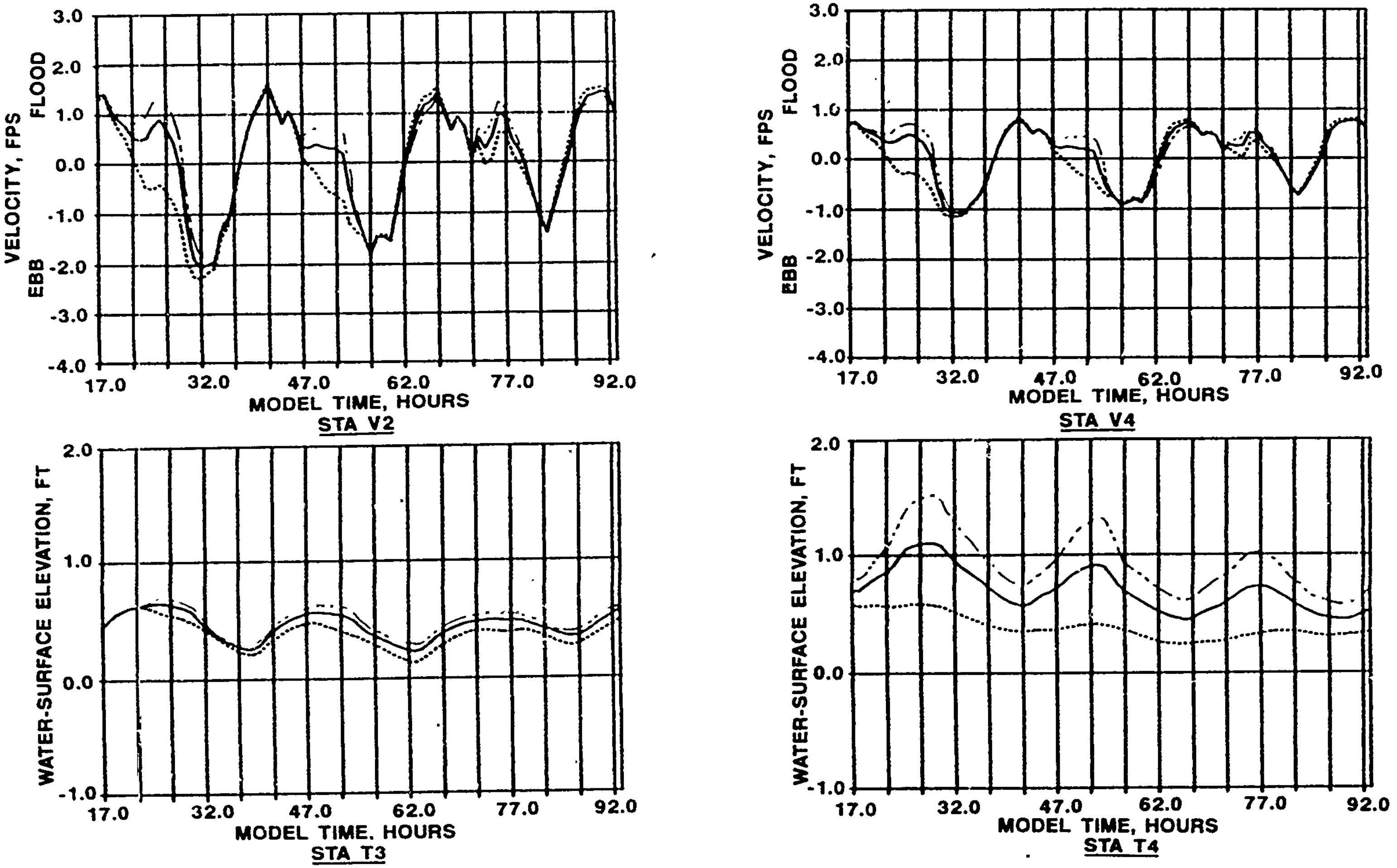


VELOCITY DATA
RMA-2V VERSUS FIELD DATA
15-18 JULY 1980
STA S2, S3, S4, S5

PLATE 4



RMA-2V SENSITIVITY TEST
ORIGINAL VERSUS REDUCED
MANNING'S n VALUES
