TxBLEND Model Calibration and Validation for the Trinity-San Jacinto Estuary

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Introduction

Senate Bill 137 (1975), House Bill 2 (1985), Senate Bill 683 (1987), and other legislative directives call for the Texas Water Development Board (TWDB) to maintain a data collection and analytical study program focused on determining freshwater inflow needs which are supportive of economically important and ecologically characteristic fish and shellfish species and the estuarine life upon which they depend. More recent legislative directives, Senate Bill 1 (1997) and Senate Bill 3 (2007), also direct TWDB to provide technical assistance in support of regional water planning and development of environmental flow regime recommendations, which include consideration of coastal ecosystems. In response to these directives, the Bays & Estuaries Program at TWDB has continued to develop and implement TxBLEND, a two-dimensional, depth-averaged hydrodynamic and salinity transport model, to simulate water circulation and salinity condition within the bays. Because TxBLEND produces high-resolution, dynamic simulations of estuarine conditions over long-term periods, the model has been used in a variety of projects including freshwater inflow studies, oil spill response, forecasts of bay conditions, salinity mitigation studies, and environmental impact evaluations.

Presently, TWDB has calibrated TxBLEND models for all seven of the major estuaries in Texas including Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas and Copano Bays, Corpus Christi Bay, and the Laguna Madre. In some cases, TWDB has multi-bay models, such as presented in the TWDB report on *TxBLEND Model Calibration and Validation for the Nueces Estuary* (Schoenbaechler *et al.*, 2011). While TxBLEND continues to be the principal hydrodynamic model used by TWDB for estuary analyses, staff is exploring the use of three-dimensional hydrodynamic models for future efforts.

This report is one in a series which documents the calibration and validation of TxBLEND for the major estuarine systems. This report focuses on the calibration and validation of TxBLEND for the Trinity-San Jacinto Estuary, or Galveston Bay system. The Galveston Bay TxBLEND model was calibrated for velocity, surface elevation, and salinity for the period 1987 - 1996. The model subsequently was validated for salinity for the period 1997 - 2005. Model validation focused on model performance near established long-term monitoring locations. However, additional sites may be validated upon request or as data becomes available. Future updates to model calibration or validation will be documented in later versions of this report.

Study System

The Trinity-San Jacinto Estuary, or Galveston Bay, is located along the upper Texas coast and includes Trinity Bay, East Bay, and West Bay. Major freshwater inflow sources include the Trinity and San Jacinto Rivers, Buffalo Bayou and a number of smaller bayous, such as Oyster Bayou, Double Bayou, Cedar Bayou, Clear Creek, Dickinson Bayou, and Chocolate Bayou. The Trinity River discharges into Trinity Bay on the northeast side of Galveston Bay, while the San Jacinto River discharges into the northwest side of Galveston Bay via the Houston Ship Channel (HSC). The HSC runs north to south through the west side of Galveston Bay. The estuary is directly connected to the Gulf of Mexico via the Entrance Channel at Bolivar Roads, San Luis Pass in West Bay, and Rollover Pass in East Bay.

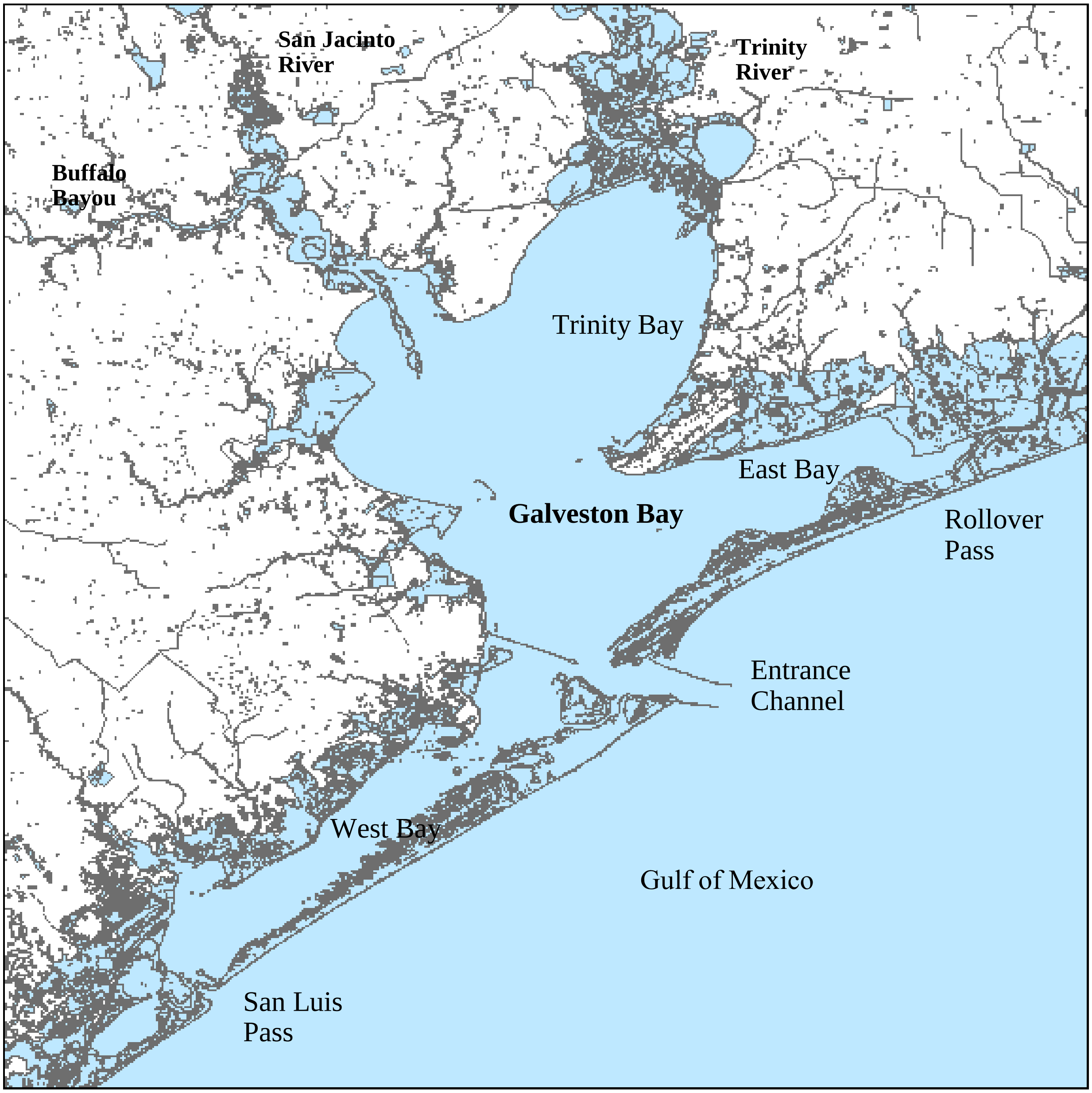


Figure 1. Regional map of the Trinity-San Jacinto Estuary on the Texas coast. Galveston Bay receives freshwater from the Trinity and San Jacinto Rivers and has direct connections with the Gulf of Mexico via the Entrance Channel at Bolivar Roads, at San Luis Pass in West Bay and at Rollover Pass in East Bay.

Model Description

TxBLEND is a computer model designed to simulate water levels, water circulation, and salinity condition in estuaries. The model is based on the finite-element method, employs triangular elements with linear basis functions, and simulates movements in two horizontal dimensions (hence vertically averaged). TxBLEND is an expanded version of the BLEND model developed by William Gray of Notre Dame University to which additional input routines for tides, river inflows, winds, evaporation, and salinity concentrations were added along with other utility routines to facilitate simulation runs specific to TWDB's needs (Gray 1987, TWDB 1999). The current version of TxBLEND being used for model applications is Version S8HH.f (July 20, 2009). Important parameters and features of the model are explained in Table 1.

Water levels and water circulation (velocity) are simulated by solving the generalized wave continuity equation and the momentum equation, often jointly called the *shallow water equations* (TWDB 1999). Salinity transport is simulated by solving a mass transport equation known as the advection-diffusion equation. Several assumptions are inherent to using the shallow water equations to simulate two-dimensional flow in a horizontal plane, specifically:

1. Fluid depth is small relative to the horizontal scale of motion
2. Vertical pressure distribution is hydrostatic
3. Vertical stratification is negligible
4. Fluid density variations are neglected except in the buoyancy term (Boussinesq approximation).

Texas bays are generally very shallow, wide, bodies of water which are relatively un-stratified, thus satisfying the above assumptions.

Model output includes time-varying depth and vertically-averaged horizontal velocity components of flow and salinity throughout the model domain. TxBLEND thus provides water velocity and direction, surface elevation, and salinity at each node in the model grid (see below for details about the model grid for the Trinity-San Jacinto Estuary). The model does not provide information about vertical variation within the water column, but rather provides information about horizontal variation, such as salinity zonation patterns throughout the estuary. The model is run in two or three minute time-steps, typically with hourly output. Model simulations may be run to represent brief periods of time, a week or month, or may be run for years.

Table 1. Description of TxBLEND model parameters, features, and inputs.

Feature	*Description*
Generalized Wave Continuity Equation (GWCE)	A special form of the continuity equation designed to avoid spurious oscillation encountered when solving the primitive continuity equation using the finite element method. Solved by an implicit scheme prior to solving the momentum equation. The GWCE is an established equation used to solve mass-balance or flow continuity in 2-D finite element hydrodynamic models (Kinnmark and Gray 1984).
Momentum Equation	2-D, Depth Integrated Momentum Equation is solved for most applications. Non-linear terms are neglected most of the time.
Advection-Diffusion Equation	Used to calculate salinity transport.
BigG	A parameter in the generalized wave continuity equation. Larger values of BigG reduce mass balance errors by increasing the enforcement of the continuity equation at the price of increased numerical difficulty (TWDB 1999). Typically, set at 0.01 – 0.05.
Manning's n Roughness Coefficient	Used to represent bottom friction stress. For TxBLEND, 0.015 to 0.02 is a reasonable default value, but can be increased to 0.03 or higher for a seabed with thick grasses or debris or lowered to 0.01 or less to represent a smooth bay bottom.
Turbulent Diffusion Term	A diffusion factor, representing horizontal diffusion, used to diffuse momentum as a result of the non-linear term in the momentum equation.
Boundary Conditions	Three types of boundaries form the edge of the model domain. (1) *River Boundary* – portion of river entering the bay; (2) *Tidal Boundary* – the limited portion of Gulf of Mexico included where salinity and tidal boundary conditions are set; and, (3) *Shoreline Boundary* – enclosing boundary of the bay.
Wind Stress	Used to impose the effect of wind on circulation.
Dispersion Coefficient	Uses a modified version of the Harleman's equation which contains a dispersion constant (DIFCON) that can be varied depending on expectations for mixing rates and to better simulate salinity conditions. Due to variable velocities, the dispersion coefficient is updated in 30-minute intervals during simulation. For most applications, constant dispersion coefficients are used.
Coriolis Term	Used to impose the Coriolis Effect on the hydrodynamics
Tide Data	Water surface elevations at the ocean boundary are specified by input tides.
River Inflow Data	Daily river inflows are introduced at identified inflow points. The data are obtained from TWDB Coastal Hydrology estimates based on gaged and ungaged inflows.
Meteorological Data	Includes evaporation, precipitation, wind speed, and wind direction. Wind data may be input as daily average, 3-hour average, or as hourly data. Evaporation data is used to reflect the effect of evaporation on salinity (Masch 1971). Evaporation rate is a modification of the Harbeck equation to estimate daily evaporation from estuaries developed by Brandes and Masch (1972). Precipitation is input as daily values.

TxBLEND Model Domain for the Trinity-San Jacinto Estuary

The TxBLEND computational grid for the Trinity-San Jacinto Estuary contains 5,070 nodes and 8,041 elements (Figure 2). The model grid has nine inflow points which correspond to flows coming from the Trinity and San Jacinto Rivers, Oyster Bayou, Double Bayou, Cedar Bayou, Buffalo Bayou, Clear Creek, Dickinson Bayou, and Chocolate Bayou. Bathymetric information was obtained from the Coastal Relief Model of the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA).

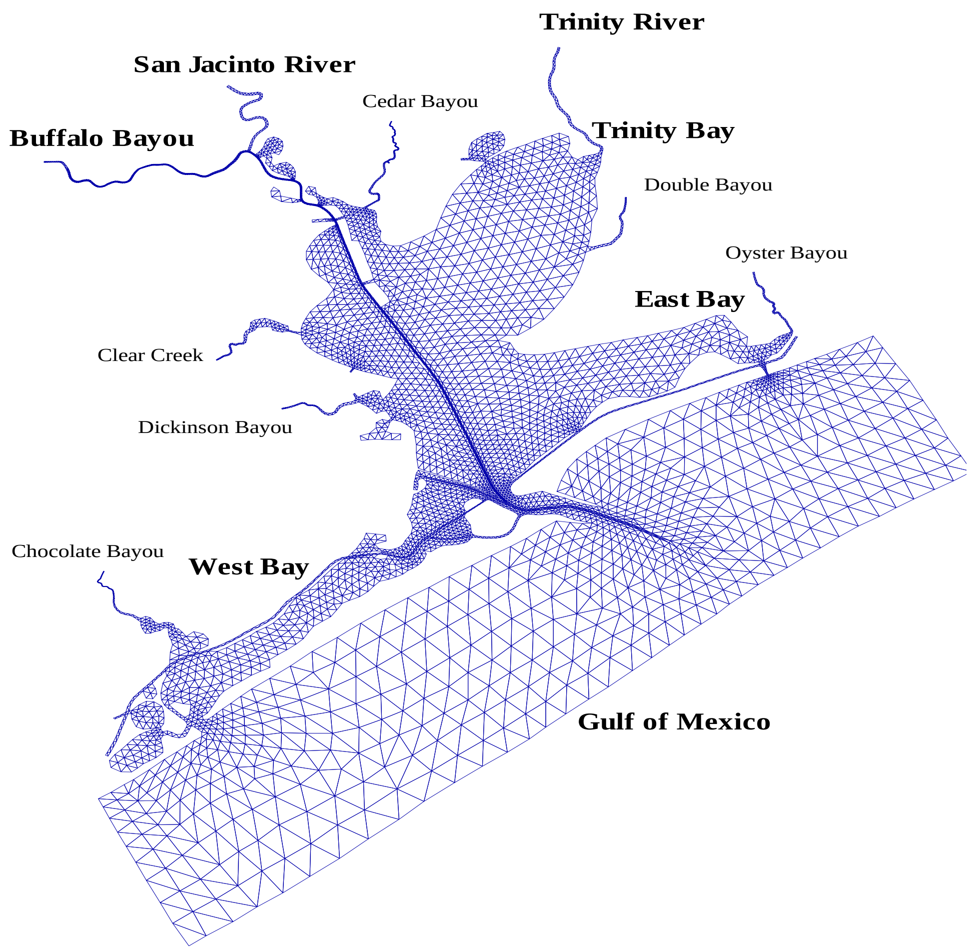


Figure 2. Computational grid and nine inflow points for the Trinity-San Jacinto Estuary TxBLEND model.

Inflows

Daily inflow values were taken from TWDB coastal hydrology dataset version #TWDB201001 for the Trinity-San Jacinto Estuary (Schoenbaechler *et al*., 2012). While these datasets extend back as far as 1941, inflow values were applied only as needed depending on the time period of the model run. Hydrology version #TWDB201001 for the Trinity-San Jacinto Estuary includes estimates for inflows through 2008, though diversion data was updated only through 2005 and return flow data through 2007.

