



**US Army Corps
of Engineers®**
Engineer Research and
Development Center

ERDC
INNOVATIVE SOLUTIONS
for a safer, better world

Three-Dimensional Shallow Water Adaptive Hydraulics (ADH-SW3) Validation: Galveston Bay Hydrodynamics and Salinity Transport

Gaurav Savant and R. Charlie Berger

April 2015

The US Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdclibrary.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at <http://acwc.sdp.sirsi.net/client/default>.

Three-Dimensional Shallow Water Adaptive Hydraulics (ADH-SW3) Validation Report 1: Galveston Bay Hydrodynamics and Salinity Transport

Gaurav Savant

*Dynamic Solutions LLC
6421 Deane Hill Dr. Suite 1.
Knoxville, TN 37919*

R. Charlie Berger

*Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Rd.
Vicksburg, MS 39180-6199*

Final report

Approved for public release; distribution is unlimited.

Abstract

The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), has developed the multimodule Adaptive Hydraulics (ADH) hydrodynamic, sediment, water quality, and transport model. As a natural progression of this development process, verification of ADH was performed to known solutions for the basic physics contained in the numerical model. This report documents a validation of the model performed by applying the three-dimensional shallow water module (ADH-SW3) to Galveston Bay and comparing results to field observations. The validation exercise shows good agreement with the field for water surface elevations, velocities, and salinity.

DISCLAIMER: The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

Contents

Abstract	ii
Figures and Tables.....	iv
Preface.....	vi
Unit Conversion Factors	vii
1 Introduction.....	1
Purpose of study.....	1
Validation approach	2
2 Model Development	3
Grid development.....	3
Boundary conditions	6
3 Model Results and Validation.....	10
4 Summary and Conclusions	30
References	32
Report Documentation Page	

Figures and Tables

Figures

Figure 1. ADH-SW3 mesh vertical layer distribution.....	3
Figure 2. Oblique view of model mesh with elements (vertical co-ordinate in meters).....	5
Figure 3. Ocean tidal boundary (Hour 0 = 1 Jan 1990, 12:00 a.m.).....	7
Figure 4. Ocean salt boundary (Hour 0 = 1 Jan 1990, 12:00 a.m.).....	8
Figure 5. Trinity River discharge (Hour 0 = 1 Jan 1990, 12:00 a.m.).....	8
Figure 6. San Jacinto River discharge (Hour 0 = 1 Jan 1990, 12:00 a.m.).....	9
Figure 7. Salinity distribution (no adaption).....	10
Figure 8. Salinity distribution (adaption).....	10
Figure 9. Location map and water surface and salinity observation stations.....	11
Figure 10. Velocity observation locations.....	12
Figure 11. Harmonic amplitude for S1 model and field results (all values in meters).....	13
Figure 12. Harmonic amplitude for S10 model and field results (all values in meters).....	13
Figure 13. Harmonic amplitude for S16 model and field results (all values in meters).....	14
Figure 14. Comparison of model and field average phase lag.....	14
Figure 15. Observed and model velocities for range 1A.....	15
Figure 16. Observed and model velocities for range 1B.....	16
Figure 17. Observed and model velocities for range 1C.....	16
Figure 18. Observed and model velocities for range 1D.....	17
Figure 19. Observed and model velocities for range 2A.....	17
Figure 20. Observed and model velocities for range 2B.....	18
Figure 21. Observed and model velocities for range 2C.....	18
Figure 22. Observed and model velocities for range 2D.....	19
Figure 23. Observed and model velocities for range 3A.....	19
Figure 24. Observed and model velocities for range 3B.....	20
Figure 25. Observed and model velocities for range 3C.....	20
Figure 26. Observed and model velocities for range 3D.....	21
Figure 27. Observed and model velocities for range 4A.....	21
Figure 28. Observed and model velocities for range 4B.....	22
Figure 29. Observed and model velocities for range 4C.....	22
Figure 30. Observed and model velocities for range 4D.....	23
Figure 31. Mid-depth salinity comparison for station S1.....	24
Figure 32. Mid-depth salinity comparison for station S2.....	24
Figure 33. Mid-depth salinity comparison for station S5.....	25
Figure 34. Mid-depth salinity comparison for station S5.5.....	25
Figure 35. Mid-depth salinity comparison for station S6.....	26
Figure 36. Mid-depth salinity comparison for station S12.....	26

Figure 37. Mid-depth salinity comparison for station S12.1.	27
Figure 38. Mid-depth salinity comparison for station S13.	27
Figure 39. Mid-depth salinity comparison for station S14.	28

Tables

Table 1. ADH-SW3 n and Smagorinski Coefficient values.....	6
Table 2. Willmott Coefficients for salinity values.....	29

Preface

This report represents the findings of the three-dimensional shallow water module (ADH-SW3) validation effort for the Galveston Bay Estuary. ADH-SW3 demonstrates the stratified environment associated with the navigation channel, the rebound of salinity after a major flood event, as well as appropriate tidal behavior and circulation. This validation exercise along with prior verification studies confirms the ability of ADH-SW3 to represent complex systems with stratification and deep, incised navigation channels, such as Galveston Bay.

This investigation was conducted from January 2012 through March 2012 at the U.S. Army Engineer Research and Development Center (ERDC) by Dr. Gaurav Savant of Dynamic Solutions LLC and Dr. R.C. Berger of the Coastal and Hydraulics Laboratory (CHL). Funding was provided by the Flood and Coastal Storm Damage Reduction Program of the U.S. Army Corps of Engineers (USACE).

This work was performed under the general direction of Dr. William Martin, Director, CHL; Dr. Ty V. Wamsley, Chief, Flood and Storm Protection Division; and Dr. Robert McAdory, Chief, Estuarine Engineering Branch, CHL.

At the time of publication of this report, Dr. Jeffery P. Holland was Director of ERDC, and LTC John T. Tucker III was the Acting Commander.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
knots	0.5144444	meters per second
microns	1.0 E-06	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force)	4.448222	newtons
slugs	14.59390	kilograms
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

1 Introduction

The U.S. Army Corps of Engineers (USACE), through the U.S. Army Engineer Research and Development Center (ERDC), has developed a robust multidimensional mass conservative finite element hydrodynamic and constituent transport numerical code, Adaptive Hydraulics (ADH).

ADH is a modular code with the ability to simulate varied physics such as saturated and unsaturated groundwater flow, Navier Stokes flow, overland flow, as well as two-dimensional (2D) shallow water flow. As part of the natural progression of ADH, a three-dimensional (3D) shallow water module (ADH-SW3) has been developed and is currently undergoing testing for robustness, accuracy, and sufficiency of model numerics.

ADH-SW3 represents a generational improvement in USACE ability to model riverine, estuarine, and reservoir physics due to the following:

1. Linear triangle-based meshing allows for accurate and adequate representation of bathymetry.
2. Vertical meshing that is neither Sigma or Z-grid based and, hence, is not encumbered by the drawbacks of either.
3. Run-time adaption in the horizontal and vertical allows for accurate representation of hydrodynamics as well as transport.
4. Internal time-step size adaption allows for time-step changes to capture rapidly changing physics during run time.
5. Fluid and constituent mass are conserved.
6. Easy transition is accomplished from the 2D realm to the 3D realm.

Purpose of study

The objective of this study was to evaluate the ability of ADH-SW3 to accurately replicate complex hydrodynamics and salinity transport through comparisons to observed data.

Galveston Bay was selected as the validation test site due to the availability of a large observational database as well as the familiarity of the developers and beta testers with the bay as demonstrated by several previously completed successful studies (Berger et al. 1995; Tate et al. 2008; Tate and Ross 2009). A quality controlled dataset collected during June 1990

through January 1991 was also available for use in this validation exercise. The dataset consisted of water surface elevations and velocity profiles as well as observed salinity concentrations in the bay.

In addition, the bay also has a deep, incised navigation channel that divides the bay into two regions and has a dramatic impact on salinity propagation into the upper bay.

The reasons mentioned above made the selection of Galveston Bay as the validation site ideal from a developer's point of view.

Validation approach

This validation exercise followed the basic strategy utilized for project level studies: (1) The first step is the validation of water surface elevations; (2) the second step is the validation of velocities; (3) and the final step is the validation of salinity transport. The dataset that is most complete is for the channel conditions present in 1990. This consisted of a channel that was nominally 400 feet (ft) wide at the base with a depth of 40 ft mean low water. Since that time, and partially as a result of a prior study, the channel was deepened to 45 ft with a base width of 530 ft.

The separation of the steps does not imply that three separate simulations are performed. This separation implies that the first validation quantity to be analyzed is the water surface elevations. Then, if the water surface elevations are comparable, the velocities are compared. Finally, if the velocities are comparable, the salinity values are compared. If at any step the model and field values are not comparable, a determination is made as to why the model and field are different, and model parameters such as bottom roughness, etc., are modified within physically acceptable ranges to better represent the field observations, and new comparisons are made.

2 Model Development

Grid development

An ADH-SW3 mesh with enough initial resolution to adequately capture the underlying bathymetry was constructed for this study; this mesh consisted of a spatially variable vertical layer distribution. ADH refines and coarsens the mesh (both horizontally and vertically) as needed to represent the flow and salinity transport. However, no mesh will be coarser than the original mesh. The number of layers of the initial mesh varies from four in the navigation channel to one in the shallow areas around the mesh nontidal boundary. The total number of original nodes in the mesh is 64,333, and the total number of original tetrahedral elements is 269,507. Most of this resolution is focused in the navigation channel and the connections of Galveston Bay to the open ocean. Figures 1 and 2 illustrate the distribution of vertical layers and resolution in the mesh, respectively.

Figure 1. ADH-SW3 mesh vertical layer distribution.

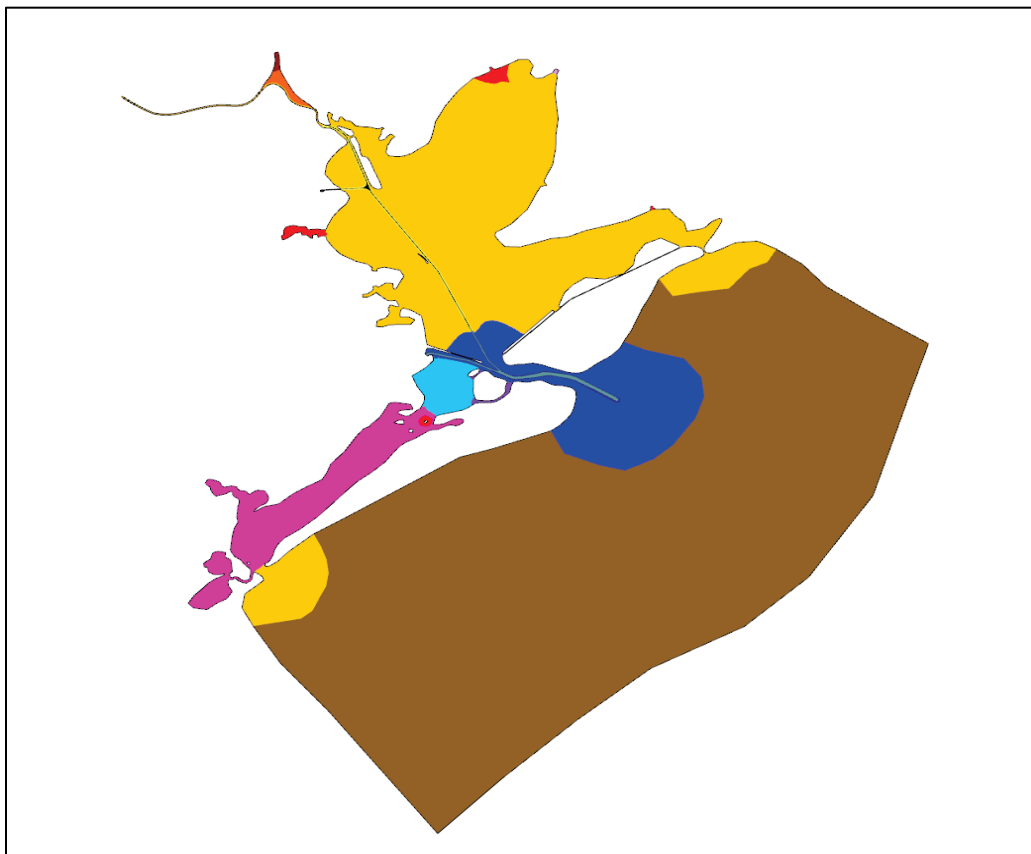
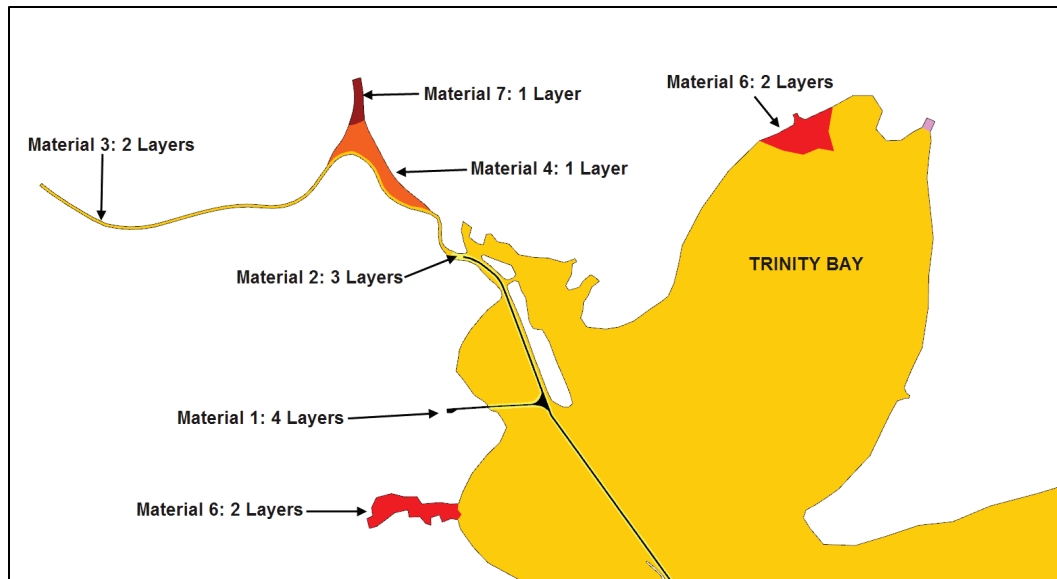
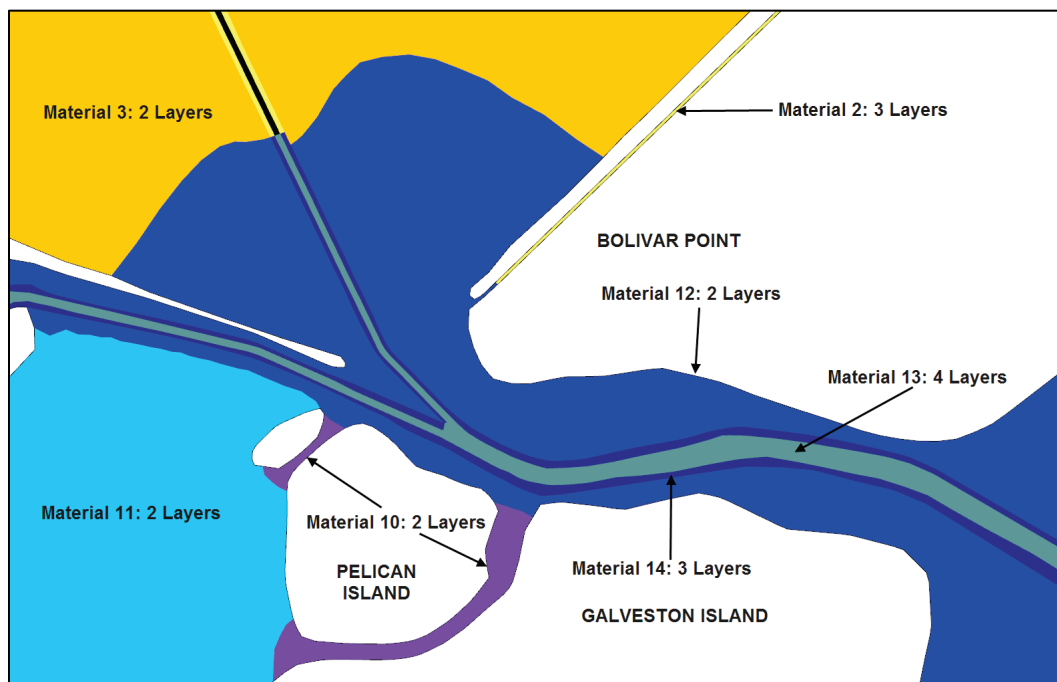


