Technical Report HL-92-7
July 1995

US Army Corps of Engineers
Waterways Experiment Station

Houston-Galveston Navigation Channels, Texas Project

Report 3
Three-Dimensional Hydrodynamic Model Verification

by R. C. Berger, R. T. McAdory, W. D. Martin, J. H. Schmidt

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Report 3 of a series

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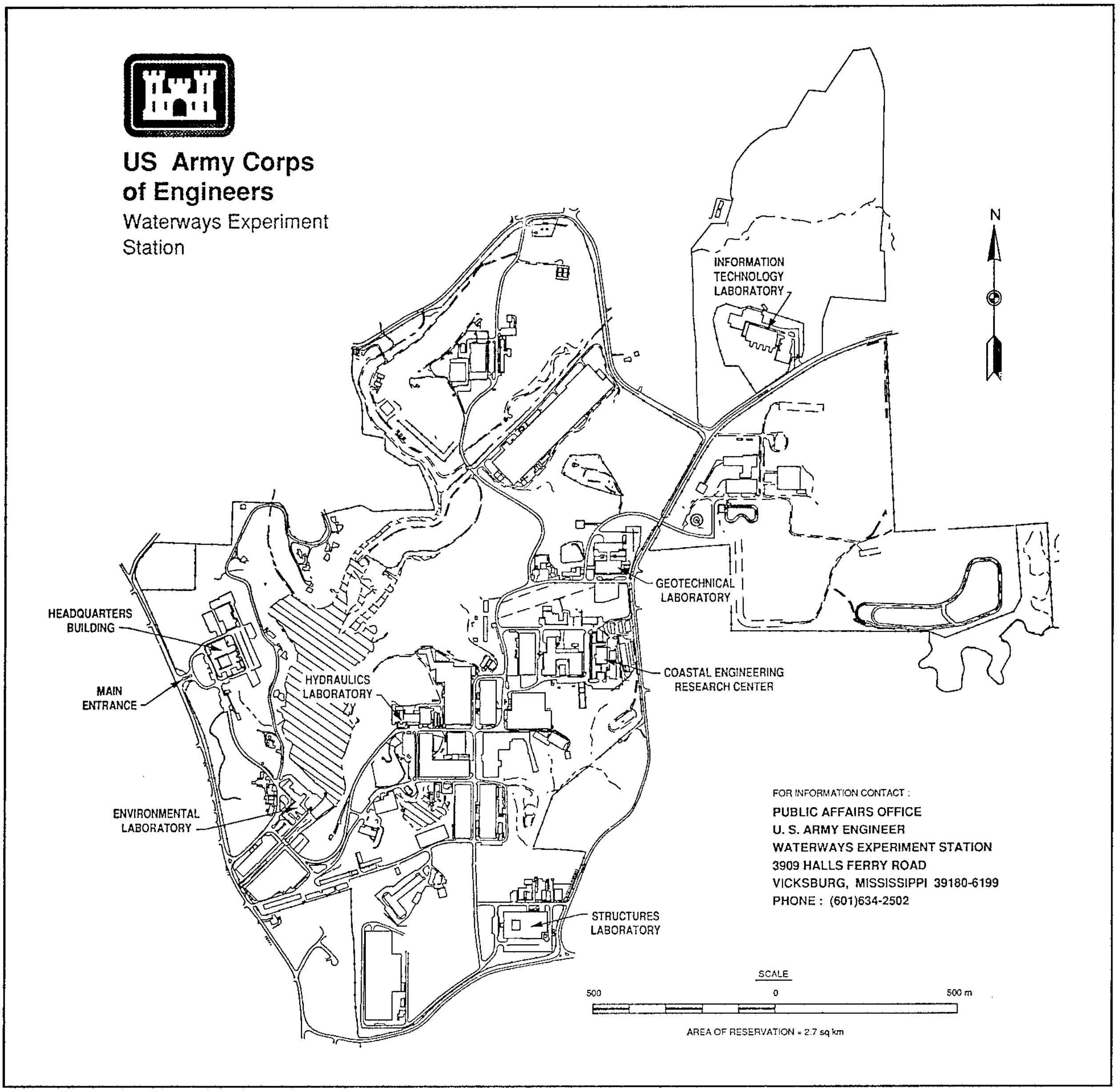

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Contents

Preface

The three-dimensional numerical model verification of hydrodynamic conditions for the Houston-Galveston Navigation Channels Project, Texas, as documented in this report, was performed for the U.S. Army Engineer District, Galveston. Galveston District personnel participating in the study were Mr. Mike Kieslich, Life Cycle Project Manager; Mr. Martin Howland, Study Manager; and Mr. Ed Reindl, Engineering Division, point of contact.

This is Report 3 of a series. Report 1 describes the data collection, Report 2 presents the two-dimensional numerical modeling of hydrodynamics for the navigation study, and Report 4 presents the three-dimensional numerical modeling of hydrodynamics and salinity testing program.

The study was conducted in the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period December 1990 to March 1994 under the direction of Messrs. F. A. Herrmann, Jr., Director, HL; R. A. Sager, Assistant Director, HL; and W. H. McAnally, Jr., Chief, Estuaries Division (ED), HL. Mr. W. D. Martin, Chief, Estuarine Engineering Branch (EEB), ED, was Project Manager.

This work was performed and the report prepared by Dr. R. C. Berger, ED; Dr. R. T. McAdory, EEB; Mr. W. D. Martin, EEB, and Mr. J. H. Schmidt, EEB. Much of the data manipulation, plotting and daily computer operations on this project were performed by Mr. Jay Hardy and Mr. Lenwaski Campbell, ED, and Ms. Cassandra Gaines, EEB.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
feet	0.3048	meters
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

1 Introduction

Background

In the 19th century, Galveston Bay existed as an immense, shallow estuary accessible to light-draft vessels. The study area is shown in Figure 1. Conditions then, as today, created a fertile environment for shell and fin fish. Areas of the bay, such as Red Fish Reef, were, according to verbal reports, so shallow that during low tides cattle could be driven across the bay. Subsequently, as the Texas Gulf Coast developed, channels were constructed to provide access to Galveston, Texas City, and Houston, TX, for increasingly deeper draft vessels.

The U.S. Army Engineer District, Galveston, in conjunction with the study sponsors, the Ports of Houston and Galveston, propose to deepen the existing navigation channels. Specifically the Houston Ship Channel is to be deepened to 45 ft[1] and widened to 530 ft. The Galveston Channel is to be deepened to 45 ft and widened to 450 ft.

A memorandum dated January 8, 1990, from the Chief of Engineers to the Secretary of the Army established a commitment by the U.S. Army Corps of Engineers (USACE) to incorporate several recommendations or actions concerning the proposed Houston-Galveston Navigation Channel project. Among these recommendations were the following items:

a. Conduct ship simulation modeling to refine proposed channel widths.

b. Use a state-of-the-art model of hydrodynamics and salinity to assist in refining estimates of project-induced changes to the circulation patterns and salinity regime of Galveston Bay, and to assist in the identification of beneficial uses of dredged material.

c. Refine evaluation of project-induced environmental impacts, including those to shrimp and fin fish, and develop adequate, feasible mitigation, if required.

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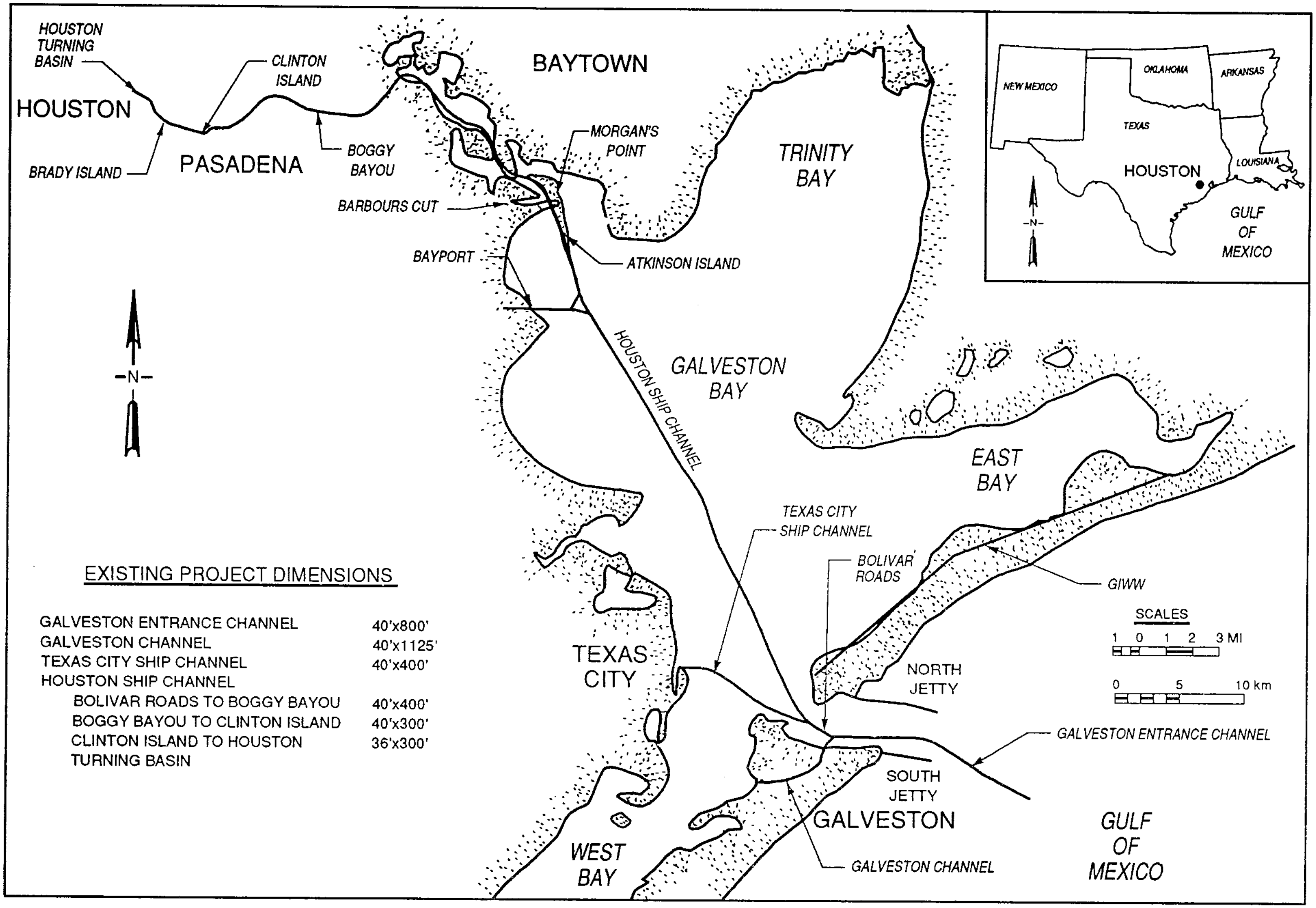
[1] A table of factors for converting non-SI units of measurement to SI units is found on page v.



EXISTING PROJECT DIMENSIONS

GALVESTON ENTRANCE CHANNEL	40'x800'
GALVESTON CHANNEL	40'x1125'
TEXAS CITY SHIP CHANNEL	40'x400'
HOUSTON SHIP CHANNEL	
BOLIVAR ROADS TO BOGGY BAYOU	40'x400'
BOGGY BAYOU TO CLINTON ISLAND	40'x300'
CLINTON ISLAND TO HOUSTON TURNING BASIN	36'x300'

Figure 1. Location map of Houston-Glaveston Navigation Channel Project

d. Continue to coordinate project studies with concerned Federal and State resource agencies.

The ship simulation was conducted previously (Lin 1992; Hewlett 1994; and Webb and Daggett 1994). This report deals with item *b*. In order to achieve these recommendations, a fully verified three-dimensional (3-D) hydrodynamic model would be required. This report outlines the model development and verification to actual conditions that existed during the period July 1990 to January 1991. This is report 3 of a series of four reports describing field and numerical modeling conducted in support of these commitments. The purpose of this report is to describe validation of the 3-D circulation and salinity model.

Objective

The objective of this investigation is to produce a 3-D hydrodynamic and salinity model validation sufficient to demonstrate the model capability to estimate project-induced change. Since the primary interest of the overall study is the impact of the project upon oyster production, the measure of validation sufficiency is based upon the needs of the oyster model.

2 The Model

Background

The numerical model of Galveston Bay is actually the combination of three components:

a. The analytic equations. These equations describe the physics of the system. These are basically conservation of water and salt mass and momentum equations (Newton's Second Law). Within these equations the most important simplification is the hydrostatic assumption. This is a common assumption in open channel flow equations, and means that vertical accelerations are assumed to be negligible.

b. The computer program. This code contains the discretized description of these basic equations. Care must be taken in the development of the program so that these discrete equations converge to the analytic equations as the resolution is increased. The program also includes representations for boundary forcing functions, such as the tide, wind, bed shear stresses, freshwater inflow, and Gulf salinity. There are also the descriptions of the vertical turbulence and the density/salinity relationship.

c. The discrete representation. This is the node and element topology (the mesh), bathymetric representation, actual boundary data.

This collection is the Galveston Bay model.

The task of modeling Galveston Bay hydrodynamics and salinity regimes in three dimensions for long periods of simulation with several different geometries requires use of a sophisticated numerical code. Several codes were considered before choosing RMA10-WES. These codes can be generally classified as either structured or unstructured and explicit or implicit. A structured code expects a certain inherent order for the mesh topology. This allows relatively fast solving of the algebraic equations, but it is difficult to generate useful grids for complex geometries. An unstructured code, often a finite element approach, allows tremendous flexibility in matching geometric features; and the generation of numerical meshes is fast, even in these complex regions. This flexibility, however, can come at computational expense.

The terms "explicit" and "implicit" imply, respectively, a trade-off between computational speed per time-step but with a short time-step, versus a slower computational speed per time-step without a severe time-step length restriction. The RMA10-WES is unstructured and implicit. This mode is a better approach to handle a complex estuary in which many plan meshes are to be developed and which needs high resolution in regions of large velocity gradients. The need for multiple meshes in a complex geometry rules out a structured approach, and the large velocity where the resolution must be high poses too severe a penalty for the explicit approach.

Model Description

The RMA10-WES code is a Galerkin-based finite element solution to simulate 3-D unsteady open channel flow. The model was originally developed by Dr. Ian King of Resource Management Associates (King 1988) and extensively modified by the staff of the Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station (WES). The code represents 3-D hydrodynamics using conservation of fluid mass, horizontal momentum, and salinity/temperature transport equations. As is typical of shallow-water models, the vertical accelerations are assumed to be negligible (the hydrostatic assumption), which allows the vertical velocity to be calculated through mass conservation. In the interest of computational efficiency the code also simulates one-dimensional (1-D) and two-dimensional (2-D) flow as well as transitions between 1-, 2-, and 3-D. The code is implicit in time and resolves the nonlinearities via Newton-Raphson iteration.

In a 3-D model, or a laterally integrated 2-D model, the vertical extent of the domain is not known until the depth is calculated, and of course, one cannot make the calculations until the computational mesh is developed. This apparent impasse is avoided by transforming the domain at each time-step to a mesh grid. The particular transformation used maps the water surface to a constant elevation, the bed is unchanged, and all elevations in between are stretched proportionally. The mesh representing existing conditions is shown in plan view in Figure 2. The mesh consisted of 6,190 surface nodes in 1,996 surface elements and 12,270 nodes in 5,112 total 3-D elements. The model was configured as largely 3-D within the bay except for the West Bay west of the causeway (Figure 3). The 3-D portion consisted of one layer in the shallow areas of the bay and up to three layers (seven nodes) in the channel.

The salinity/density relationship in the model is based on Pritchard (1980). The vertical turbulence is a combination of the Mellor-Yamada Level II (Mellor and Yamada 1982; Adams and Weatherly 1981) and Henderson-Sellers (1984). The wind stress is a quadratic relationship using the specific coefficients developed by Wu (1980). The effect of wind waves on vertical

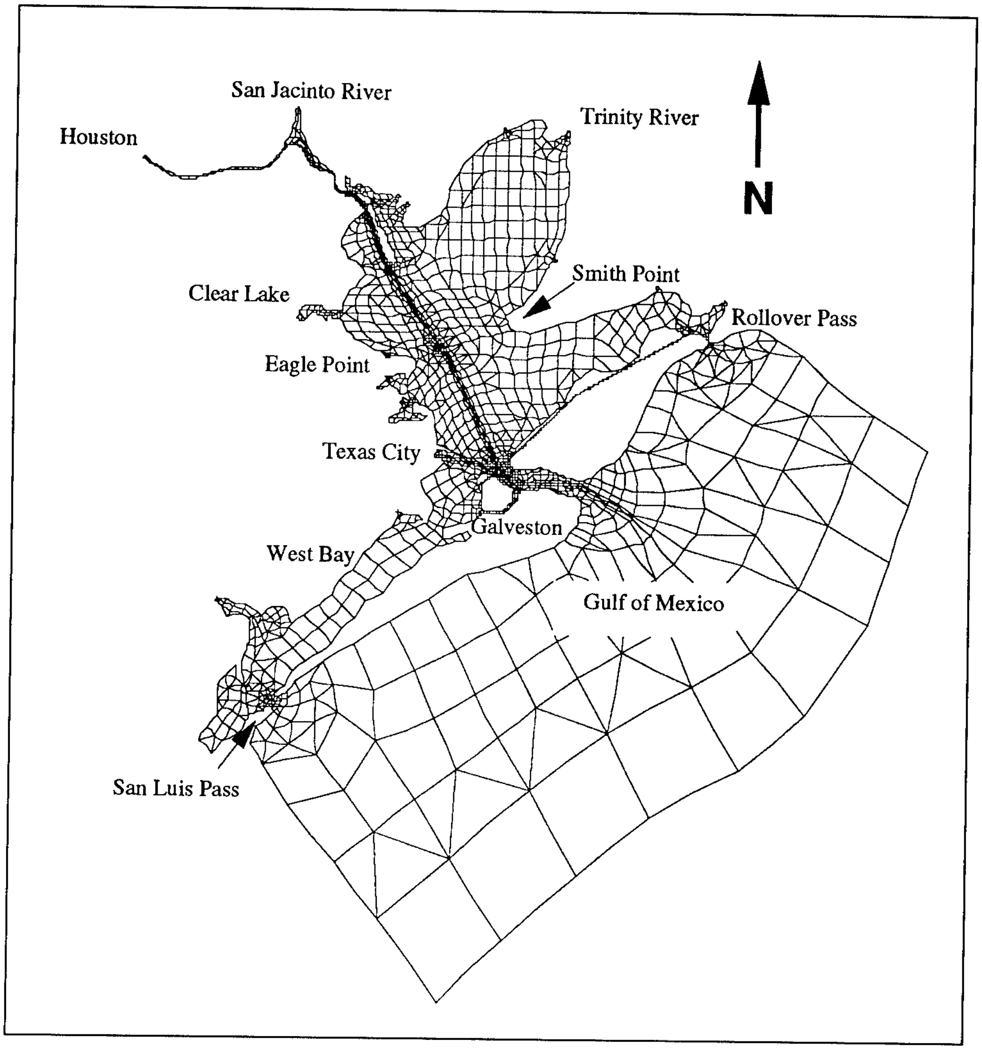


Figure 2. Mesh representing existing conditions

mixing is simulated in the manner of the numerical model CE-QUAL-W2 (U.S. Army Engineer Waterways Experiment Station 1986).

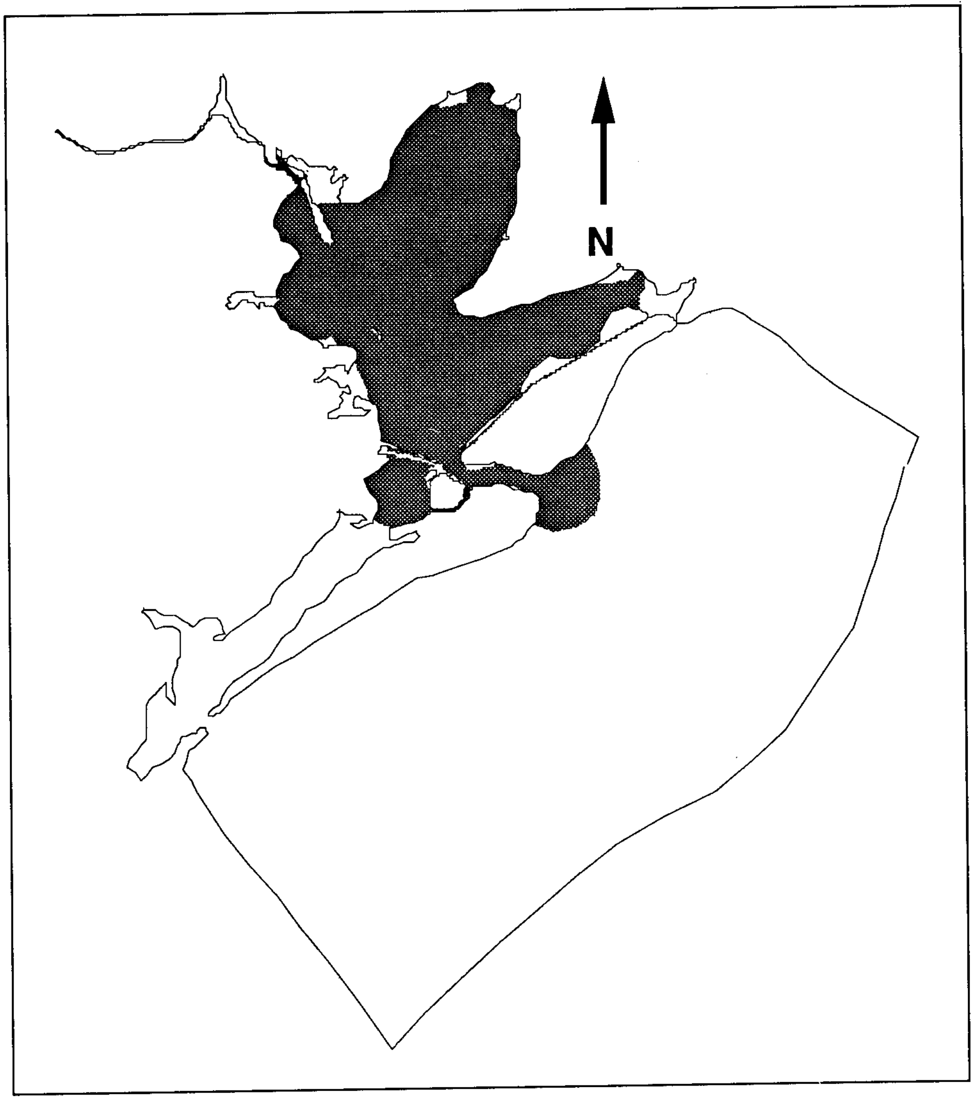


Figure 3. 2-D and 3-D portions of the model. Gray areas are 3-D

3 Model Validation

Data

The period of field data collection was from 19 July 1990 to 15 January 1991. The bulk of these data was collected by moored salinity and velocity meters, as well as tide gauges mounted throughout the system. Within this 6-month time, a short-duration intense field data collection was conducted on 19-20 July 1990. These data included velocity and salinity measurements over depth at five ranges along the navigation channel. Complete details of the field collection may be found in Fagerburg et al. (1994).

Boundary files were constructed with the best available observed data. The data used to drive the model tide were the National Ocean Service/National Oceanic and Atmospheric Administration Station 877-1510 Pleasure Pier tide gauge data shifted forward 1.31 hr to account for the model boundary approximately 26 miles offshore from Pleasure Pier. The actual data were filtered to remove signals of periods less than 3 hr. The salinity at the boundary was estimated by using the published averages supplied by Cochrane and Kelly (1986). Figure 4 presents these data as the solid line composed of long-term monthly average salinity values. The discrete points are actual measurements made during the year of the field data collection, 1990. The WES field data collection began about day 200 and continued through the year. The long-term average Pleasure Pier data of Cochrane and Kelly are not so strongly subject to local short-term dilution and so appear to be a better boundary condition data set for the WES model boundary, which is far off shore. This was the source of the model boundary salinity values. The wind data were provided by two sources. WES established a meteorological station at location S10.1 (Figure 6) for the period 19 July 1990 to 15 January 1991. The National Weather Service data at Houston International Airport were also obtained for this period. A correlation was derived between the National Weather Service and WES data so that readings at Houston International could be used in Galveston Bay. This correction was only for wind magnitude, not direction. The correlation was as follows:

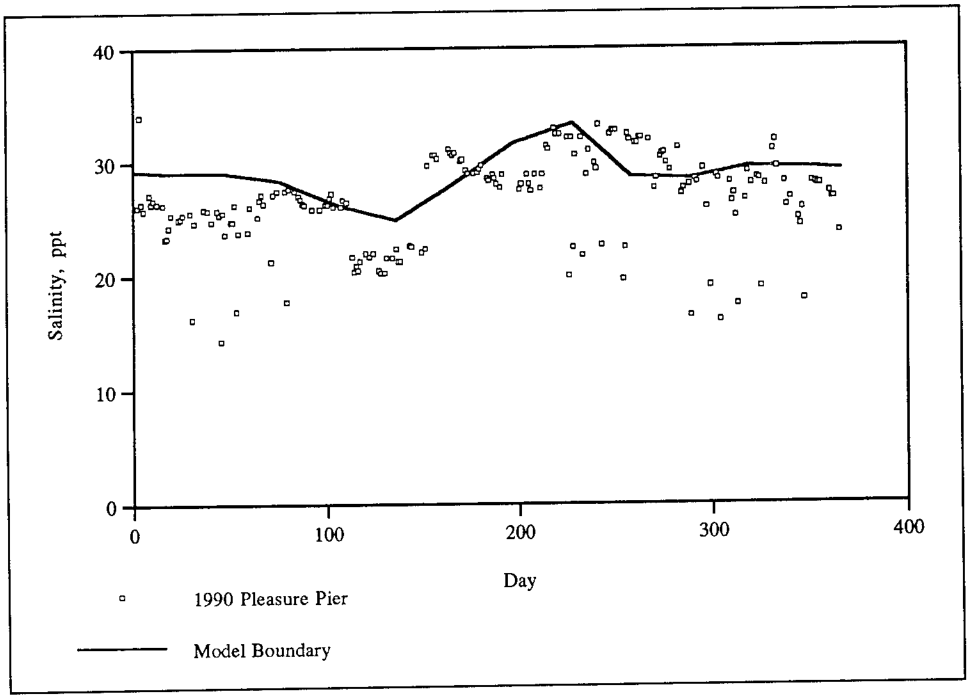


Figure 4. Comparison of model boundary and 1990 Pleasure Pier salinities

$$W_G = 0.850 W_A + 5.92 \tag{1}$$

where

W_G = wind speed, mph, in Galveston Bay
W_A = wind speed, mph, at Houston Intercontinental Airport

These data in turn were used to calculate the shear stress at the water surface τ_s using the expression:

$$\tau_s = C \rho_a W^2 \tag{2}$$

C is described by Wu's (1980) relationship and W is wind speed, mph, and ρ_a is air density

$$C = (0.8 + 0.0656W) \times 10^{-3} \tag{3}$$

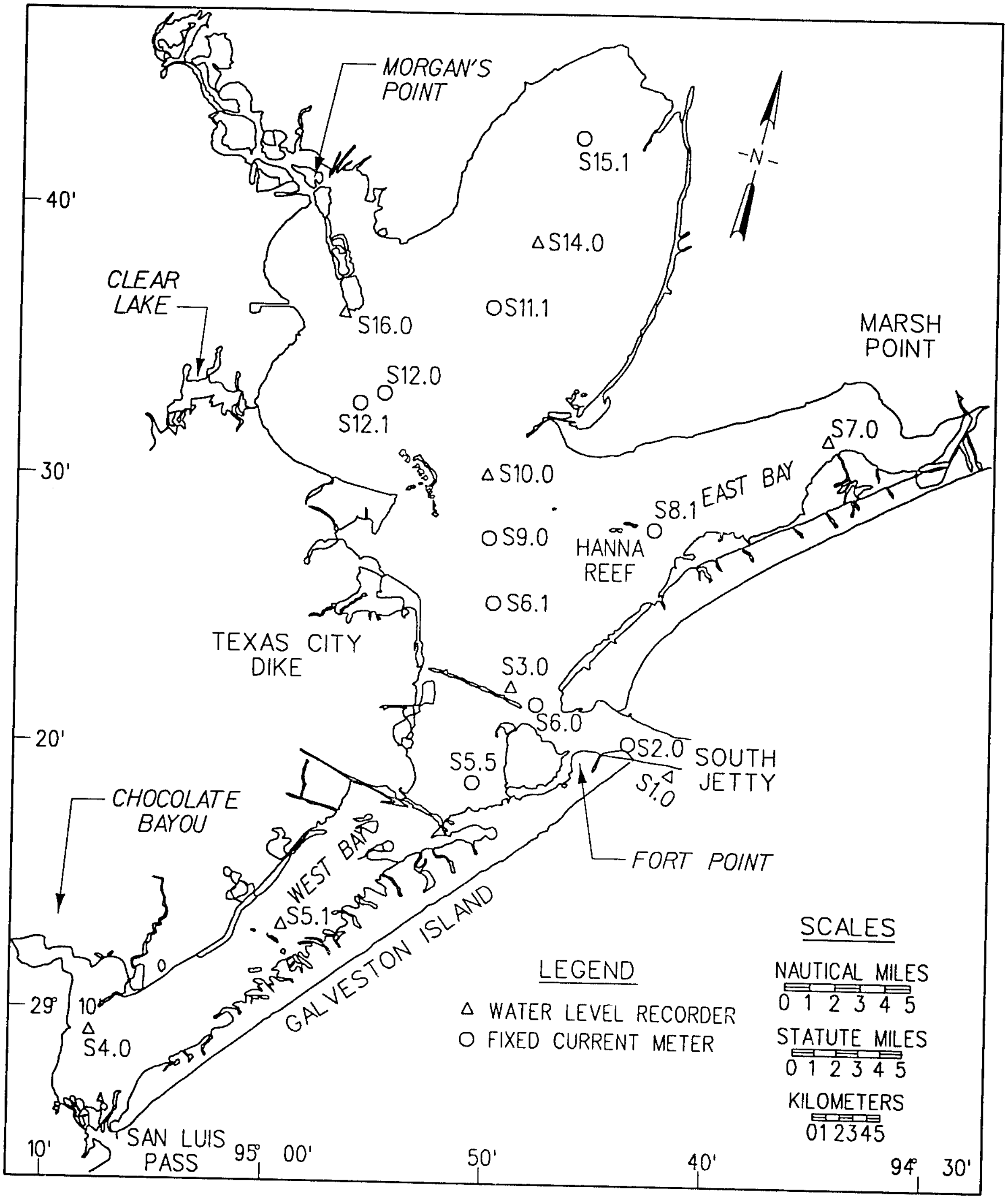


Figure 5. Basic long-term survey data collection equipment locations. (Stations S1.0, S2.0, S5.5, S6.0, S6.1, S8.1, S9.0, S11.1, S12.0 and S15.1 record salinity as well.)

Validation Approach

A two-stage model validation process was used. In the first stage, adjustments were made in the bed roughness of the estuary, since this parameter has a significant uncertainty. The normal process is to first adjust the roughness to match the tides, after which point one then considers the velocity and salinity results. The first stage consisted of comparison to the brief period around the time of the intensive over-the-side data collection, 19-20 July 1990.

In the second stage, the model was run and compared with the long-term prototype data set with no additional adjustment. The second stage, used to verify that the model behaves as the prototype with no additional adjustment, covered the time from 19 July 1990 to 15 January 1991. A very high flow for the Trinity Basin rivers occurred in June, so the data include significant salinity variations as the system moved from flood to near drought conditions during the 6 months data were collected. Modeling such a period of drastic change was a very rigorous test of the model's capability.

The purpose of the validation process is to determine the ability of the model to reproduce the prototype system. It is important that the parameters that are critical to the ecosystem be reliably reproduced. In order to answer the basic question of whether any further adjustment should be made to the model, the sensitivity of the model to the boundary conditions of Gulf salinity and freshwater inflow was evaluated. This, coupled with an estimate of the uncertainty in boundary condition values, was used to determine that the reproduction of salinity is within the uncertainty of the boundary conditions. Having insured this, no further model adjustments would be useful for the purpose of this study. The second basic question is whether the degree of agreement is sufficient for the environmental decisions.

The model behavior was also compared to historical observations and field reports to check the overall ability of the model to not only reproduce measured values at discreet points, but also to qualitatively reproduce hydrodynamic and salinity results over large areas of the bay. This comparison was concerned with the model behavior rather than measured values. The ability of the model to reproduce known phenomena and demonstrate causes of known phenomena greatly strengthens the credibility of the model.

Estuarine model adjustments proceed in order from tides, velocity, and then salinity. The initial comparison was based on the prototype data from the period of the intense over-the-side survey conducted on 19-20 July 1990. The adjustment parameter was the bed roughness as this is the parameter about which the uncertainty is the greatest. In the tidal adjustment phase the roughness for fairly large general regions and bed types is set so that model tide results compare well with the prototype observations. The further adjustments for velocity consist of some additional finer scale roughness changes so that the distribution of velocity may be slightly improved, but the overall roughness is the same as that from the tidal adjustment phase. If the salinity values then do not match, the usual problems are inaccurate freshwater inflow or the initial startup causing error since the salinity in and of itself is only indirectly affected by roughness. In the 3-D model the bed friction is a function of Manning's n; and since it uses bed velocity instead of cross-section averaged velocity, the value of n is somewhat higher than data from literature might indicate. The bulk of the 2-D regions and shallow bay was modeled using Manning's roughness of 0.023 while the channel was about 0.038.

Verification

This section discusses the comparison of model and prototype through a series of plates for water surface elevation, current velocity, and salinity over a specific time period. These plates depict the period August-November displayed in 1,000-hour segments. Long-term salinity comparisons are important for this study. Therefore these plates show the complete verification period salinities on a single plot for each station, as well as the 1,000-hour segment plots. The locations of the stations are shown in Figures 5, 6, and 7.

These plates include all model/prototype comparison data. The reader must be aware that the field meters are subject to a variety of interferences and can occasionally give bad readings. These are usually more frequently seen in the salinity and velocity readings than in the water surface elevations. None of the raw data values have been eliminated in the plots though problems with meter drift or other erratic behavior have been noted.

Water surface elevation comparisons are shown for the entire 6 months for stations 1.0, 3.0, 5.0, 7.0, 10.0, 14.0 and 16.0 in 1,000-hr segments in Plates 1-15. The station 1 plots show a gage failure for hours 4900-5700, and the plot could only interpolate a straight line through this gap. An example of another type of field data anomaly is shown by the spikes at hours 4800, 4900, and 5250 for station 10. These are caused by boat waves, localized storms, or gage error. The model is not intended to reproduce such events. These comparisons represent the model's ability to reproduce water surface elevations driven by the astronomical tides as well as the wind fields.

Direct comparisons for currents are shown in Plates 16-45. Here positive is taken as landward-directed flow and negative is ebb or gulfward flow. These velocity meters are moored at a fixed elevation. There are at most two recording heights: roughly middepth and three-quarters depth. A suffix of *m* or *t* following the station number indicates middepth or three-quarters depth, respectively. The model and field data show two dominant periods, one diurnal and the other fortnightly. The velocity comparisons are generally quite good near the entrance and near the upstream region of the model, but magnitudes are somewhat low just inside the entrance, station 6.0, i.e. at stations 6.1 and 9.0.

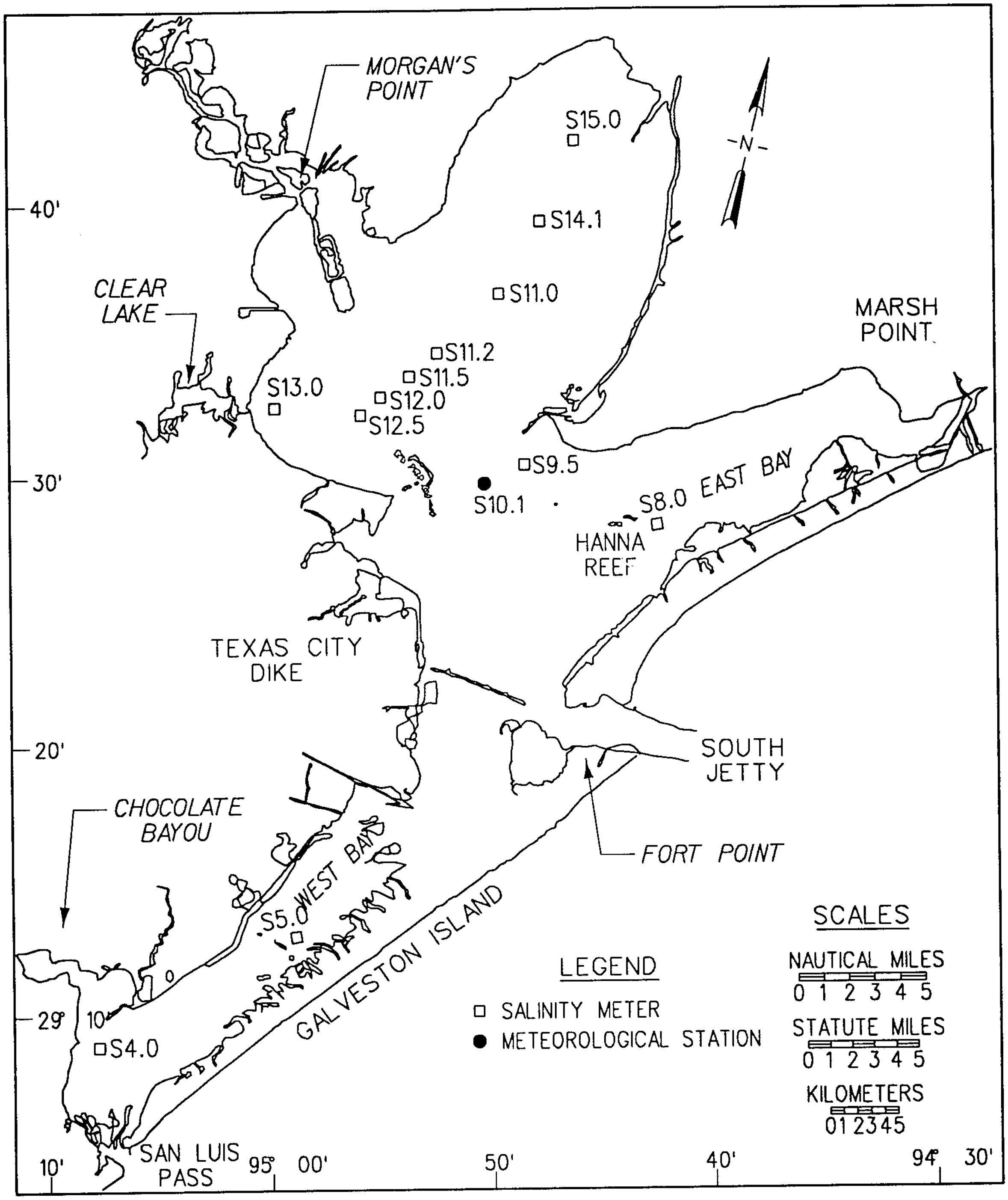


Figure 6. Supplementary long-term data collection equipment locations

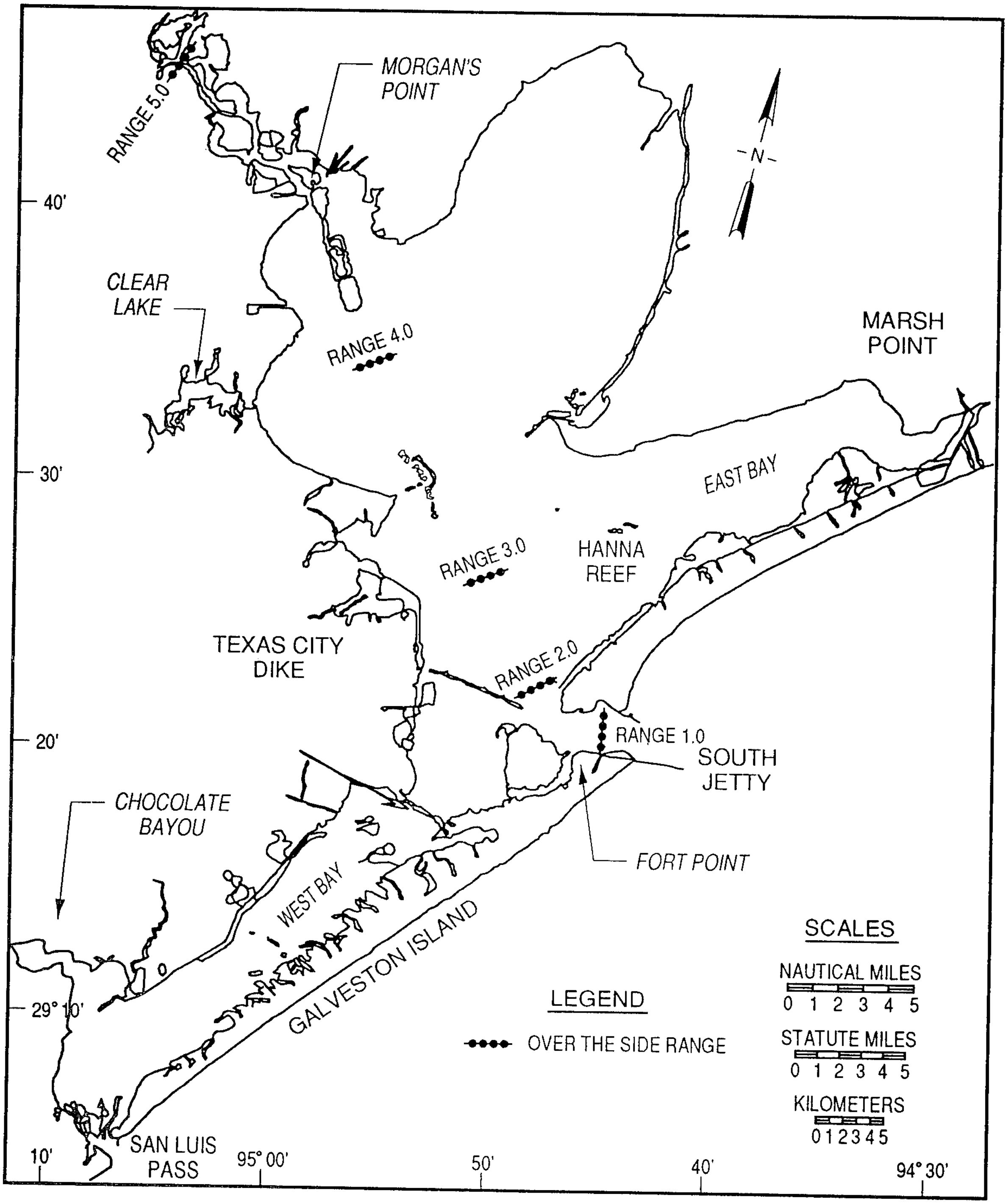


Figure 7. Intensive survey data collection boat ranges

Plates 46-93 are the salinity histories of model and prototype.[1] Plates 46-53 show the complete history of model to prototype comparisons, with the field data represented by discrete measurements made during meter servicing. This allows one to see the ability of the model to track large salinity variations. Detailed data are shown on Plates 54-93 in 1,000-hr increments for August-January. An additional set of symbols is also shown to indicate a discrete sample retrieved during servicing of the moored meter. These are particularly important in the near-Gulf, or high-salinity, stations. Here biological fouling is a significant problem causing meter drift. When the meters were serviced, they were cleaned and the problem temporarily fixed. Their readings abruptly returned to closely match these discrete samples. The drift is generally quite obvious: hours greater than 6000 for station 1.0, hours 6400-7600 on station 2.0m, near hour 7000 at station 6.1m, and hours 6100-6500 on station 6.1t are examples of readings obtained from a fouled meter.

The stations in West Bay (stations 4.0 and 5.0) show the model salinity to be low compared with prototype early in the simulation but tending to converge over time. This appears to be an artifact of the low energy (high residence time) of West Bay. If the initial salinity field is in error, it takes a long time for the model to "heal" this region. Throughout most of the bay system the comparison is very good.

The current velocity over the ranges that were taken during the over-the-side survey are shown in Plates 94-109, and the corresponding salinity values are Plates 110-125. These data were collected at each range along a transect that crossed the channel from west to east. The planned layout was for station A on each range to be in the shallows west of the channel and similarly station D to be east of the channel. Stations B and C were located at the bottom edges of the channel. However, at ranges 3 and 4 all stations were placed outside the channel to avoid ship traffic.

Discussion

Model sensitivity

The comparison of the model to prototype undertaken in a verification needs to be judged based upon knowledge of associated uncertainties. If the uncertainties in the prototype data, boundary conditions, and driving forces have an impact larger than the differences between the model and prototype, then there is certainly no need to go back and make additional adjustments and undertake another verification. The uncertainties in the prototype data are difficult to ascertain without a great deal more sampling. There are also some uncertainties generated by driving forces such as the wind field that are difficult to quantify. Two of the most prominent items that affect salinity

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[1] Salinity meter data were combined for the meter pairs S8.0 and S8.1, S11.0 and S11.1, S15.0 and S15.1.

distribution in the bay are the freshwater inflow and the Gulf salinity boundary. The variability or sensitivity of the model to variations in these boundary conditions can be defined. In summation there are many sources of uncertainty in the model study. Only two of these sources in are considered in this analysis. Therefore, the calculated uncertainty is lower than the true uncertainty, but serves as a useful indicator.

Figure 4 shows the Pleasure Pier monthly average salinities (using 15 years of data) as the solid line and the individual readings taken in 1990 as squares. A straight line connection is shown between average points for each month. The verification begins about day 200. The Gulf boundary for verification as well as the subsequent testing uses the 15-year average value. Though the 15-year average line is an imperfect fit, it is not apparent that any other single monthly average line would be superior. From this record it was estimated that a probable uncertainty is at least 2 ppt; i.e., the true value has a 50% probability of being within ±2 ppt of the average curve.

In the case of freshwater inflow it was estimated that the probable uncertainty was about 10 percent. It is likely that 10 percent may be low since variations of 10 percent are considered appropriate for a good discharge measurement. In this case there is a significant ungauged area, so these freshwater discharge values are probably somewhat less accurate. However, for the sake of the sensitivity analysis, this value is sufficient.

Galveston Bay system sensitivity to these parameters can vary throughout the year. For example, during flood conditions, all of Trinity Bay is fresh water (salinity of 0 ppt), and so a 10 percent variation in freshwater inflow will have minimal to no effect on salinity there. An important period of time for the oyster model (low freshwater inflow, high salinities) occurs in later summer, so this is the time frame considered.

The freshwater sensitivity was evaluated using low-, medium-, and high-flow runs, from which a regression analysis supplied the salinity for a 10 percent freshwater inflow change. The Gulf boundary sensitivity was evaluated by rerunning the verification period with a 2-ppt increase in the boundary salinity. The results are shown in Table 1.

The first column is the general location in the bay and the specific point used in this analysis (Figure 8). The second column is the probable uncertainty in bottom salinity due to a 10 percent decrease in freshwater inflow, and the third column is the variation in bottom salinity due to a 2-ppt variation in the Gulf boundary. The fourth column is a combination of these two (assuming these uncertainties to be independent, the vector sum of the two boundary uncertainties is appropriate).

Table 1
Model Salinity Response Due To Boundary Uncertainty

Location	Salinity Uncertainty due to 10 percent Variation in Freshwater Boundary, ppt	Salinity Uncertainty due to 2-ppt Variation in Gulf Salinity Boundary, ppt	Combined Salinity Uncertainty, ppt
Trinity Bay Point 2	1.0	1.1	1.5
Upper West Bay Point 15	0.8	1.4	1.5
Midbay Point 6	0.8	1.3	1.5
Point 9	0.6	1.0	1.2
East Bay Point 7	1.0	0.5	1.1
West Bay Point 12	0.5	1.4	1.5
Boliver Roads Point 5	0.2	1.8	1.8

Generally, the areas most upstream are more sensitive to freshwater inflow and less sensitive to the Gulf salinity boundary. Conversely, the areas near the Gulf are typically relatively insensitive to freshwater inflow variation but are strongly affected by the Gulf boundary variation. The major exception is East Bay, which is far from the freshwater sources and quite near the Gulf but sensitive to freshwater inflow (1.0 ppt variation) and fairly insensitive to the Gulf variation (0.5 ppt variation). This demonstrates that the Trinity River inflow reaches East Bay and is responsible for the depressed salinity there. The overall bay combined uncertainty is about 1.5 ppt. Therefore, if the model to prototype comparison is generally within this range, no additional adjustment is useful. The effect will be drowned by boundary uncertainty.

Quantitative comparison

In this section the model verification to the recorded prototype data is discussed. The discussion is focused upon the needs of the oyster model.

The oyster model uses the output of the 3-D hydrodynamic and salinity model. It then computes oyster production under various biological influences. A complete discussion of this model can be found in Hofmann, Powell, Klinck, and Wilson (1992). The oyster feeding is dependent upon the velocity magnitude, and the growth and mortality rates are strongly dependent upon the salinity. These data as well as the water depth (or tides) are supplied by the hydrodynamic model. Since the oyster response is slow, the long-term fluctuations in salinity are considered more important than the diurnal and semidiurnal variations. Therefore, the hydrodynamic verification discussion will consider the comparison of velocity magnitude in the form of the root

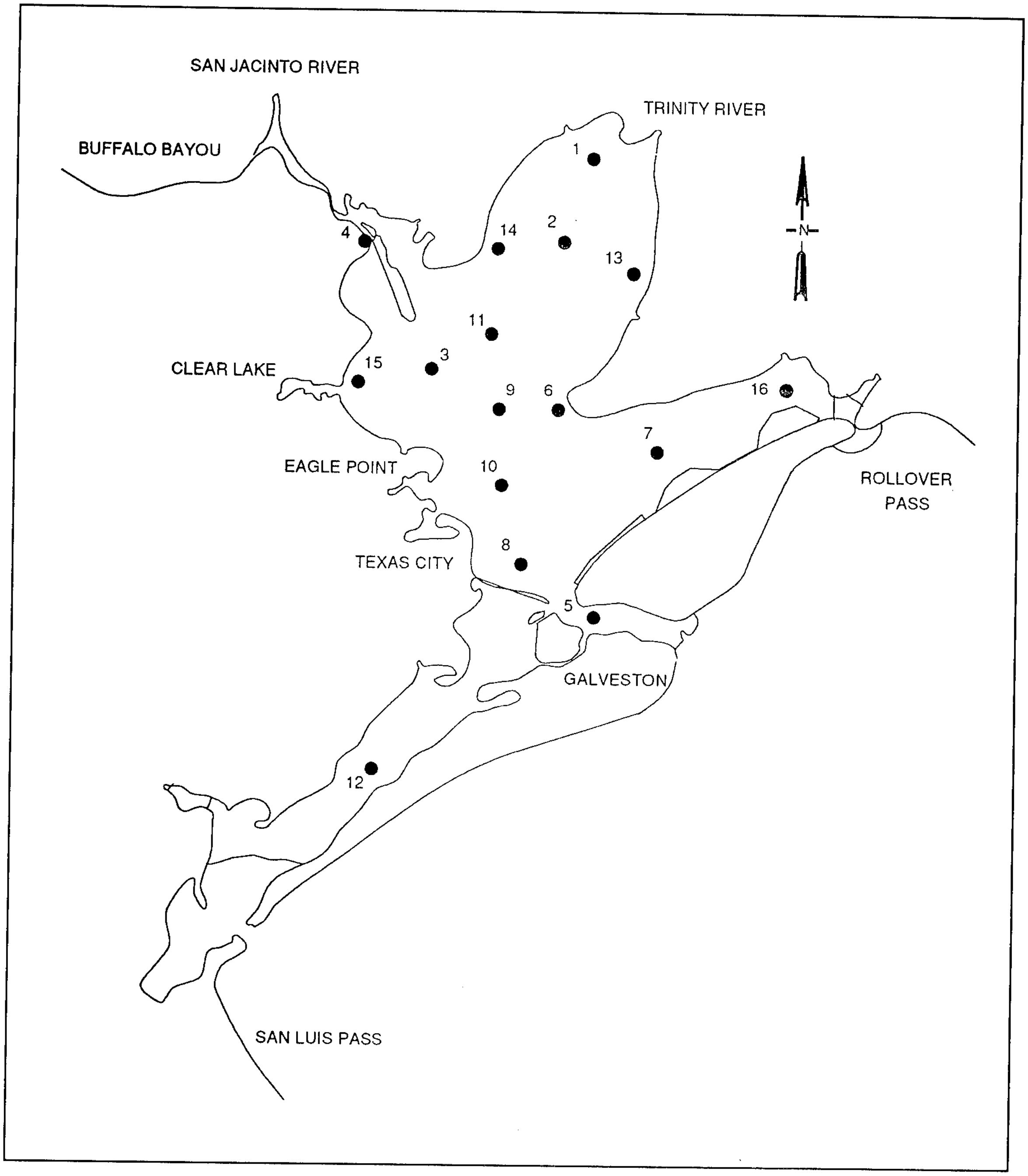

Figure 8. Location of time-series points

mean square (RMS) velocity, and the salinity verification discussion will consider the mean difference between the model and prototype, trends from the correlation coefficient, and a relative error term *d*.

A model's verification is usually judged as successful or not in a somewhat arbitrary manner. Typically, this is solely based on the model investigator's experience. Here, however, the hydrodynamic model's suitability to deliver input hydrodynamics and salinity for the oyster model can be judged based upon other input parameters used in this oyster model. For example if the regressions describing oyster growth dependence upon salinity have uncertainty that is larger than the salinity difference from model to prototype, then the hydrodynamic model should certainly be sufficient.

Tides

In order to understand the model tidal behavior, it is necessary to remove the wind-driven signal and conduct a harmonic analysis of the tidal signal. In this manner the major tidal components of amplitude and phase can be discerned. This was conducted for the stations along the navigation channel, stations S1.0, S3.0, S10.0 and S16.0 (Figure 5). The data were filtered to remove periods shorter than 3 hr and longer than 35 hr. This left the principal diurnal and semidiurnal components. Of these, the most significant prototype tidal constituent amplitudes at station S1.0 are listed in the following tabulation:

Constituent	Period, hr	Amplitude, ft
K_1	23.93	0.64
O_1	25.82	0.57
M_2	12.42	0.44
P_1	24.07	0.18

The overall amplification is computed by calculating a group amplitude as the vector sum of each constituent. Figure 9 is a plot of the tidal amplification along the channel. This is the ratio of the group amplitude at each station to that at station S1.0. The most significant drop in amplitude occurs across Bolivar Roads (mile 2). From station S1.0 to S3.0 (miles 0 and 8.1) the drop is roughly 44 percent of the tidal range. The model matches this precisely. Upstream of this point the prototype shows a slight amplification of the tide in spite of the relatively shallow bay. The model continues to drop at station S10.0 (mile 16.3) to 81 percent of prototype. The model amplitude increases at station S16.0 (mile 26.4) and is 85 percent of prototype. The amplification in the upper bay is quite likely due to local features such as the reef above station S10.0 and the estuary boundary above station S16.0. The model will generally be deeper than the prototype at these nearshore features to avoid element drying. If the amplification is local, then the overall tide range in the prototype away from these features would be lower than shown, the tidal prism would be correct in the model and the velocity and salinity distribution would match. The overall model roughness values appear reasonable and the model salinity distribution is excellent.

As further support for the model's roughness, consider the phase lag predicted by the model. Figure 10 shows the average model and prototype phase

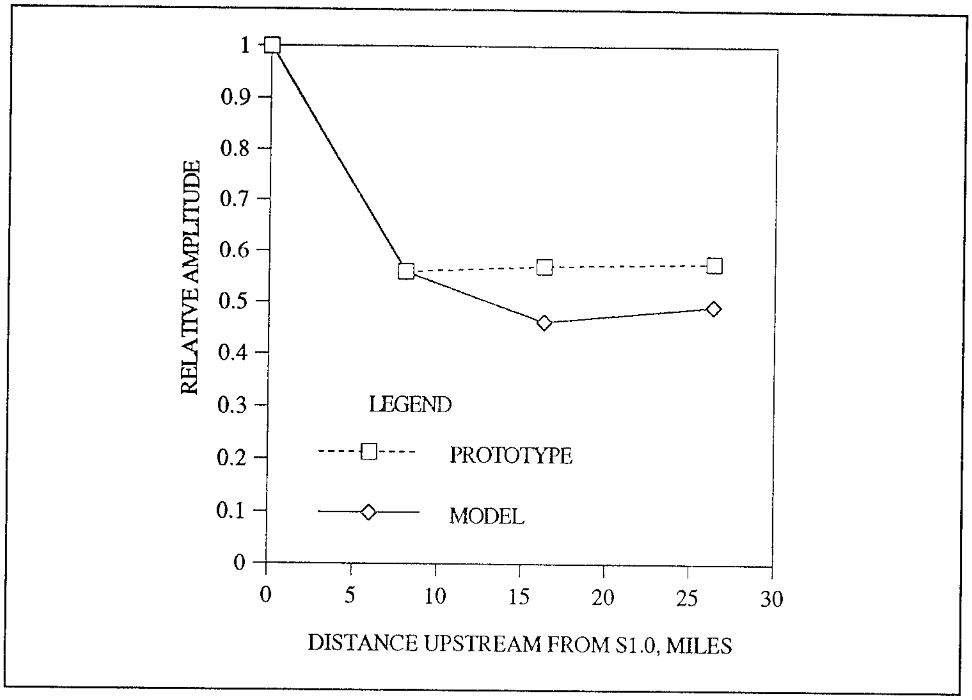

Figure 9. Model/prototype tidal amplitude comparison

lag relative to station S1.0. The average phase lag is calculated as the arithmetic average of the four major tidal constituents. At station S3.0 (mile 8.1) the model leads the prototype by 23 min; at station S10.0 (mile 16.3) the model lags the prototype by 11 min; and at station S16.0 (mile 26.4) the model leads the prototype by 7 min. Above station S10.0 the character of the tide appears to be that of a standing wave, and Gulfward of station S10.0 it is a progressive wave. The overall lag from entrance to upper bay is 6 hr, and the model is off by only 7 min. These phases are very good, indicating that the overall depths and roughness in the model are good as well, and it is likely that the discrepancy in amplification in the upper bay is due to local features.

Velocity

The key factor of interest for oyster productivity regarding velocity is the velocity magnitude. Therefore, it is useful to investigate the model's ability to reproduce velocity magnitudes compared with those of the prototype. The actual comparisons are shown in Plates 16-45. To aid in evaluation, these velocities have been summarized using RMS velocity of model and prototype as shown in Figure 11.

The stations are generally arranged from the entrance to upstream. A *t* following the station label indicates three-quarters depth (from the surface) and an *m* indicates middepth. The strongest discrepancies are at stations S2.0 and S6.1. At S2.0 the model is higher than the prototype. This is also

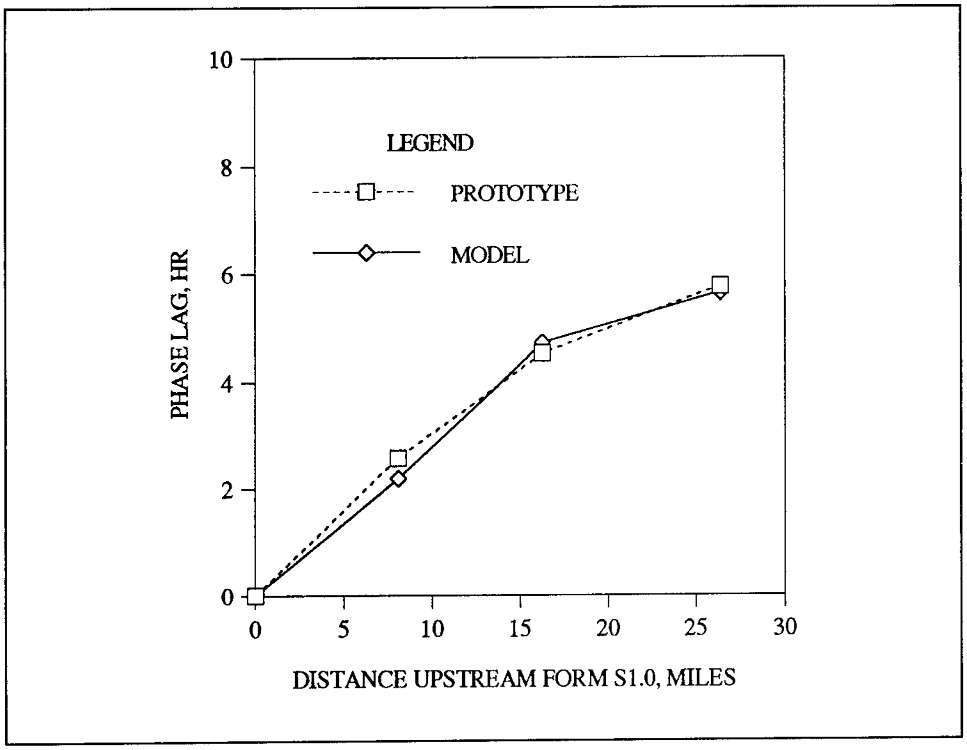

Figure 10. Comparison of model and prototype average phase lag

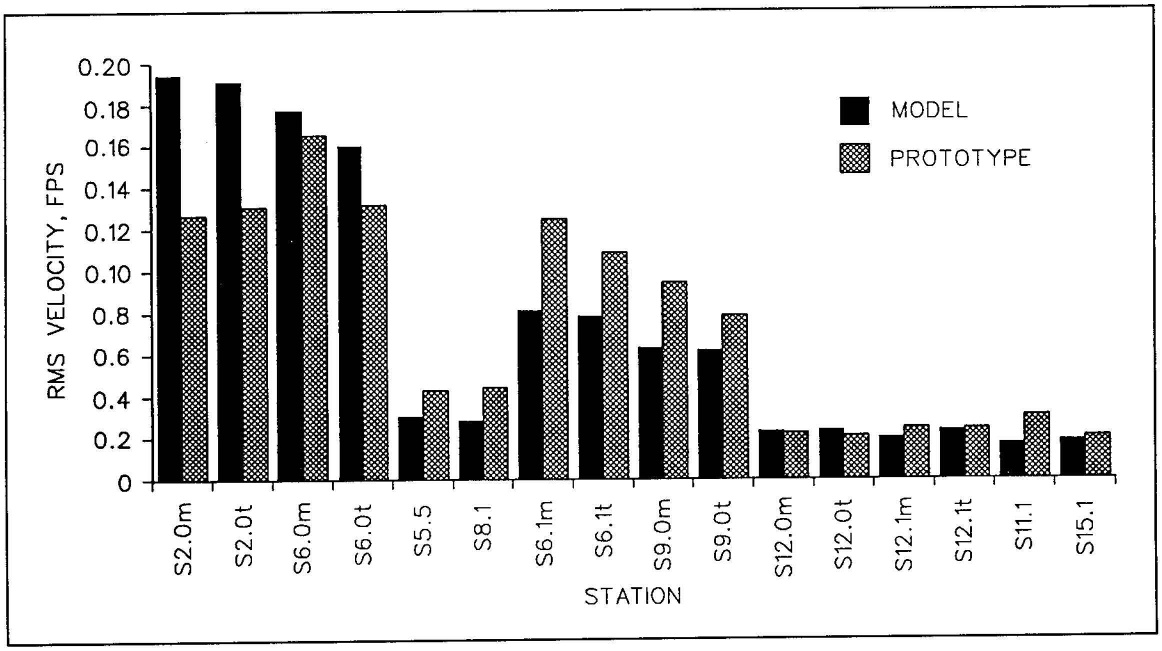

Figure 11. Comparison of RMS velocity, model and prototype

recognizable in the velocity time-history plates for this station (Plates 16, 22, 28, 34, and 40) where it is apparent that the model compares very well early in the simulation, but later the prototype readings drop substantially in magnitude. Near the end of this period the prototype records no flood direction velocity. The meter behavior is sufficiently erratic to suggest this is a problem with the prototype meter record. It may be that the location near the channel bank is the problem. The velocities are low and show almost no flood currents. At this point in the channel itself these results seem counterintuitive. For station S6.1, however, the prototype fairly consistently indicates stronger velocity than the model. Generally, over the bay the RMS velocity in the prototype varies between 0.19 and 1.65 fps; the model is from 0.17 to 1.94 fps. The ratio of model/prototype RMS overall station average is 0.93.

Salinity

The ability of the model to reproduce the long-term salinity regime of the bay is the most critical measure of the model's suitability. The period recorded begins after a very large flood on the Trinity River. The salinities in Galveston Bay are then quite low. The flows drop off and the salinity rebounds. This results in a rigorous test of the model to track salinities over a large range. Since oysters' response to salinity variation is slow, the adequacy of the salinity verification is judged principally by the model's ability to match the long-term mean and trends rather than shorter period fluctuations. For this reason statistics have been chosen that reflect these important elements. Table 2 shows the results for the long-term verification.

The first column is the station identification (Figures 5 and 6). An *m* or *t* after the station indicates middepth or three-quarters depth, respectively. Stations reported in this table are those that did not suffer from severe biological growth-induced drift. This was a problem only in the Bolivar Roads and Gulf of Mexico region. There was no editing of obviously bad prototype data such as early in the verification period at station S8.0. Such editing would improve the comparison but would call into question the decisions made in deleting bad data. On occasion the moored meter failed but the servicing continued, which reflects a longer record, in which case these handheld meter readings give a better picture of the prototype behavior and were used in this analysis for three stations (S7.0, S13.0, and S14.0). The second column is the number of hours covered in the data record. This is the difference between the first and last recorded hours. The major trends occurred during the first 3 months (2,200 hr), and so correlation coefficients and statistical agreement are calculated only for stations that include much of this period. The third column is simply the mean difference between the model and the prototype. The fourth column is the mean absolute error (MAE), or the mean of the absolute values of the differences. The fifth column is the correlation coefficient of the model in comparison to the prototype readings. This statistic indicates how well the model follows the prototype trends; however, it is an incomplete indicator in that uniform model to prototype

Table 2
Long-Term Salinity Verification Statistics

Station	Length of Record, hr	Mean Difference (model - prototype)	MAE (|model - prototype|)	Correlation	*d*
Trinity Bay					
S11.0	3389	-0.3	1.3	0.85	0.91
S11.2	1060	-1.8	2.0	---	---
S14.0[1]	3694.5	-0.4	1.1	0.97	0.98
S15.0	4137	-0.8	1.8	0.89	0.94
Upper West Bay					
S12.0m	883	0.0	2.2	---	---
S12.0t	883	-2.2	2.4	---	---
S12.1t	382	-0.6	1.4	---	---
S12.1t	1940	0.5	2.0	---	---
S13.0[1]	3459.5	-3.3	3.3	0.98	0.74
Midbay					
S6.1m	1269	-0.4	2.4	---	---
S9.0m	1419	-1.2	2.4	---	---
S9.0t	1419	-1.6	3.1	---	---
East Bay					
S7.0[1]	3454.5	-0.3	0.8	0.97	0.98
S8.0	3692	-1.4	1.9	0.81	0.85
West Bay					
S4.0	4155	-1.5	3.0	-0.45	0.10
S5.0	2318	-3.7	3.7	0.78	0.56
S5.5	1090	0.6	0.8	---	---

[1] Based on hand-held meter readings taken during servicing.

offsets are not revealed. This can be seen from the mean and MAE values. The sixth column is the statistic *d*, proposed by Willmott (1982) and Willmott et al. (1985), which is a fairly good reflection of the model's capability, indicating how well it captures trends and also predicts any shift in salinity. It is defined as follows:

$$d = 1 - \left[\frac{\Sigma \left(M_i - P_i\right)^2}{\Sigma \left(|M'_i| + |P'_i|\right)^2} \right], \quad 0 \le d \le 1 \tag{4}$$

where

M_i is the model reading i

P_i is the prototype reading i

M'_i is the model reading i minus the prototype average value

P'_i is the prototype reading i minus the prototype average value

The stations are grouped by topographic regions of the bay. It is evident that West Bay provides a much poorer comparison than the other regions. This can be substantiated by checking the salinity plots of this region (Plate 47). The differences appear to be a result of a substantially low initial salinity in the model (these were input, based upon the modeler's judgment) and the very high residence time of West Bay. It takes longer for the initial salinity estimate to be swept out of the system. After about 3 months the comparison is good.

Leaving aside the readings in West Bay, the model mean salinity is 1.0 ppt lower than the prototype. The average station MAE is 2.0 ppt. The worst station mean comparison is S13.0, which is low by 3.3 ppt. Ten of the fourteen stations had means that were within 1.5 ppt of prototype (this is approximately the precision that the sensitivity analysis attributed to the probable uncertainty in the boundary conditions). Six station means are off by less than 0.5 ppt. The comparison of the mean error shows the model to be in excellent agreement with the prototype.

The correlation coefficient is an indicator of how well the model follows the trends of the prototype. Outside of the West Bay area the correlation coefficients range between 0.81 and 0.98, with an average value of 0.91. A correlation of 1.0 indicates perfect linear correlation. Again the model is reproducing the trends of prototype salinity very well. Together the correlation coefficient and the mean give a relatively complete picture, though individually each is insufficient. The statistic *d* seems to do a better job of reflecting the model performance than does the correlation coefficient or the mean alone. This statistic combines effects of not only how well the computed value follows the actual trend, but also how close the actual values compare to those computed. The parameter *d* gives results which are more intuitive than the others. For example, S13.0 results show a mean error of 3.3 ppt but the correlation coefficient is 0.98. These together imply that the model values are parallel to the prototype but shifted by about 3 ppt. The value of *d* for S13.0 is 0.74, which, unlike the correlation coefficient, is not the best comparison found in the model. In fact, the best values of this statistic in the model are S14.0 and S7.0, which are about 0.98 each. These are stations in which the comparison appears to be very good. The values of *d* at stations S11.0 and S15.0 are also above 0.9, and the value at station S8.0 is 0.85, all of which are rather good.

While experience indicates that overall the salinity verification is an excellent comparison, there are two basic questions that need to be answered to determine if the model is suitable for its intended purpose:

a. Is there a sound reason to require any further adjustments to the model?

b. Is this model adequate (as determine by this verification) to drive the oyster model?

One must remember that this long-term verification was made with no changes beyond the original adjustments made during the early short-term period. For a study in which the model is expected to make predictions, it is reassuring to see that the model represents the physics of the system well, so that it can follow prototype trends unaided by further adjustments.

As a result of the sensitivity analysis, it can be stated that the model-to-prototype differences are comparable to or less than the salinity uncertainty due to the freshwater inflow and Gulf salinity. Therefore, any further adjustment improvement will be swamped by the uncertainty of the boundary conditions alone, and no additional adjustment is advisable.

The second question remains whether this is good enough for input to the oyster model. The answer depends upon the error in the input parameters used in ecosystem models and environmental evaluations. In this regard the average salinity correlation coefficient within the bay is 0.91, which is higher than many other parameters used to describe the oyster productivity. For example, a description of seed production is given by Chatry, Dugas, and Easley (1983) as seed production = -43.89 + 2144.5 (sum monthly salinity deviations from the optimum regime). This has a correlation coefficient of 0.837. Other rules of thumb are that the salinity variability of the oyster parameters is between 10 and 20 percent, which is on the order of 2 ppt or so, and so is less restrictive than the results of the boundary uncertainty in this study. Therefore, the input from the hydrodynamic model lies within the acceptable bounds of the other input to the oyster model, and it cannot alone be unacceptable. Hence the verification is good and the hydrodynamic model should be suitable for that purpose.