Inflow datasets use measurements from U.S. Geological Survey (USGS) stream gages along with rainfall-runoff estimates from the Texas Rainfall-Runoff (TxRR) model. These flows are adjusted for known diversion and return flows obtained from the Texas Commission on Environmental Quality (TCEQ) and the TWDB Irrigation Water Use estimates to develop daily inflows for the estuaries. Table 2 lists the USGS stream gages used to develop the gaged inflow component of inflows for the nine inflow control points identified in Figure 2. Table 3 lists the distribution of inflows from surrounding gaged and ungaged watersheds that were applied to the inflow control points. Approved USGS stream gage data was available through December 2008. Figure 3 displays the watershed boundaries, including the ungaged watersheds modeled with TxRR, during the period 1941 – 2008 for the Trinity and San Jacinto River inflows. Ungaged flows were estimated using precipitation data from the National Weather Service, which was complete through December 2008. Diversion data was obtained from TCEQ for the period January 1941 – December 2005. Similarly, industrial and municipal return flow data was obtained from TCEQ for the period January 1941 – December 2007. Additional return flow data was obtained from TWDB's agricultural return flow estimates through December 2005. Daily inflows from the surrounding river basins and coastal watersheds were applied to the model at the nine inflow points specified in Figure 2.

Table 2. USGS streamflow gages used to develop freshwater inflow estimates for the Trinity-San Jacinto Estuary.

USGS Gage Station Number	USGS Gage Location	Utilized Period of Record
8067500	Cedar Bayou near Crosby	1987 - 2005
8075000	Brays Bayou at Houston	1987 - 2005
8075500	Sims Bayou at Houston	1987 - 2005
8076000	Greens Bayou near Houston	1987 - 2005
8076500	Halls Bayou at Houston	1987 - 2005
8075770	Hunting Bayou at IH 610	1987 - 2005
8075730	Vince Bayou at Pasadena	1987 - 2005
8074500	Whiteoak Bayou at Houston	1987 - 2005
8073600	Buffalo Bayou at West Belt Drive	1987 - 2005
8077000	Clear Creek near Pearland	1987 - 2005
8078000	Chocolate Bayou near Alvin	1987 - 2005
8066500	Trinity River at Romayor	1987 - 2005
8072000	Lake Houston (reservoir contents gage)	1987 - 2005

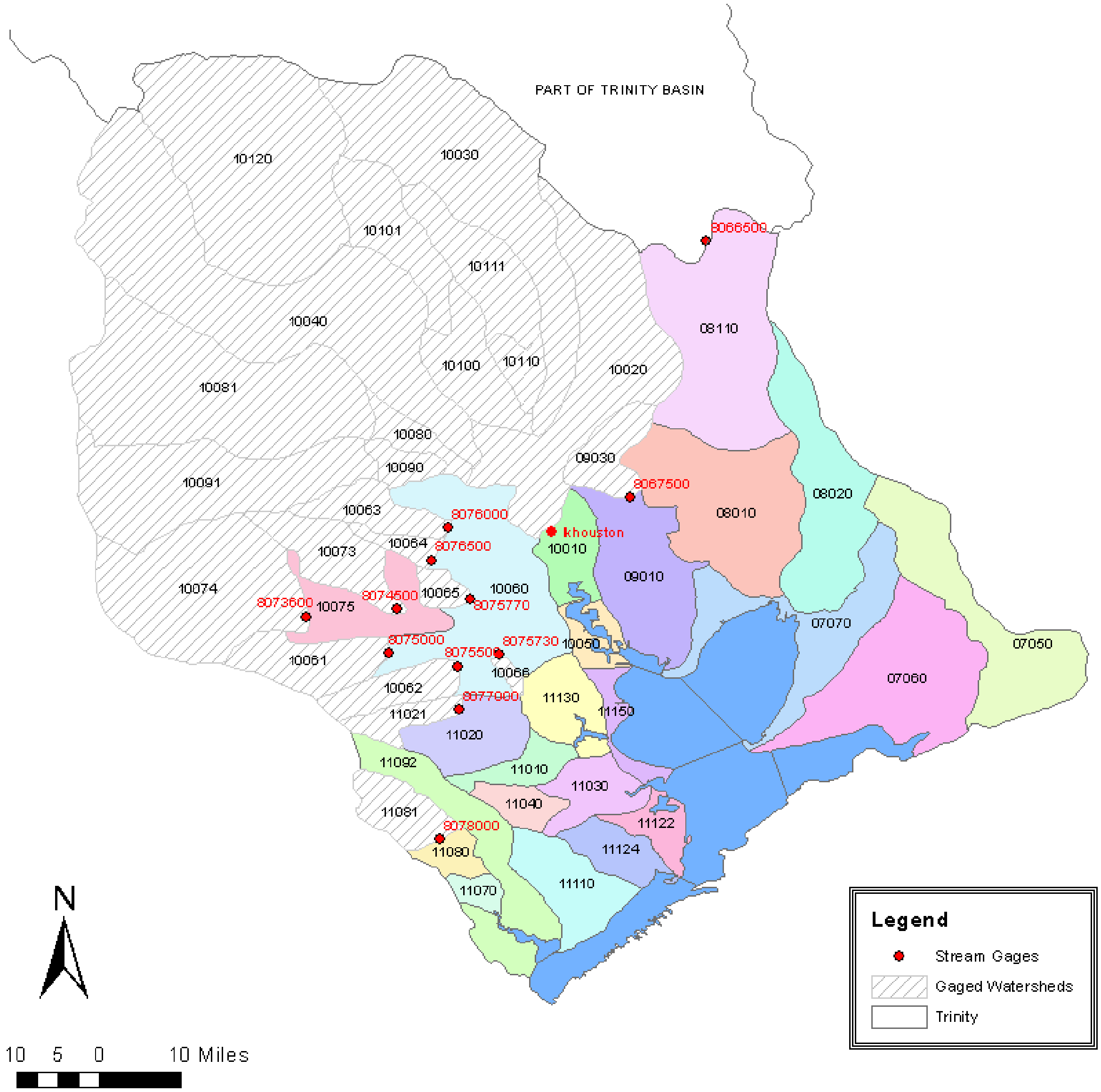


Figure 3. Ungaged watershed delineation used to determine ungaged inflows to the Trinity-San Jacinto Estuary. Gaged watersheds are represented with hatch marks, with associated stream gage locations designated by red circles. Watershed #08020 was not used in the calculation of coastal hydrology estimates from 1987 – 2005 due to a lack of available data.

Table 3. Distribution of inflows from surrounding river basins and coastal watersheds to the nine inflow points of the Trinity-San Jacinto Estuary TxBLEND model (Figure 2). Watersheds with partial contributions are indicated by their percent contribution in parentheses.

Inflow Point for Galveston Bay TxBLEND Model	Gaged Watersheds (USGS Gage #)	Ungaged Watersheds	Returns	Diversions
Trinity River	#8066500 Trinity at Romayor	07070 (25%), 08010, 08110	07070 (25%), 08010, 08110, 24220	07070 (25%), 08010, 08110
San Jacinto River	#8072000 Lake Houston	10010, 10050	10010, 10050	
Oyster Bayou	None	07050, 07060	07050, 07060, 24235	07050, 07060
Double Bayou	None	07070 (75%)	07070 (75%)	07070 (75%)
Cedar Bayou	09030 (#8067500)	09010, 09030	09010	09010
Buffalo Bayou	10063 (#8076000), 10064 (#8076500) 10074 (#8073600), 10073 (#8074500) 10065 (#8075770), 10061 (#8075000) 10062 (#8075500), 10066 (#8075730)	10060, 10062, 10064, 10075	10060,10075	10060, 10075
Clear Creek	11021 (#8077000)	11010, 11020, 11021, 11130, 11150 (50%)	11010, 11020, 11130, 11150 (50%), 24210, 24250	None
Dickinson Bayou	None	11030, 11040, 11150 (50%)	11030, 11040, 11150(50%), 24390 (25%)	None
Chocolate Bayou	11081 (#8078000)	11070, 11080, 11092, 11110	11070, 11080, 11092, 11110, 24240	11080, 11092, 11110

Tides

Tidal elevations at Pleasure Pier in Galveston Bay were obtained from the Texas Coastal Ocean Observation Network (TCOON; http://lighthouse.tamucc.edu/TCOON/HomePage) and applied at the Gulf open boundary for the model period (1987 – 2005).

Meteorology

Time-varying and spatially uniform meteorology data was used to drive the model, including wind field, air temperature, precipitation, and evaporation. A large portion of the meteorology data (wind speed and direction and air temperature) used to drive the model was obtained from the National Climatic Data Center (NCDC). Wind data was obtained for Galveston for the period of 1987 - 1997 from the NCDC and for 1998 - 2005 from TCOON. Evaporation data for Galveston was calculated based on the Harbeck Equation (Brandes and Masch 1972) using temperature data from the NCDC (Scholes International Airport in Galveston) for the period from 1987 - 2005. Precipitation data used for model calibration and validation simulations was obtained from the National Weather Service (NWS) and subsequently was processed to provide an estimate of precipitation across the Trinity-San Jacinto estuary. TWDB archived records of this data provided precipitation for the period of 1987 - 2005.

Model Calibration

The TxBLEND model was calibrated for both hydrodynamic performance, by using water velocity and surface elevation data from intensive field studies, and salinity transport performance, by using long-term time-series salinity data. Model calibration efforts focused on improving model performance by adjusting parameters such as the dispersion coefficient and Manning's *n*.

Velocity

For the calibration of this TxBLEND model, four intensive inflow data sets were available. Velocity measurements were collected by TWDB in Galveston Bay during an intensive inflow study at eight sites from May 7 - 10, 1989. The Army Corps of Engineers conducted an intensive inflow study in July 1990, and their data also was used as an independent data set for calibration. TWDB conducted additional intensive inflow studies at four sites from May 23 - 24, 2001 and two sites from July 18 - 19, 2001. At most locations, velocity was measured at three depths, $2/10^{th}$, $5/10^{th}$, and $8/10^{th}$ from the water surface. Some of these sites are shown in Figure 4.

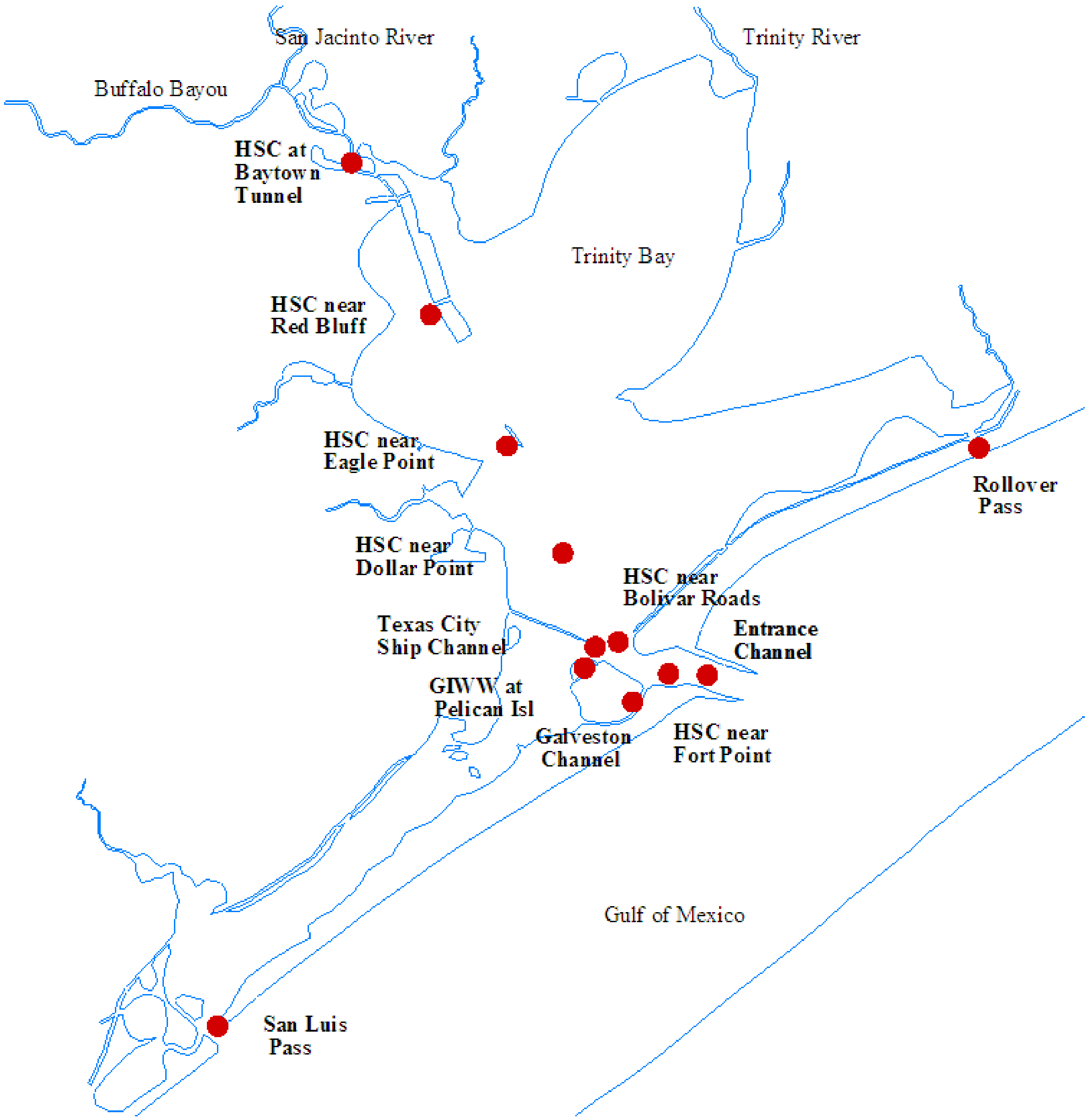


Figure 4. Velocity measurement sites during intensive inflow studies in Galveston Bay.

Water Surface Elevation

Tidal elevations were obtained from TCOON at a total of eight sites (Pleasure Pier, Pier 21, Eagle Point, Morgan's Point, Clear Lake, Lynchburg, Anahuac, Alligator Point) over three years in the Trinity-San Jacinto Estuary to be used for model calibration (Figure 5). Simulated and observed tides were compared at four sites in 1993, four sites in 1994, eight sites in 1995, and eight sites in 1996.