Figure 1. (continued)

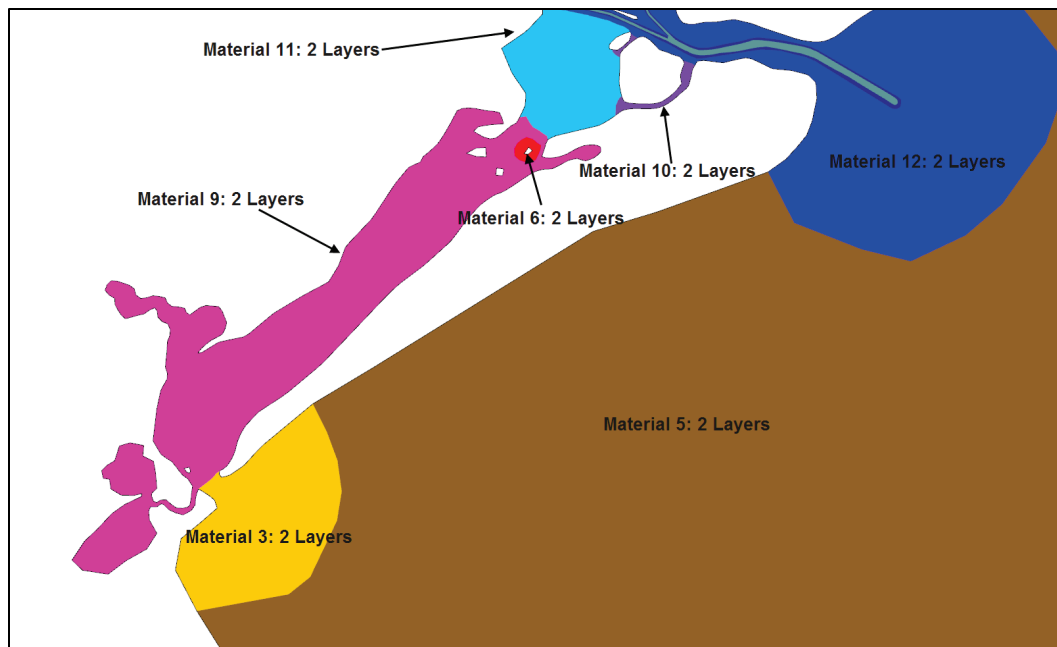


Layer distribution in upper bay.



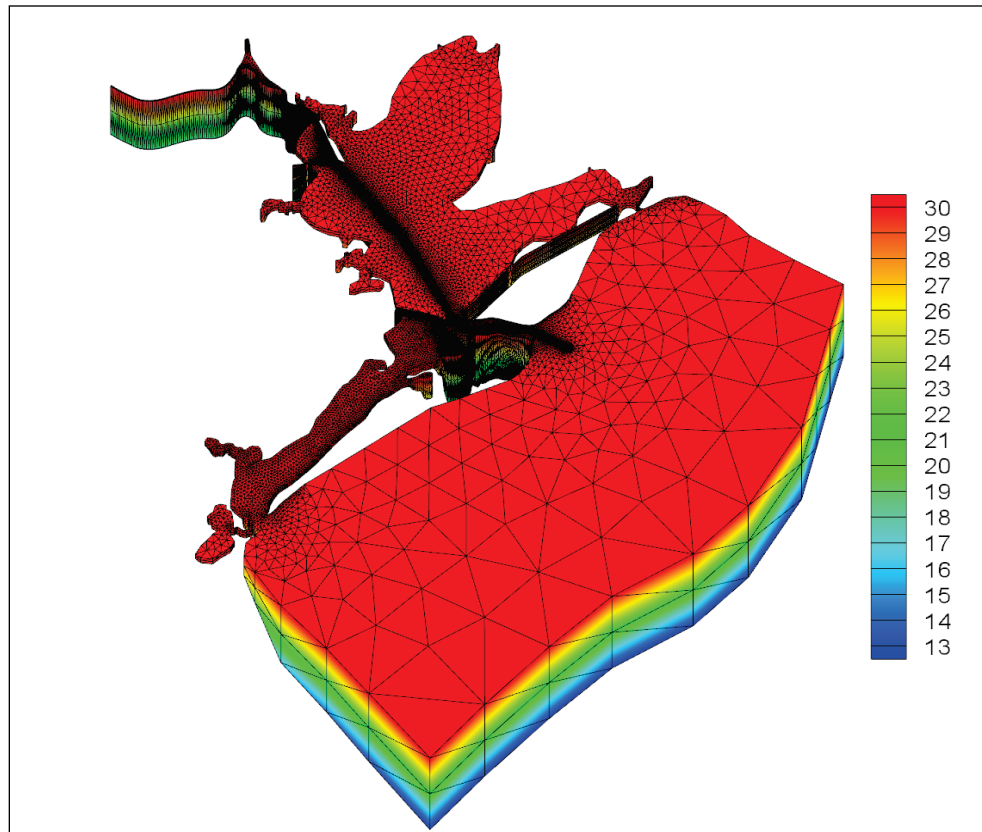
Layer distribution in inlet.

Figure 1. (concluded)



Layer distribution in West Bay and open ocean.

Figure 2. Oblique view of model mesh with elements (vertical co-ordinate in meters).



Variable roughness and turbulence characteristics were assigned to the ADH-SW3 material regions to properly define the hydrodynamic and transport characteristics of the system. Roughness was assigned based on a Manning's-type formulation utilizing Manning's n values. The turbulence model utilized for this study was the Mellor-Yamada level 2 in the vertical and the Smagorinski formulation in the horizontal. Table 1 provides a detailed breakdown of the Manning's and Smagorinski values utilized in this study. These values are assigned based on the characteristics of the prototype. For example, much of the Trinity Bay is covered with a fine silt, and the bed is fairly smooth; the dredging of the channel, as well as the oysters along the side slopes, results in a more variable roughness when compared to the shallow areas of the mesh. So, the bed roughness in the channel (material 1) is higher than the surrounding shallows.

Table 1. ADH-SW3 n and Smagorinski Coefficient values.

Material	n value	Smagorinski Coefficient
1	0.025	0.2
2	0.025	0.2
3	0.021	0.2
4	0.022	0.2
5	0.018	0.2
6	0.021	0.2
7	0.022	0.2
8	0.022	0.2
9	0.021	0.2
10	0.021	0.2
11	0.021	0.2
12	0.018	0.2
13	0.018	0.2
14	0.018	0.2

The model was executed for a period of several months from July 1990 to January 1991 to coincide with the data collection timeframe (Fagerburg et al. 1994).

Boundary conditions

The model was forced by a tidal boundary applied at the ocean boundary, Trinity and San Jacinto River inflows, and wind stresses. An artificial ocean

boundary was applied to simulate the net longshore current from the east to the west. Wind data were obtained from a long-term collection effort undertaken by the ERDC for the simulated time (Fagerburg et al. 1994).

Figures 3, 4, 5, and 6 show the tidal forcing, the ocean salt boundary, the inflows from Trinity River, and the inflows from San Jacinto River. The salinity in the Gulf of Mexico is found by using average monthly values supplied by Cochrane and Kelly (1986). This variability in salinity in the Gulf is attributed to the freshwater flow from the Mississippi and the Atchafalaya Rivers. Cedar Point power plant flows, the intake (near Morgan's Point), and outflow (in Trinity Bay) can have an impact on the salinity in upper Trinity Bay and were included in these simulations. A general location map is provided in Figure 9. These boundary conditions are described in detail in Berger et al. (1995).

Figure 3. Ocean tidal boundary (Hour 0 = 1 Jan 1990, 12:00 a.m.).

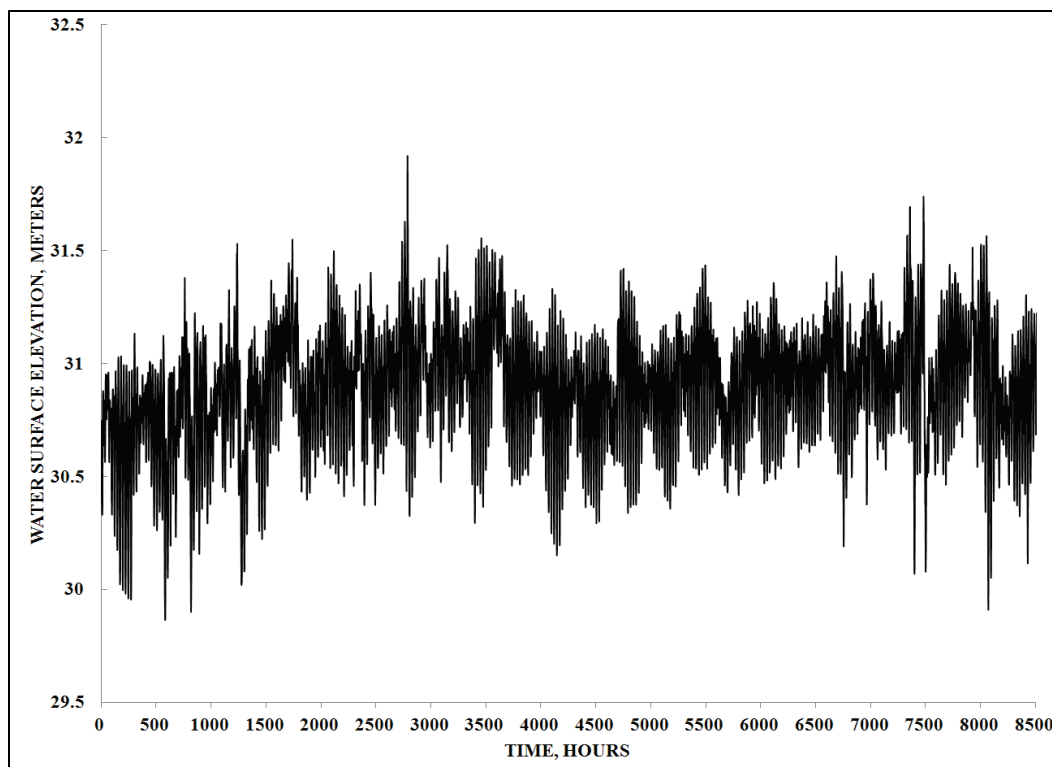


Figure 4. Ocean salt boundary (Hour 0 = 1 Jan 1990, 12:00 a.m.).

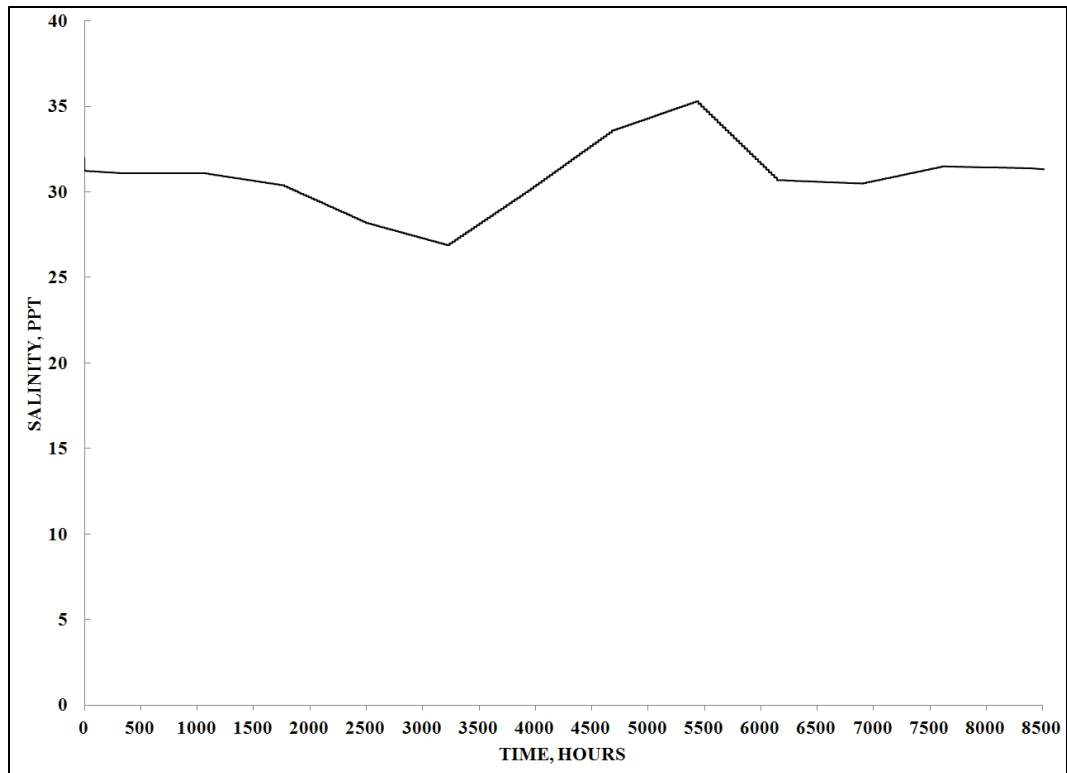


Figure 5. Trinity River discharge (Hour 0 = 1 Jan 1990, 12:00 a.m.).