STA V2, V4, T3, T4

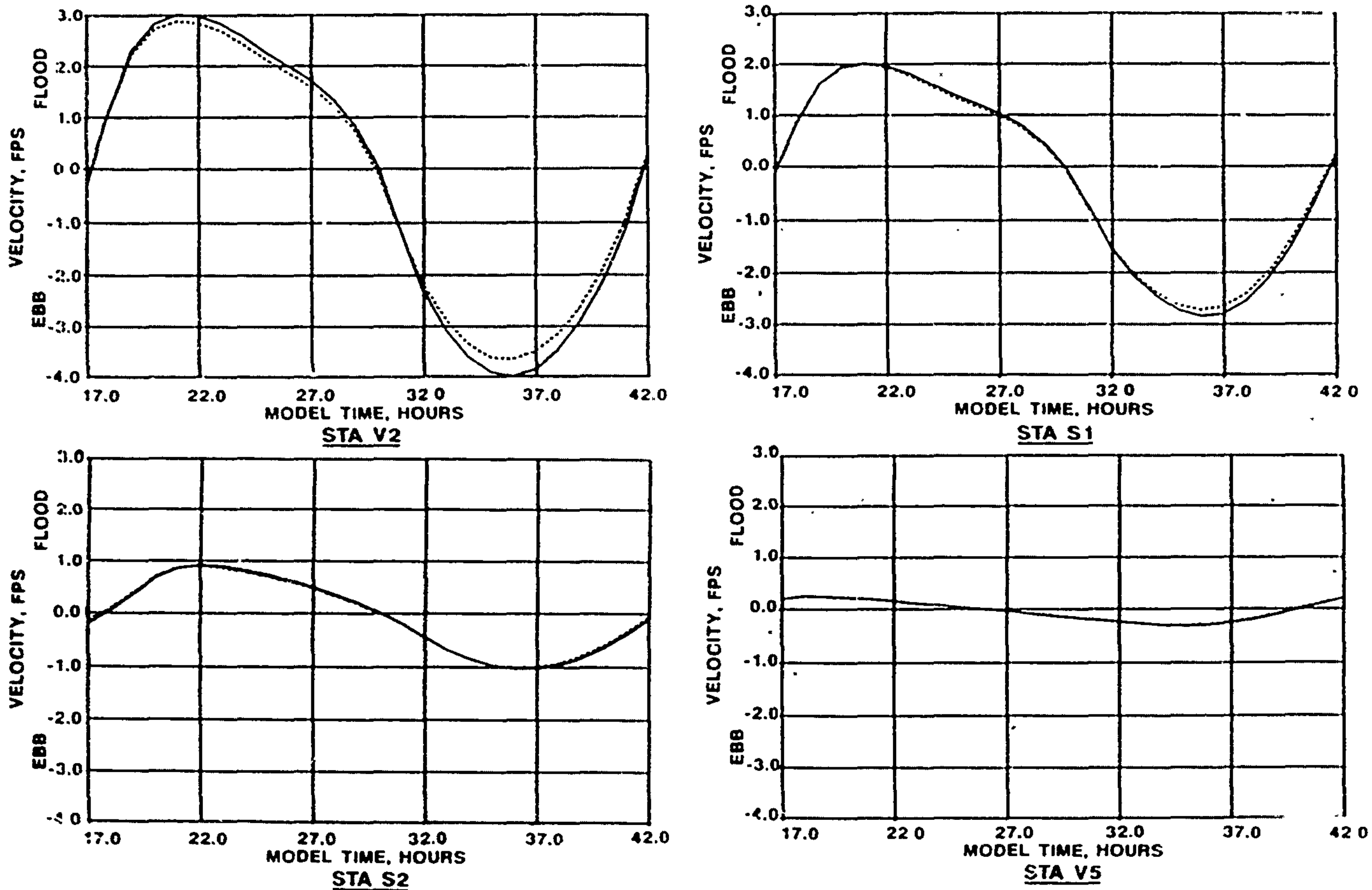


LEGEND

- – - - – WU FORMULA
- - - - - NO WIND
- ——— VERIFICATION FORMULA

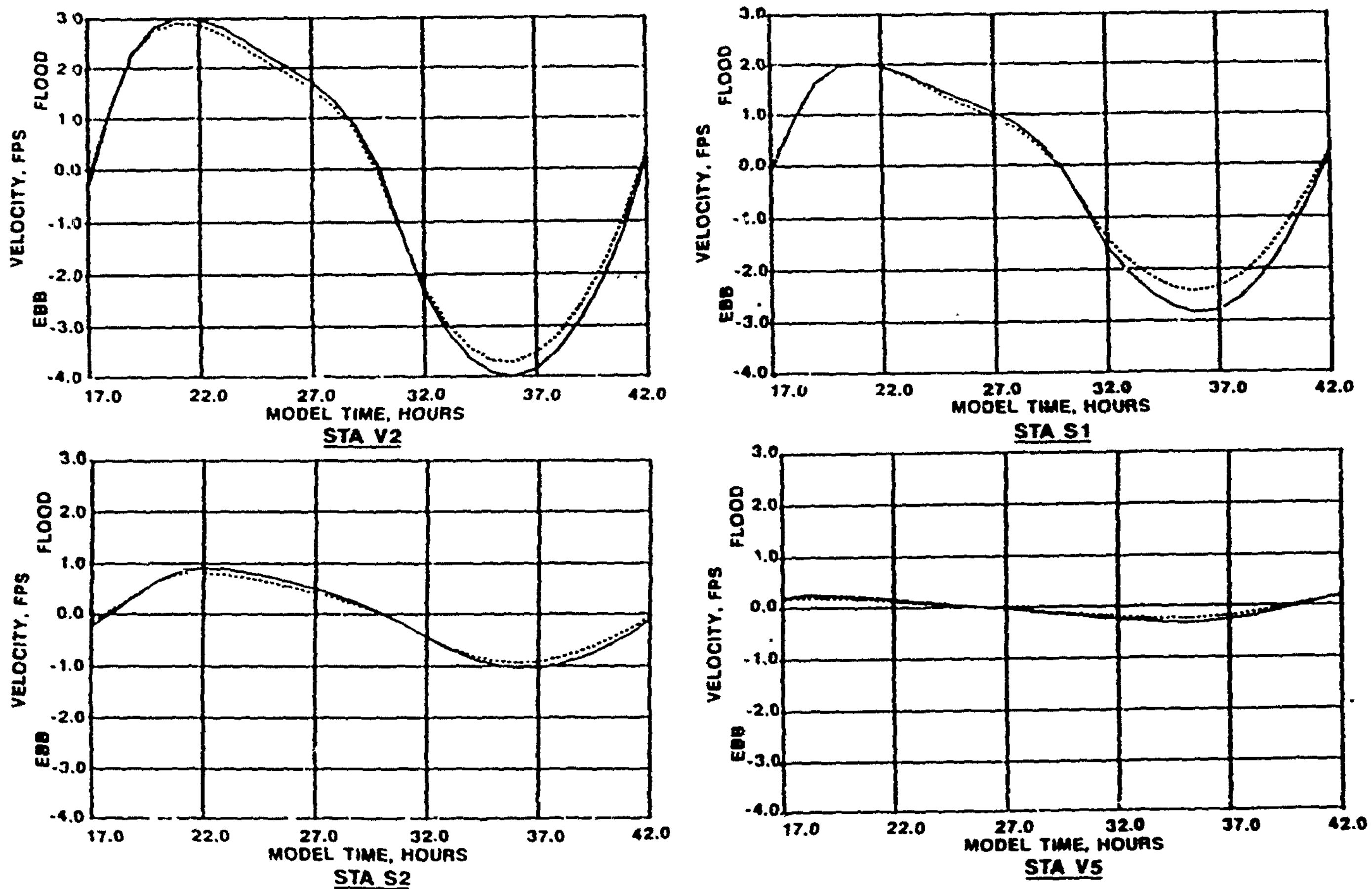
RMA-2V SENSITIVITY TEST