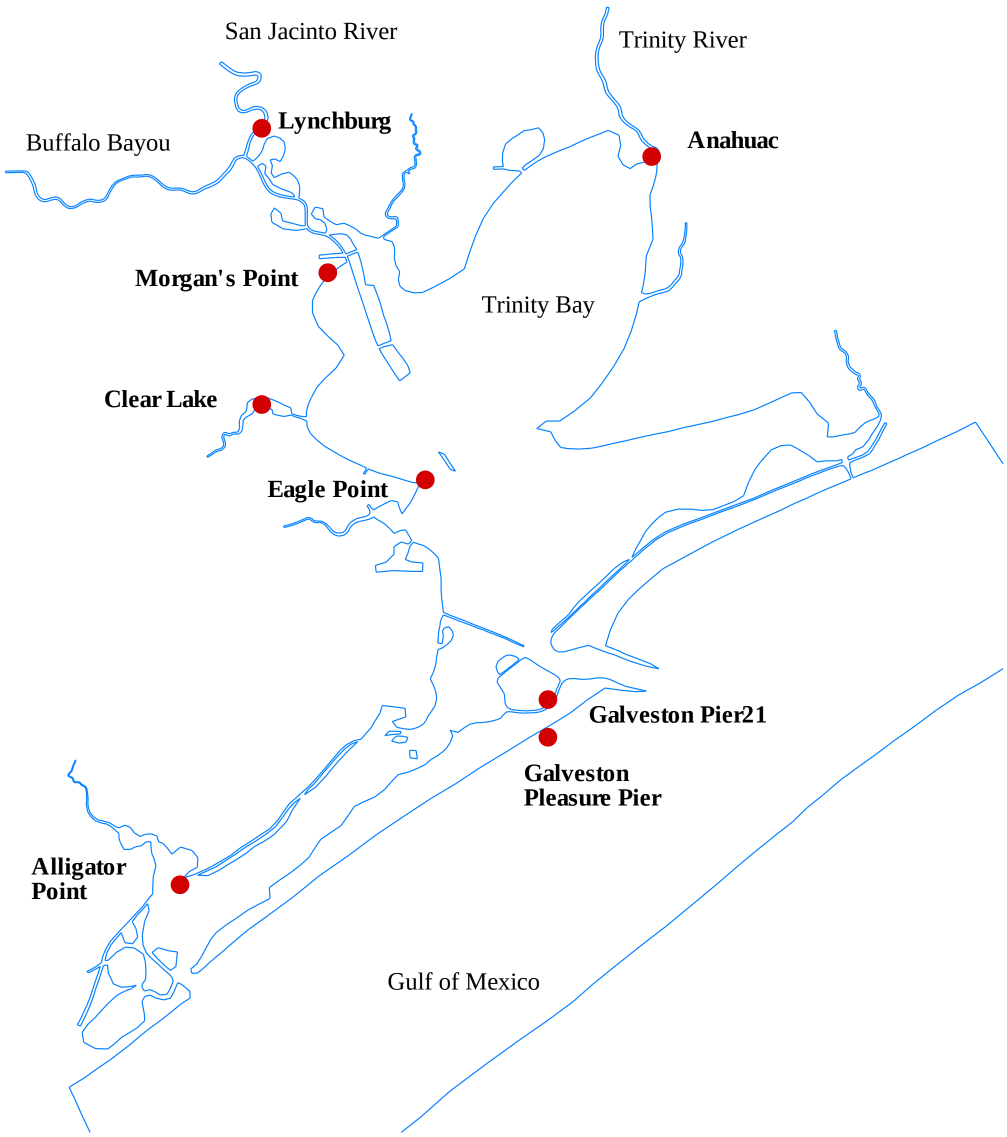


Figure 5. Eight tide gaging stations used to calibrate the Trinity-San Jacinto TxBLEND model for water surface elevation. Gaging stations are maintained by the Texas Coastal Ocean Observation Network (TCOON).

Salinity

Salinity initial conditions were determined by setting the river inflow points at 0 parts per thousand (ppt) salinity and by using time-varying salinity boundary conditions obtained from the Texas Parks & Wildlife Department (TPWD) Coastal Fisheries database to specify salinity at the Gulf boundary off Galveston Bay. Long-term salinity records collected for the TWDB Datasonde Program by the TPWD at hourly or more frequent intervals provided important data for calibrating and validating the TxBLEND model. Model runs allowed for a several month ramp-up period, prior to running simulations for model calibration or validation, to allow the model to distribute salinity appropriately. Within-bay salinity data from the Datasonde Program was used for model calibration at four long-term monitoring sites (Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads) for the period 1987 – 1996 (Figure 6).

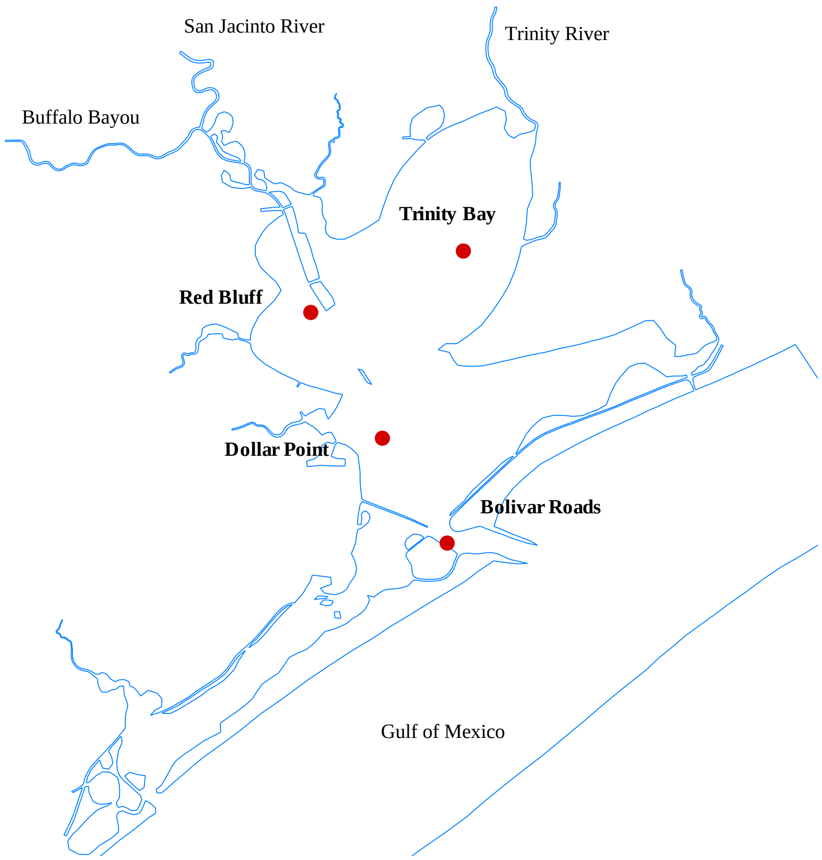


Figure 6. Four long-term monitoring stations which provided time-series salinity data for use in model calibration and validation.

Model Calibration Parameters

Model parameters adjusted during the calibration of the TxBLEND model included BigG, the dispersion coefficient, and Manning’s *n*. BigG is a non-physical parameter which ensures mass conservation and was set to 0.03. Another important parameter for hydrodynamic calibration is Manning's *n*, which represents bottom roughness where larger values of *n* slow water movement and smaller values increase water movement. Values used in the calibrated model are shown in Figure 7. Similarly, the dispersion coefficient, which represents physical mixing processes, is the key parameter for salinity calibration. The larger the dispersion coefficient, the more effectively dissolved salt disperses. Figure 8 shows the values for the dispersion coefficients used in the model. Larger values were assigned to the Gulf and major ship channels, and smaller values were assigned to shallow bays.

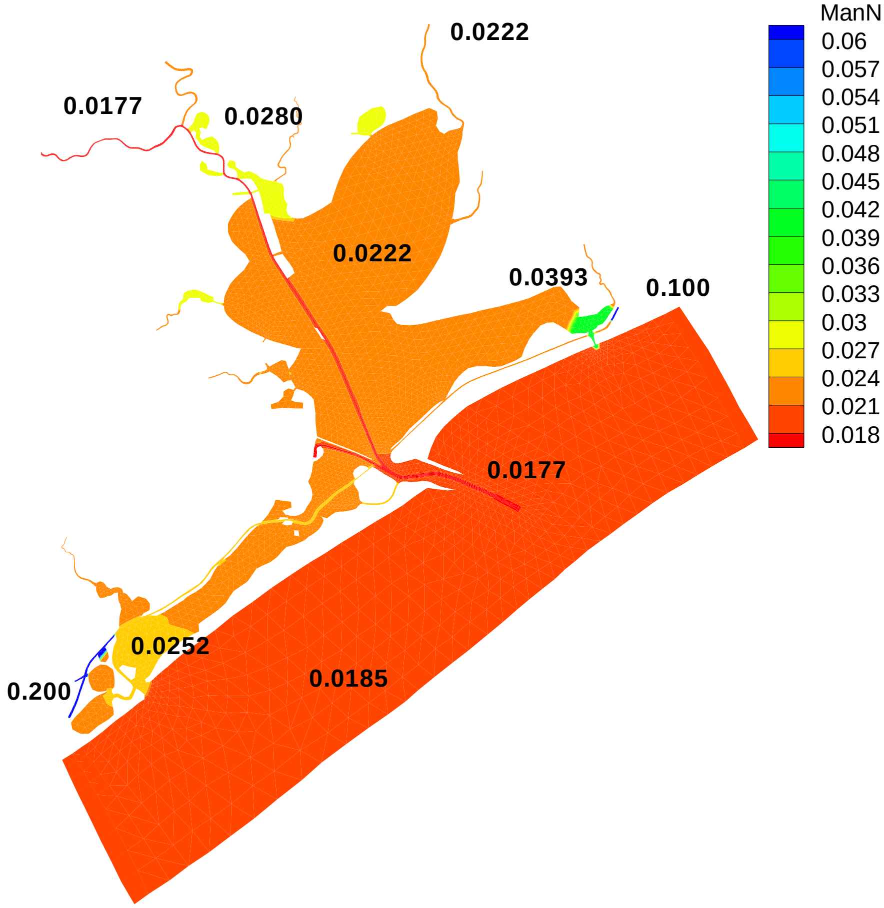


Figure 7. Values of Manning’s *n* (bottom roughness coefficient) used in the calibrated TxBLEND model for Galveston Bay.

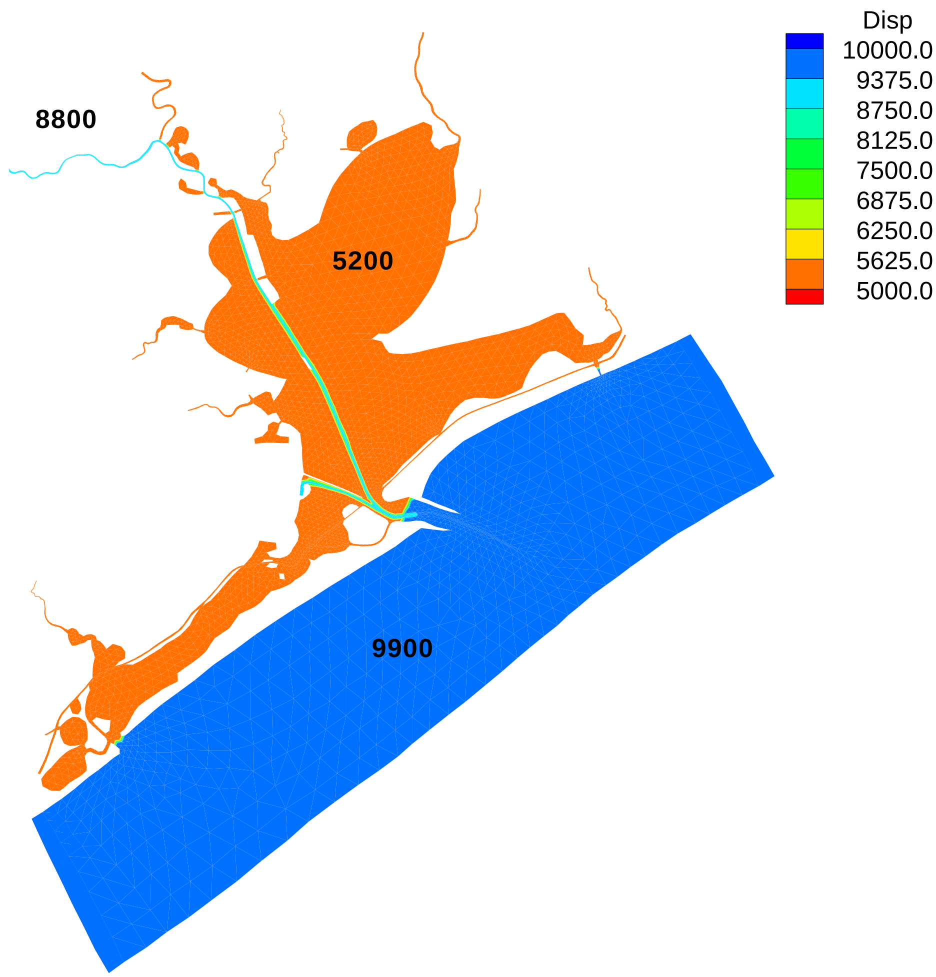


Figure 8. Values of the dispersion factor (ft^2/sec) used in the calibrated TxBLEND model for Galveston Bay. The Gulf region was set to 9,900 ft^2/sec.

Calibration Results

Calibration results for velocity, surface elevation, and salinity for the Trinity-San Jacinto TxBLEND model are presented below.

Velocity Results

TxBLEND was calibrated for water velocity using data obtained from four intensive inflow studies that were conducted during May 7 - 10, 1989, July 1990 (measured by Army Corps of Engineers), May 23 - 24, 2001, and July 18 - 19, 2001 (refer to Figure 4 for sampling locations). Calibration results are presented in a series of plots showing simulated velocities as compared to observed field measurements for a number of locations throughout the system (Figures 9 - 13). The depth-averaged horizontal velocity output from the model is displayed against measured velocity profiles at three depths, or at mid-depth if only one measurement is available. Table 4 lists summary statistics for observed and simulated velocities.

Figures 9 and 10 display calibration results at eight locations as compared to observed velocities measured during the intensive inflow study from May 7 - 10, 1989. Simulated velocities were generally representative of observed velocities at all sites, although the model either over- or under-predicted velocity in some instances. For example, the model slightly under-predicted maximum velocity at the Texas City Dike near the Houston Ship Channel (r^2 ranged from 0.61 to 0.66), but over-predicted maximum velocity at Rollover Pass (r^2 ranged from 0.43 to 0.46). The model captured general patterns of swift tidal currents in the Galveston Bay Entrance Channel (r^2 ranged from 0.65 to 0.74), Bolivar Roads (r^2 ranged from 0.70 to 0.72), and San Luis Pass (r^2 ranged from 0.0.51 to 0.52). Figure 11 displays calibration results for velocity at four locations during the intensive inflow study of July 1990. The model adequately captured swift tidal currents in the Houston Ship Channel near Fort Point (r^2 = 0.89) and the Texas City Dike (r^2 ranged from 0.90 to 0.92), as well as reduced currents near Dollar Point (r^2 = 0.83) and Clear Lake (r^2 = 0.56). Good model performance was observed at the Houston Ship Channel near Fort Point and the Texas City Dike sites, as indicated by high Nash-Sutcliffe Efficiency Criterion values ranging from 0.85 to 0.91, where values equal to one represents a match between model output and observed data and values less than zero suggests that the model is a poor predictor. Figure 12 shows calibration results for velocity at four locations during an intensive inflow study from May 23 - 24, 2001. The model performed well at the Houston Ship Channel near Bolivar Roads (r^2 ranged from 0.78 to 0.90) and near Texas City (r^2 ranged from 0.62 to 0.81), but was less representative at the Galveston (r^2 ranged from 0.47 to 0.70) and Texas City Ship Channel sites (r^2 ranged from 0.01 to 0.11). Figure 13 displays results for velocity at two more locations in the Houston Ship Channel during an intensive inflow study from July 18 - 19, 2001. Generally, the model under-predicted velocity at both of those locations (r^2 ranged from 0.01 to 0.55 for both sites); however, there was little observed data available for comparison at one of the sites (HSC near Eagle Point, n = 13).

Table 4. Comparison statistics for observed and simulated velocities during the 1989, 1990, and 2001 intensive inflow studies.