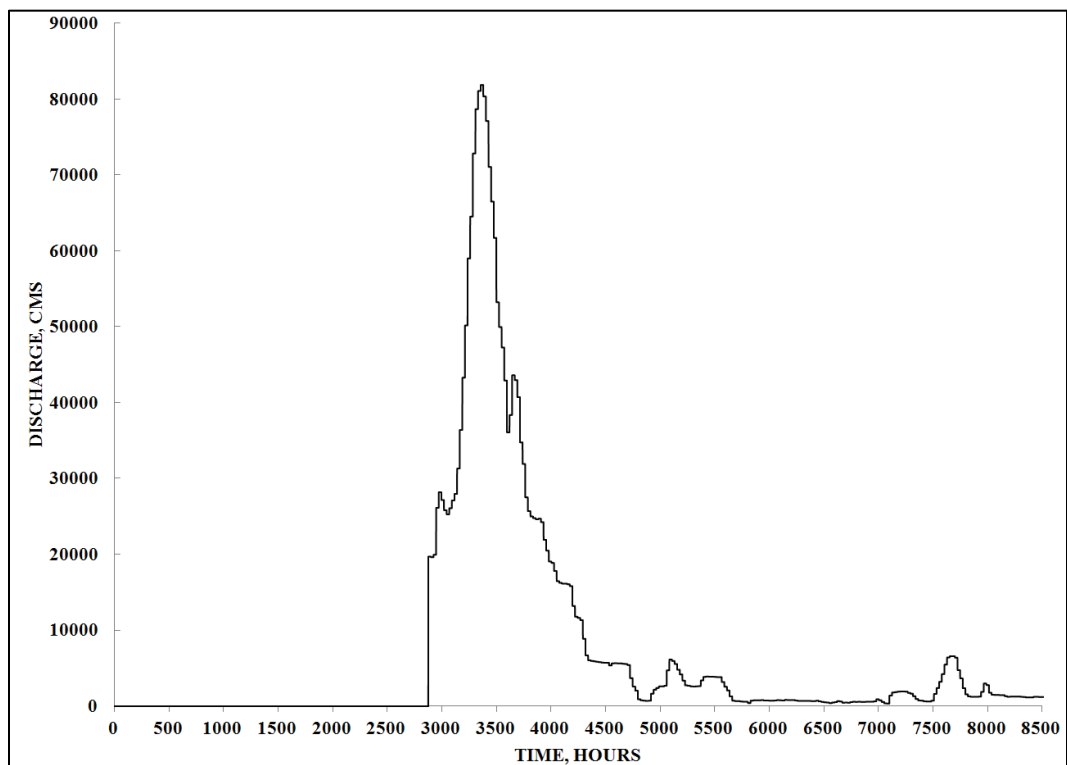
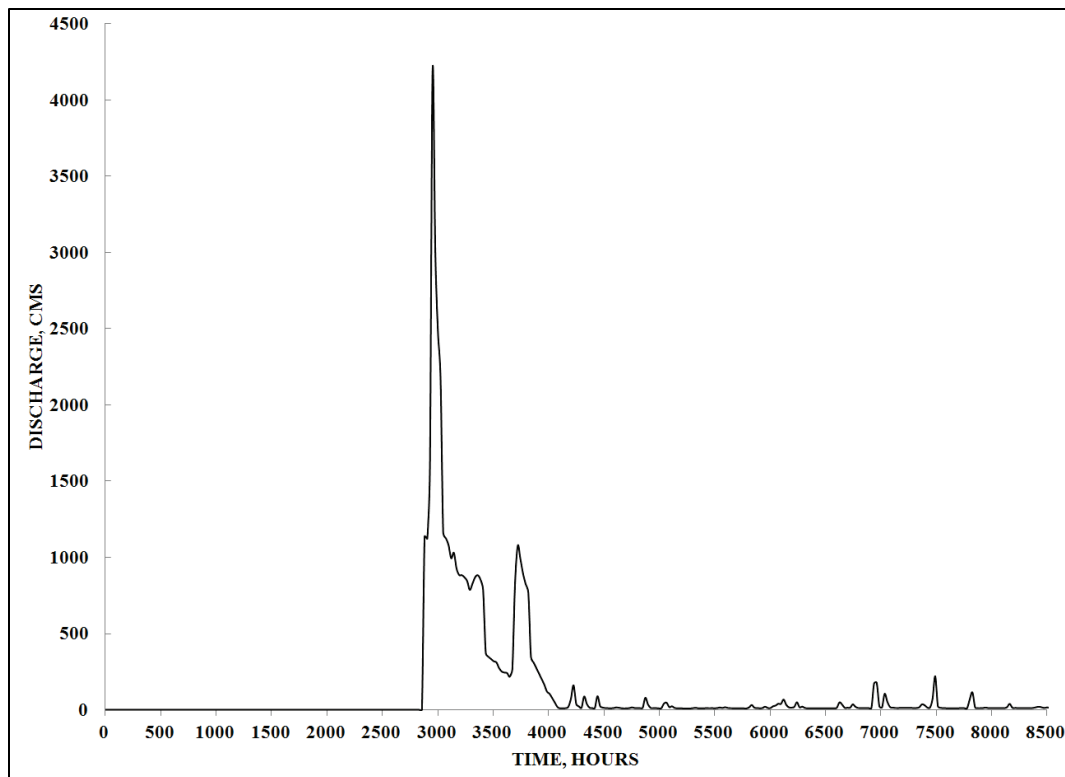


Figure 6. San Jacinto River discharge (Hour 0 = 1 Jan 1990, 12:00 a.m.).



Model runs are begun with an initial configuration of currents, water surface, and salinity. The model is then run for a long enough period of time that the solution converges to a condition that is independent of the initial *guess*. This is termed the *spin-up* period. In this case, the model was first run for a period of 1000 hours (hr), followed by the simulation beginning at the start of year 1990. The period of interest begins after time 3500 hr; a large pulse of freshwater is introduced into the bay at this time (Figure 5) and drives salinity out of the entire bay. Therefore, the total spin-up period before the presented results is approximately 4500 hr (or approximately half a year).

3 Model Results and Validation

The ADH-SW3 model results are compared to observed water surface elevations, velocities, and salinities.

Figures 7 and 8 present the effect of utilizing ADH-SW3 mesh adaption on the salinity distribution in the vertical and intrusion in the horizontal plane at a point in time in the navigation channel.

Figure 7. Salinity distribution (no adaption).

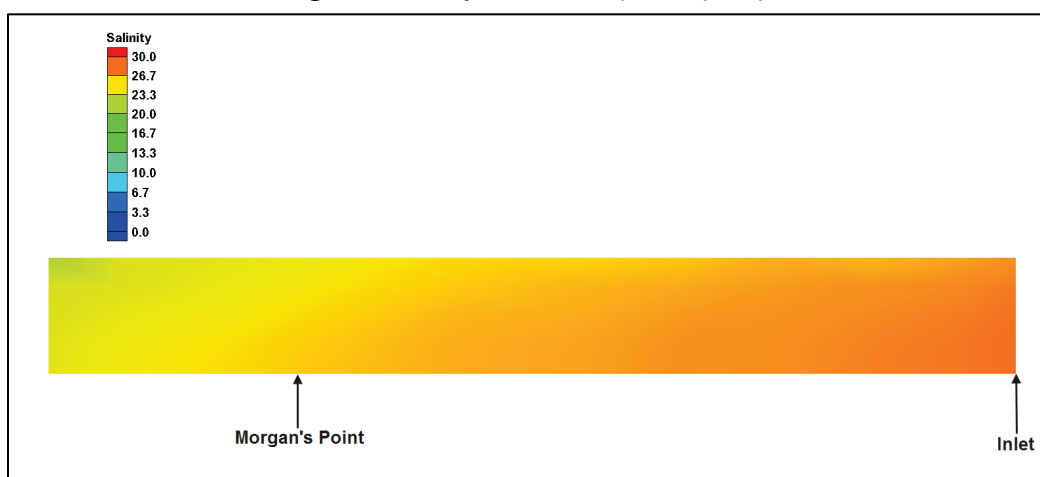
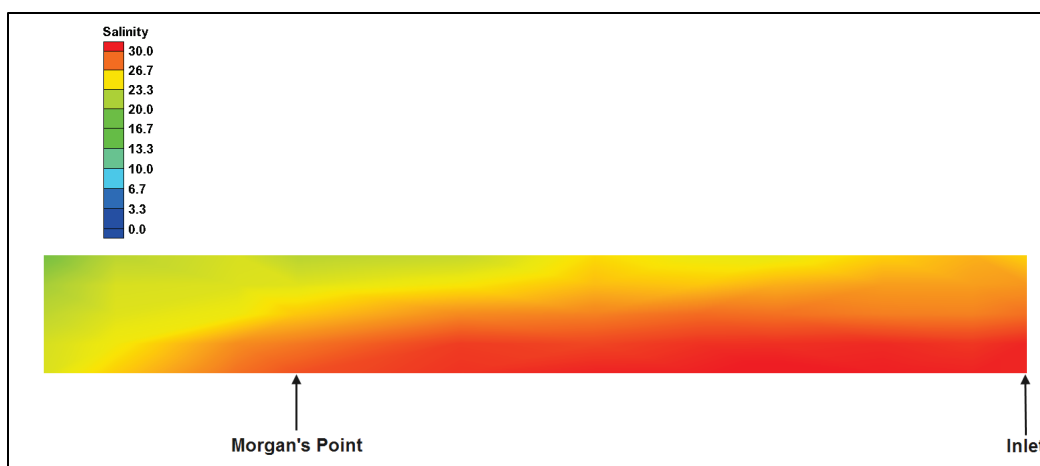


Figure 8. Salinity distribution (adaption).



It is observed that the salinity distribution and propagation is captured when adaption is turned on, whereas salinity is smeared throughout the water column if adaption is not utilized. The maximum number of nodes

the mesh adapted to was 75,269 (an increase of 17% over the initial number of nodes).

Water surface elevations are compared at stations S1, S10, and S16 (Figure 9), velocities are compared at several ranges along the navigation channel (Figure 10), and salinities are compared to the stations shown in Figure 9. This validation approach closely follows the methodology in Berger et al. (1995).

Digital copies of the water surface elevation observations were not available; therefore, a harmonic decomposition was performed on the model data and compared to the three major tidal components reported for the data in Berger et al. (1995). Figures 11, 12, and 13 show the harmonic breakdown comparison between the model results and the observed data.

Figure 9. Location map and water surface and salinity observation stations.

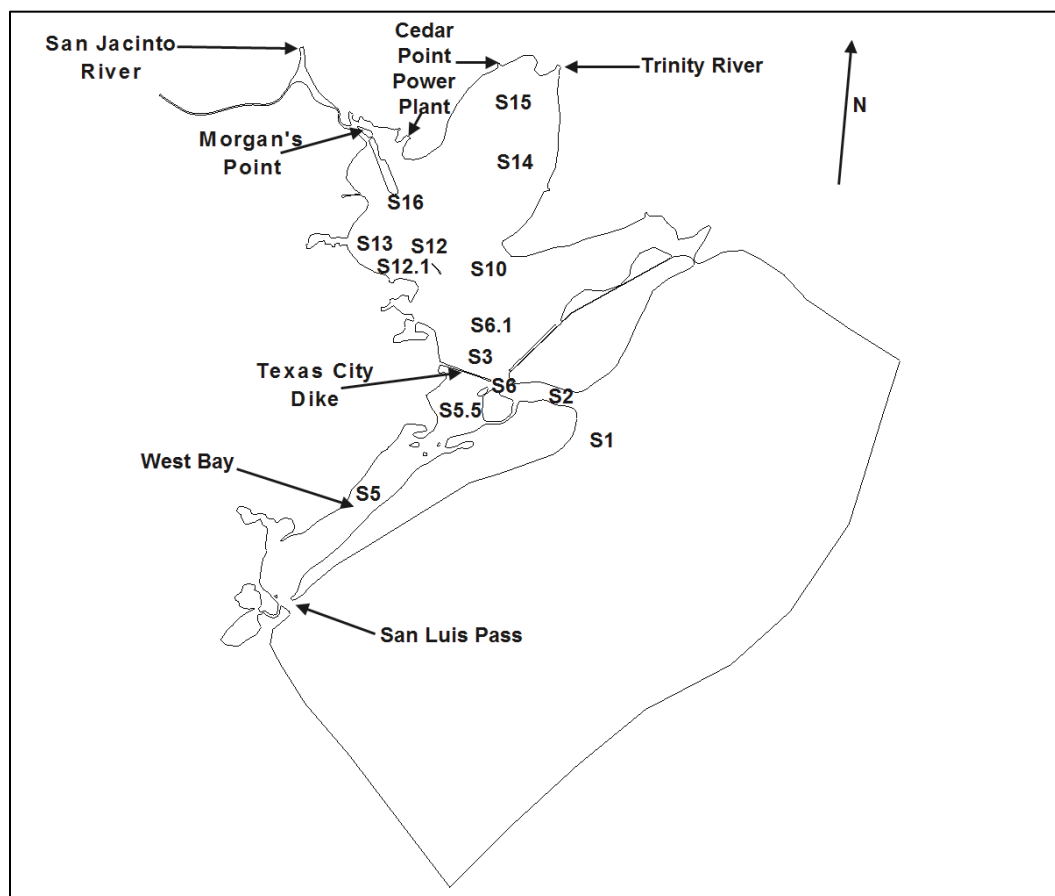


Figure 10. Velocity observation locations.



These tidal harmonic results show that the semidiurnal (M2) tide is more dissipated through the entrance than the longer diurnal components (K1 and O1). This is expected. Also noteworthy is the amplification of tidal components due to the reflection at the upper end of the bay. Figure 14 shows the average model and field phase lags and further supports the model robustness. The phase lag (relative to S1, Figure 9) is the average phase lag of the three largest harmonic components (K1, O1, and M2). It is observed that the model phase lag is in close agreement to the field phase lag. At station S3 (mile 8.1), the model leads the field by approximately 12 minutes; at S10 (mile 16.3), the model leads the field by approximately 5 minutes; and at station S16 (mile 26.4), the model lags the field by approximately 11 minutes for an average model lag of 11.5 minutes. Above station 10 (mile 16.3), the behavior appears to be that of a standing wave.

Figure 11. Harmonic amplitude for S1 model and field results (all values in meters).

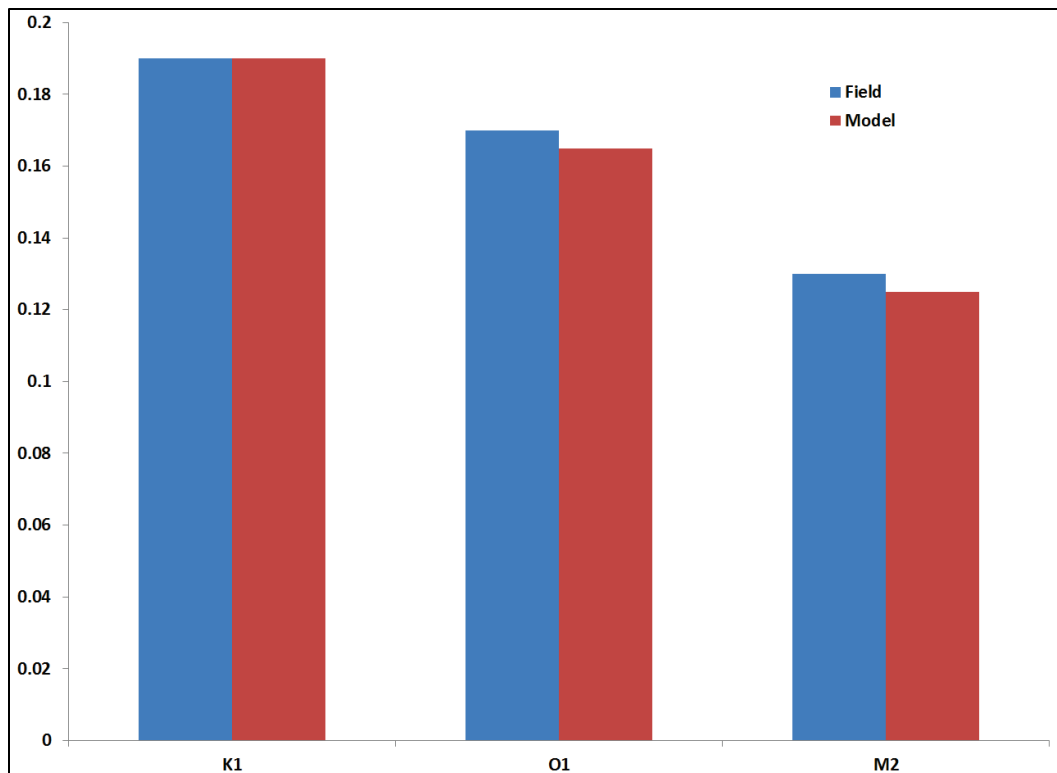


Figure 12. Harmonic amplitude for S10 model and field results (all values in meters).

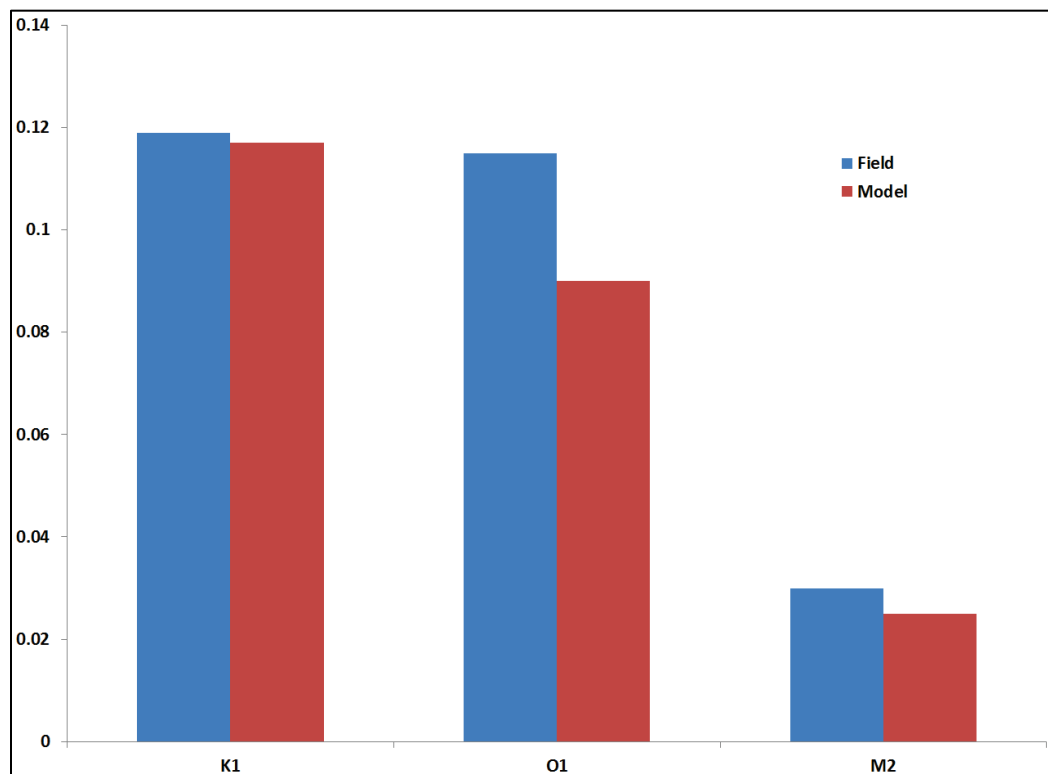


Figure 13. Harmonic amplitude for S16 model and field results (all values in meters).