Qualitative comparison

Finally, it can be shown that the model produces general patterns of behavior that can be compared with descriptions of the bay from literature or from observations. While these items are generally not quantifiable, they do provide a strong basis to indicate that the model is a reliable archetype/replica for the natural system. These model observations are as follows:

a. From Figure 12 it is apparent that a strong freshwater flow from Trinity River flows around Smith Point into East Bay in the model. This has been observed in the prototype in the location of large oyster kills near Smith Point during high-flow periods. Furthermore, this explains the low salinity of East Bay, even though it is close to the Gulf and has very few direct freshwater sources. Figure 13, which was derived from long-term prototype data collection and presented in Orlando et al. (1991), shows isohalines for the period April-June 1985 from which one can also infer this flow feature.

b. There is a flood-dominant channel up the center of Trinity Bay in both the model (Figure 12) and the prototype (Figure 13).

c. The salinity is lower east of Atkinson Island than west. This has also been confirmed by nonpublished field measurements made by Texas A&M University.[1]

d. There is net drift outward along the sides of Trinity Bay in the model. This was noted by WES field investigation personnel observing shrimp boats that drifted outward along the shore.

e. There is an eddy in the net circulation in upper Trinity Bay in the spring (Figures 14, 15, and 16). Results from a NASA (1971) study of isotherms from discharge from the first completed generator at the Cedar Bayou Power Plant from May 17, 1971, show the likelihood of there being an eddy as well.

f. The model shows a flood dominance along the channel (Figure 17) that is particularly strong in the upper bay. This is confirmed in the data of previous WES prototype data (Bobb, Boland, and Banchetti 1973) as well as Ward (1980), who states, "In the open bay, the lower 25 miles, the tidal mean flow is directed upstream *throughout* the depth." Figure 17 is contours of ebb predominance calculated at a point as the time integral of ebb velocity divided by the time integral of velocity magnitude over a tidal cycle, and expressed as a percentage. One

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[1] Personal communication, December 1992. Dr. Eric Powell, Texas A&M University, College Station, TX.

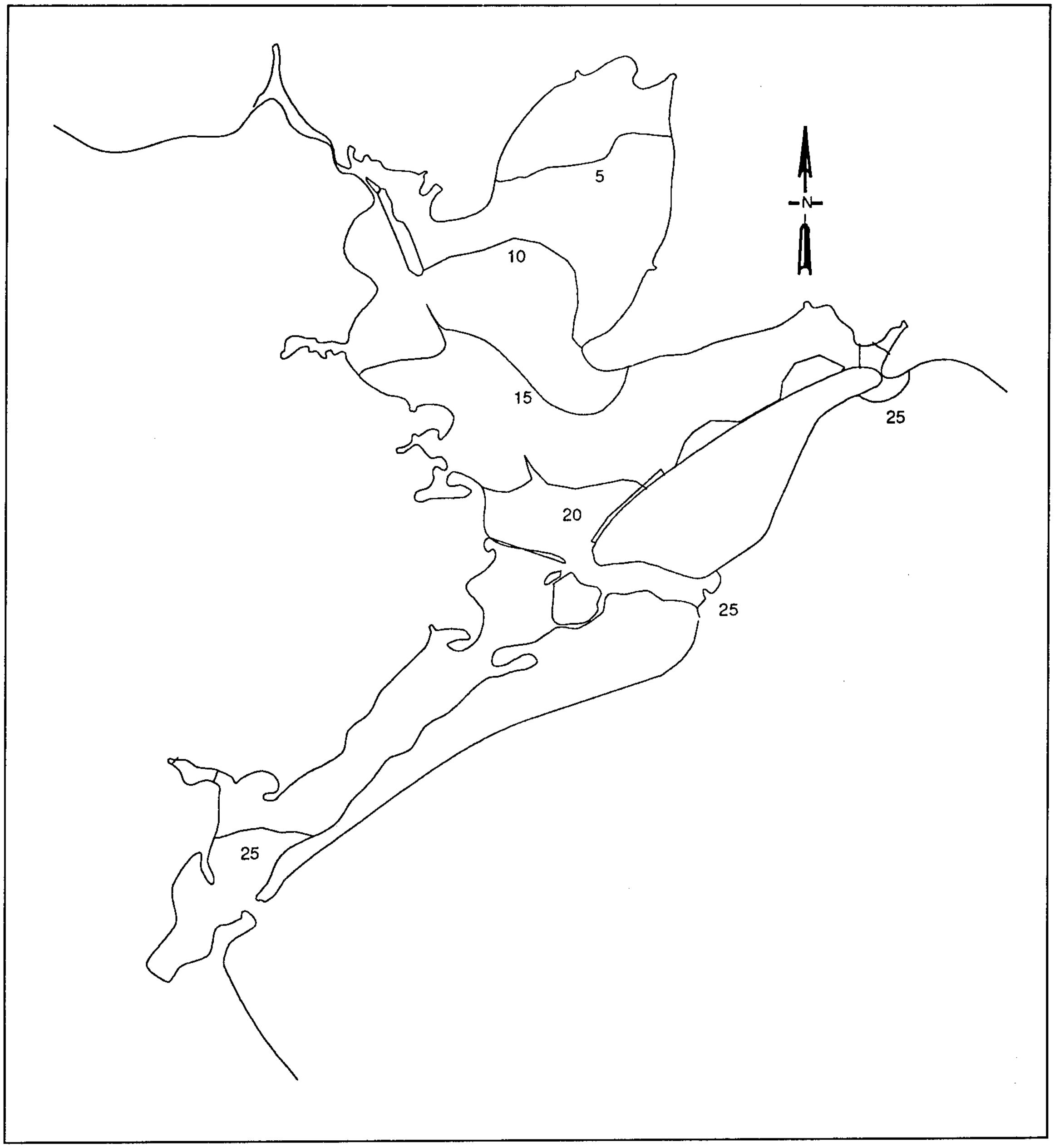

Figure 12. Isohaline plots, BASE versus Phase I bathymetry, low freshwater inflow, existing hydrology, bottom salinity

hundred percent indicates flow downstream at all times, and 0 percent is flow upstream at all times.

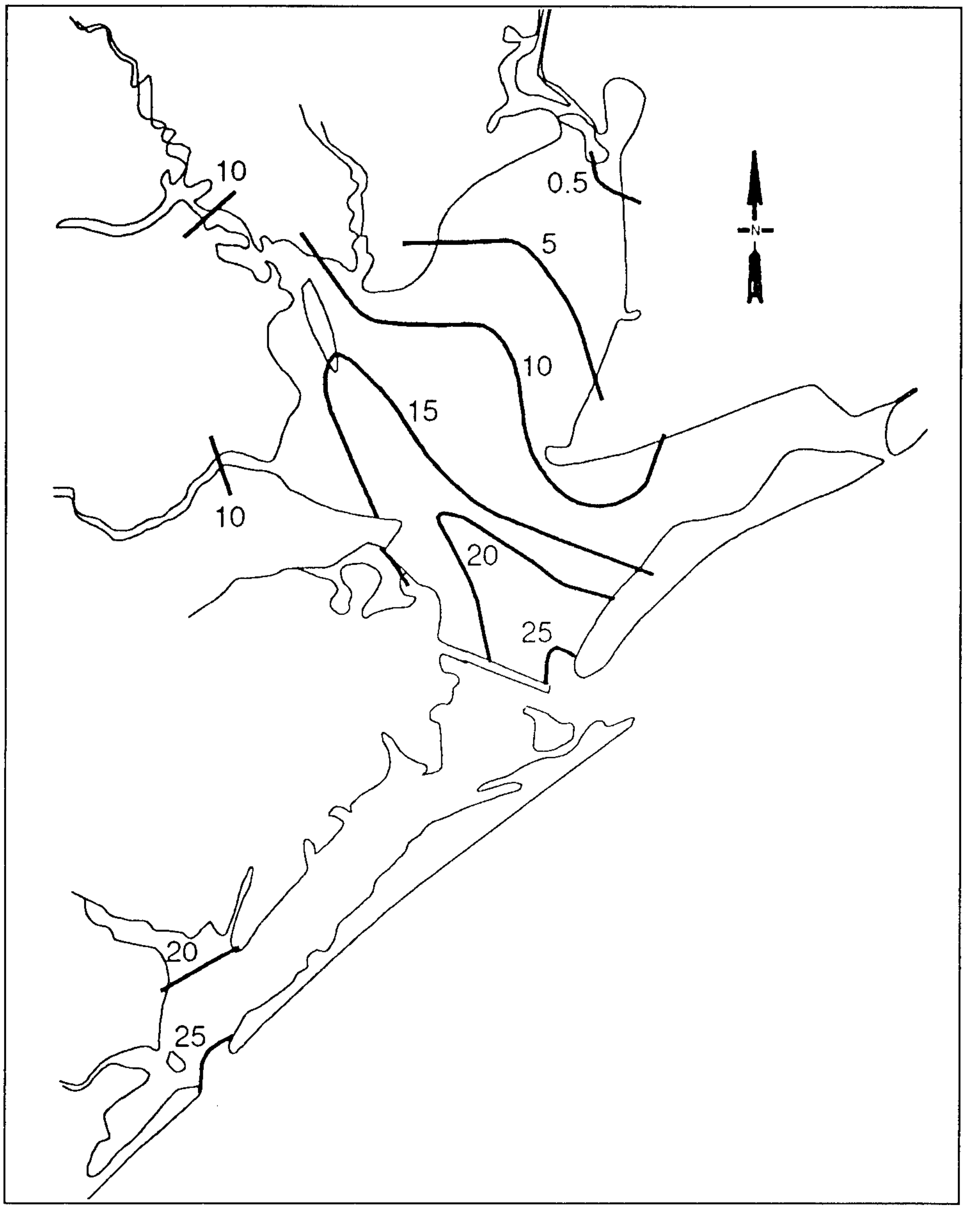

Figure 13. Bottom salinity April-June 1985, modified from Orlando et al. (1991)

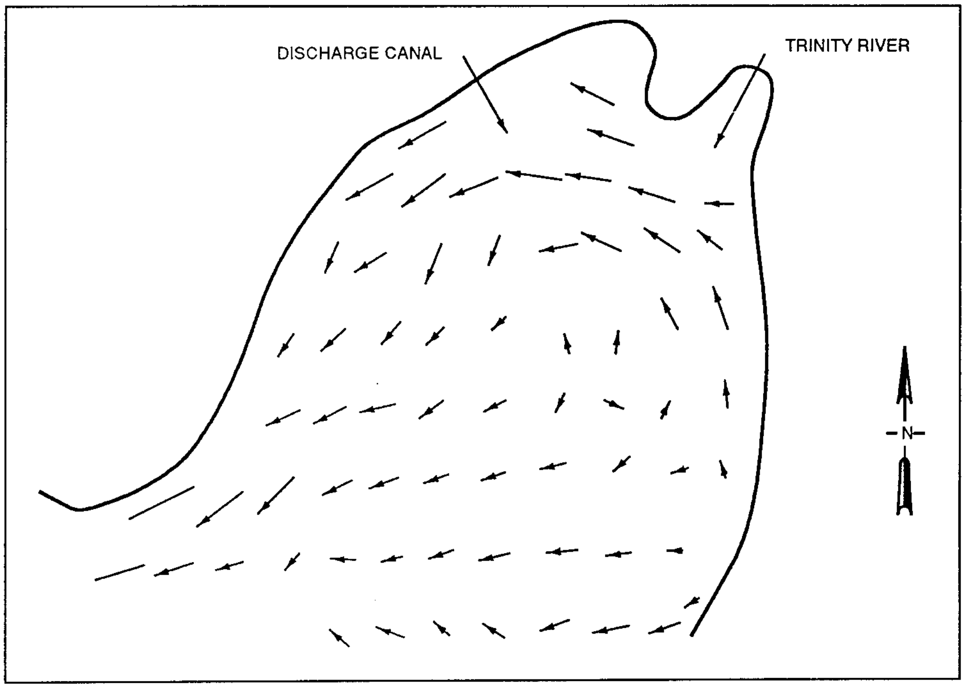

Figure 14. Monthly average May model surface velocity

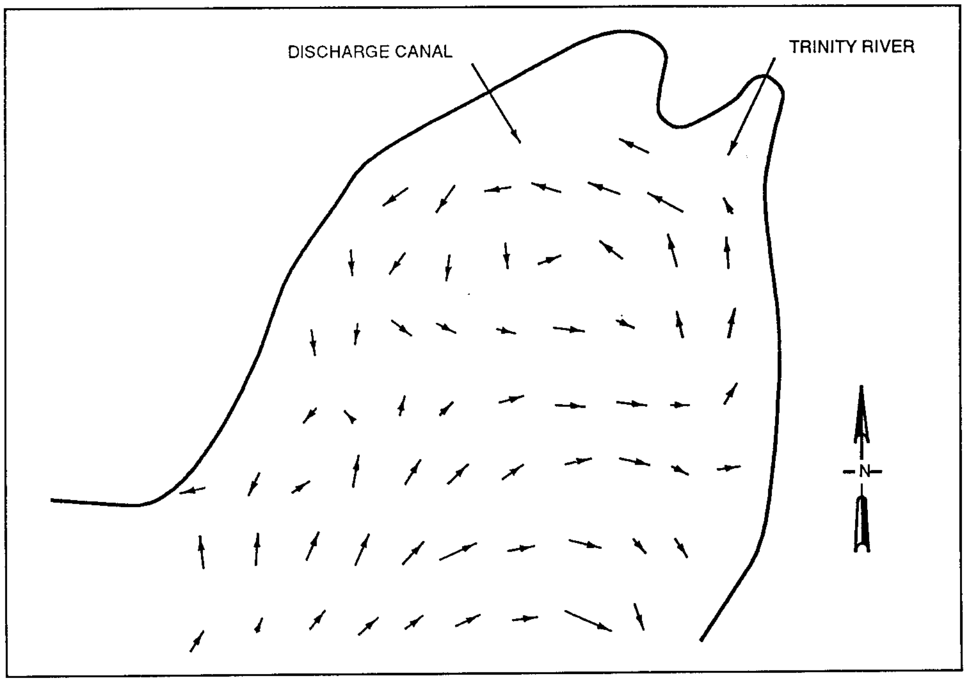

Figure 15. Monthly average May model bottom velocity

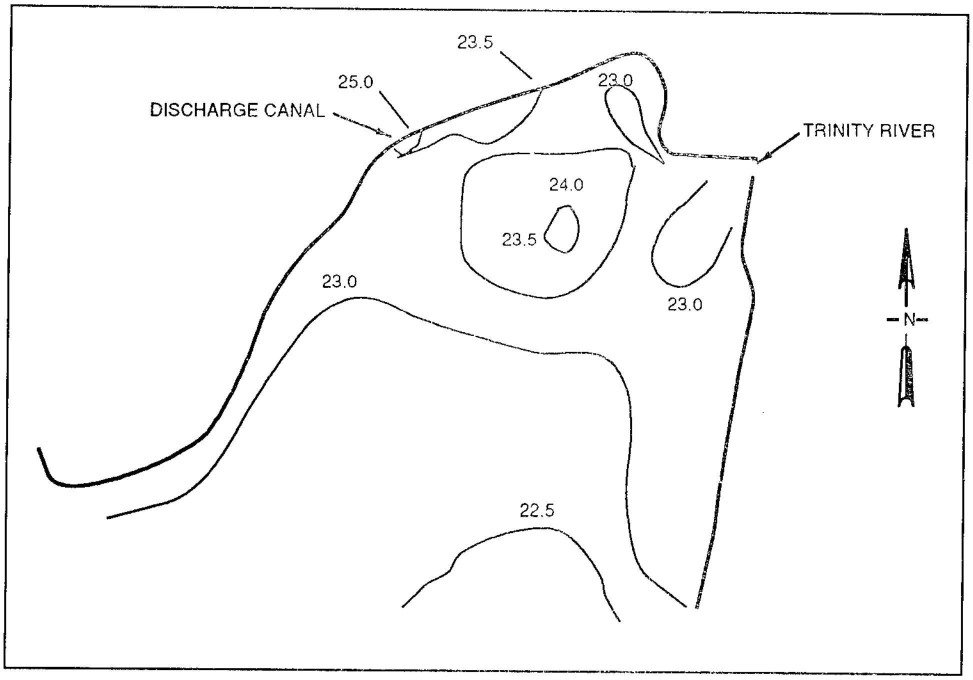

Figure 16. Temperature isohalines (°C) (from NASA 1971), May 1971

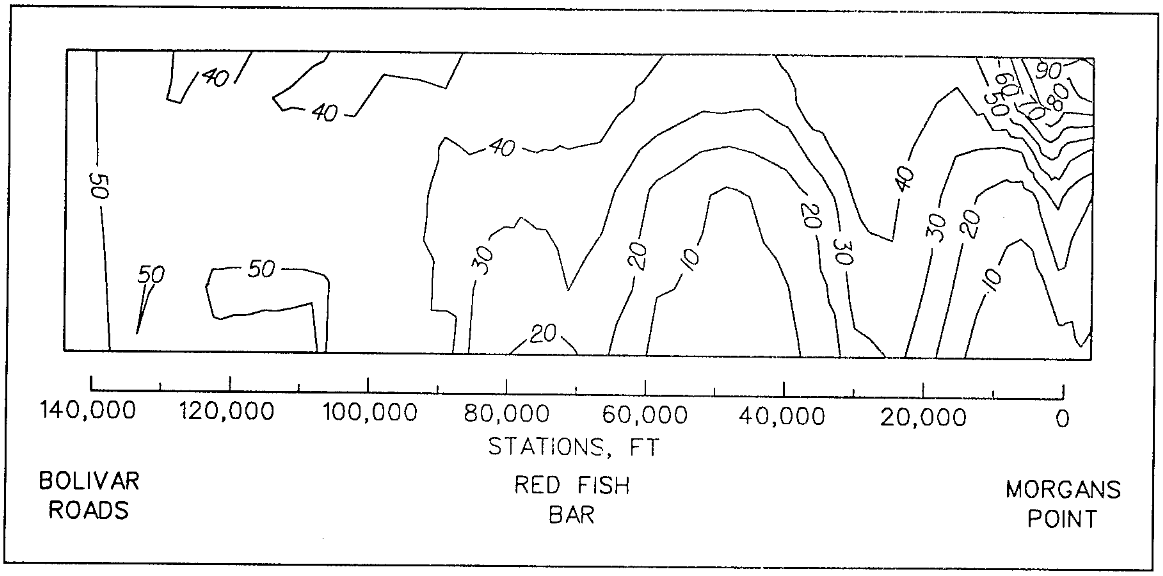

Figure 17. Model ebb predominance profile for channel center line

4 Conclusions

This report records the development of a 3-D state-of-the-art hydrodynamic and salinity numerical model for the Galveston Bay estuary. The model's purpose is to produce flow fields and salinity fields for evaluation of the impact of the proposed deepening of the Houston-Galveston Navigation Channel. The results of this model are to be used as input to an ecosystem model to evaluate oyster production. This report details the validation of the numerical hydrodynamic and salinity model.

The actual numerical code used herein is the RMA10-WES 3-D finite element program. Its principal advantage is that it can reproduce complex geometric features quite easily.

In the validation process the first step undertaken was to run the model and make appropriate adjustments to reasonably match a short period of prototype data. The major adjustment in this step was to the bay roughness. After the completion of this process, the model was run with no additional adjustment for 6 months during which extensive field data were collected. Comparisons were then made between the model and the field results. The period of the field record includes the salinity response to a very high freshwater inflow and the salinity rebound during the subsequent dry period. This period offers a very rigorous test of model reliability.

An uncertainty analysis of the primary boundary conditions concluded that no additional adjustment of the model was warranted, since the difference between model and prototype salinity is generally less than the impact of the uncertainty of the Gulf salinity and upland freshwater inflow magnitude.

The environmental resource agencies associated with this project chose oysters as the indicator species for determination of the project impact. The suitability of the model to serve as a tool for evaluation of the environmental impact of plan modifications was decided based upon the variability of other input used in the oyster model. The difference between the model results and those of the prototype was of the same relative magnitude as the other input parameters used by the oyster model. Therefore the hydrodynamic model has been shown to be valid for evaluation of tides, velocity fields, and salinity fields within Galveston Bay and can serve as a reliable driver for the subsequent oyster model evaluations.

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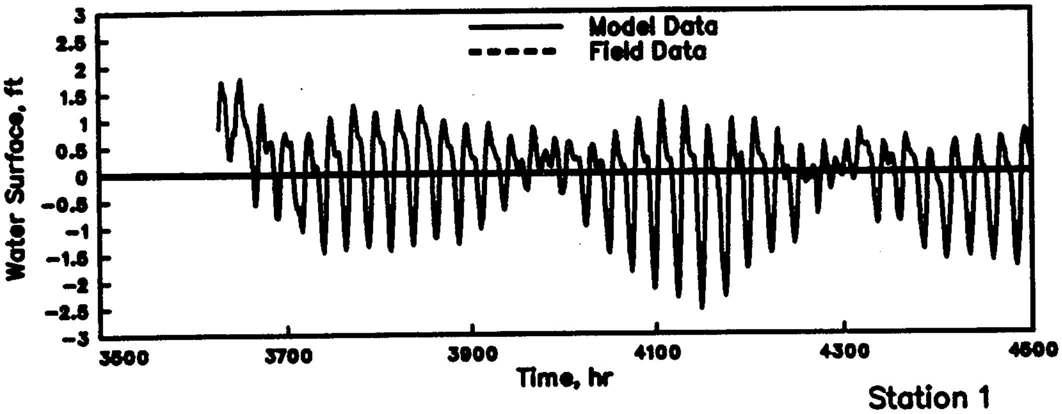

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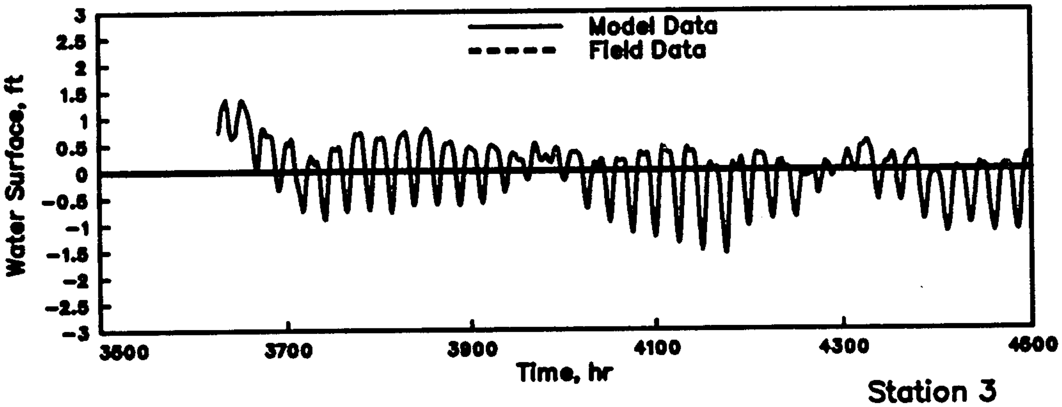

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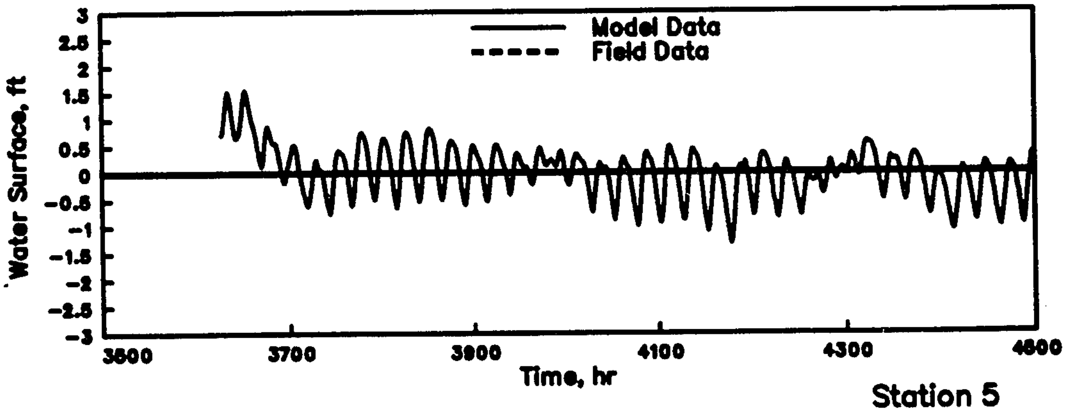
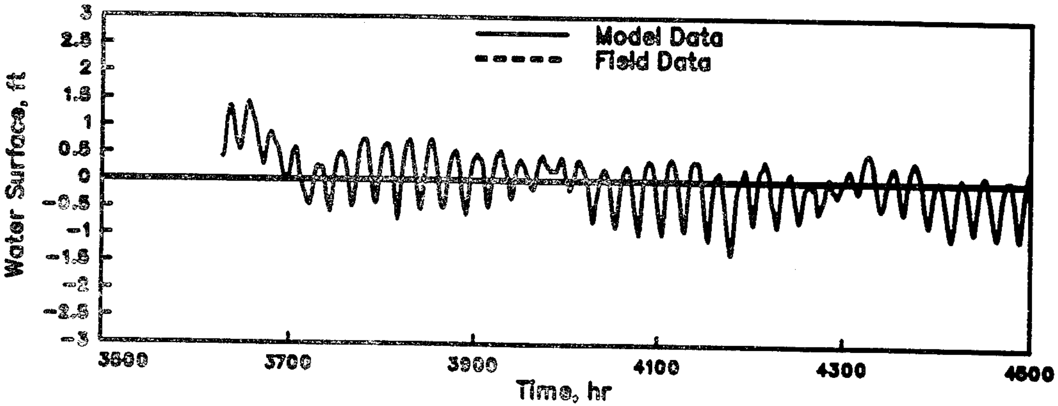


Station 5

WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 1, 3, AND 5
HOURS 3500-4500



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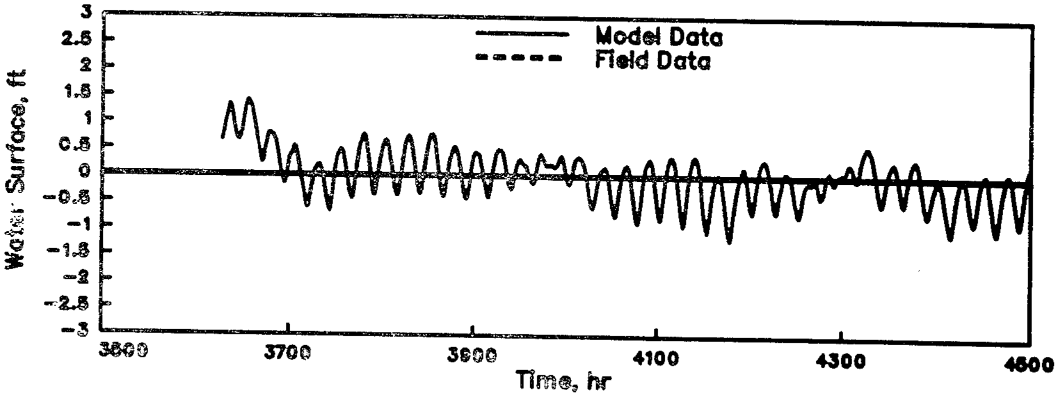

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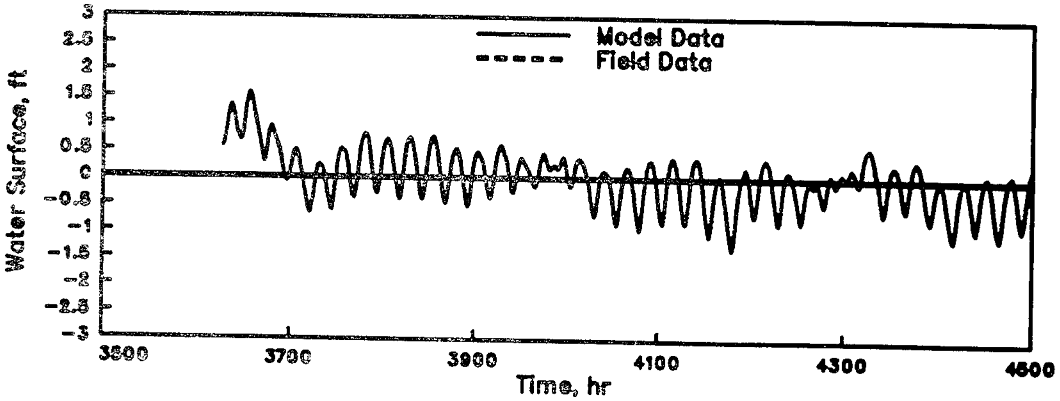
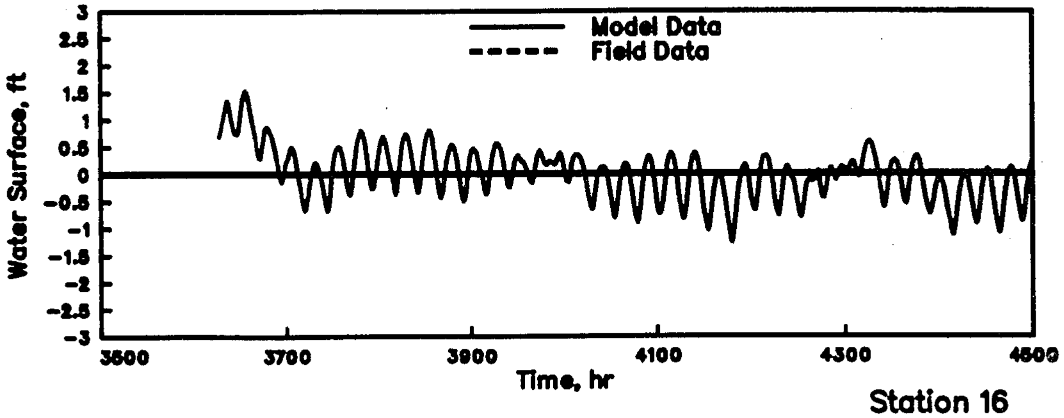


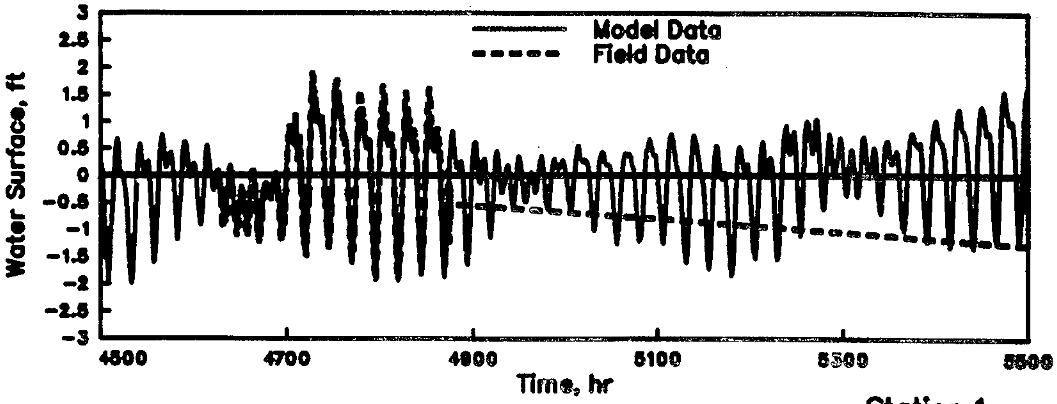
Station 14

WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 7, 10, AND 14
HOURS 3500-4500

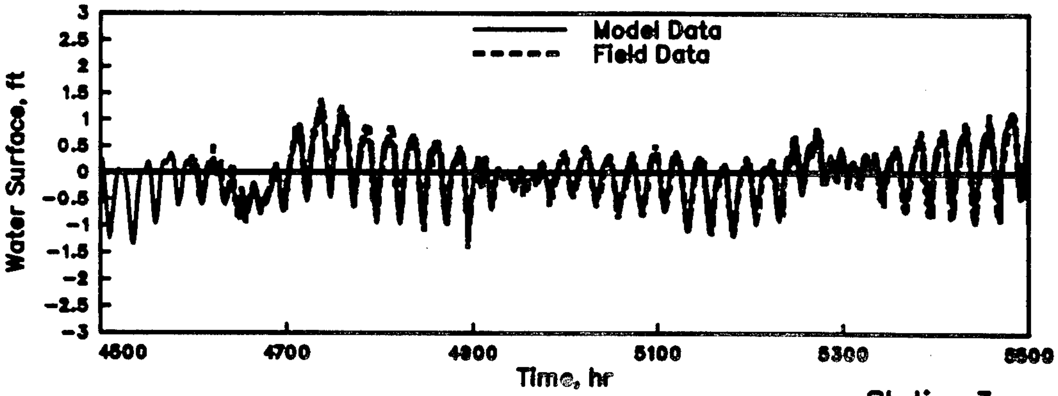


Station 16

WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATION 16
HOURS 3500-4500



Station 1



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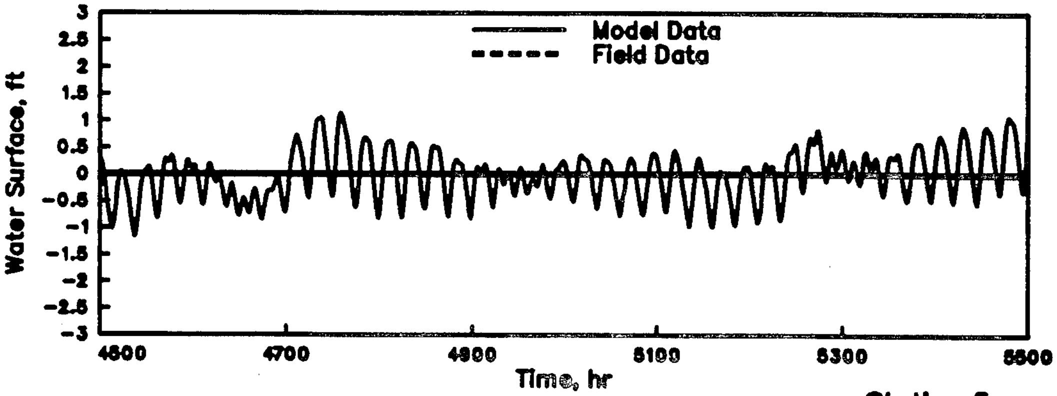
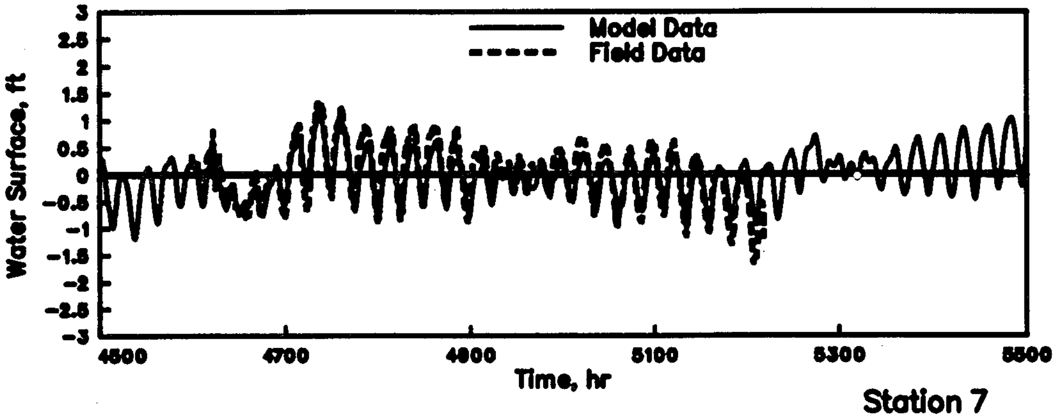


Station 5

WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 1, 3, AND 5
HOURS 4500-5500



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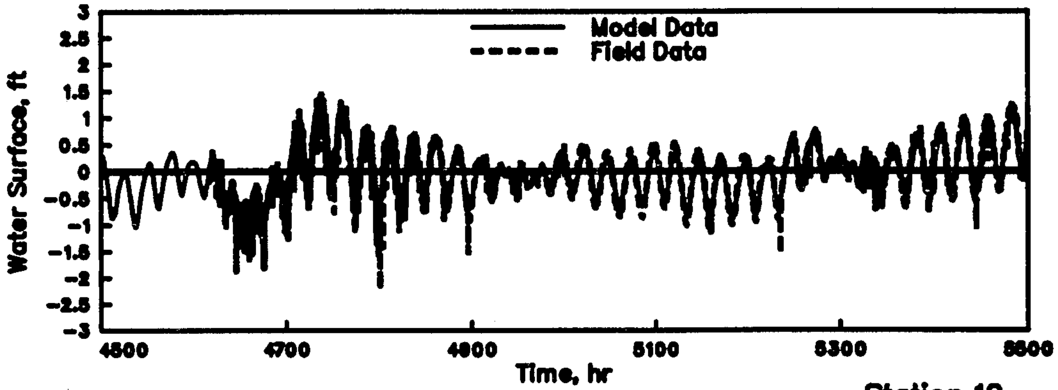

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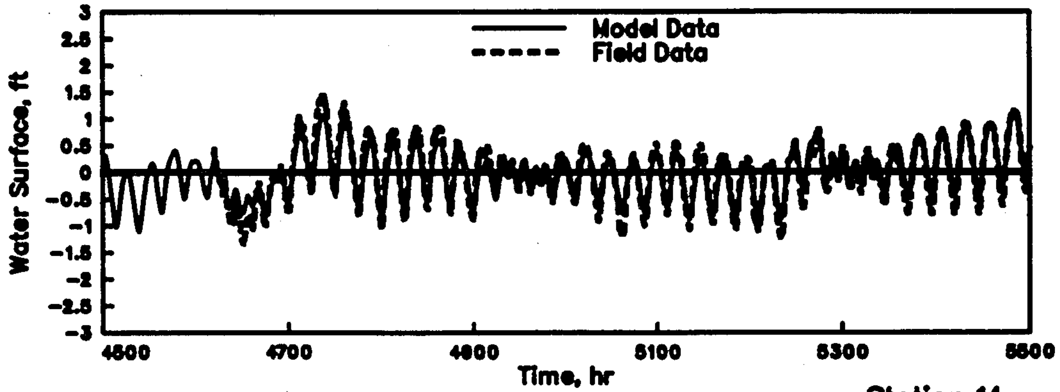
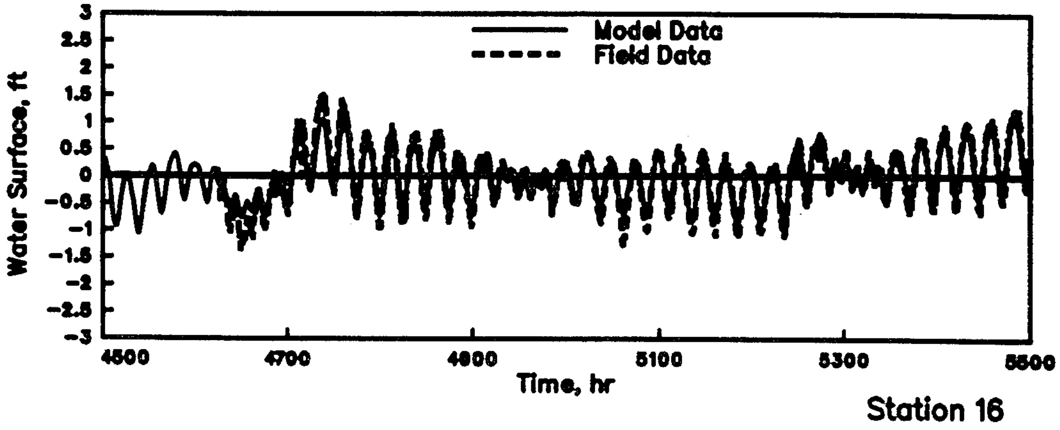
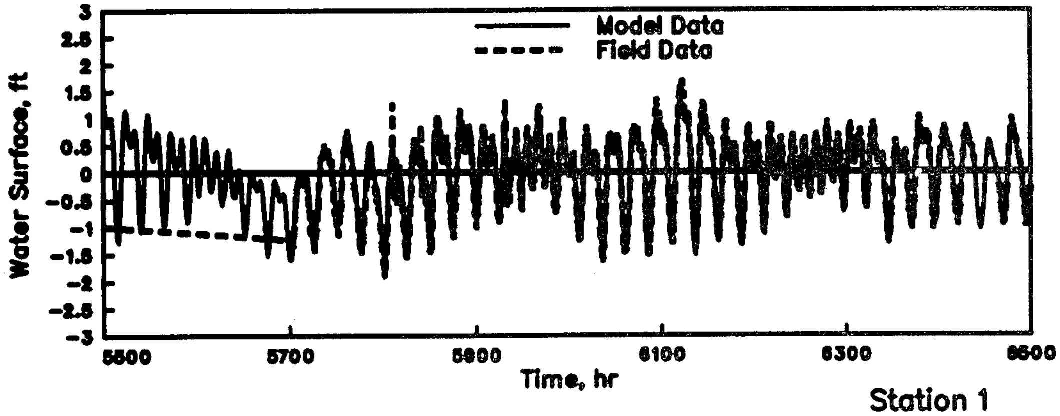


Station 14

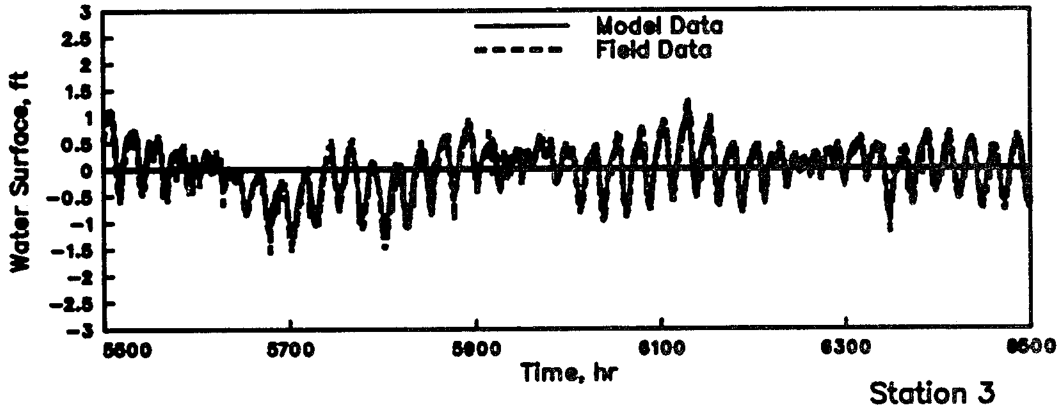
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 7, 10, AND 14
HOURS 4500-5500



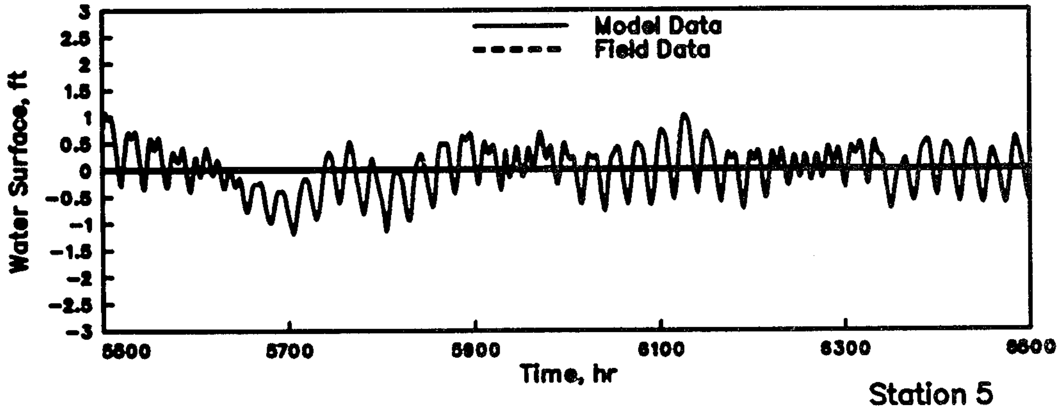
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATION 16
HOURS 4500-5500



Station 1

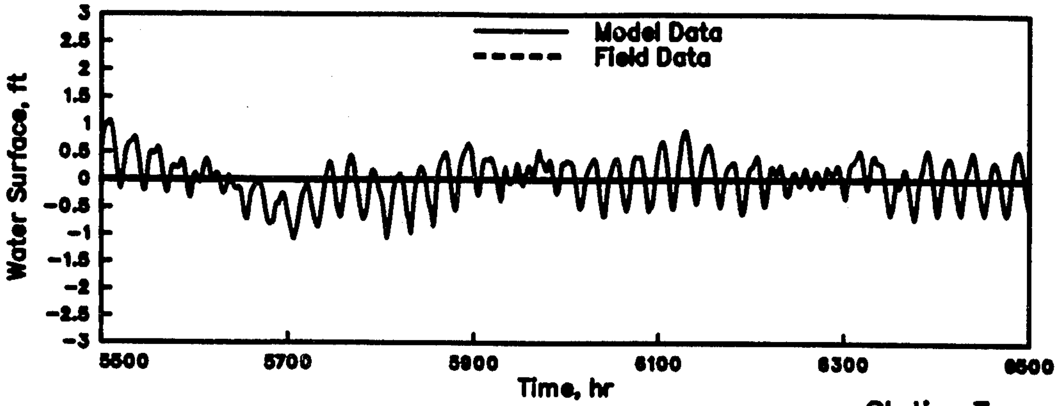


Station 3

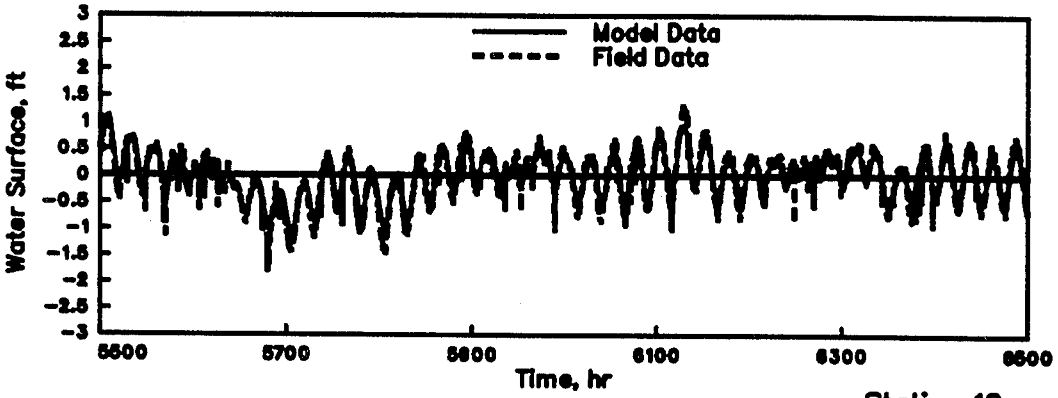


Station 5

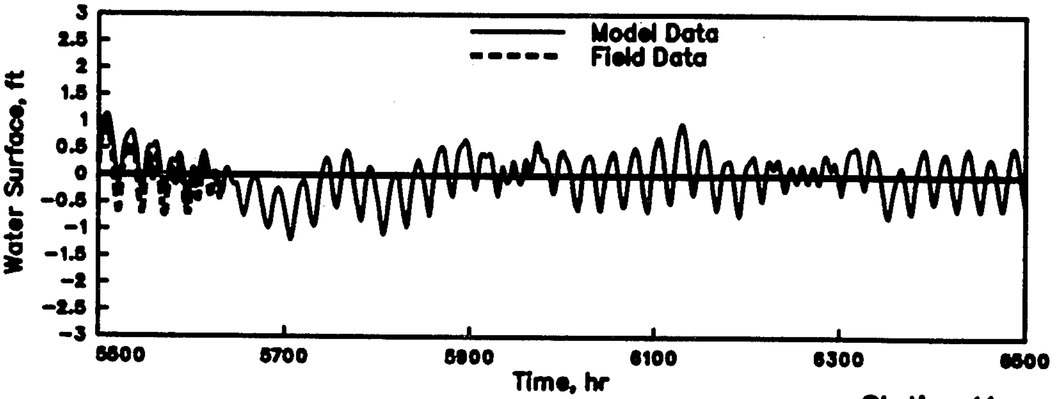
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 1, 3, AND 5
HOURS 5500-6500



Station 7

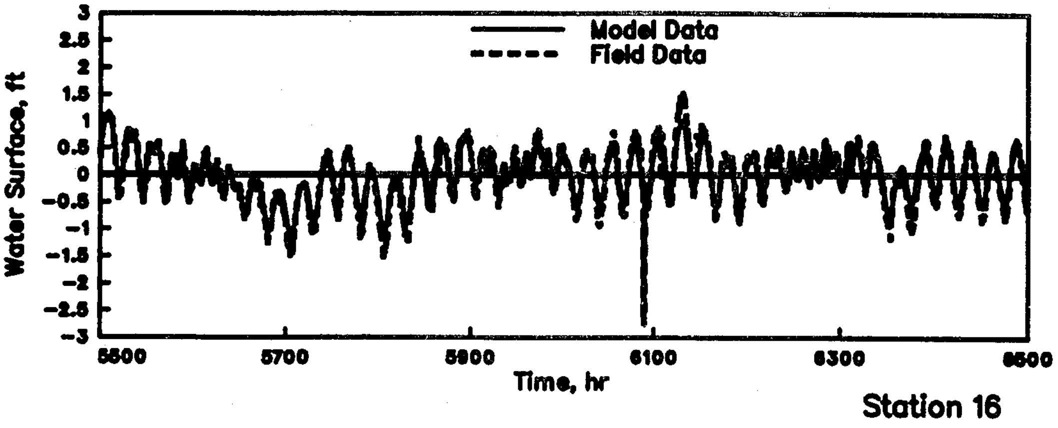


Station 10

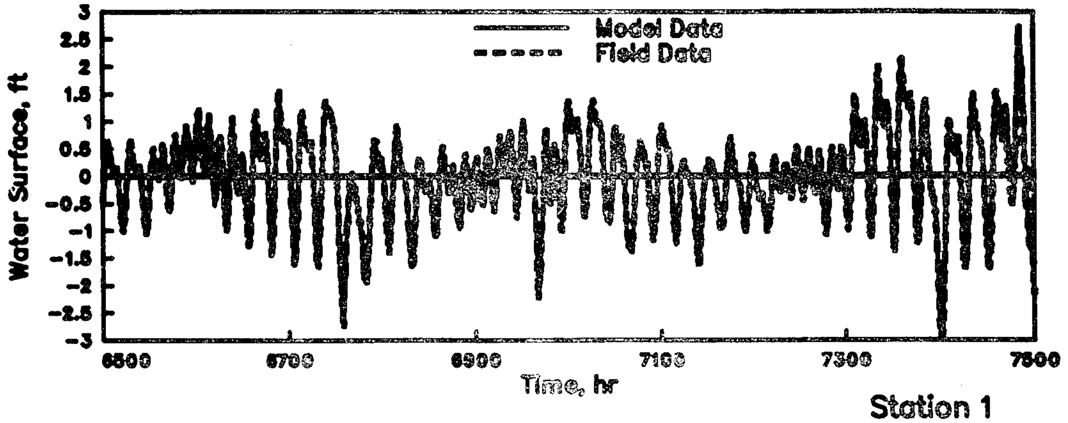


Station 14

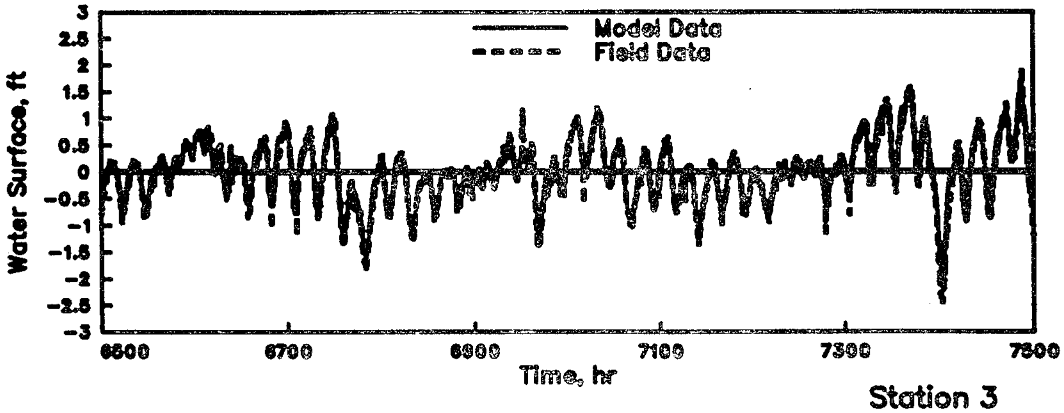
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 7, 10, AND 14
HOURS 5500-6500



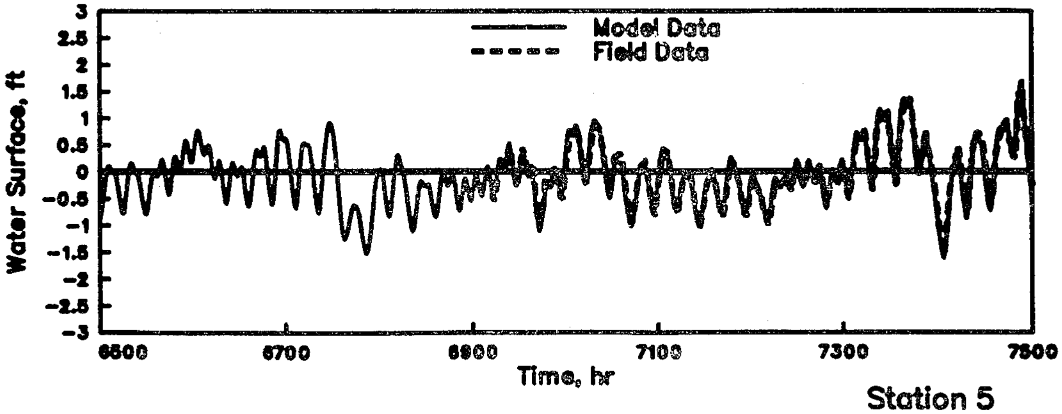
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATION 16
HOURS 5500-6500



Station 1

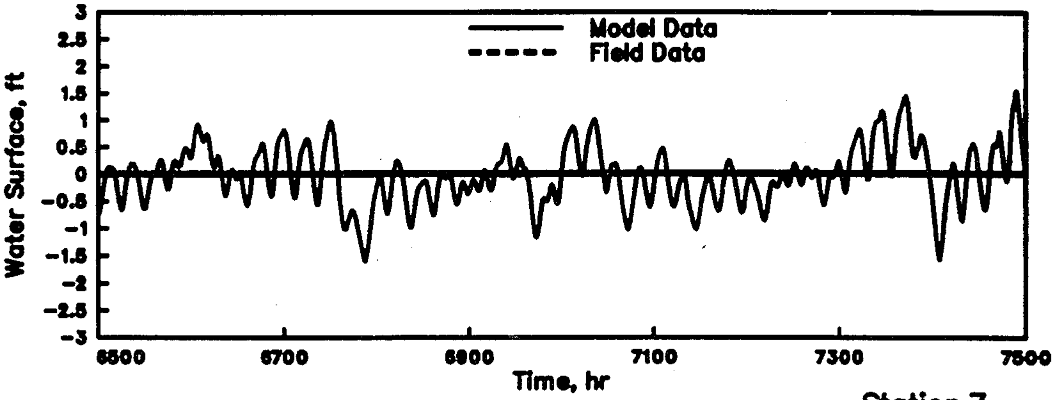


Station 3

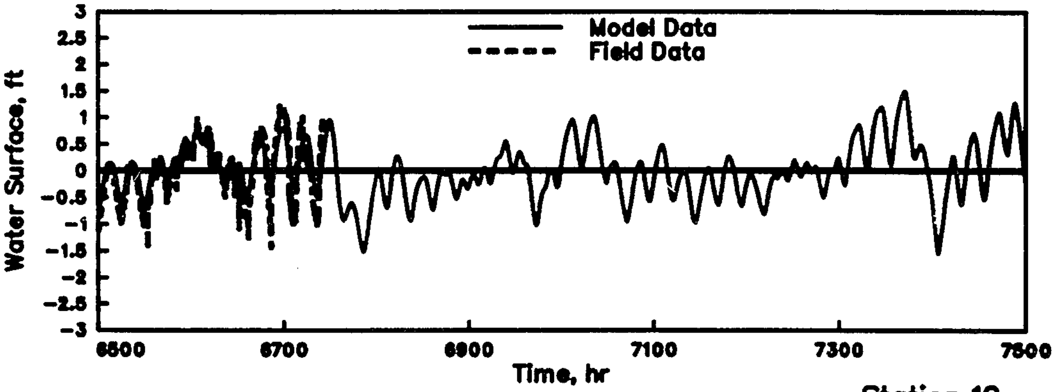


Station 5

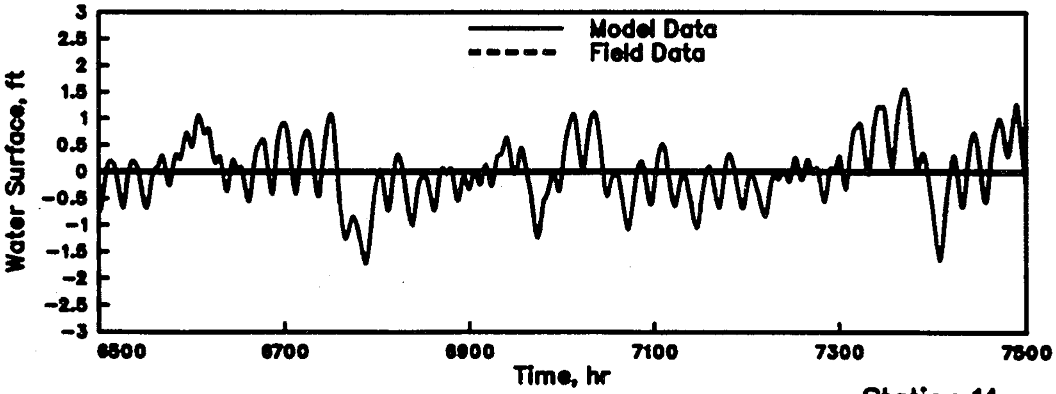
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 1, 3, AND 5
HOURS 6500-7500



Station 7

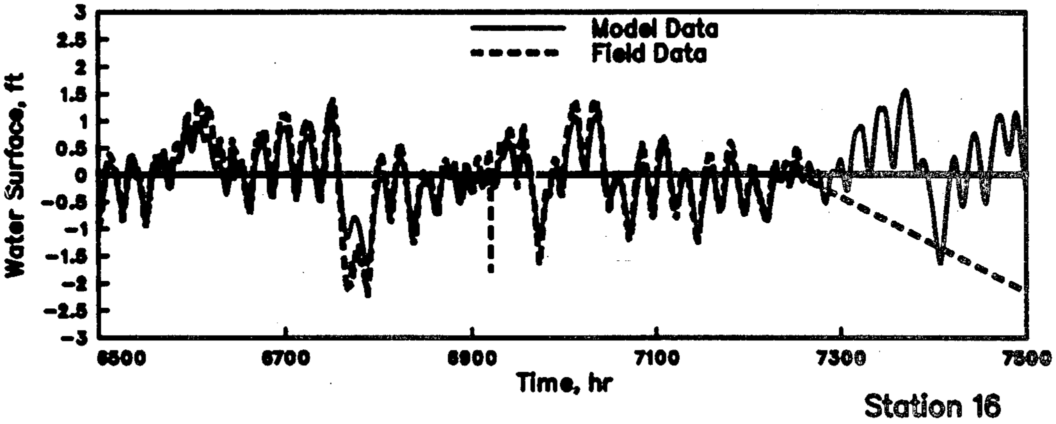


Station 10

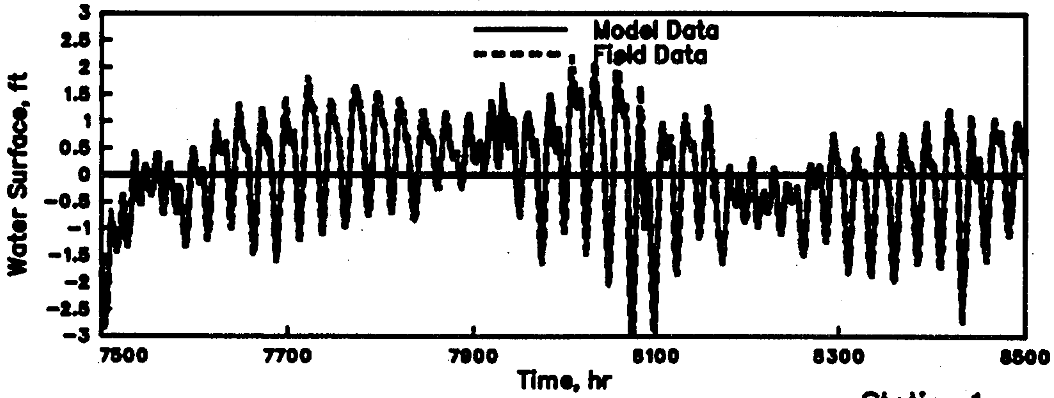


Station 14

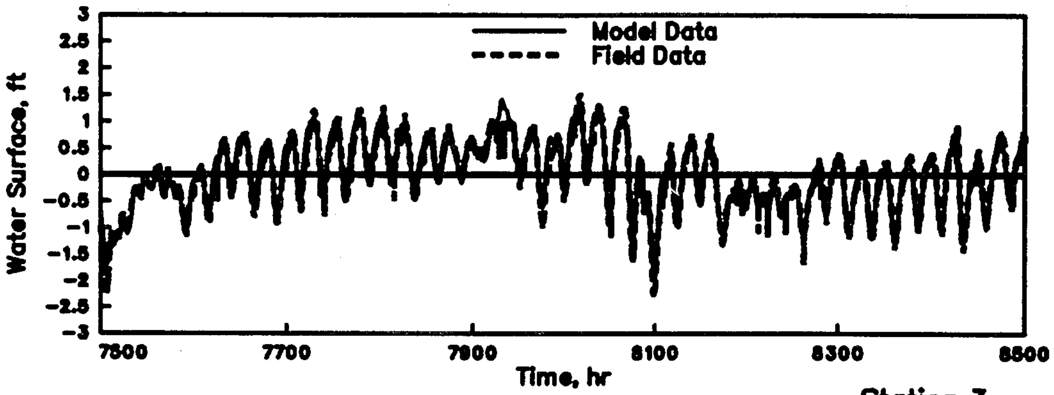
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 7, 10, AND 14
HOURS 6500-7500



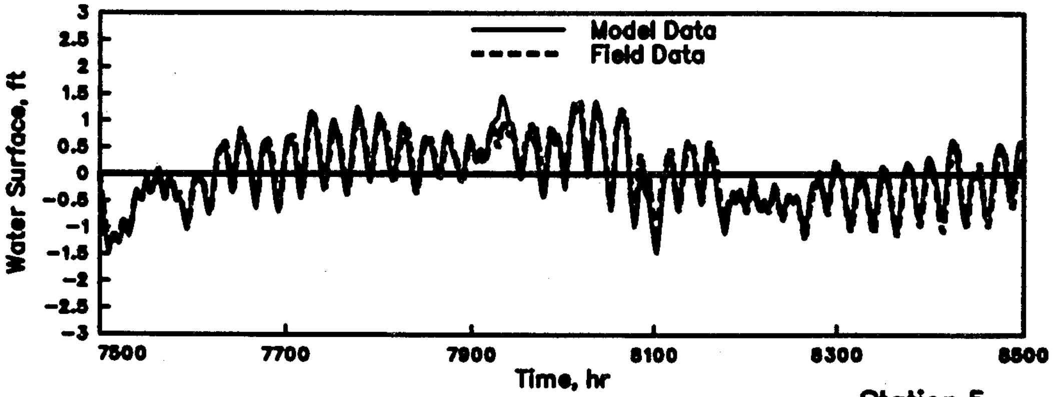
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATION 16
HOURS 6500-7500



Station 1

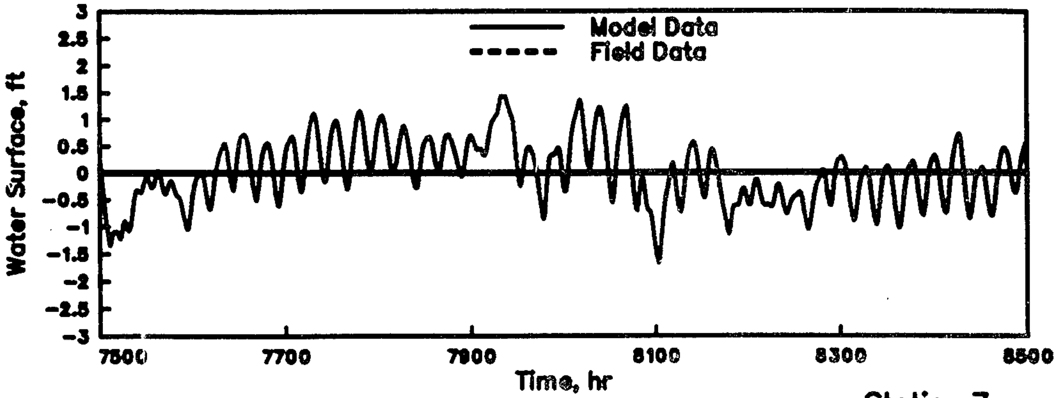


Station 3

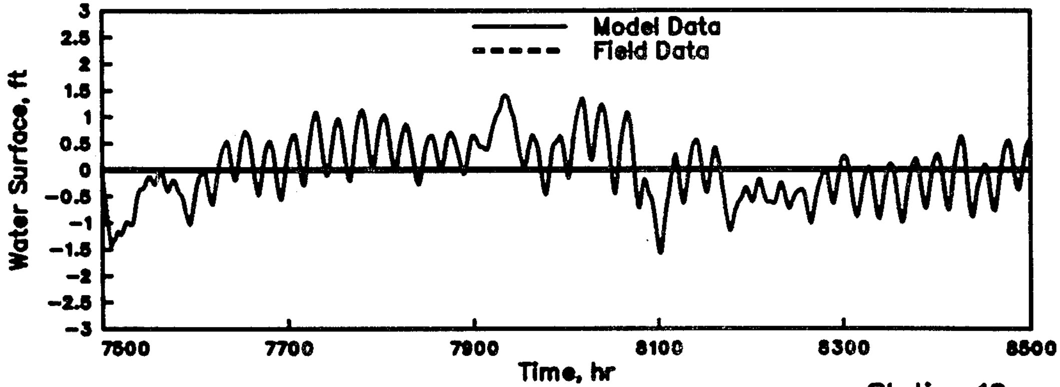


Station 5

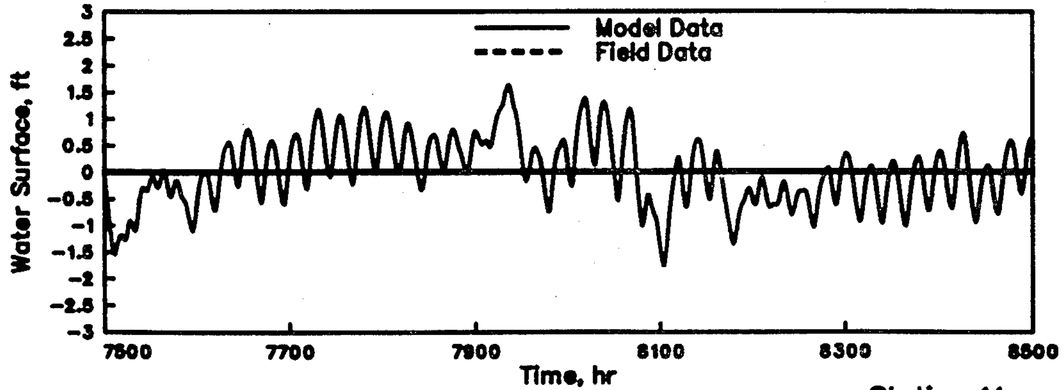
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 1, 3, AND 5
HOURS 7500-8500



Station 7

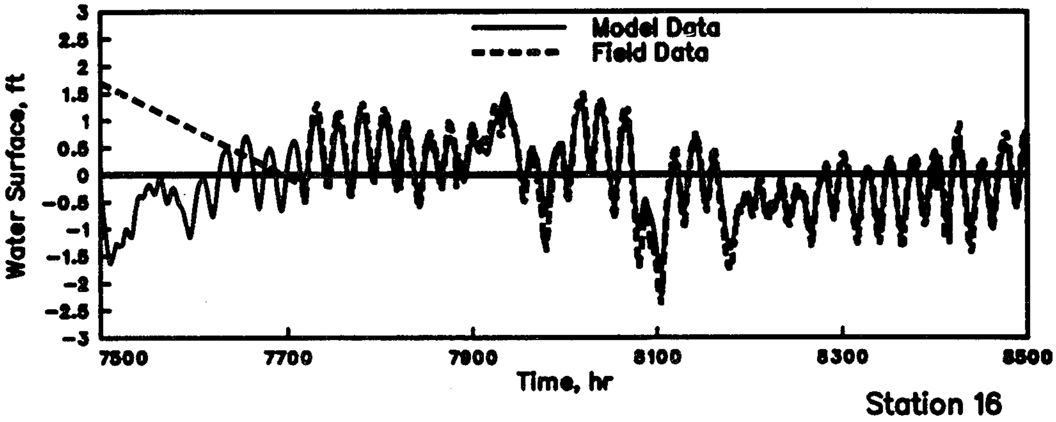


Station 10

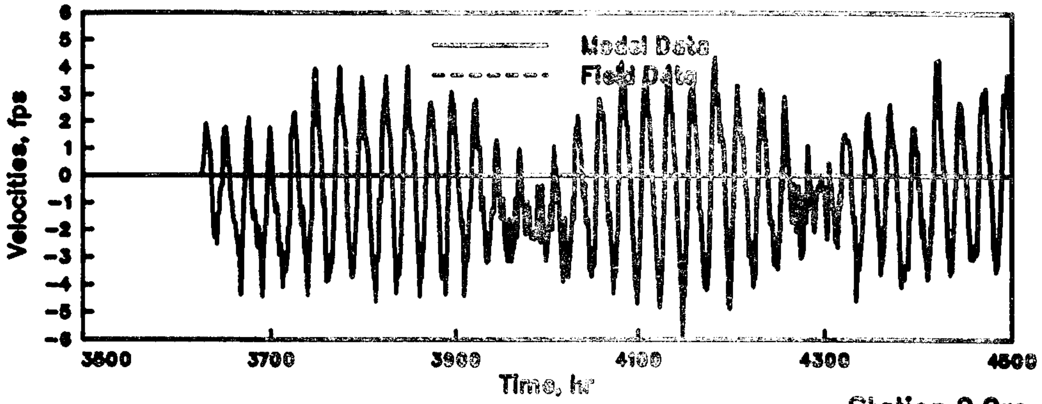


Station 14

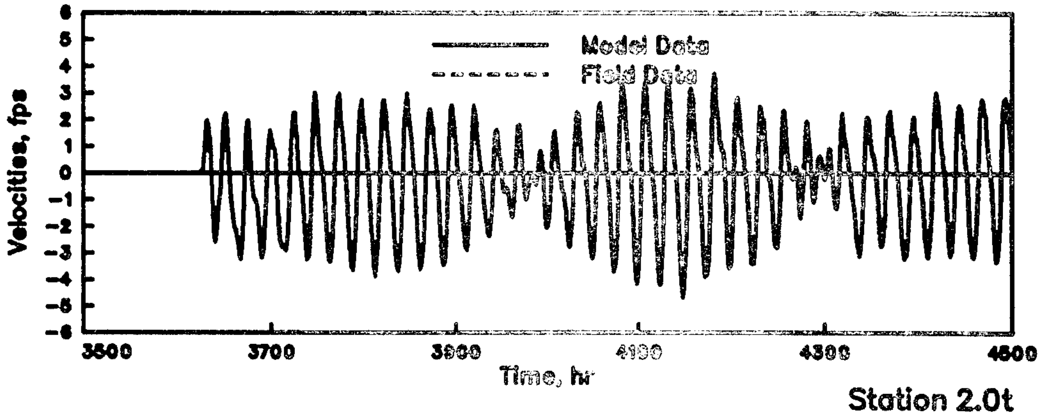
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATIONS 7, 10, AND 14
HOURS 7500-8500