Site	**Velocity Depth**[†]	**n**	**r^2**	**RMS**[*]	**NSEC**[**]
	May 1989				
Entrance Channel	Vel-8/10	71	0.69	1.28	0.67
	Vel-5/10	70	0.74	1.27	0.68
	Vel-2/10	70	0.65	1.71	0.40
Bolivar Roads	Vel-8/10	64	0.72	0.96	0.68
	Vel-5/10	64	0.73	1.09	0.58
	Vel-2/10	64	0.70	1.26	0.44
Galveston Channel	Vel-8/10	70	0.45	0.85	0.38
	Vel-5/10	70	0.54	0.80	0.45
	Vel-2/10	70	0.58	0.76	0.51
Texas City Dike side near HSC	Vel-8/10	49	0.61	1.30	0.56
	Vel-5/10	49	0.65	1.30	0.56
	Vel-2/10	49	0.66	1.35	0.53
HSC near Eagle Point	Vel-8/10	33	0.36	0.64	-0.44
	Vel-5/10	33	0.38	0.72	-0.82
	Vel-2/10	33	0.34	0.80	-1.23
HSC at Baytown Tunnel	Vel-8/10	65	0.40	0.49	-0.18
	Vel-5/10	65	0.47	0.44	0.05
	Vel-2/10	65	0.49	0.45	0.01
Rollover Pass	Vel-8/10	72	0.43	1.18	0.40
	Vel-5/10	72	0.46	1.14	0.43
	Vel-2/10	72	0.46	1.18	0.40
San Luis Pass	Vel-8/10	71	0.52	1.38	0.45
	Vel-5/10	71	0.52	1.50	0.36
	Vel-2/10	71	0.51	1.57	0.29
	July 1990				
HSC near Fort Point	Vel-2/10	21	0.89	1.17	0.85
	Vel-5/10	21	0.88	1.11	0.86
	Vel-8/10	21	0.89	1.03	0.88
HSC near Texas City Dike	Vel-2/10	25	0.91	0.94	0.89
	Vel-5/10	25	0.90	0.92	0.90
	Vel-8/10	25	0.92	0.89	0.91
HSC near Dollar Point	Vel-2/10	26	0.83	0.51	0.71
HSC near Clear Lake	Vel-2/10	24	0.56	0.33	0.45

Site	Velocity Depth†	n	r^2	RMS*	NSEC**
May 2001					
HSC near Bolivar Roads	Vel-2/10	26	0.90	1.53	0.17
	Vel-5/10	26	0.89	1.22	0.47
	Vel-8/10	26	0.78	1.47	0.23
HSC near Texas City	Vel-2/10	20	0.62	1.46	0.59
	Vel-5/10	20	0.84	0.92	0.84
	Vel-8/10	20	0.81	1.10	0.77
Galveston Channel	Vel-2/10	23	0.47	1.72	-3.32
	Vel-5/10	23	0.63	1.83	-3.88
	Vel-8/10	23	0.70	1.78	-3.61
Texas City Ship Channel	Vel-2/10	20	0.10	0.82	-5.53
	Vel-5/10	20	0.01	1.11	-11.04
	Vel-8/10	20	0.11	1.19	-12.92
July 2001					
HSC near Eagle Point	Vel-2/10	13	0.31	1.16	-0.26
	Vel-5/10	13	0.27	1.74	-1.84
	Vel-8/10	13	0.55	2.08	-3.03
HSC near Redbluff	Vel-2/10	19	0.07	0.37	-1.37
	Vel-5/10	19	0.01	1.29	-27.27
	Vel-8/10	19	0.09	1.76	-51.38

†Velocity Depths: Vel-2/10 is the velocity measurement near the surface, Vel-5/10 is the velocity measurement at mid-depth, and Vel-8/10 is a measurement near the bottom.
*RMS is the root mean square.
**NSEC is the Nash-Sutcliffe Efficiency Criterion (E) and describes model performance, where E = 1.0 represents a match between model output and observed data, and E < 0 suggests the model is a poor predictor.

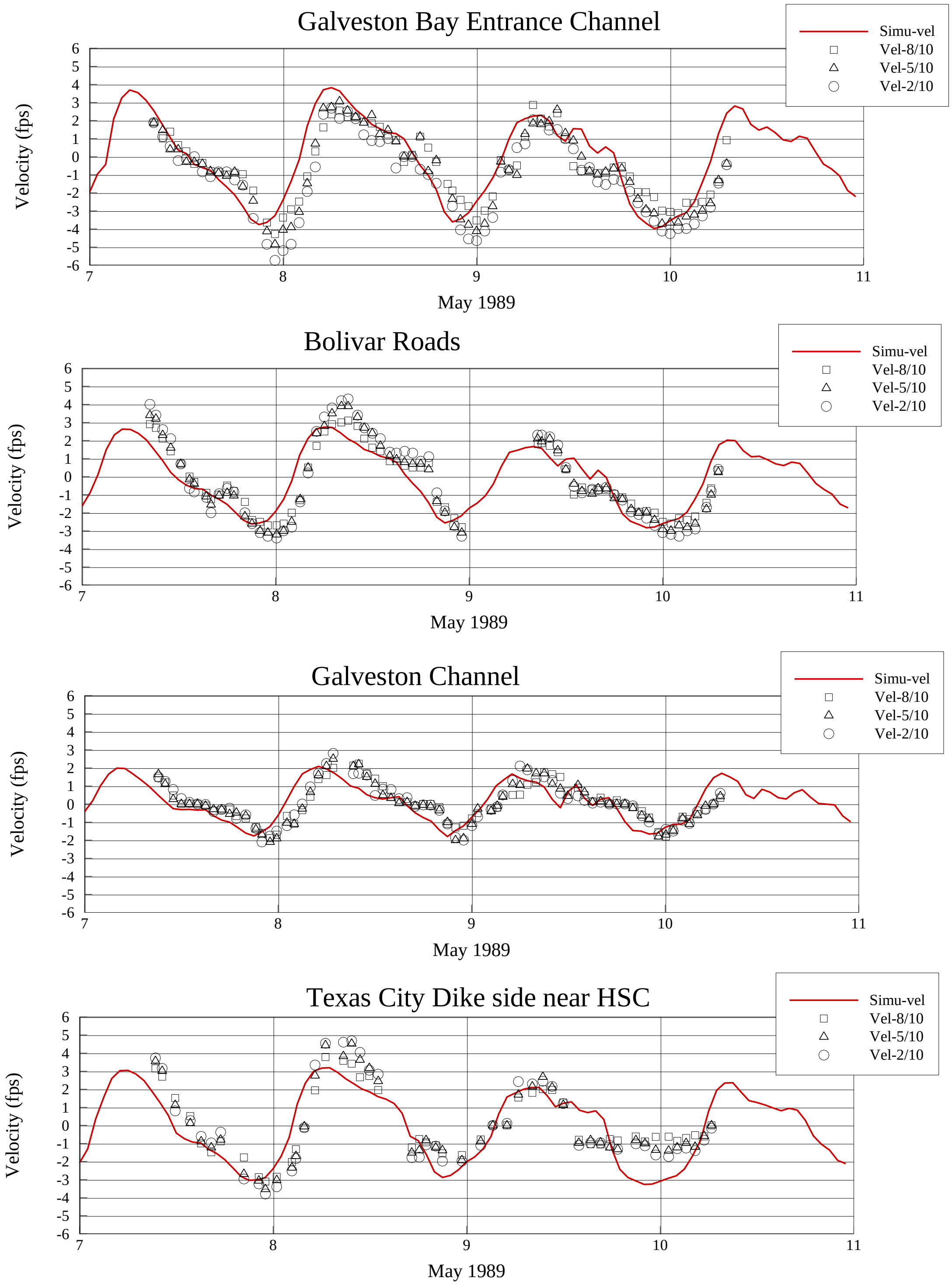


Figure 9. Simulated (*red line*) and observed (*open symbols*) velocities for the following sites from top to bottom: Galveston Bay Entrance Channel, Bolivar Roads, Galveston Channel, and Texas City Dike near Houston Ship Channel for May 7-10, 1989 in Galveston Bay.

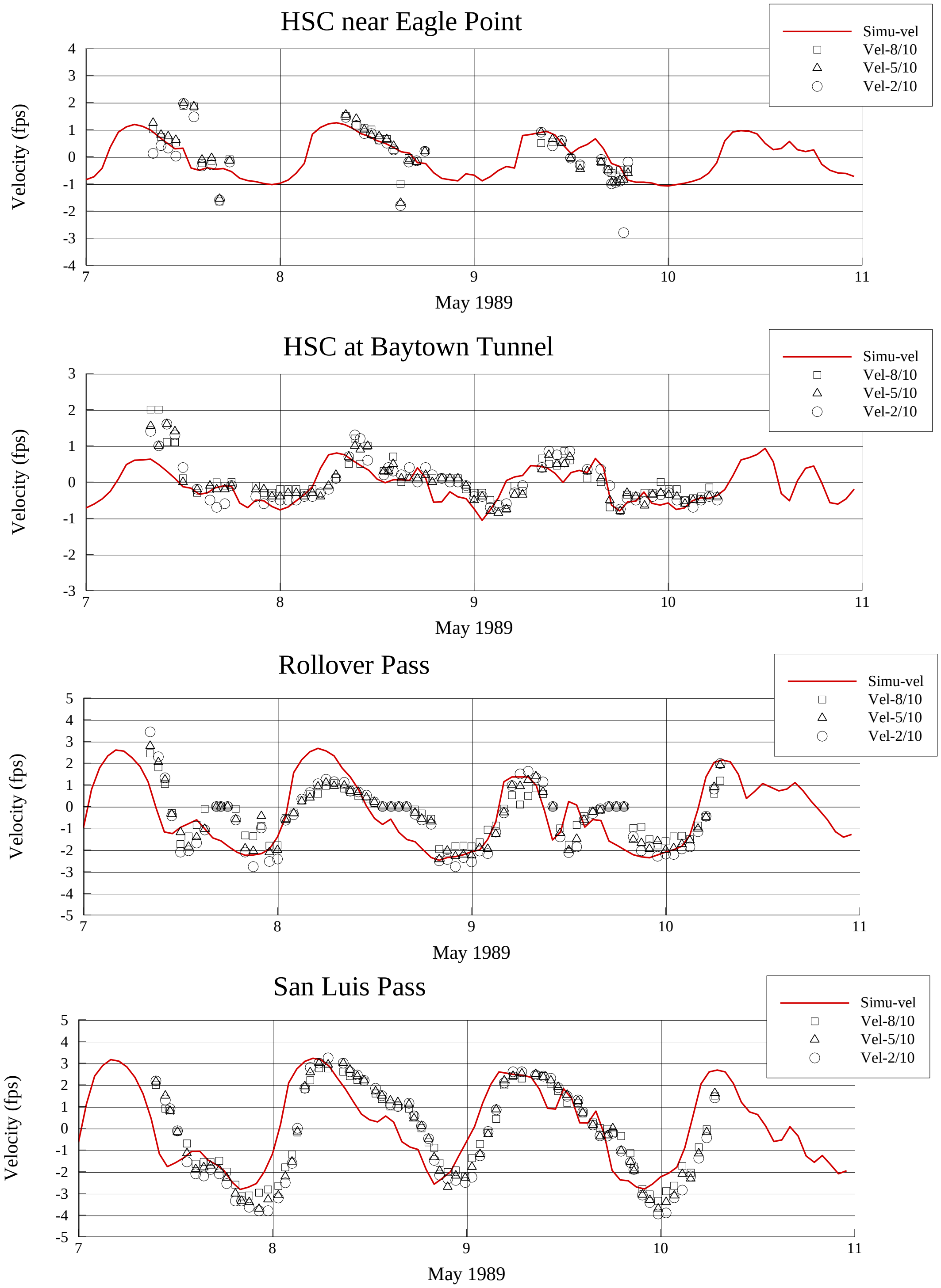


Figure 10. Simulated (*red line*) and observed (*open symbols*) velocities for the following sites from top to bottom: Houston Ship Channel near Eagle Point, Houston Ship Channel at Baytown Tunnel, Rollover Pass, and San Luis Pass for May 7-10, 1989 in Galveston Bay.

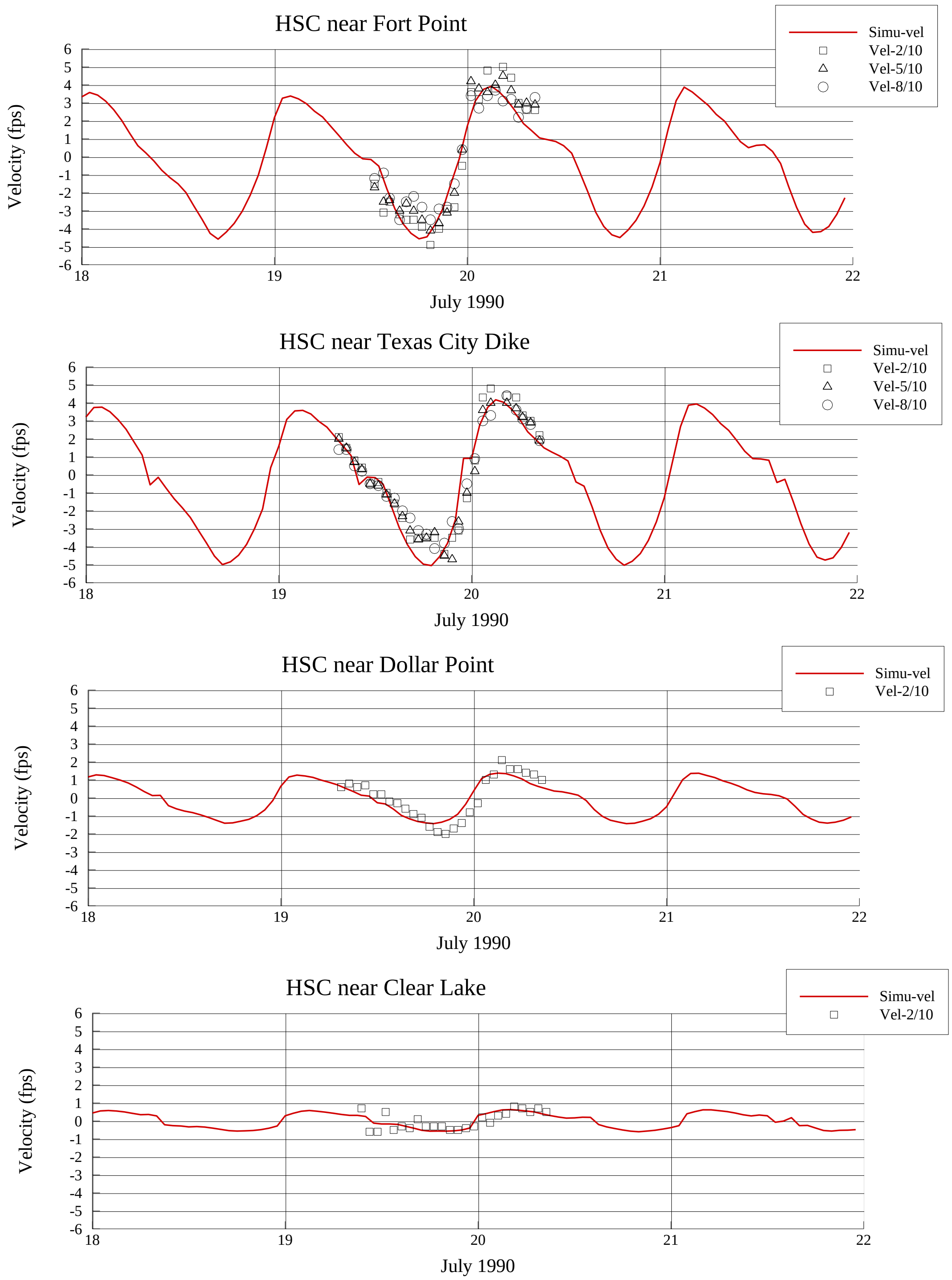


Figure 11. Simulated (*red line*) and observed (*open symbols*) velocities for the following sites from top to bottom: Houston Ship Channel near Fort Point, Houston Ship Channel near Texas City Dike, Houston Ship Channel near Dollar Point, and Houston Ship Channel near Clear Lake that were measured by the Army Corps of Engineers during July 1990 in Galveston Bay.