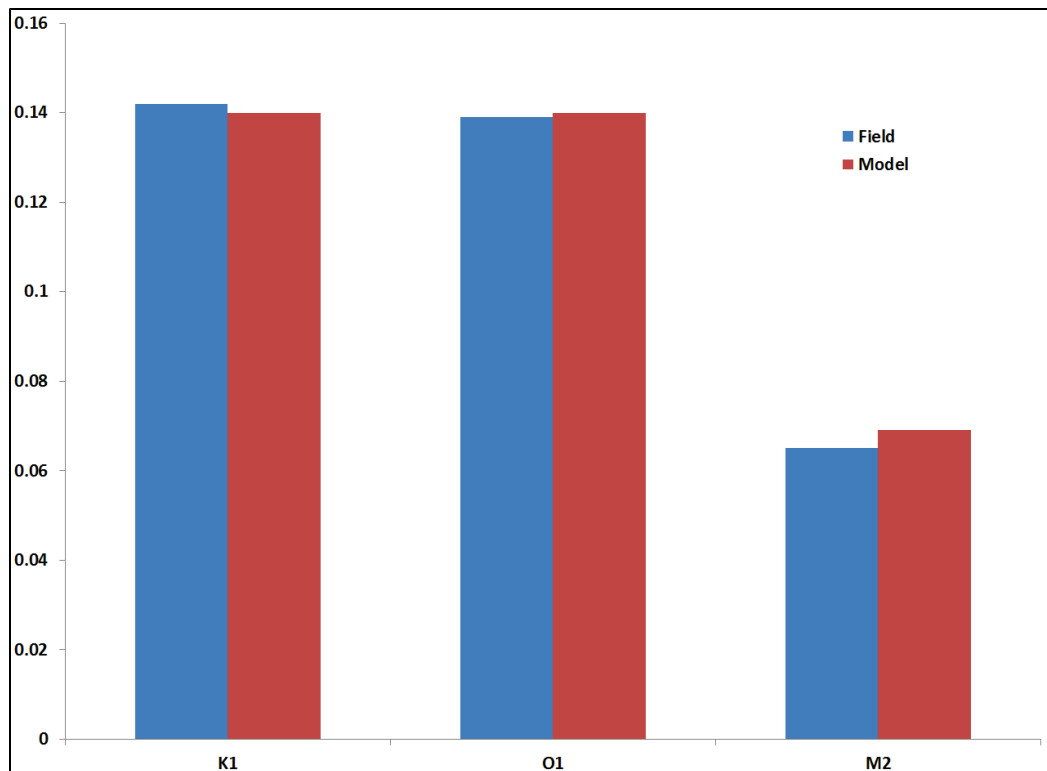
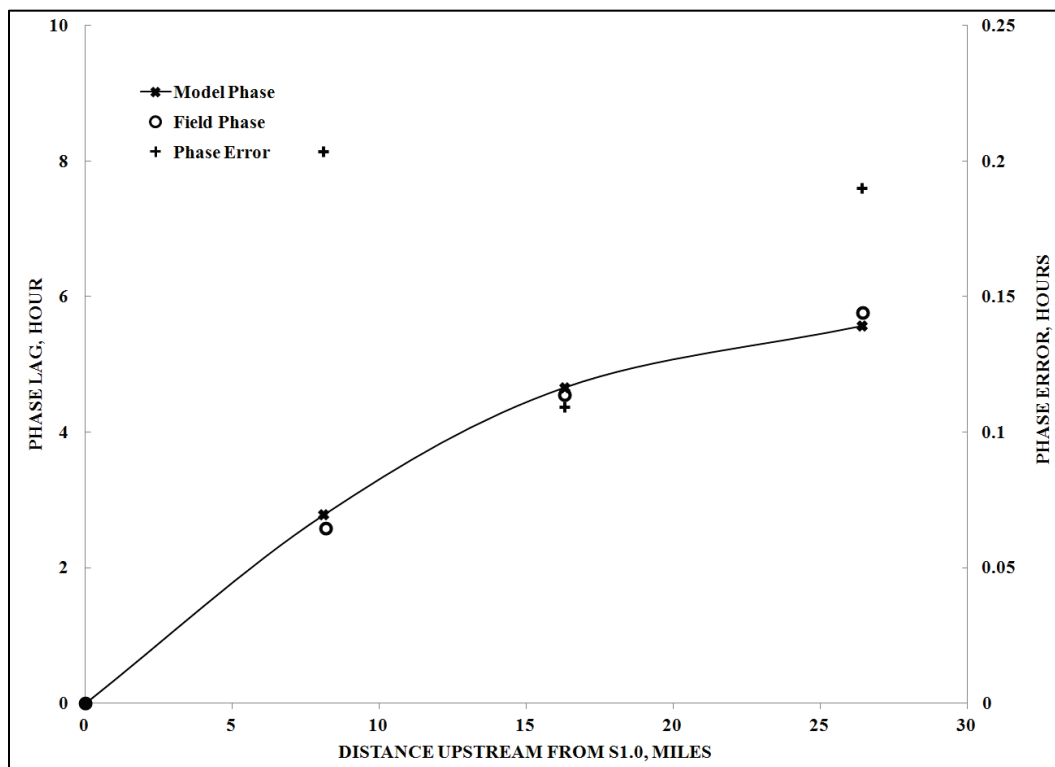


Figure 14. Comparison of model and field average phase lag.



Velocity results from the model are compared to velocity data measurements taken along the navigation channel from the inlet to just downstream of Morgan's Point. Figure 10 provides the location of these velocity ranges. Each velocity range consists of four observation stations, one on each flat at the two channel sides and two in the channel near each side. These stations are labeled from *a* to *d* going from west to east. Model velocities were converted to feet per second in accordance with the unit system used in the observation data.

Figures 15 through 30 illustrate the comparisons of model velocities to those observed in the field. The model results show adequate agreement with observed velocities in the top as well as bottom layers for ranges 1, 2, 3, and 4 (Figure 10). At range 4, the observed velocities are <0.5 feet per second (fps), and the model simulated velocities are of the same magnitude. However, at such low velocities, localized influences such as small waves can introduce substantial noise to the observations in addition to the increased uncertainty in the measurements of such flows.

Figure 15. Observed and model velocities for range 1A.

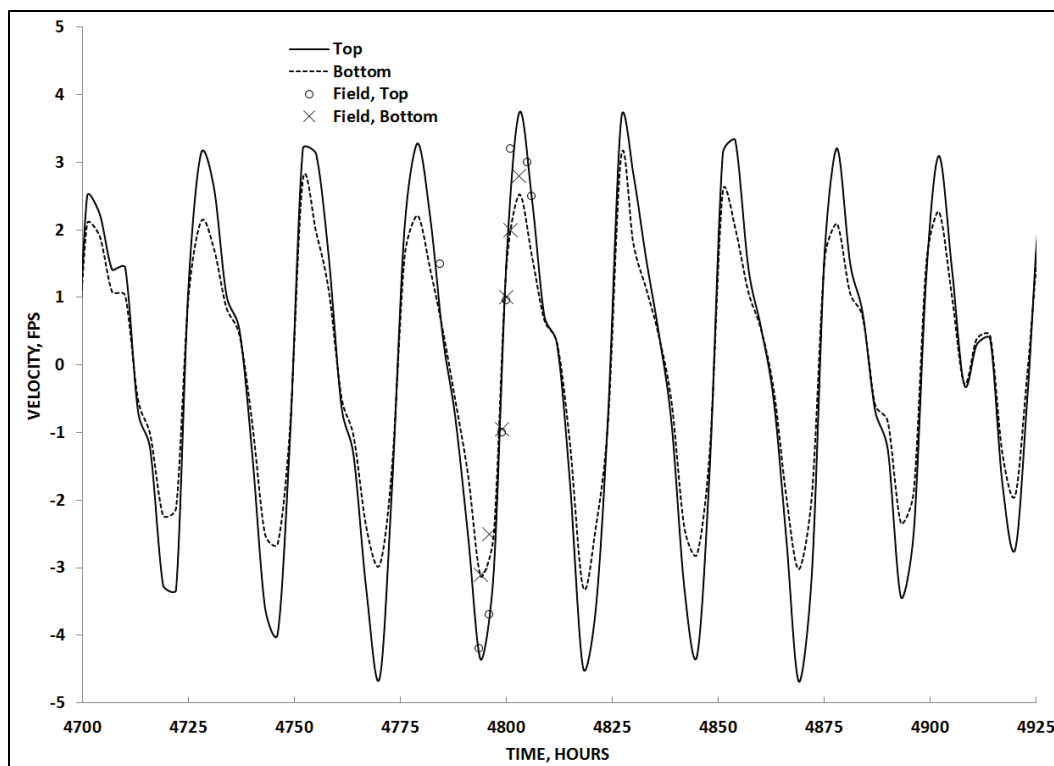


Figure 16. Observed and model velocities for range 1B.

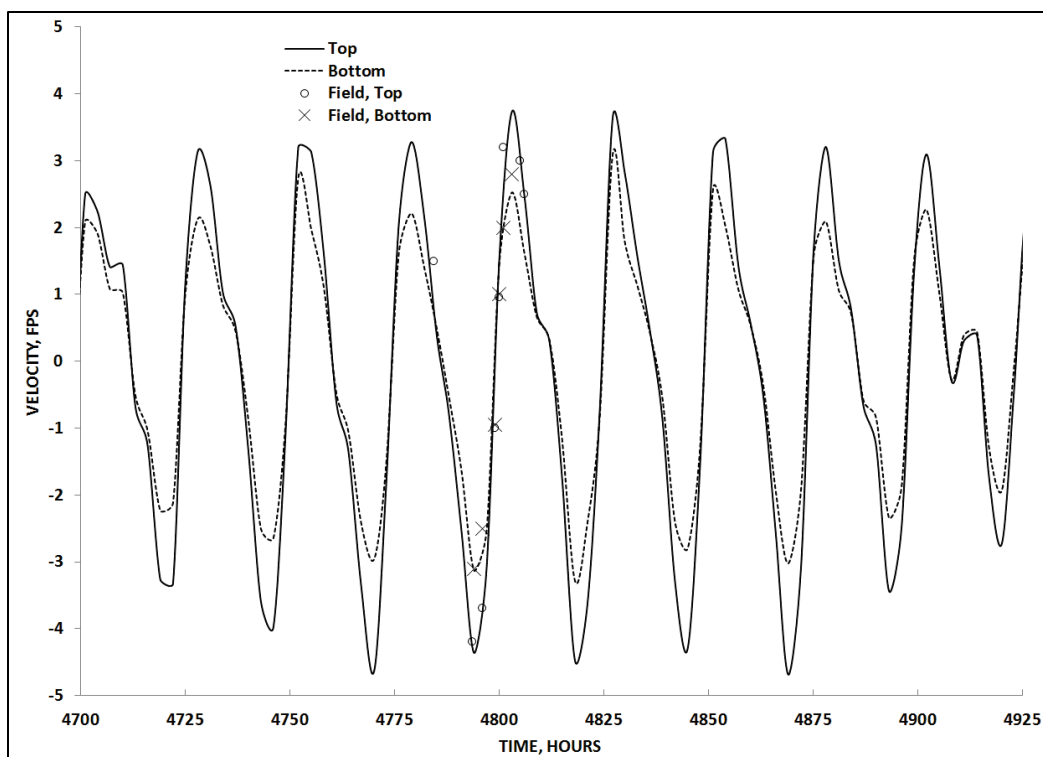


Figure 17. Observed and model velocities for range 1C.

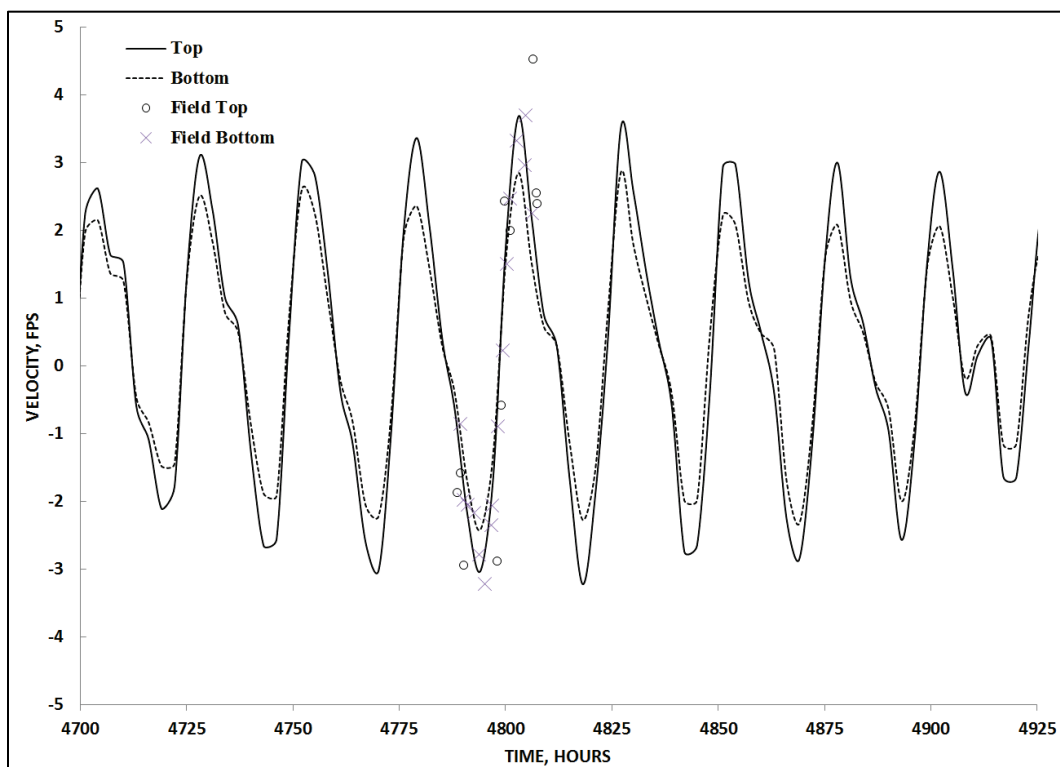


Figure 18. Observed and model velocities for range 1D.