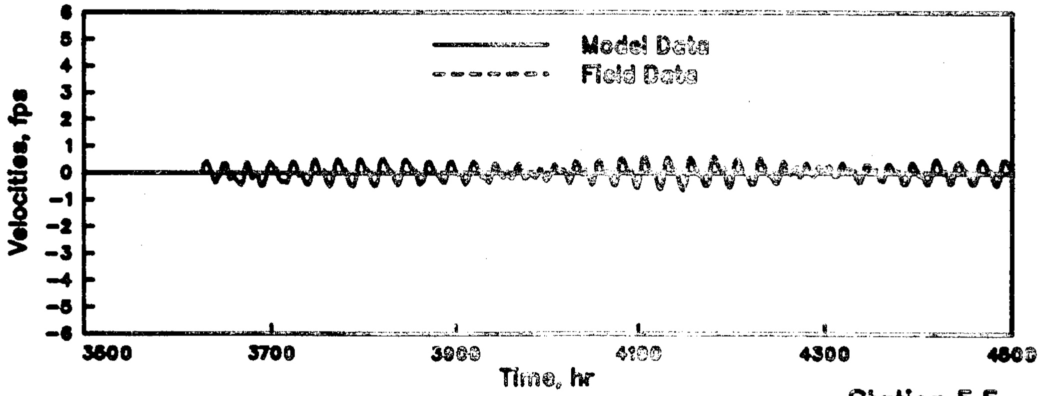
WATER-SURFACE ELEVATIONS
MODEL VERIFICATION
STATION 16
HOURS 7500-8500



Station 2.0m

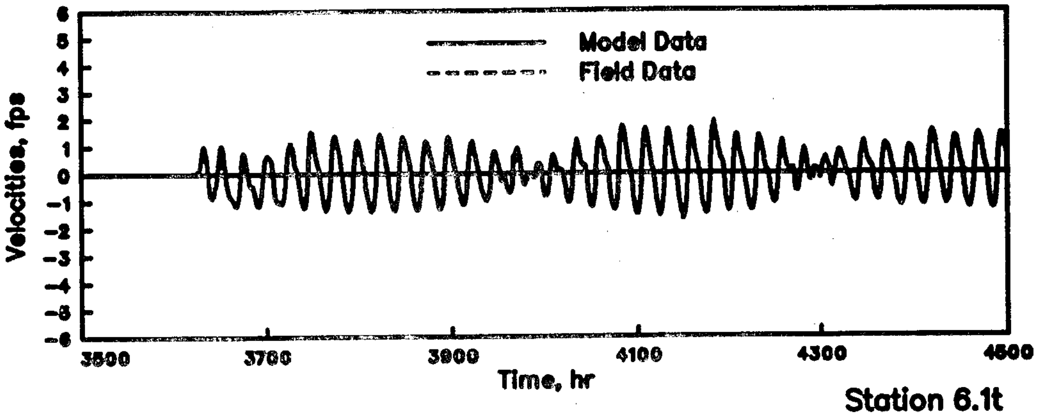


Station 2.0t

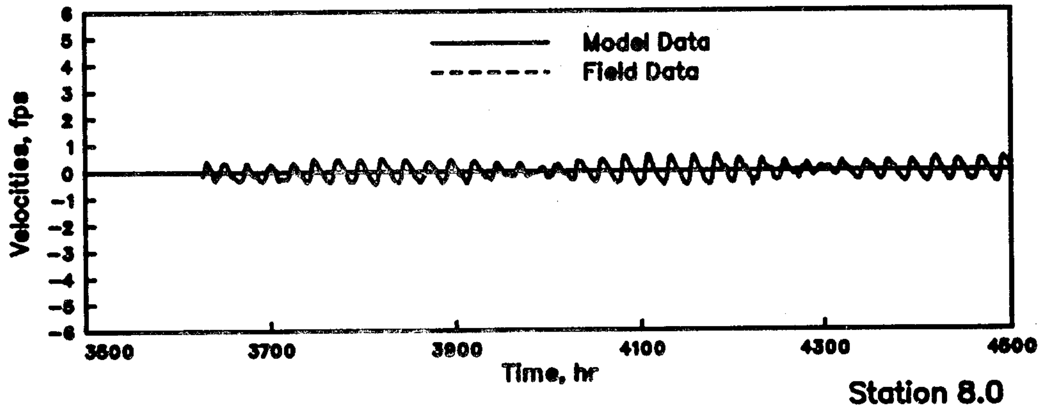


Station 5.5

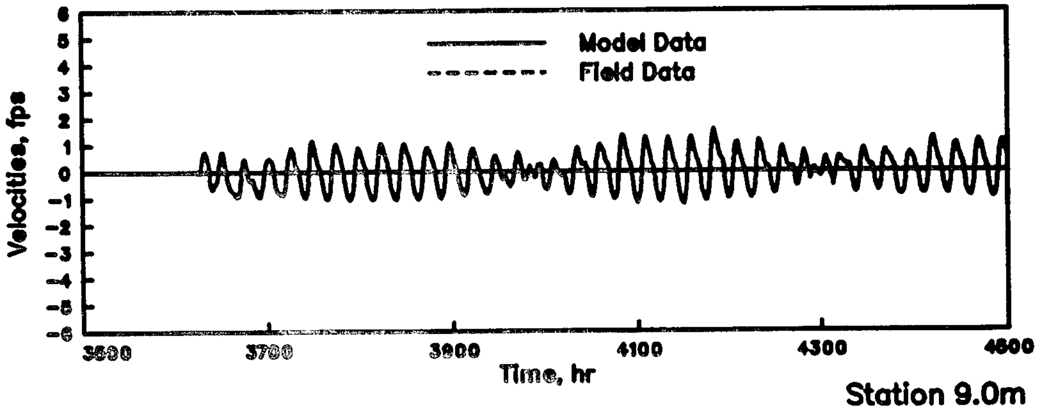
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 2.0m, 2.0t, AND 5.5
HOURS 3500-4500



Station 6.1t

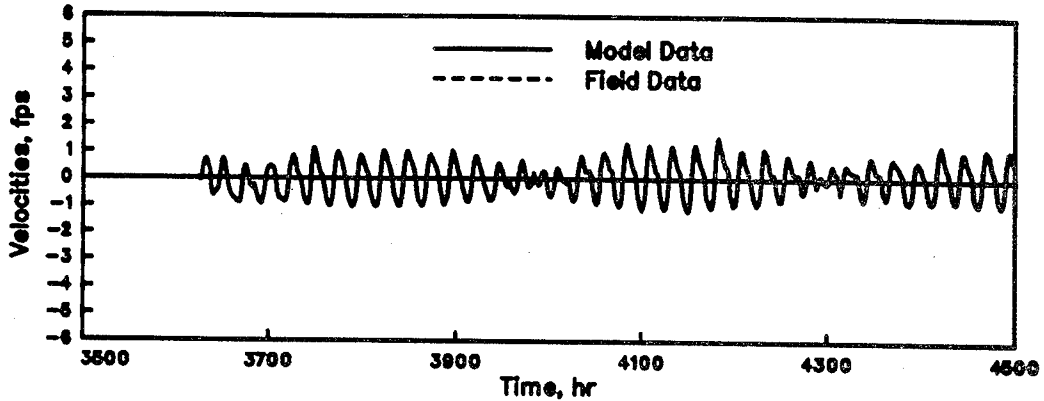


Station 8.0

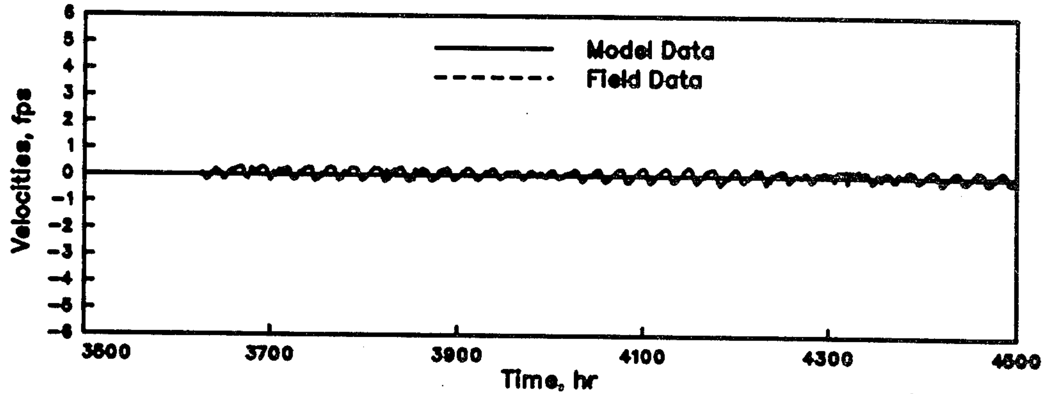


Station 9.0m

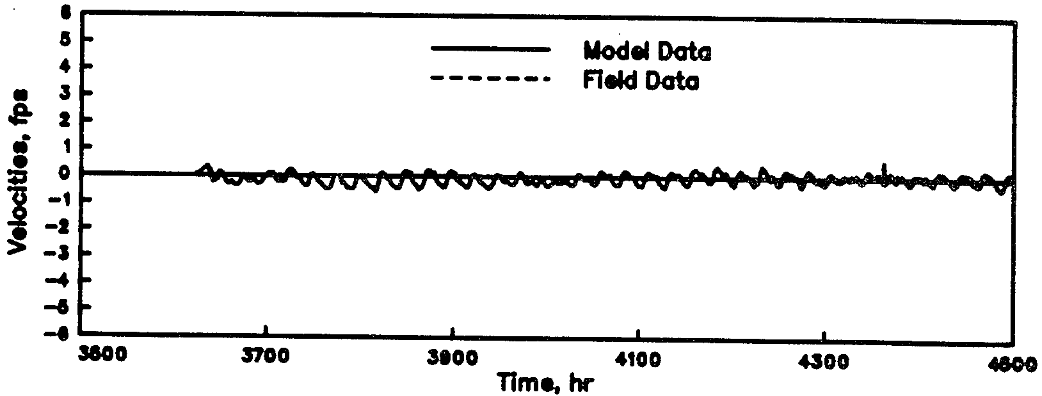
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.1t, 8.0, AND 9.0m
HOURS 3500-4500



Station 9.0t

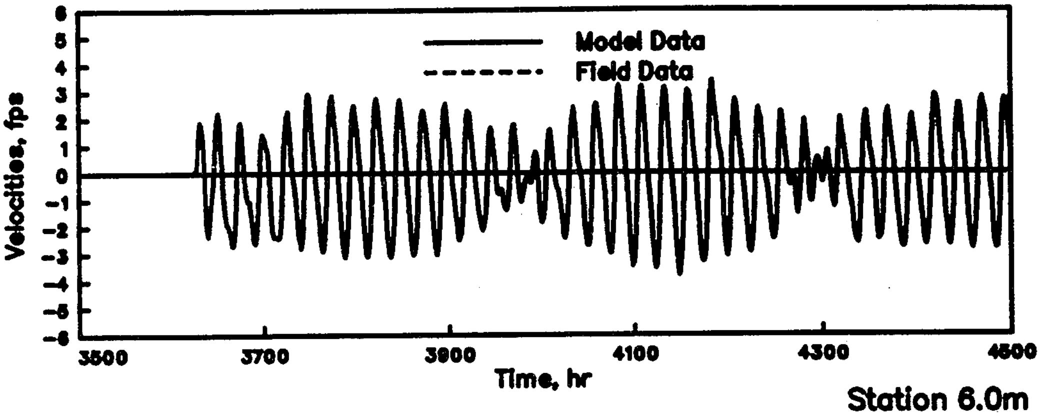


Station 11.1

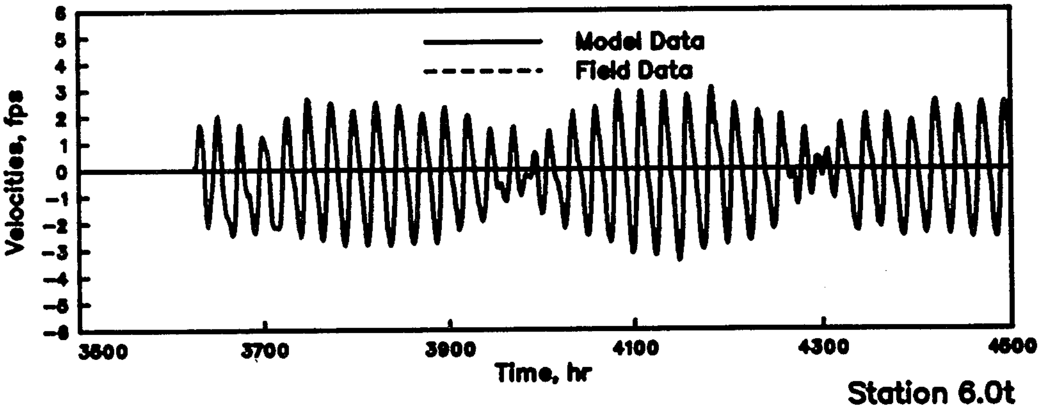


Station 12.0m

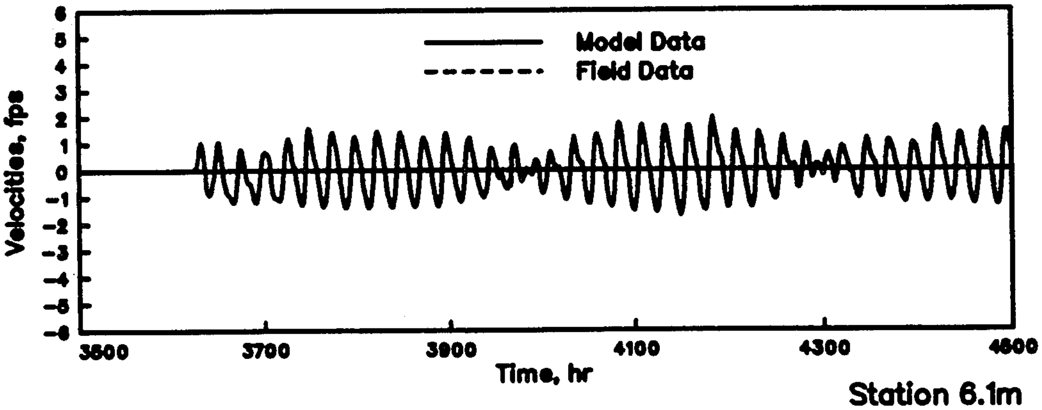
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 9.0t, 11.1, AND 12.0m
HOURS 3500-4500



Station 6.0m

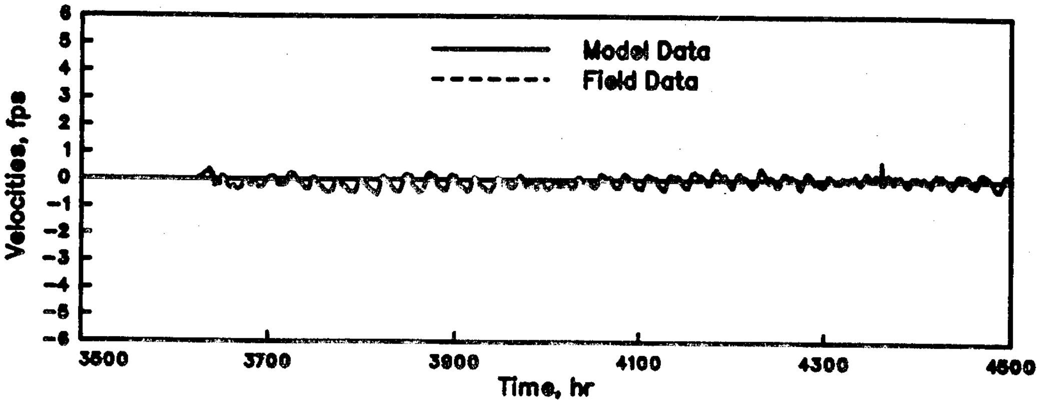


Station 6.0t

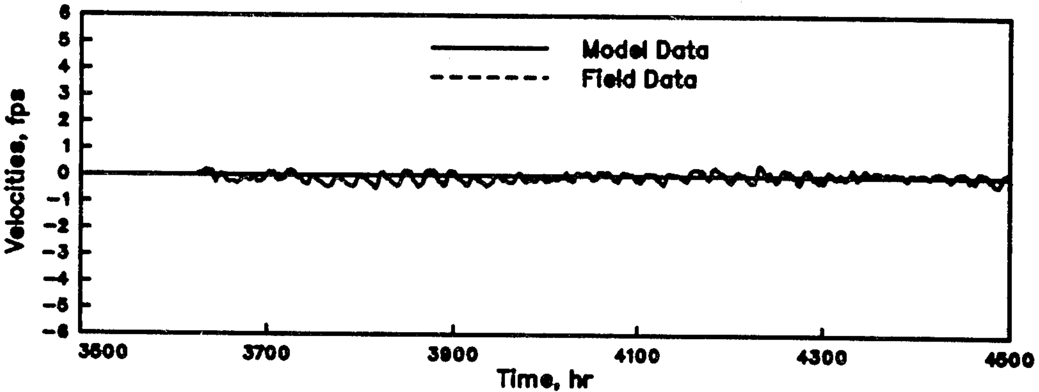


Station 6.1m

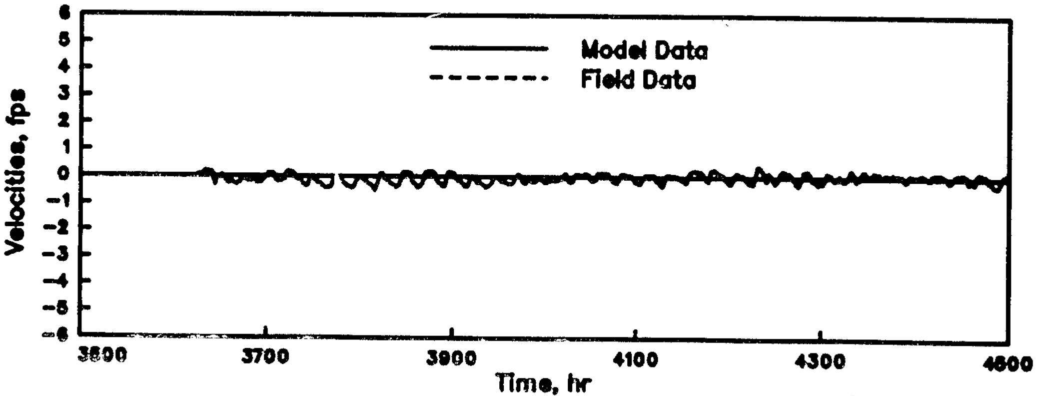
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 3500-4500



Station 12.0t

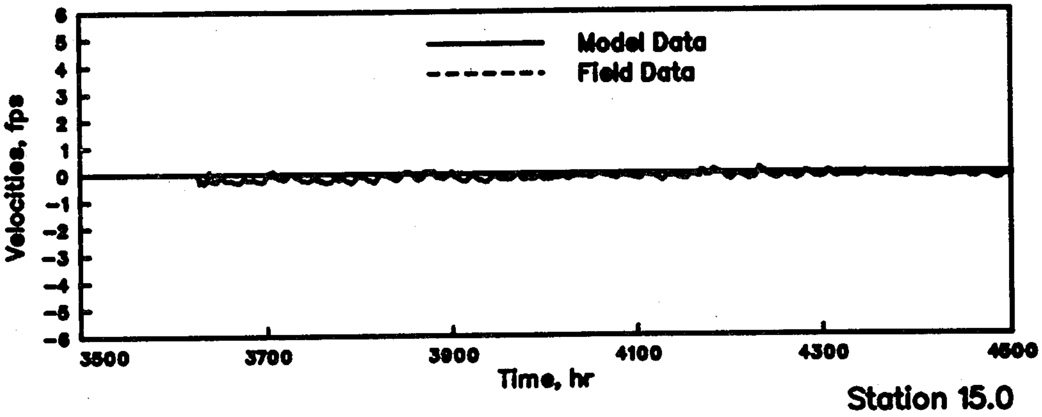


Station 12.1m

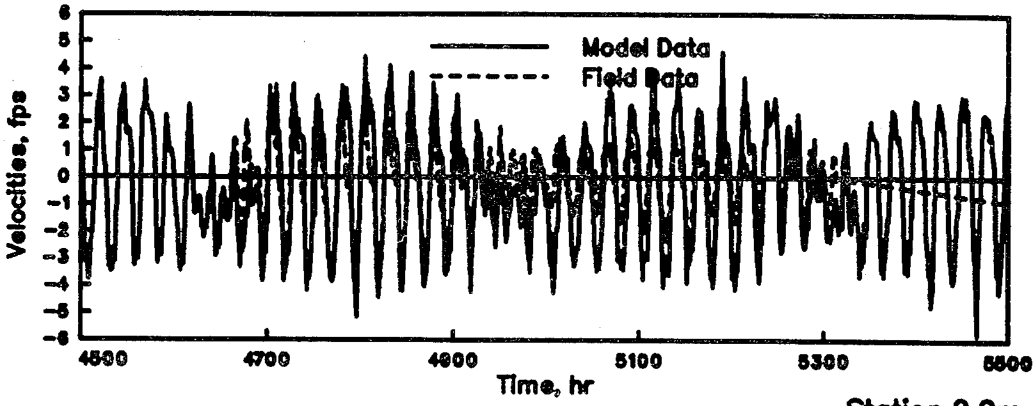


Station 12.1t

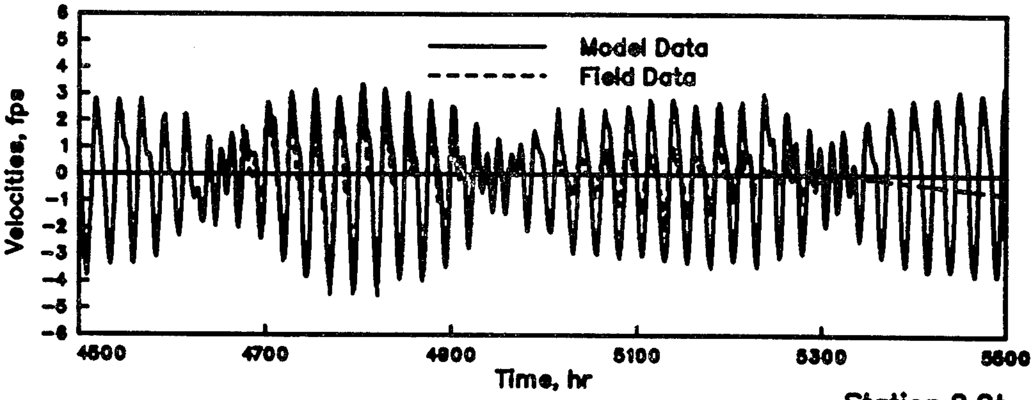
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 12.0t, 12.1m, AND 12.1t
HOURS 3500-4500



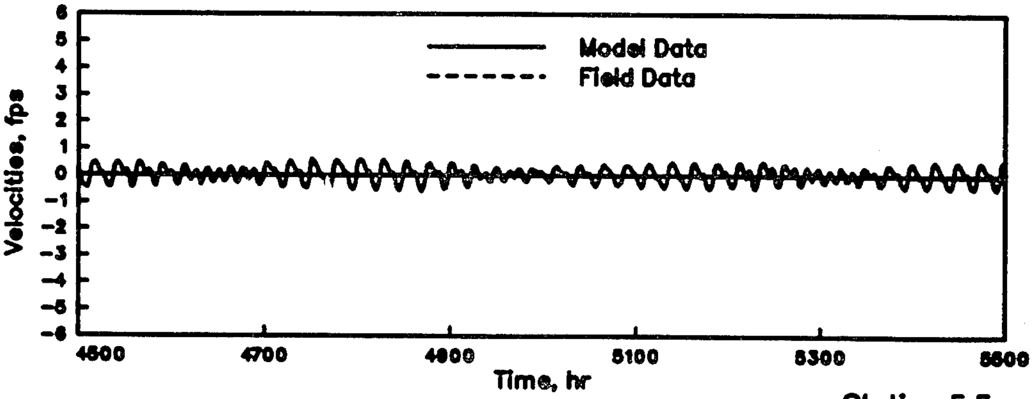
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 15
HOURS 3500-4500



Station 2.0m

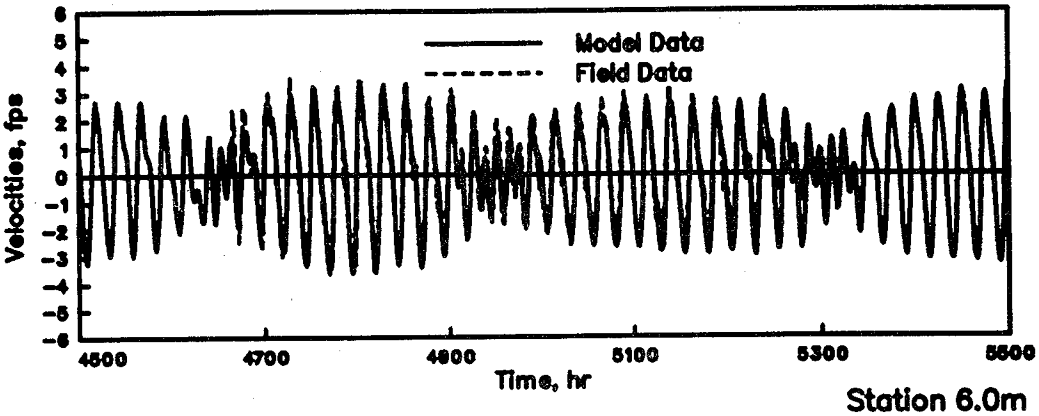


Station 2.0t

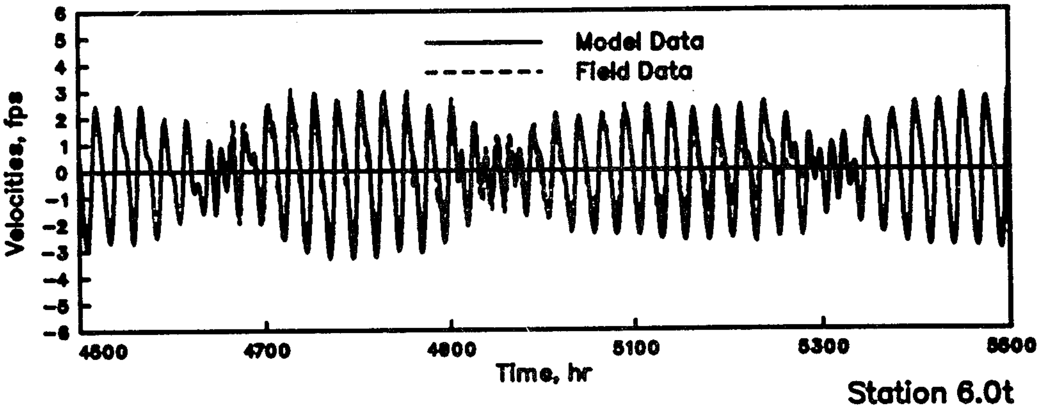


Station 5.5

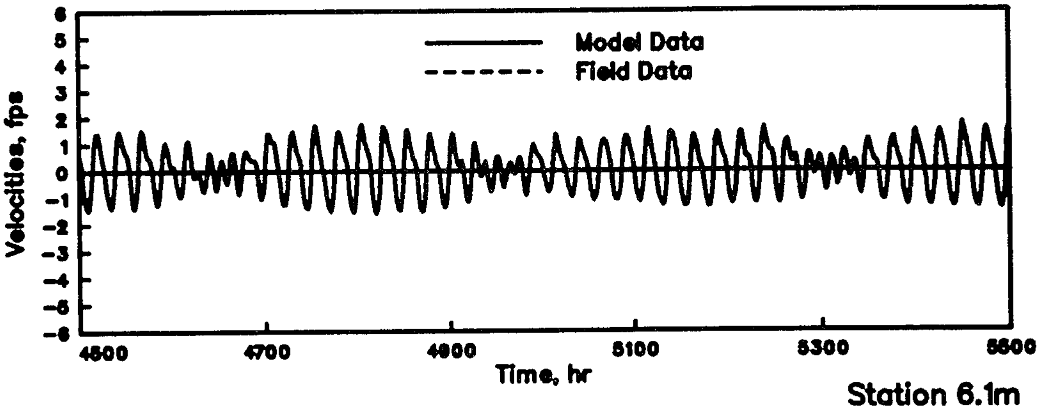
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 2.0m, 2.0t, AND 5.5
HOURS 4500-5500



Station 6.0m

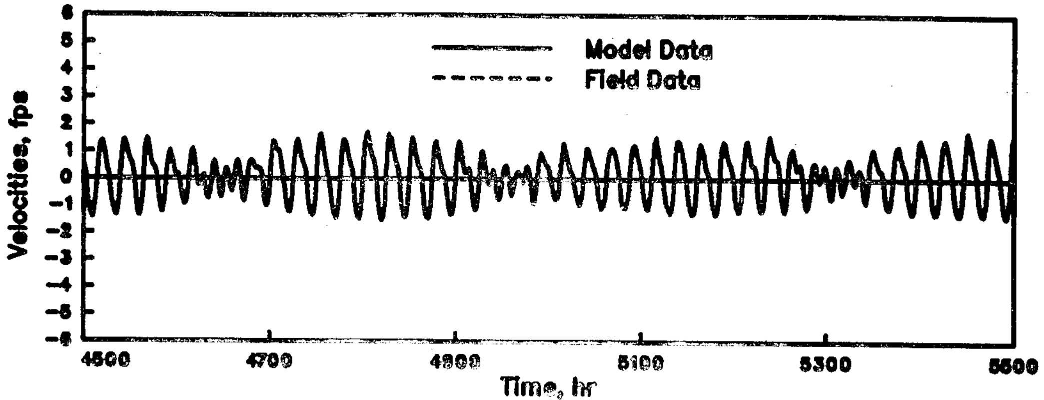


Station 6.0t

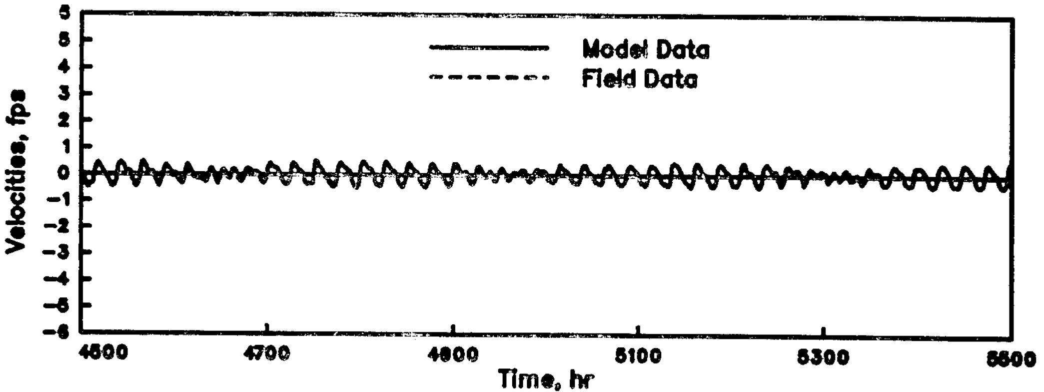


Station 6.1m

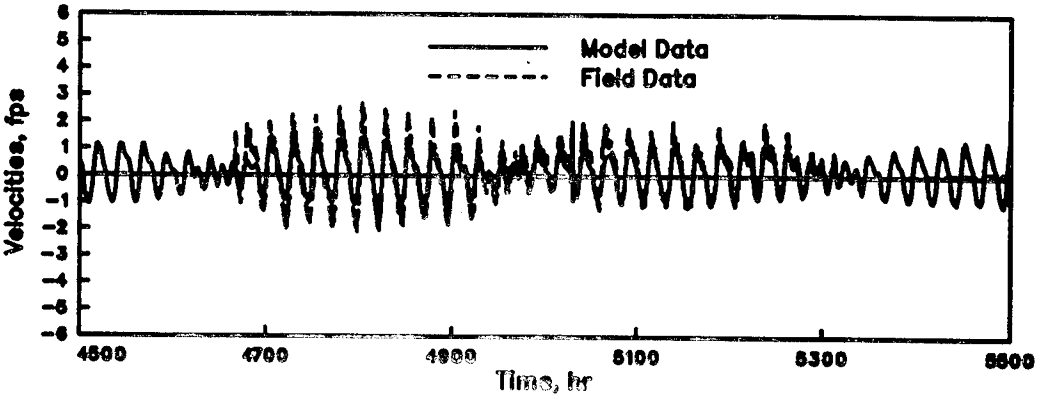
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 4500-5500



Station 6.1t

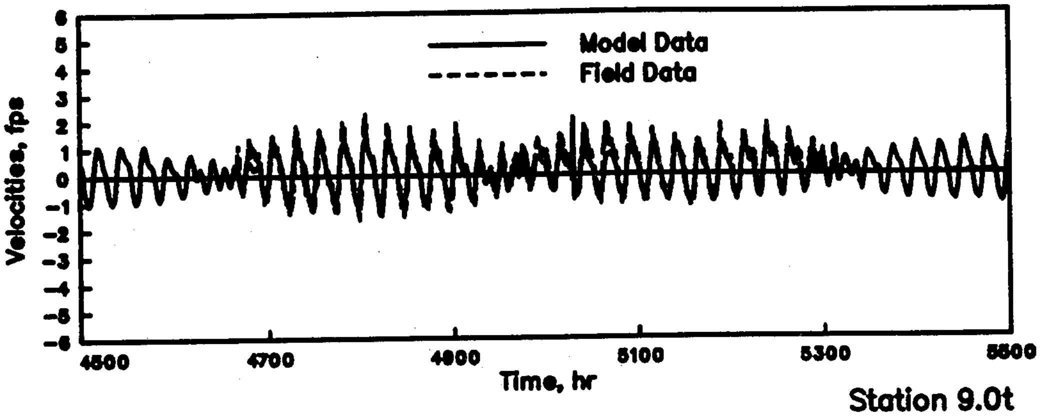


Station 8.0

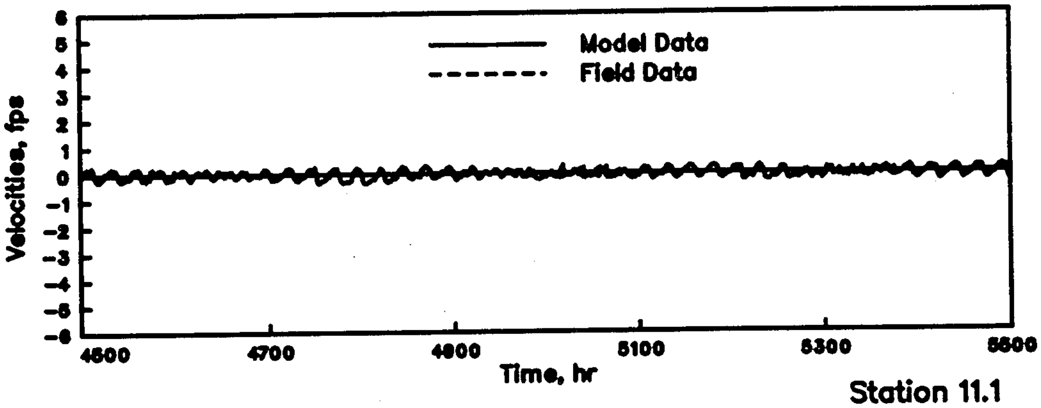


Station 9.0m

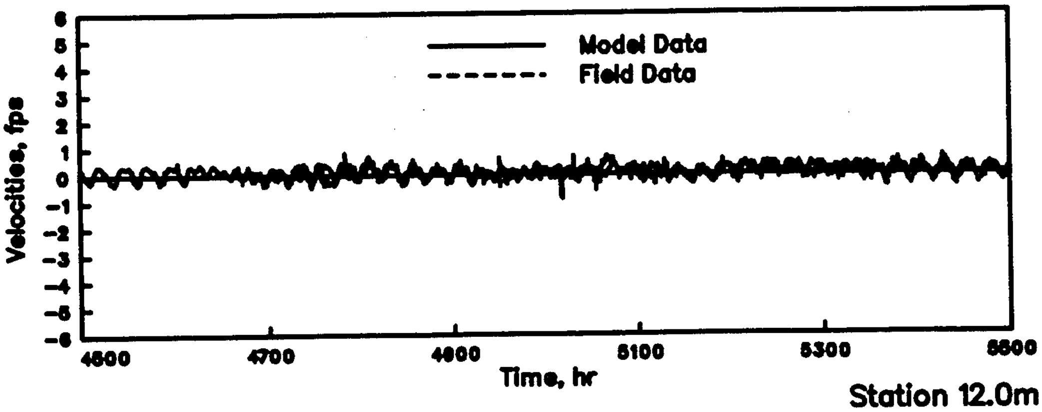
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.1t, 8.0, AND 9.0m
HOURS 4500-5500



Station 9.0t

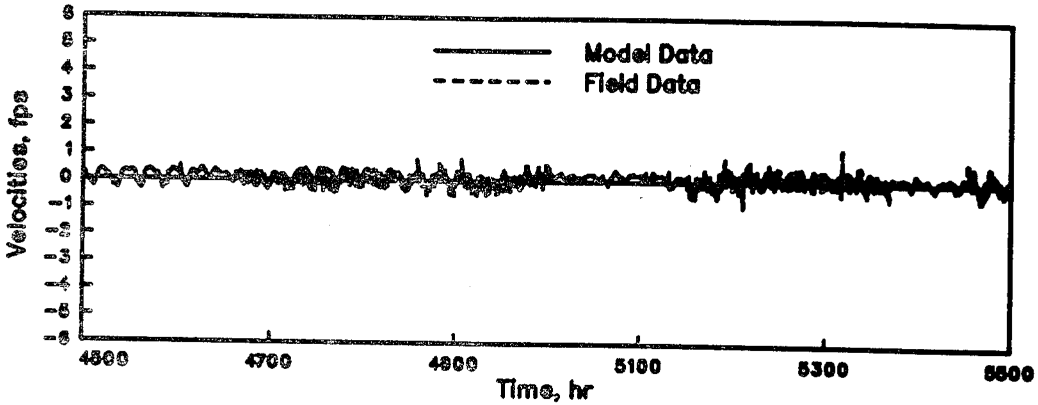


Station 11.1

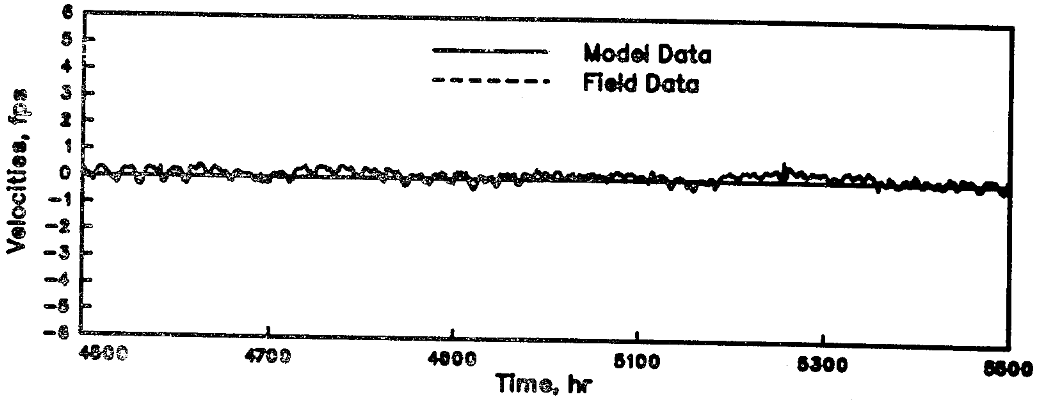


Station 12.0m

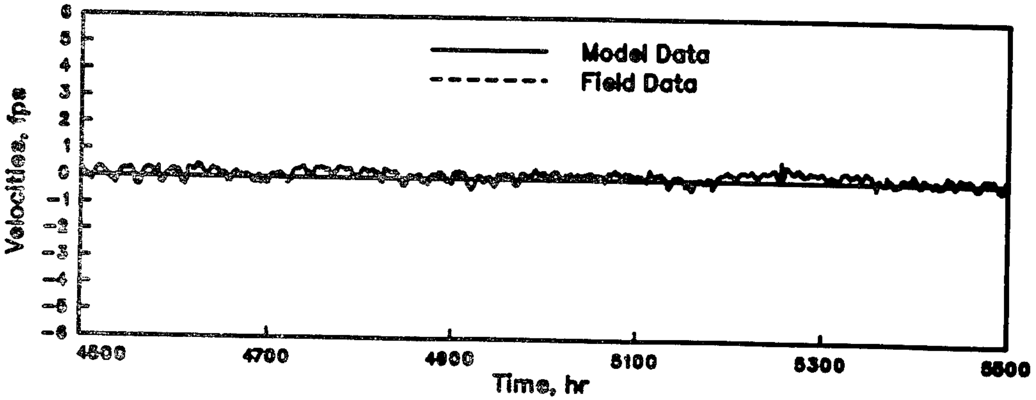
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 9.0t, 11.1, AND 12.0m
HOURS 4500-5500



Station 12.0t

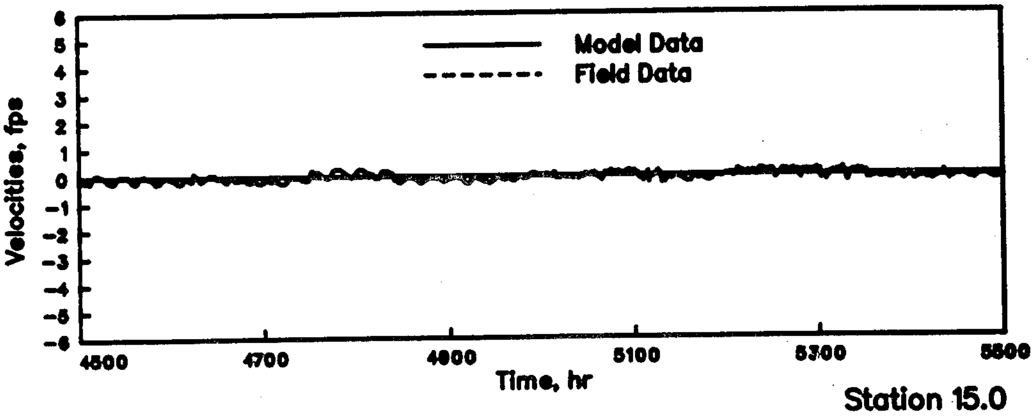


Station 12.1m

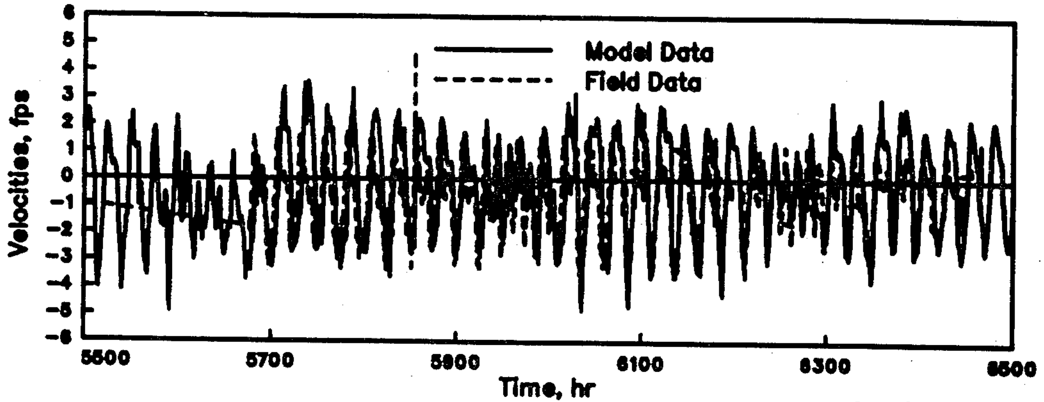


Station 12.1t

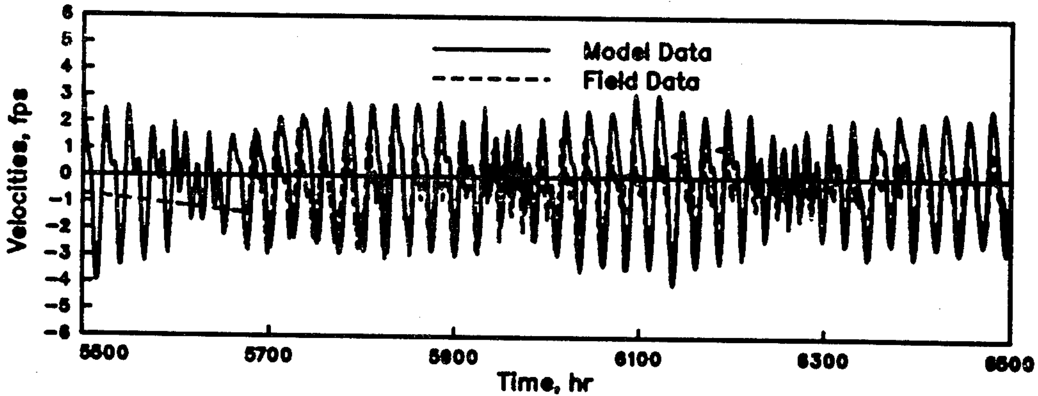
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 12.0t, 12.1m, AND 12.1t
HOURS 4500-5500



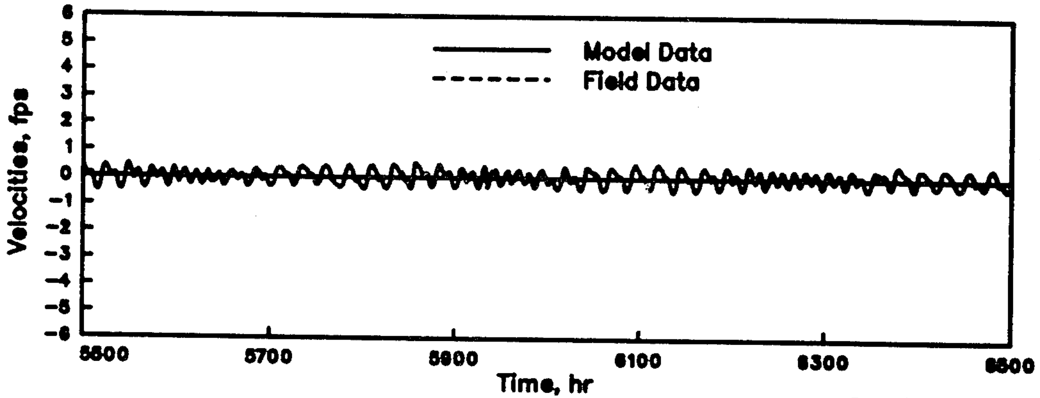
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 15
HOURS 4500-5500



Station 2.0m

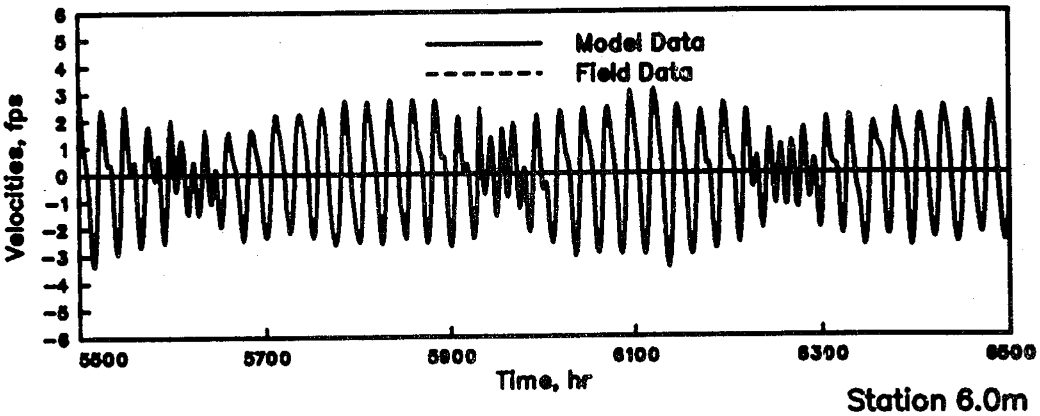


Station 2.0t

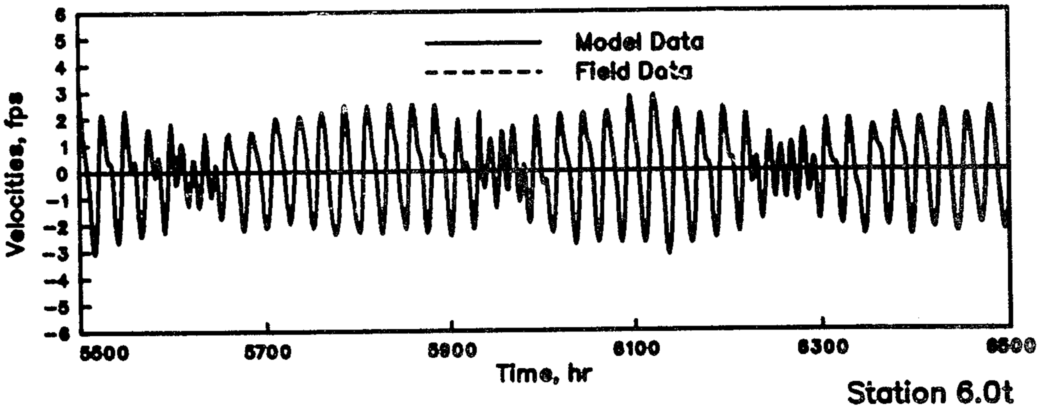


Station 5.5

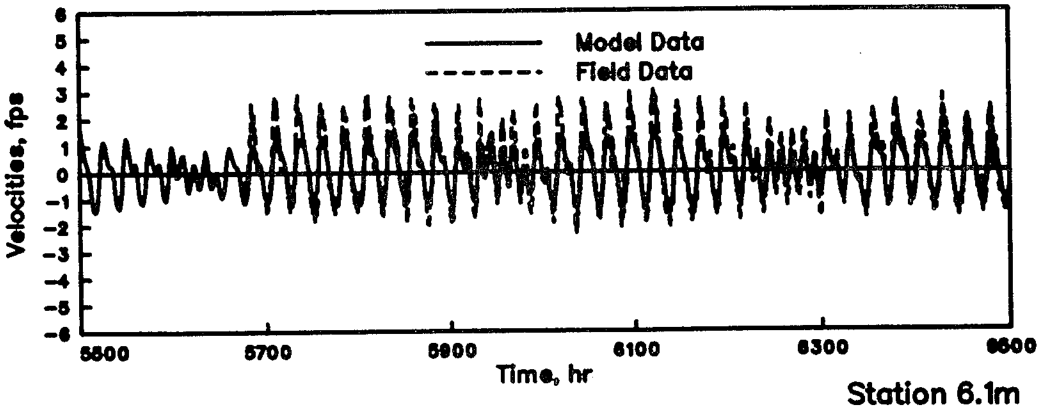
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 2.0m, 2.0t, AND 5.5
HOURS 5500-6500



Station 6.0m

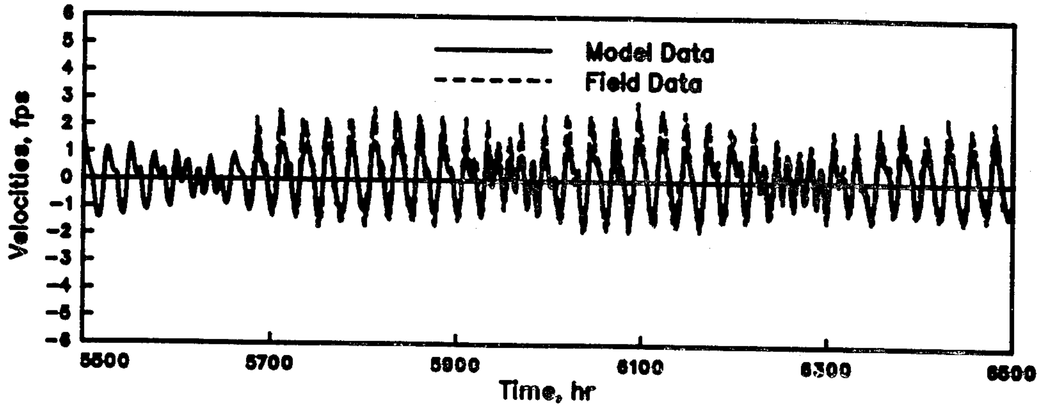


Station 6.0t

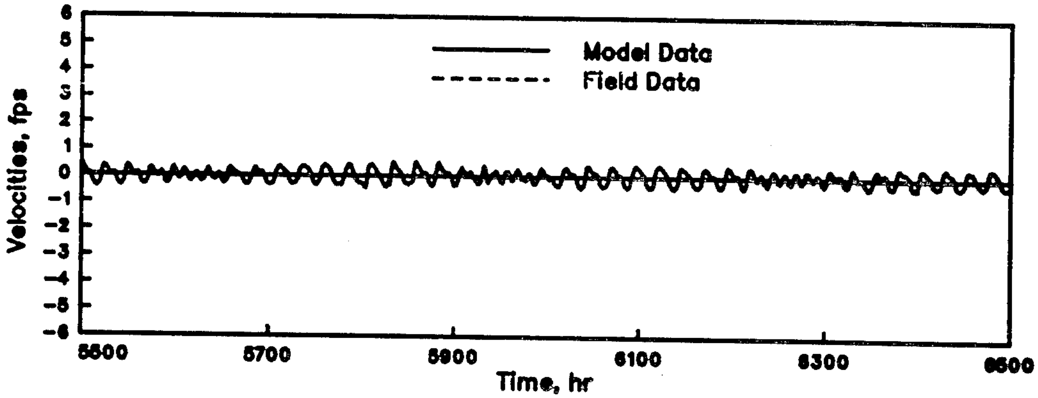


Station 6.1m

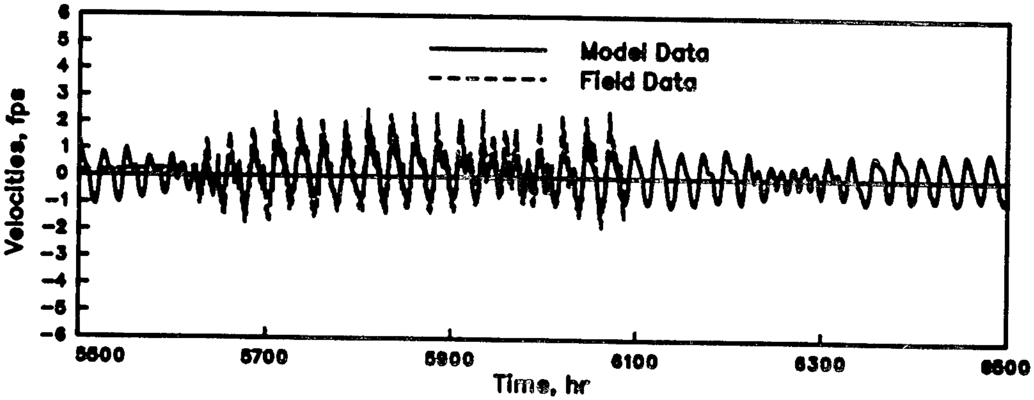
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 5500-6500



Station 6.1t

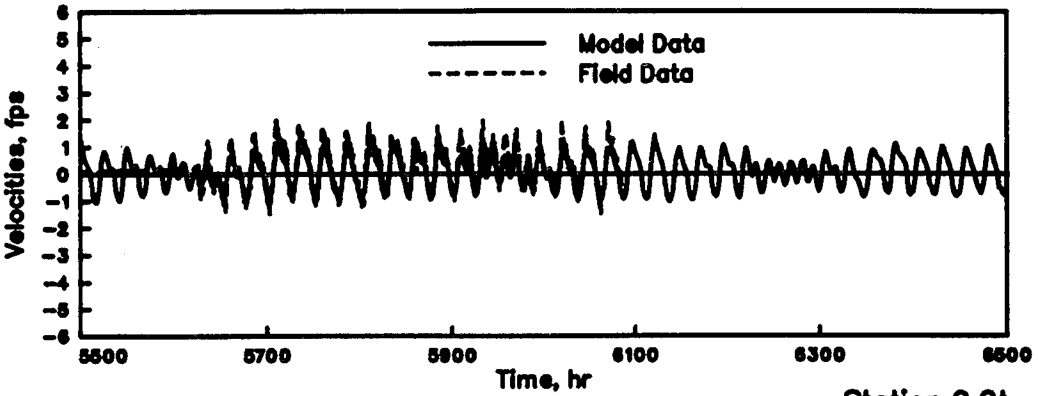


Station 8.0

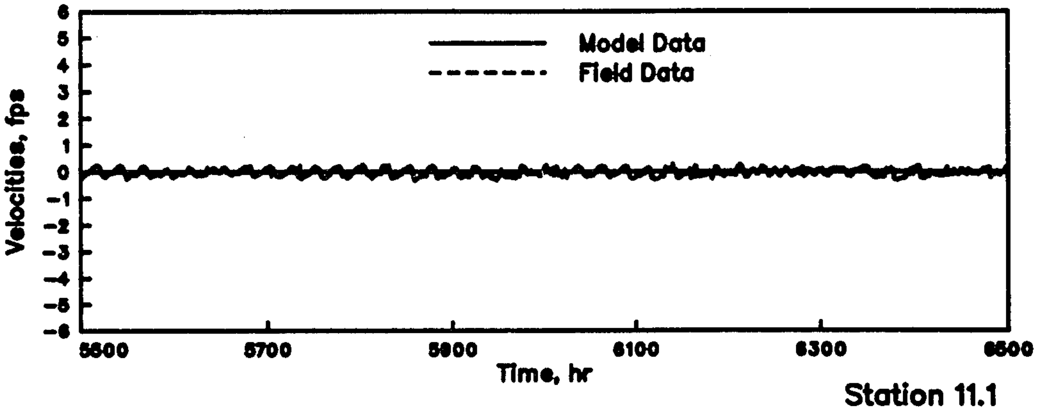


Station 9.0m

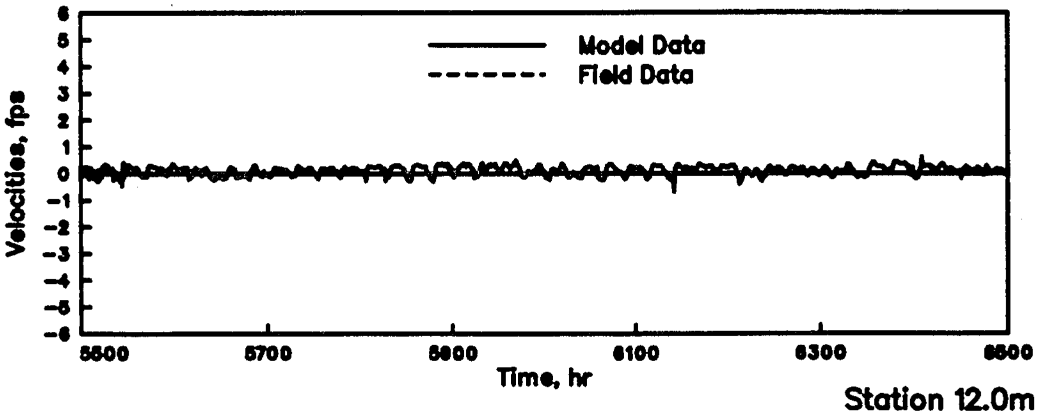
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.1t, 8.0, AND 9.0m
HOURS 5500-6500



Station 9.0t

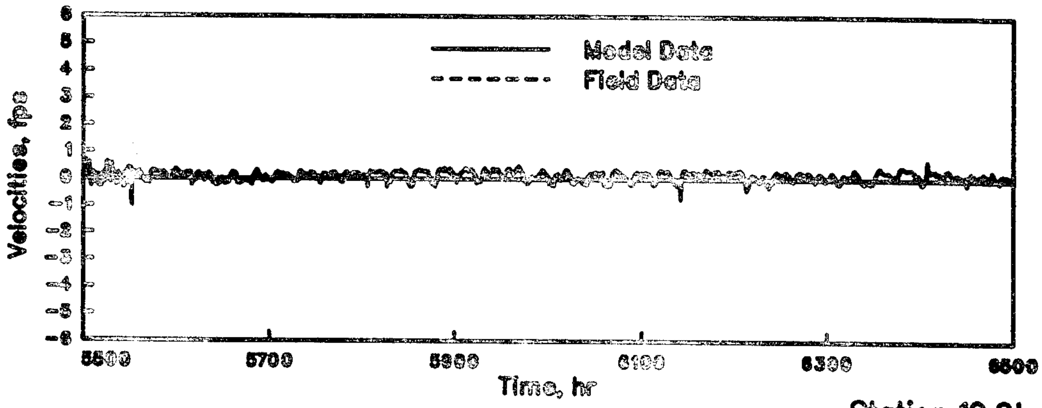


Station 11.1

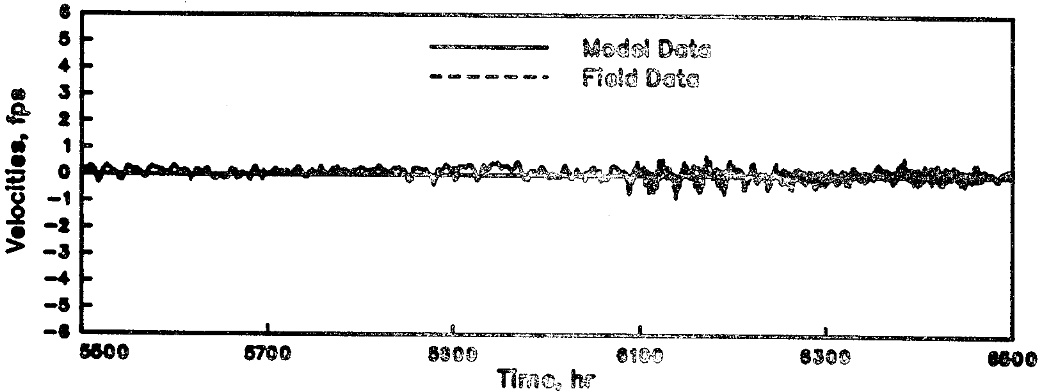


Station 12.0m

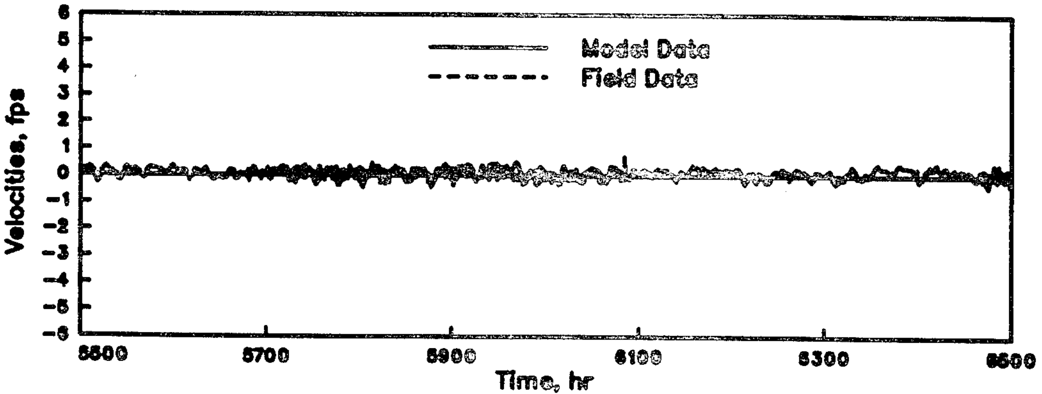
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 9.0t, 11.1, AND 12.0m
HOURS 5500-6500



Station 12.0t

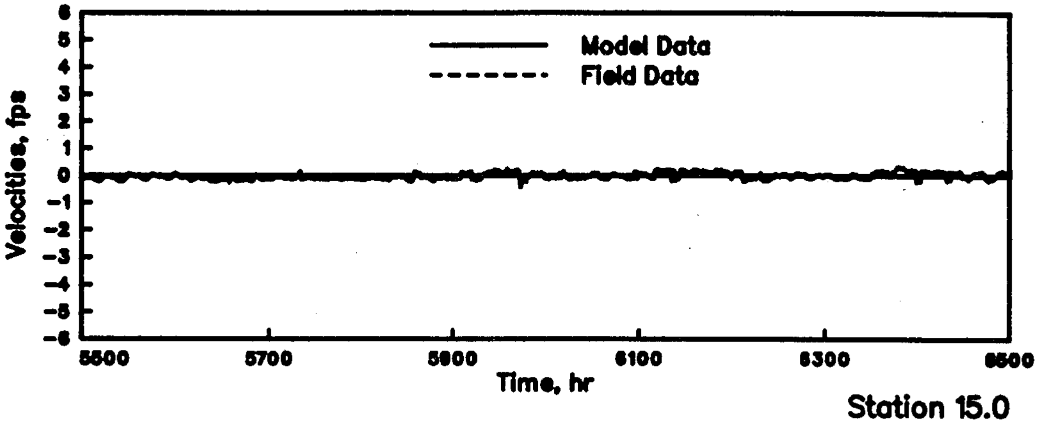


Station 12.1m

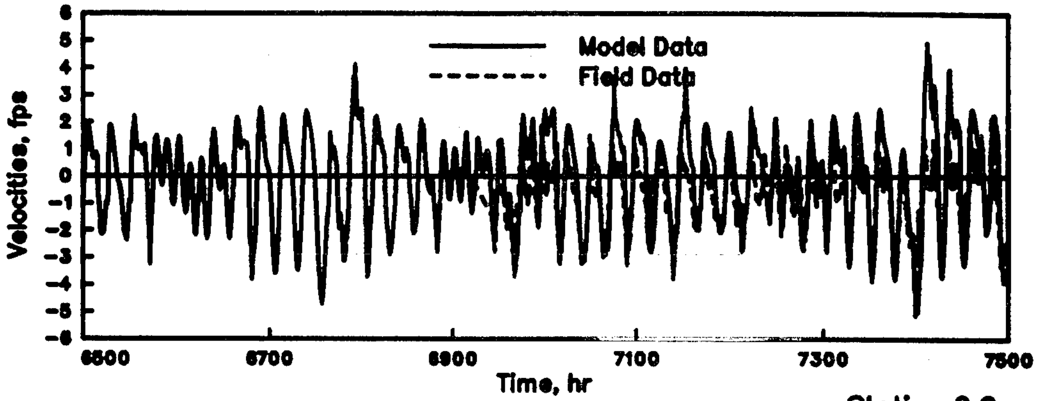


Station 12.1t

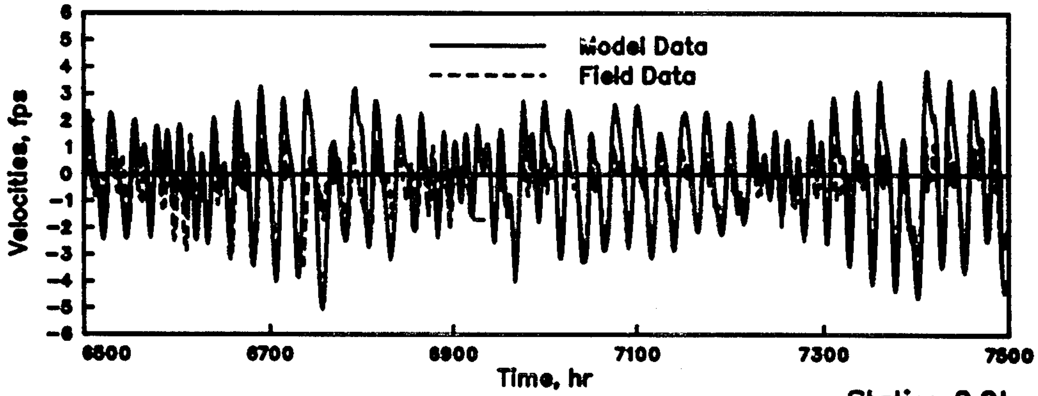
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 12.0t, 12.1m, AND 12.1t
HOURS 5500-6500



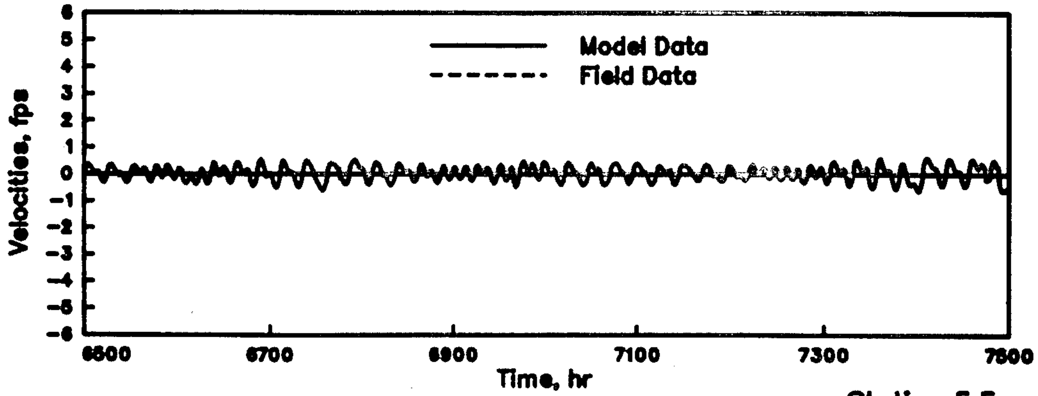
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 15
HOURS 5500-6500