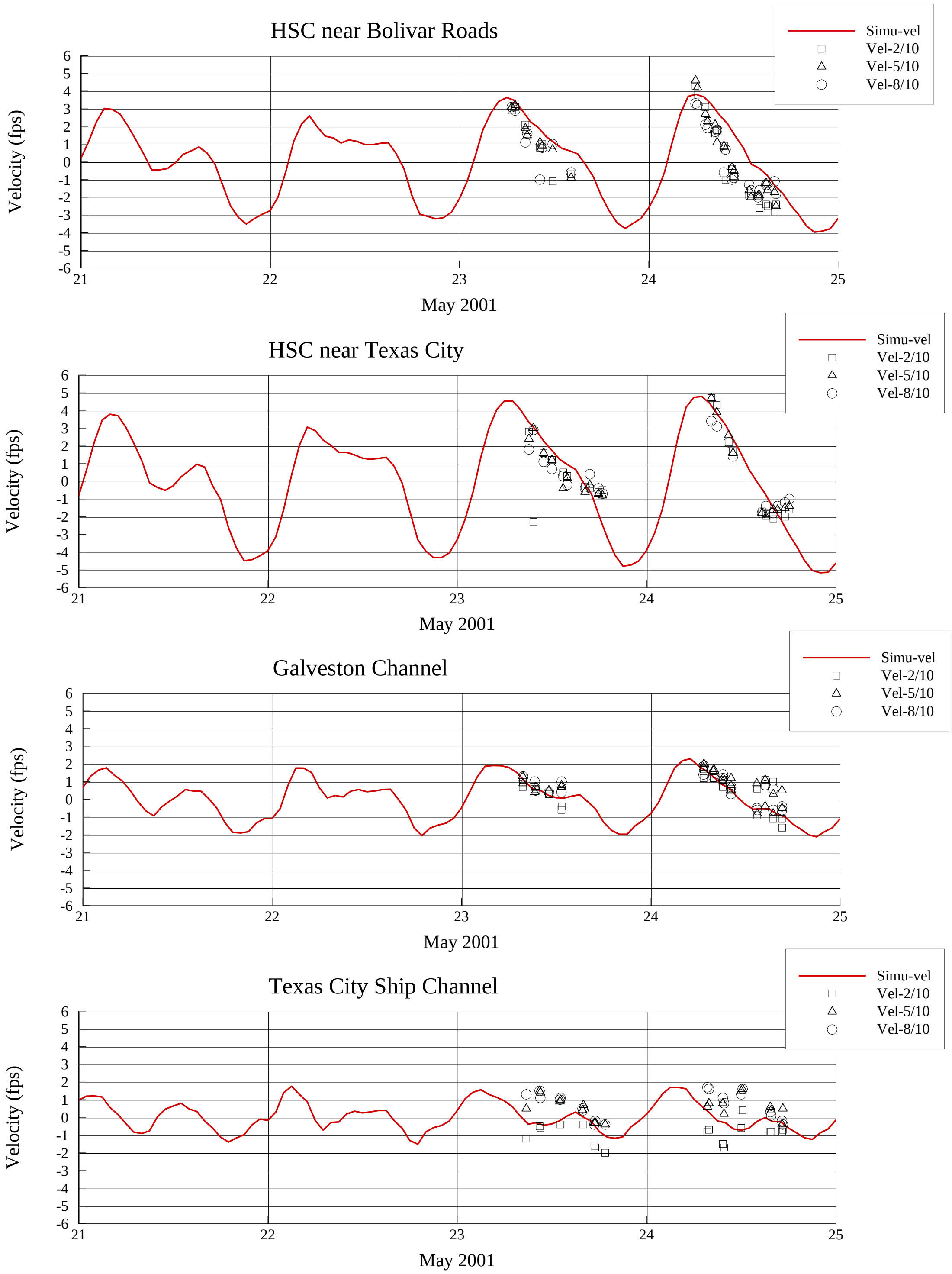
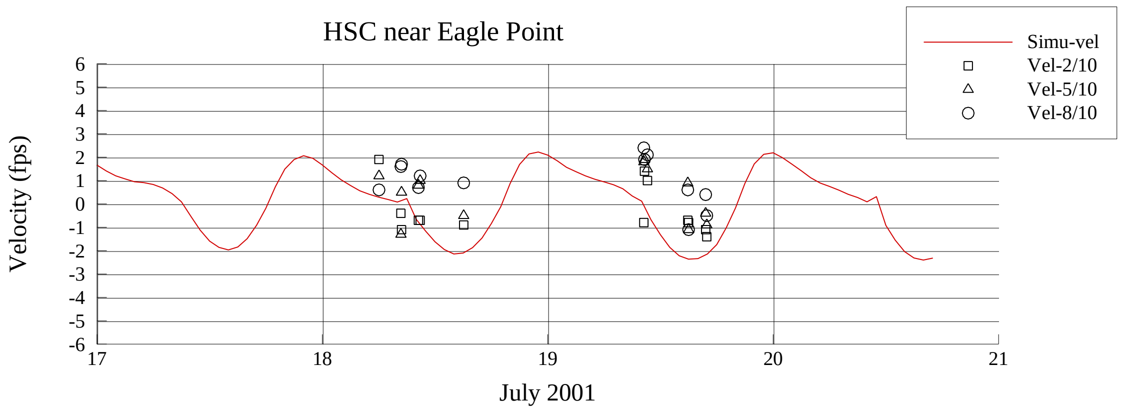


Figure 12. Simulated (*red line*) and observed (*open symbols*) velocities for the following sites from top to bottom: Houston Ship Channel near Bolivar Roads, Houston Ship Channel near Texas City, Galveston Channel, and Texas City Ship Channel for May 23-24, 2001 in Galveston Bay.



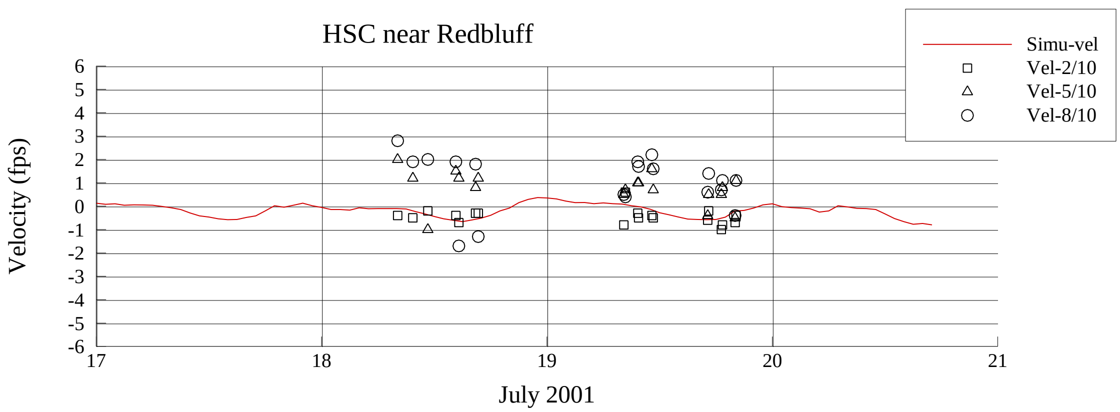


Figure 13. Simulated (*red line*) and observed (*open symbols*) velocities for the Houston Ship Channel near Eagle Point and the Houston Ship Channel near Red Bluff for July 18-19, 2001 in Galveston Bay.

Water Surface Elevation Results

Tidal comparisons were made at eight locations from 1993 – 1996 (refer to Figure 5). Table 5 displays the simulated and observed hourly tide comparison statistics, and Table 6 displays the statistics of daily tides for 1993 - 1996. High r^2 values ranging from 0.63 to 0.99 for hourly tides at all locations indicate good model performance. Additionally, high values for the Nash-Sutcliffe Efficiency Criterion ranging from 0.76 to 0.98 indicate good model performance in simulating daily tides, where values equal to one indicate a match between model output and observed data, and values less than zero suggest the model is a poor predictor. Scatter plots in Figures 14 and 15 also show good agreement between model simulations for daily water surface elevations and observed data throughout the Trinity-San Jacinto Estuary from 1993 – 1996. To more easily visualize the comparison between simulated and observed hourly tide data, Figures 16 - 20 show time-series of tide elevations for part of the year at each location. Model simulations of water surface elevations accurately simulate observed data at the different sites. The model over-predicted water surface elevations in a few instances, such as at Eagle Point in late October 1993 ($r^2 = 0.83$) and Alligator Point in 1996 ($r^2 = 0.82$). Water surface elevation comparisons were made for the year 1994, but are not displayed as plots in this report; rather, comparison statistics are listed in Table 5.

Table 5. Comparison statistics for hourly tidal elevations during the period 1993 - 1996 for the Trinity San Jacinto Estuary.

Location	Year	n (days)	n	r^2	RMS(ft)*
Pleasure Pier	1993	365	8760	0.99	0.10
Pier 21	1993	360	8644	0.93	0.19
Eagle Point	1993	257	6170	0.83	0.30
Morgan’s Point	1993	363	8719	0.89	0.28
Anahuac	1993	358	8592	0.82	0.30
Pleasure Pier	1994	365	8760	0.99	0.10
Pier 21	1994	365	8750	0.97	0.12
Eagle Point	1994	358	8595	0.83	0.29
Morgan’s Point	1994	364	8739	0.90	0.25
Anahuac	1994	365	8749	0.63	0.48
Pleasure Pier	1995	365	8760	0.98	0.14
Pier 21	1995	365	8749	0.95	0.18
Eagle Point	1995	342	8196	0.94	0.20
Morgan’s Point	1995	363	8700	0.89	0.28
Anahuac	1995	364	8723	0.84	0.32
Clear Lake	1995	360	8639	0.90	0.25
Lynchburg	1995	211	5053	0.89	0.26
Alligator Point	1995	364	8731	0.90	0.25
Pleasure Pier	1996	366	8784	0.99	0.09
Pier 21	1996	366	8776	0.98	0.11
Eagle Point	1996	342	8197	0.92	0.23
Morgan’s Point	1996	344	8244	0.92	0.25
Anahuac	1996	348	8354	0.90	0.23
Clear Lake	1996	358	8586	0.95	0.19
Lynchburg	1996	353	8482	0.91	0.27
Alligator Point	1996	351	8416	0.93	0.21

* RMS is the root mean square.

Table 6. Comparison statistics for daily tides during the period 1993 - 1996.

Location	n (days)	r^2	RMS(ft)	NSEC*
Pleasure Pier	1457	0.98	0.08	0.98
Pier 21	1458	0.97	0.10	0.97
Eagle Point	1334	0.94	0.15	0.94
Morgan's Point	1452	0.92	0.18	0.92
Anahuac	1453	0.80	0.29	0.76
Clear Lake	723	0.95	0.16	0.95
Lynchburg	576	0.94	0.19	0.94
Alligator Point	731	0.97	0.12	0.97

*NSEC is the Nash Sutcliffe Efficiency Criterion (E) and describes model performance, where E = 1.0 represents a match between model output and observed data, and E < 0 suggests the model is a poor predictor.

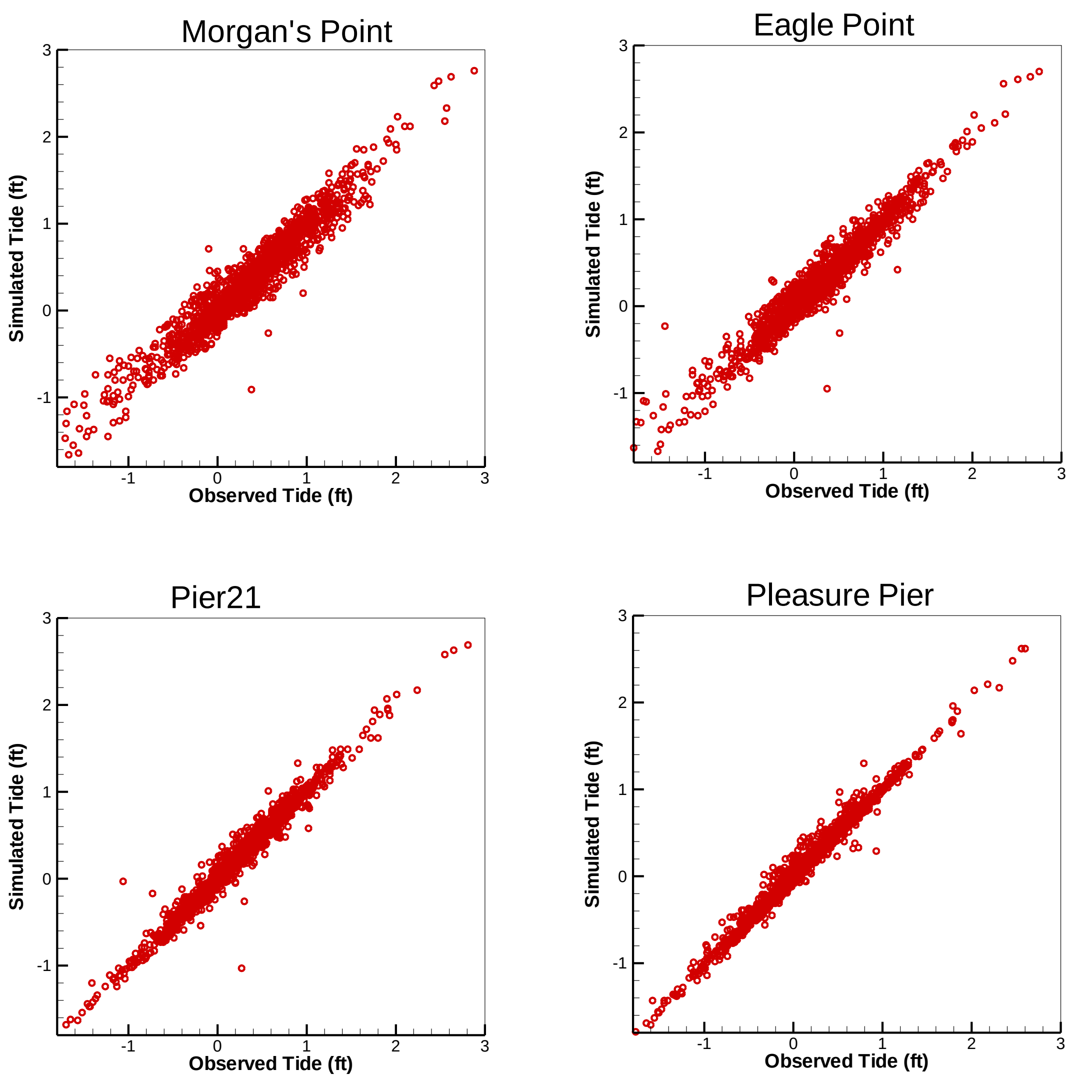


Figure 14. Scatter plots of observed versus simulated daily tidal elevations at Morgan's Point, Eagle Point, Pier 21, and Pleasure Pier locations in the Trinity-San Jacinto Estuary for 1993 - 1996.