WIND DRAG COEFFICIENT
STA V2, V4, T3, T4

PLATE 6

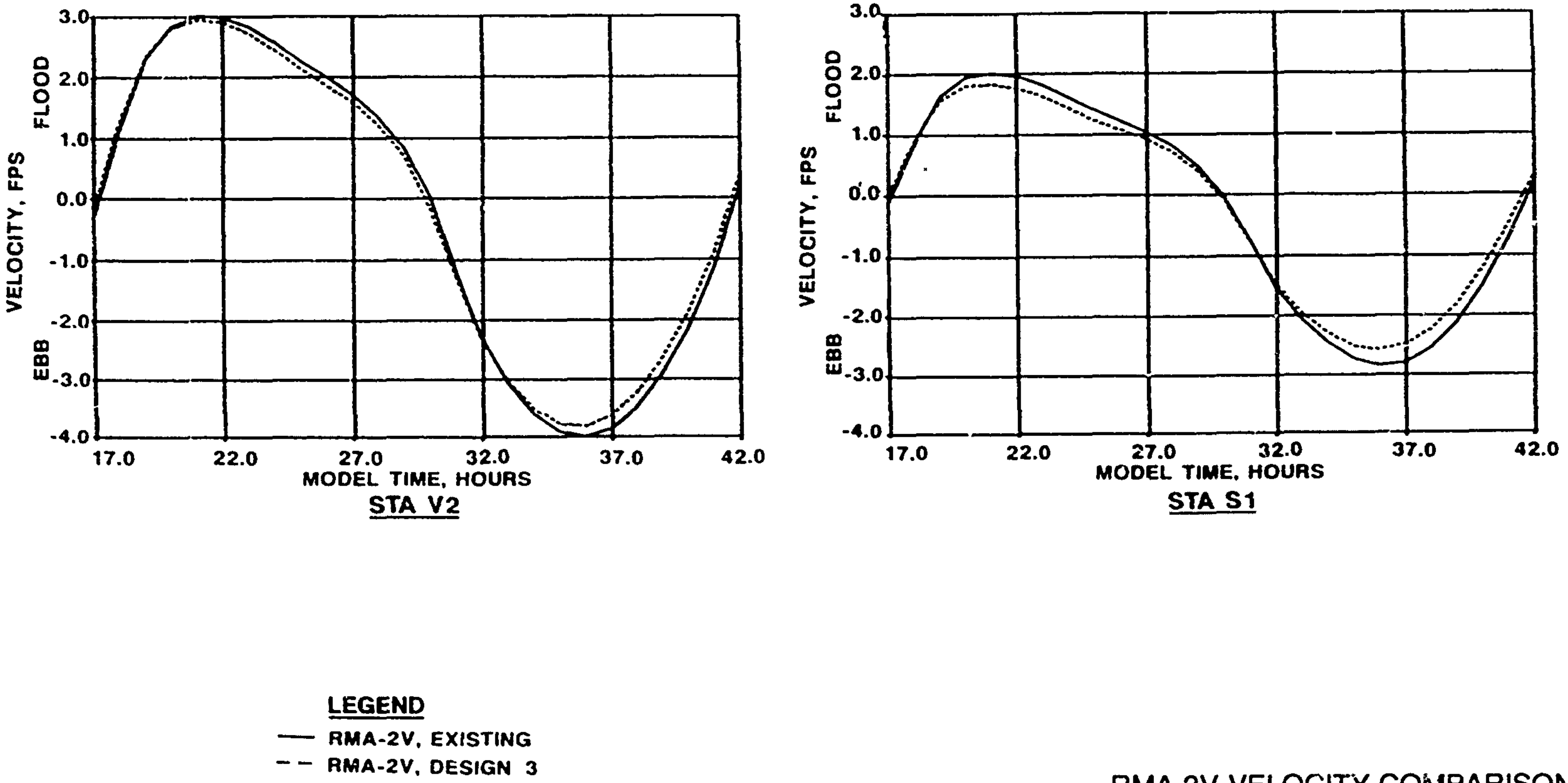


LEGEND
— RMA-2V, EXISTING
- - RMA-2V, DESIGN 1

RMA-2V VELOCITY COMPARISON
EXISTING VERSUS DESIGN 1