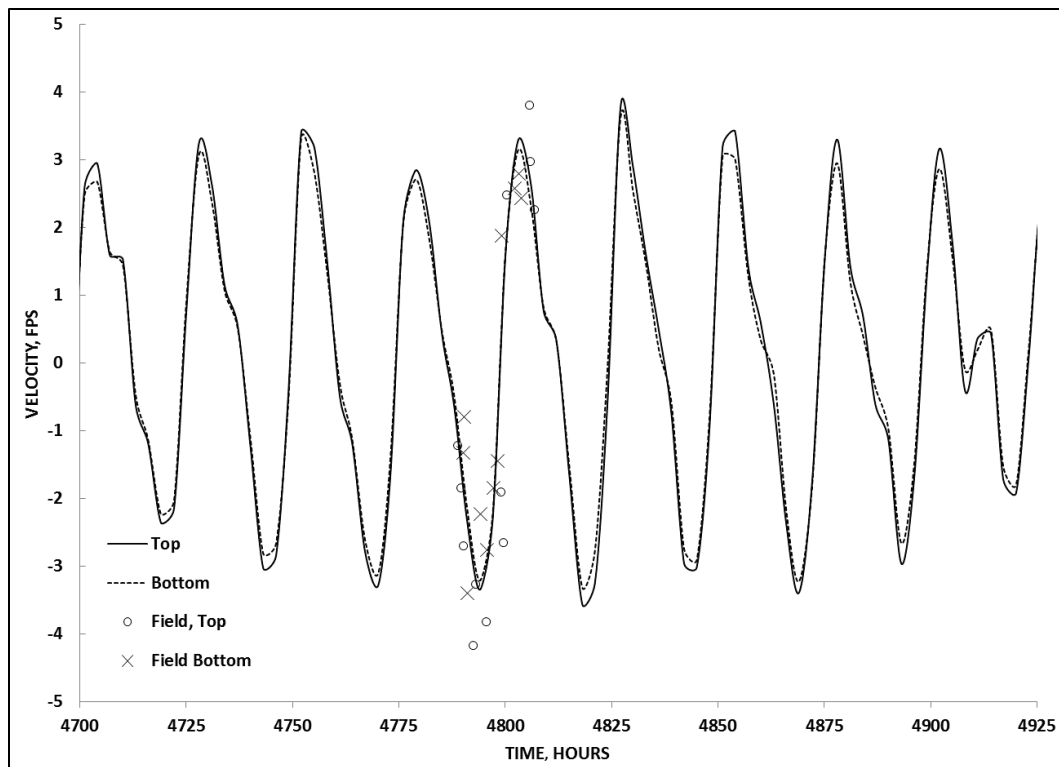


Figure 19. Observed and model velocities for range 2A.

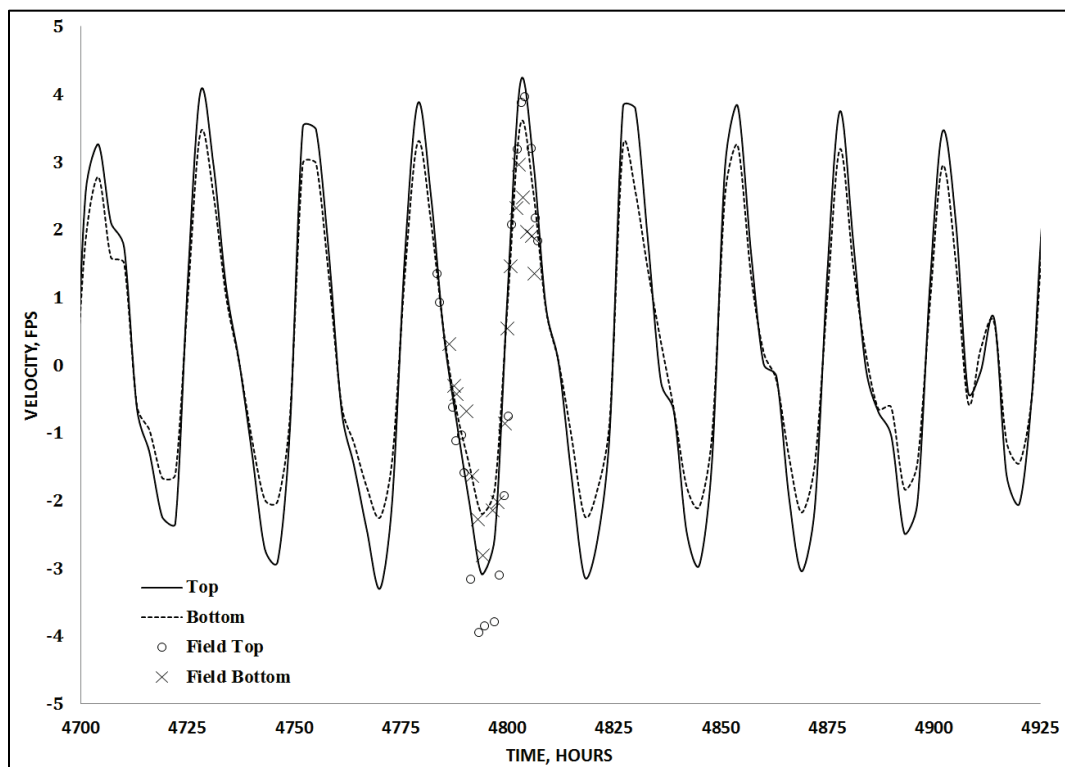


Figure 20. Observed and model velocities for range 2B.

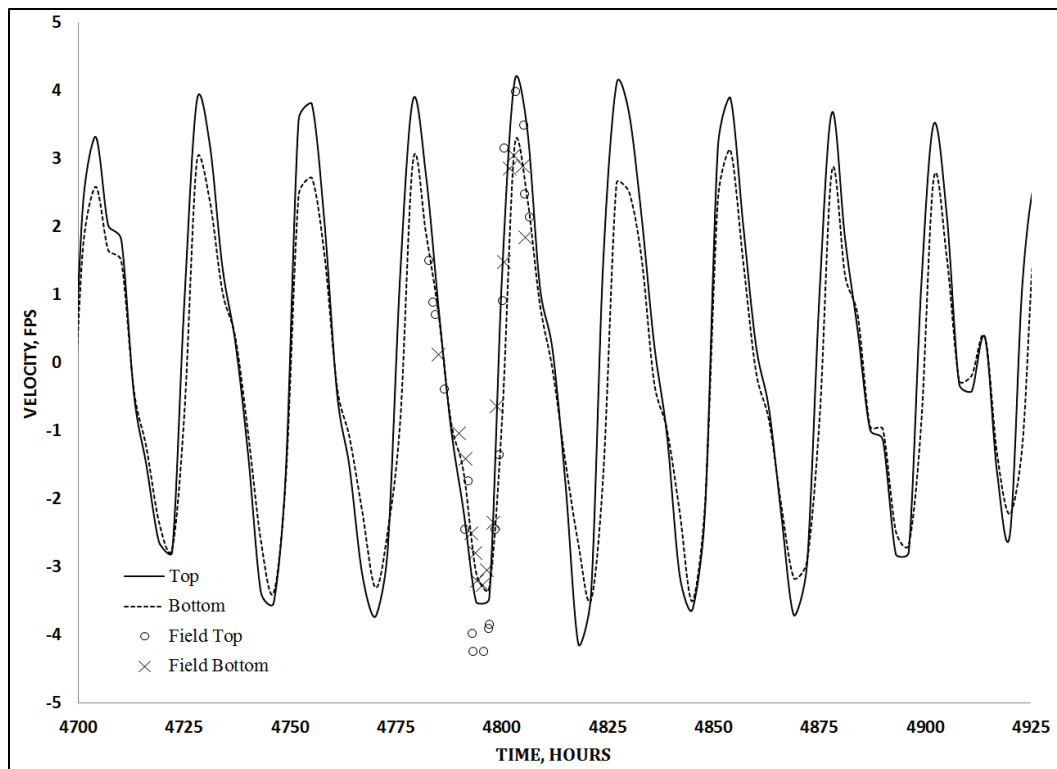


Figure 21. Observed and model velocities for range 2C.

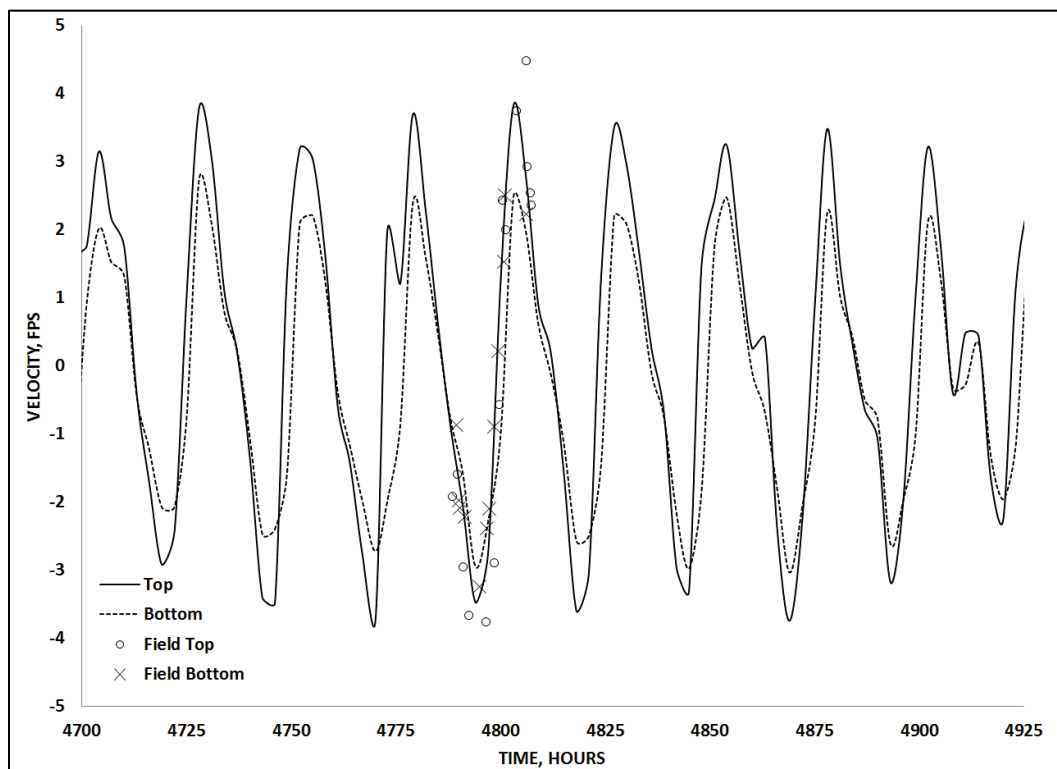


Figure 22. Observed and model velocities for range 2D.

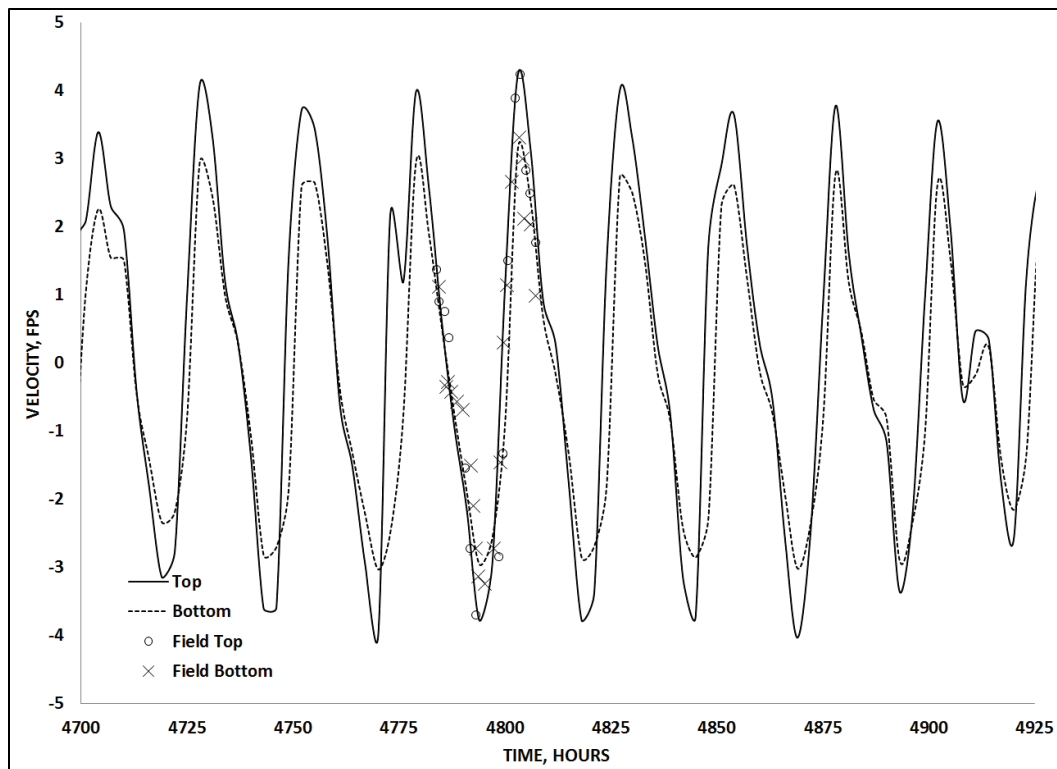


Figure 23. Observed and model velocities for range 3A.

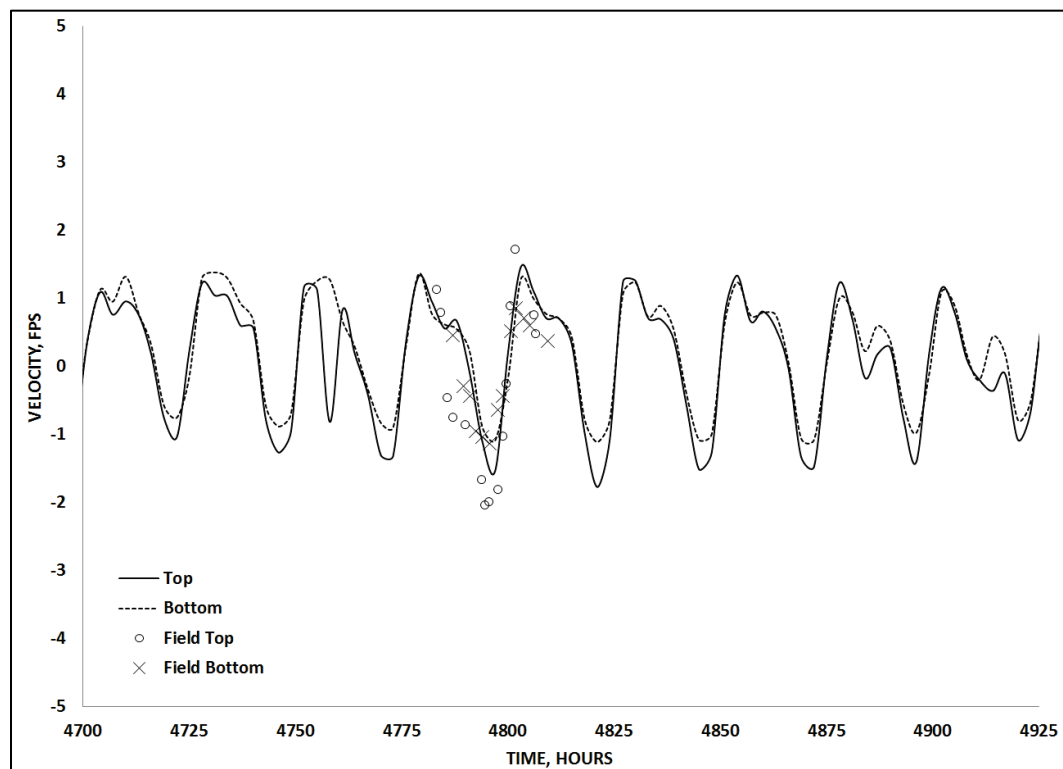


Figure 24. Observed and model velocities for range 3B.