Station 2.0m

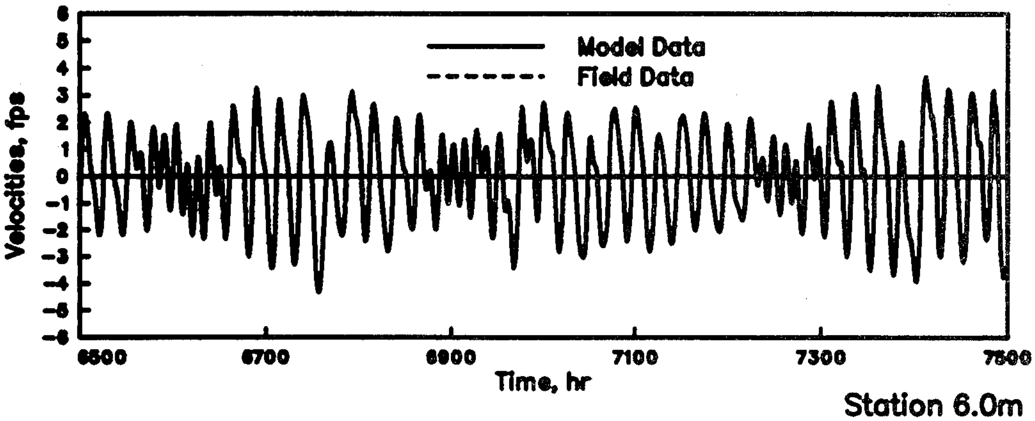


Station 2.0t

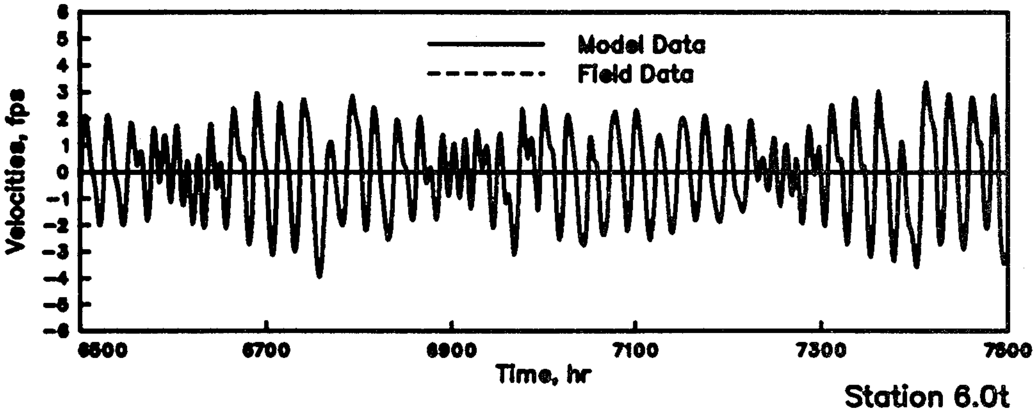


Station 5.5

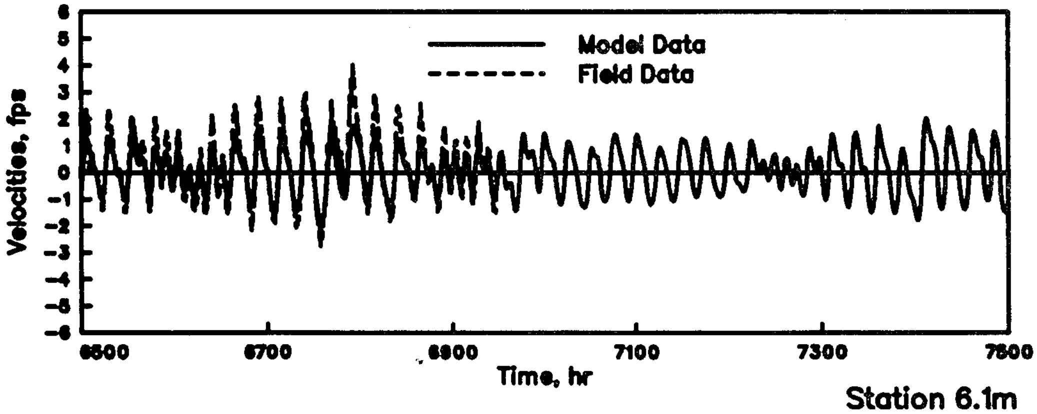
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 2.0m, 2.0t, AND 5.5
HOURS 6500-7500



Station 6.0m

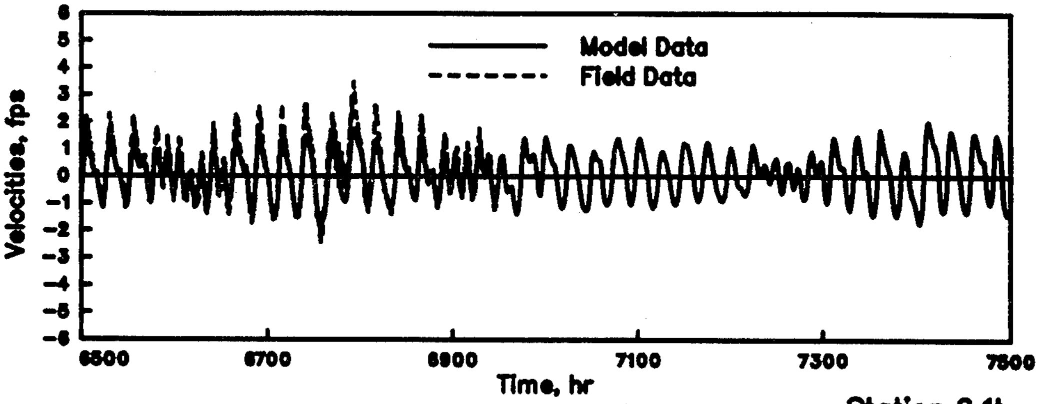


Station 6.0t

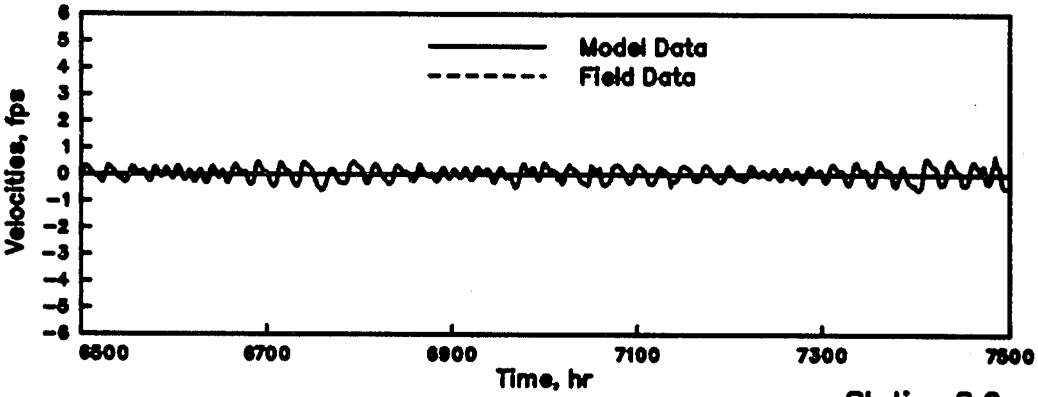


Station 6.1m

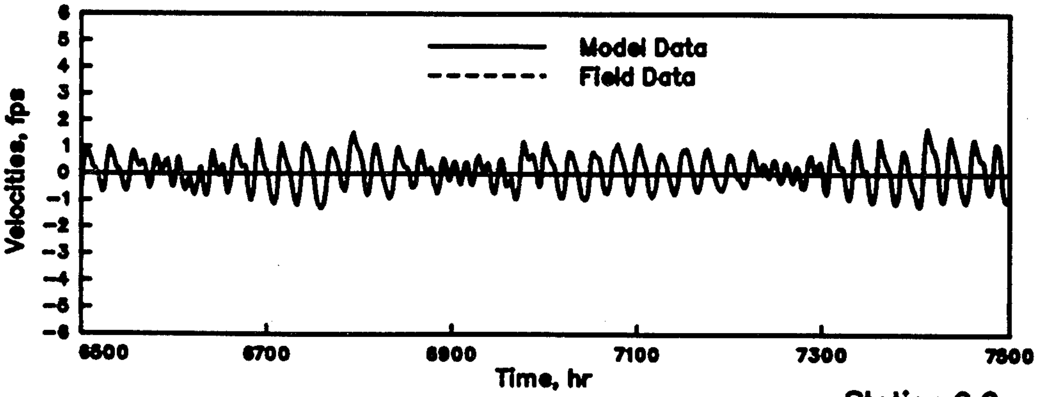
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 6500-7500



Station 6.1t

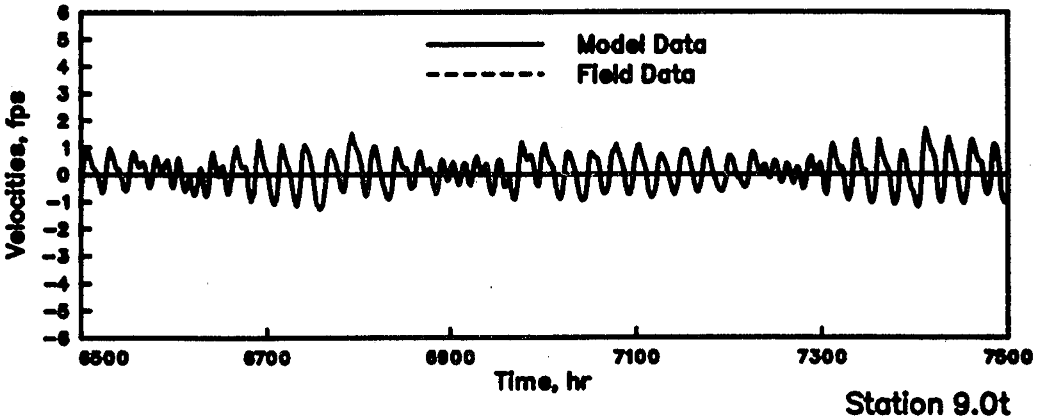


Station 8.0

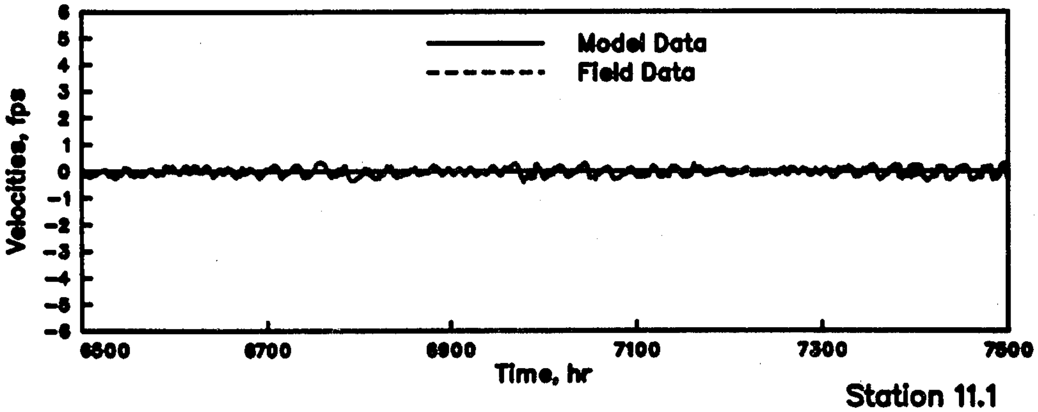


Station 9.0m

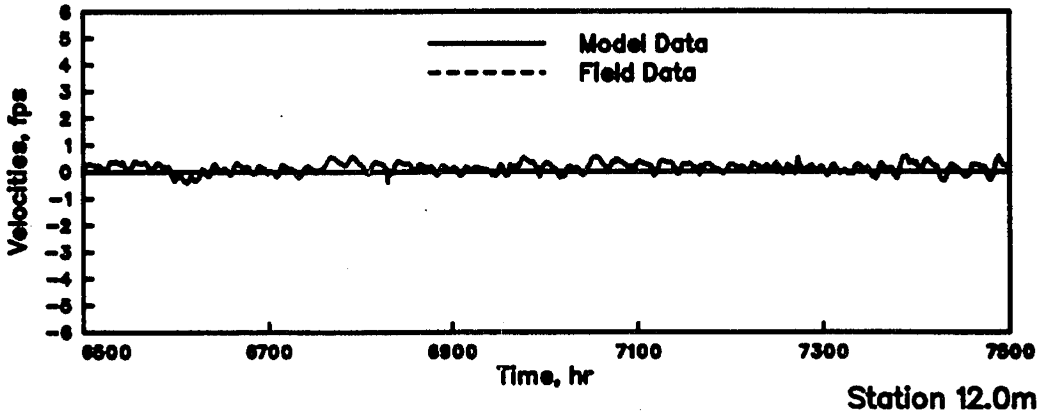
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.1t, 8.0, AND 9.0m
HOURS 6500-7500



Station 9.0t

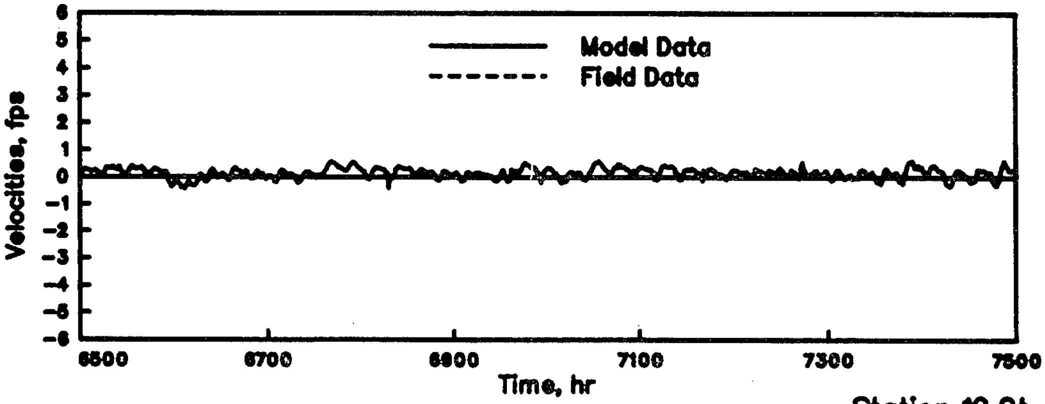


Station 11.1

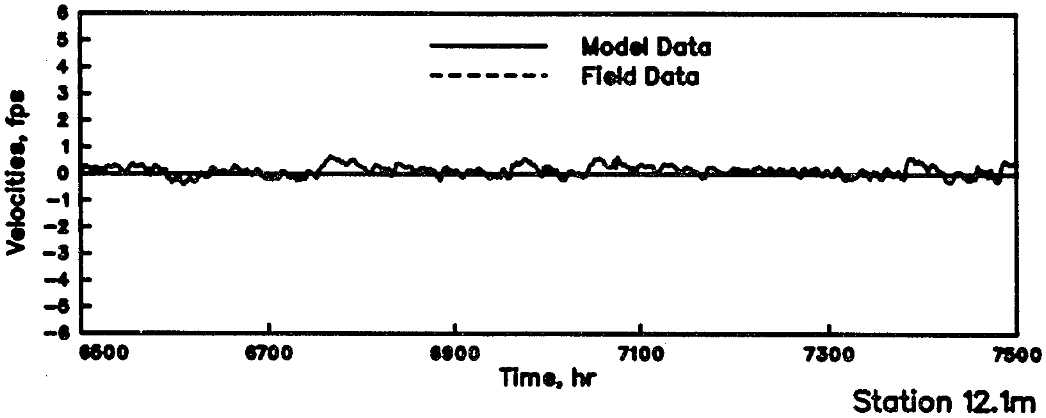


Station 12.0m

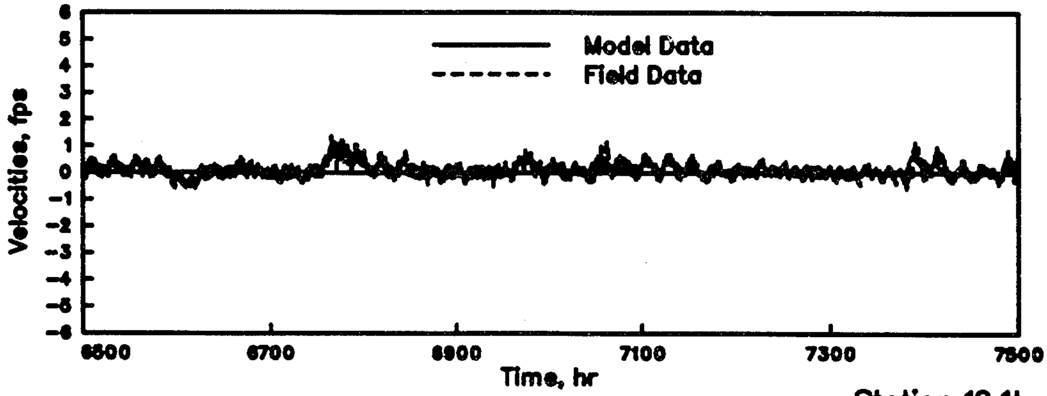
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 9.0t, 11.1, AND 12.0m
HOURS 6500-7500



Station 12.0t

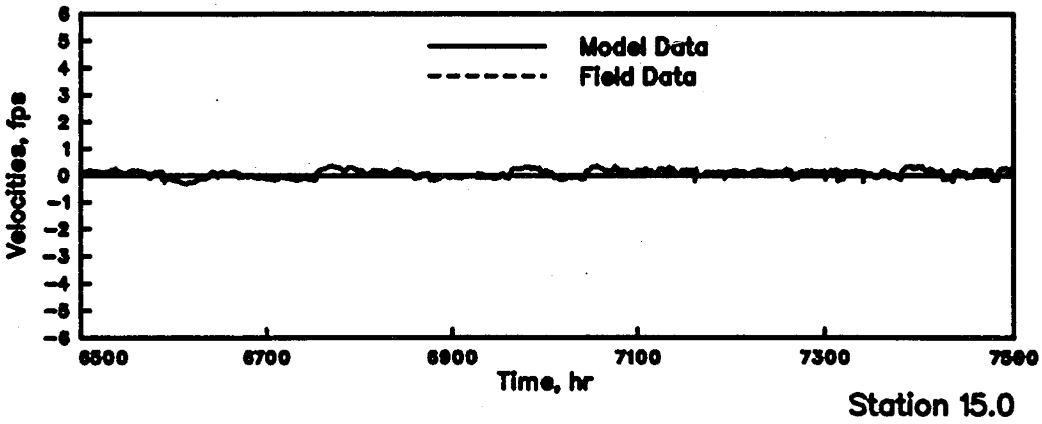


Station 12.1m

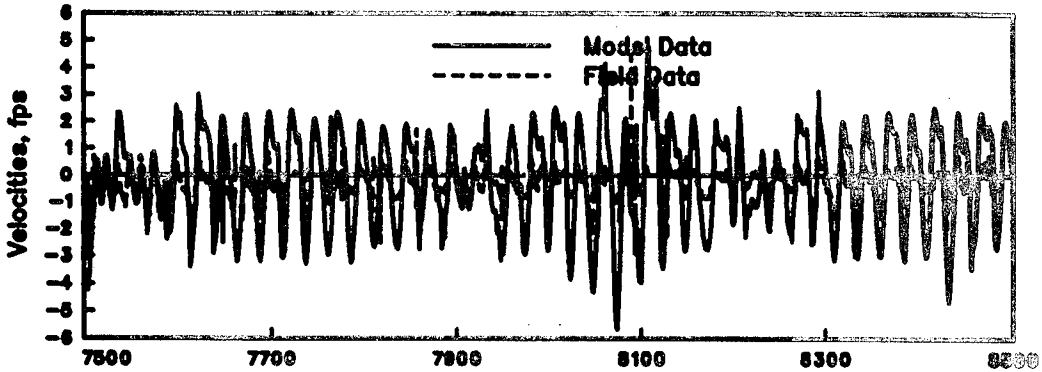


Station 12.1t

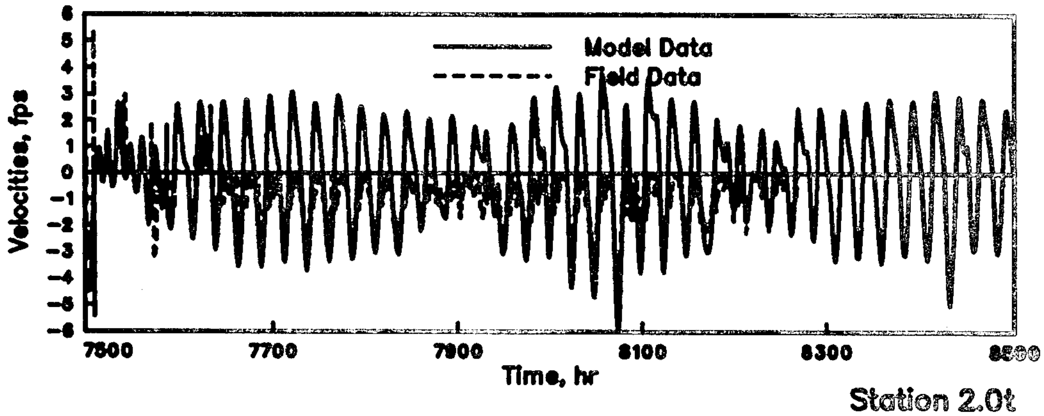
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 12.0t, 12.1m, AND 12.1t
HOURS 6500-7500



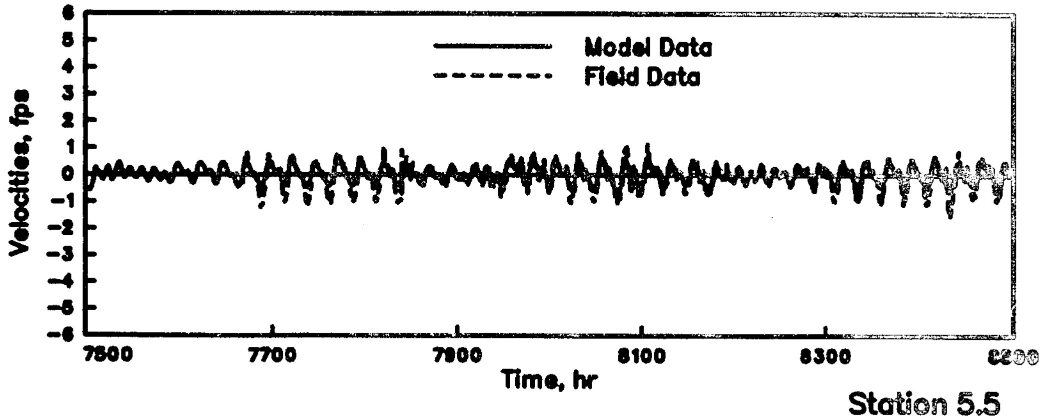
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 15
HOURS 6500-7500



Station 2.0m

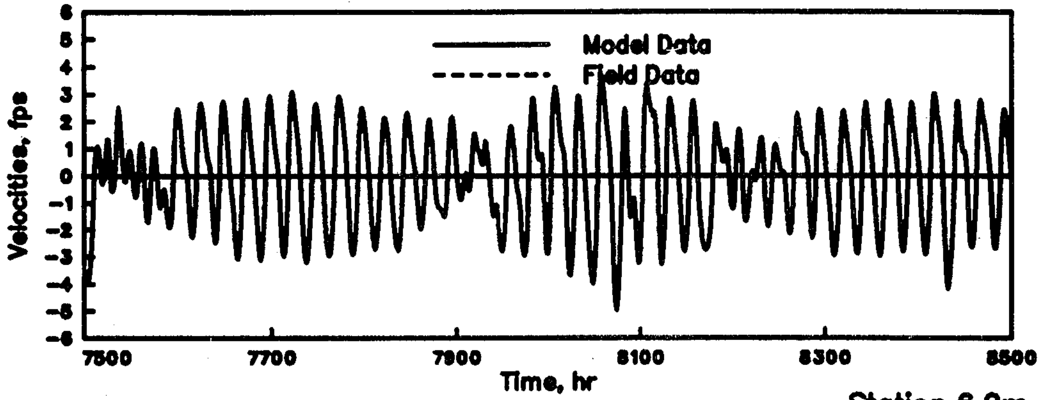


Station 2.0t

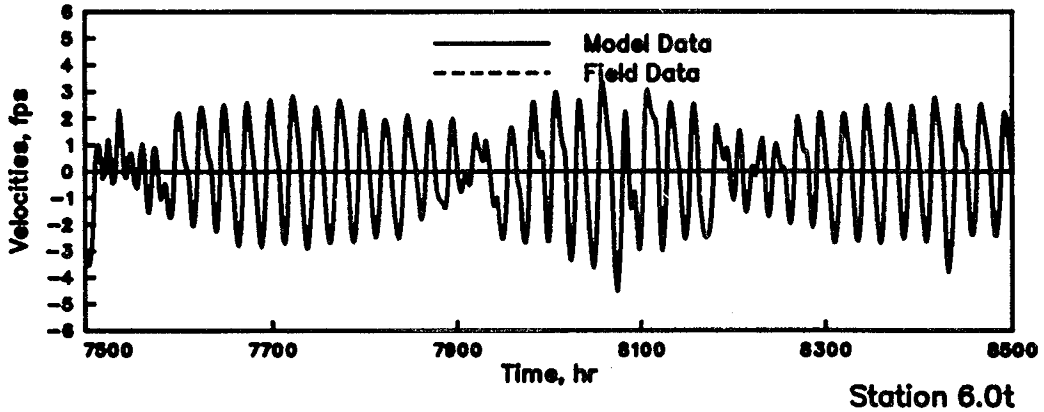


Station 5.5

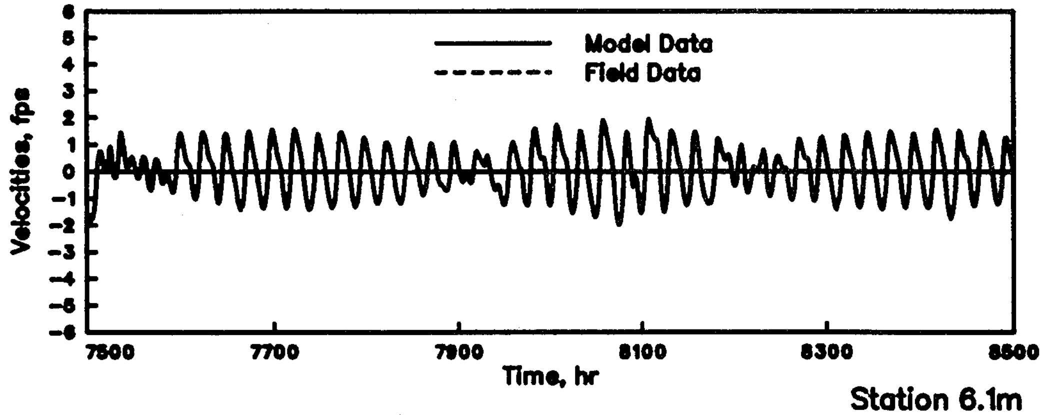
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 2.0m, 2.0t, AND 5.5
HOURS 7500-8500



Station 6.0m

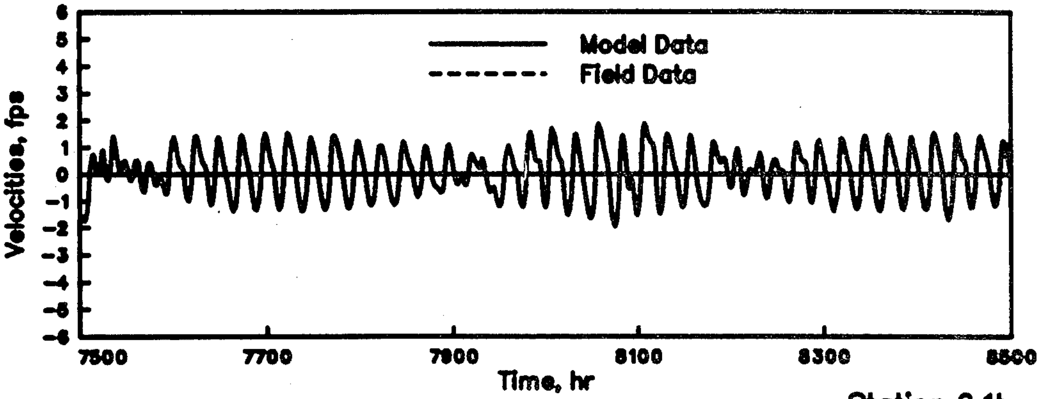


Station 6.0t

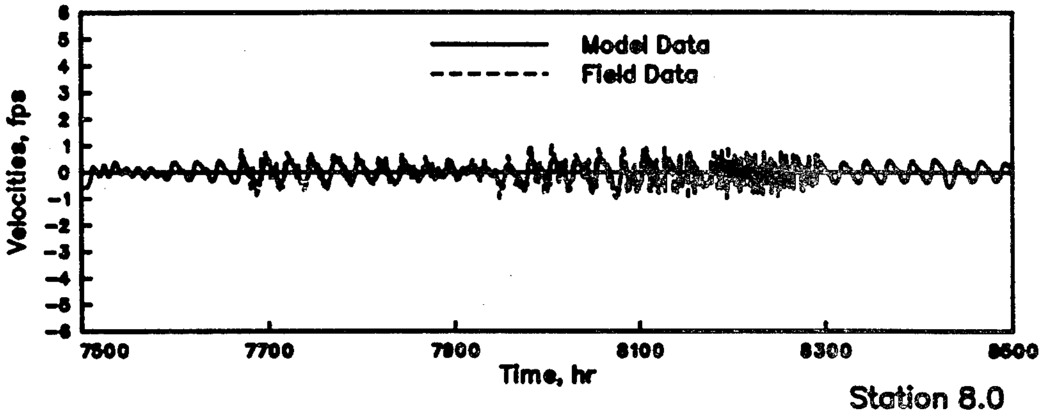


Station 6.1m

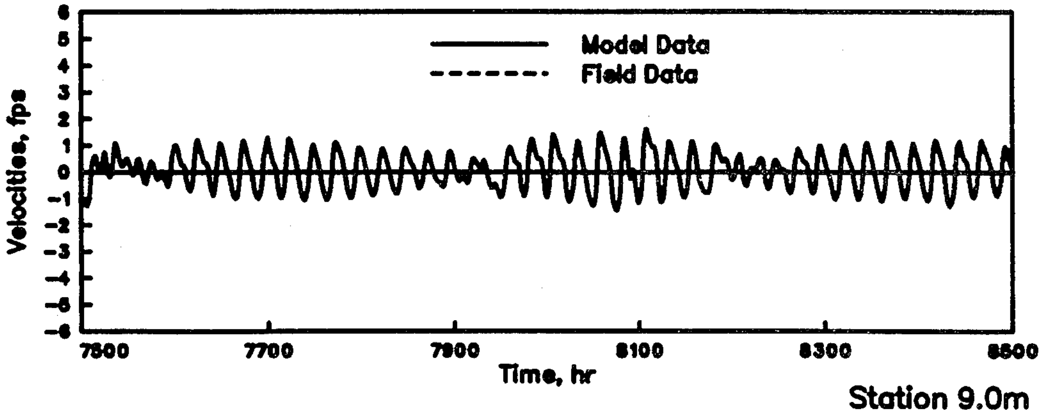
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 7500-8500



Station 6.1t



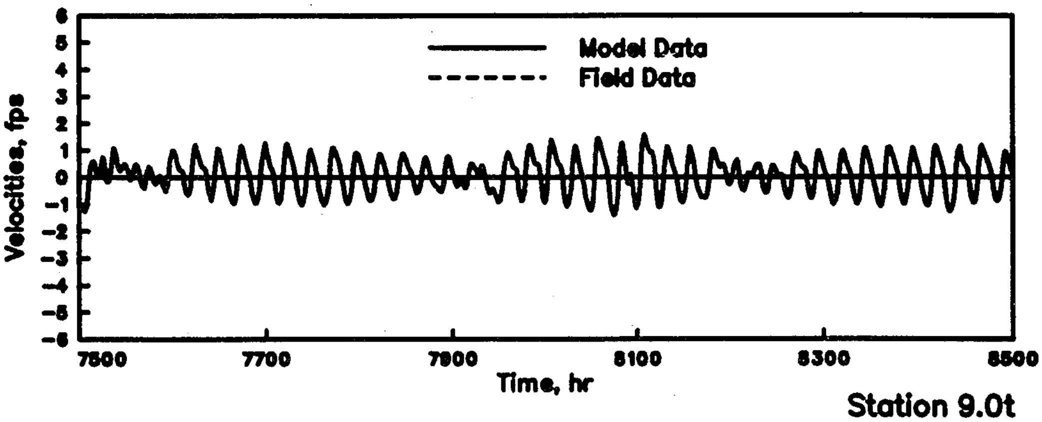
Station 8.0



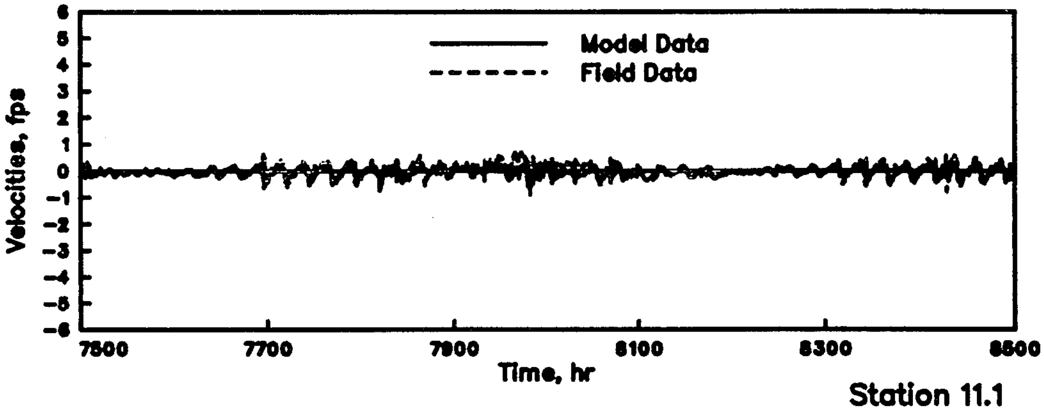
Station 9.0m

GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 6.1t, 8.0, AND 9.0m
HOURS 7500-8500

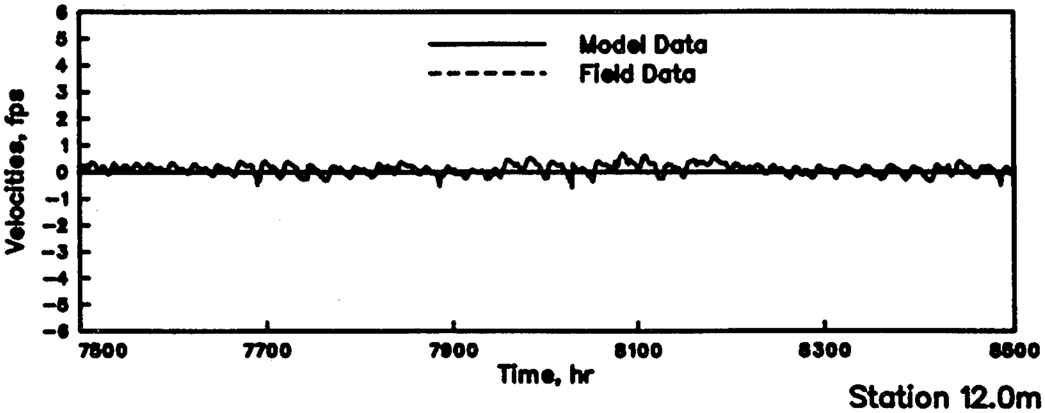
Plate 42



Station 9.0t

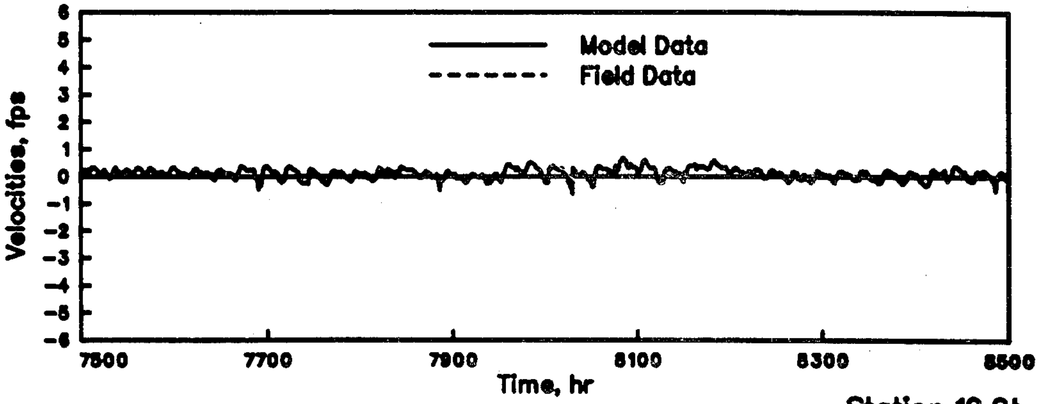


Station 11.1

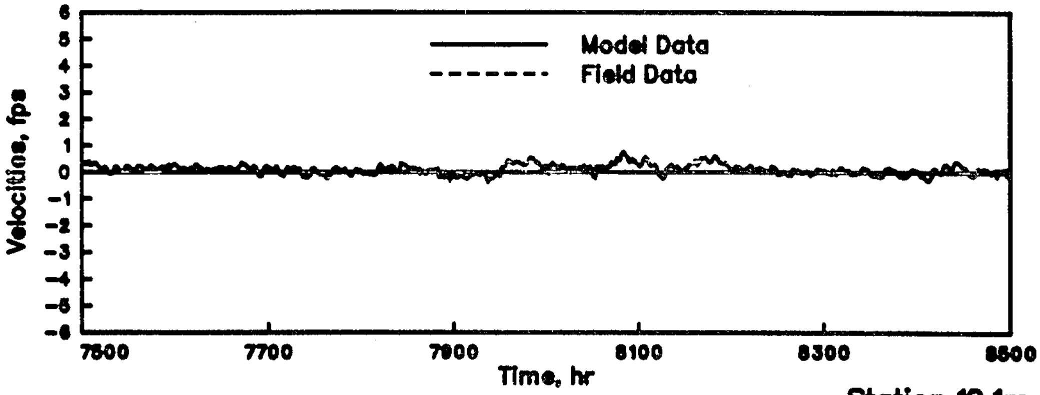


Station 12.0m

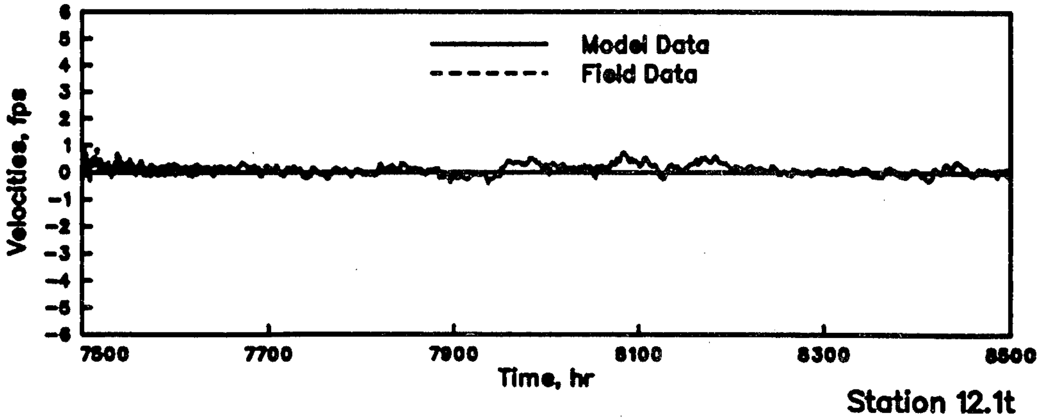
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 9.0t, 11.1, AND 12.0m
HOURS 7500-8500



Station 12.0t

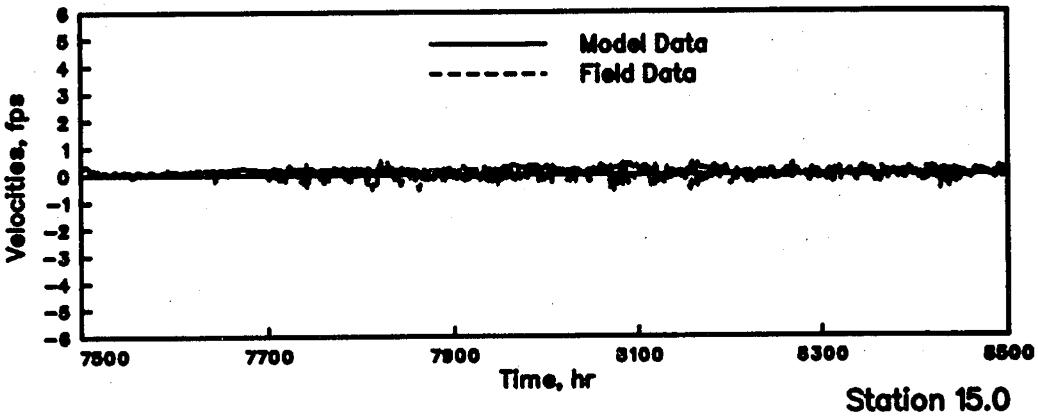


Station 12.1m

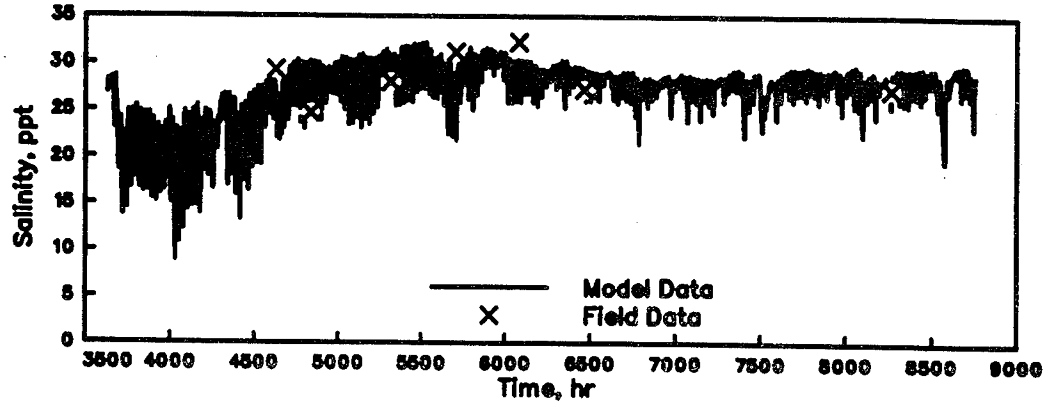


Station 12.1t

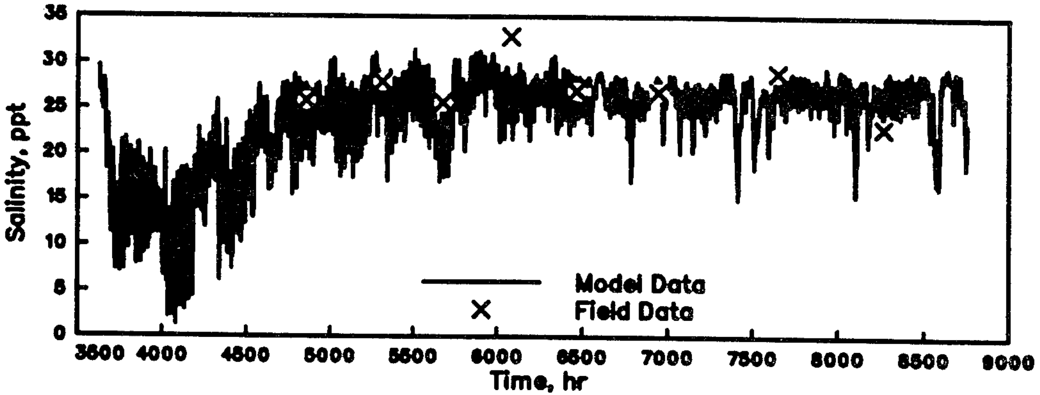
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATIONS 12.0t, 12.1m, AND 12.1t
HOURS 7500-8500



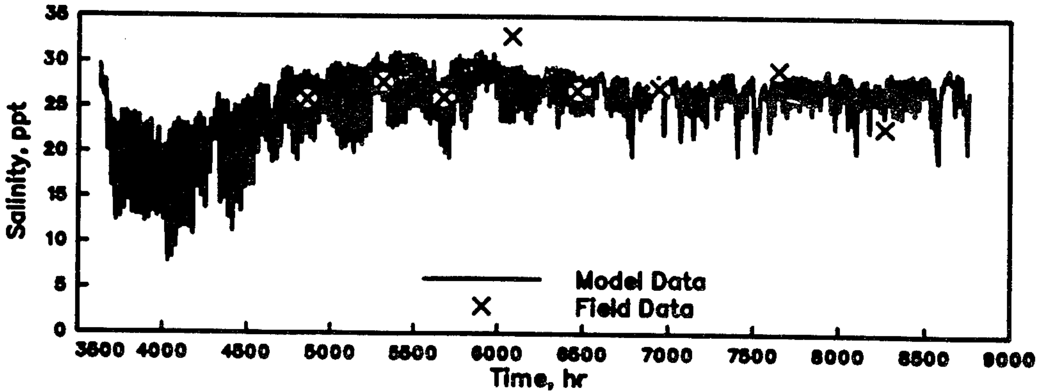
GALVESTON BAY VELOCITIES
MODEL VERIFICATION
STATION 15
HOURS 7500-8500



Station 1.0



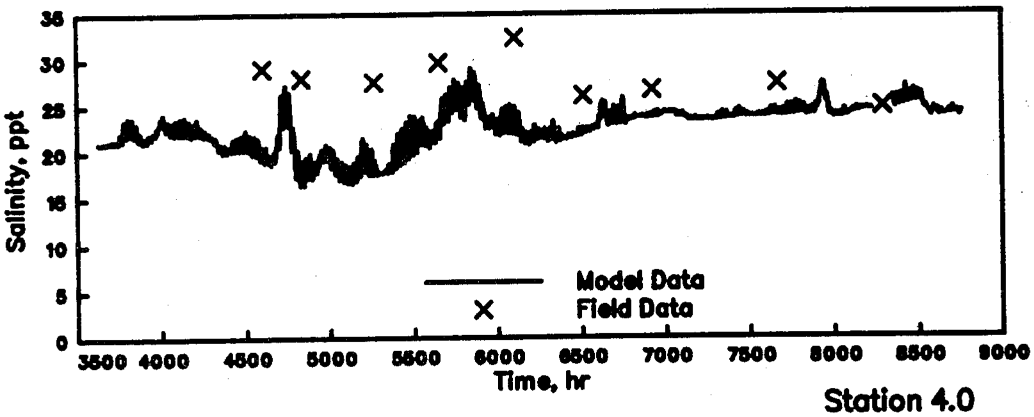
Station 2.0m



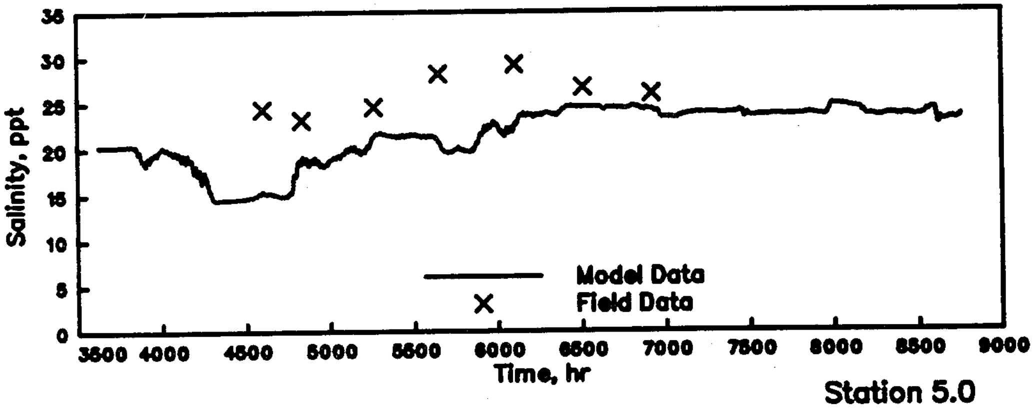
Station 2.0t

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 3500-9000

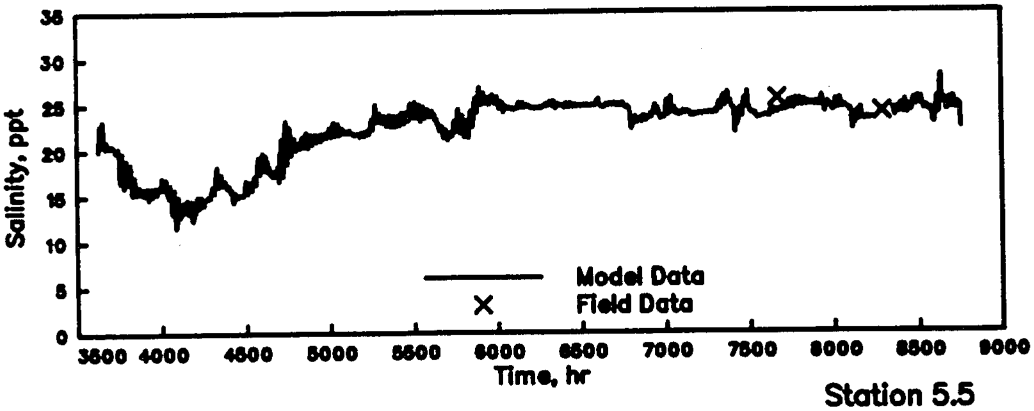
Plate 46



Station 4.0

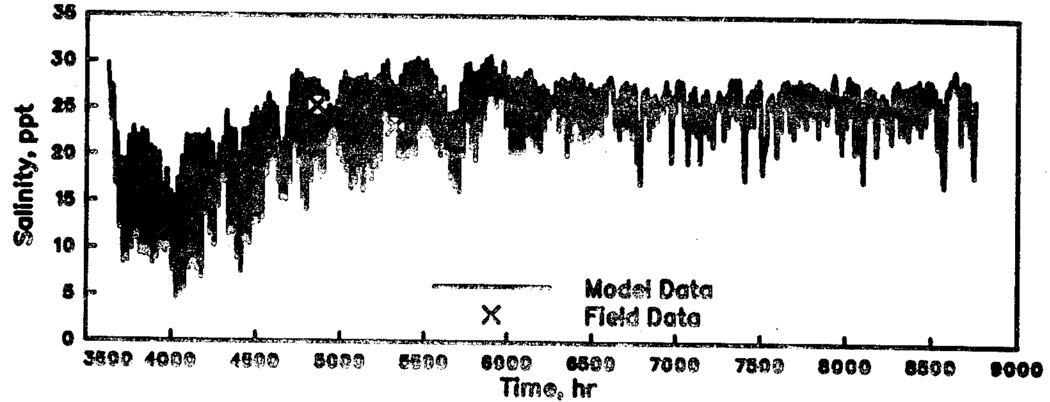


Station 5.0

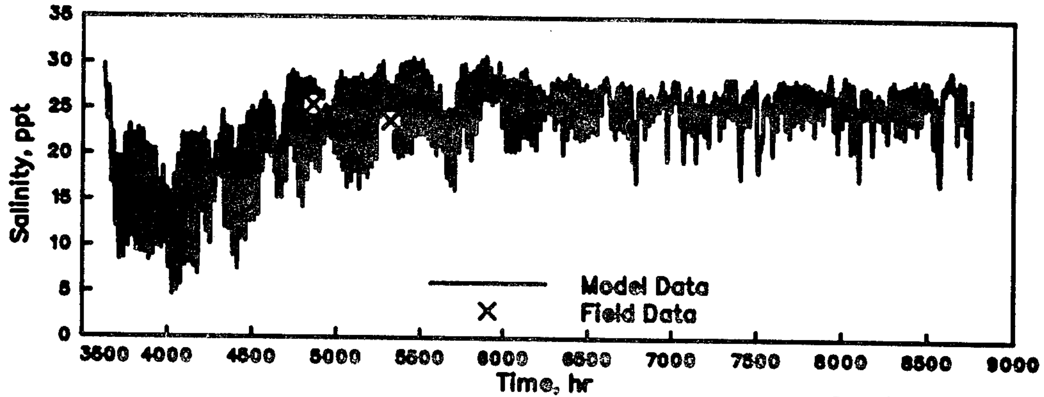


Station 5.5

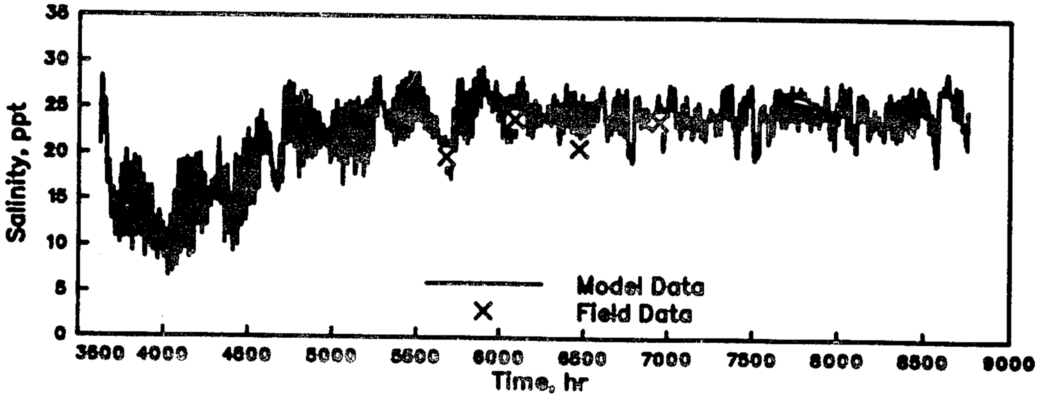
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 3500-9000



Station 6.0m

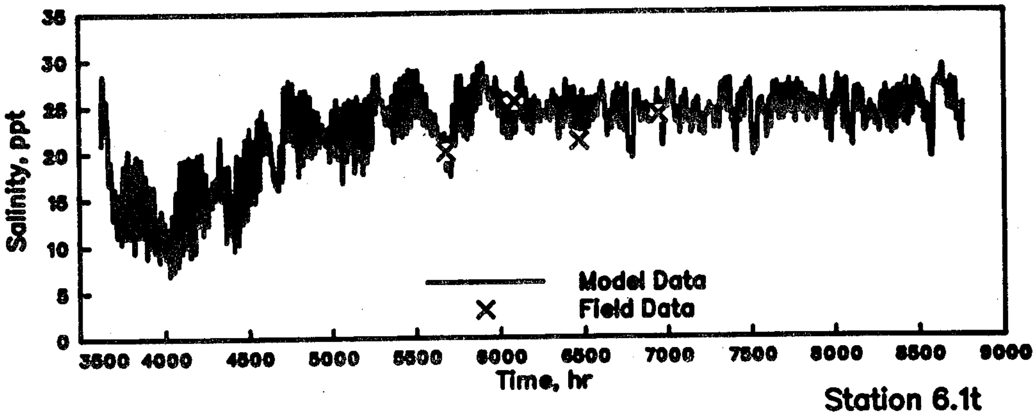


Station 6.0t

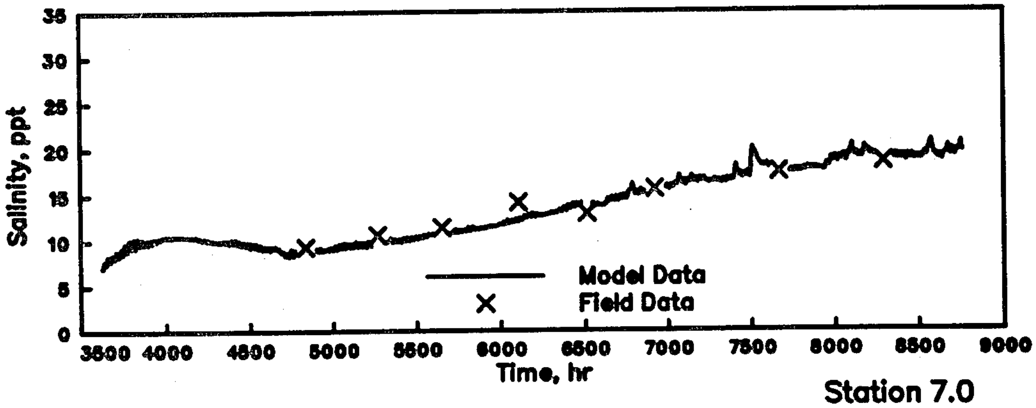


Station 6.1m

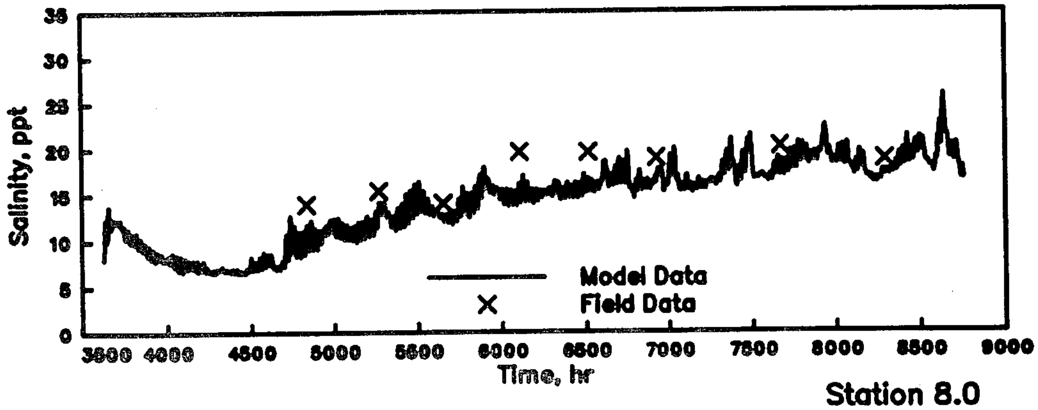
GALVESTON BAY SALINITIES,
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 3500-9000



Station 6.1t

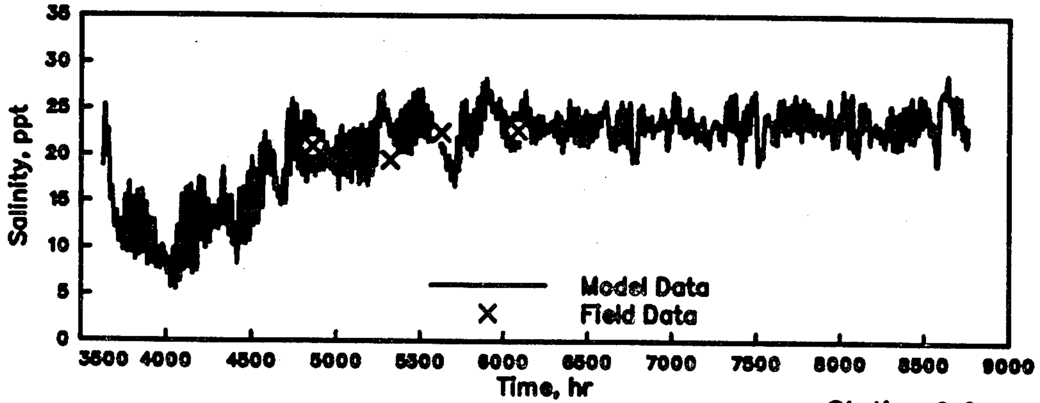


Station 7.0

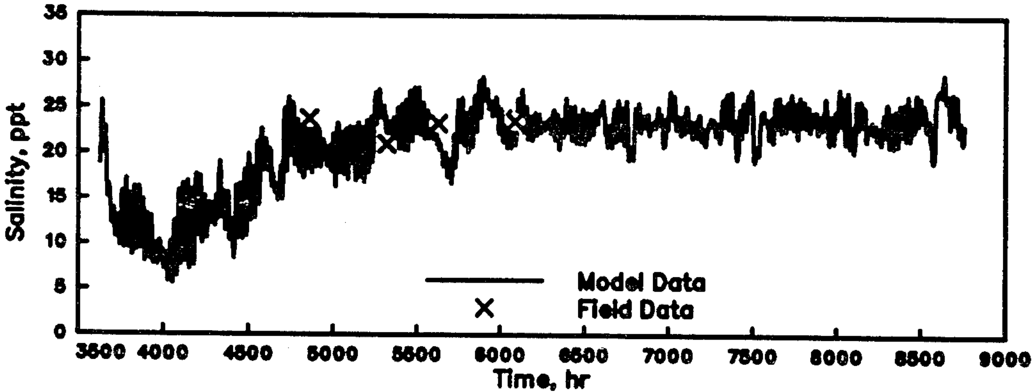


Station 8.0

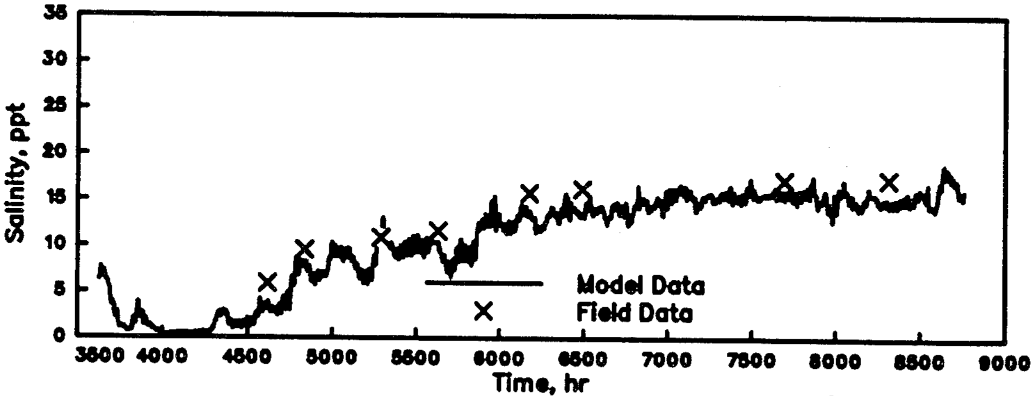
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 3500-9000



Station 9.0m

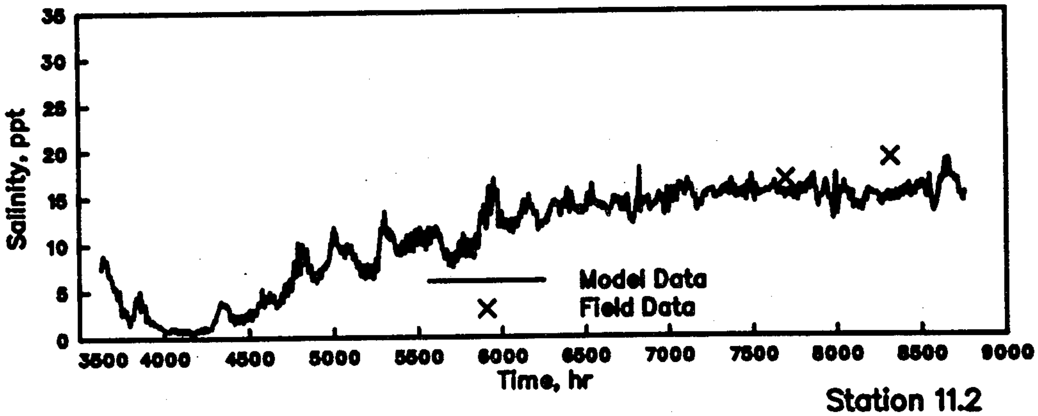


Station 9.0t

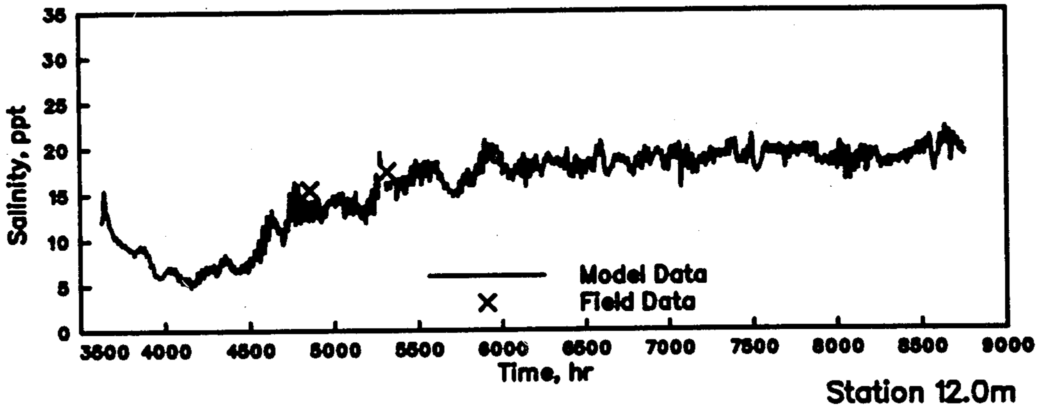


Station 11.0

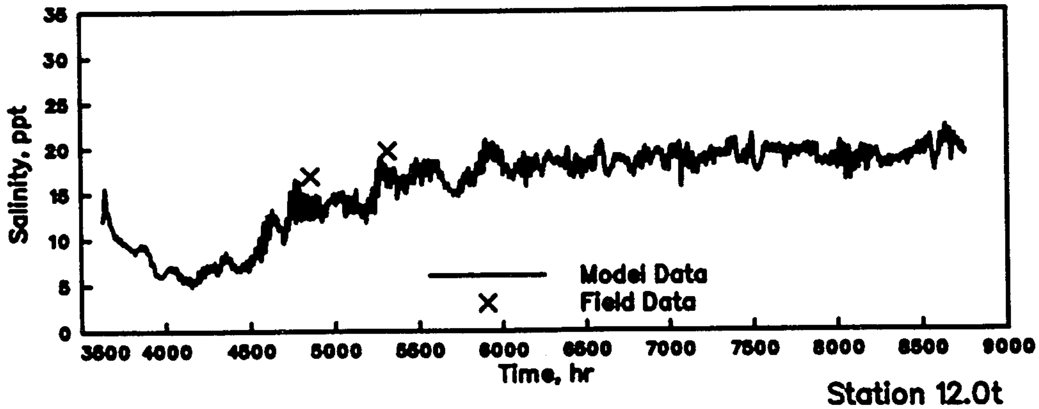
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 3500-9000



Station 11.2

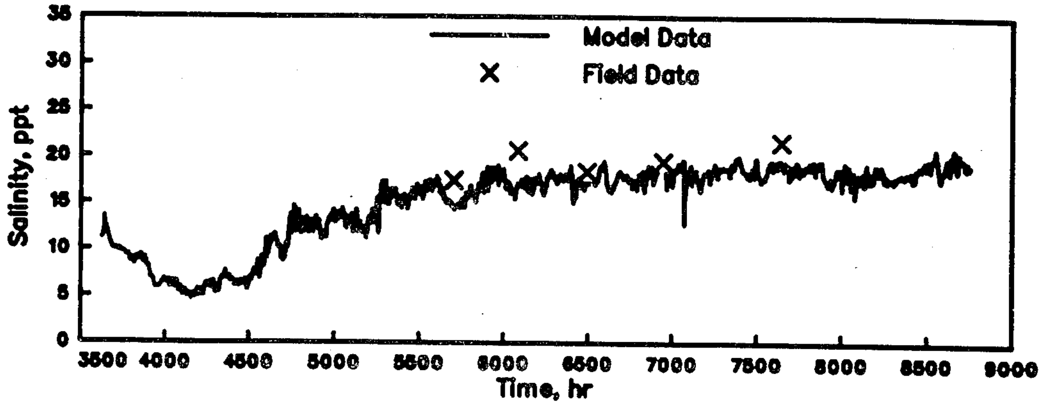


Station 12.0m

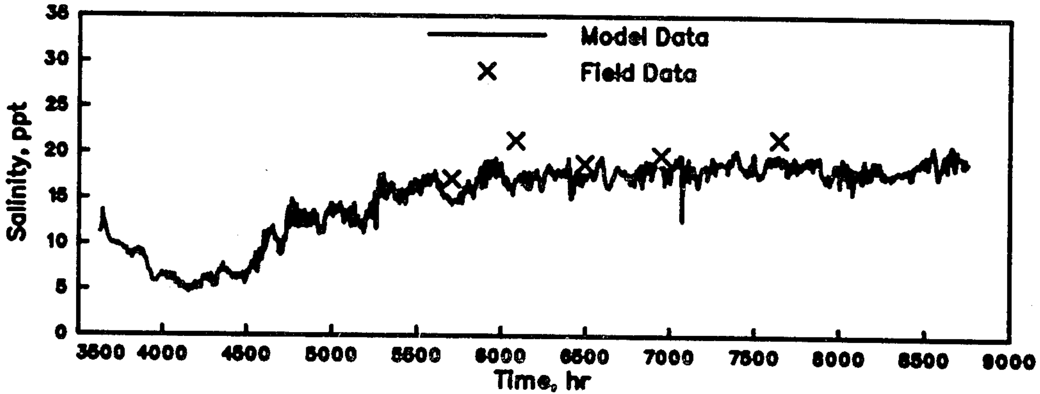


Station 12.0t

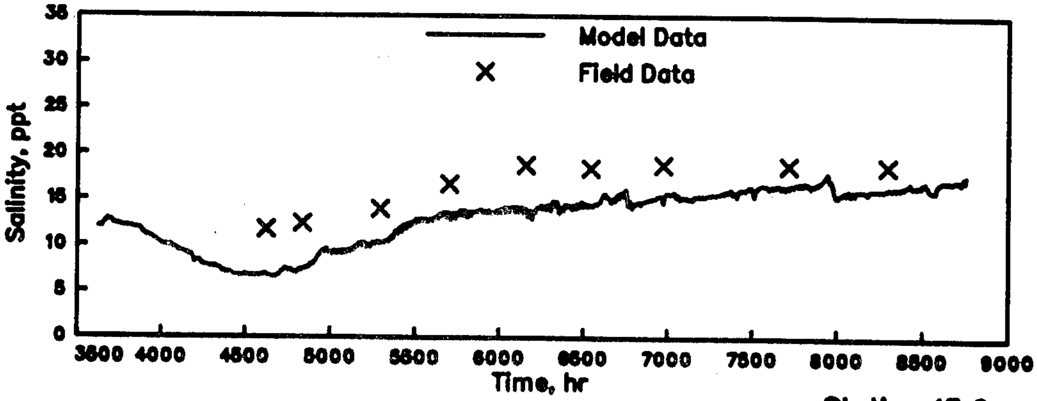
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 3500-9000



Station 12.1m

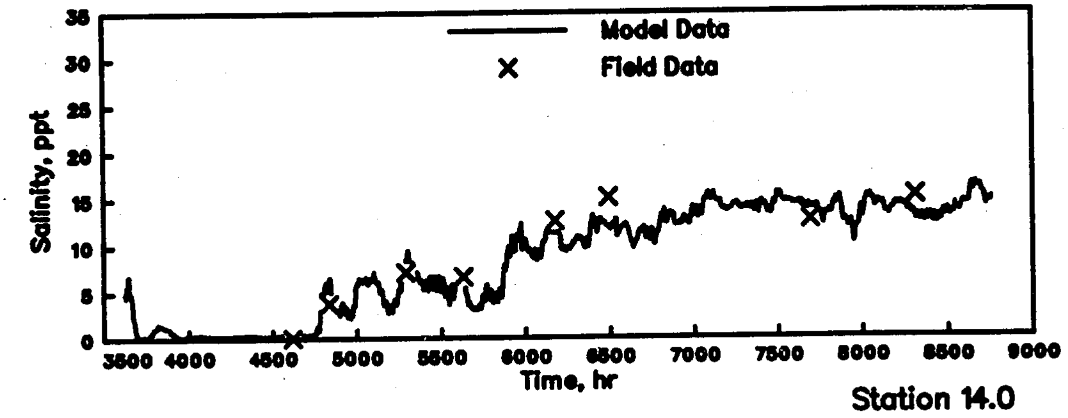


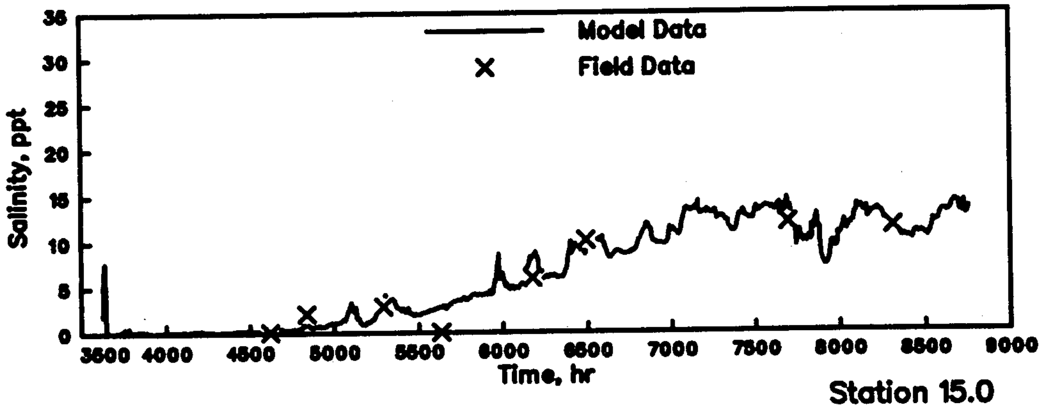
Station 12.1t



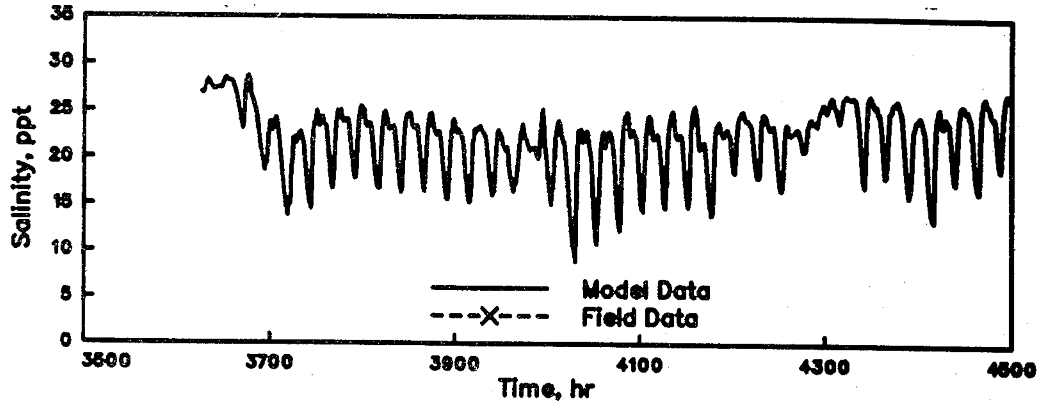
Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 3500-9000