SPRING TIDE, VARIABLE WIND
STA V2, S1, S2, V5



RMA-2V VELOCITY COMPARISON
EXISTING VERSUS DESIGN 2
SPRING TIDE, VARIABLE WIND
STA V2, S1, S2, V5



RMA-2V VELOCITY COMPARISON
EXISTING VERSUS DESIGN 3
SPRING TIDE, VARIABLE WIND
STA V2, S1

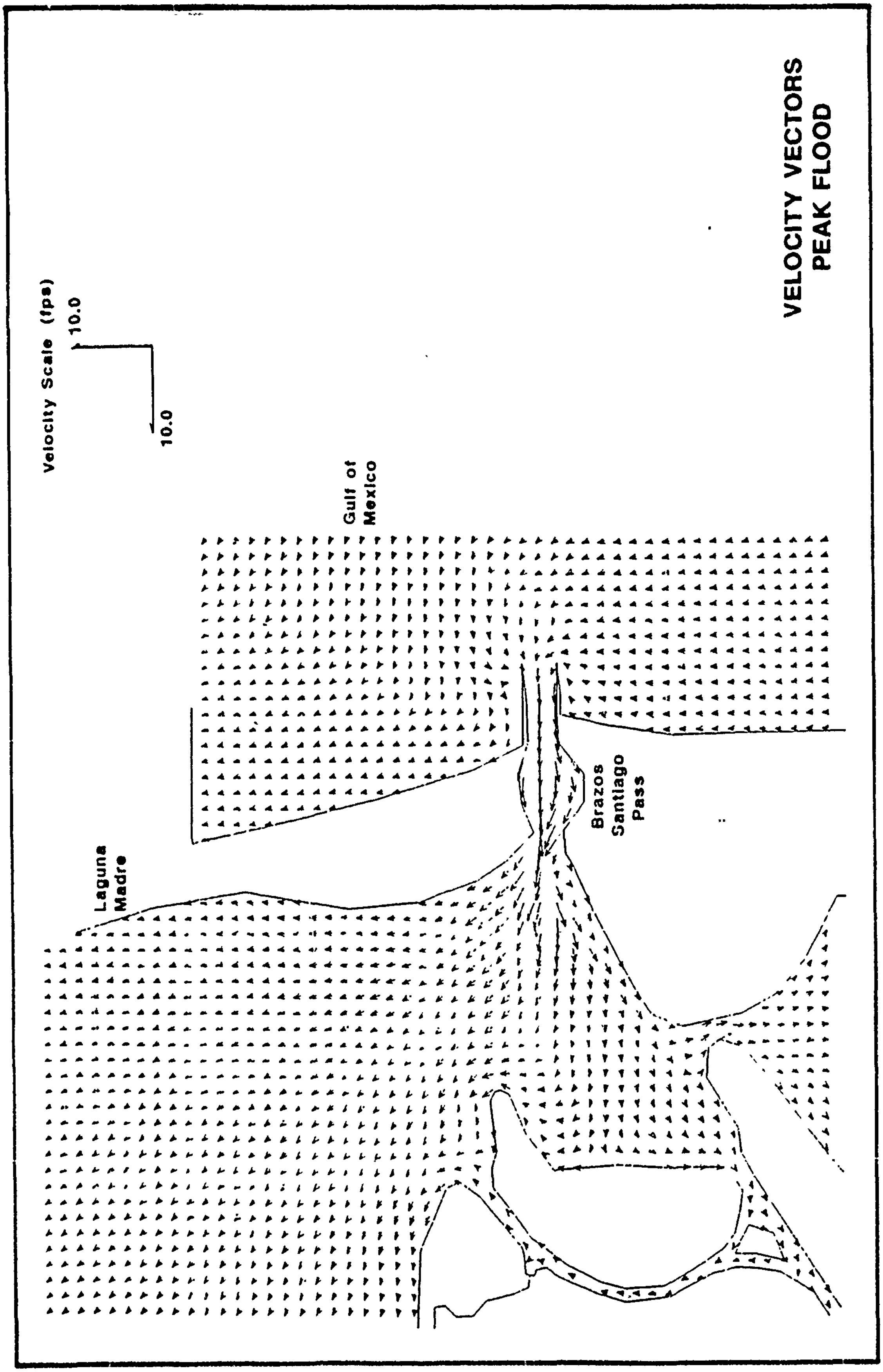

VELOCITY VECTORS
PEAK FLOOD
Velocity Scale (fps)
10.0
10.0
Gulf of
Mexico
Laguna
Madre
Brazos
Santiago
Pass