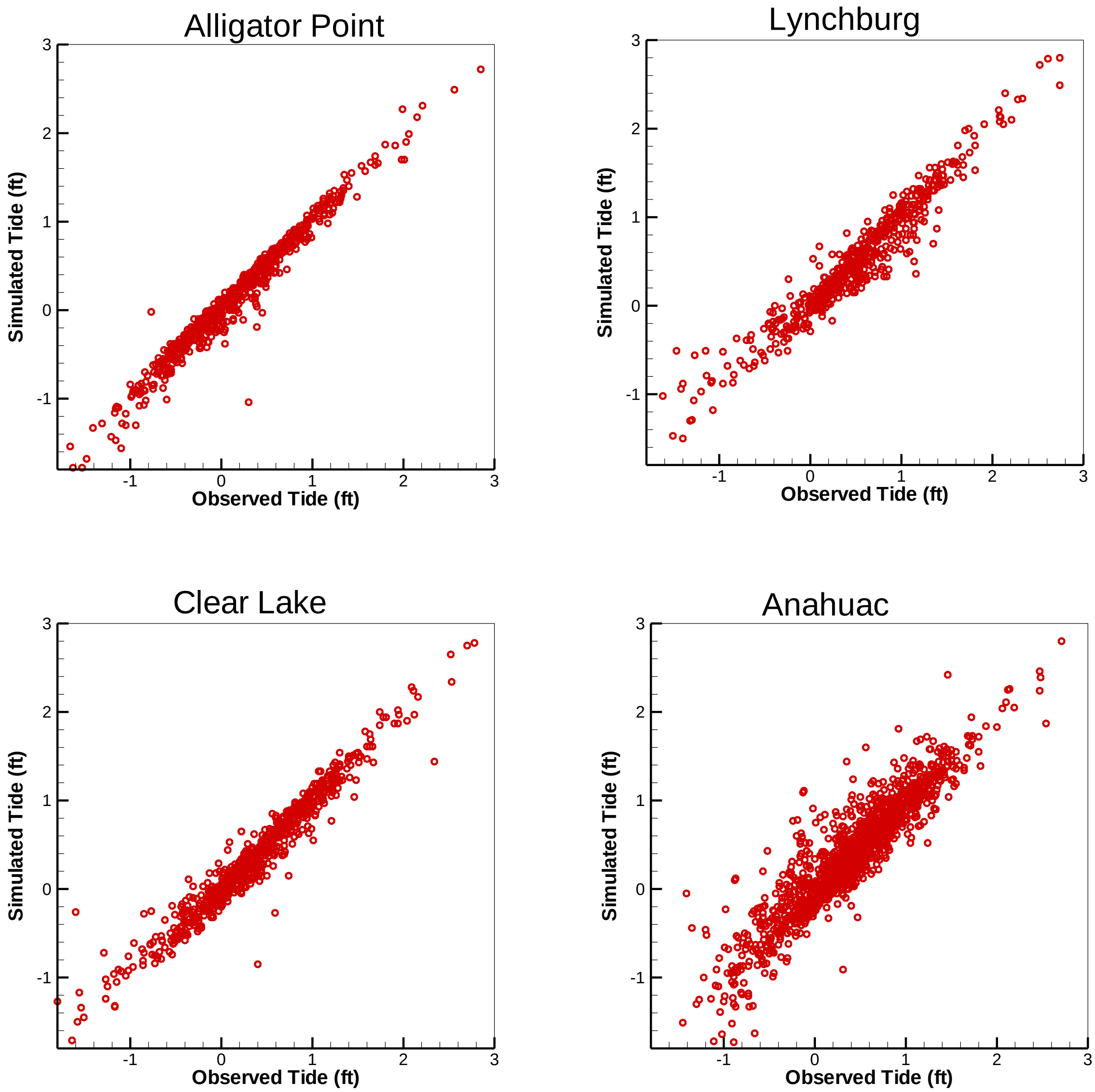


Figure 15. Scatter plots of observed versus simulated daily tidal elevations at Alligator Point, Lynchburg, Clear Lake, and Anahuac locations in the Trinity-San Jacinto Estuary for 1995 - 1996. Tides for Alligator Point were adjusted by +0.5 ft. from April 18, 1996 to December 31, 1996.

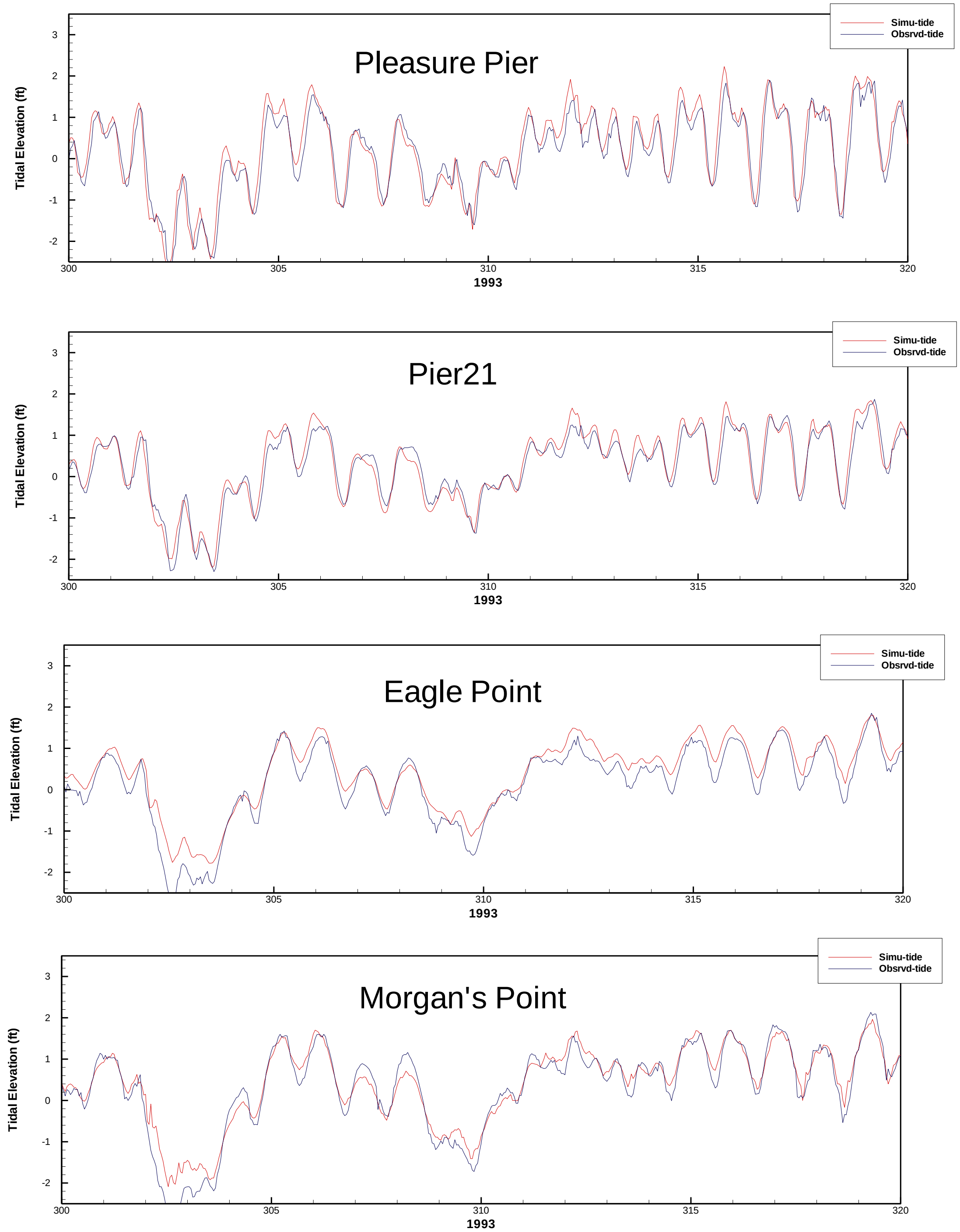


Figure 16. Time-series plots for observed (*black)* and simulated (*red*) hourly tide data at four tide gages (from top to bottom: Pleasure Pier, Pier 21, Eagle Point, and Morgan's Point) during 1993.

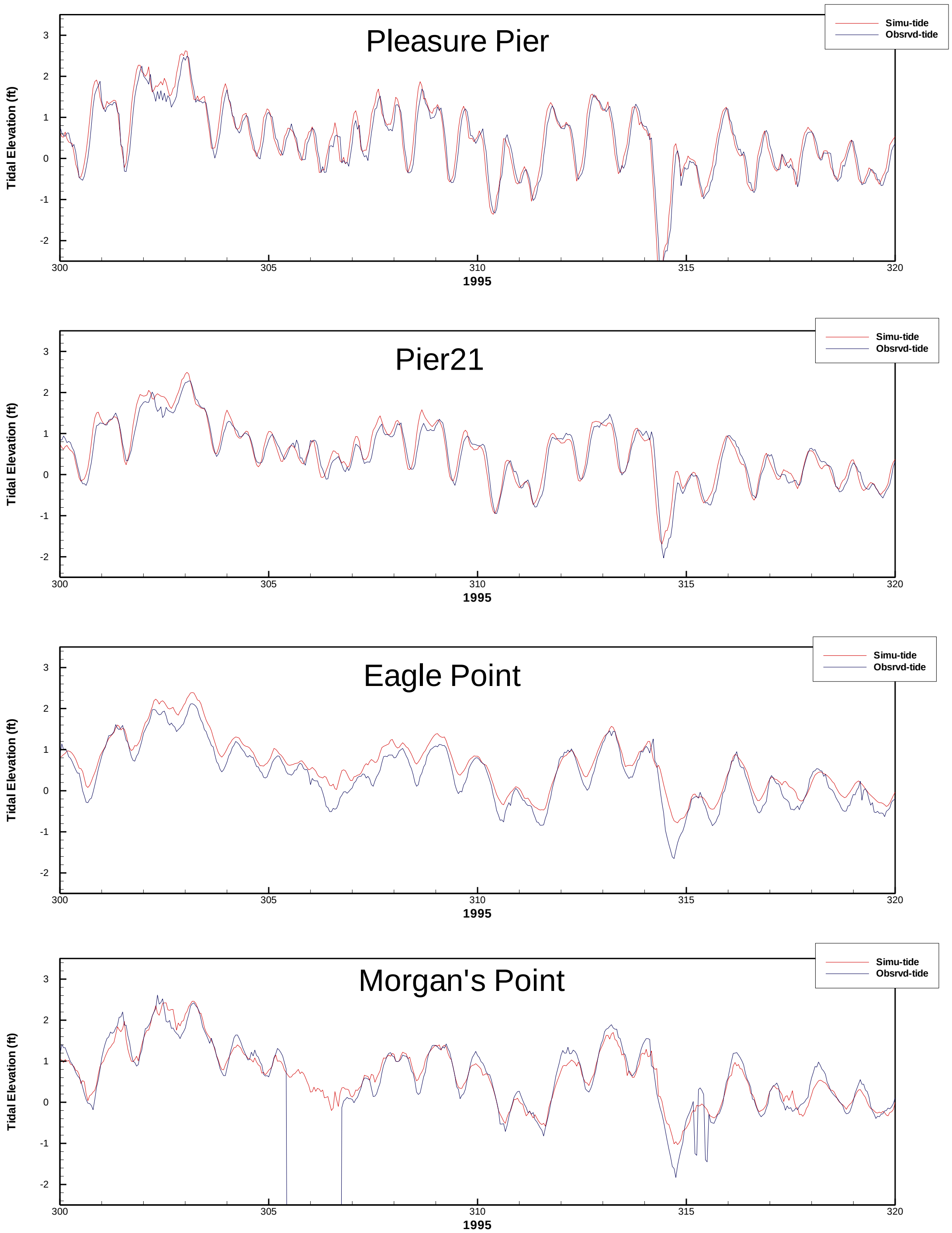


Figure 17. Time-series plots for observed (*black*) and simulated (*red*) hourly tide data at four tide gages (from top to bottom: Pleasure Pier, Pier 21, Eagle Point, and Morgan's Point) during 1995.

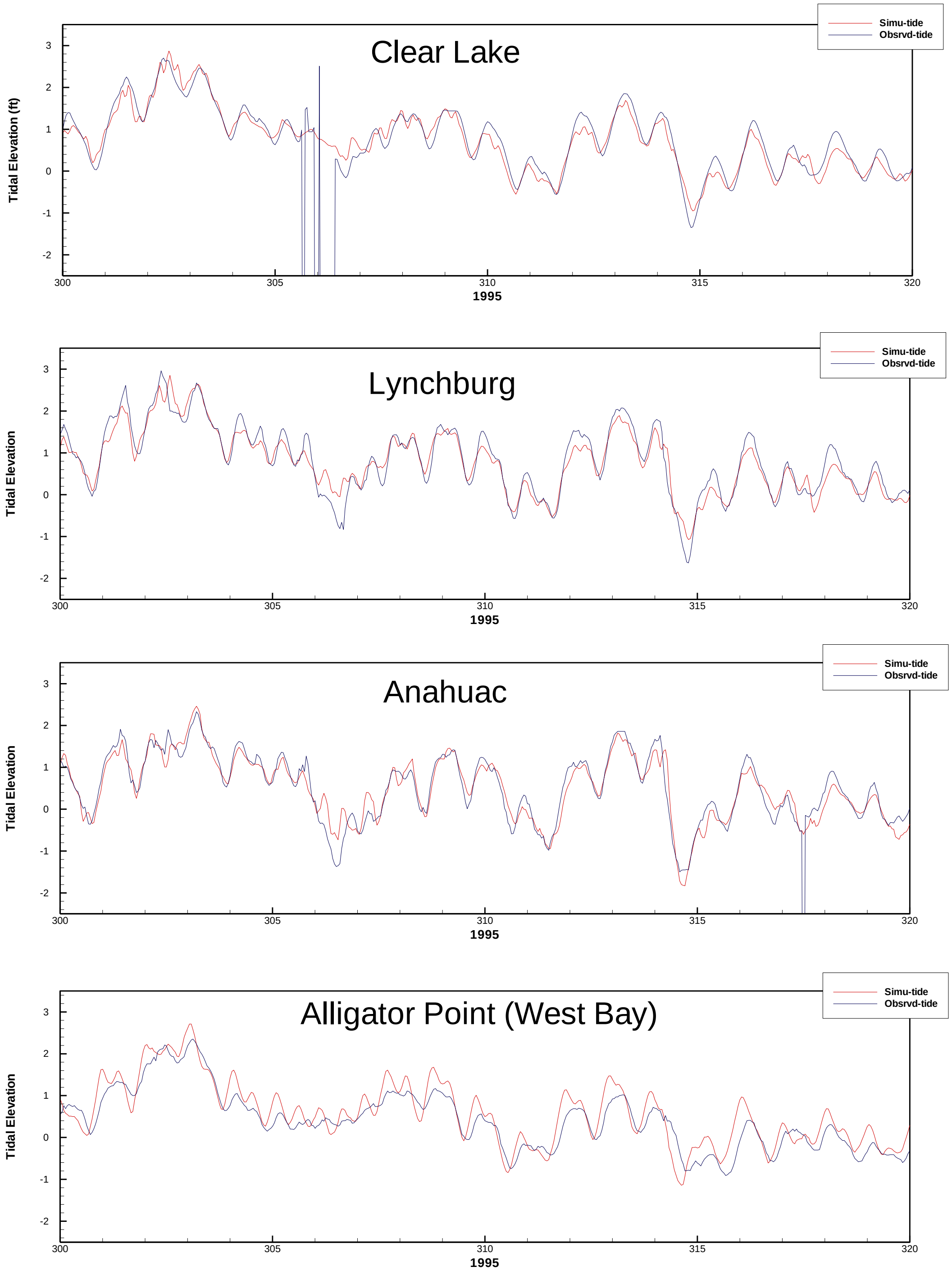


Figure 18. Time-series plots for observed (*black*) and simulated (*red*) hourly tide data at four tide gages (from top to bottom: Clear Lake, Lynchburg, Anahuac, and Alligator Point in West Bay) during 1995.