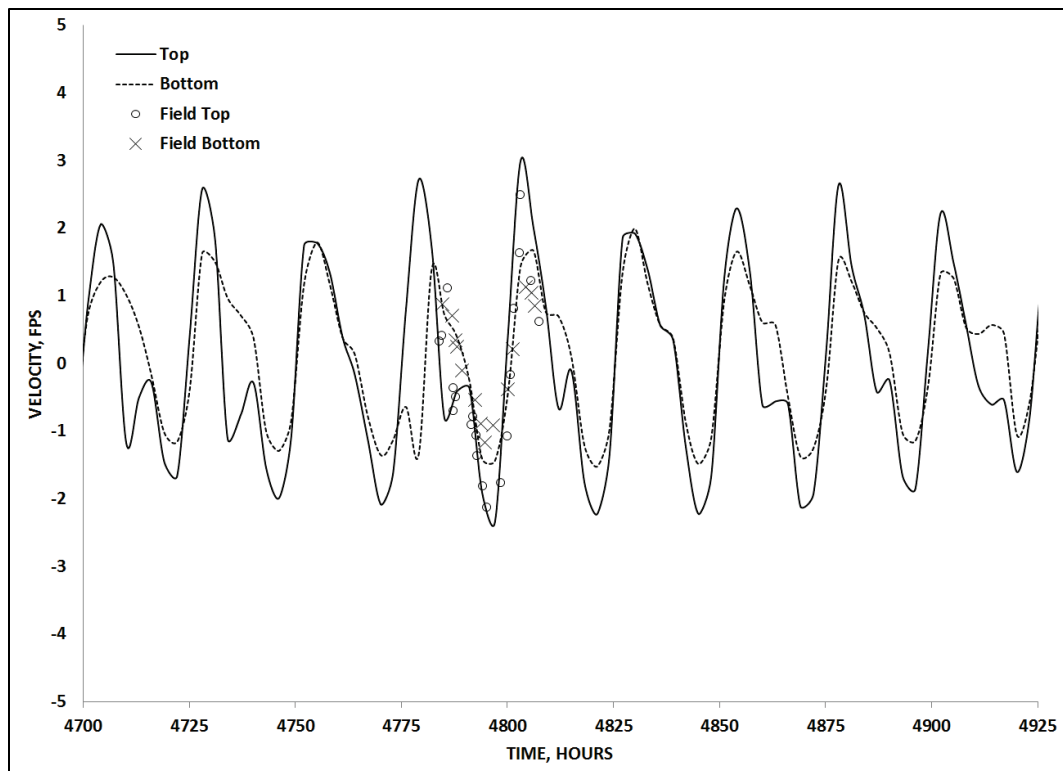


Figure 25. Observed and model velocities for range 3C.

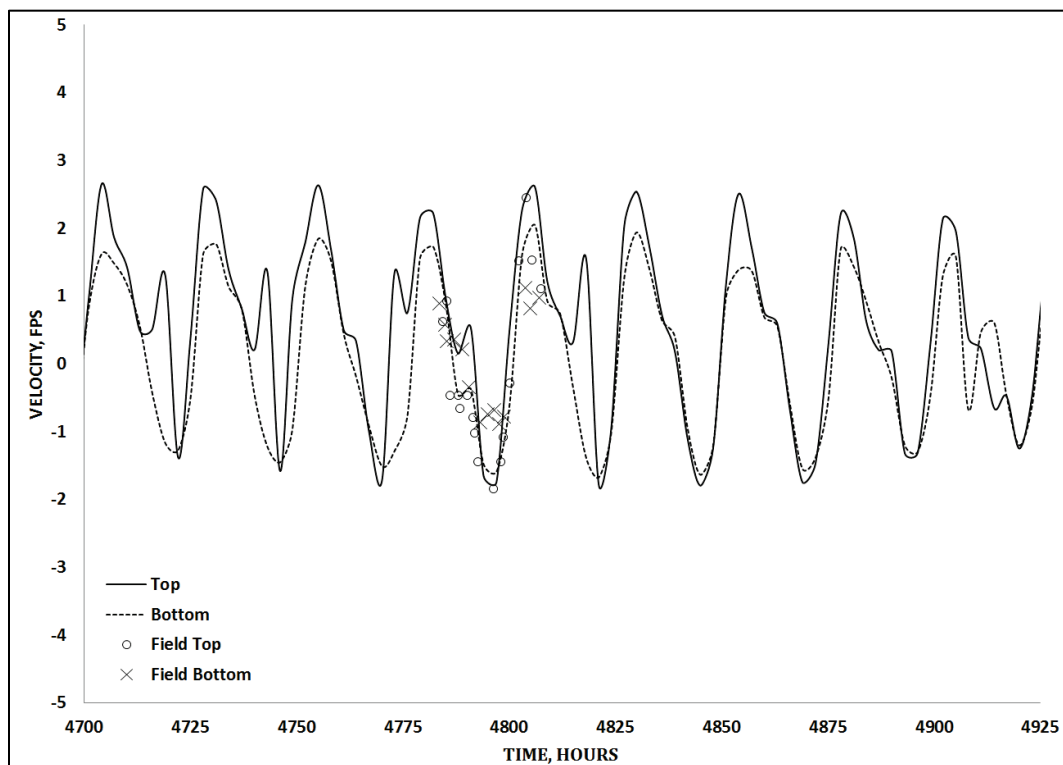


Figure 26. Observed and model velocities for range 3D.

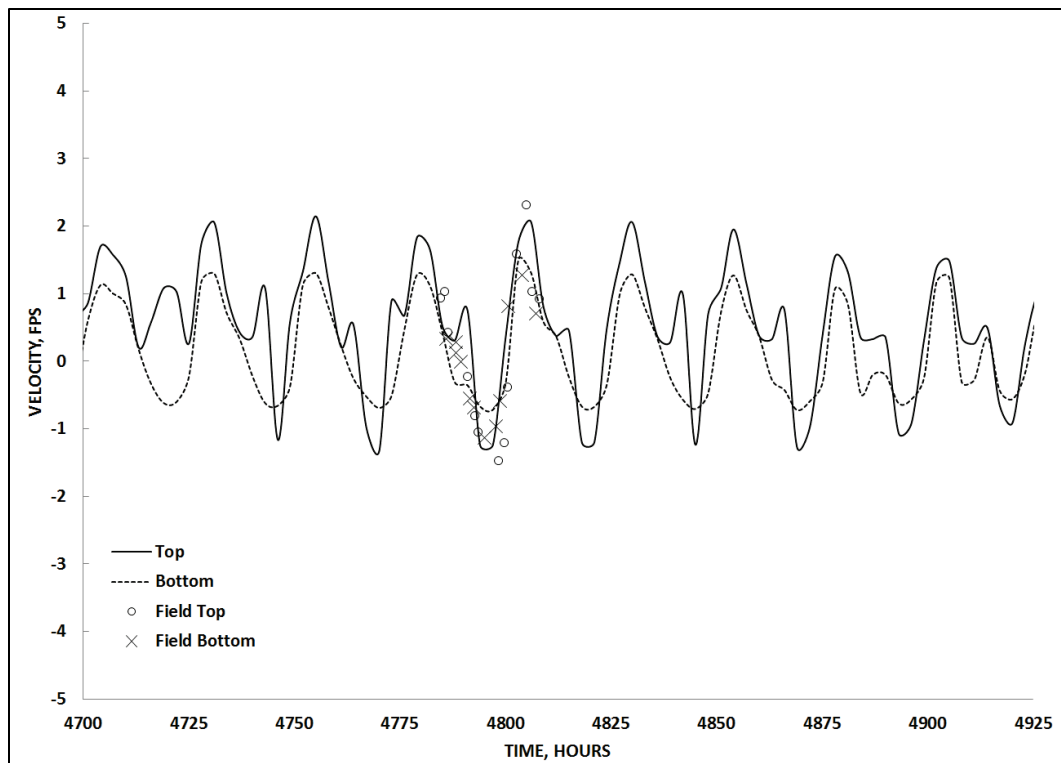


Figure 27. Observed and model velocities for range 4A.

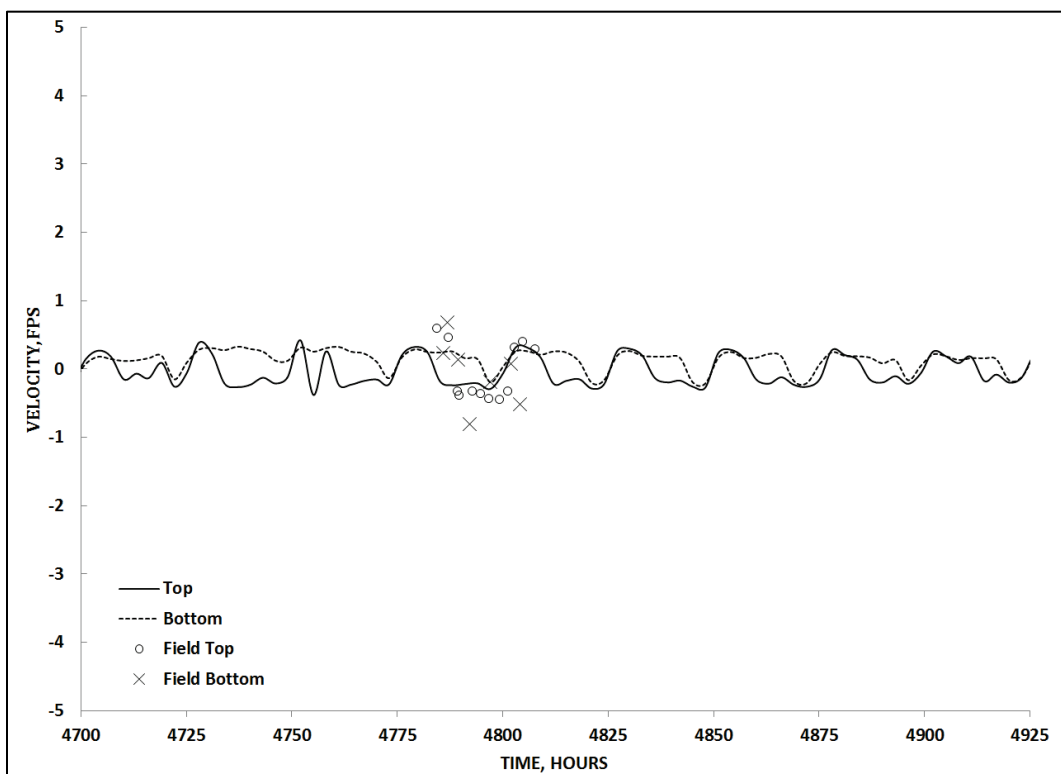


Figure 28. Observed and model velocities for range 4B.

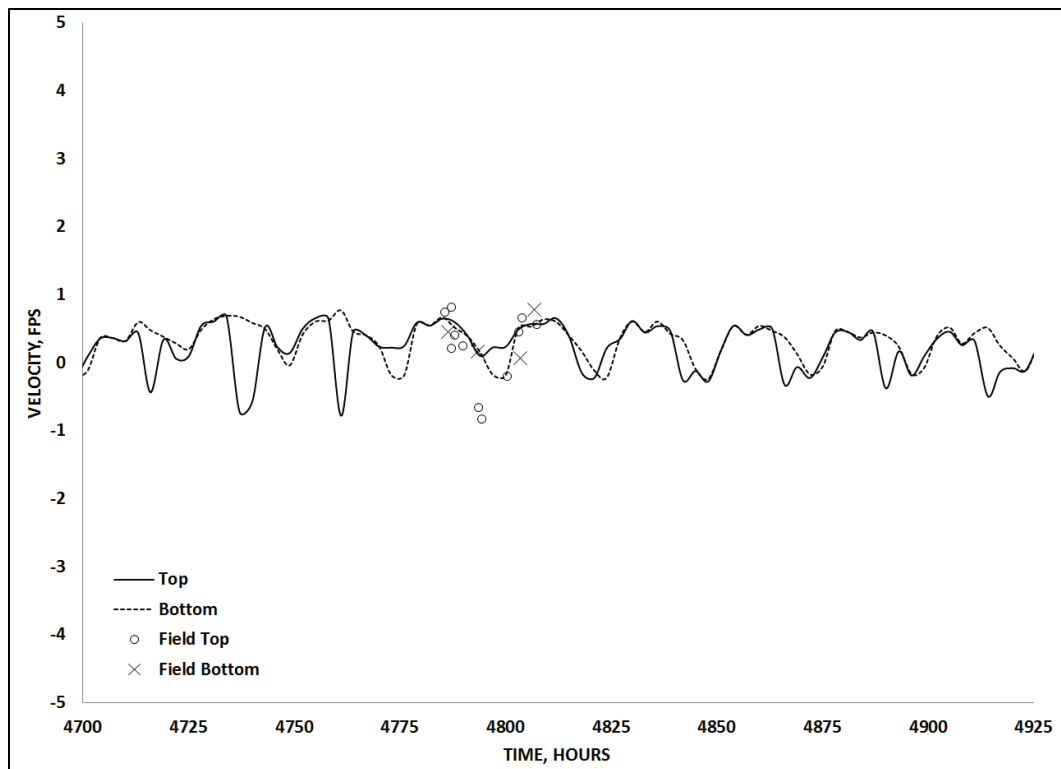


Figure 29. Observed and model velocities for range 4C.

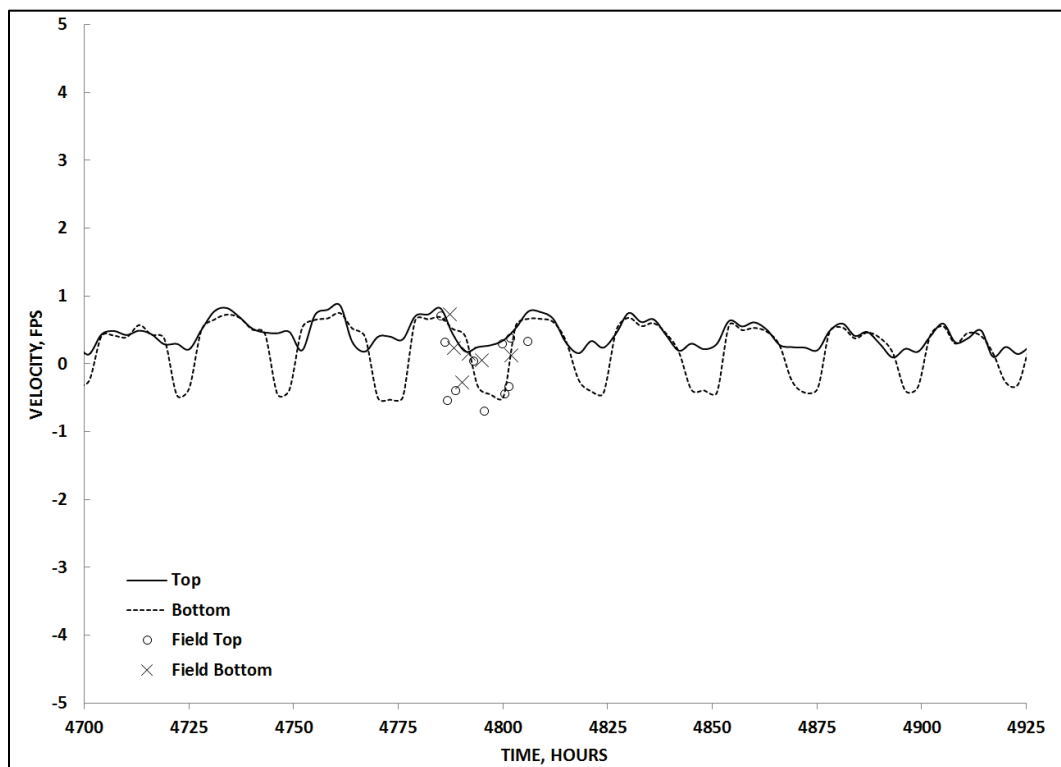
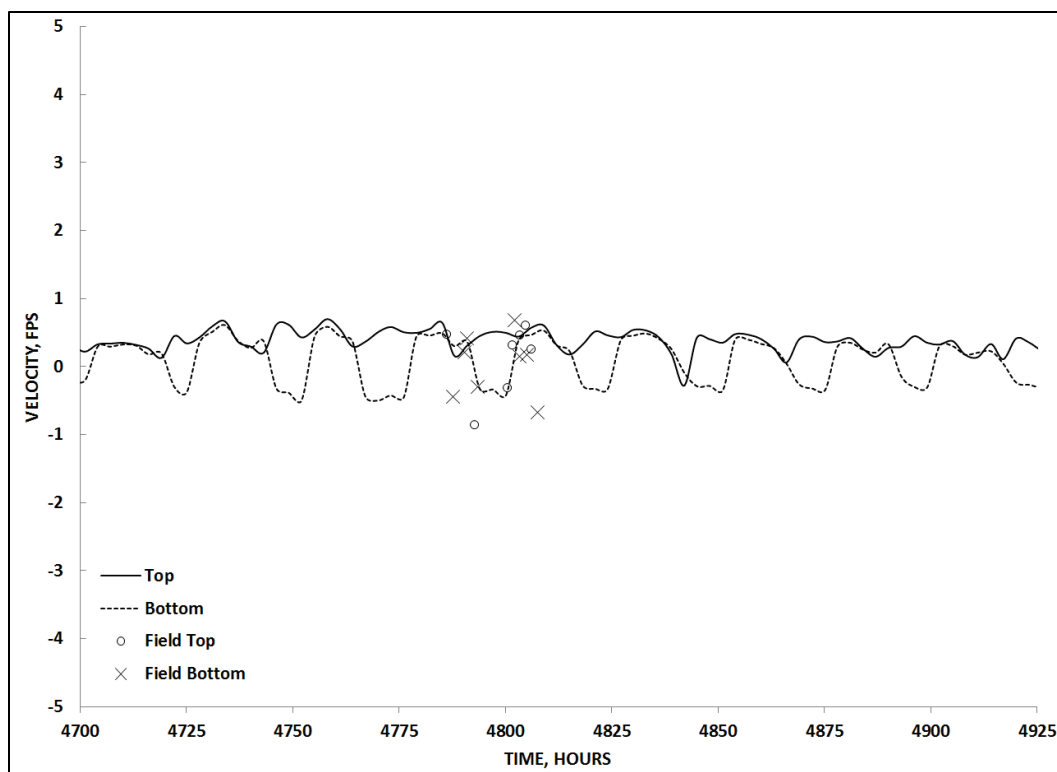


Figure 30. Observed and model velocities for range 4D.