PLATE 10

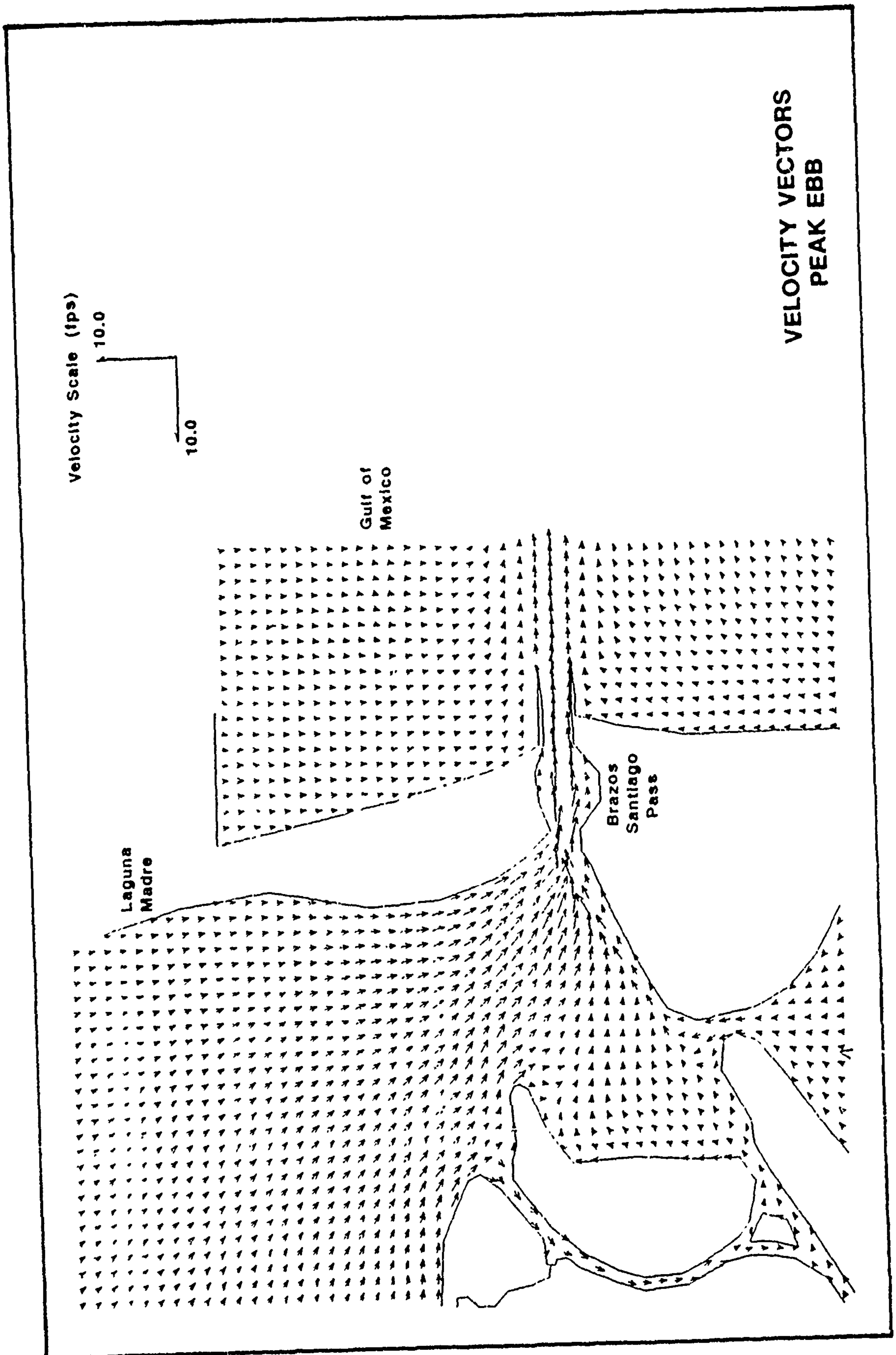

VELOCITY VECTORS
PEAK EBB
Velocity Scale (fps)
10.0
10.0
Gulf of
Mexico
Laguna
Madre
Brazos
Santiago
Pass

PLATE 11

APPENDIX A: THE TABS-2 SYSTEM

1. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydrodynamics, sedimentation, and transport problems in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure A1. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, sediment erosion, transport and deposition, the resulting bed surface elevations, and the feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact on sedimentation of project designs and to determine the impact of project designs on salinity and on the stream system. The system is described in detail by Thomas and McAnally (1985).

2. The three basic components of the system are as follows:

a. "A Two-Dimensional Model for Free Surface Flows," RMA-2V.

b. "Sediment Transport in Unsteady 2-Dimensional Flows, Horizontal Plane," STUDH (not used in this study).

c. "Two-Dimensional Finite Element Program for Water Quality," RMA-4 (not used in this study).

3. RMA-2V is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with Manning's equation and eddy viscosity coefficients are used to define the turbulent losses. A velocity form of the basic equation is used with side boundaries treated as either slip or static. The model automatically recognizes dry elements and corrects the mesh accordingly. Boundary conditions may be water-surface elevations, velocities, or discharges and may occur inside the mesh as well as along the edges.

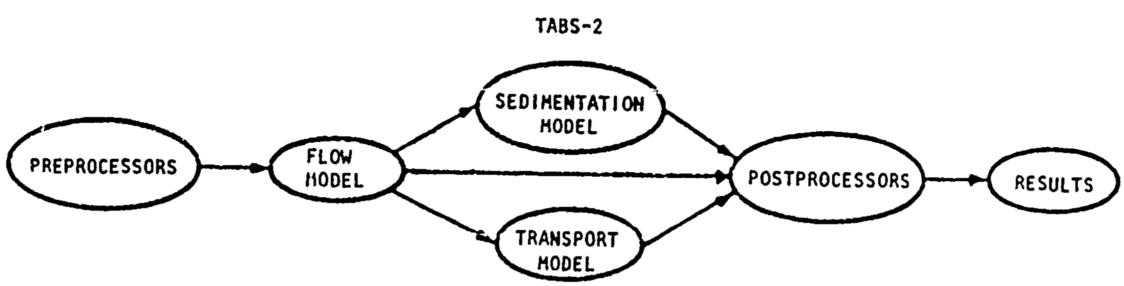


Figure A1. TABS-2 schematic

4. The sedimentation model, STUDH, solves the convection-diffusion equation with bed source terms. These terms are structured for either sand or cohesive sediments. The Ackers-White (1973) procedure is used to calculate a sediment transport potential for the sands from which the actual transport is calculated based on availability. Clay erosion is based on work by Partheniades (1962) and Ariathurai and the deposition of clay utilizes Krone's equations (Ariathurai, MacArthur, and Krone 1977). Deposited material forms layers, as shown in Figure A2, and bookkeeping allows up to 10 layers at each node for maintaining separate material types, deposit thickness, and age. The code uses the same mesh as RMA-2V.