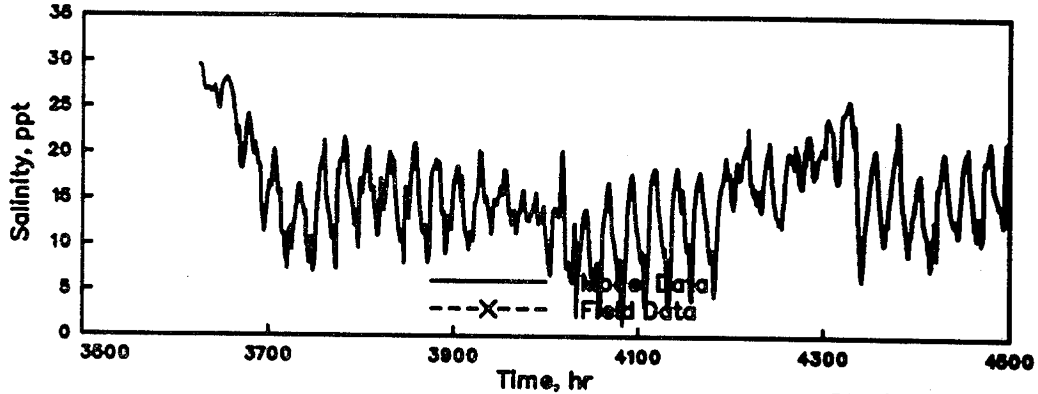




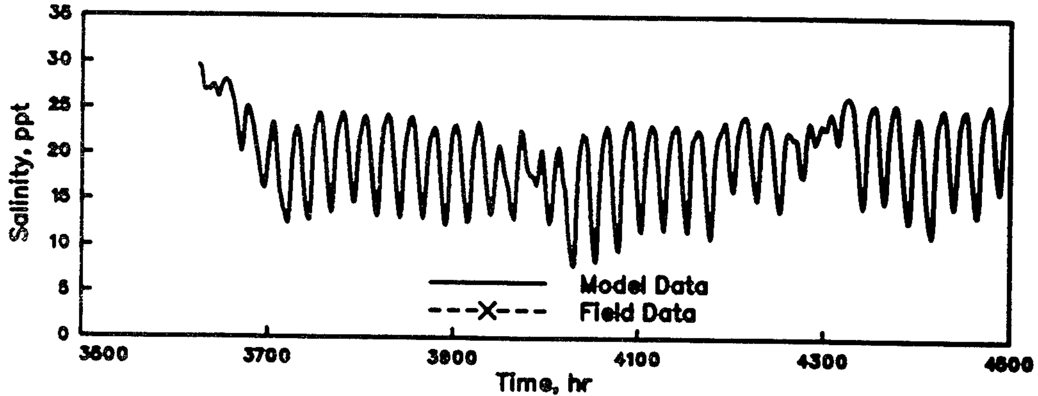
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 3500-9000



Station 1.0

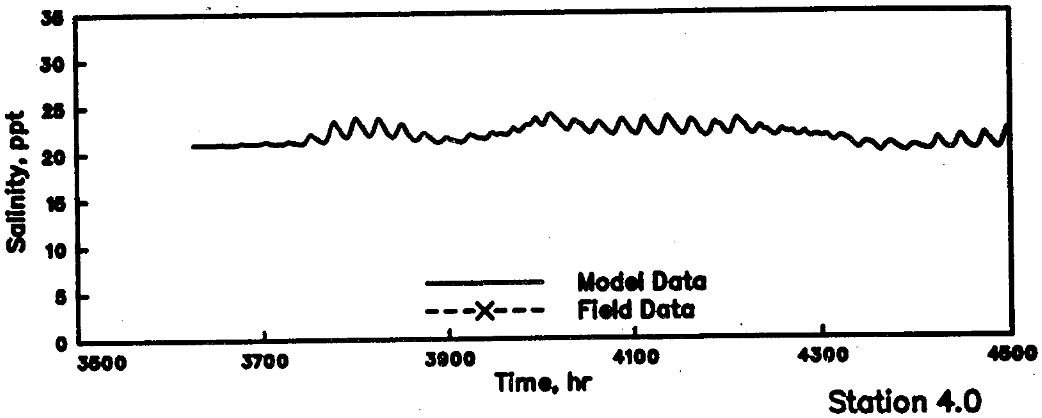


Station 2.0m

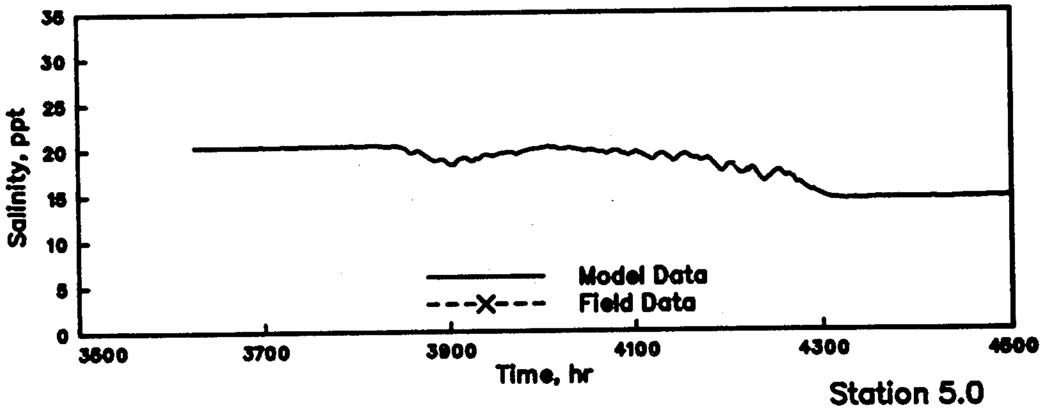


Station 2.0t

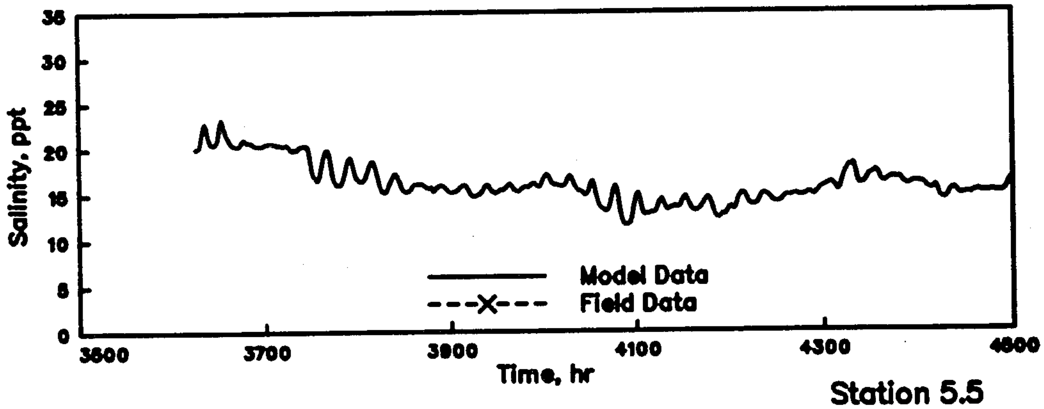
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 3500-4500



Station 4.0

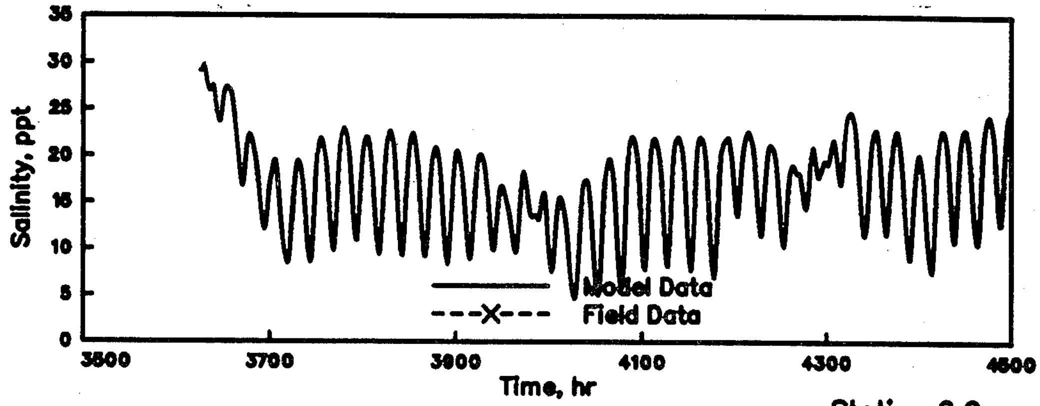


Station 5.0

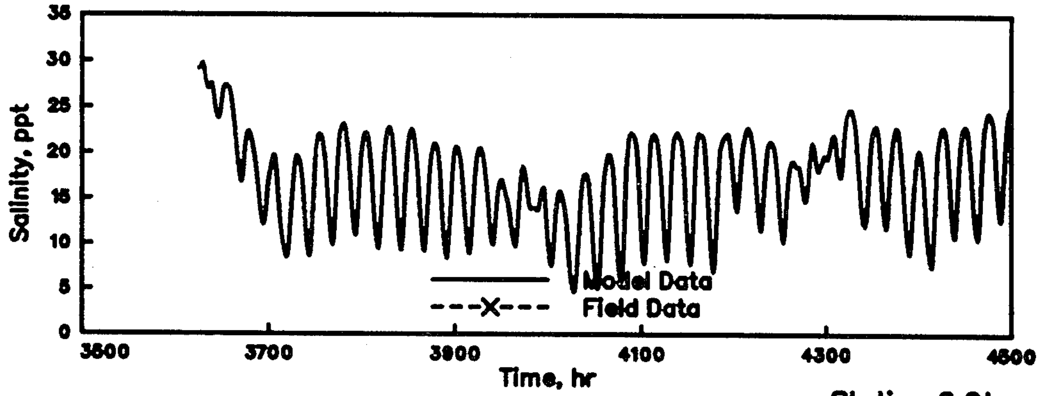


Station 5.5

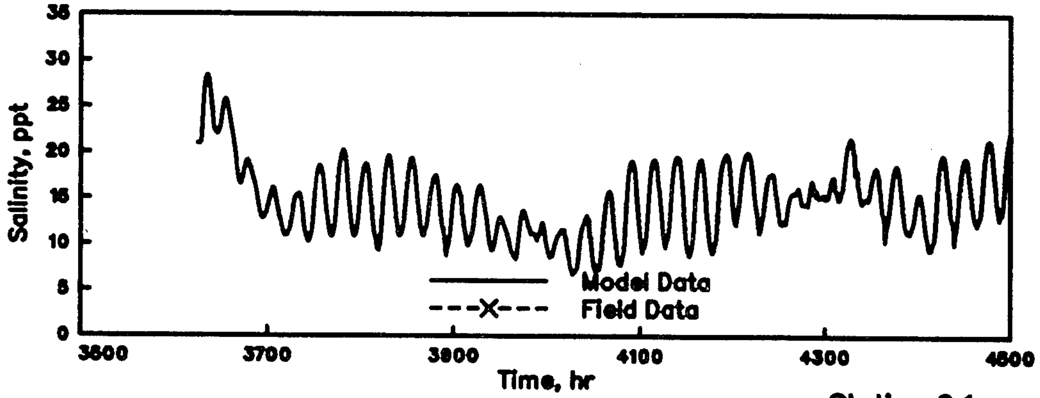
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 3500-4500



Station 6.0m

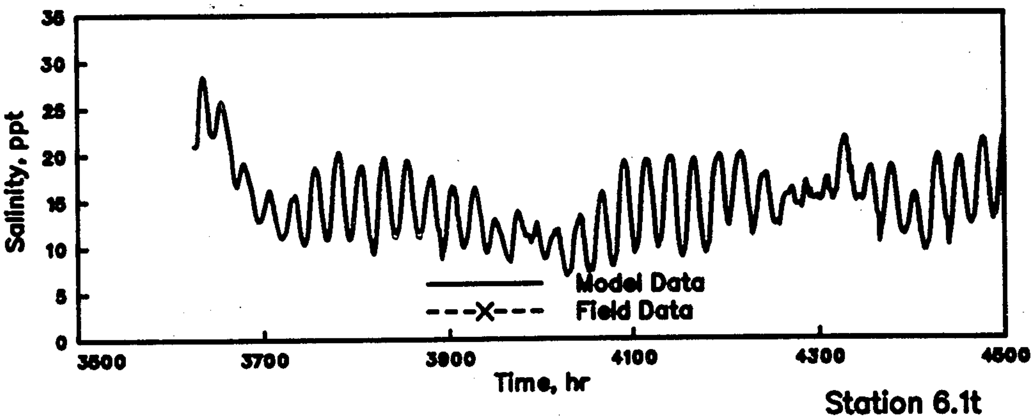


Station 6.0t

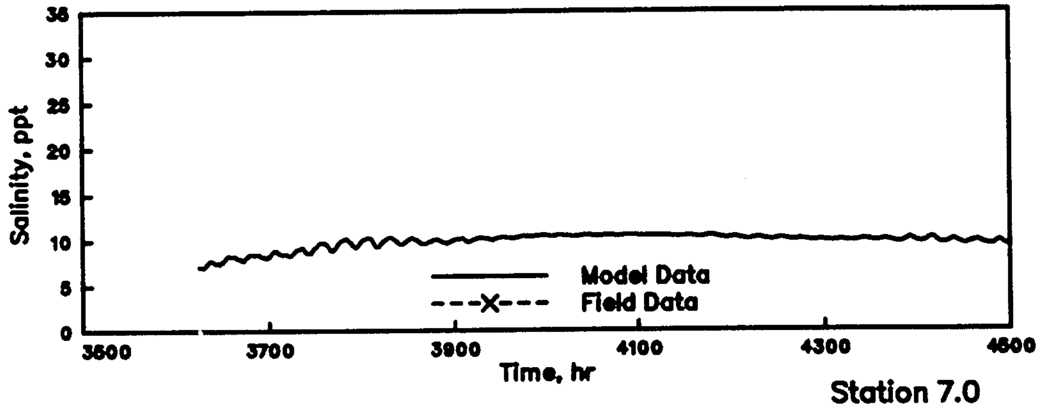


Station 6.1m

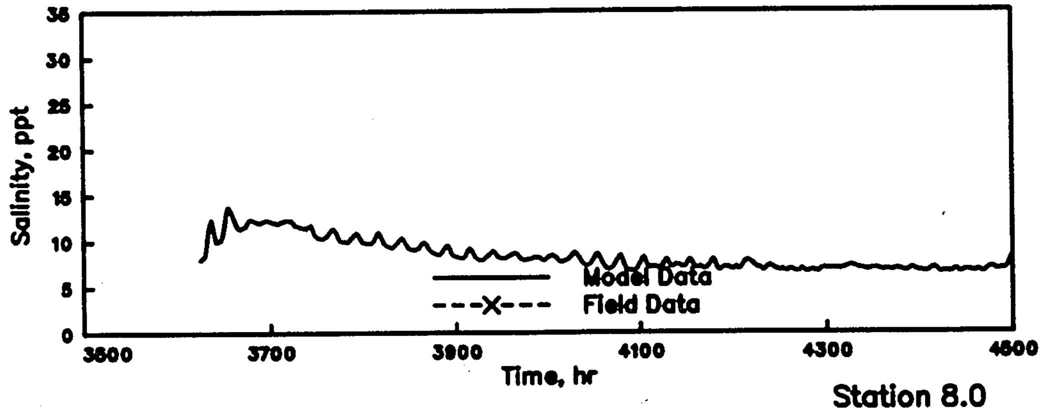
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 3500-4500



Station 6.1t

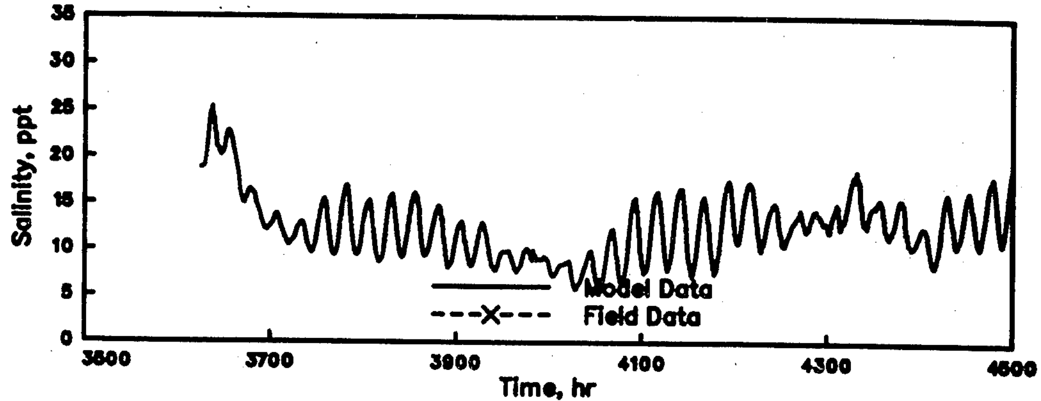


Station 7.0

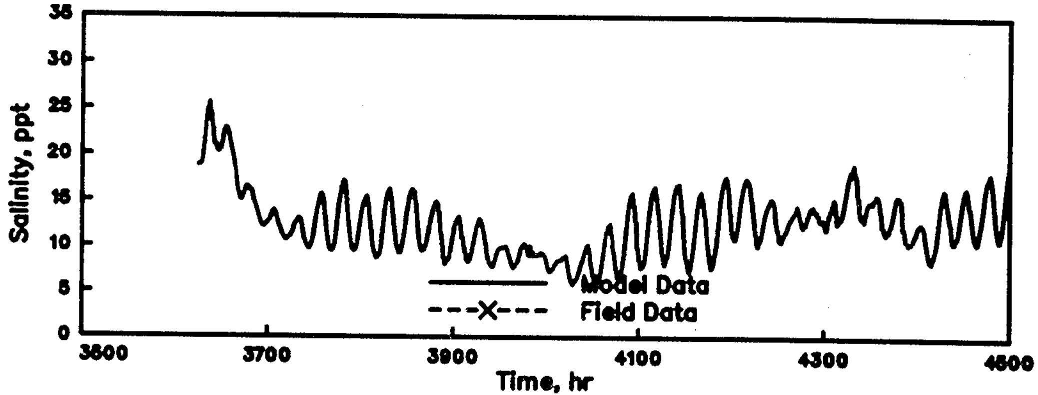


Station 8.0

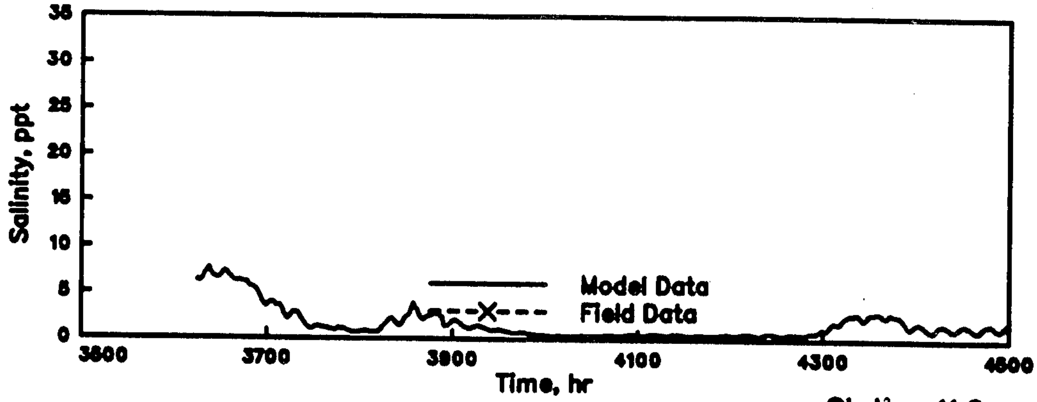
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 3500-4500



Station 9.0m

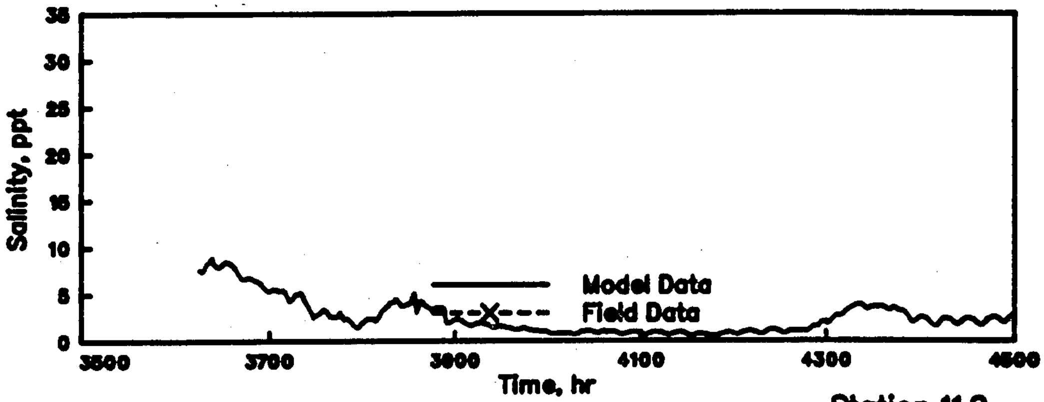


Station 9.0t

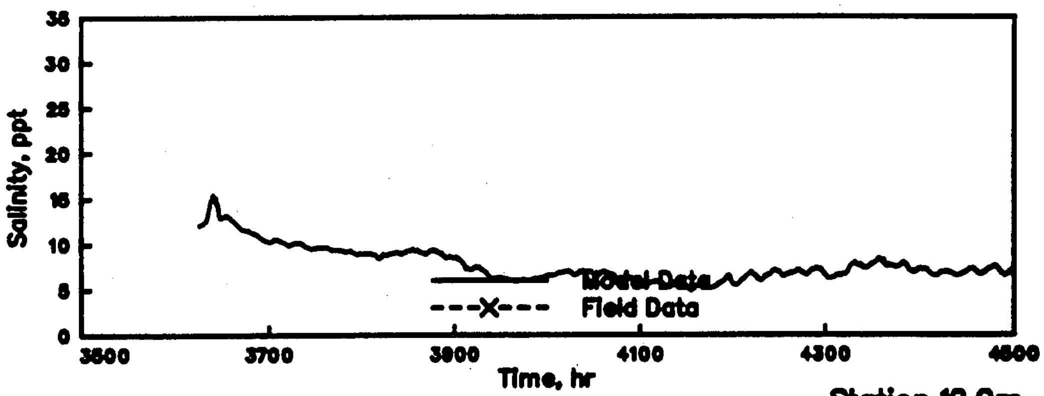


Station 11.0

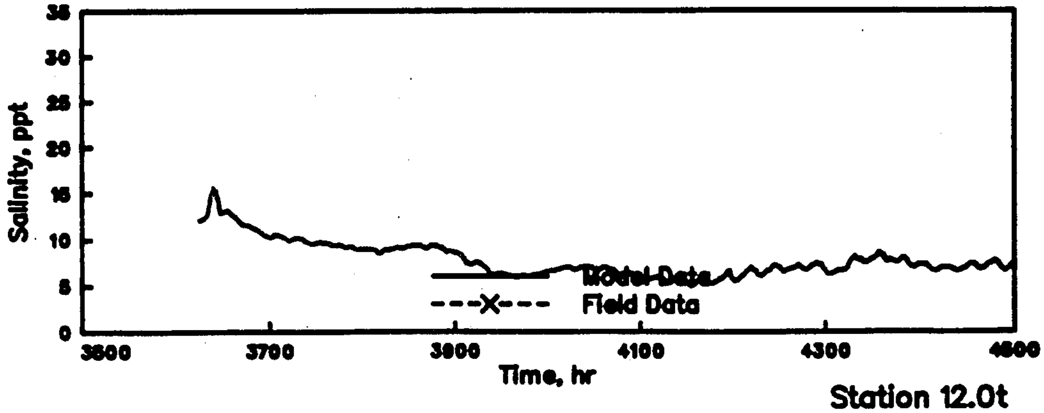
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 3500-4500



Station 11.2

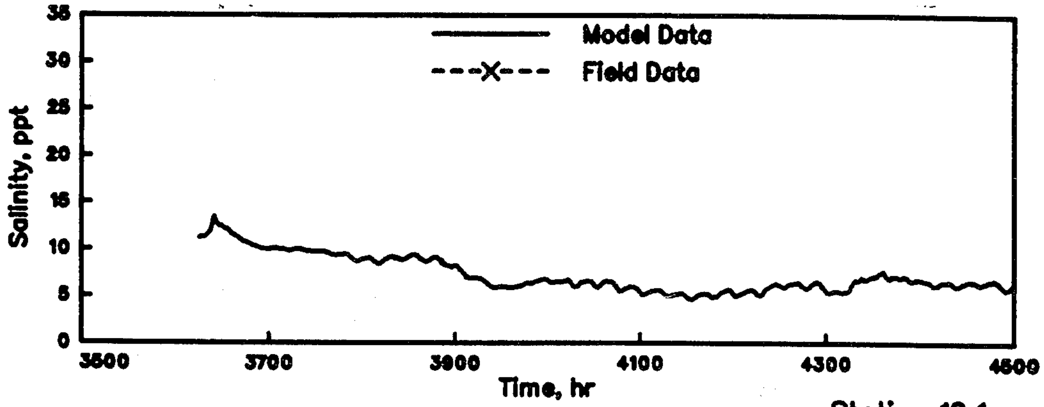


Station 12.0m

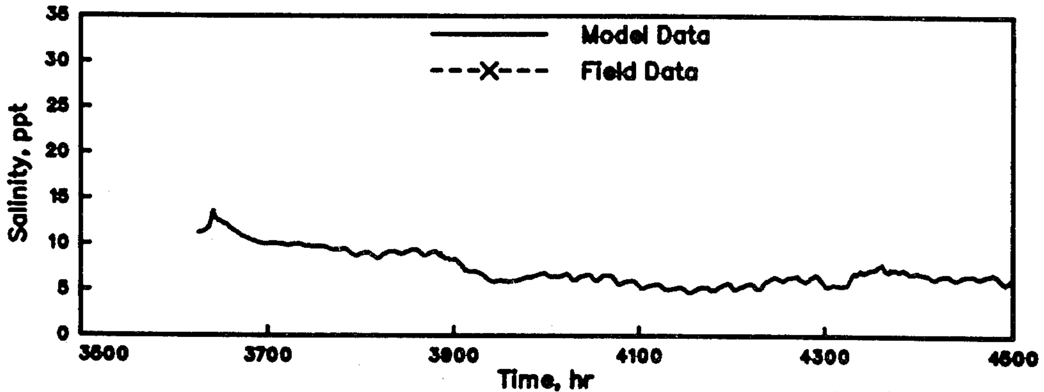


Station 12.0t

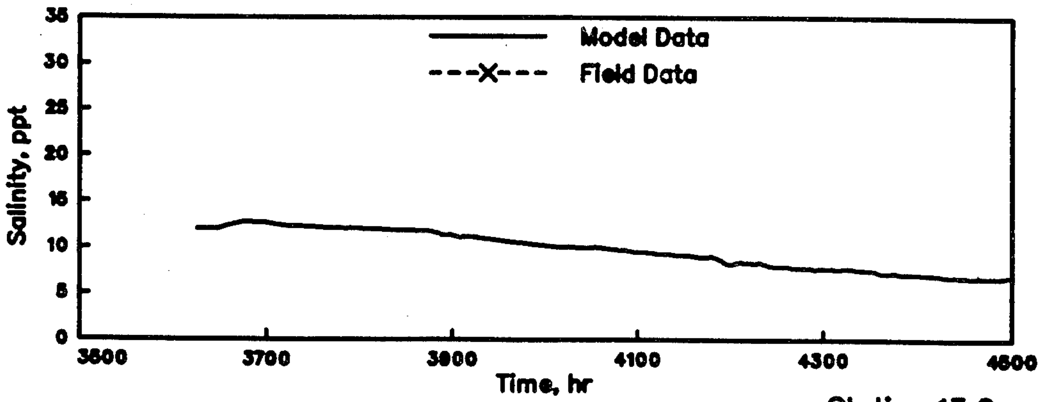
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 3500-4500



Station 12.1m

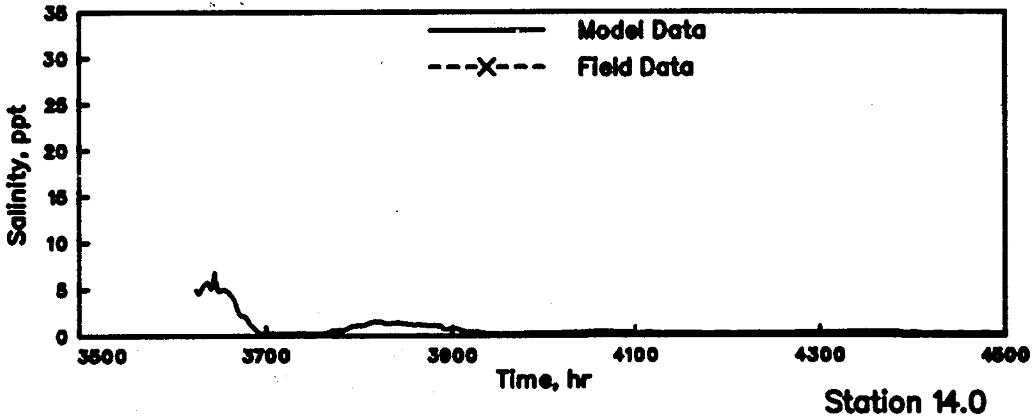


Station 12.1t

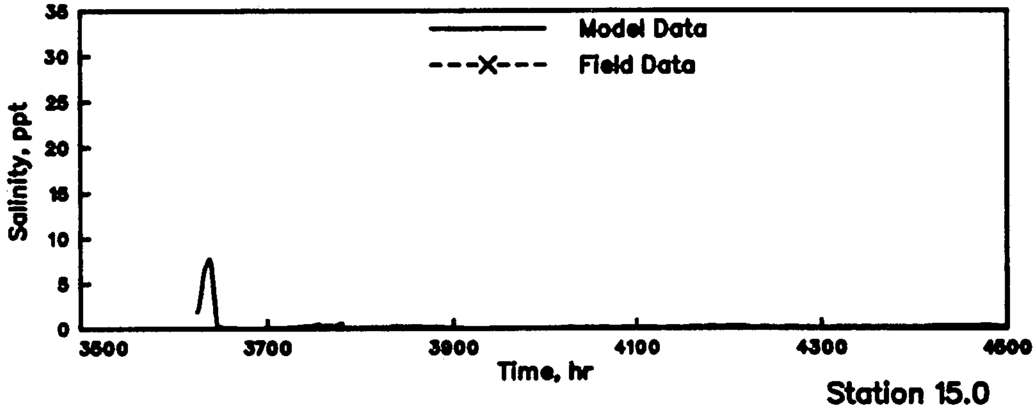


Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 3500-4500

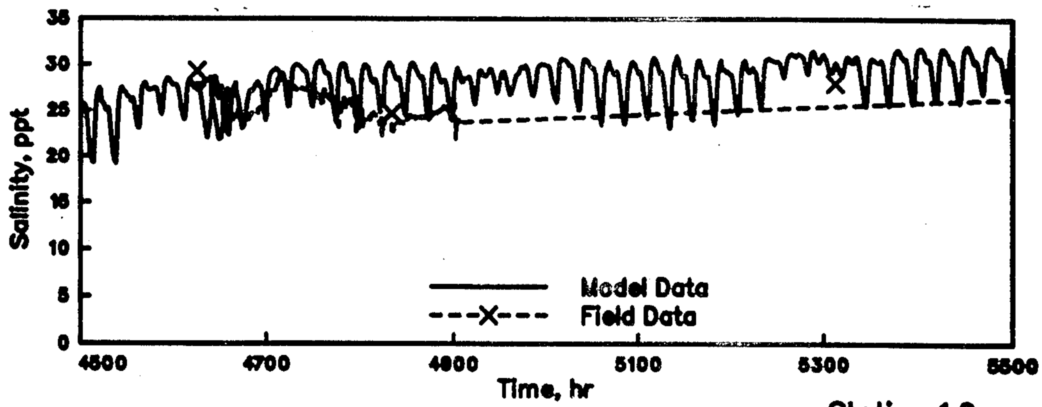


Station 14.0

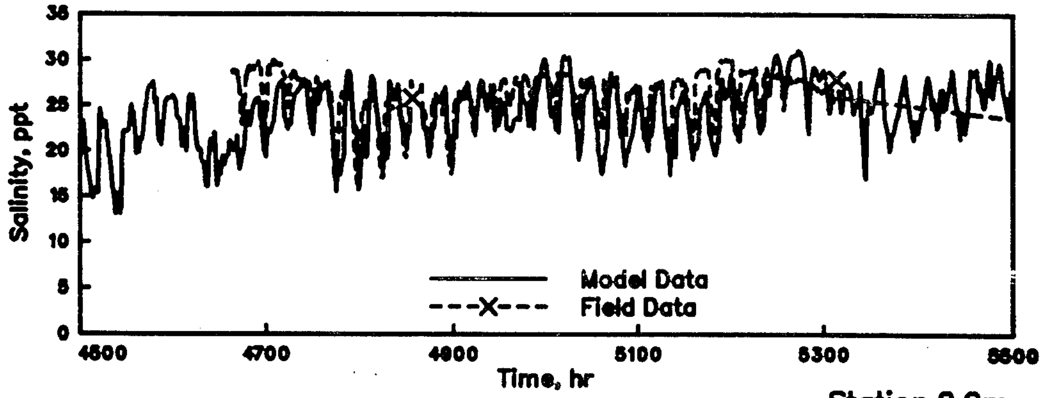


Station 15.0

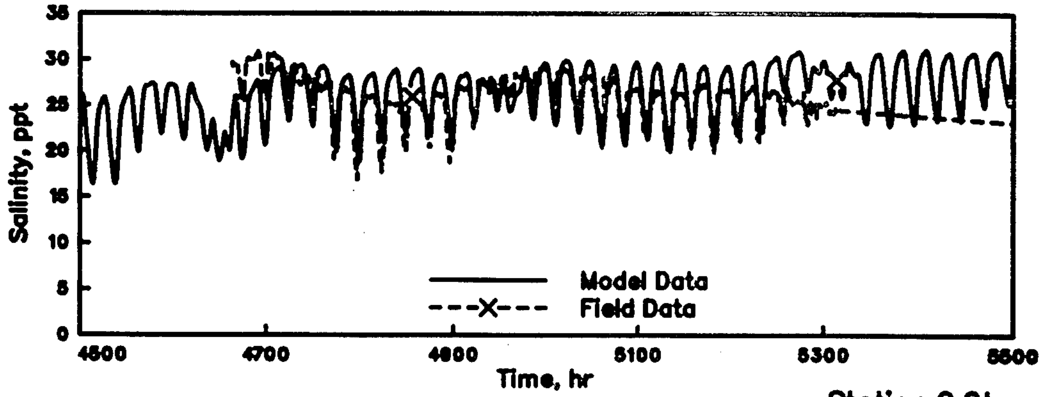
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 3500-4500



Station 1.0

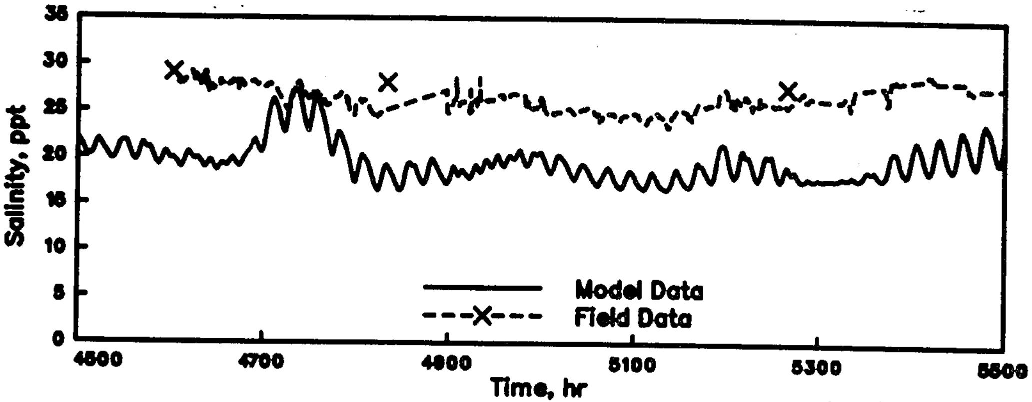


Station 2.0m

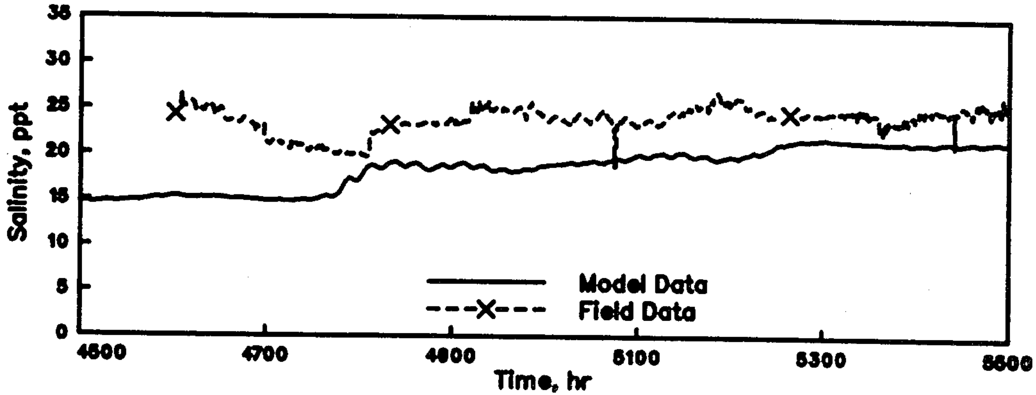


Station 2.0t

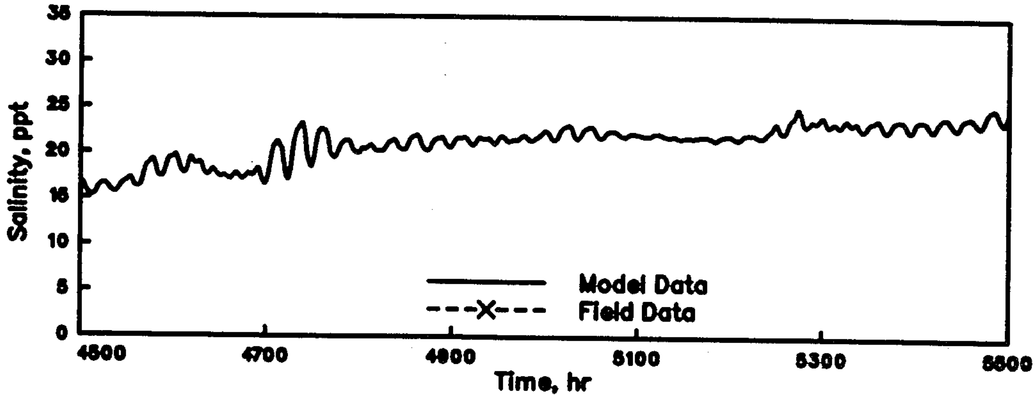
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 4500-5500



Station 4.0

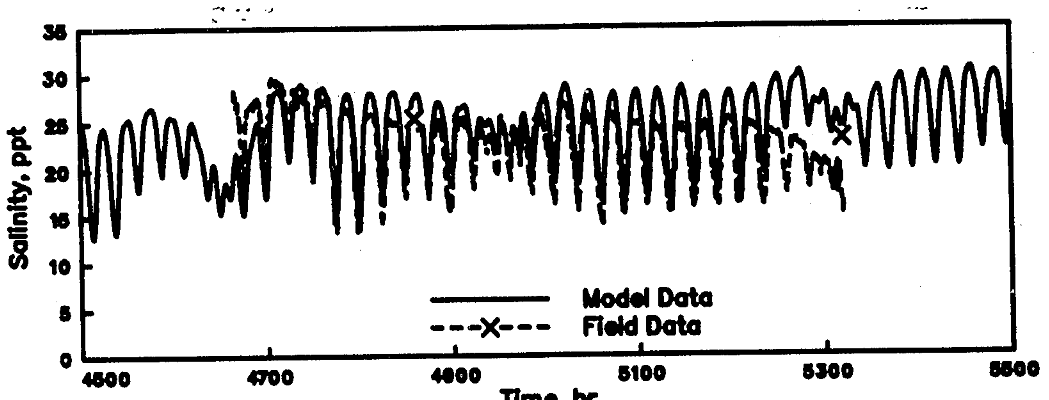


Station 5.0

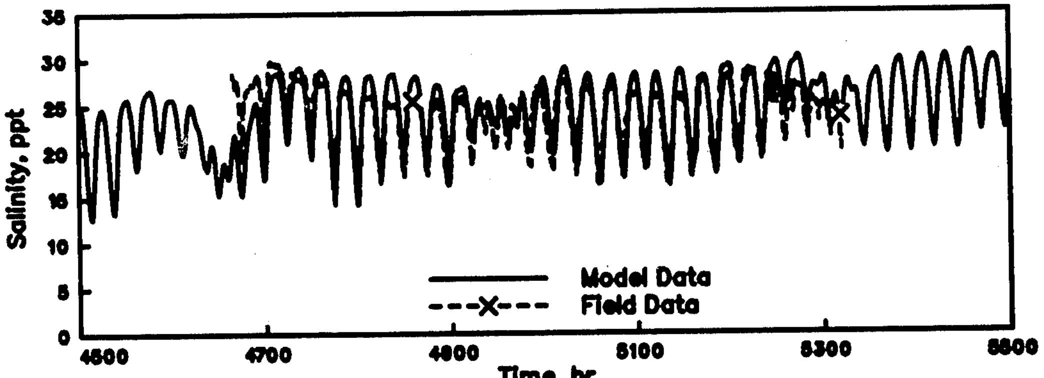


Station 5.5

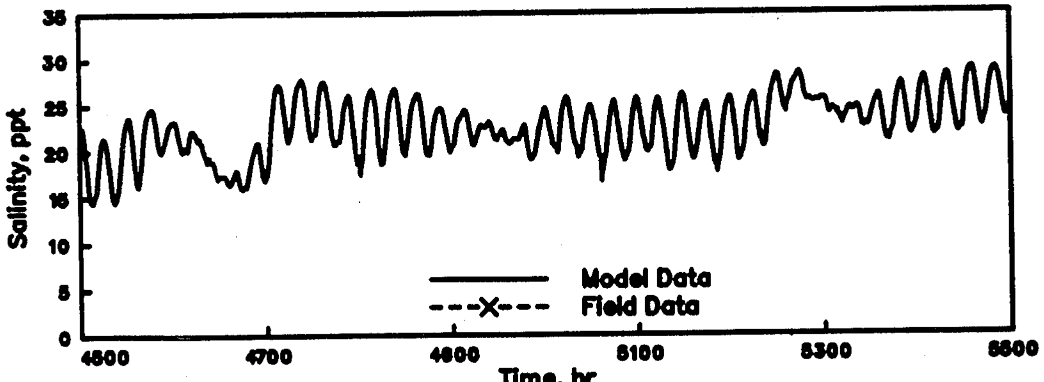
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 4500-5500



Station 6.0m



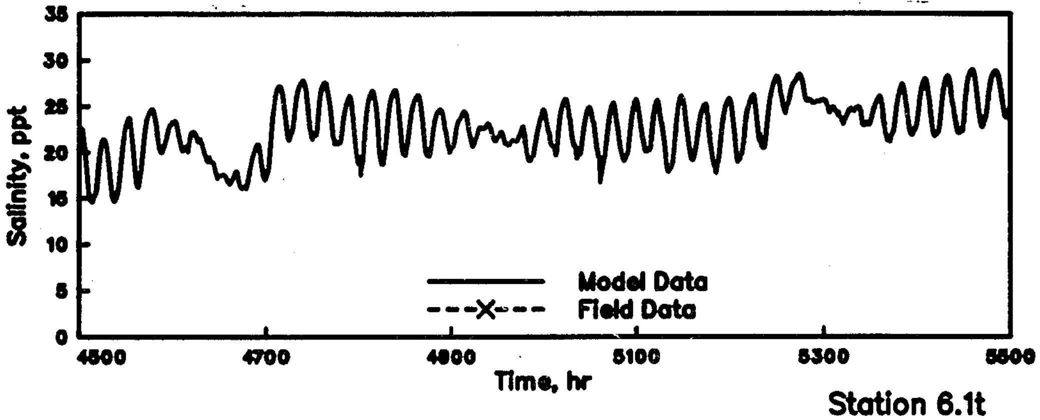
Station 6.0t



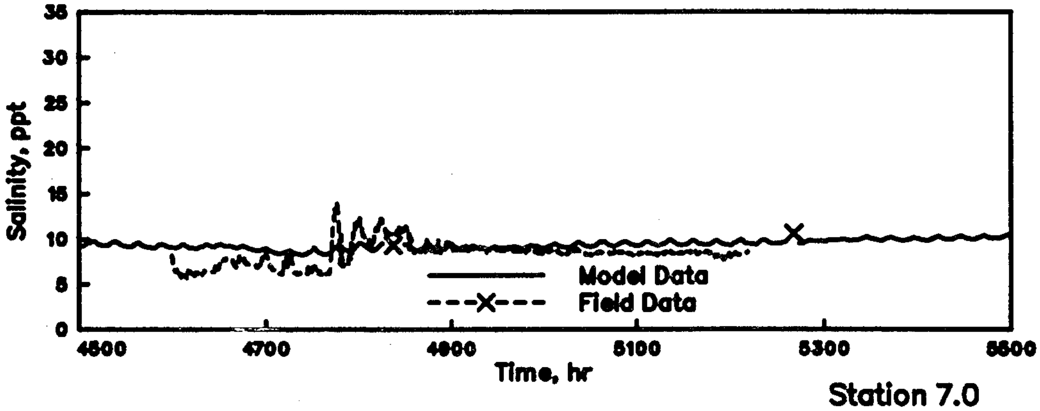
Station 6.1m

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 4500-5500

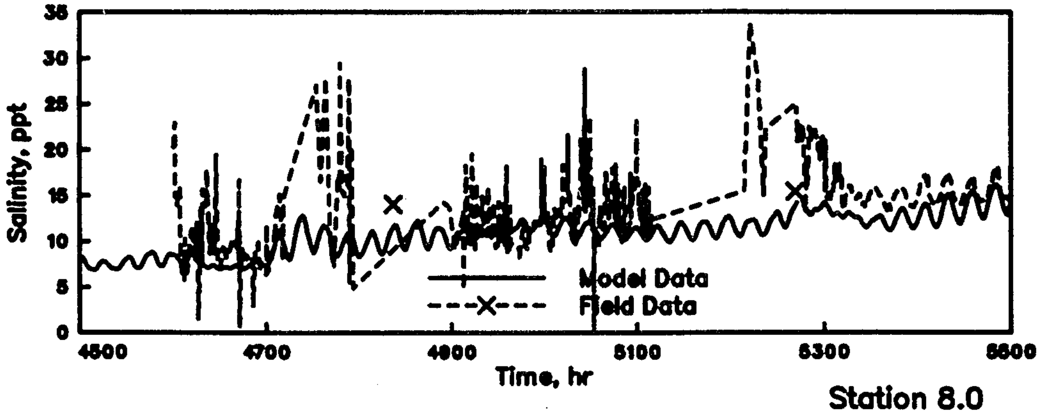
Plate 64



Station 6.1t

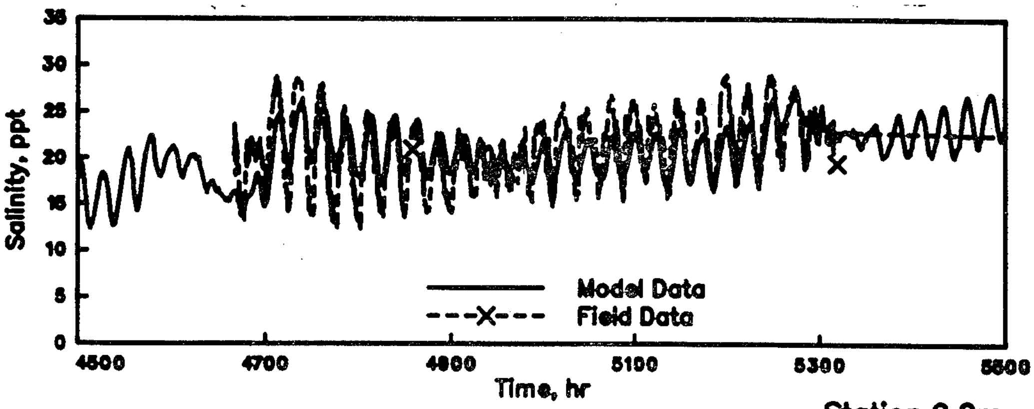


Station 7.0

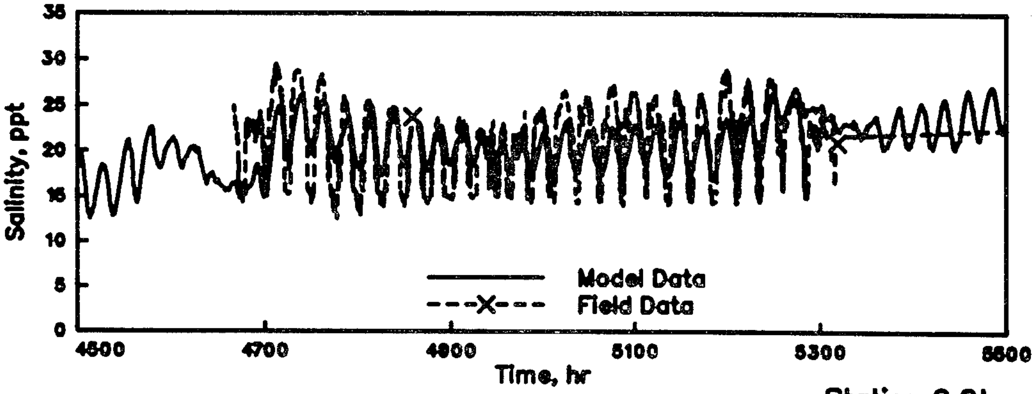


Station 8.0

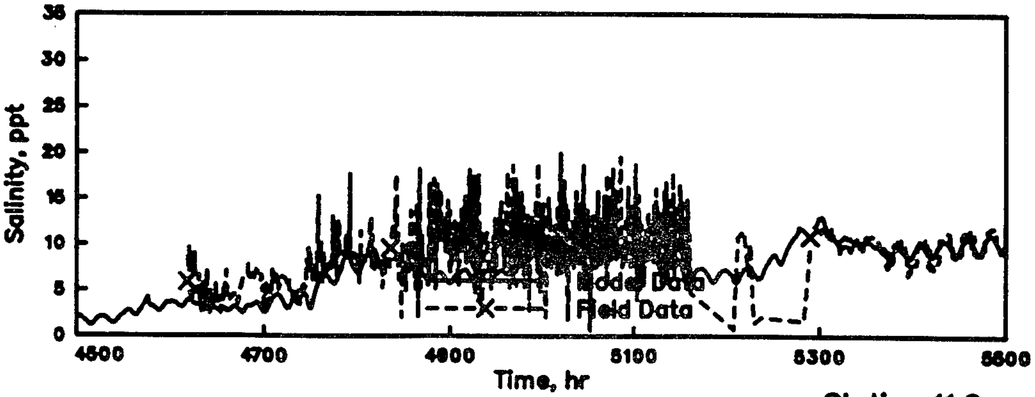
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 4500-5500



Station 9.0m

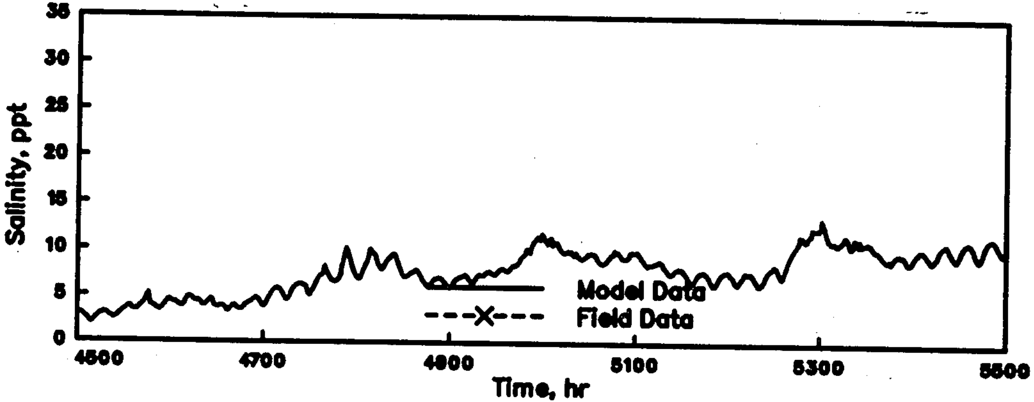


Station 9.0t

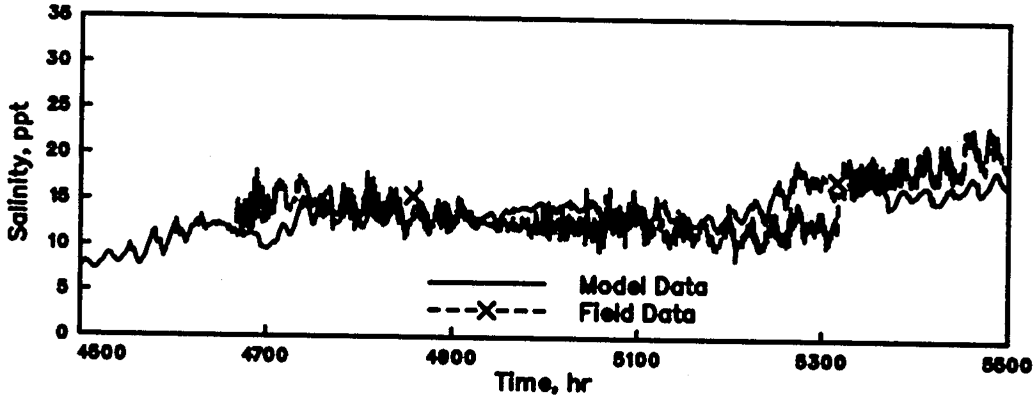


Station 11.0

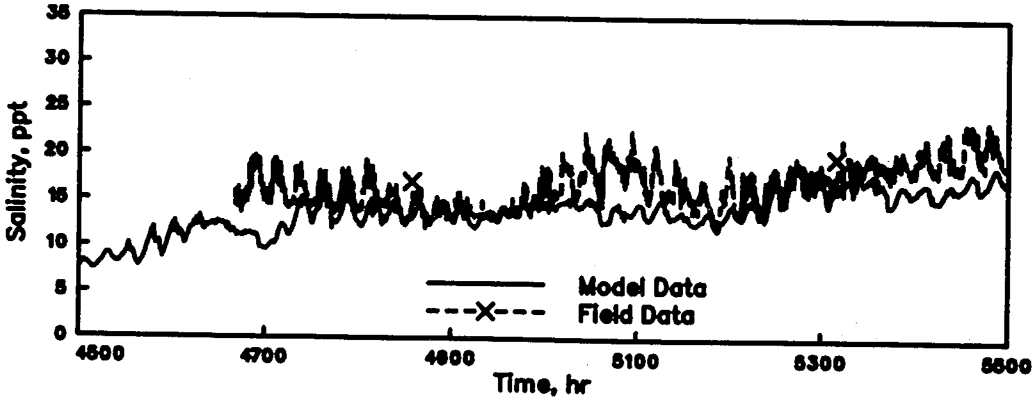
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 4500-5500



Station 11.2

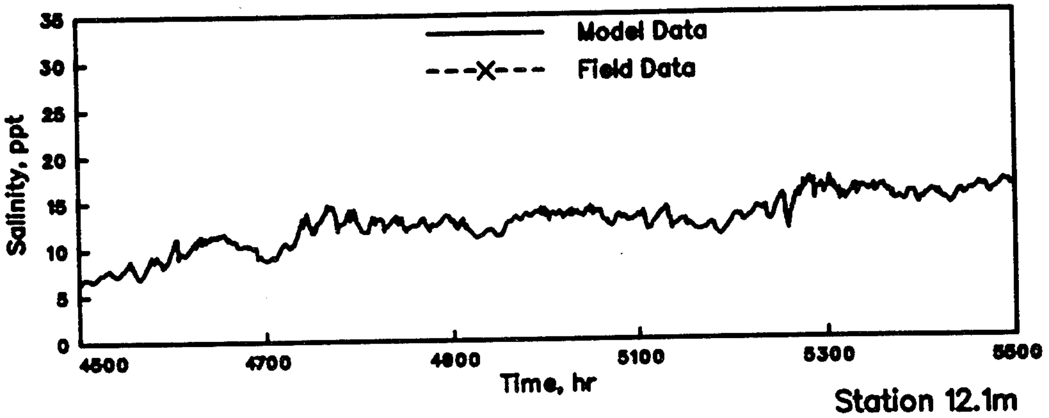


Station 12.0m

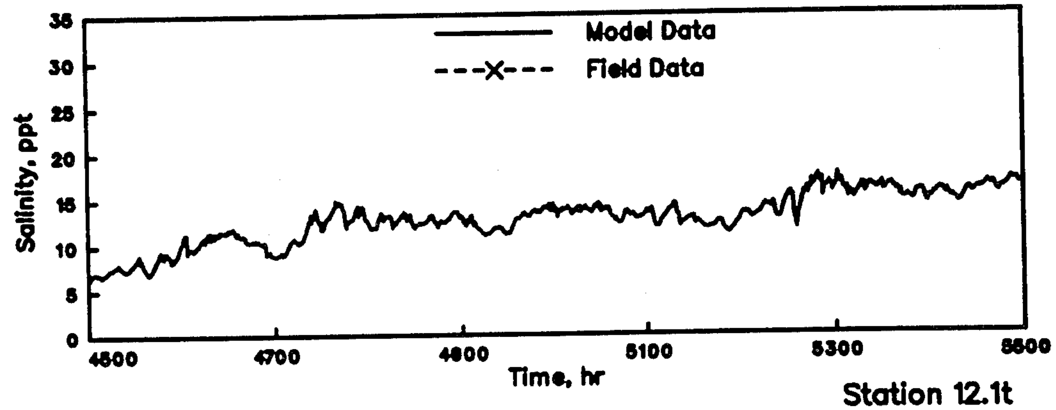


Station 12.0t

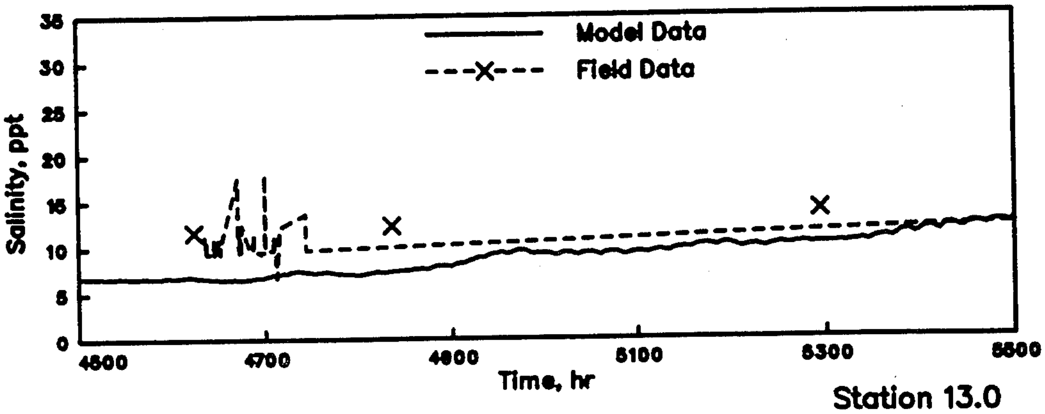
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 4500-5500



Station 12.1m

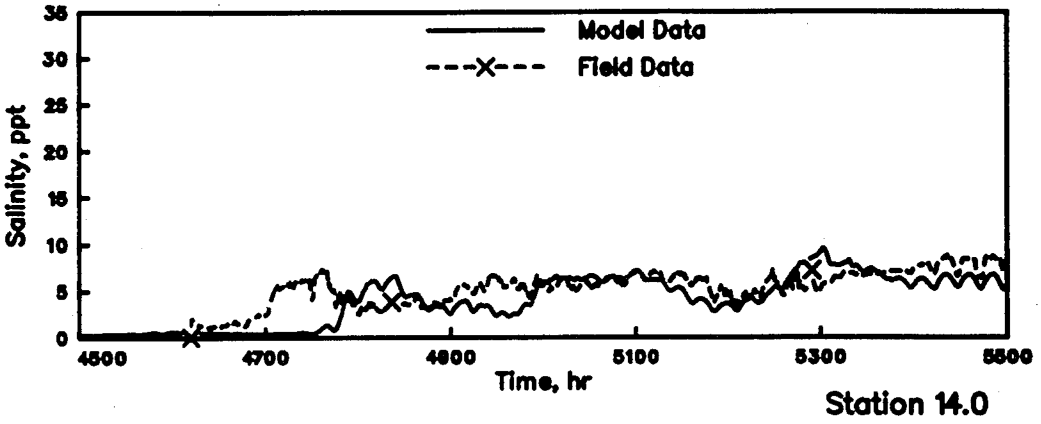


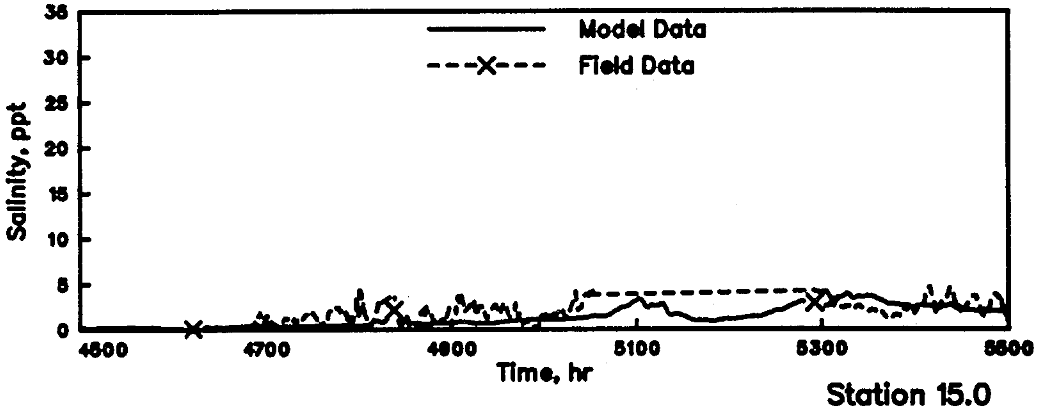
Station 12.1t



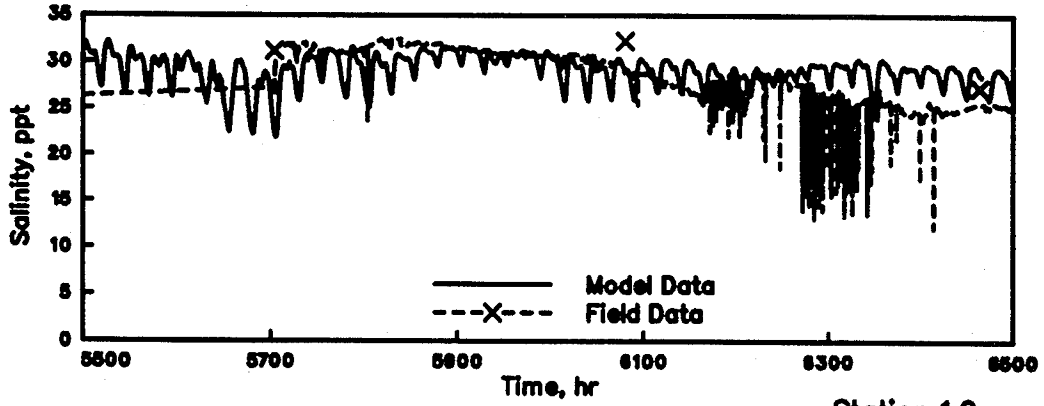
Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 4500-5500

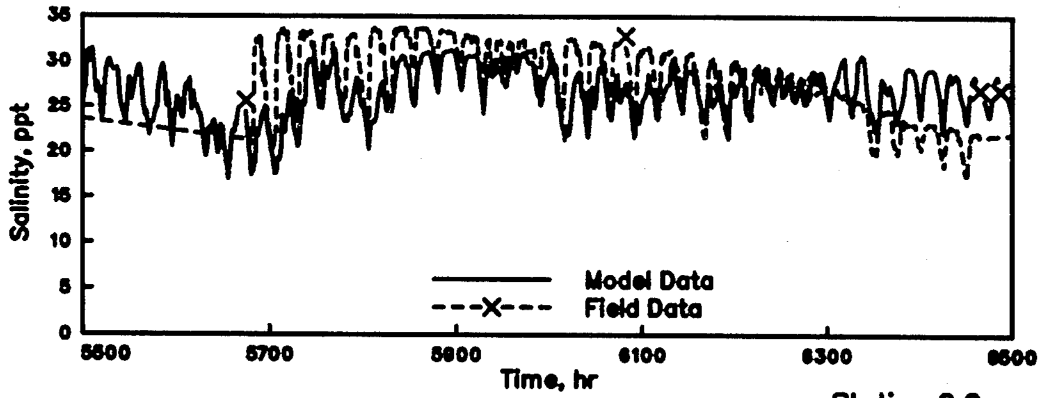




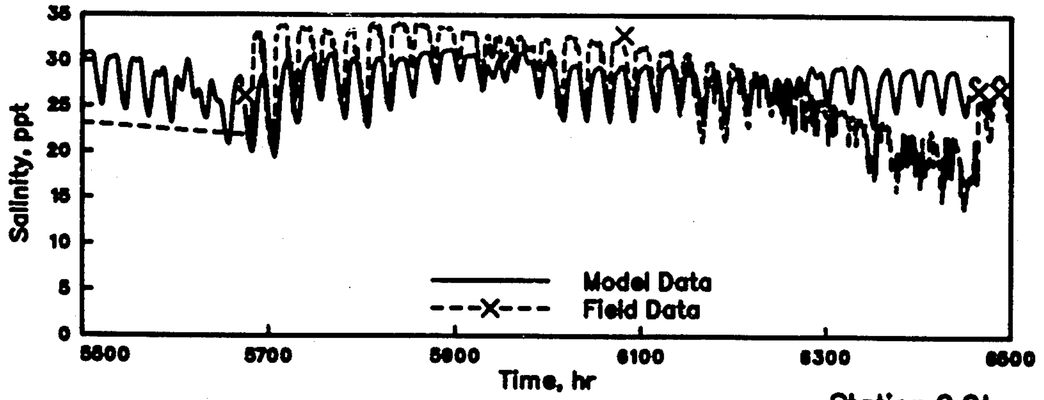
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 4500-5500



Station 1.0

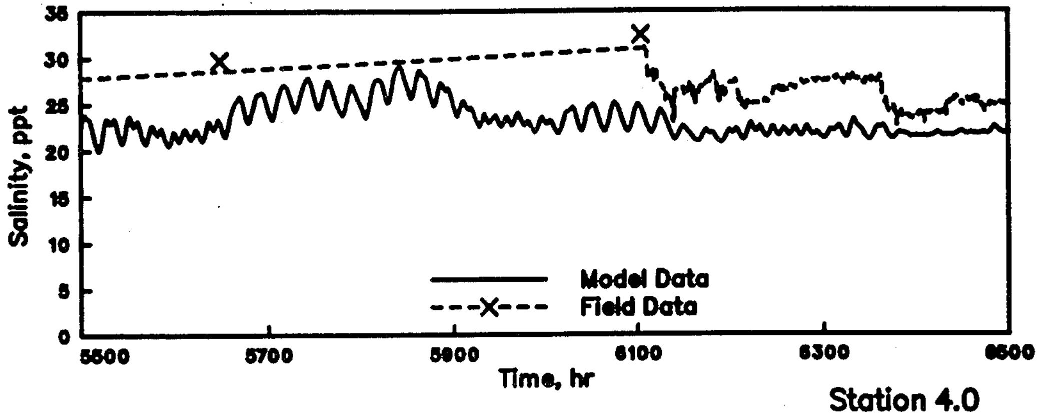


Station 2.0m

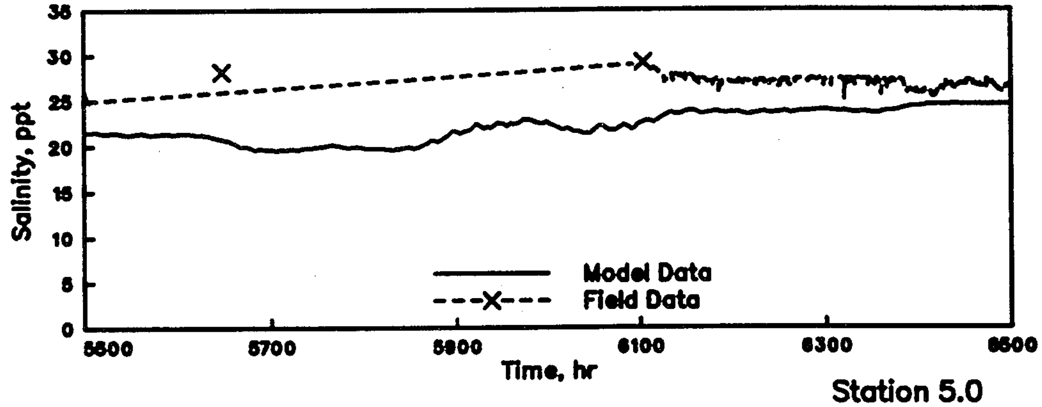


Station 2.0t

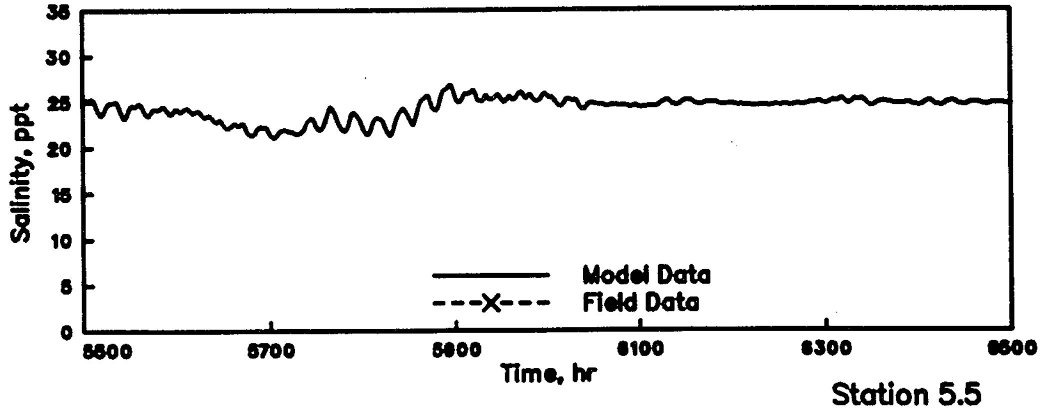
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 5500-6500