Salinity values computed by the model were compared to the hand-collected observations in the field for stations listed on Figure 9. The meters that recorded more data at that time were subject to severe biological fouling and had significant drift at the time. Comparison to the hand collection was found to be more representative. Again the model does an adequate job of recreating the field observations throughout the period of observations.

Figures 31 through 39 show the comparison for salinity values at mid-depth (hand-collection observations were only available at mid-depth).

The results of the model agree well with observed data. The weakest comparisons are near Clear Lake (Station S13 and in West Bay, S5). The model results show salinity to be lower in West Bay (Stations S5.5 and S5) than those observed in the field. These lower salinities start to converge with the field observations later in the run, indicating that the initial salinities in West Bay were lower than those in the field. West Bay is a low-energy environment compared to rest of the bay; thus, it takes West Bay longer to respond to external forcings. Throughout the rest of the bay, the model replicates the field-observed salinity values exceptionally well.

Figure 31. Mid-depth salinity comparison for station S1.

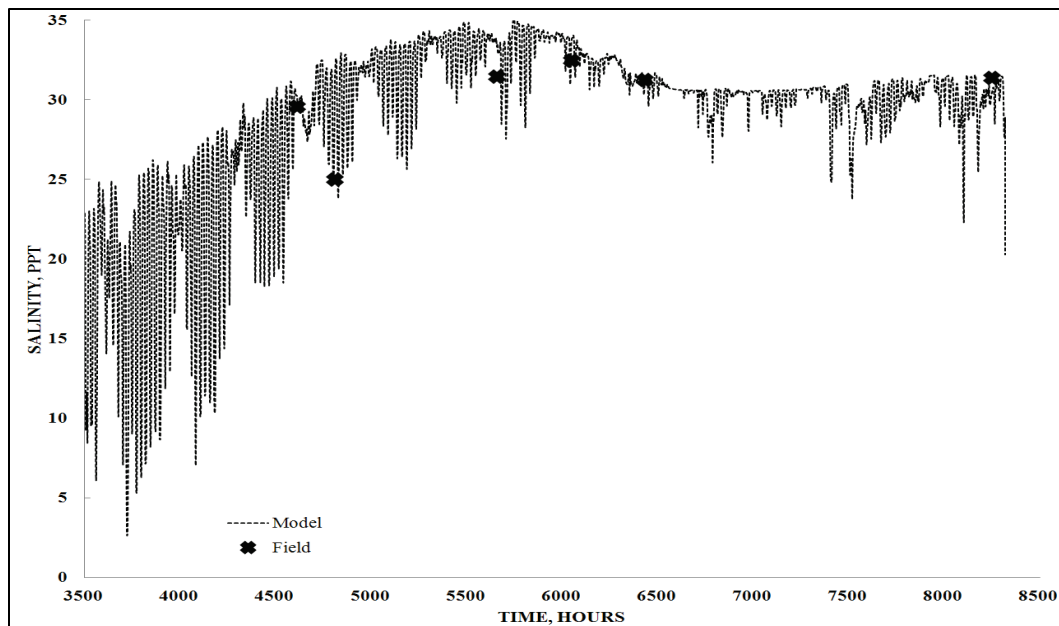


Figure 32. Mid-depth salinity comparison for station S2.

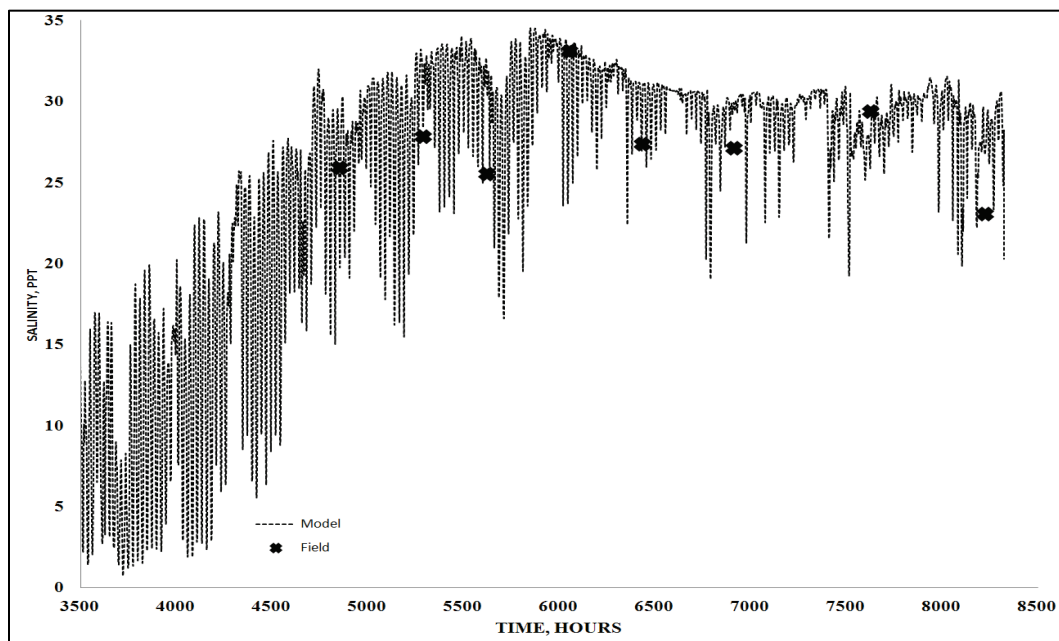


Figure 33. Mid-depth salinity comparison for station S5.

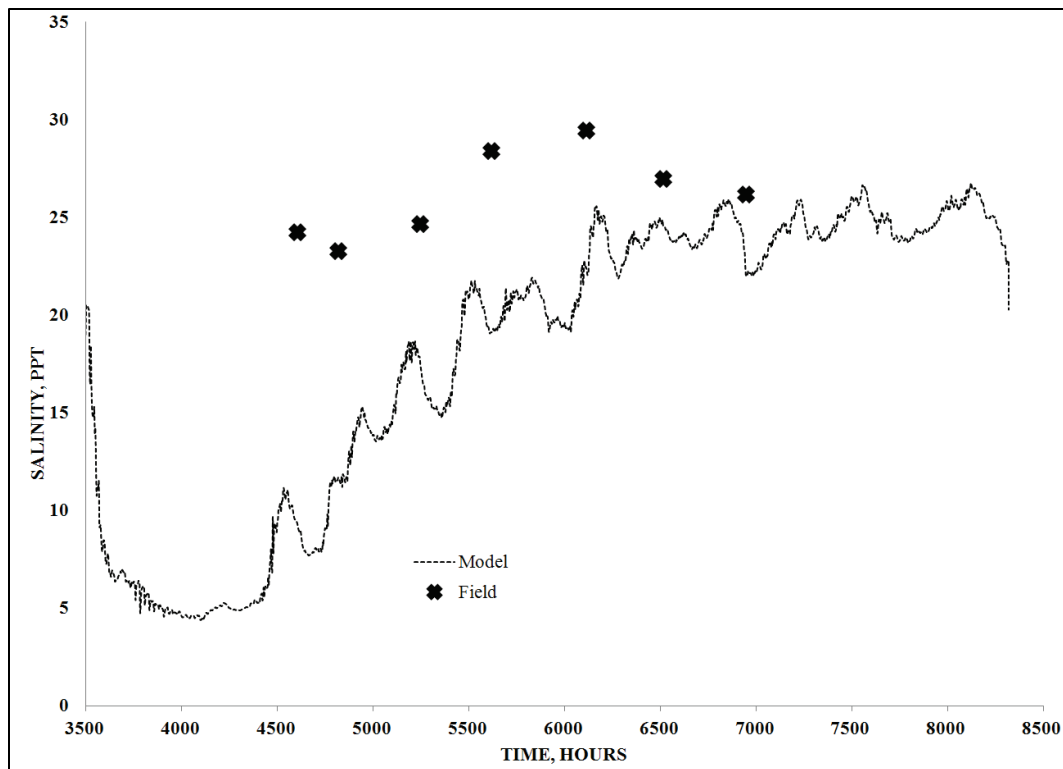


Figure 34. Mid-depth salinity comparison for station S5.5.

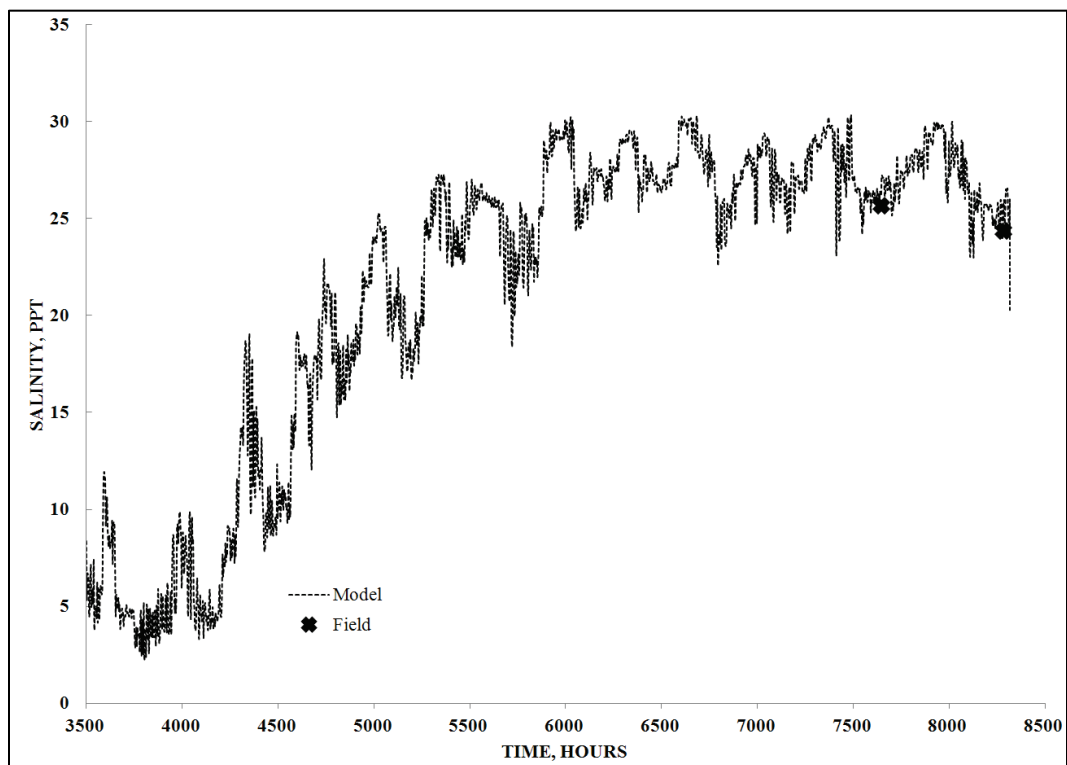


Figure 35. Mid-depth salinity comparison for station S6.

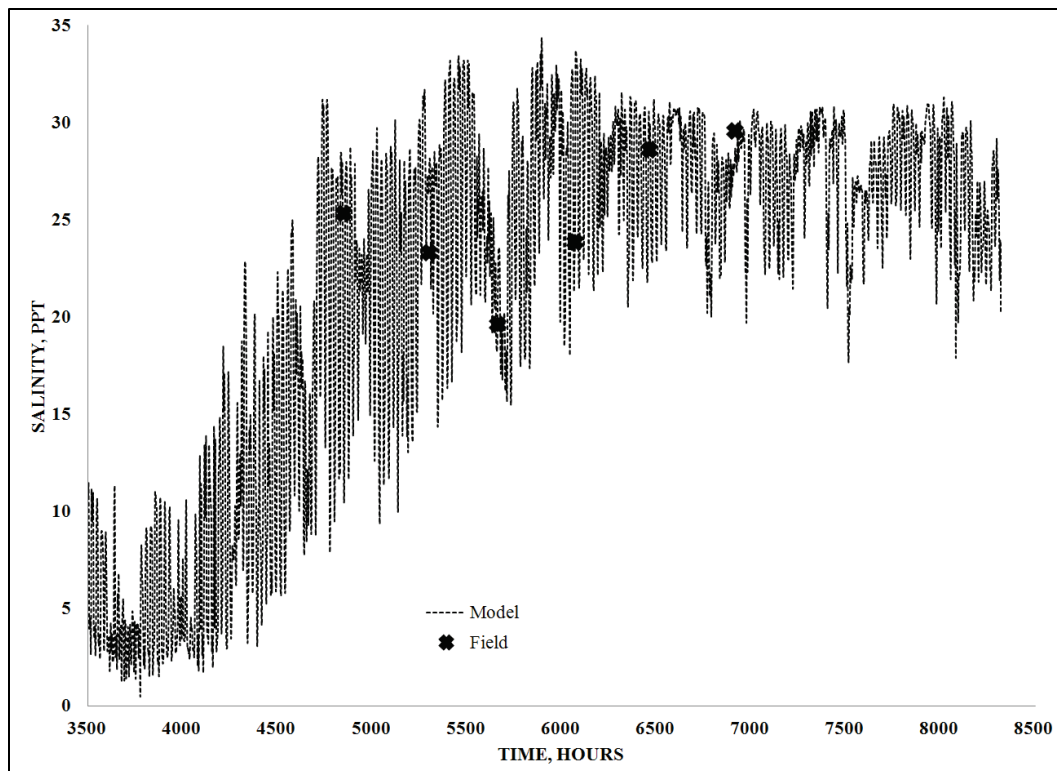


Figure 36. Mid-depth salinity comparison for station S12.