5. Salinity calculations, RMA-4, are made with a form of the convective-diffusion equation which has general source-sink terms. Up to seven conservative substances or substances requiring a decay term can be routed. The code uses the same mesh as RMA-2V.

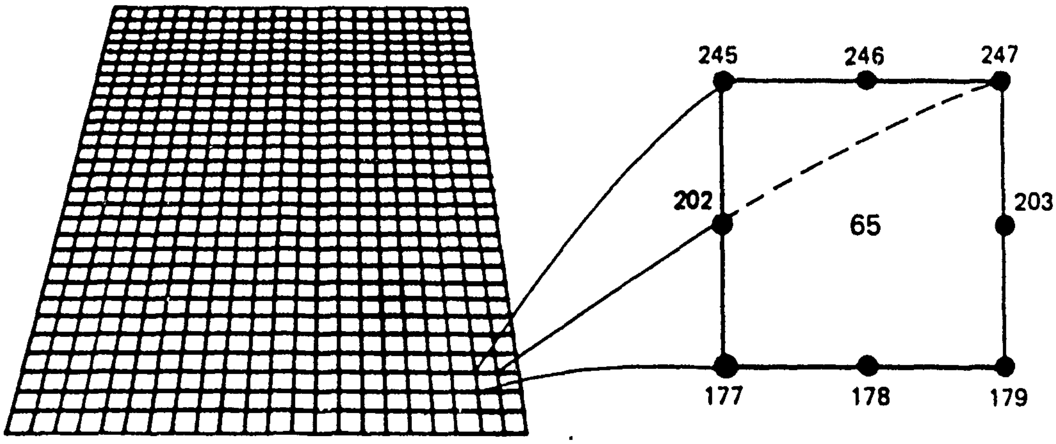
6. Each of these generalized computer codes can be used as a standalone program, but to facilitate the preparation of input data and to aid in analyzing results, a family of utility programs was developed for the following purposes:

a. Digitizing
b. Mesh generation
c. Spatial data management
d. Graphical output
e. Output analysis
f. File management
g. Interfaces
h. Job control language

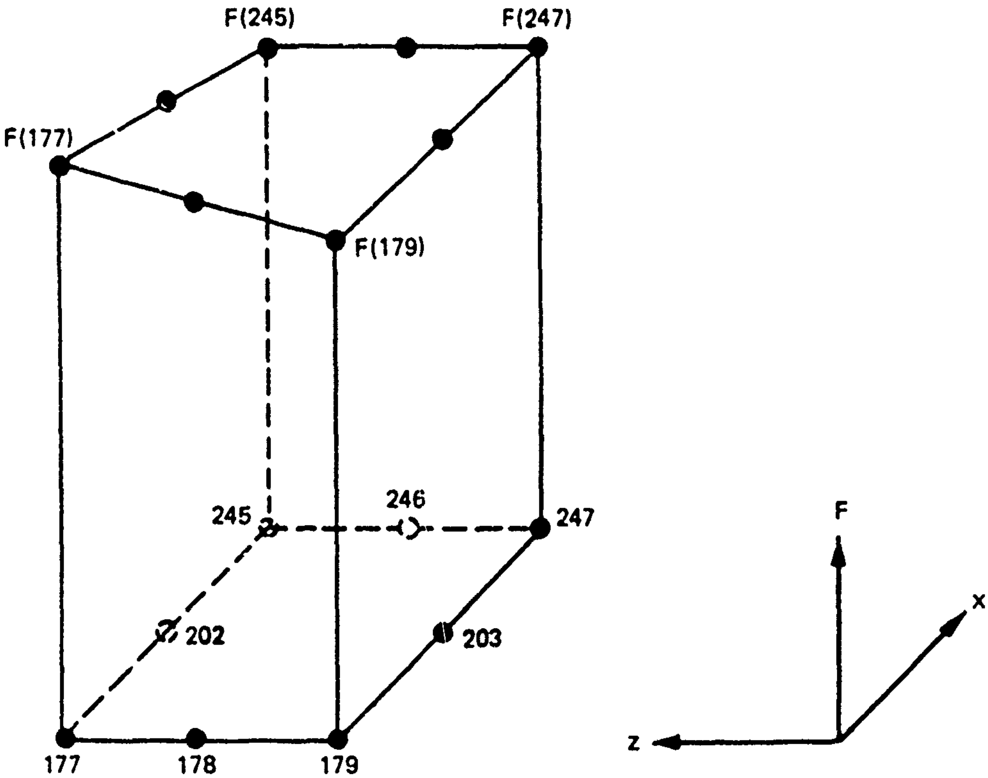
Finite Element Modeling

7. The TABS-2 numerical models used in this effort employ the finite element method to solve the governing equations. To help those who are unfamiliar with the method to better understand this report, a brief description of the method is given here.