Station 4.0

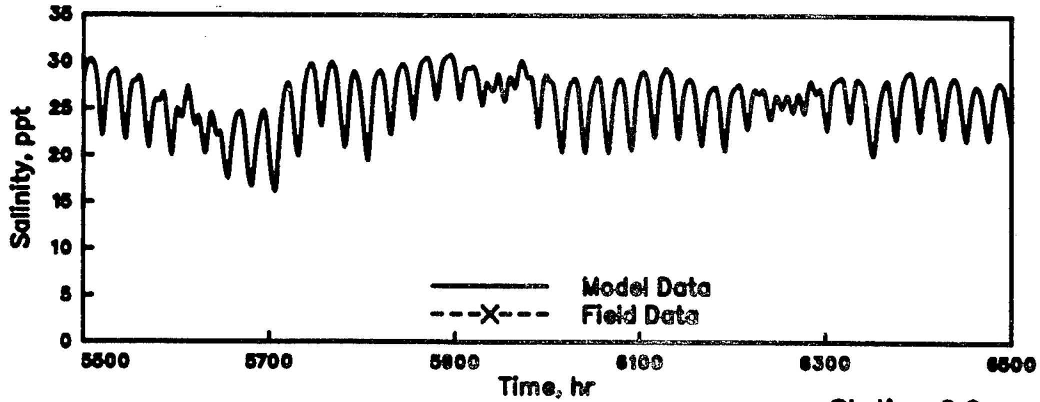


Station 5.0

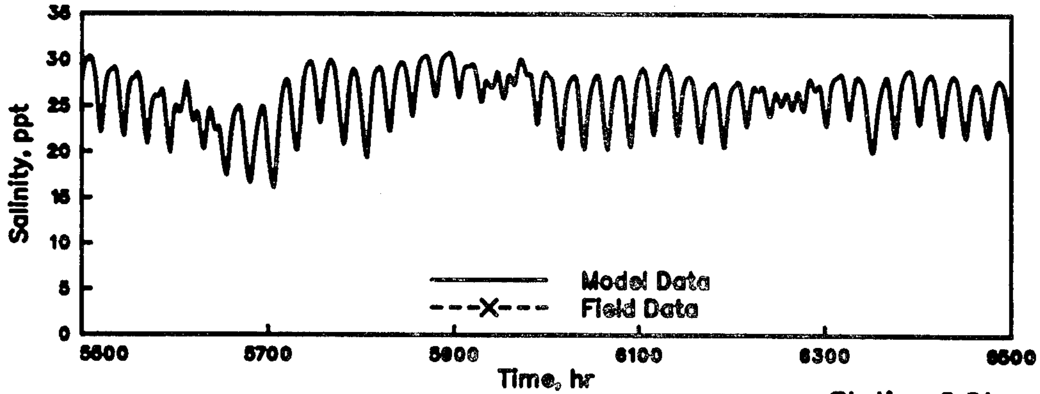


Station 5.5

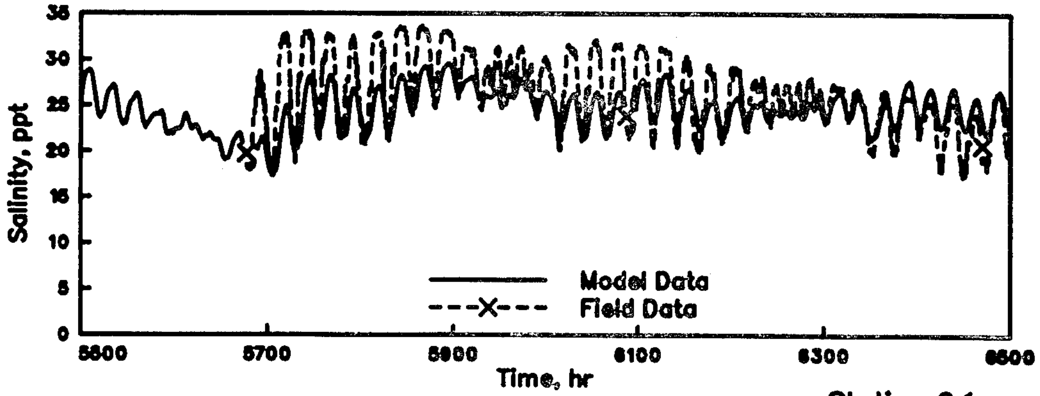
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 5500-6500



Station 6.0m

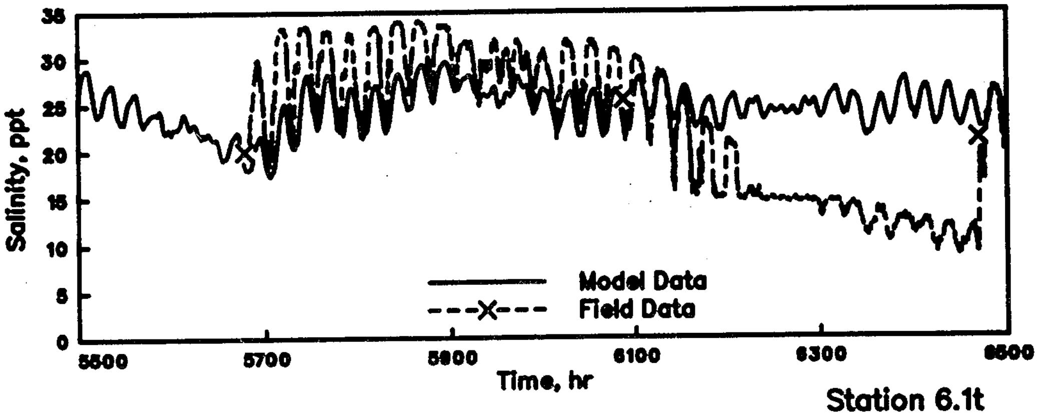


Station 6.0t

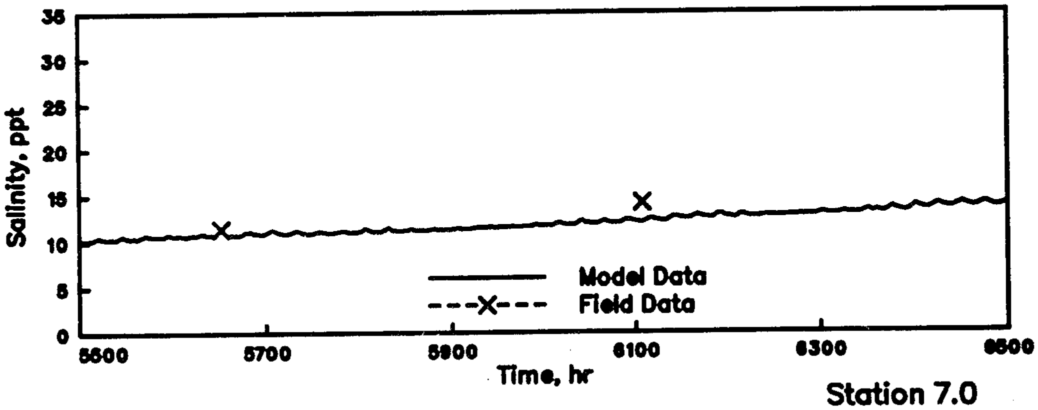


Station 6.1m

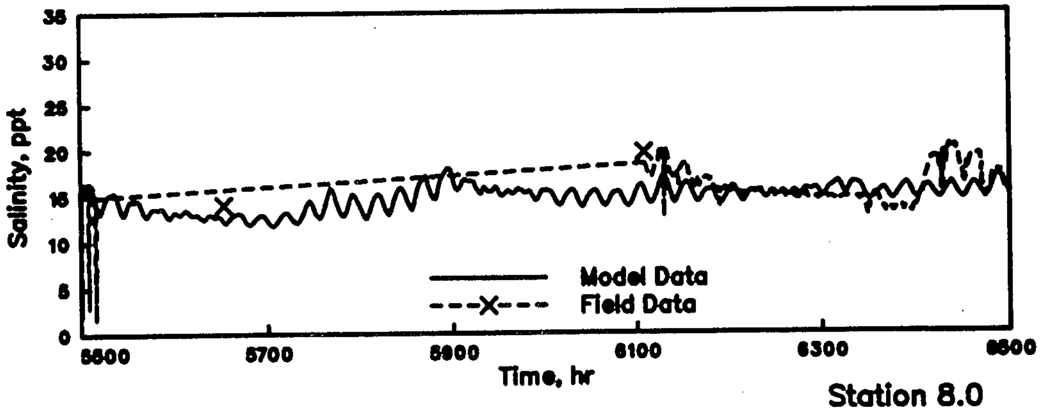
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 5500-6500



Station 6.1t

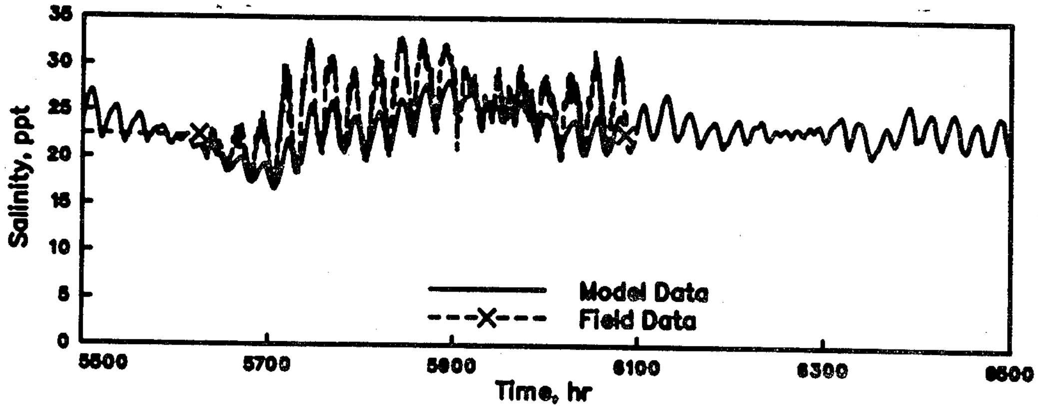


Station 7.0

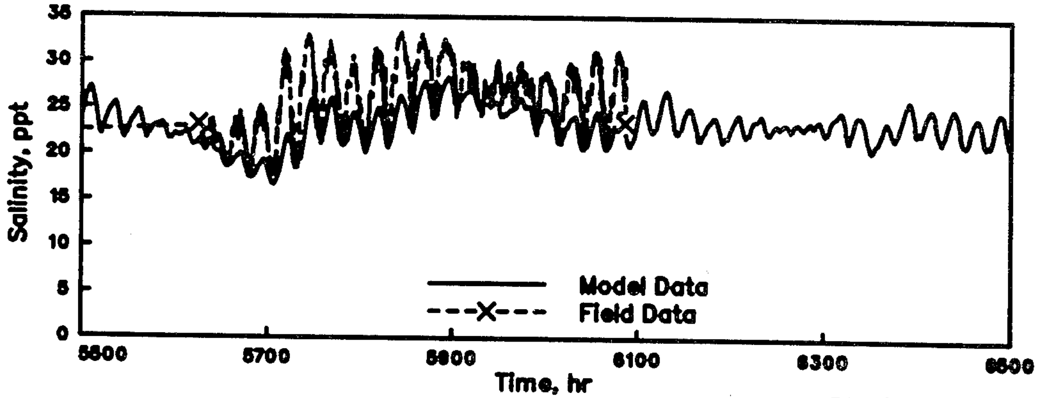


Station 8.0

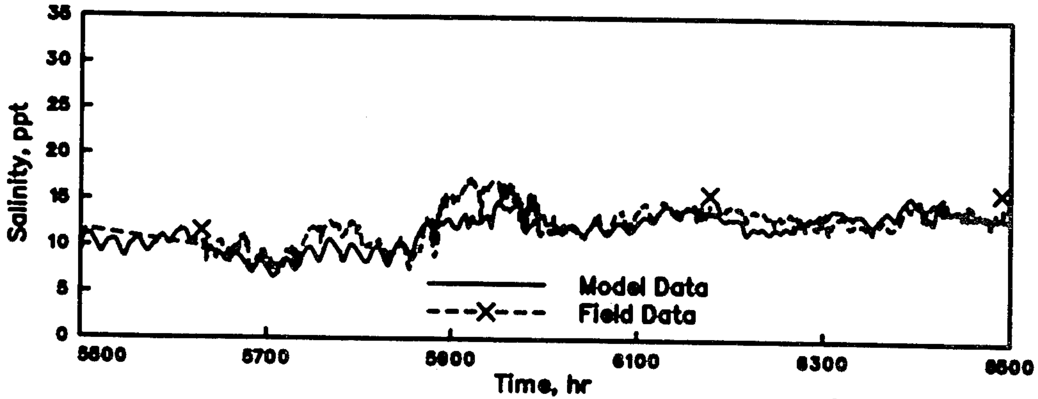
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 5500-6500



Station 9.0m



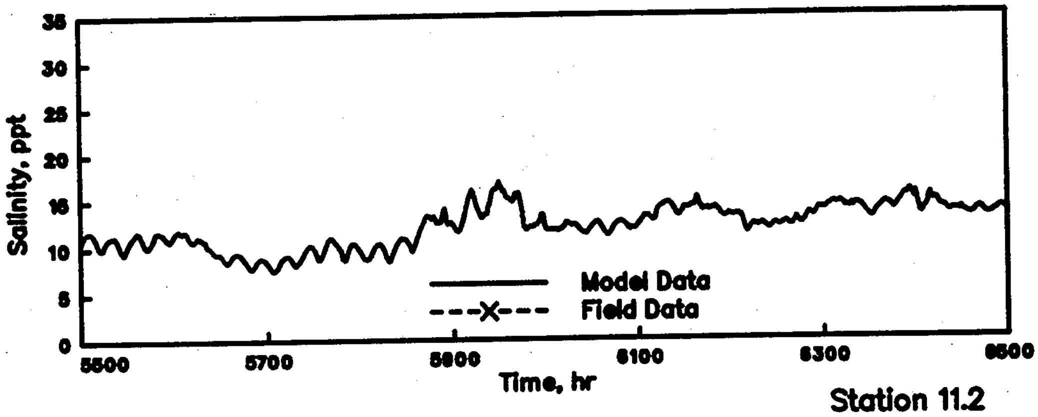
Station 9.0t



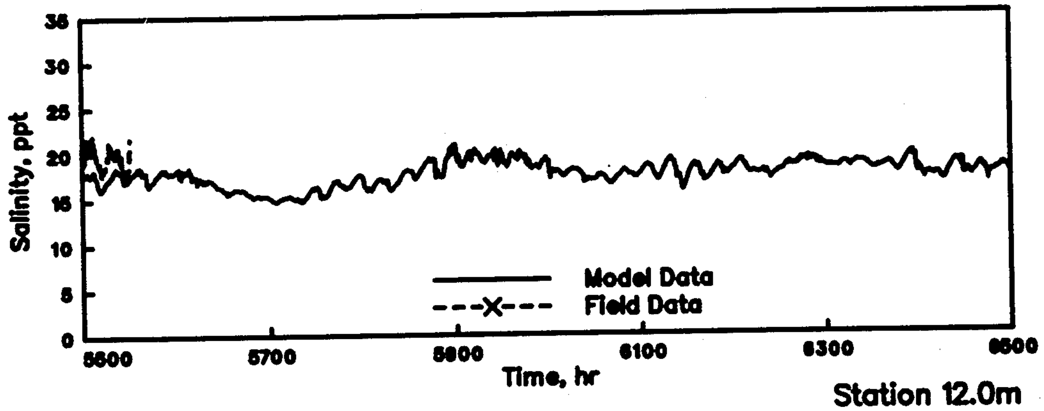
Station 11.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 5500-6500

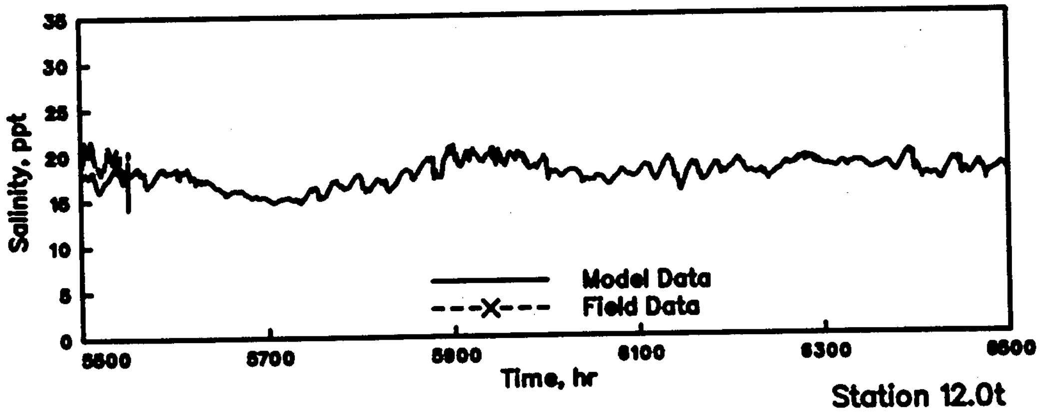
Plate 74



Station 11.2

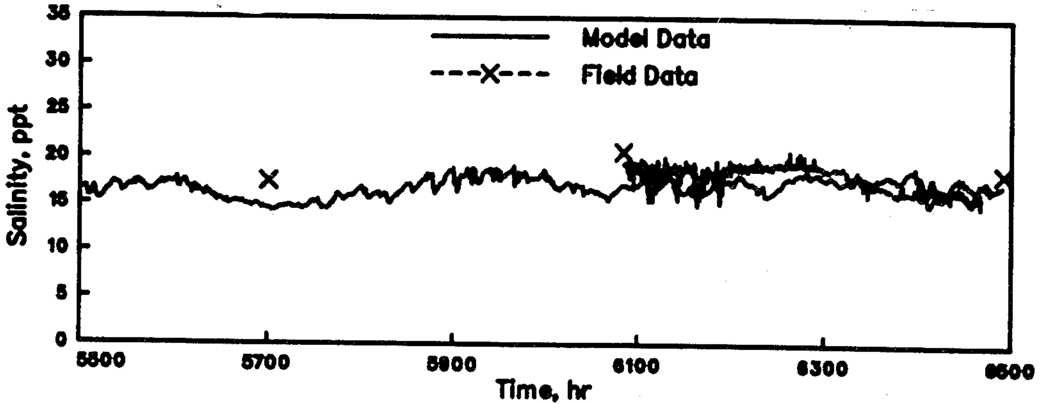


Station 12.0m

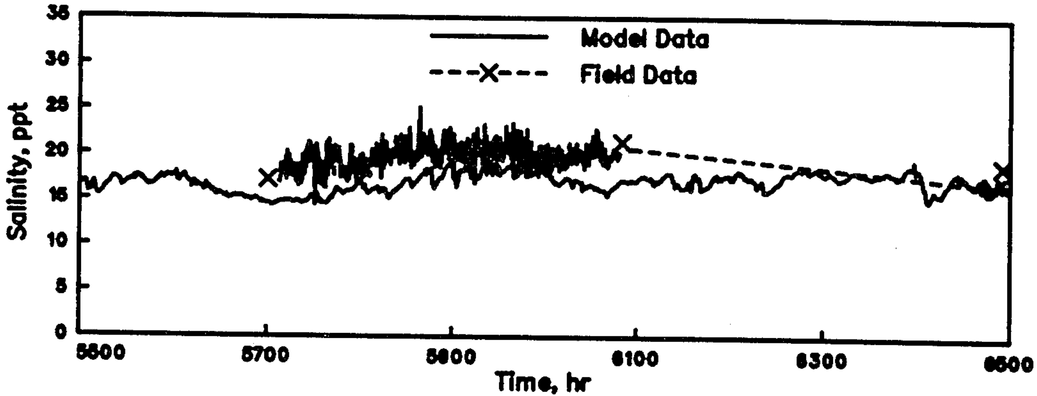


Station 12.0t

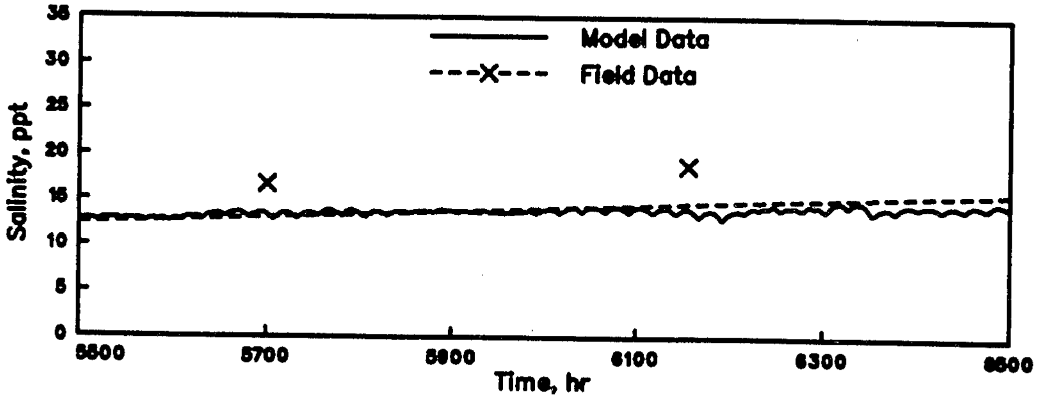
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 5500-6500



Station 12.1m

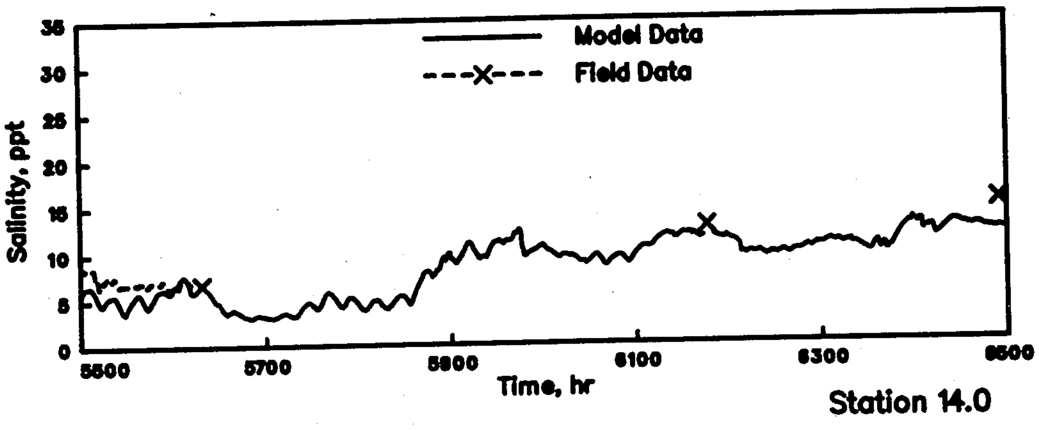


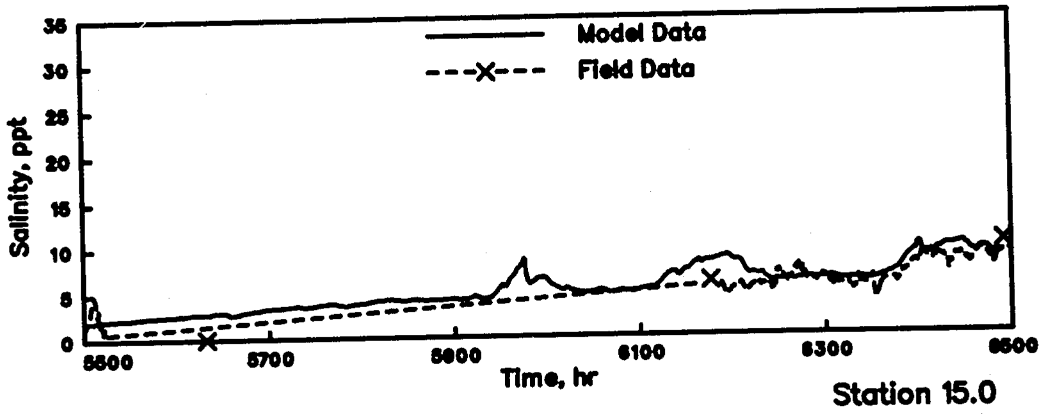
Station 12.1t



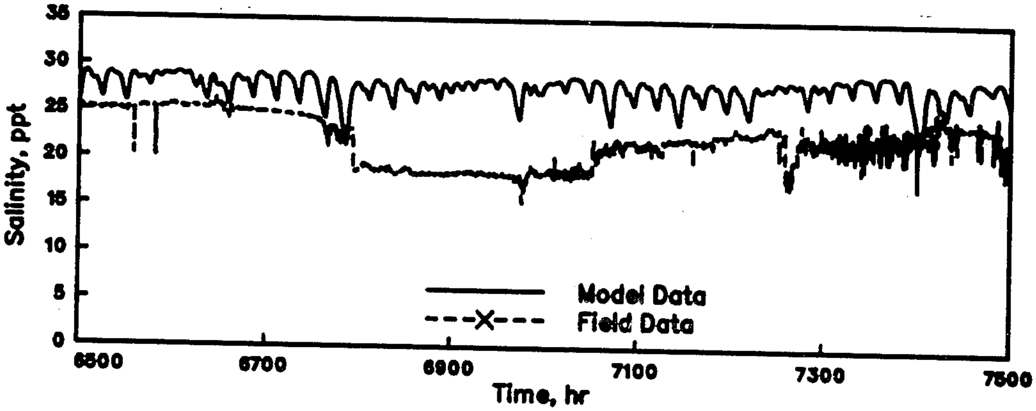
Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 5500-6500

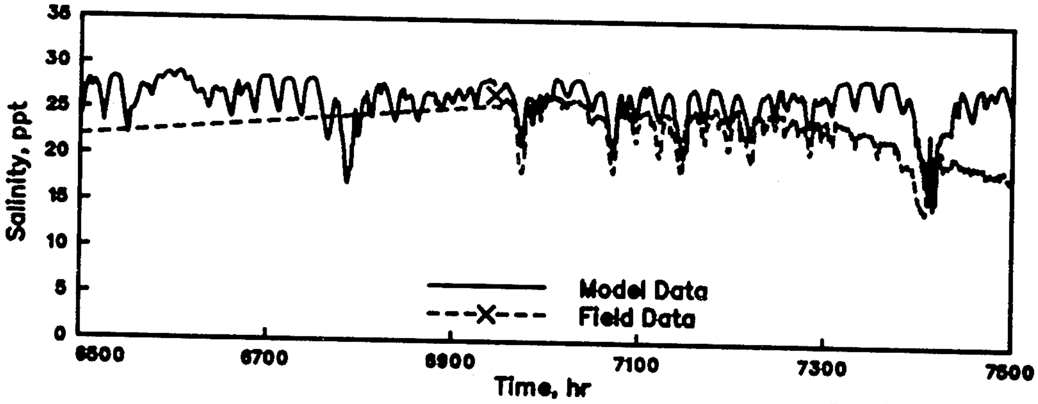




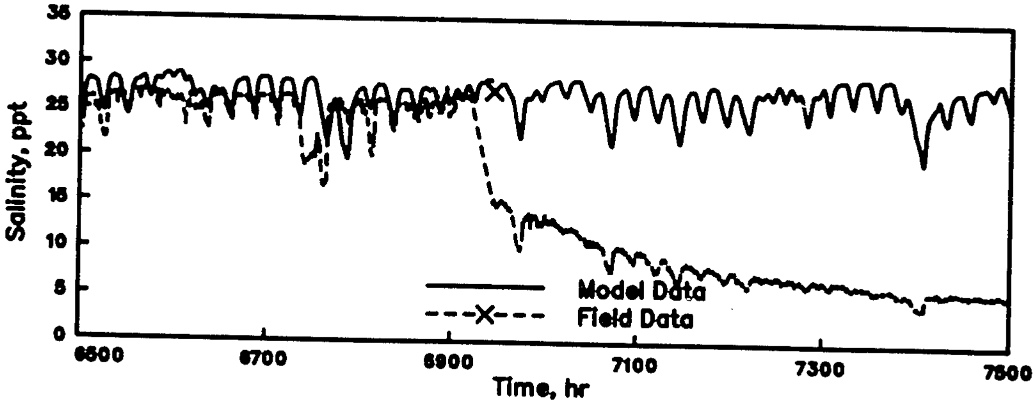
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 5500-6500



Station 1.0

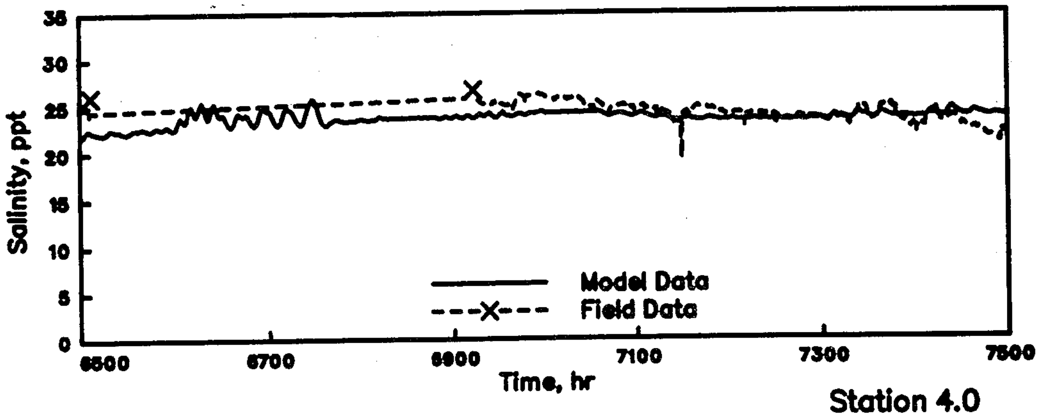


Station 2.0m

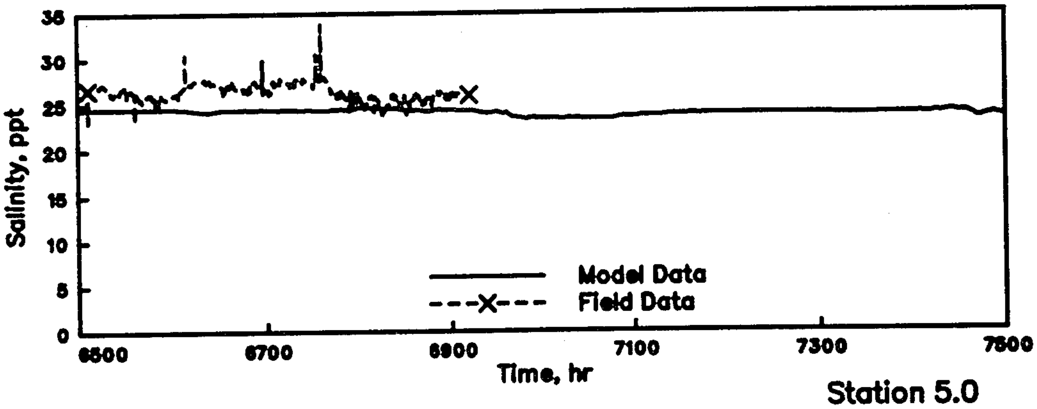


Station 2.0t

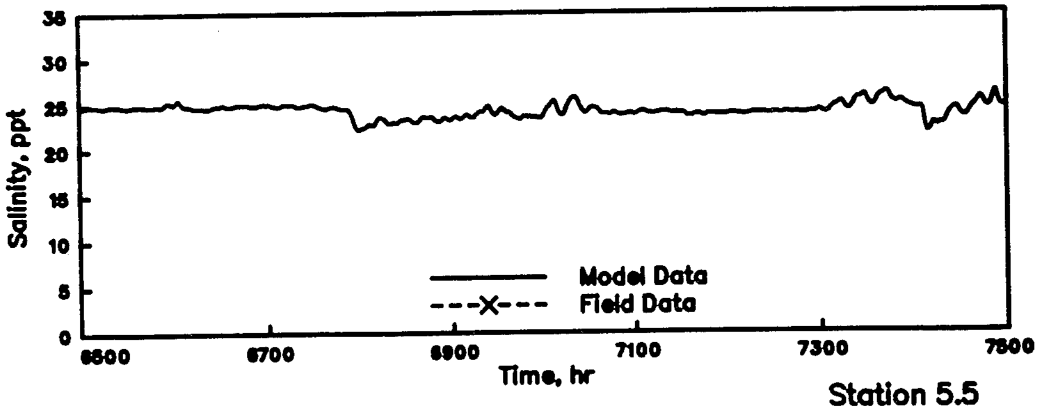
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 6500-7500



Station 4.0

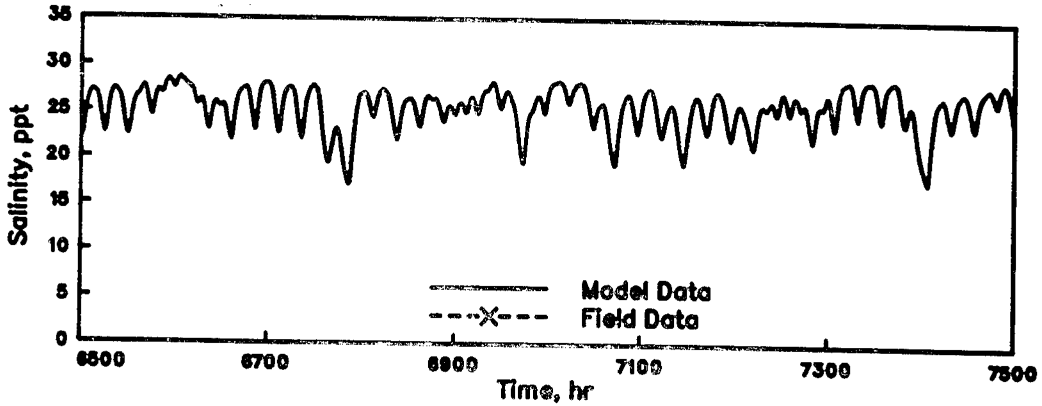


Station 5.0

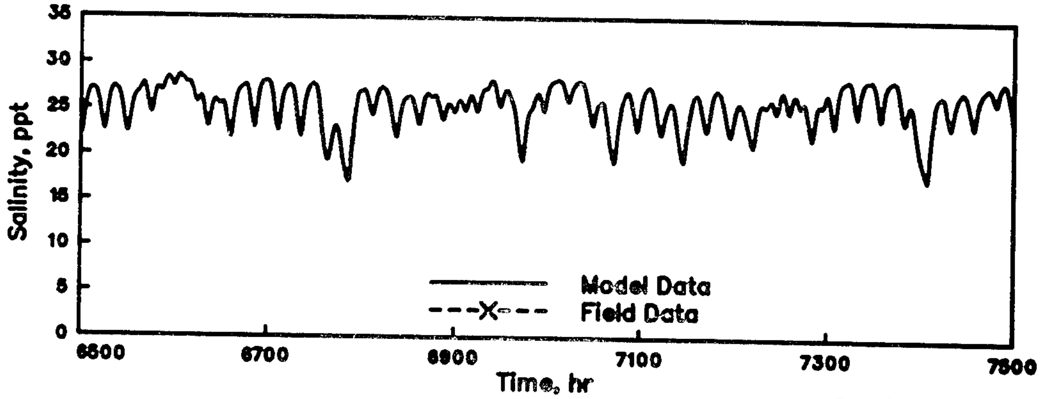


Station 5.5

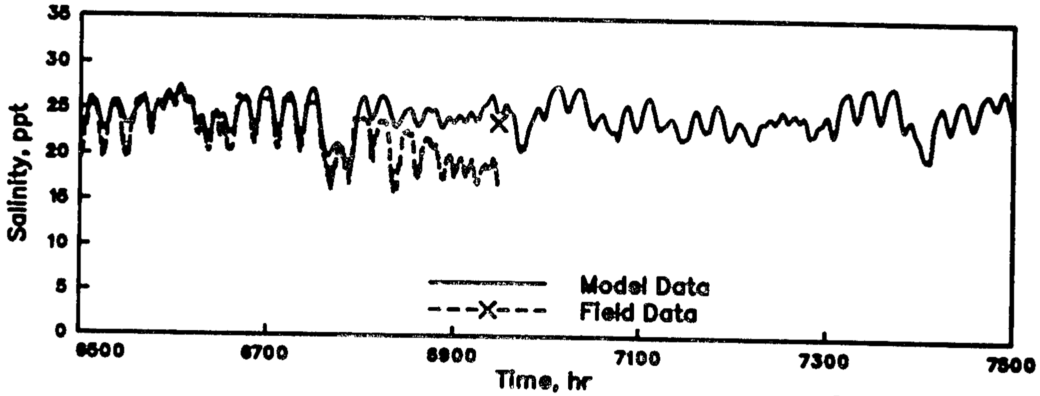
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 6500-7500



Station 6.0m



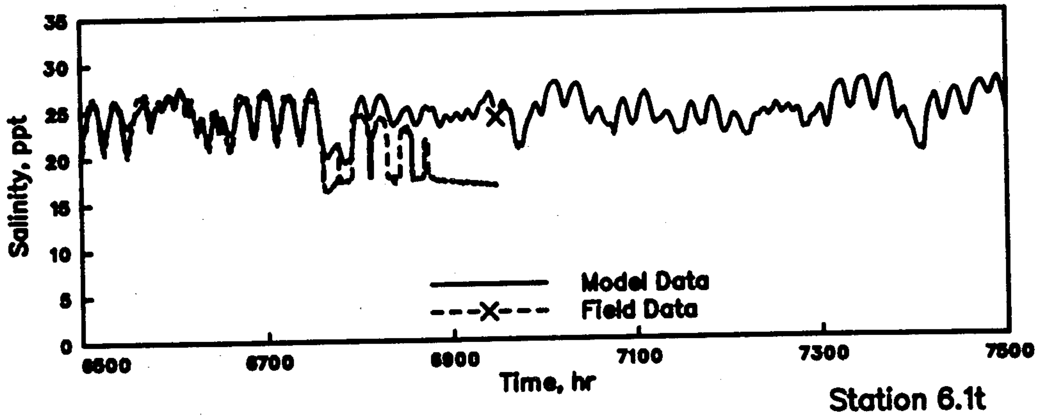
Station 6.0t



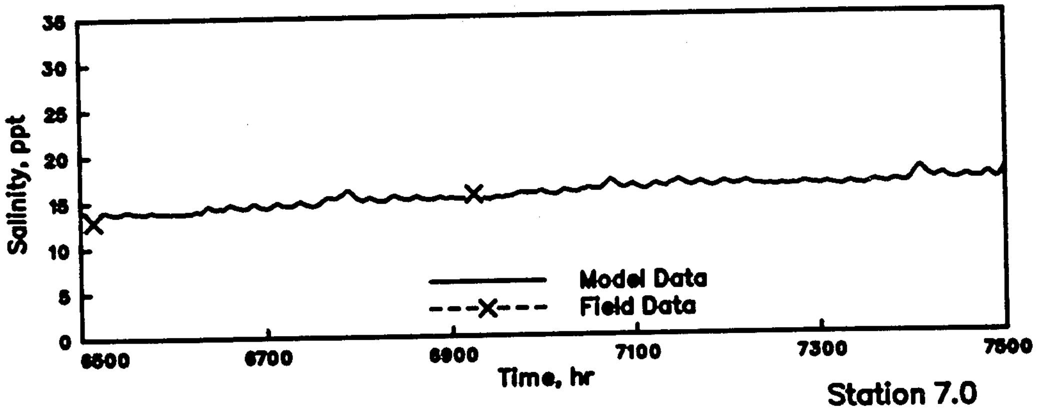
Station 6.1m

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 6500-7500

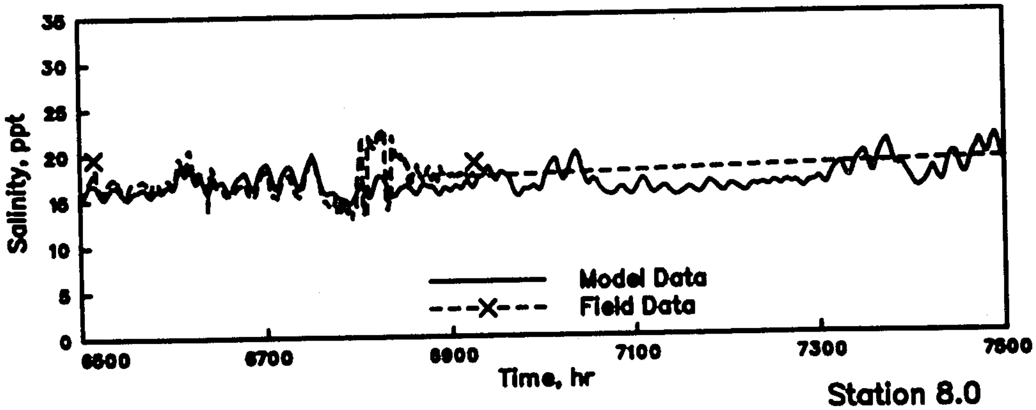
Plate 80



Station 6.1t

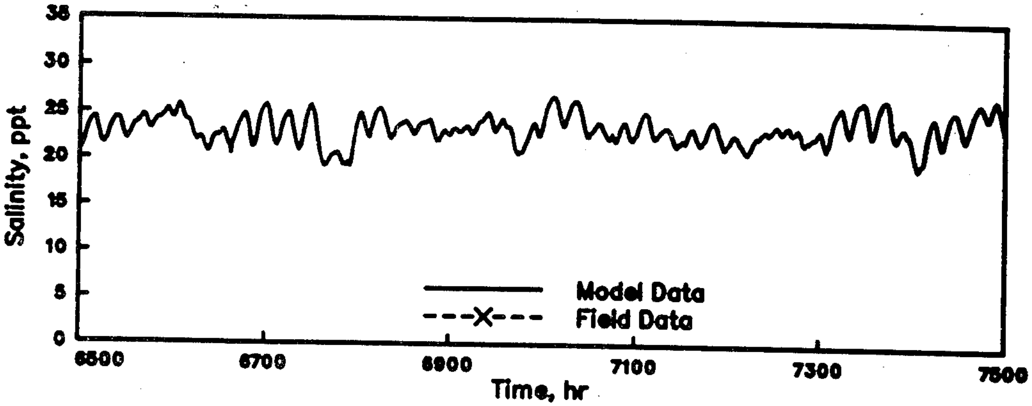


Station 7.0

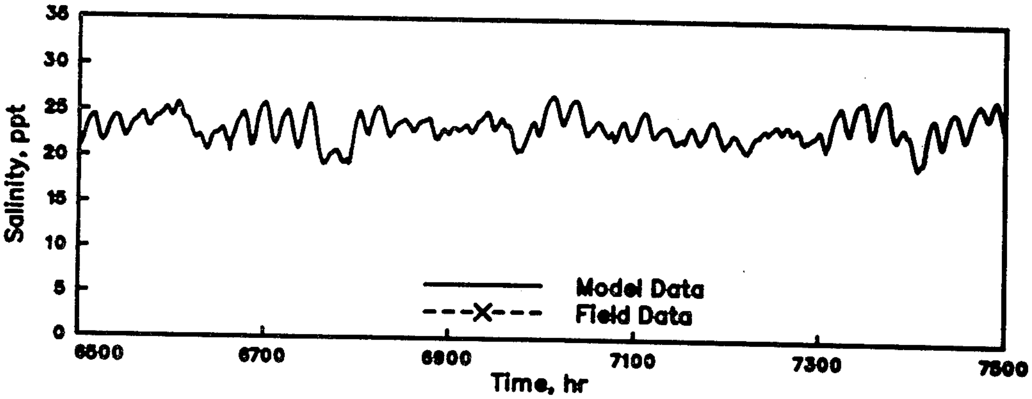


Station 8.0

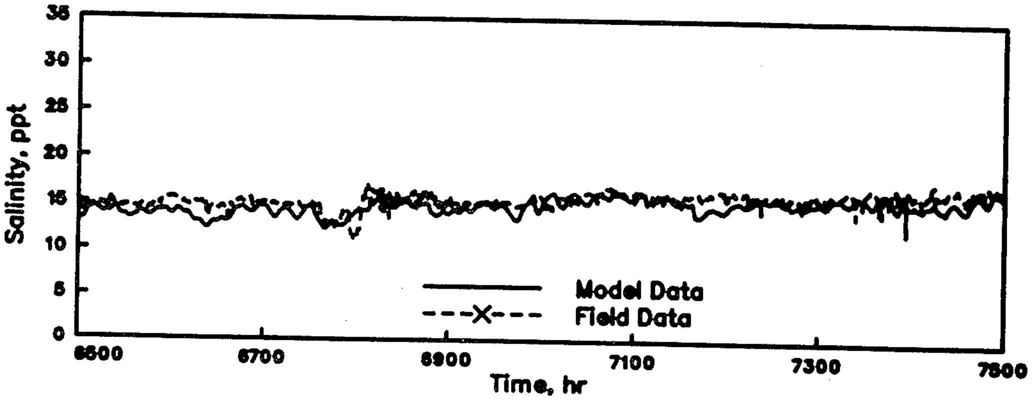
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 6500-7500



Station 9.0m

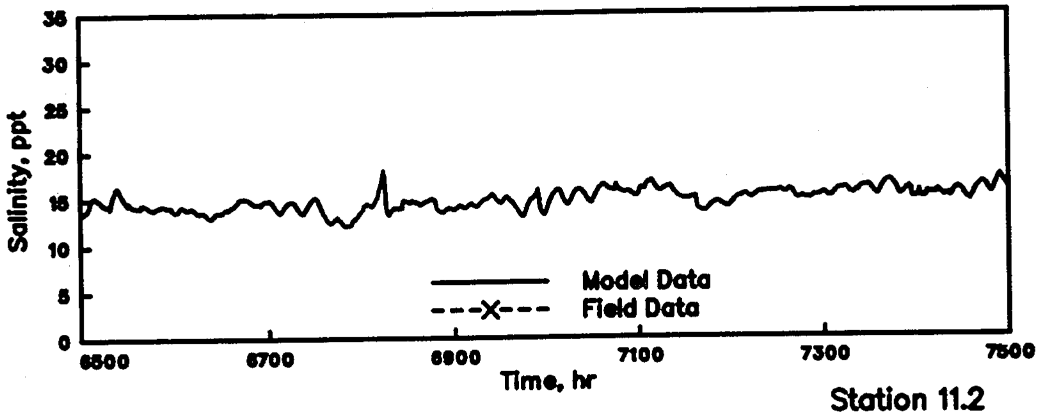


Station 9.0t

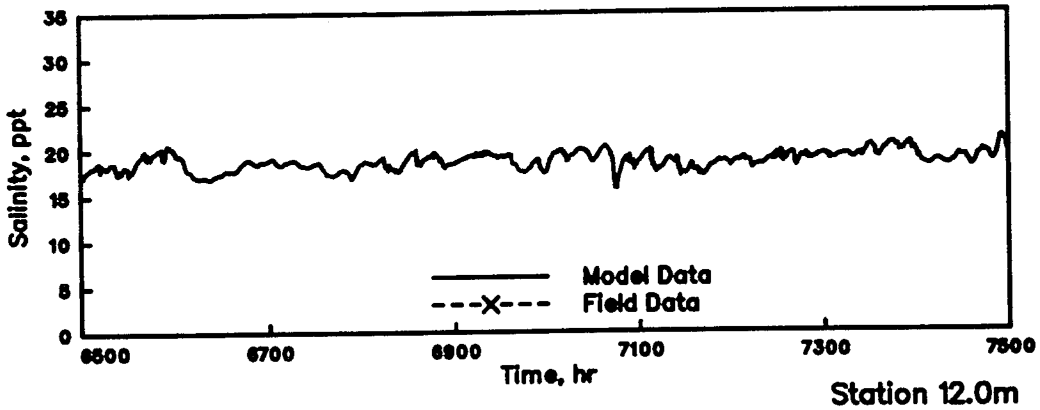


Station 11.0

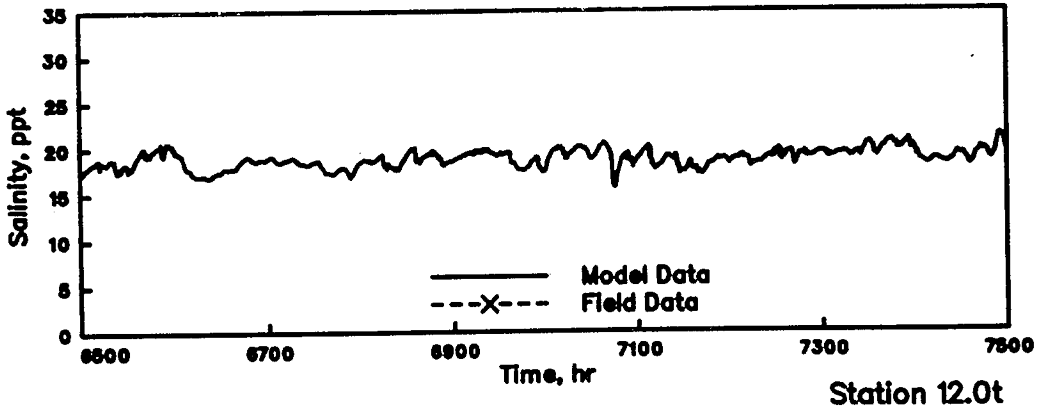
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 6500-7500



Station 11.2

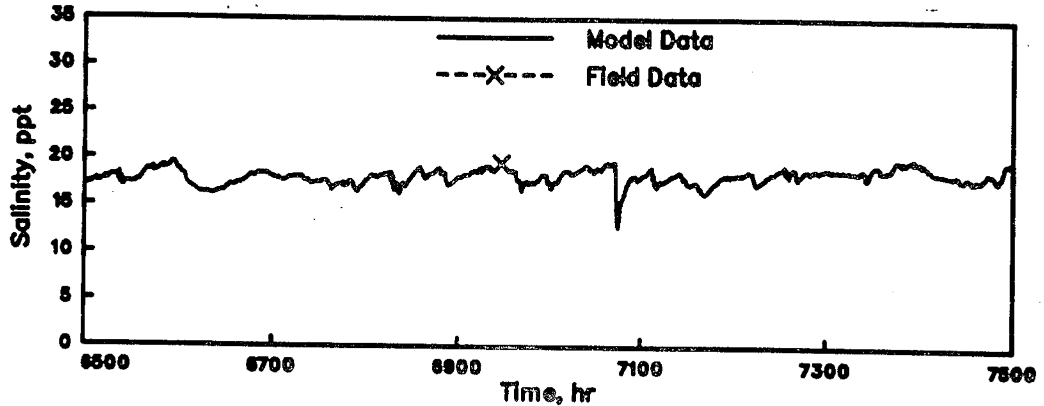


Station 12.0m

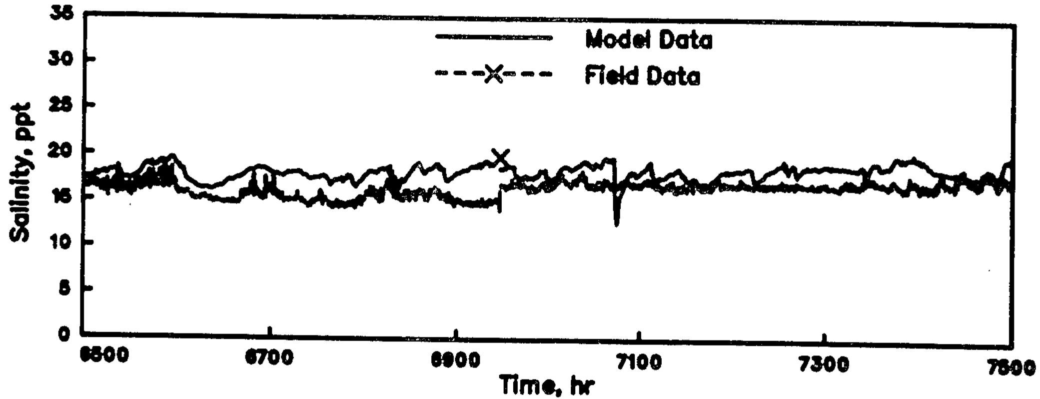


Station 12.0t

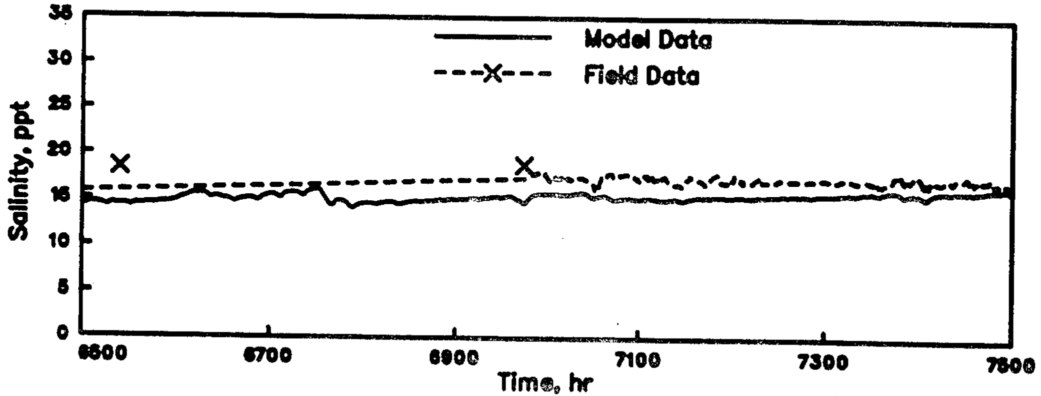
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 6500-7500



Station 12.1m



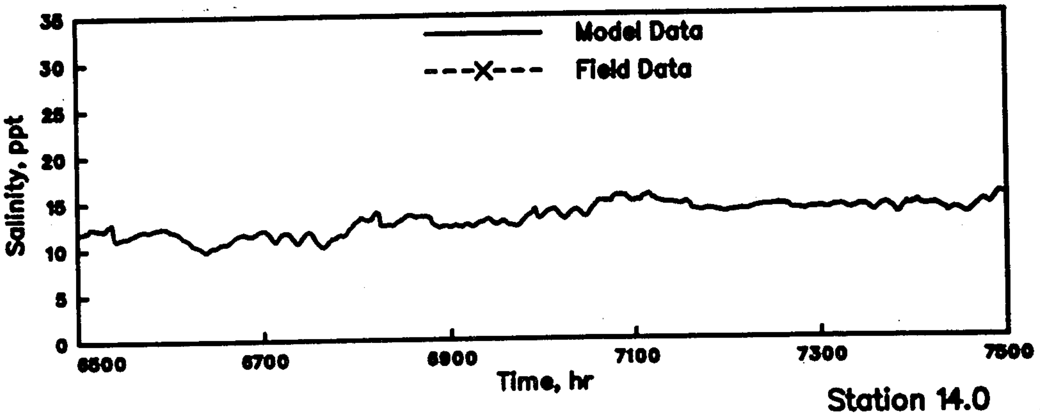
Station 12.1t



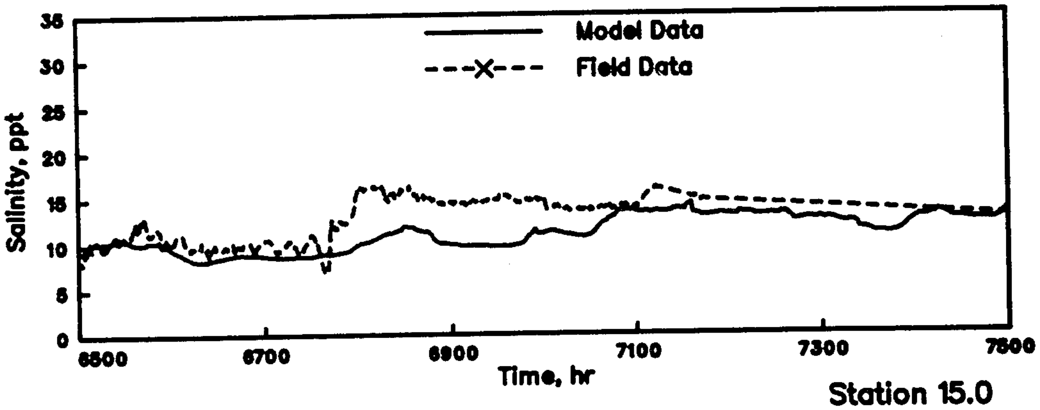
Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 6500-7500

Plate 84

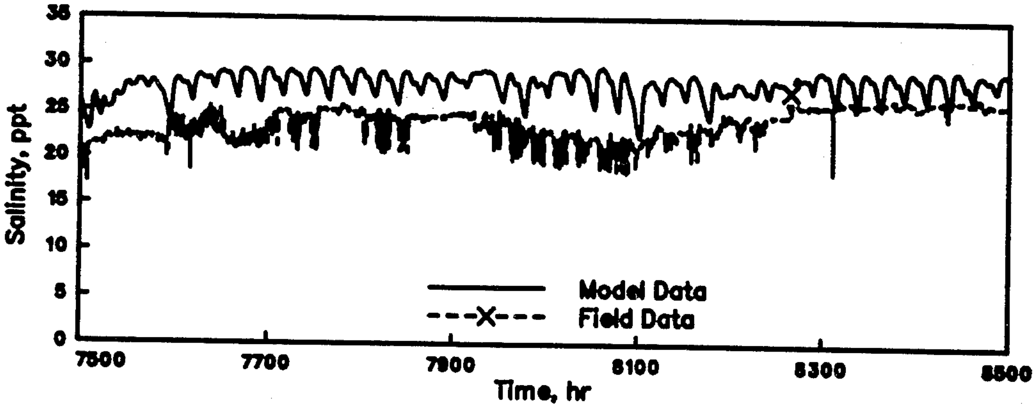


Station 14.0

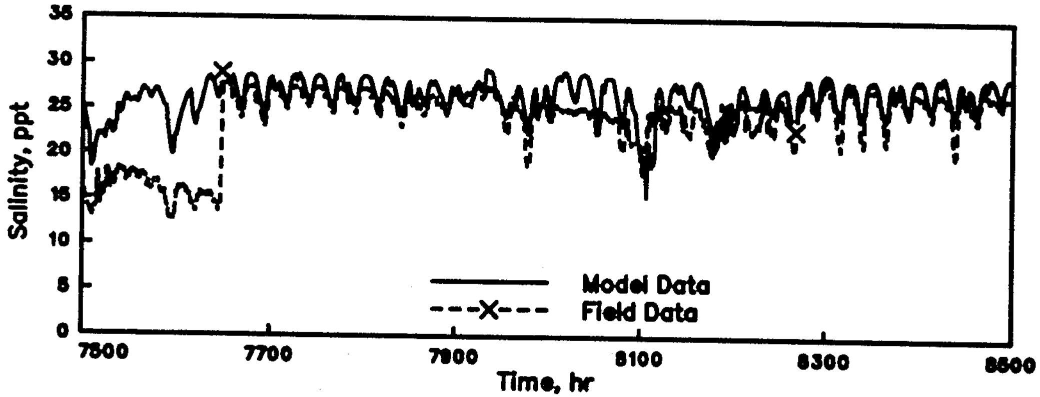


Station 15.0

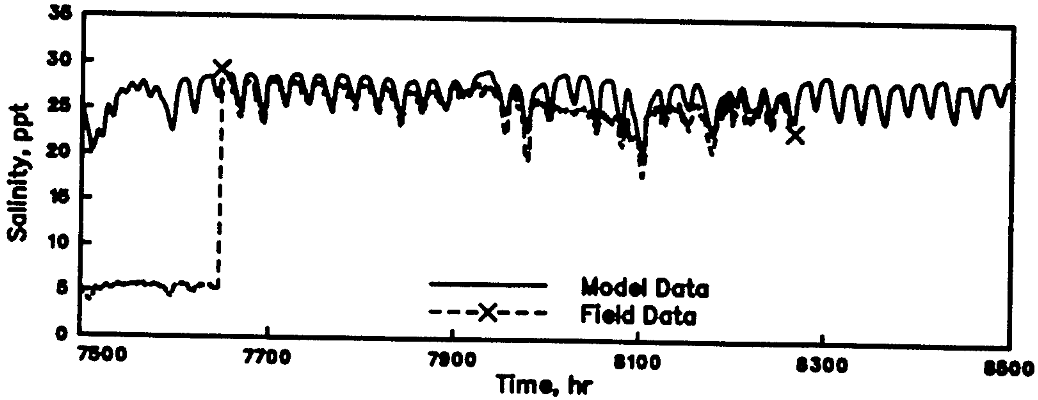
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 6500-7500



Station 1.0

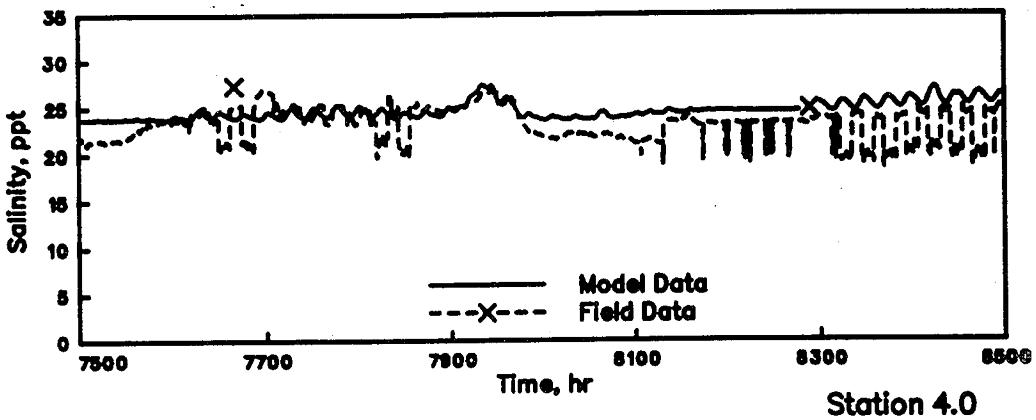


Station 2.0m

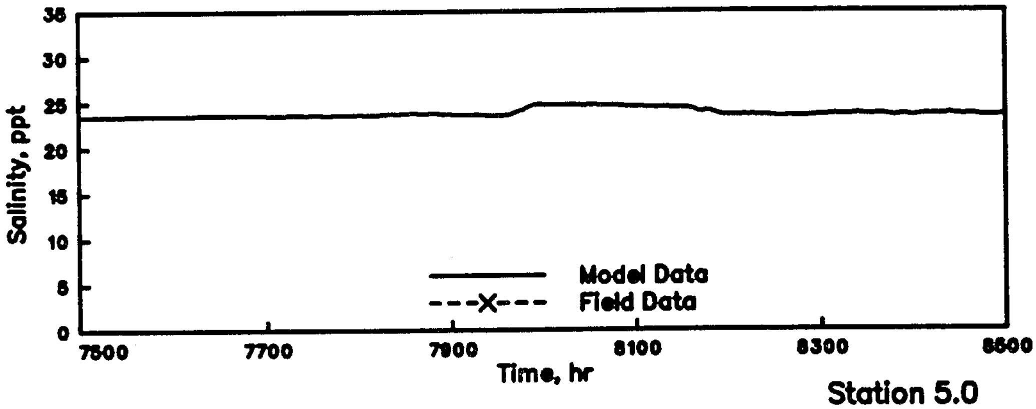


Station 2.0t

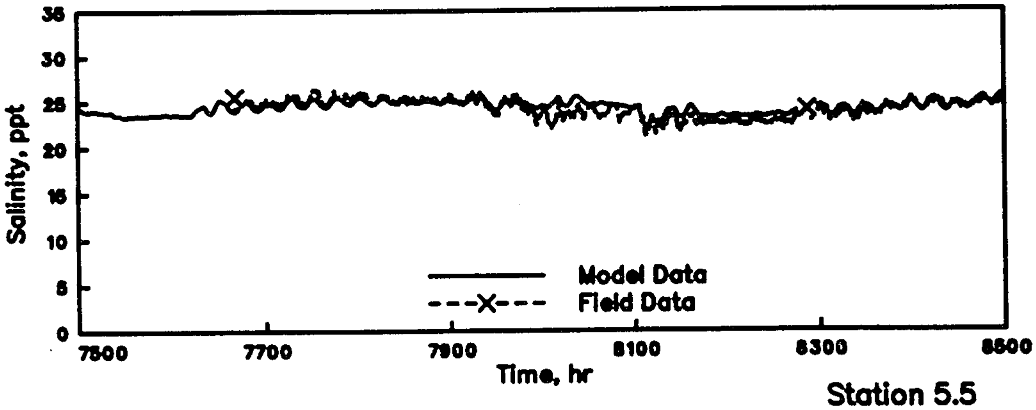
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 1.0, 2.0m, AND 2.0t
HOURS 7500-8500



Station 4.0

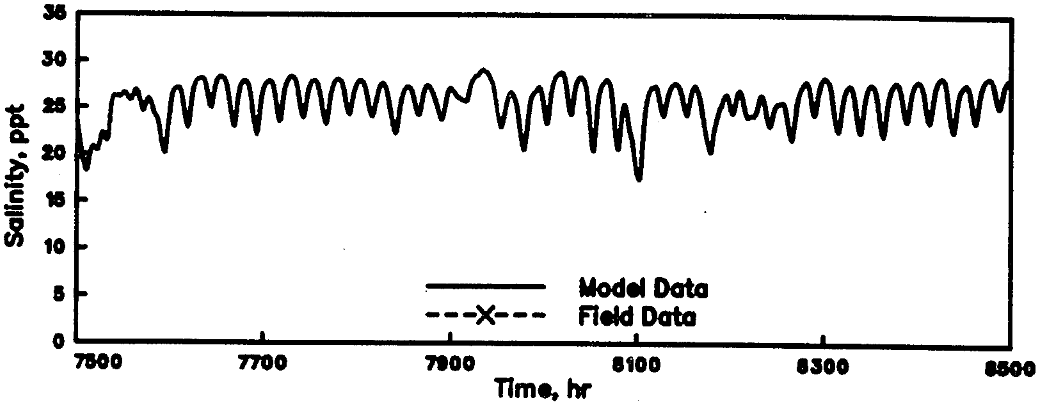


Station 5.0

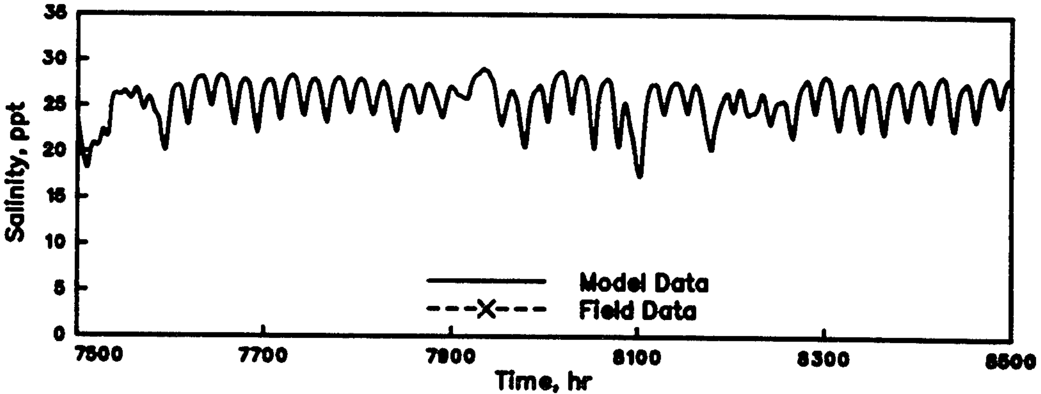


Station 5.5

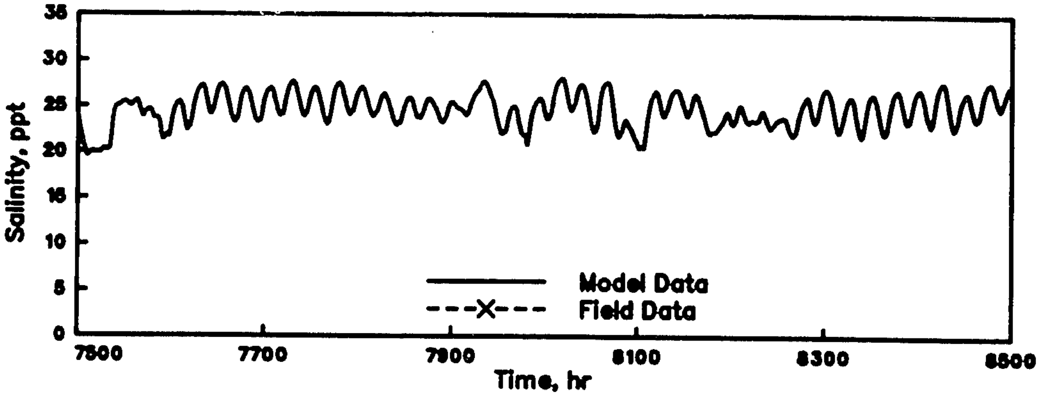
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 4.0, 5.0, AND 5.5
HOURS 7500-8500