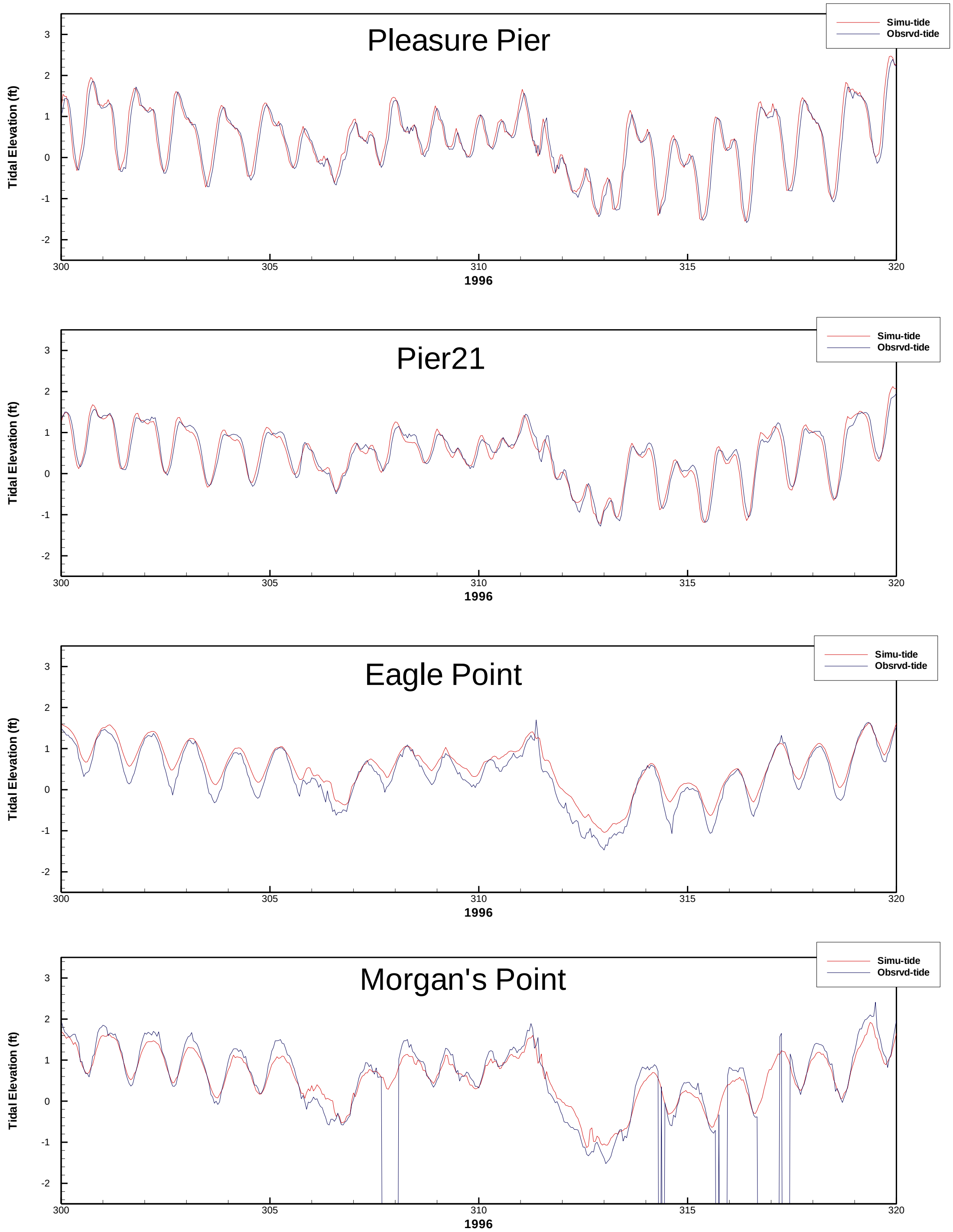


Figure 19. Time-series plots for observed (*black*) and simulated (*red*) hourly tide data at four tide gages (from top to bottom: Pleasure Pier, Pier 21, Eagle Point, and Morgan’s Point) during 1996.

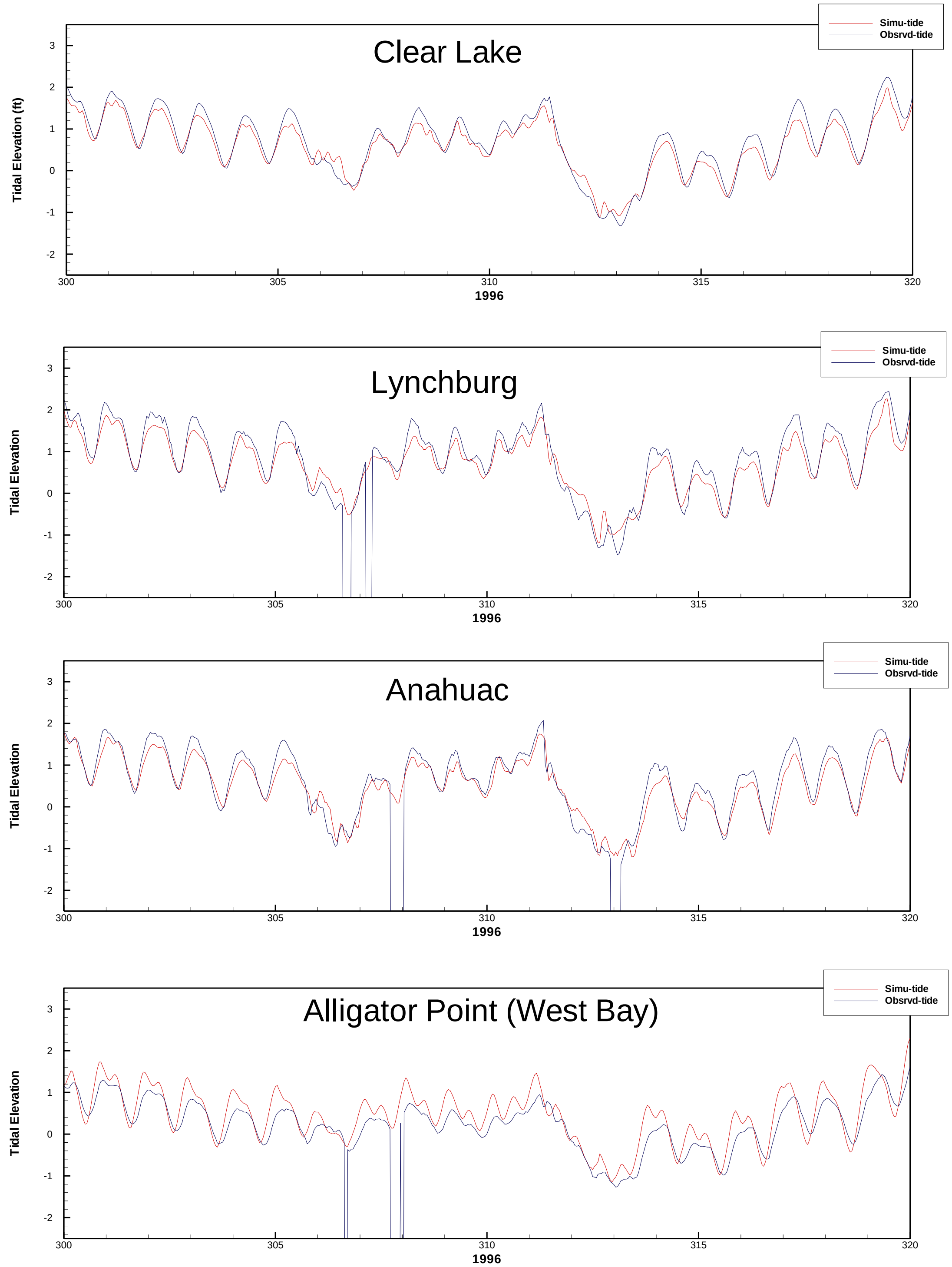


Figure 20. Time-series plots for observed (*black*) and simulated (*red*) hourly tide data at four tide gages (from top to bottom: Clear Lake, Lynchburg, Anahuac, and Alligator Point in West Bay) during 1996. Tides for Alligator Point were adjusted by +0.5 ft. from April 18, 1996 to December 31, 1996.

Salinity Results

TxBLEND was calibrated for salinity at four locations in the Trinity-San Jacinto Estuary, including Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay (refer to Figure 6), for 1987 – 1996. Table 7 lists observed and simulated mean daily salinity at the four sampling sites from 1987 - 1996. The difference in mean salinity ranged from 0.3 ppt to 2.6 ppt. Good model performance was indicated by generally high r^2 values, ranging from 0.61 to 0.84, and high Nash-Sutcliffe Efficiency Criterion values which ranged from 0.57 to 0.84. Scatter plots in Figure 21 reveals that the model more accurately predicted salinity at Dollar Point (r^2 = 0.84, NSEC = 0.83) and Red Bluff (r^2 = 0.80, NSEC = 0.79) than at the Bolivar Roads (r^2 = 0.61, NSEC = 0.58) and Trinity Bay (r^2 = 0.68, NSEC = 0.52) sites, where the data points were more spread out.

Figures 22 through 31 display simulated versus observed salinities for the calibration periods at each of the four locations. Two characteristics of the data were replicated by the model simulation; these were daily salinity variation and long-term trends. For example, the model shows that daily variation is much greater at the Bolivar Roads site as compared to the Trinity Bay site, which is consistent with tidal variation and exchange with the Gulf of Mexico. At all four sites, the model captured the long-term trend of decreasing salinity, as river inflows increase and remain high during the Spring, and also captured gradually increasing salinity through the summer months as inflows decrease. However, the model had greater difficulty simulating high frequency variability than the long-term trends, as shown by comparisons at the Red Bluff site from 1990 – 1996, except for the sudden drop in salinity due to a large inflow event (*e.g.*, Figure 29, October 1994). The model did a good job capturing such a rapid decrease in salinity throughout the estuary. However, the data suggest that the model had some difficulty simulating normal high-frequency variation in salinity and trends in salinity recovery following an inflow event in the upper estuary sites, such as in Trinity Bay where the model tended to consistently over-predict salinity, except in 1996.

Table 7. Summary statistics for observed and simulated salinity for the calibration period from 1987 - 1996 for four sites in the Trinity-San Jacinto Estuary.

Site	n	r^2	RMS* (ppt)	Observed Mean (ppt)	Simulated Mean (ppt)	Difference (ppt)	NSEC**
Bolivar Roads	1438	0.61	4.0	20.8	21.9	1.1	0.58
Dollar Point	1767	0.84	2.7	16.0	16.3	0.3	0.83
Red Bluff	1603	0.80	2.8	11.6	12.3	0.7	0.79
Trinity Bay	1571	0.68	5.0	6.9	9.5	2.6	0.52

Note: Salinity data greater than 35 ppt were excluded for Bolivar Roads, 30 ppt for Dollar Point, 26 ppt for Red Bluff, and 35 ppt for Trinity Bay.
*RMS is root mean square error.
**NSEC is the Nash-Sutcliffe Efficiency Criterion (E) and describes model performance, where E = 1.0 represents a match between model output and observed data, and E < 0 suggests the model is a poor predictor.

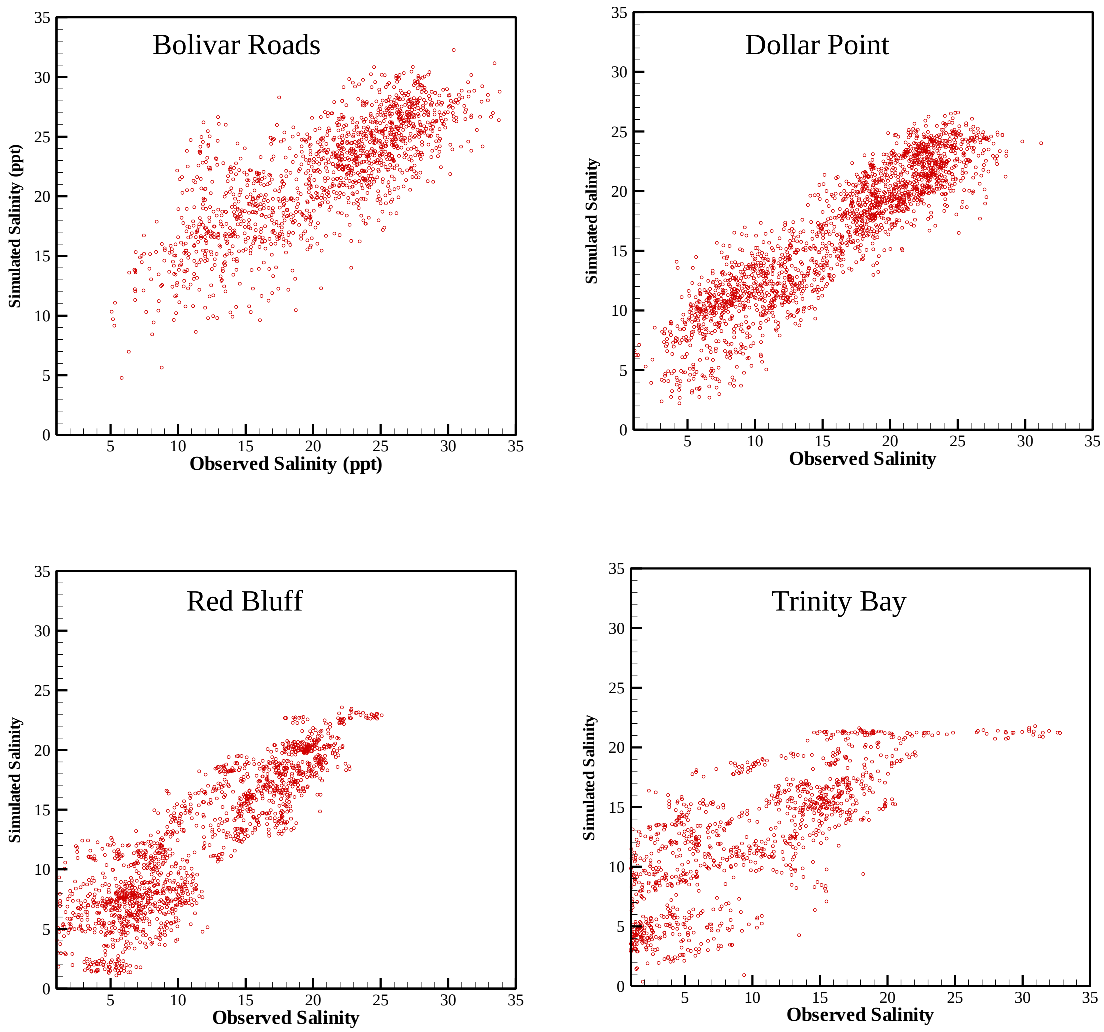


Figure 21. Scatter plots comparing simulated to observed salinities at four sites for a calibration period from 1989 - 1996.