8. The finite element method approximates a solution to equations by dividing the area of interest into smaller subareas, which are called elements. The dependent variables (e.g., water-surface elevations and sediment



a. Eight nodes define each element



b. Linear interpolation function

Figure A2. Two-dimensional finite element mesh concentrations) are approximated over each element by continuous functions which interpolate in terms of unknown point (node) values of the variables. An error, defined as the deviation of the approximation solution from the correct solution, is minimized. Then, when boundary conditions are imposed, a set of solvable simultaneous equations is created. The solution is continuous over the area of interest.

9. In one-dimensional problems, elements are line segments. In two-dimensional problems, the elements are polygons, usually either triangles or quadrilaterals. Nodes are located on the edges of elements and occasionally inside the elements. The interpolating functions may be linear or higher order polynomials. Figure A2 illustrates a quadrilateral element with eight nodes and a linear solution surface where F is the interpolating function.

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

The Hydrodynamic Model, RMA-2V

Applications

11. This program is designed for far-field problems in which vertical accelerations are negligible and the velocity vectors at a node generally point in the same directions over the entire depth of the water column at any instant of time. It expects a homogeneous fluid with a free surface. Both steady and unsteady state problems can be analyzed. A surface wind stress can be imposed.

12. The program has been applied to calculate flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; and general flow patterns in rivers, reservoirs, and estuaries.

Limitations

13. This program is not designed for near-field problems where flow-structure interactions (such as vortices, vibrations, or vertical accelerations) are of interest. Areas of vertically stratified flow are beyond this program's capability unless it is used in a hybrid modeling approach. It is two-dimensional in the horizontal plane, and zones where the bottom current is in a different direction from the surface current must be analyzed with considerable subjective judgement regarding long-term energy considerations. It is a free-surface calculation for subcritical flow problems.

Governing equations

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

$$h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - \frac{h}{\rho} \left(\epsilon_{xx} \frac{\partial^2 u}{\partial x^2} + \epsilon_{xy} \frac{\partial^2 u}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right)$$

$$+ \frac{gun^2}{\left(1.486h^{1/6}\right)^2} \left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \cos \psi - 2h\omega v \sin \phi = 0 \qquad \text{(A1)}$$

$$h \frac{\partial v}{\partial t} + hu \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} - \frac{h}{\rho} \left(\epsilon_{yx} \frac{\partial^2 v}{\partial x^2} + \epsilon_{yy} \frac{\partial^2 v}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y} \right)$$

$$+ \frac{gvn^2}{\left(1.486h^{1/6}\right)^2} \left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \sin \psi + 2\omega hu \sin \phi = 0 \qquad \text{(A2)}$$

$$\frac{\partial h}{\partial t} + h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \qquad \text{(A3)}$$

where

h = depth

u, v = velocities in the Cartesian directions

x, y, t = Cartesian coordinates and time

ρ = density

ϵ = eddy viscosity coefficient, for xx = normal direction on x-axis surface; yy = normal direction on y-axis surface; xy and yx = shear direction on each surface

g = acceleration due to gravity

a = elevation of bottom

n = Manning's n value

1.486 = conversion from SI (metric) to non-SI units

ζ = empirical wind shear coefficient

V_a = wind speed

ψ = wind direction

ω = rate of earth's angular rotation

ϕ = local latitude

15. Equations A1, A2, and A3 are solved by the finite element method using Galerkin weighted residuals. The elements may be either quadrilaterals or triangles and may have curved (parabolic) sides. The shape functions are quadratic for flow and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form

$$f(t) = f(0) + at + bt^c \qquad t_0 \leq t < t \tag{A4}$$

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

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

17. The code RMA-2V is based on the earlier version RMA-2 (Norton and King 1977) but differs from it in several ways. It is formulated in terms of velocity (v) instead of unit discharge (vh), which improves some aspects of the code's behavior; it permits drying and wetting of areas within the grid;

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and it permits specification of turbulent exchange coefficients in directions other than along the x- and z-axes. For a more complete description, see Appendix F of Thomas and McAnally (1985).