Station 6.0m

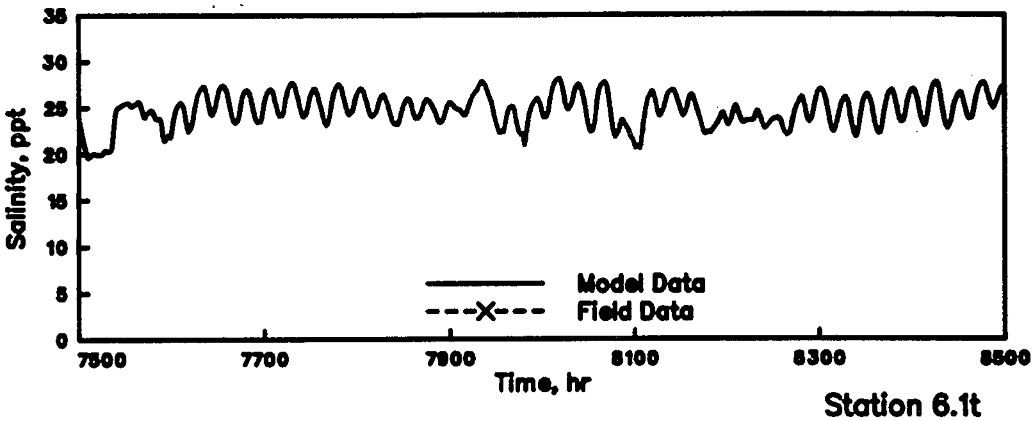


Station 6.0t

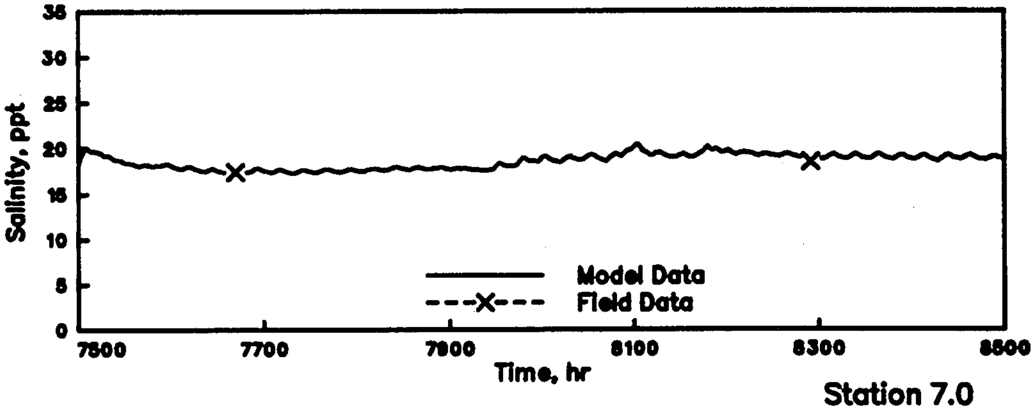


Station 6.1m

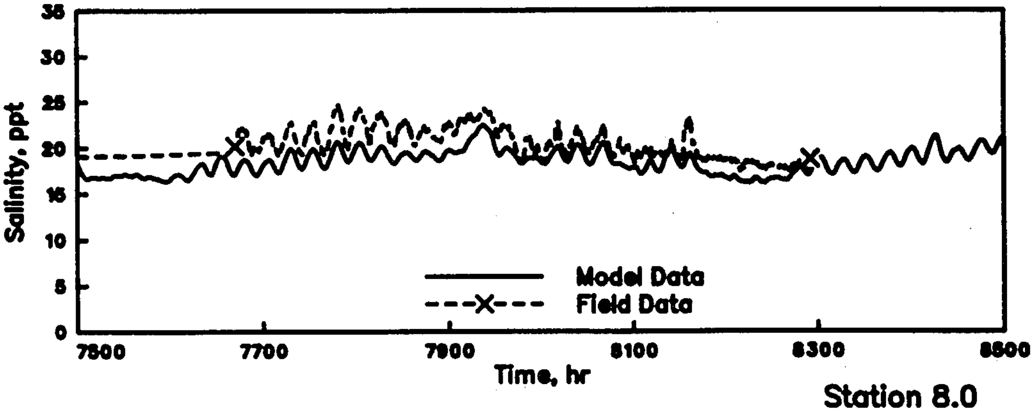
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.0m, 6.0t, AND 6.1m
HOURS 7500-8500



Station 6.1t

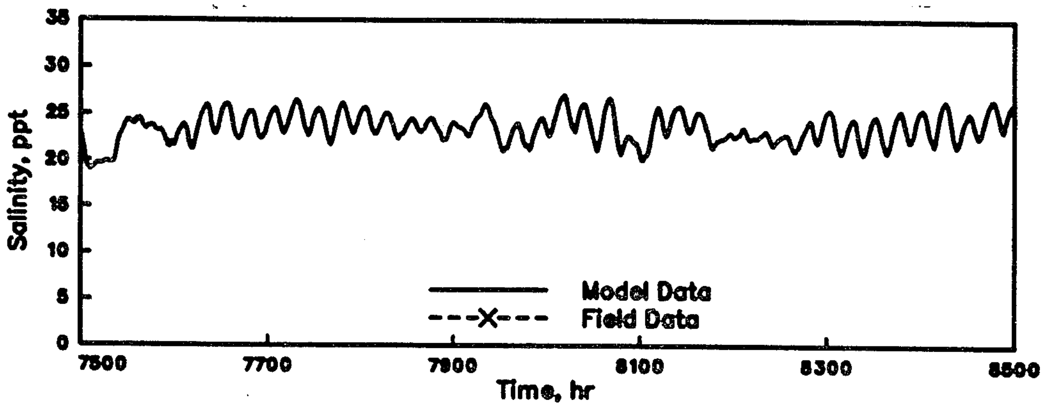


Station 7.0

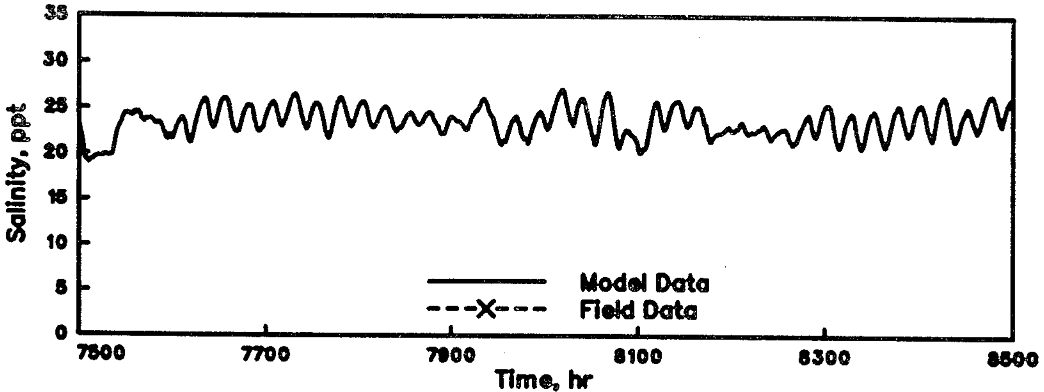


Station 8.0

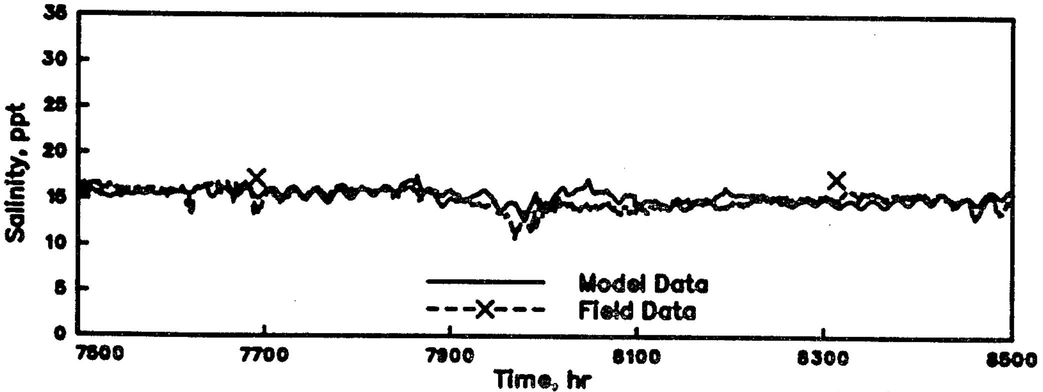
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 6.1t, 7.0, AND 8.0
HOURS 7500-8500



Station 9.0m

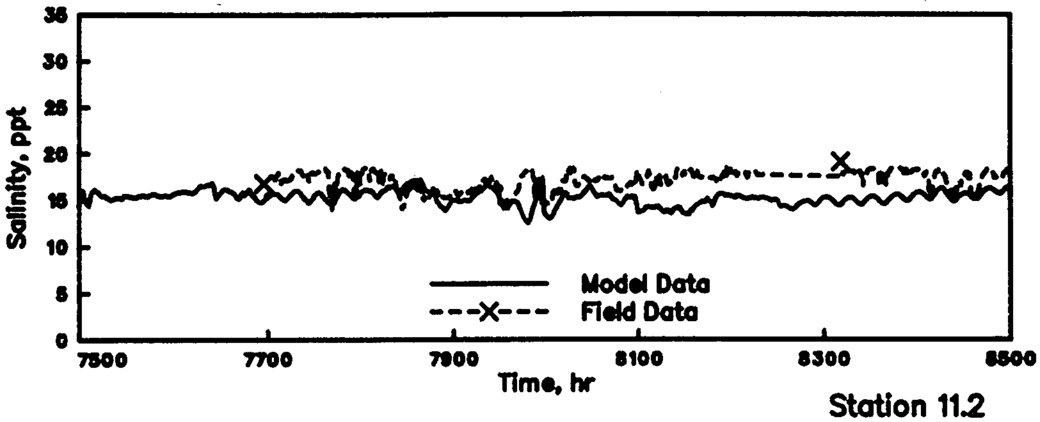


Station 9.0t

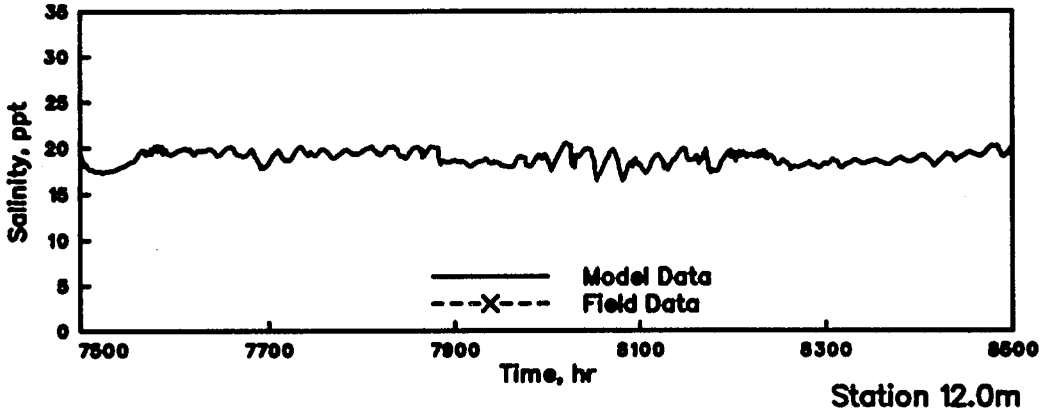


Station 11.0

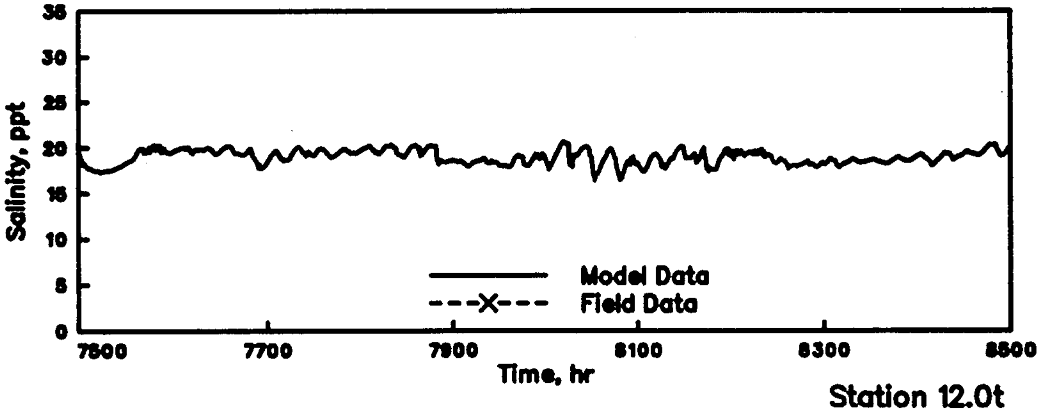
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 9.0m, 9.0t, AND 11.0
HOURS 7500-8500



Station 11.2

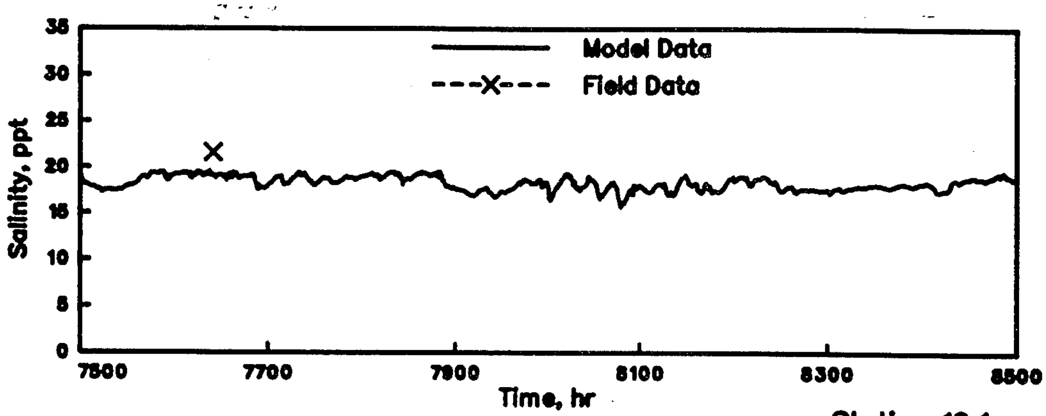


Station 12.0m

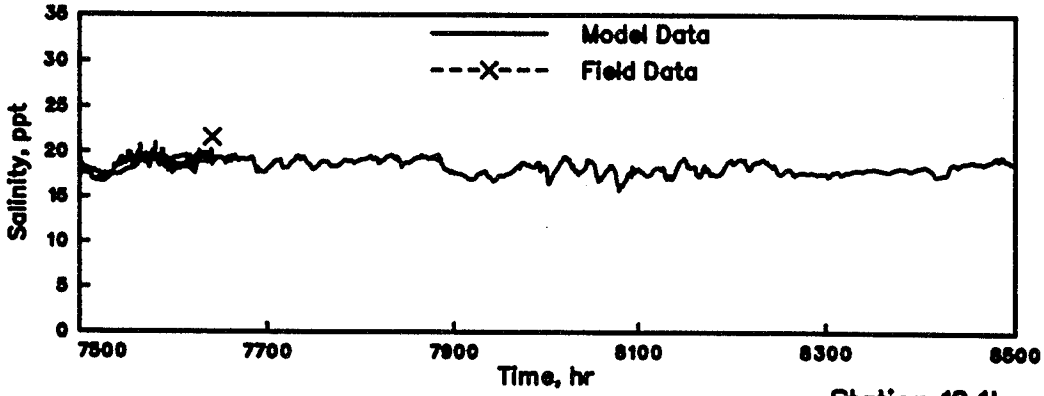


Station 12.0t

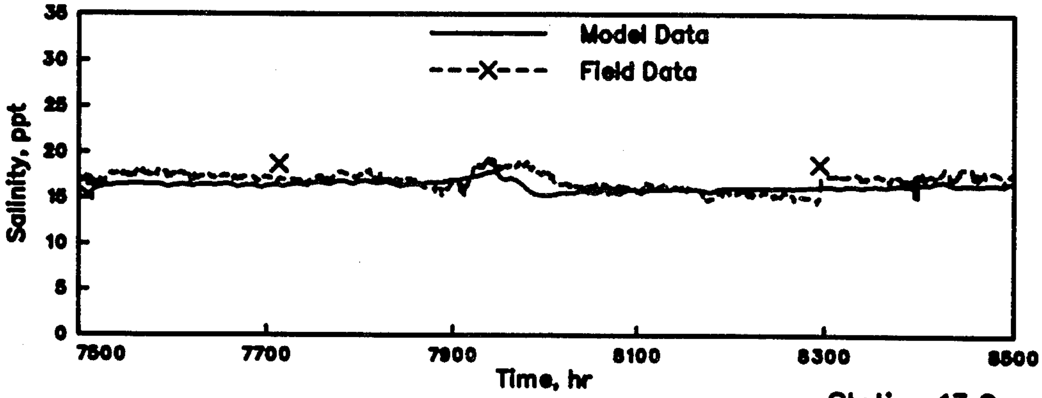
GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 11.2, 12.0m, AND 12.0t
HOURS 7500-8500



Station 12.1m

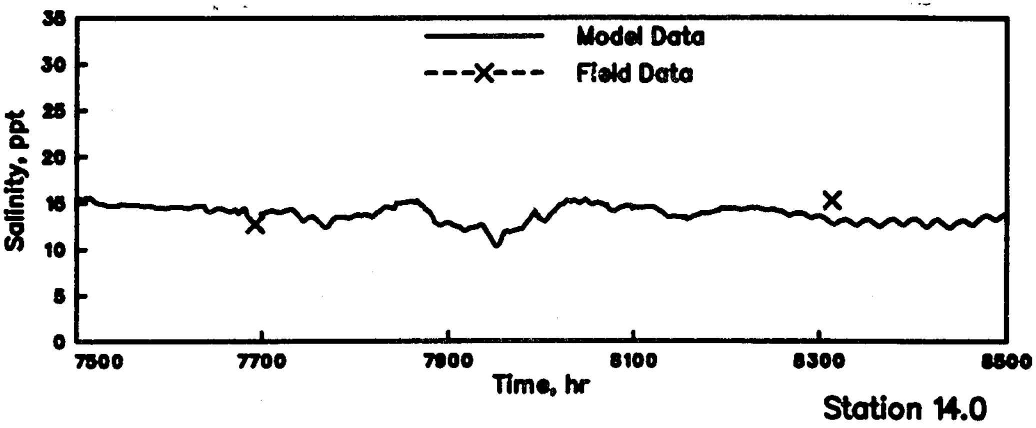


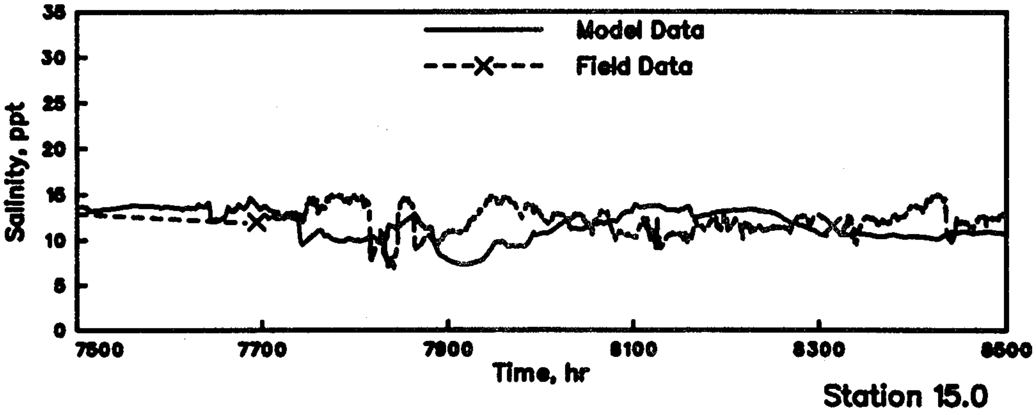
Station 12.1t



Station 13.0

GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 12.1m, 12.1t, AND 13.0
HOURS 7500-8500





GALVESTON BAY SALINITIES
MODEL VERIFICATION
STATIONS 14.0 AND 15.0
HOURS 7500-8500

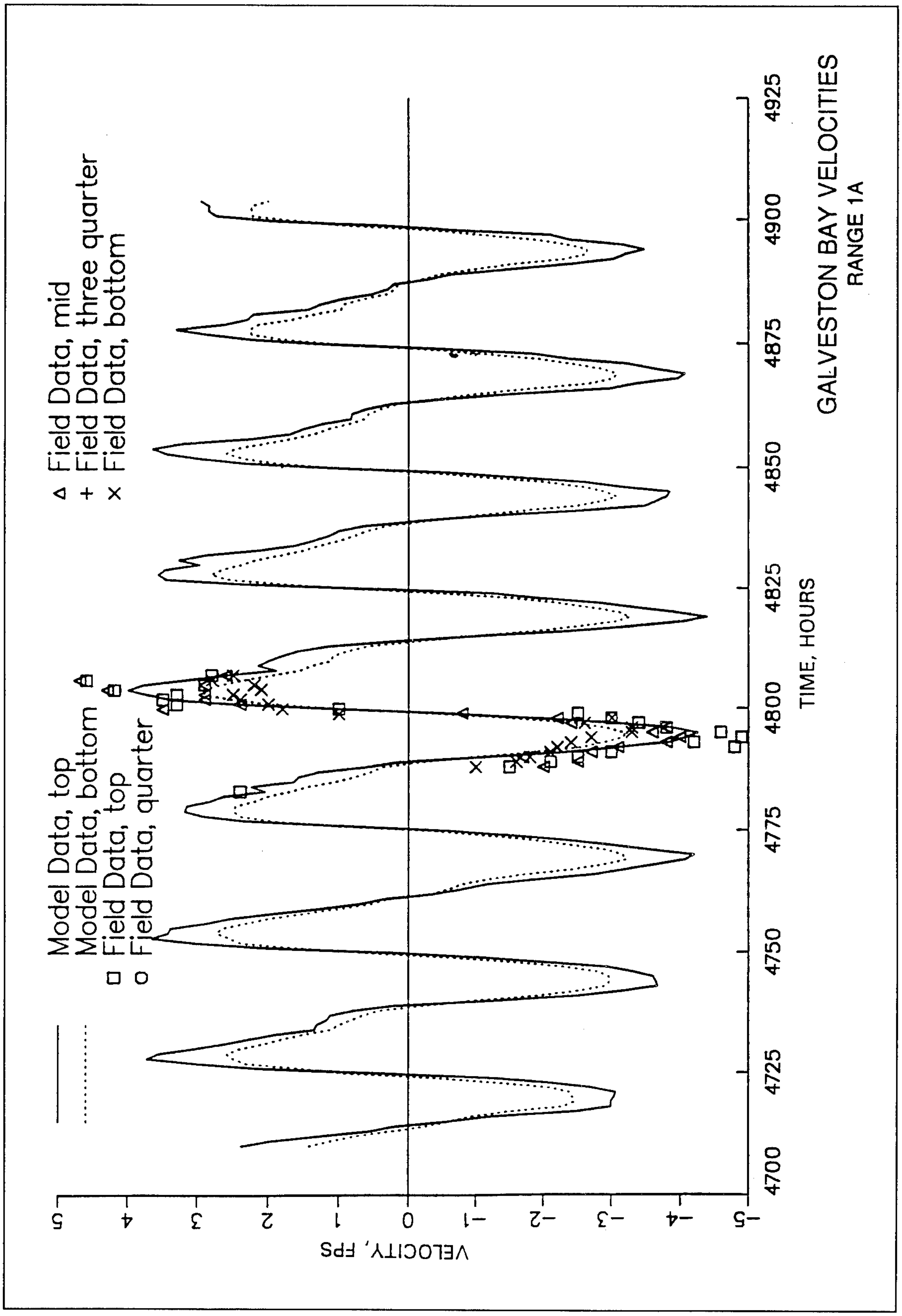
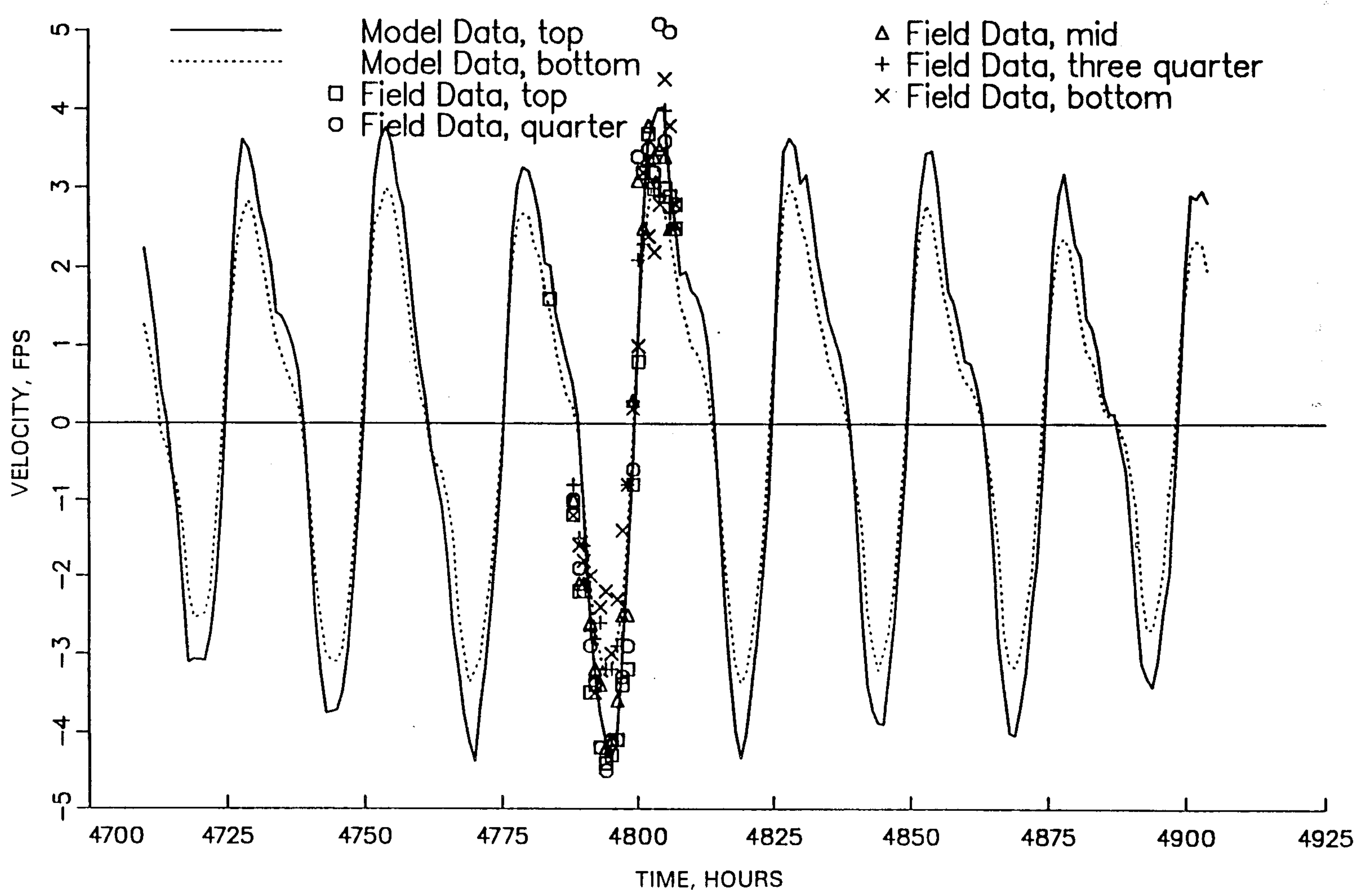

GALVESTON BAY VELOCITIES
RANGE 1A
Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
TIME, HOURS
5
4
3
2
1
0
−1
−2
−3
−4
−5
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925

Plate 94



GALVESTON BAY VELOCITIES
RANGE 1B

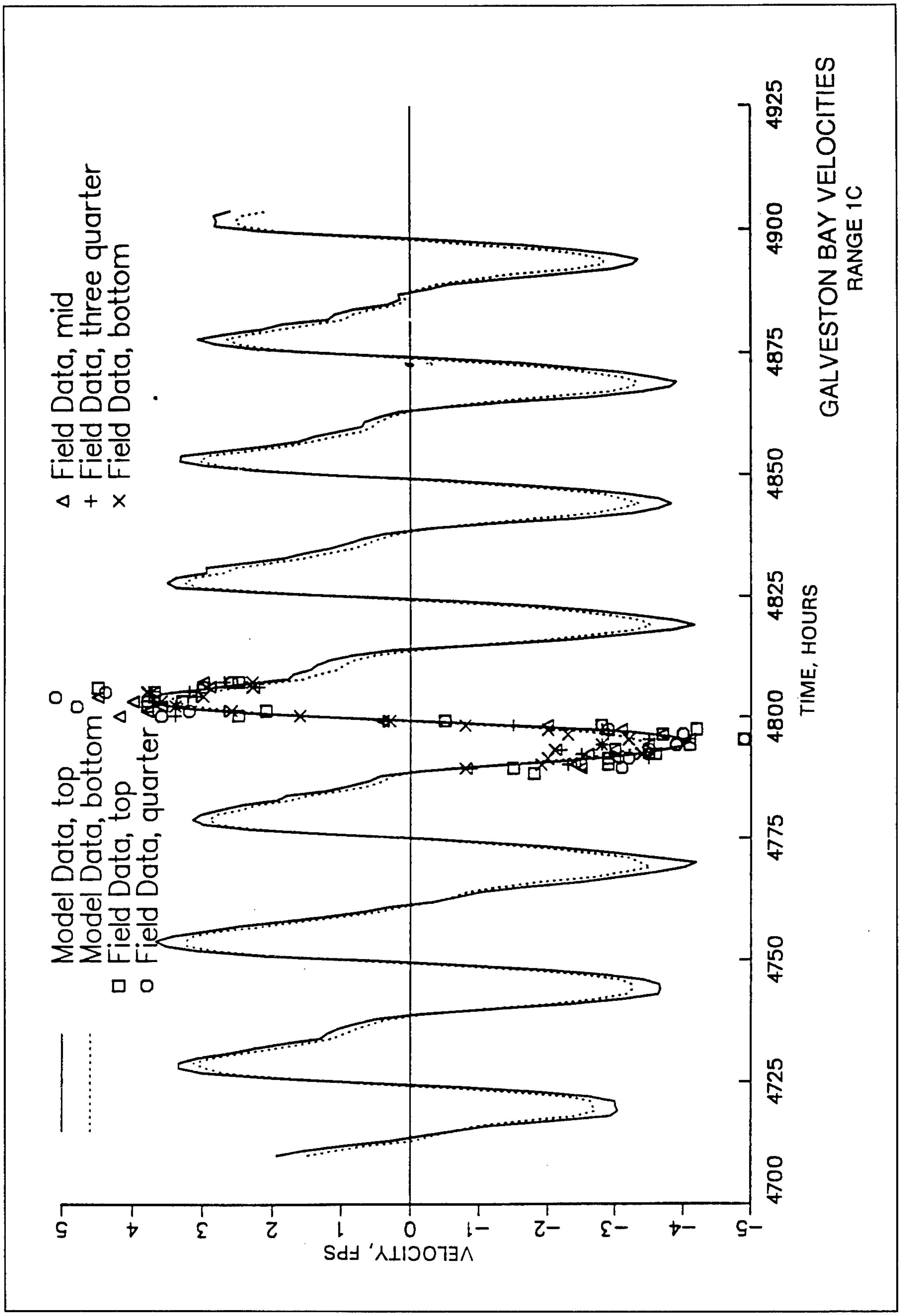
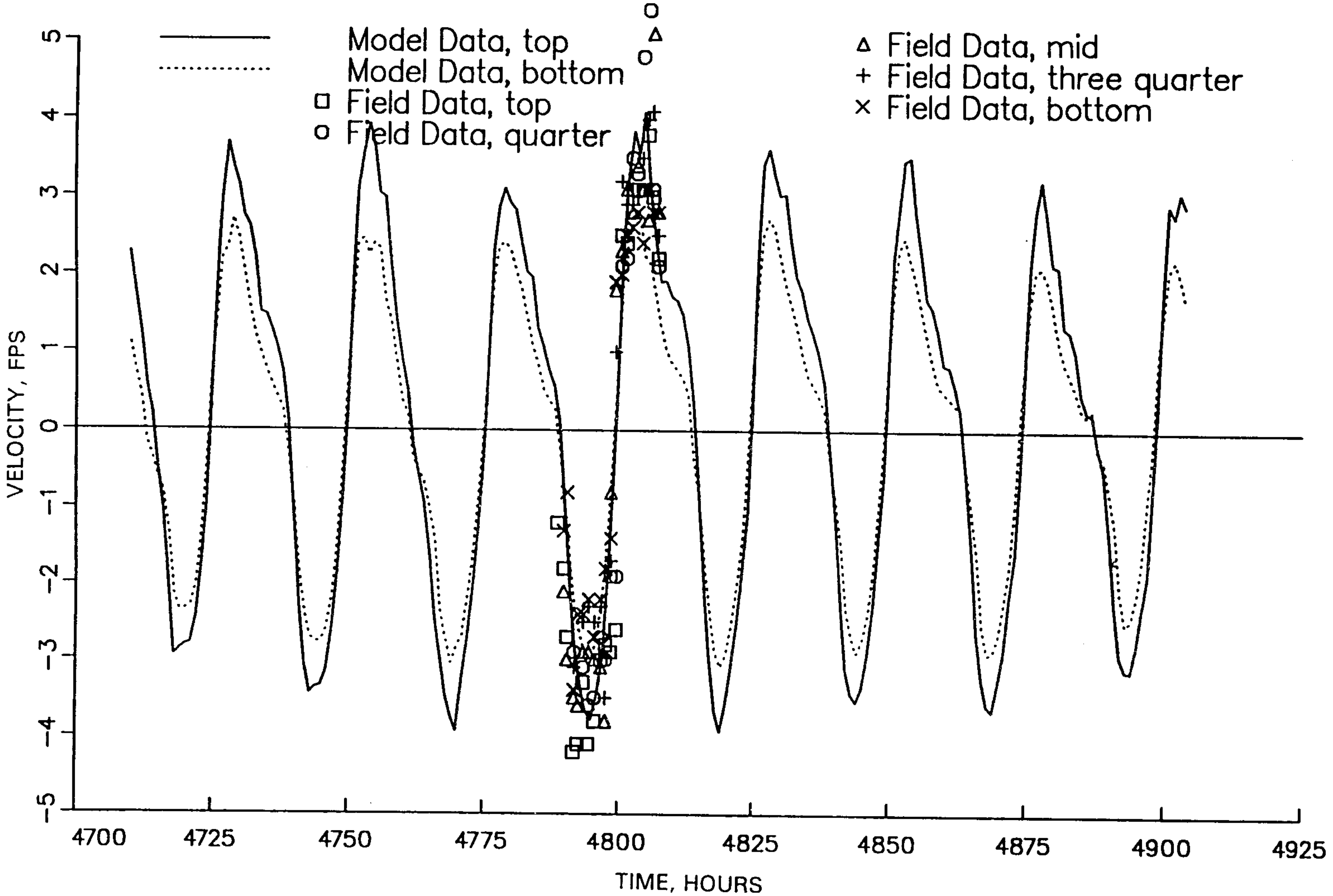
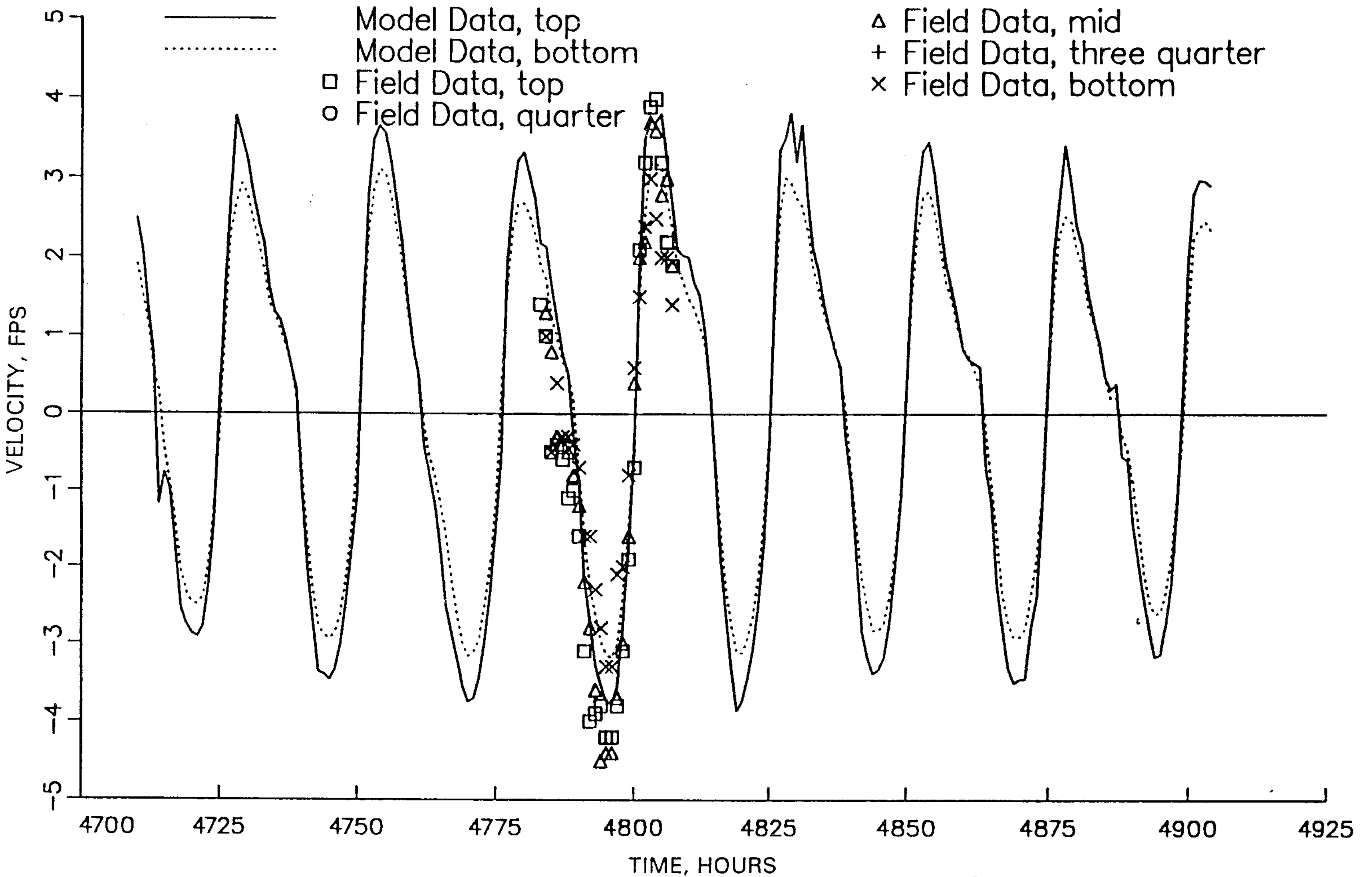

GALVESTON BAY VELOCITIES
RANGE 1C
Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
5
4
3
2
1
0
−1
−2
−3
−4
−5
TIME, HOURS
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925

Plate 96

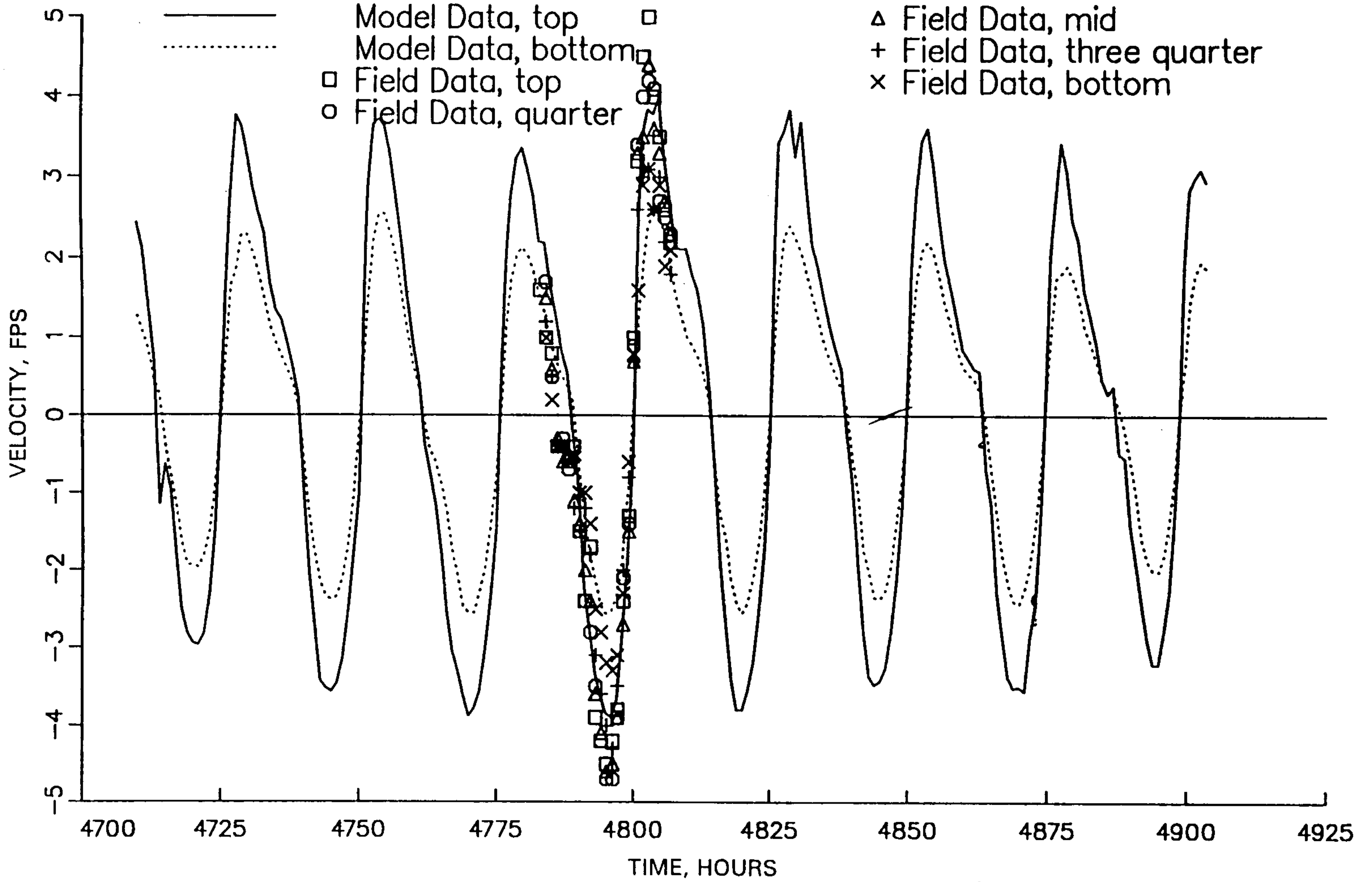


GALVESTON BAY VELOCITIES
RANGE 1D

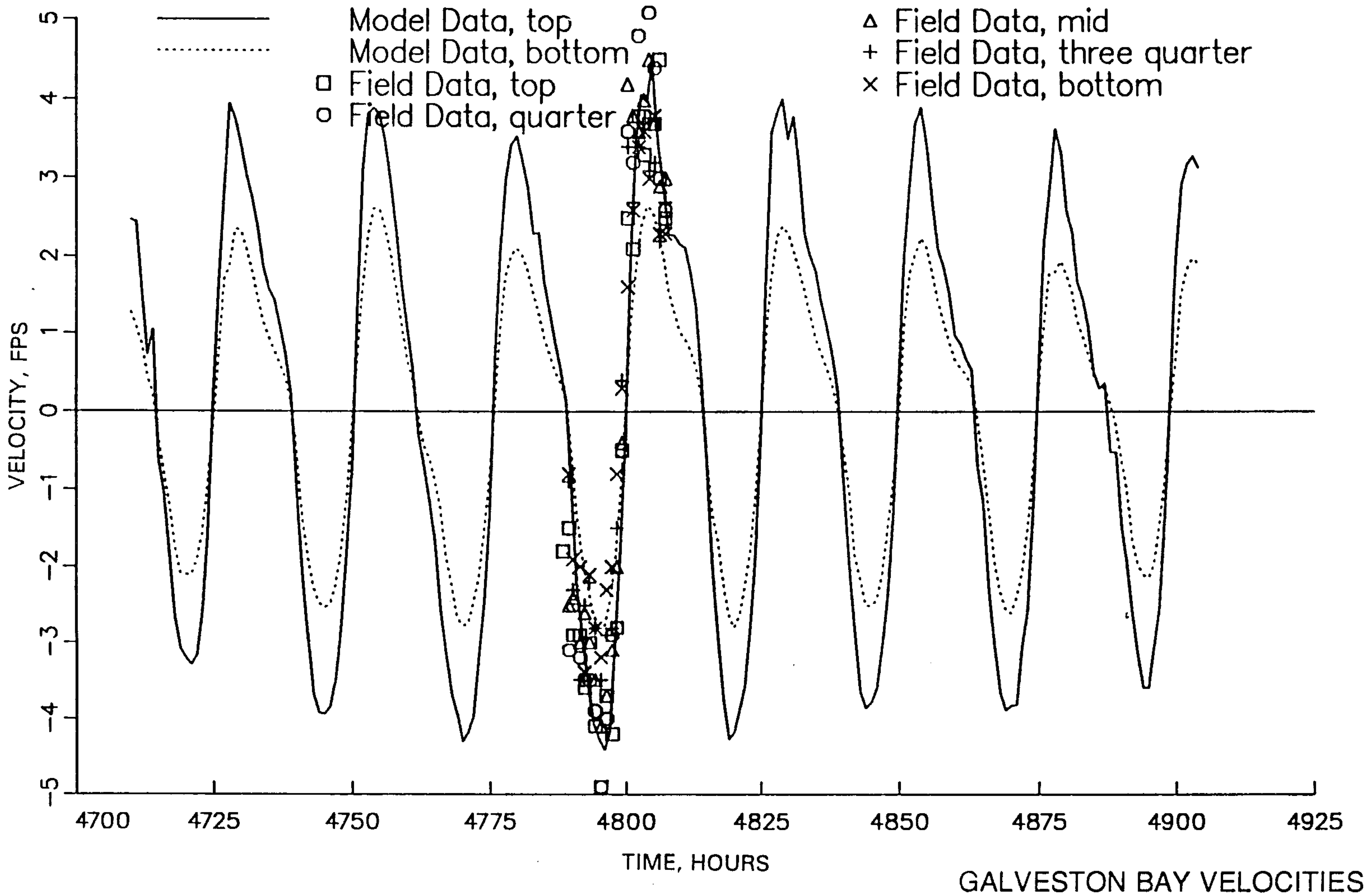


GALVESTON BAY VELOCITIES
RANGE 2A

Plate 98

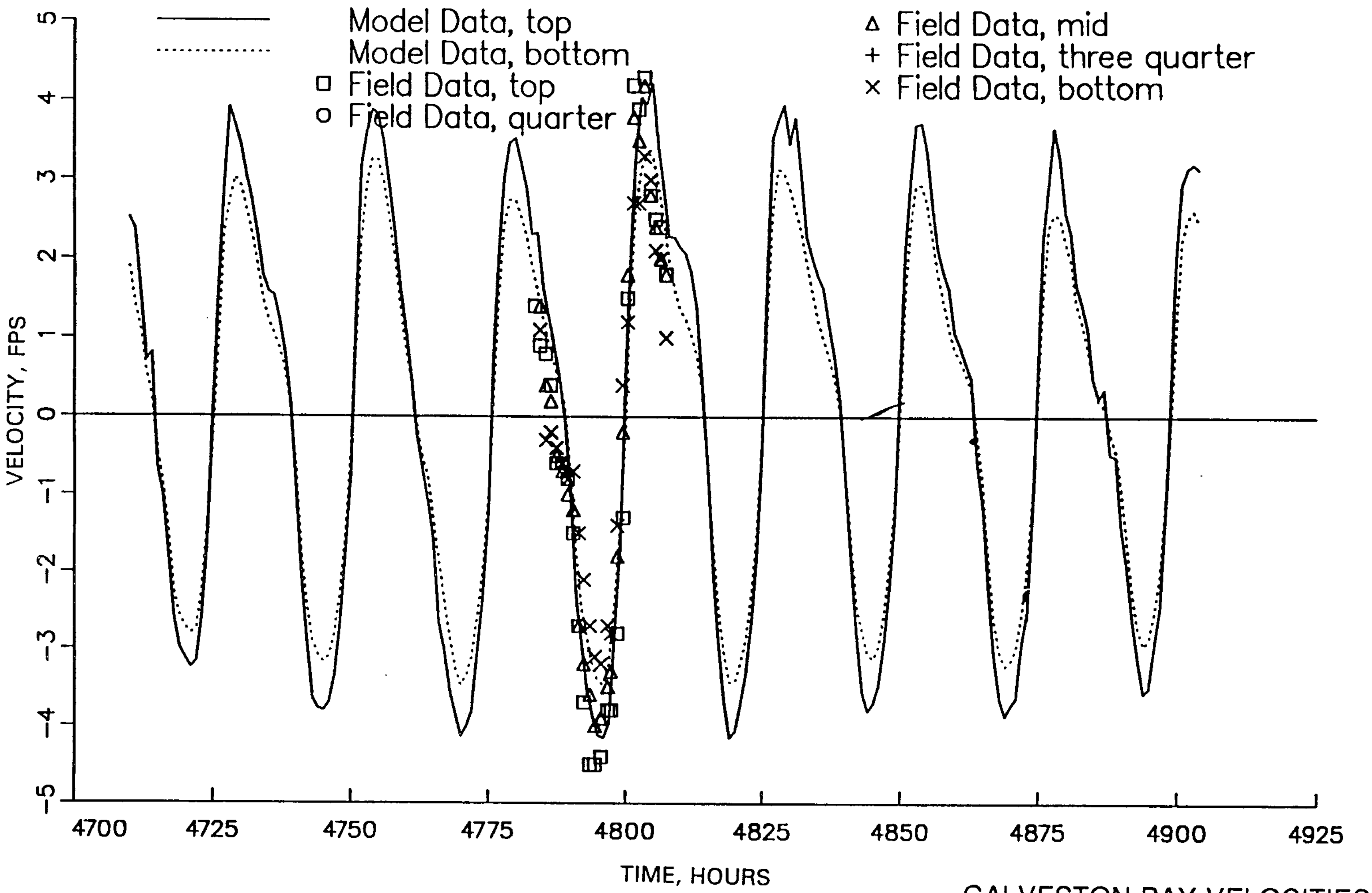


GALVESTON BAY VELOCITIES
RANGE 2B



GALVESTON BAY VELOCITIES
RANGE 2C

Plate 100



GALVESTON BAY VELOCITIES
RANGE 2D

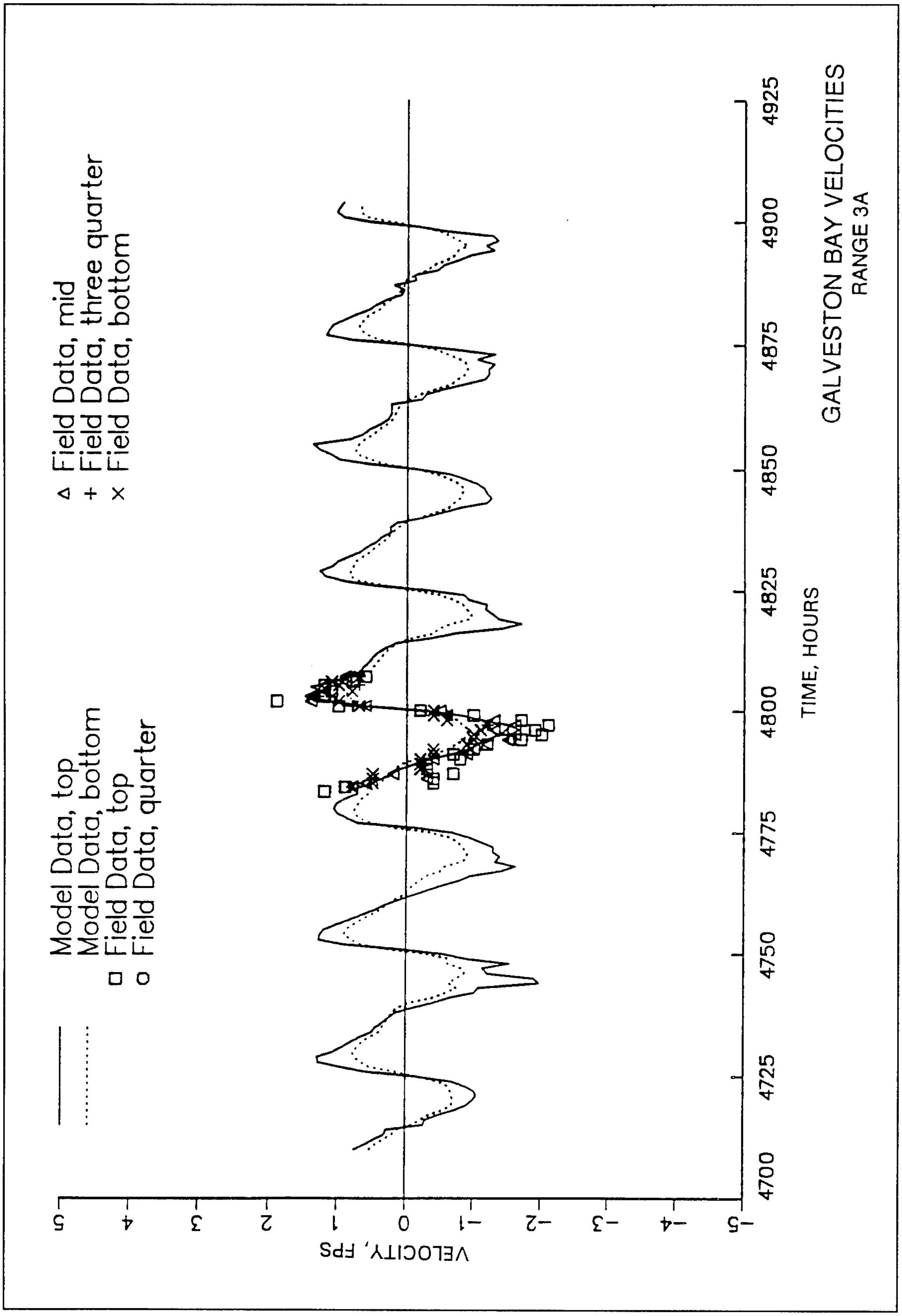
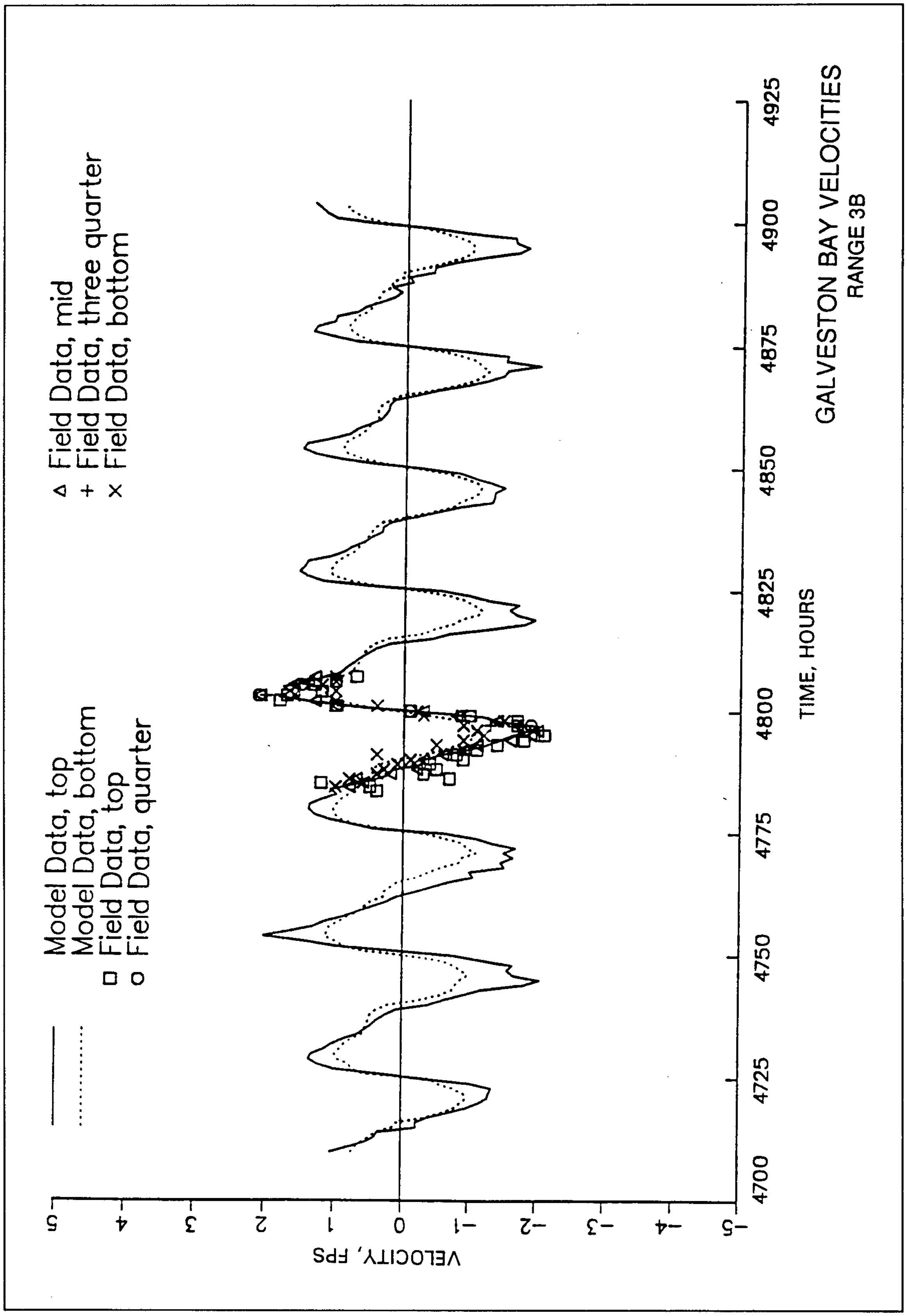

Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
5
4
3
2
1
0
−1
−2
−3
−4
−5
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
TIME, HOURS
GALVESTON BAY VELOCITIES
RANGE 3A

Plate 102


GALVESTON BAY VELOCITIES
RANGE 3B
VELOCITY, FPS
TIME, HOURS
Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
5
4
3
2
1
0
−1
−2
−3
−4
−5
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925

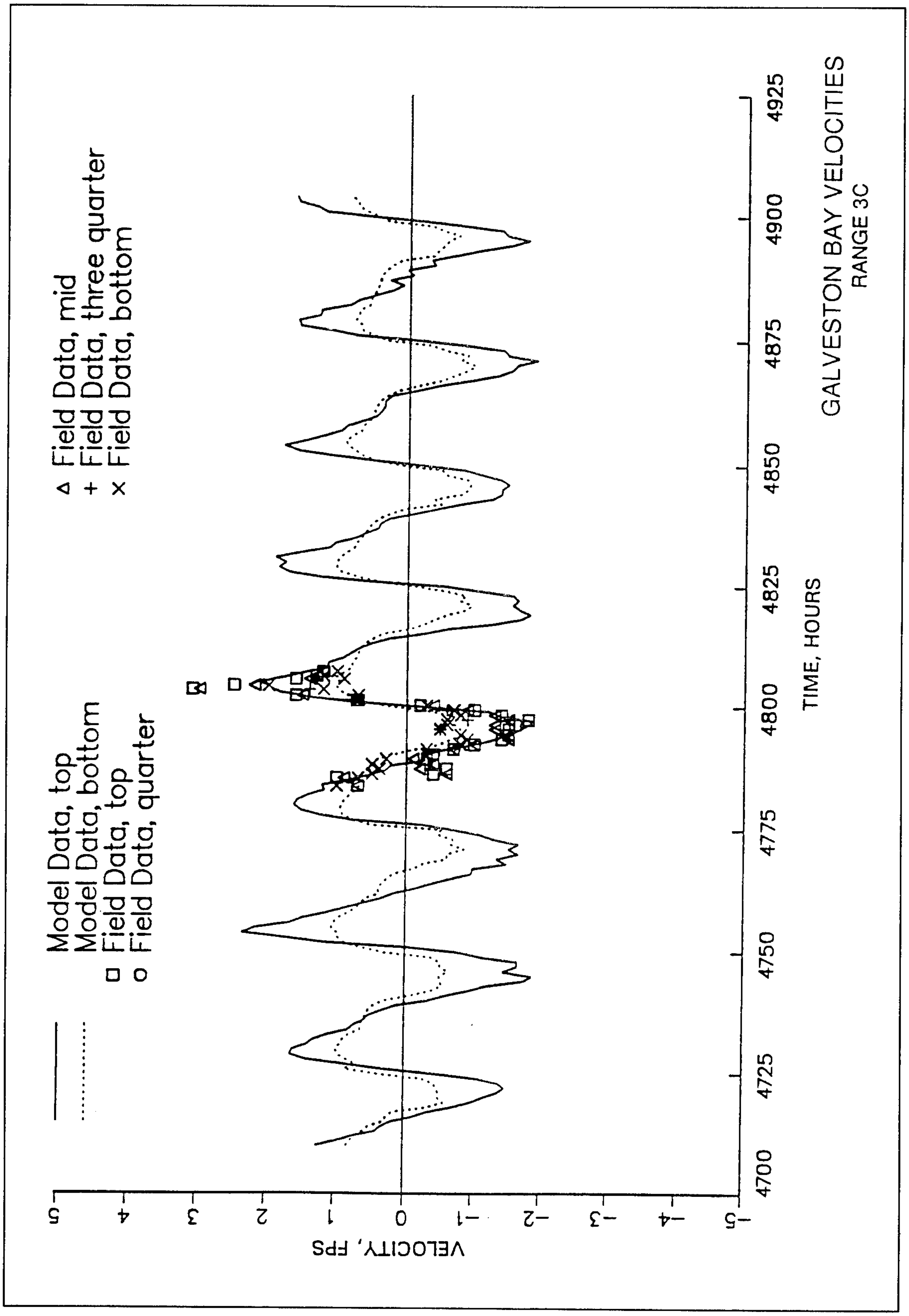
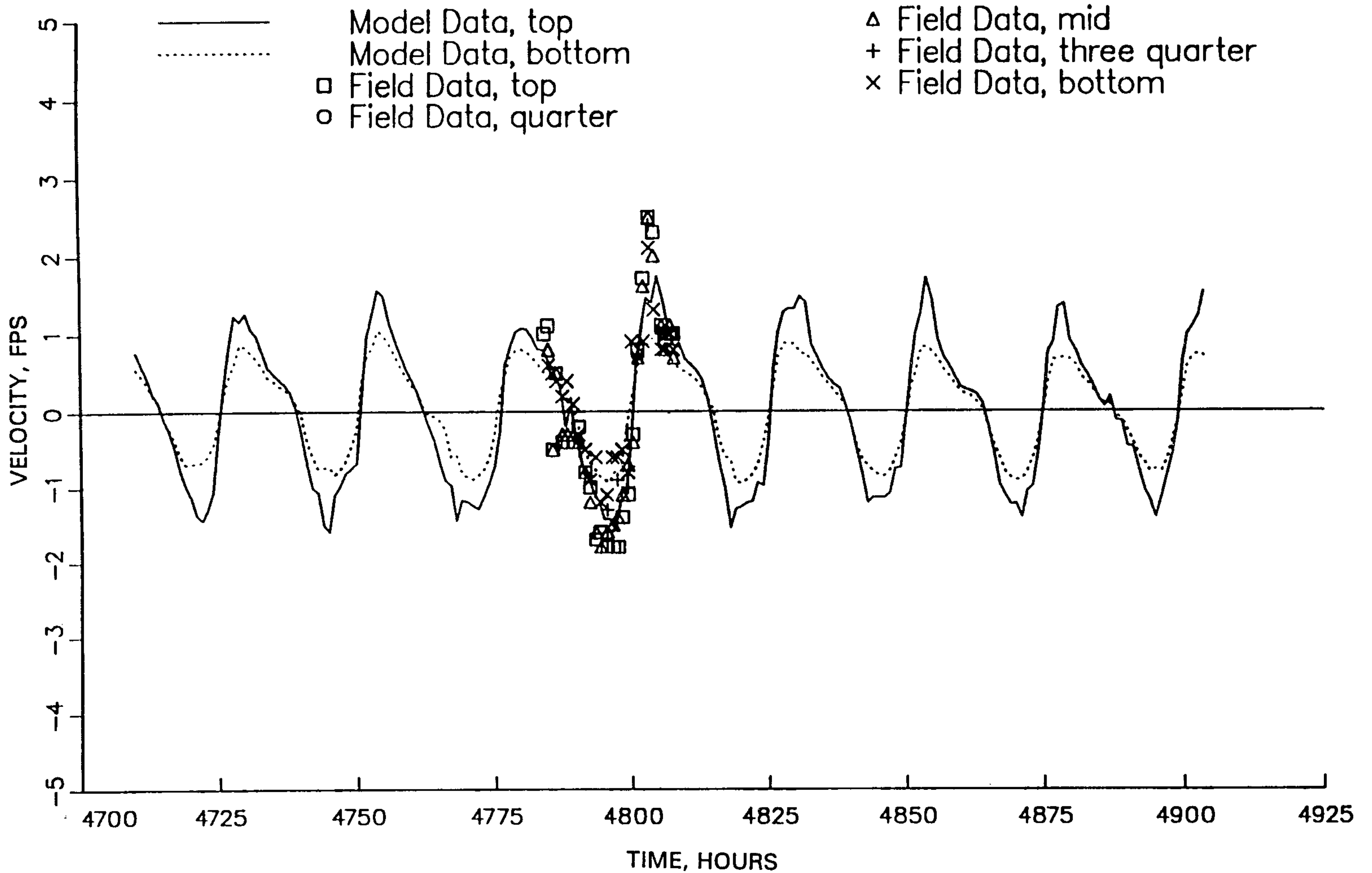

Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
5
4
3
2
1
0
-1
-2
-3
-4
-5
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
TIME, HOURS
GALVESTON BAY VELOCITIES
RANGE 3C

Plate 104



GALVESTON BAY VELOCITIES
RANGE 3D

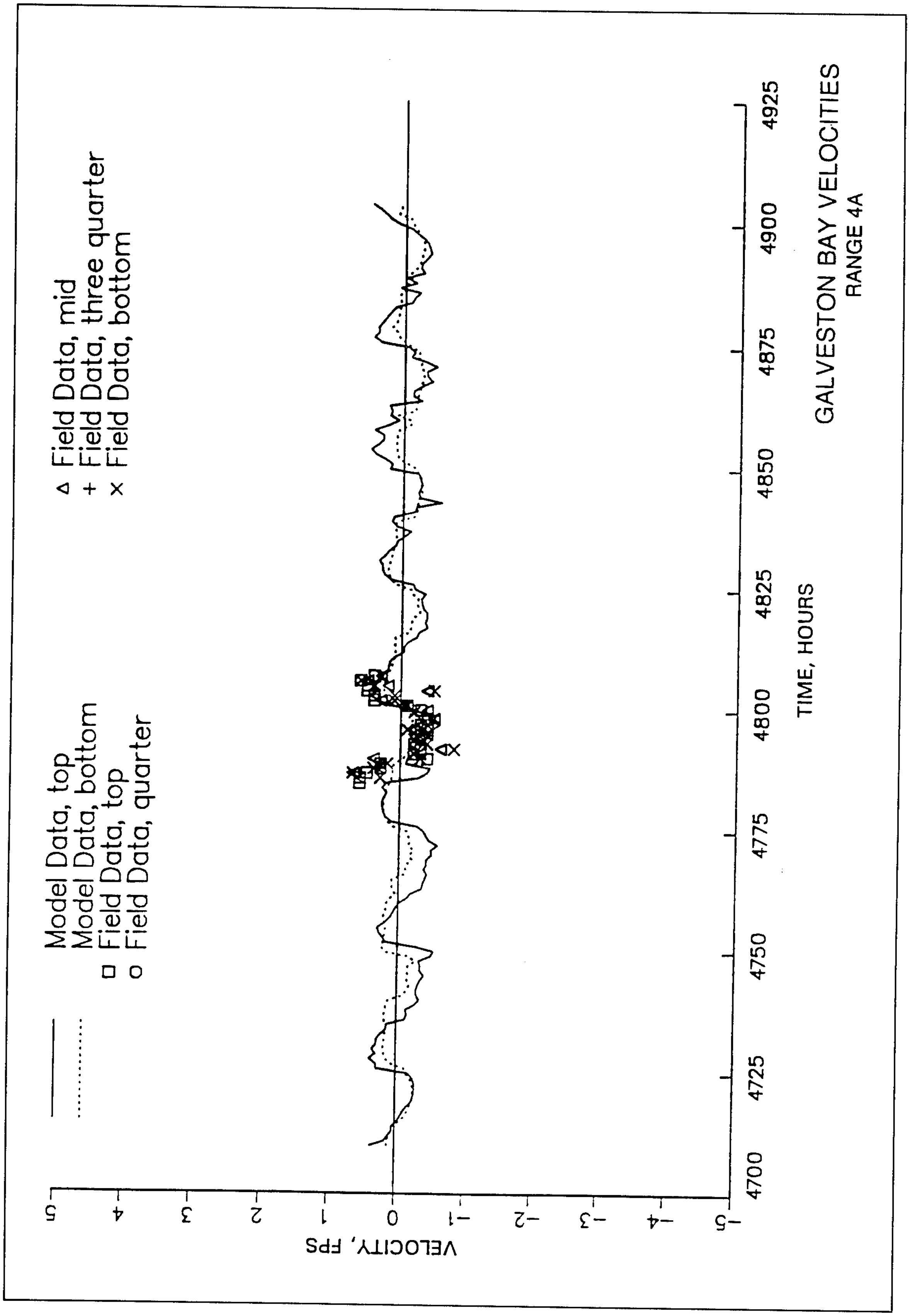

Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
5
4
3
2
1
0
−1
−2
−3
−4
−5
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
TIME, HOURS
GALVESTON BAY VELOCITIES
RANGE 4A