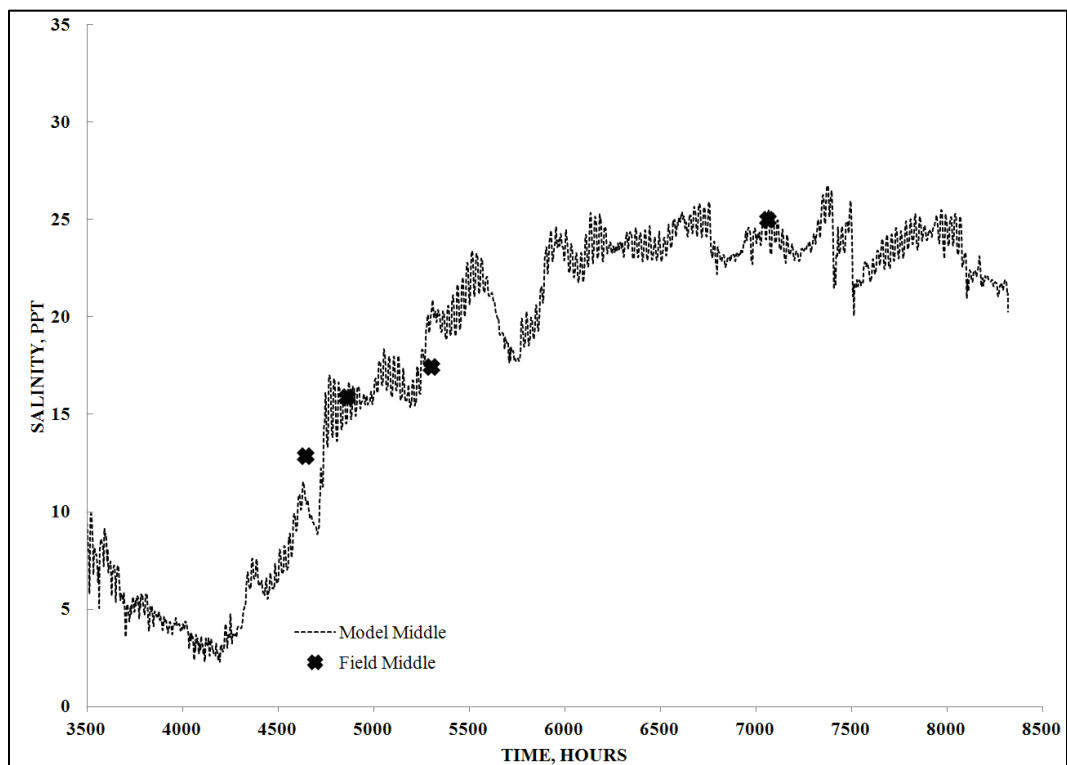


Figure 37. Mid-depth salinity comparison for station S12.1.

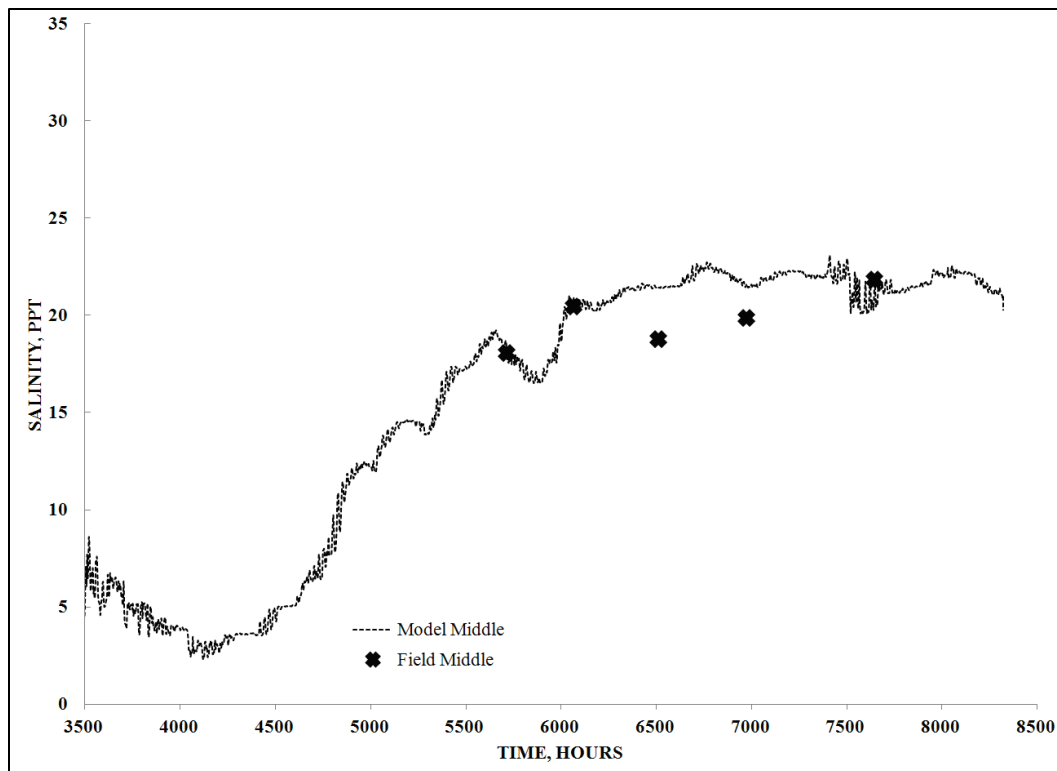


Figure 38. Mid-depth salinity comparison for station S13.

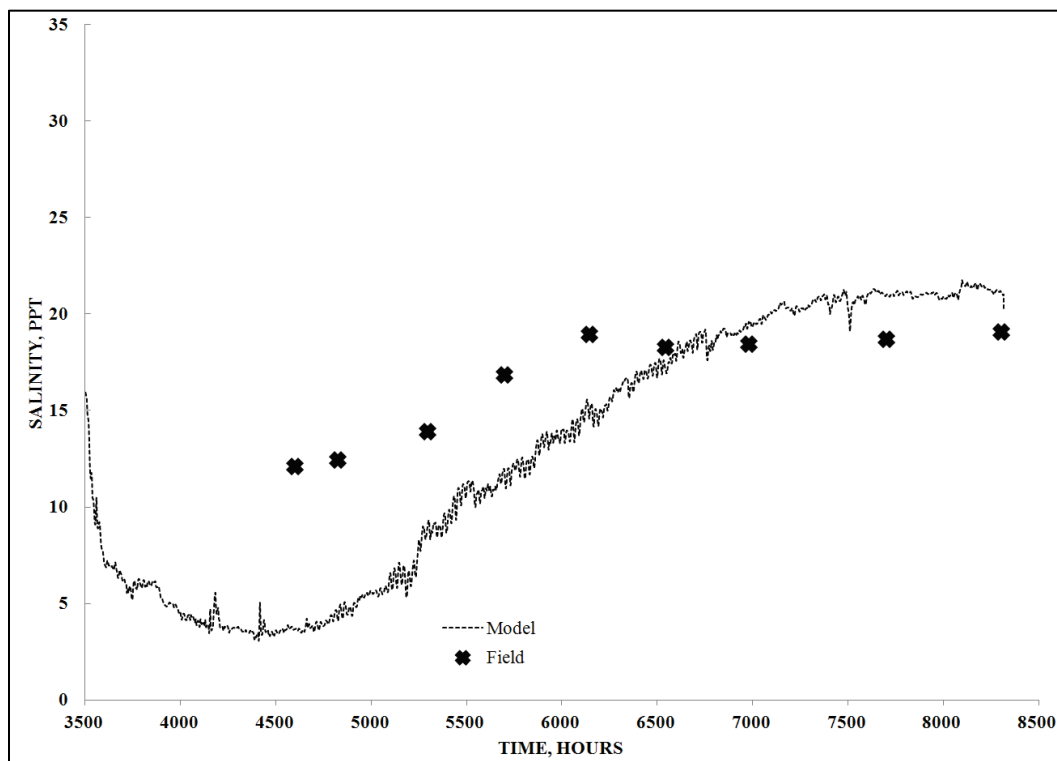
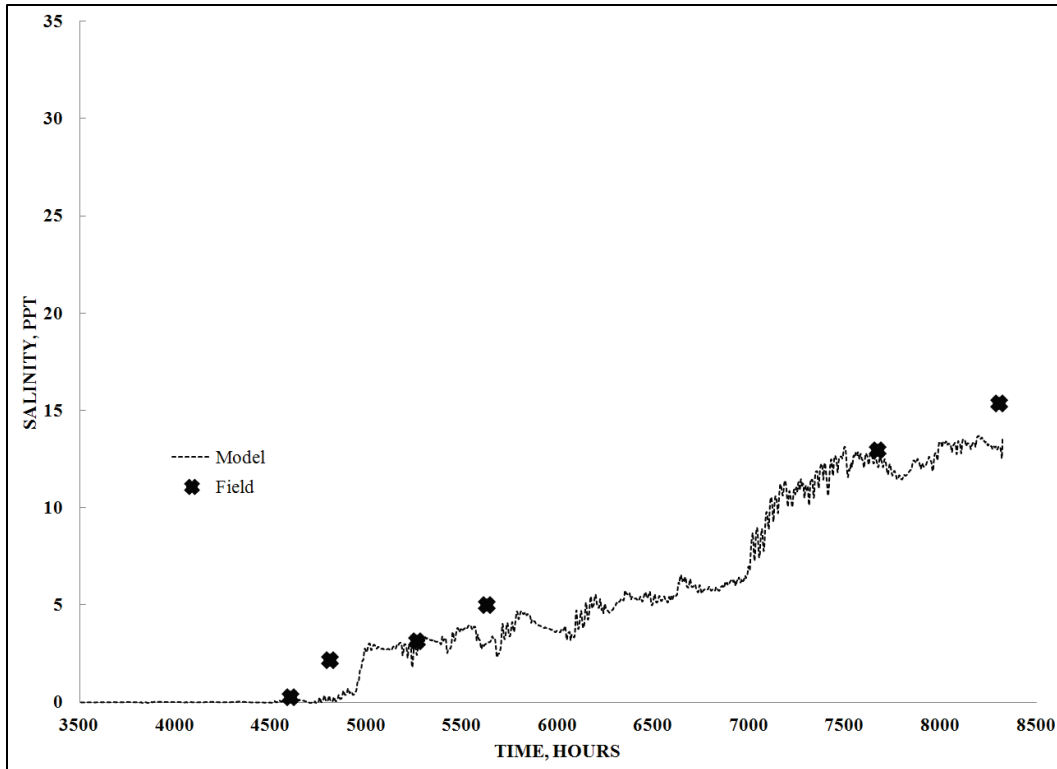


Figure 39. Mid-depth salinity comparison for station S14.



To statistically quantify the skill of the model in replicating the field, a Willmott analysis was performed. The Willmott coefficient is an indication of how well the model represents the trends and any shifts in the field data (Willmott 1982; Willmott et al. 1985) with a value of 1 indicating complete agreement, and a value of zero indicating no agreement. The coefficient d is defined as follows:

$$d = 1 - \left[\frac{\sum (M_i - F_i)^2}{\sum (|M_i'| + |F_i'|)^2} \right], \quad 0 \leq d \leq 1 \quad (1)$$

where:

M_i = the model value at i

F_i = the field value at i

M_i' = the model value at i minus the field average value

F_i' = the field value at i minus the model average value

$d = 1$ = perfect agreement.

Table 2 provides a listing of the Willmott coefficients for the stations analyzed for salinity.

Table 2. Willmott Coefficients for salinity values.

Station	Willmott Coefficient, d
S1	0.83
S2	0.75
S5	0.71
S5.5	0.96
S6	0.87
S12	0.96
S13	0.74
S14	0.98

The d values tabulated above indicate that the model is performing well in reproducing not just the values observed in the field but also the trends in the salinity values observed.

4 Summary and Conclusions

This report describes the validation of the ADH-SW3 model for Galveston Bay. Of particular interest are the navigation channel and the surrounding regions of Galveston Bay. The salinity in the bay impacts the currents through density stratification and density driven currents. The ADH-SW3 model of Galveston Bay was compared to conditions observed in July 1990 to January 1991. This was an extensive data collection effort and was used to validate the previous RMA10-WES model (Berger et al. 1995). This period contained a significant flood event on the Trinity and San Jacinto Rivers as well as the salinity recovery period. These conditions provide a good test for the model validation since it tests the capacity of the model to replicate the hydrodynamic conditions and salinity rebound in the bay. This is an especially challenging aspect to capture unless the model coding and creation have been executed properly.

The ADH-SW3 module demonstrated good comparison to the field observations for the tidal components. The model represented the loss through the entrance and the amplification found in the upper bay (Figures 11–13). The model also represented the conversion from a progressive wave in the lower bay to a standing wave from midbay into the upper bay (Figure 14). A comparison to the RMA10-WES model (Berger et al. 1995) indicates that the ADH-SW3 model better replicates tidal wave behavior.

The comparison to current velocities along the navigation channel is adequate. There are four ranges that extended from the entrance to near Atkinson Island. Each range includes four measurement stations with surface and bottom readings. The model demonstrates the decline in velocity when moving north along the channel. Also, the model compares well in the relative strength of surface and near-bed velocity (Figures 15–30). Velocity results obtained from ADH-SW3 are comparable to those from RMA10-WES model (Berger et al. 1995).

The salinity comparisons were to the hand-collected samples from 1990 at each salinity gage (Figure 31–39). Within the bay proper, the model compares well. The stations showed the rebound from the large flood event and the spatial salinity distribution within the bay. Comparisons are best along the channel and up into Trinity Bay. Generally, ADH-SW3

salinity results are better than those reported in Berger et al. (1995); however, salinity results for West Bay (stations 5 and 5.5) are worse in ADH-SW3. Since the ADH-SW3 results for station 5 are converging to field values as time goes on, it is likely that the initial choice for salinity in West Bay was too far from the actual value in this low-energy, high-residence-time part of the bay.

References

- Berger, R. C., McAdory, R. T., Martin, W. D., and Schmidt, J. H. 1995. *Houston-Galveston navigation channels, Texas project, report 3, three-dimensional hydrodynamic model verification*. Technical Report HL-92-7. Vicksburg, MS: U. S. Army Corps of Engineers, Waterways Experiment Station.
- Cochrane, J. D., and Kelly, F. J. 1986. Low-frequency circulation on the Texas-Louisiana continental shelf. *Journal of Geophysical Research* 91(C9): 10645–10659.
- Fagerburg, T. L., Fisackerly, G. M., Parman, J. W., and Coleman, C. J. 1994. *Houston-Galveston navigation channels, Texas project, report 1, Galveston Bay field investigation*. Technical Report HL-92-7. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station.
- Tate, J. N., Berger, R. C., and Ross, C. A. 2008. *Houston-Galveston navigation channels, Texas project navigation channel sedimentation study, phase 2*. ERDC/CHL TR-08-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Tate, J. N., and Ross, C. A. 2009. *Houston-Galveston navigation channels, Texas project navigation channel sedimentation study, phase 2 plan simulations*. ERDC/CHL TR-09-6. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Willmott, C. J. 1982. Some comments on the evaluation of model performance. *Bulletin of American Meteorological Society* 63(11): 1309–1313.
- Willmott, C. J., Ackelson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., O'Donnell, J., and Rowe, C. M. 1985. Statistics for the evaluation and comparison of models. *Journal of Geophysical Research* 90(C5): 8995–9005.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE April 2015		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) Jan 2012-Oct 2012		
4. TITLE AND SUBTITLE Three Dimensional Shallow Water Adaptive Hydraulics (ADH-SW3) Validation: Galveston Bay Hydrodynamics and Salinity Transport				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Gaurav Savant and R.C. Berger				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Engineer Research and Development Center 3909 Halls Ferry Rd Vicksburg, MS 39180				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CHL TR-15-3		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) ERDC		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution is unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The U.S. Army Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory (CHL) has developed the multi-module Adaptive Hydraulics (ADH) hydrodynamic, sediment, water quality and transport model. As a natural progression of this development process, verification of ADH was performed to known solutions for the basic physics contained in the numerical model. This report documents a validation of the model performed by applying the three-dimensional shallow water module (ADH-SW3) to Galveston Bay and comparing results to field observations. The validation exercise shows good agreement with the field for water surface elevations, velocities, and salinity.						
15. SUBJECT TERMS Adaption ADH		ADH-SW3 Baroclinic Finite Element Modeling			Galveston Bay Three Dimensional Adaptive Validation	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Gaurav Savant	
Unclassified	Unclassified	Unclassified	SAR	40	19b. TELEPHONE NUMBER (Include area code) 601-634-3213	