Plate 106

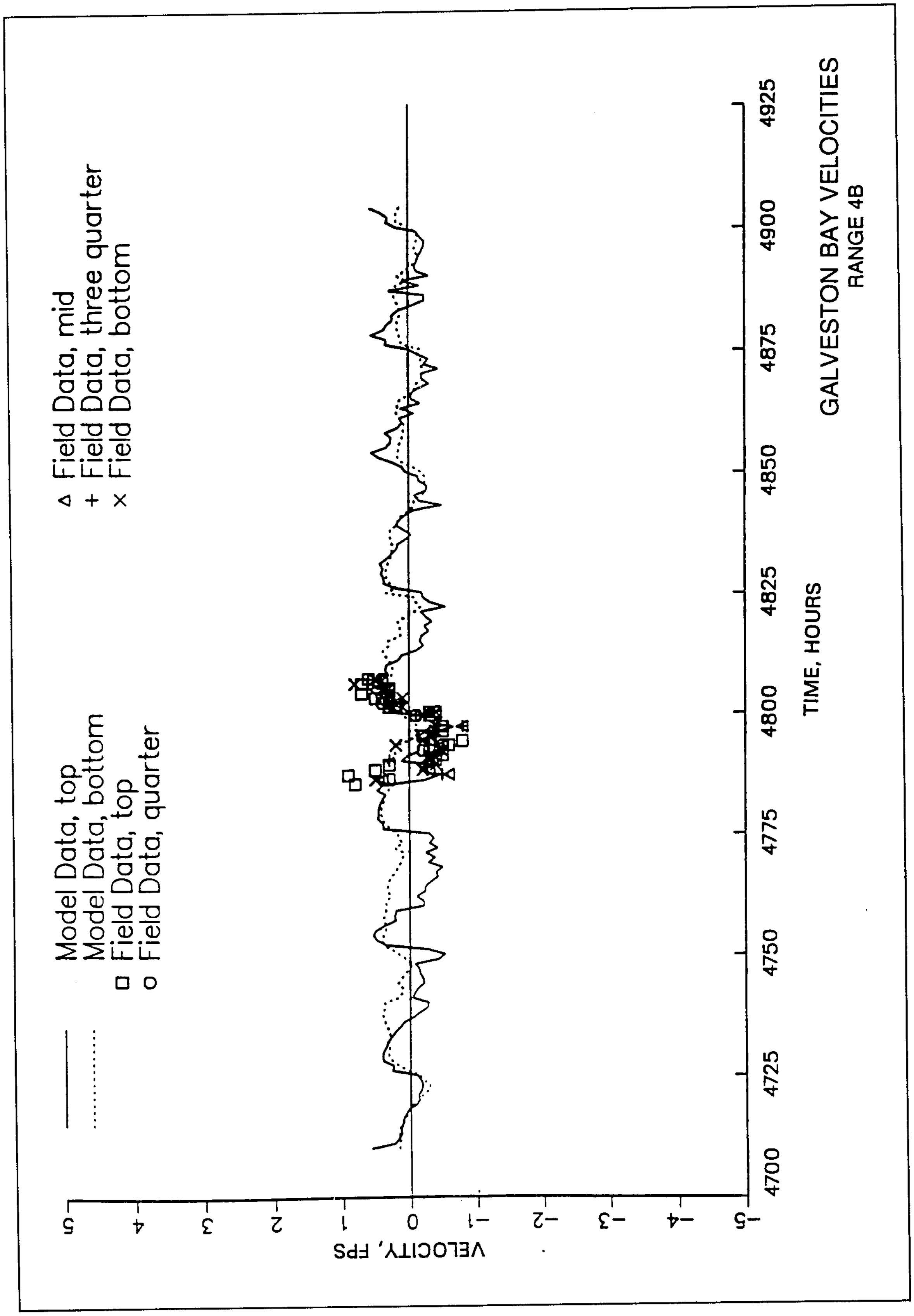
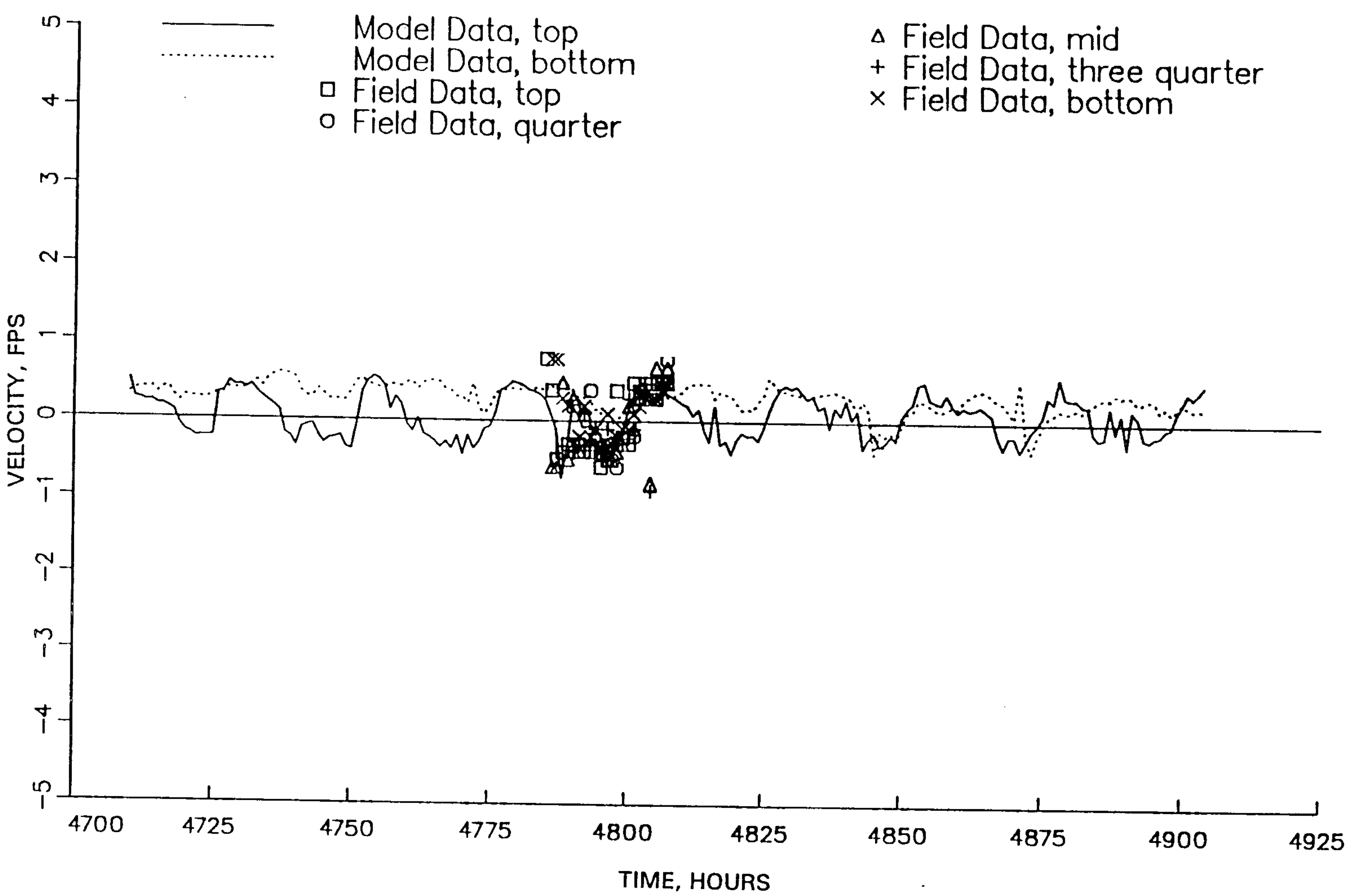
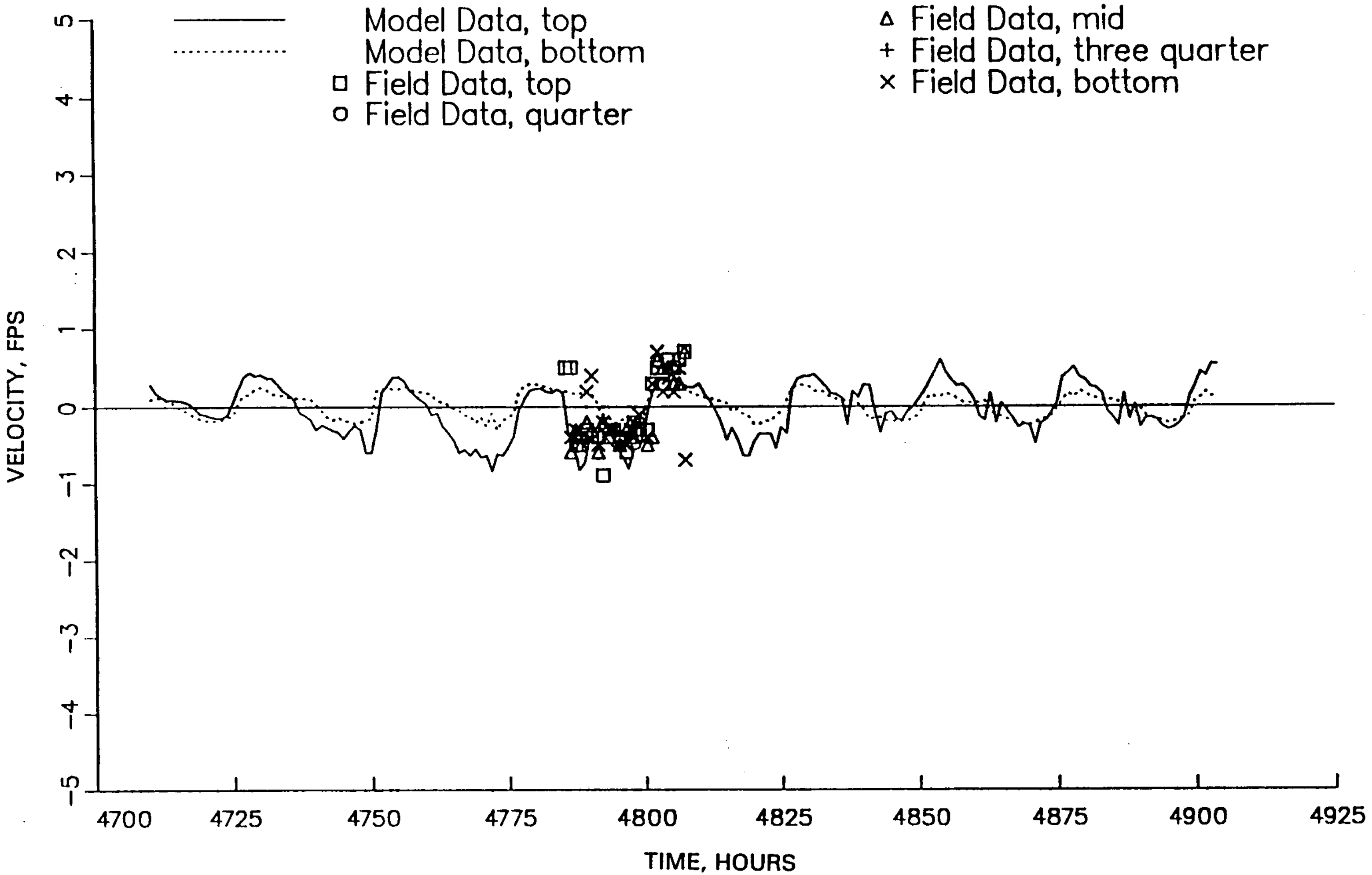

GALVESTON BAY VELOCITIES
RANGE 4B
Model Data, top
Model Data, bottom
□ Field Data, top
o Field Data, quarter
Δ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
VELOCITY, FPS
5
4
3
2
1
0
−1
−2
−3
−4
−5
TIME, HOURS
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925

Plate 107

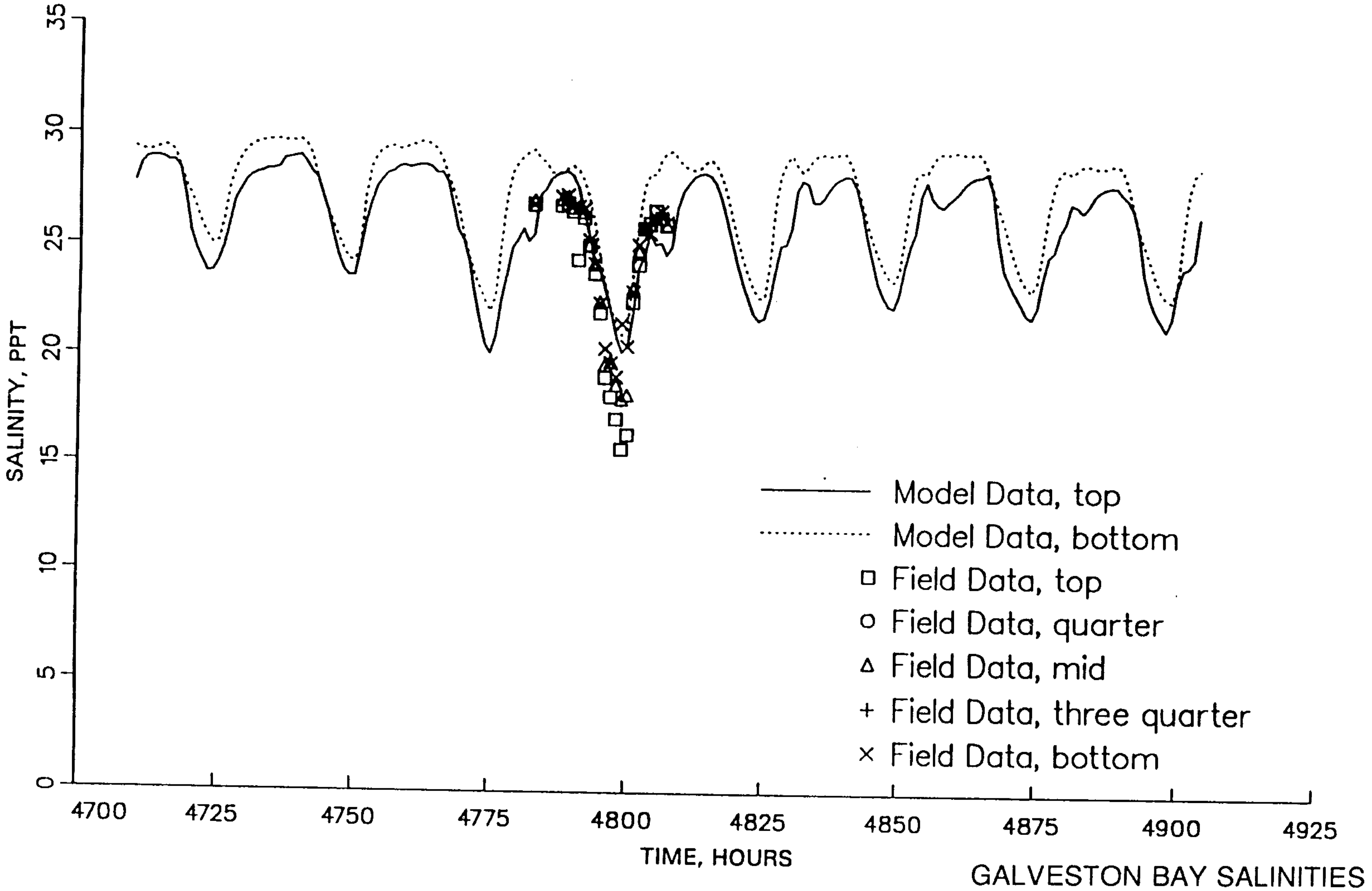


GALVESTON BAY VELOCITIES
RANGE 4C

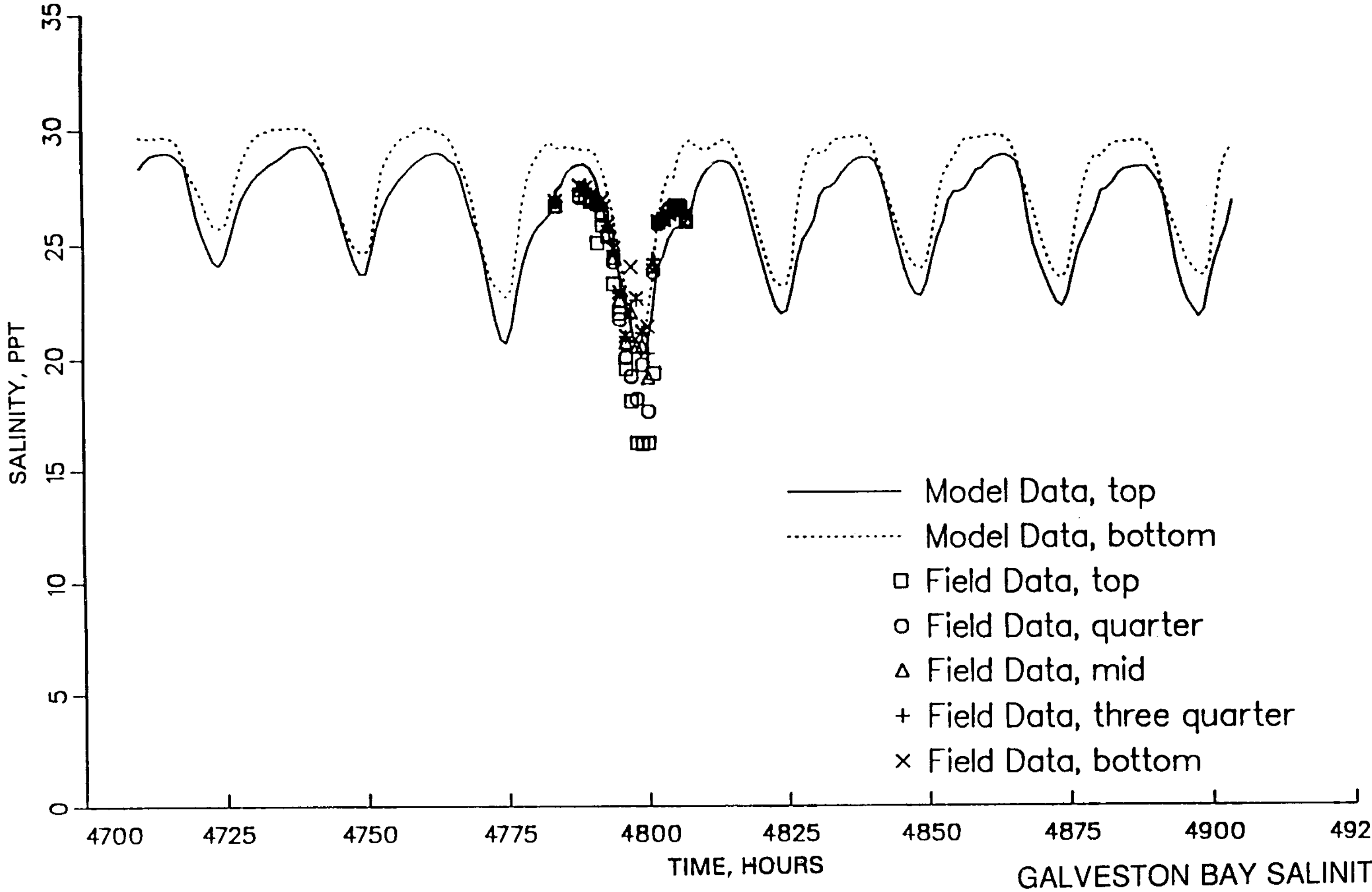


GALVESTON BAY VELOCITIES
RANGE 4D

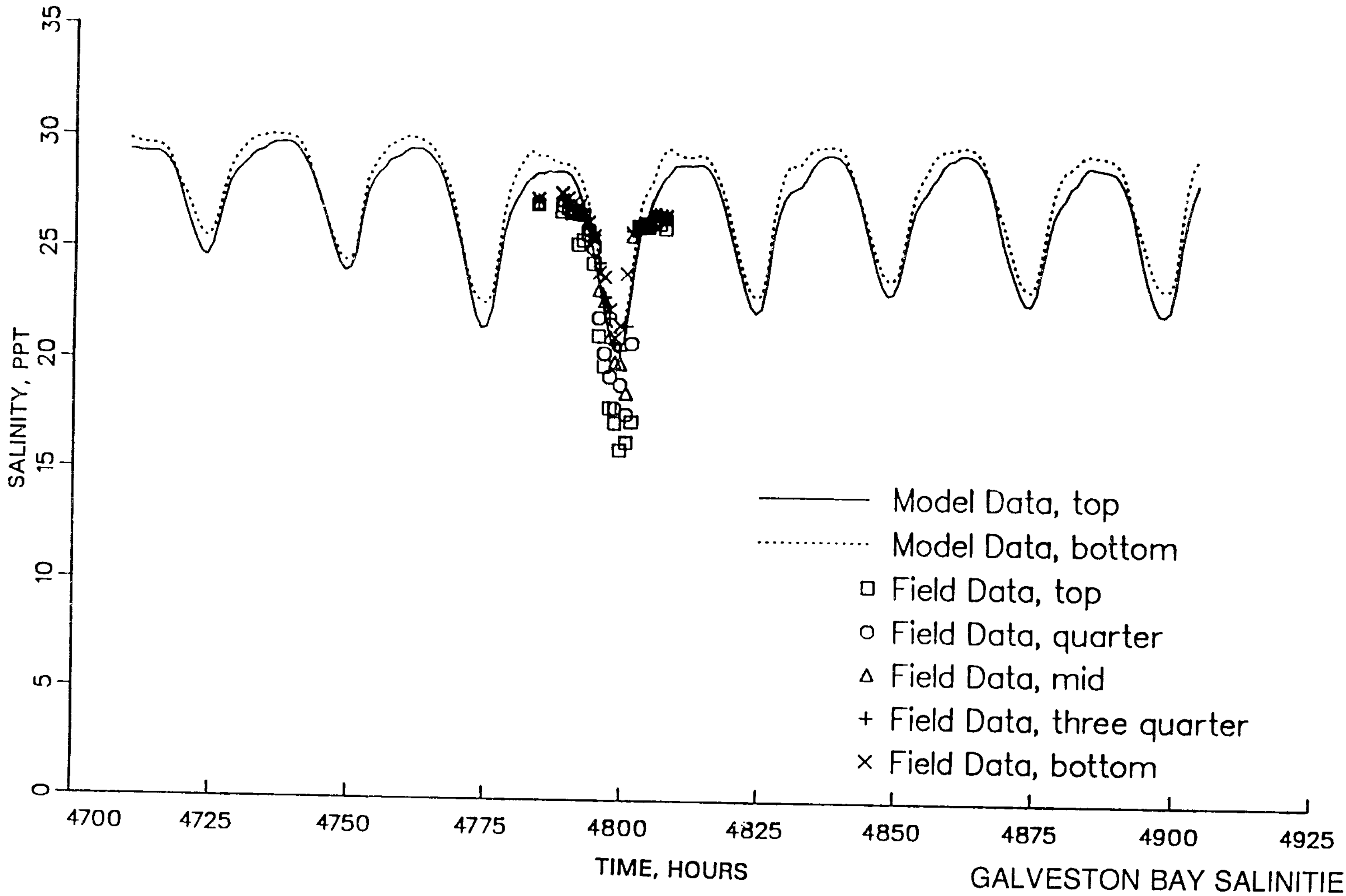
Plate 110



GALVESTON BAY SALINITIES
RANGE 1A

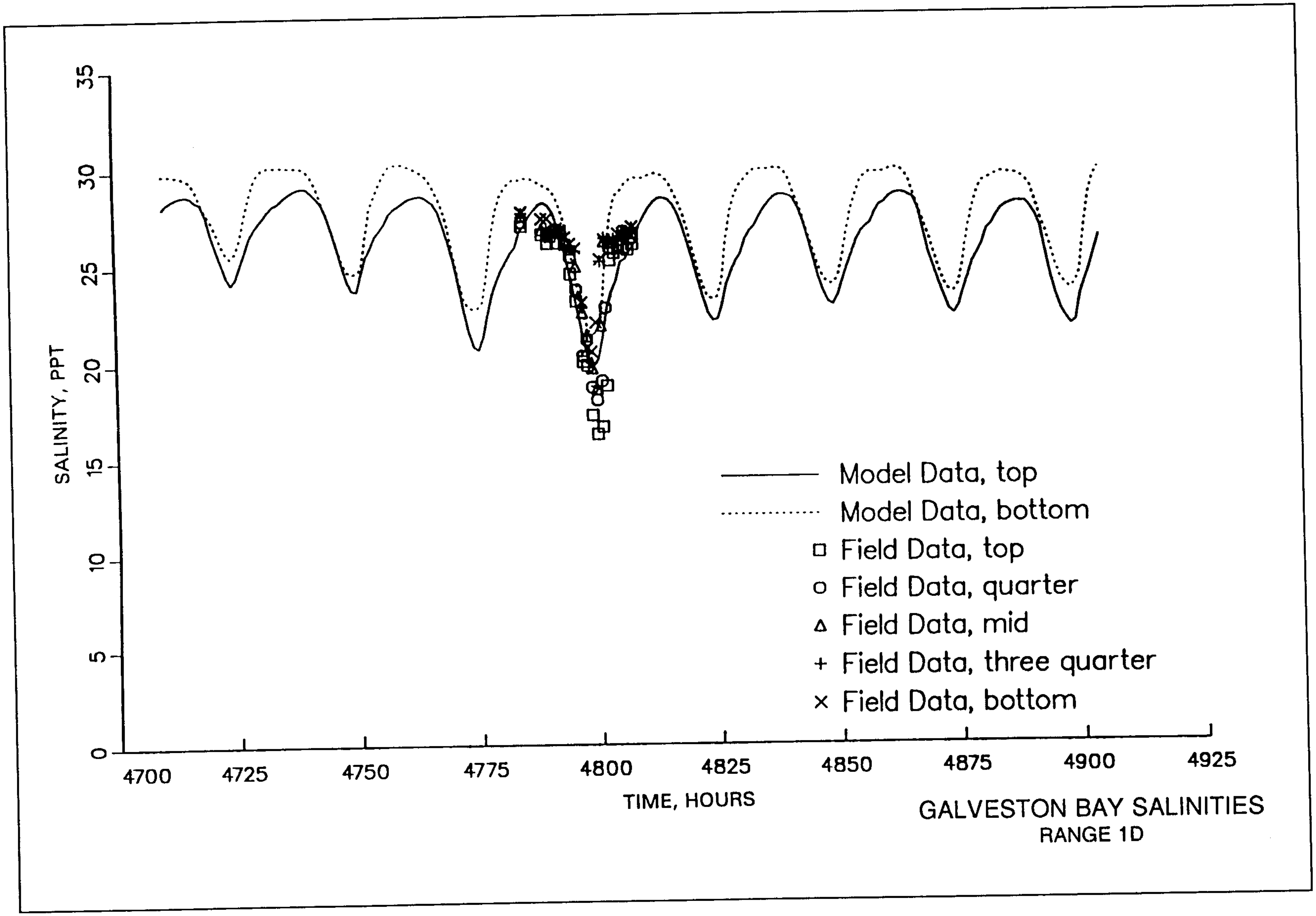


GALVESTON BAY SALINITIES
RANGE 1B



GALVESTON BAY SALINITIES
RANGE 1C

Plate 112



GALVESTON BAY SALINITIES
RANGE 1D

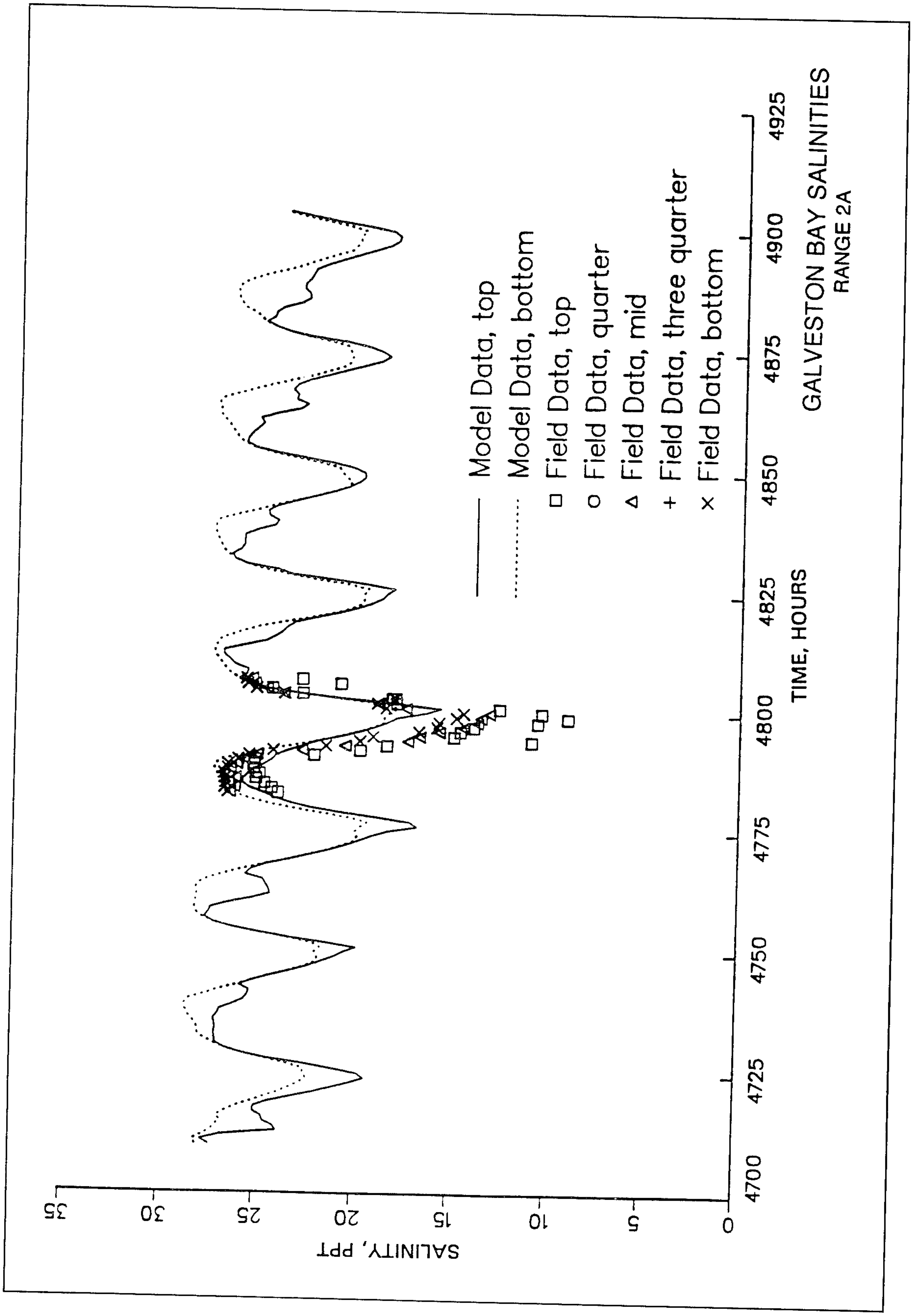

GALVESTON BAY SALINITIES
RANGE 2A
SALINITY, PPT
0
5
10
15
20
25
30
35
TIME, HOURS
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom

Plate 114

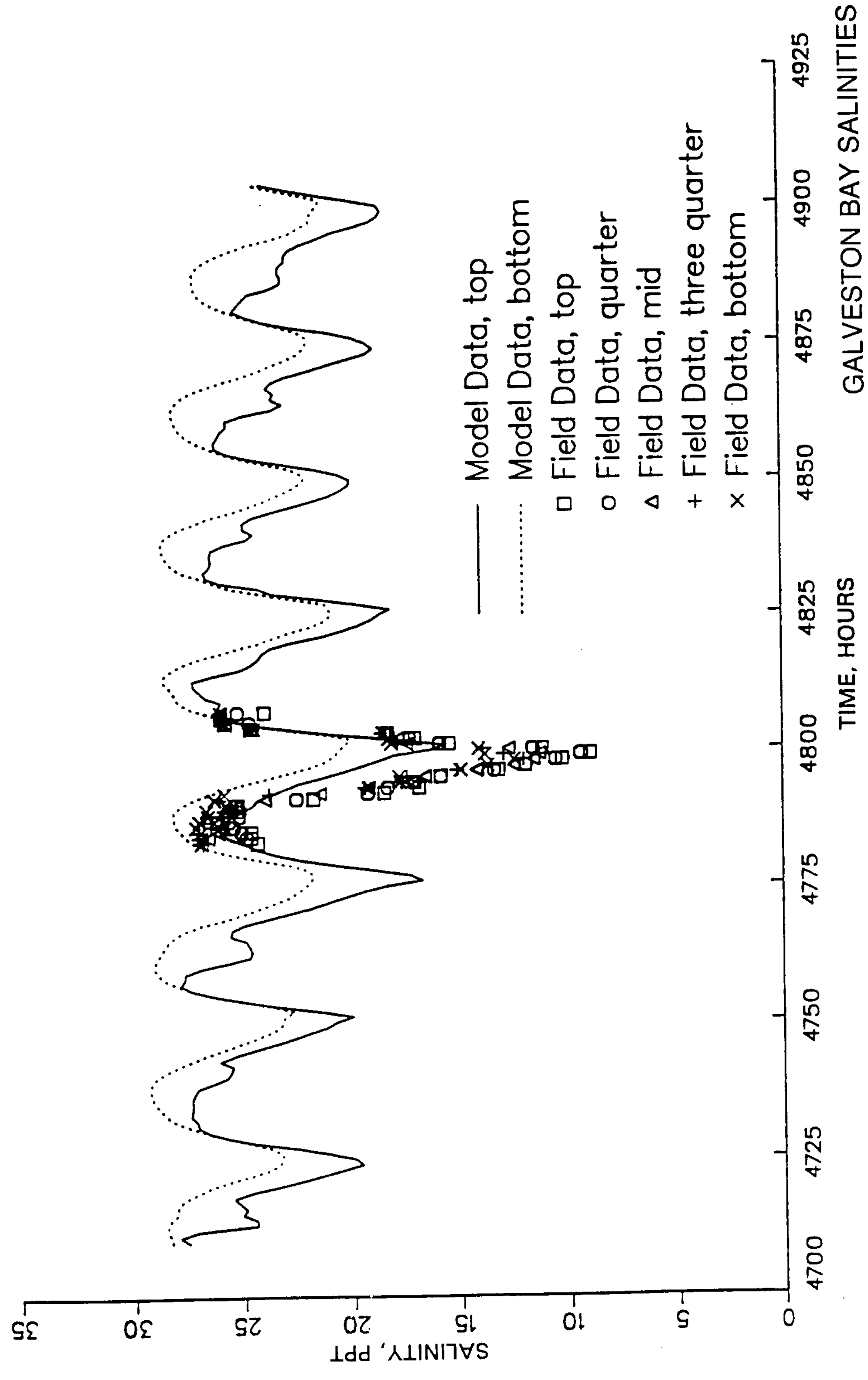
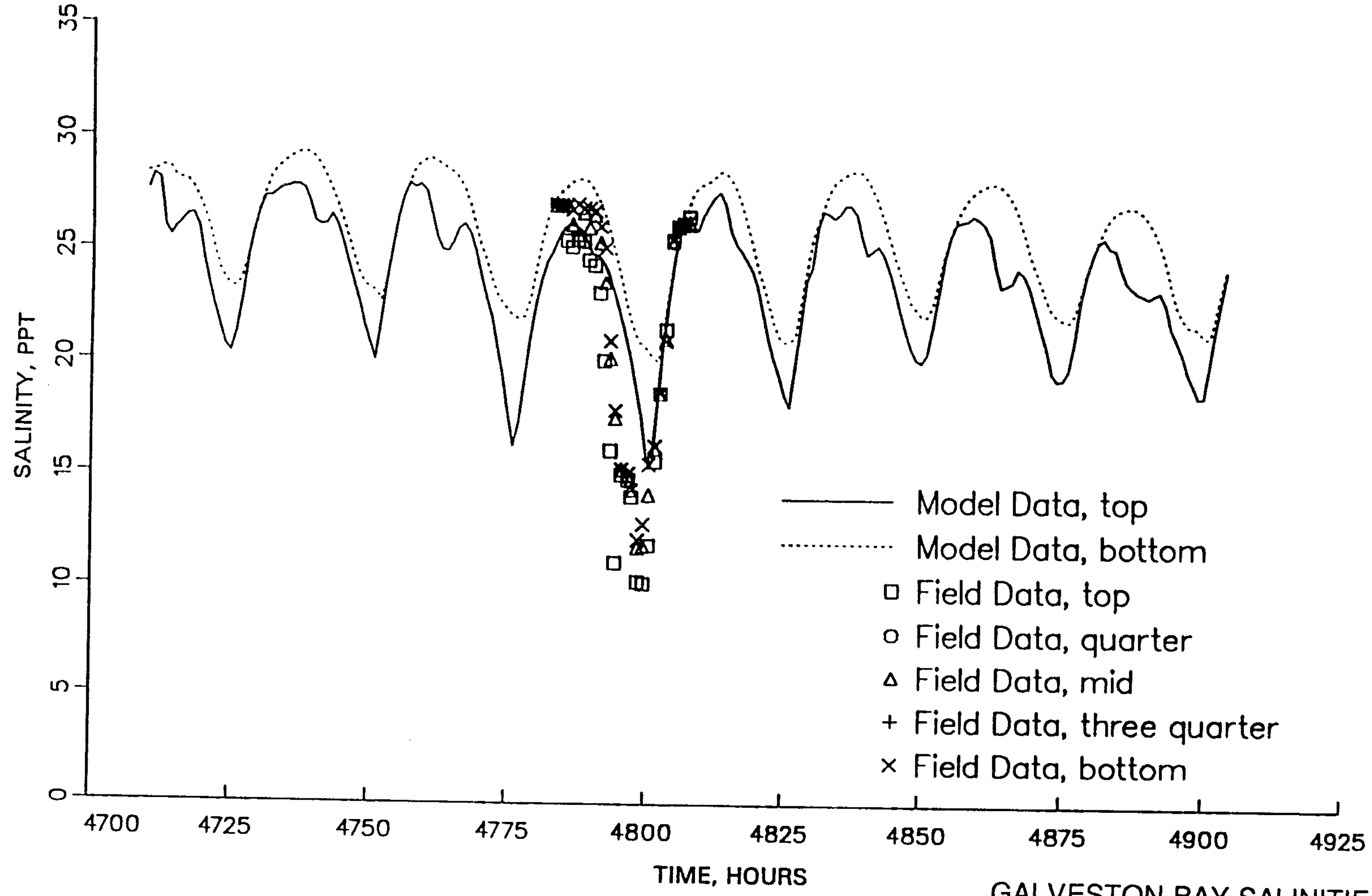
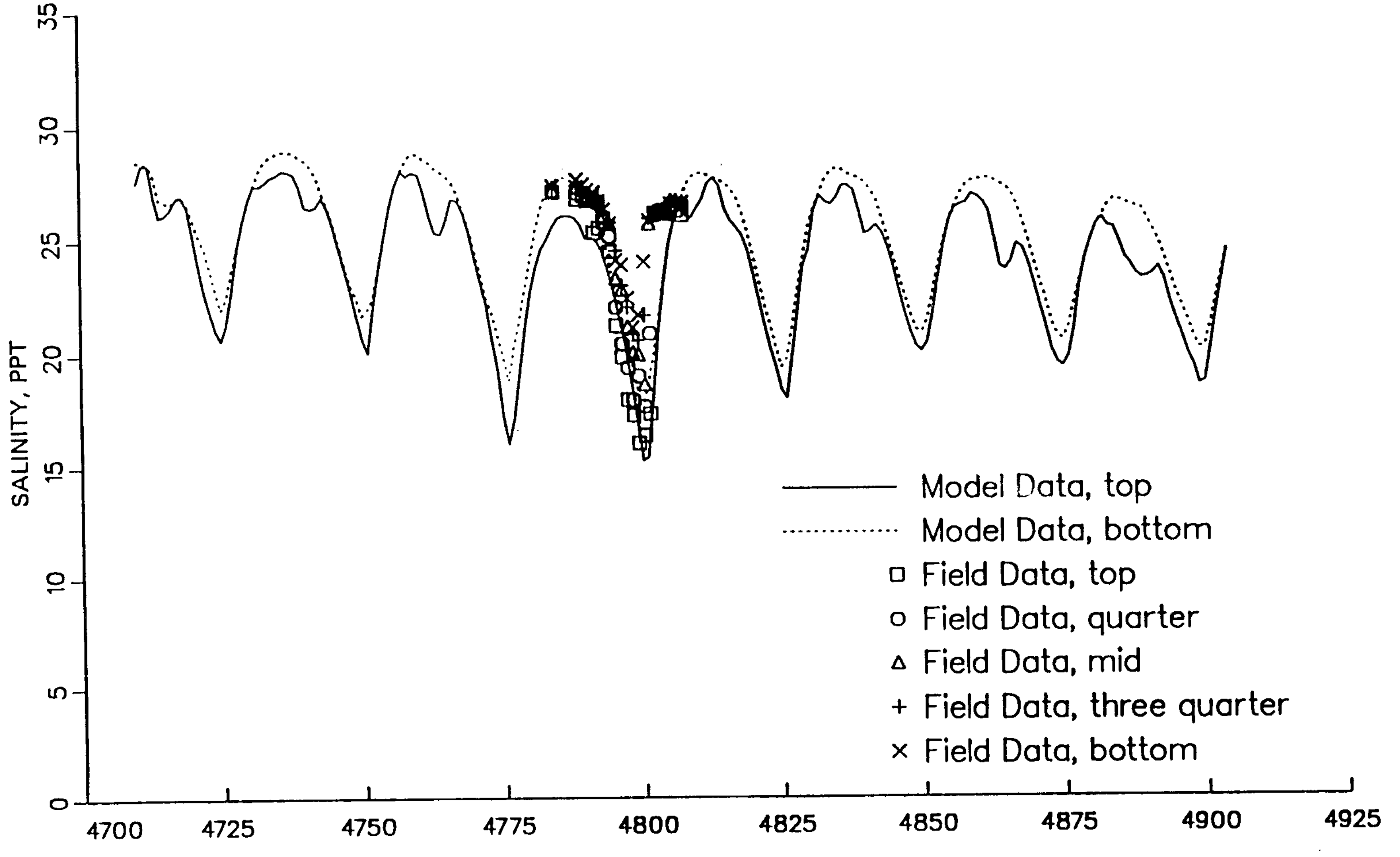

GALVESTON BAY SALINITIES
RANGE 2B
SALINITY, PPT
TIME, HOURS
0
5
10
15
20
25
30
35
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
Model Data, top
Model Data, bottom
□ Field Data, top
o Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom

Plate 116

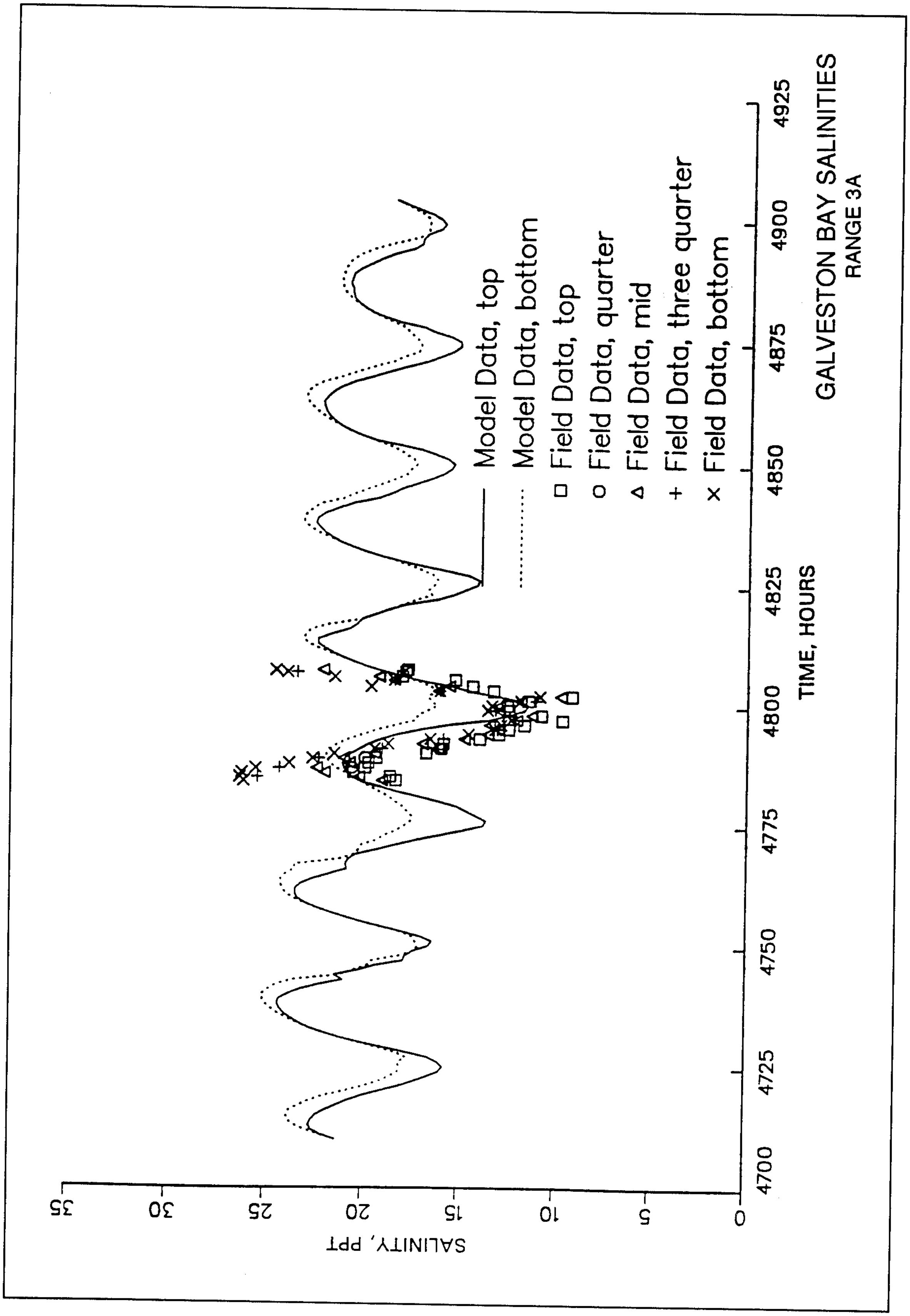


GALVESTON BAY SALINITIES
RANGE 2C



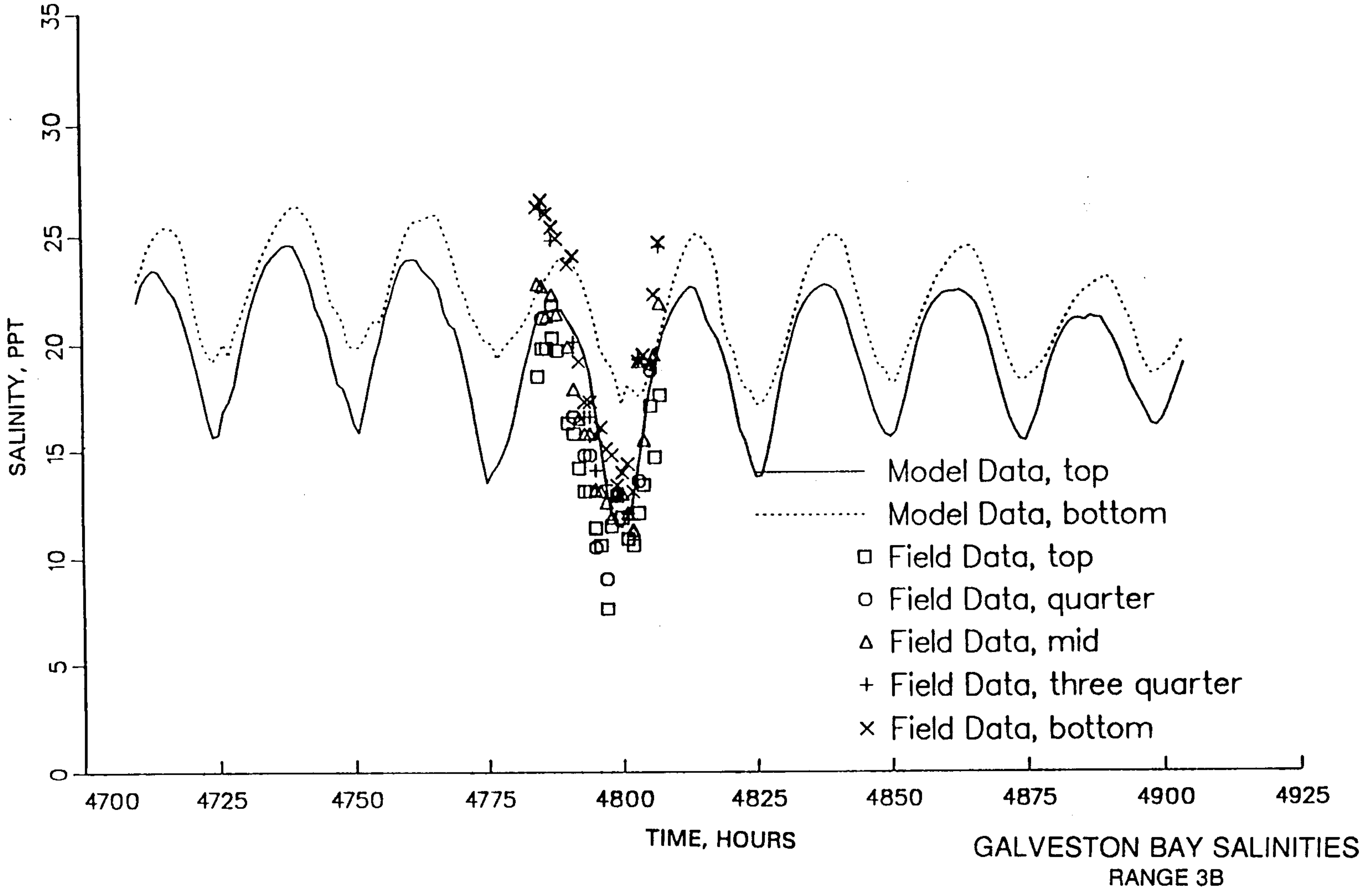
GALVESTON BAY SALINITIES
RANGE 2D

Plate 117

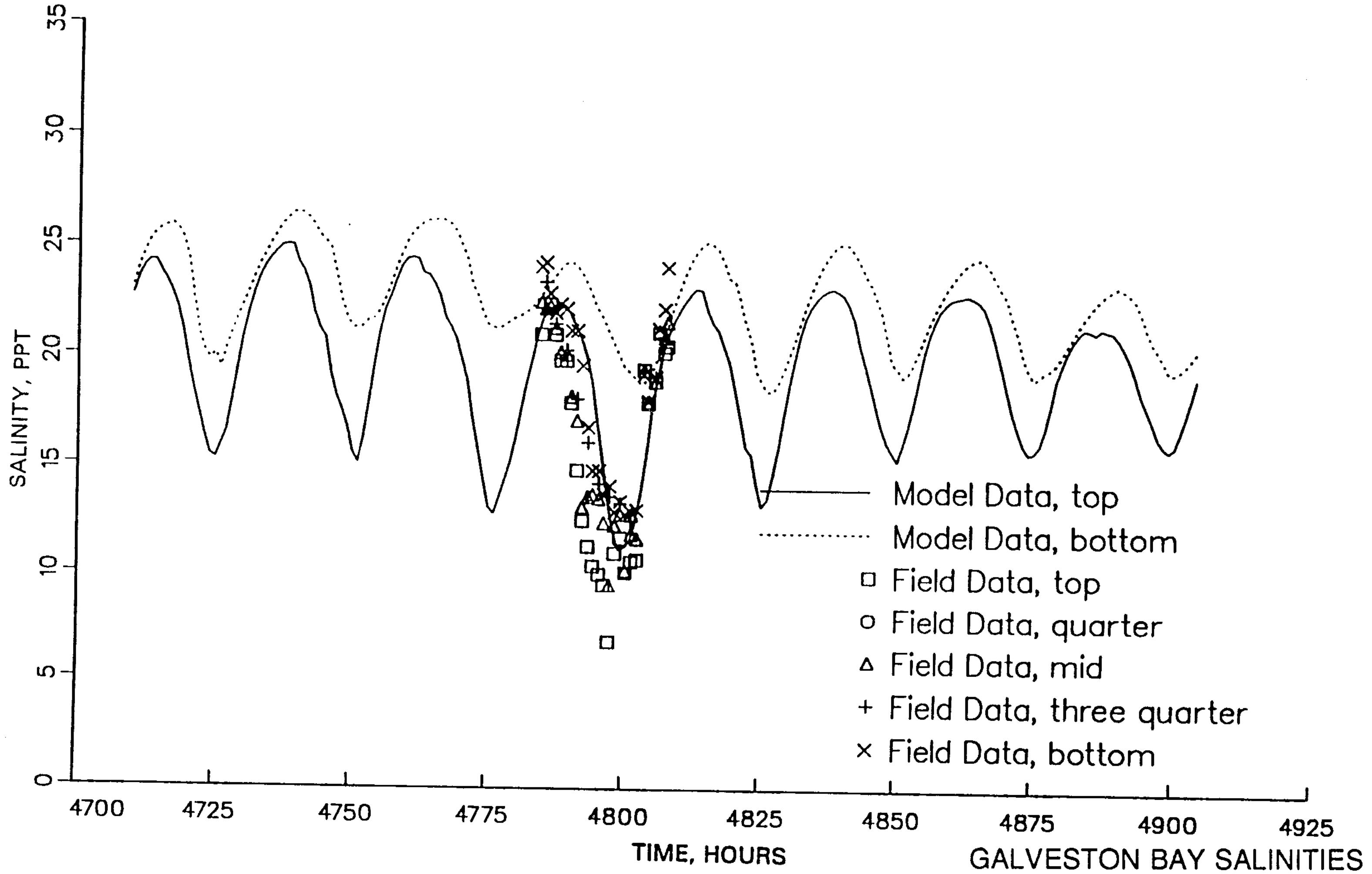


GALVESTON BAY SALINITIES
RANGE 3A

Plate 118

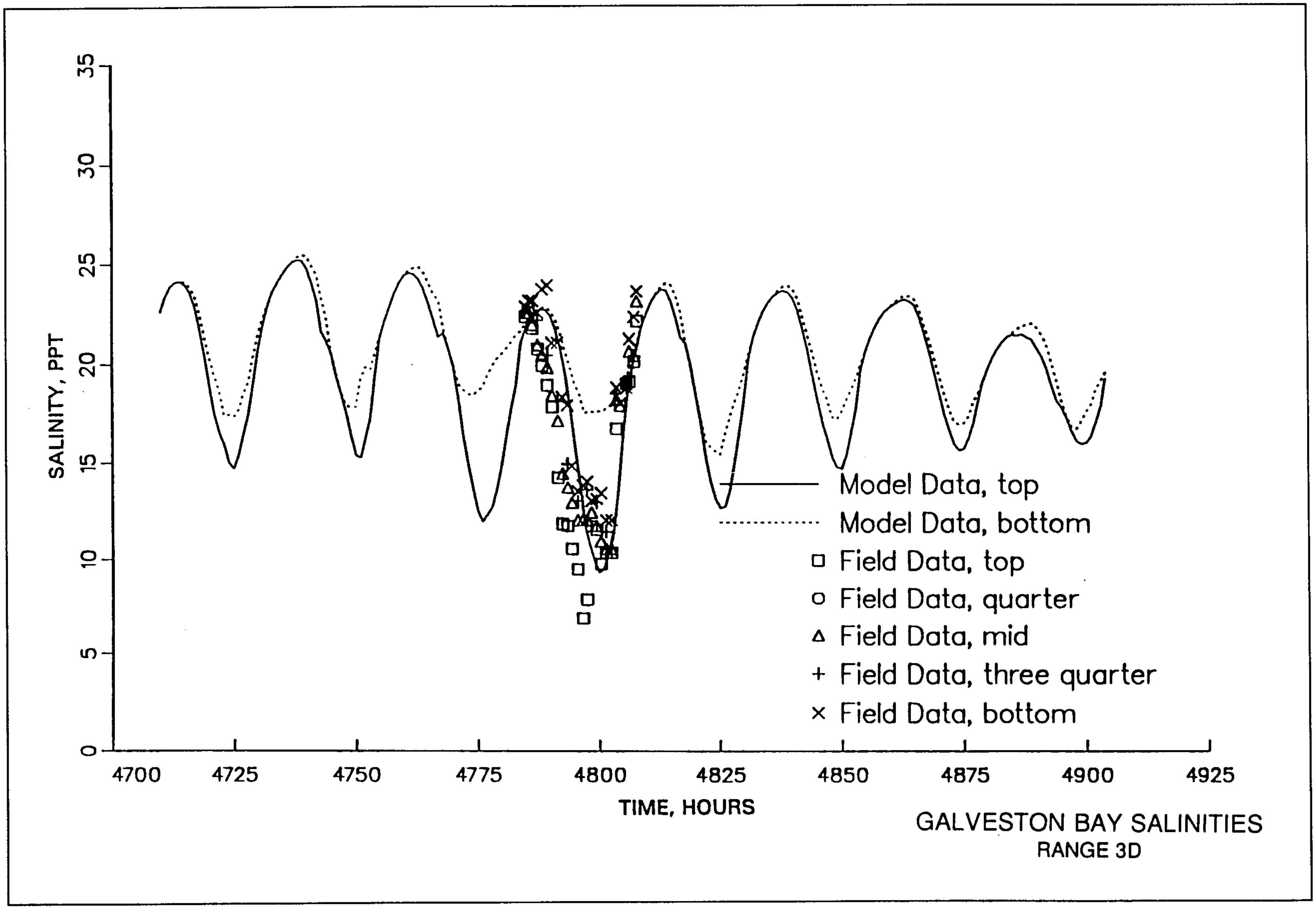


GALVESTON BAY SALINITIES
RANGE 3B



GALVESTON BAY SALINITIES
RANGE 3C

Plate 120



GALVESTON BAY SALINITIES
RANGE 3D

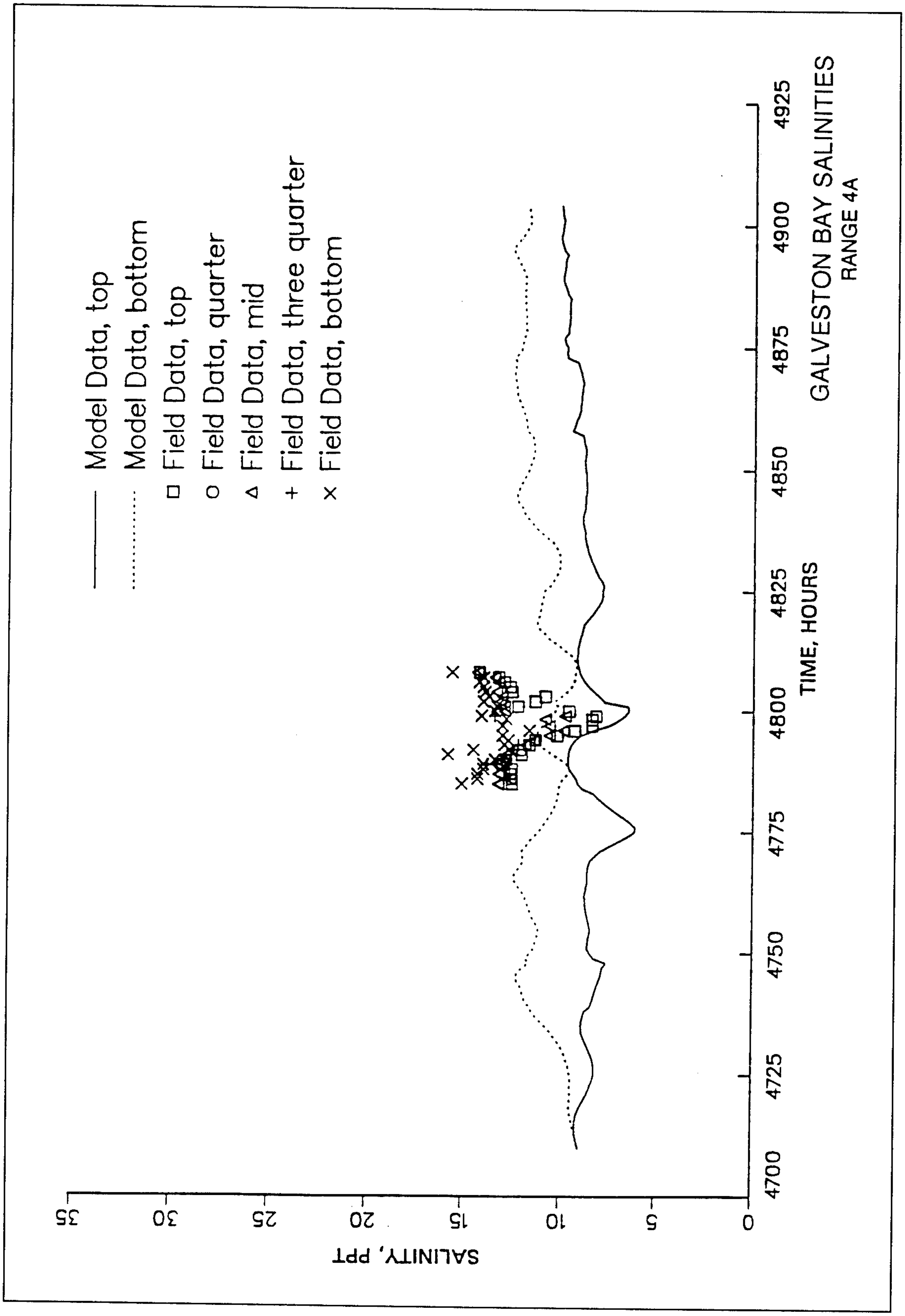
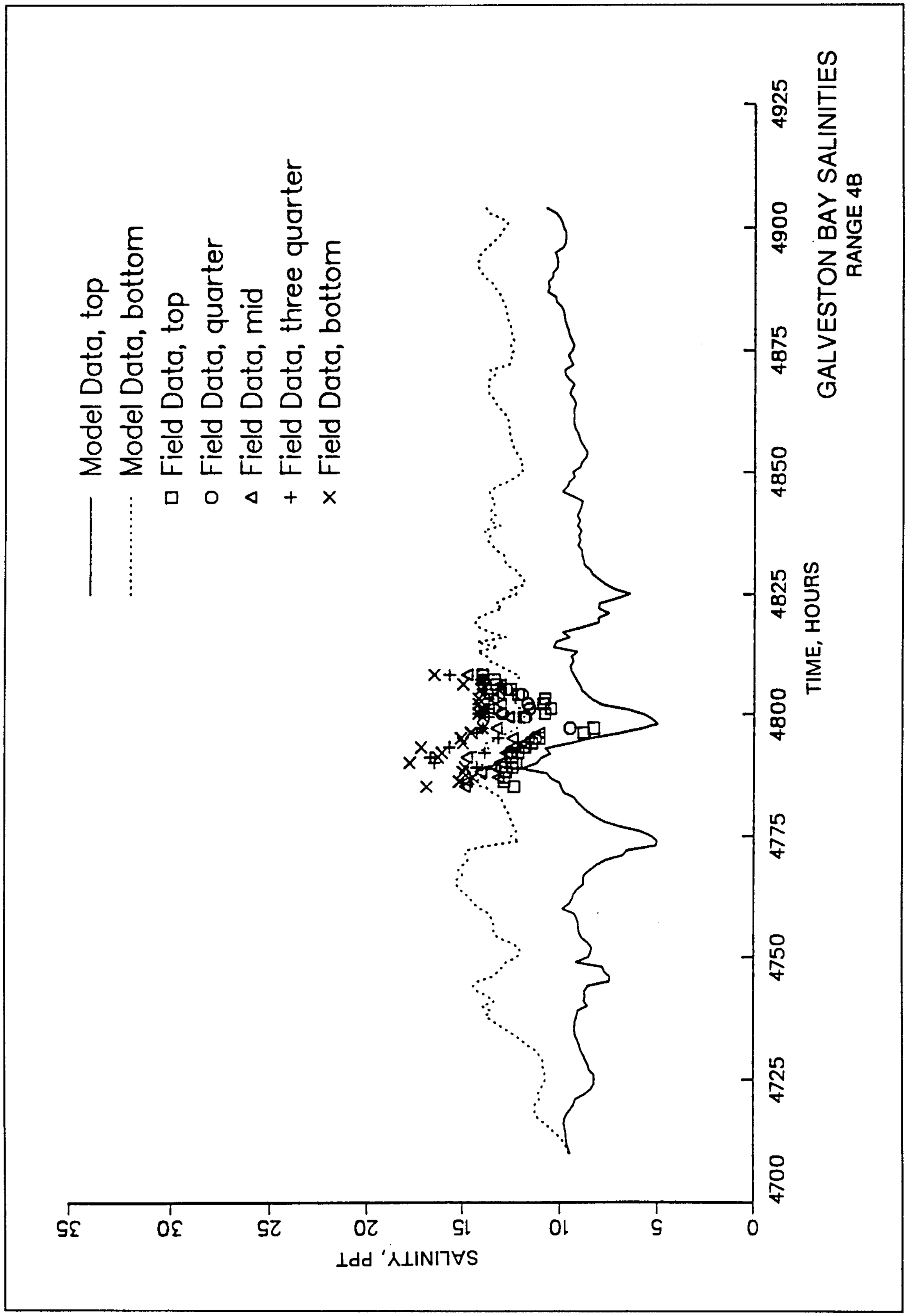

GALVESTON BAY SALINITIES
RANGE 4A
Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
SALINITY, PPT
0
5
10
15
20
25
30
35
TIME, HOURS
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925

Plate 122



GALVESTON BAY SALINITIES
RANGE 4B

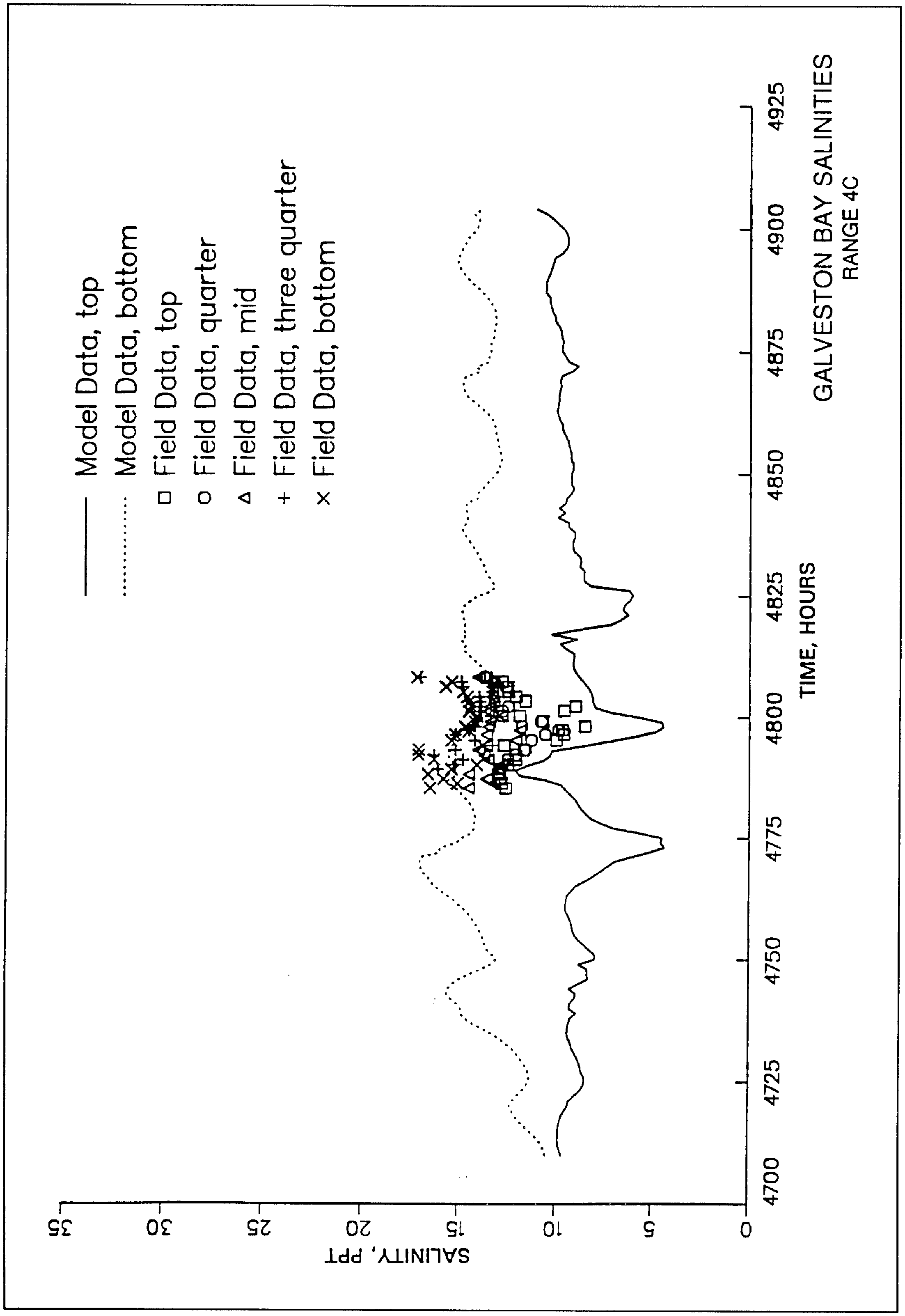
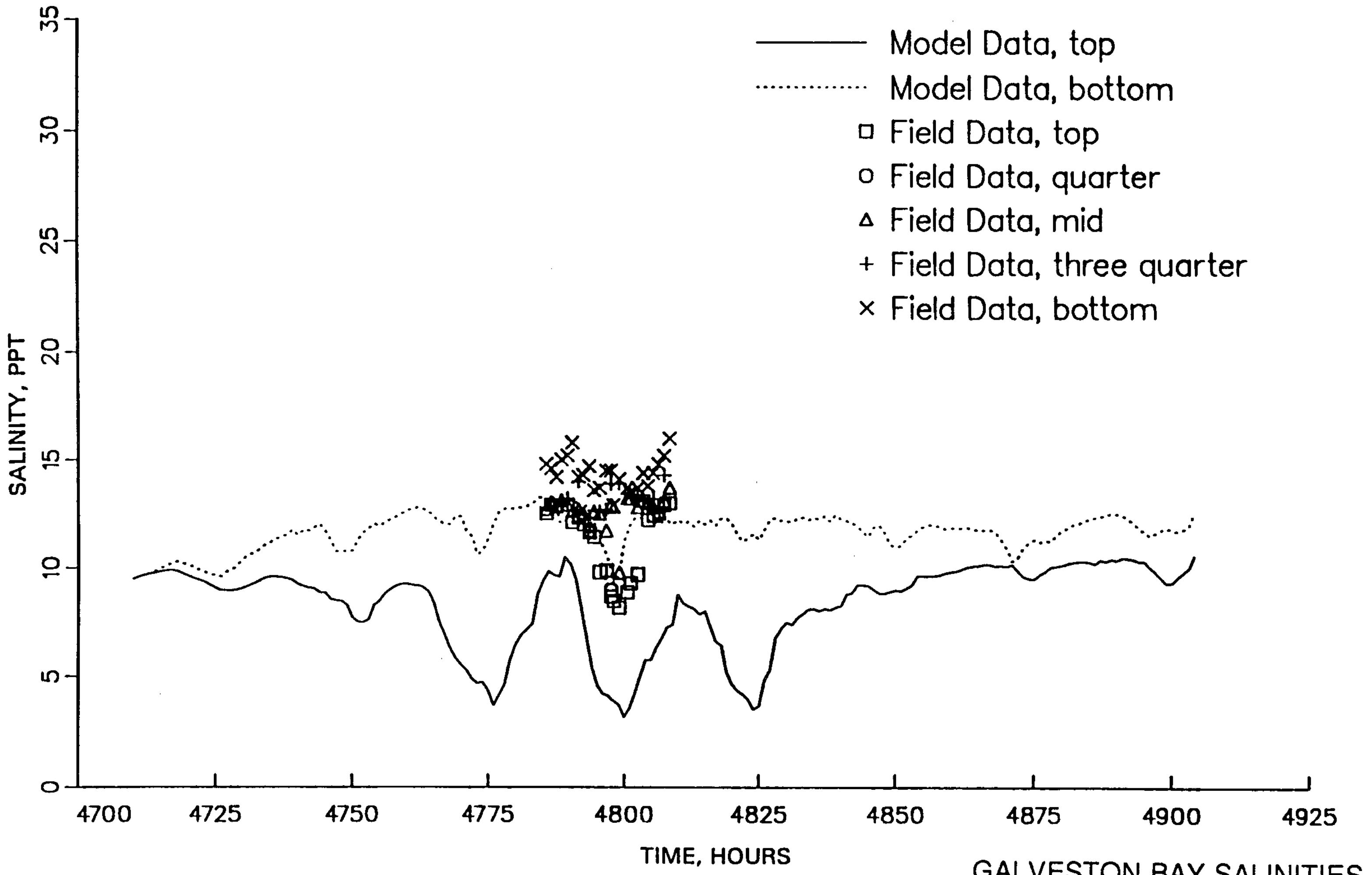

Model Data, top
Model Data, bottom
□ Field Data, top
○ Field Data, quarter
△ Field Data, mid
+ Field Data, three quarter
× Field Data, bottom
SALINITY, PPT
0
5
10
15
20
25
30
35
TIME, HOURS
4700
4725
4750
4775
4800
4825
4850
4875
4900
4925
GALVESTON BAY SALINITIES
RANGE 4C

Plate 124



GALVESTON BAY SALINITIES
RANGE 4D

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13. ABSTRACT *(Maximum 200 words)*

This report describes the verification results of the three-dimensional (3-D) hydrodynamic model used to evaluate tides, current velocities, and salinities in Galveston Bay, Texas. This is the third in a series of reports concerning the Houston-Galveston Navigation Channels. The goal of these reports is to determine the effect of the proposed channel deepening and widening upon tides, currents, salinities, and navigation. Report 1 describes the field data collection and results, Report 2 presents the two-dimensional numerical modeling of hydrodynamics for a navigation study, Report 3 presents the verification description for the 3-D model, and Report 4 details the results of tests of the 3-D model.

This report first describes the 3-D model program, RMA10-WES, which is a finite element code using mixed quadratic and linear Lagrange polynomials. The remainder of the report reveals the demonstration of the model applicability through the verification procedure. This procedure of adjustment and verification was first a comparison to a short series of data with a series of adjustments in bed roughness. Then the model was run with no adjustment over a period of roughly 6 months in comparison to field data from 19 July 1990 to 15 January 1991. This period includes the time following a major flood in the Galveston Bay system for which the

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model reproduces the timing and magnitude of the salinity rebound very well. Comparisons of model performance are drawn qualitatively between the model and description of the Bay in the literature, and also quantitatively with the field data recorded for this study.

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