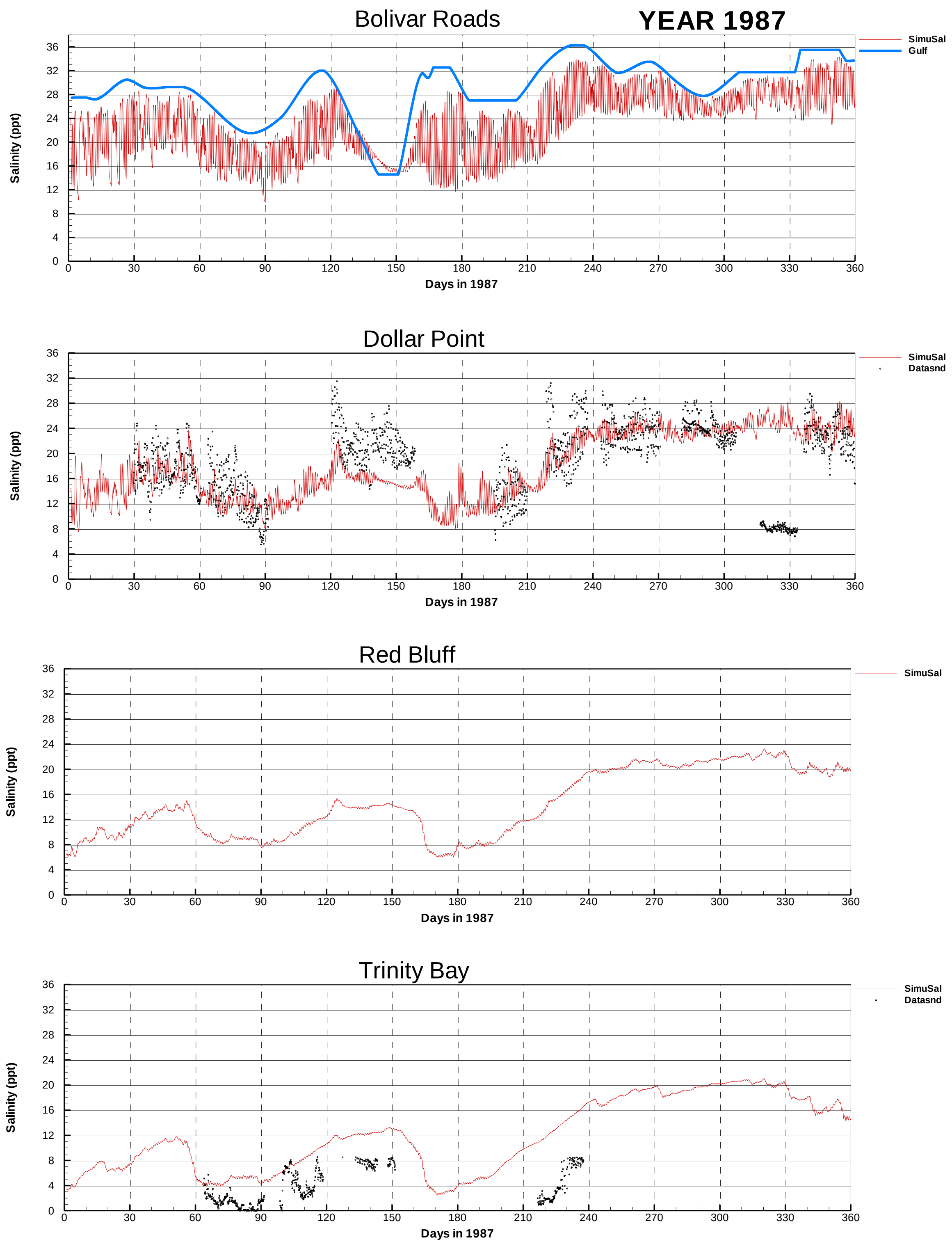


Figure 22. Simulated (*red*) versus observed (*black*) salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1987. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

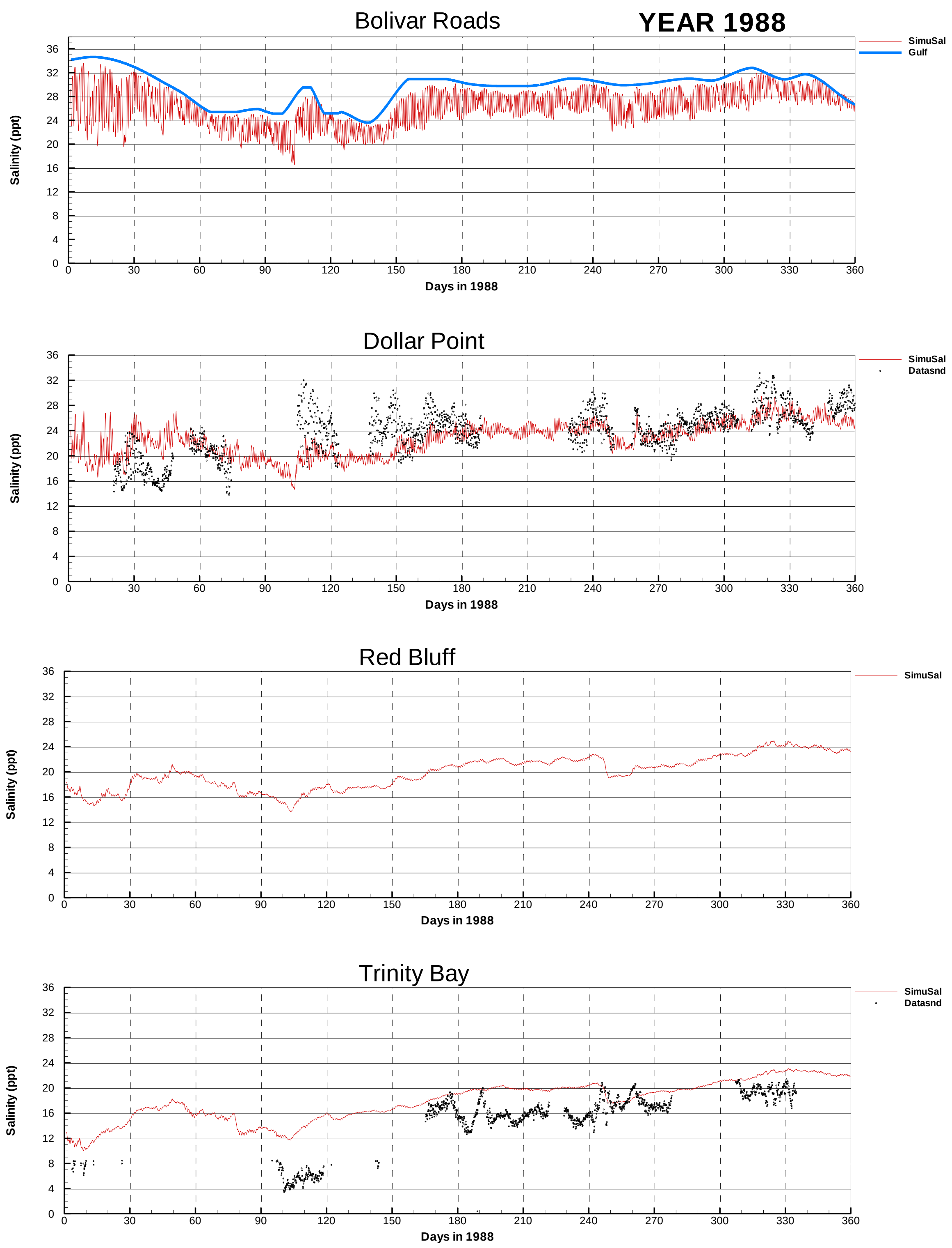


Figure 23. Simulated (*red*) versus observed (*black*) salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1988. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

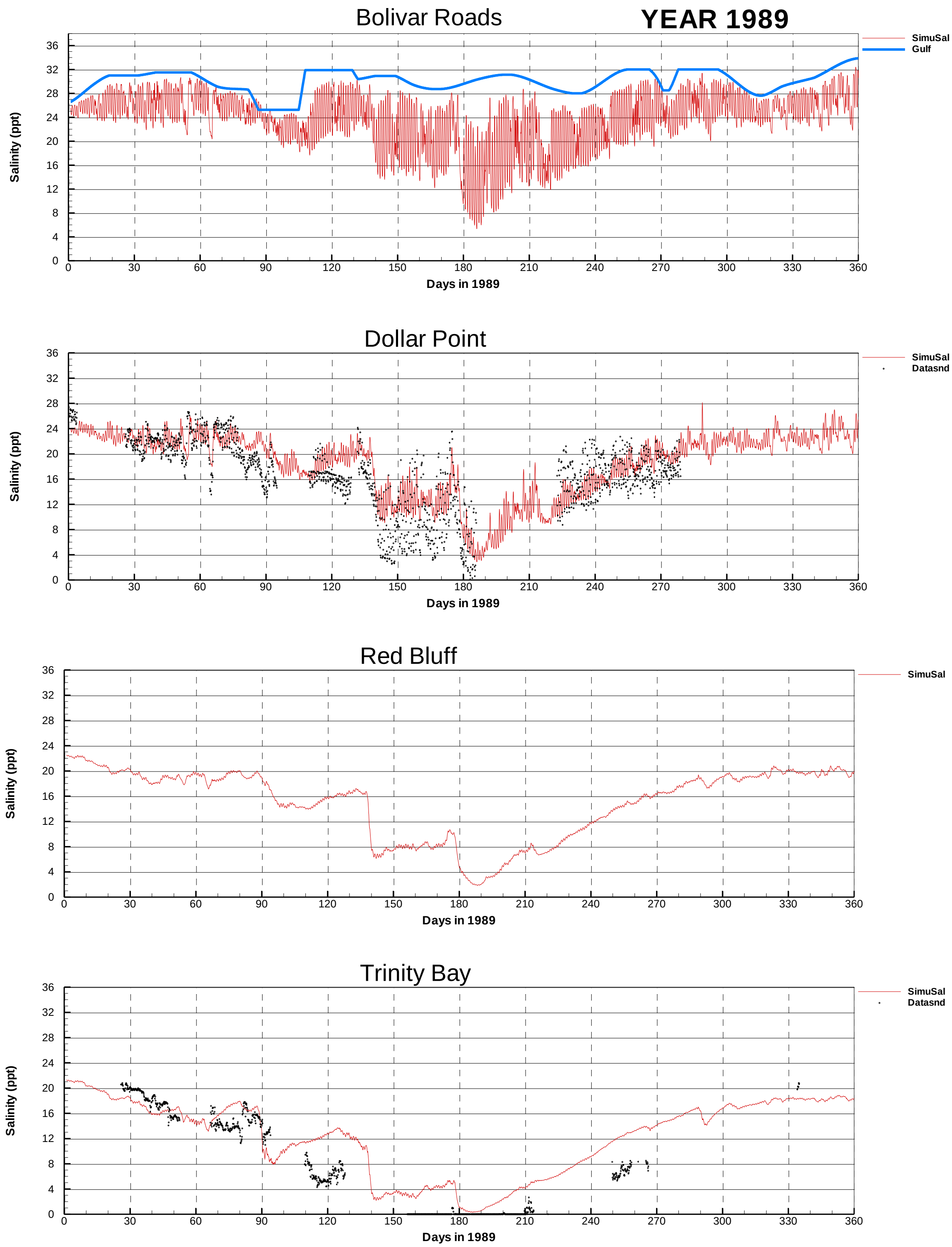


Figure 24. Simulated (*red*) versus observed (*black*) salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1989. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

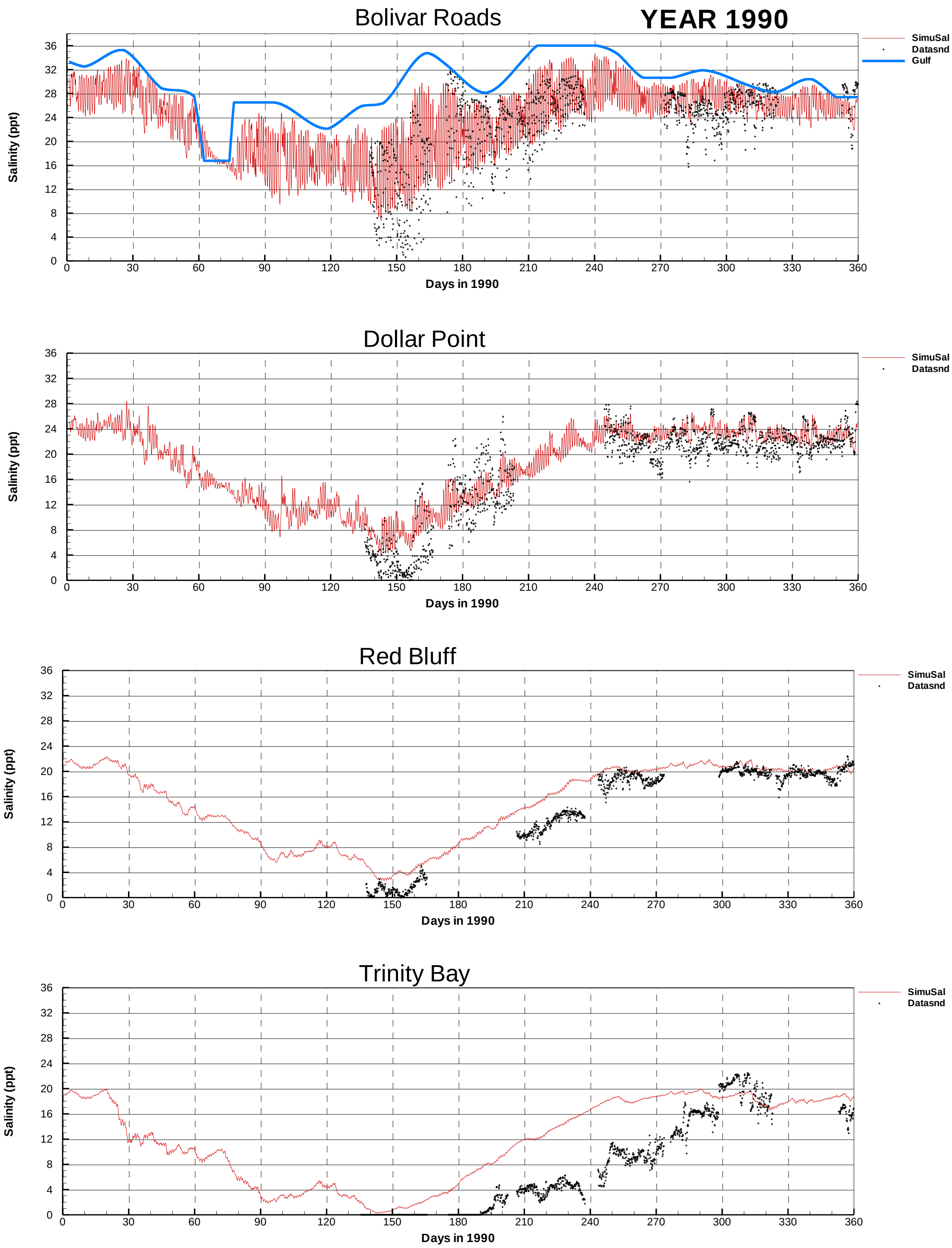


Figure 25. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1990. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

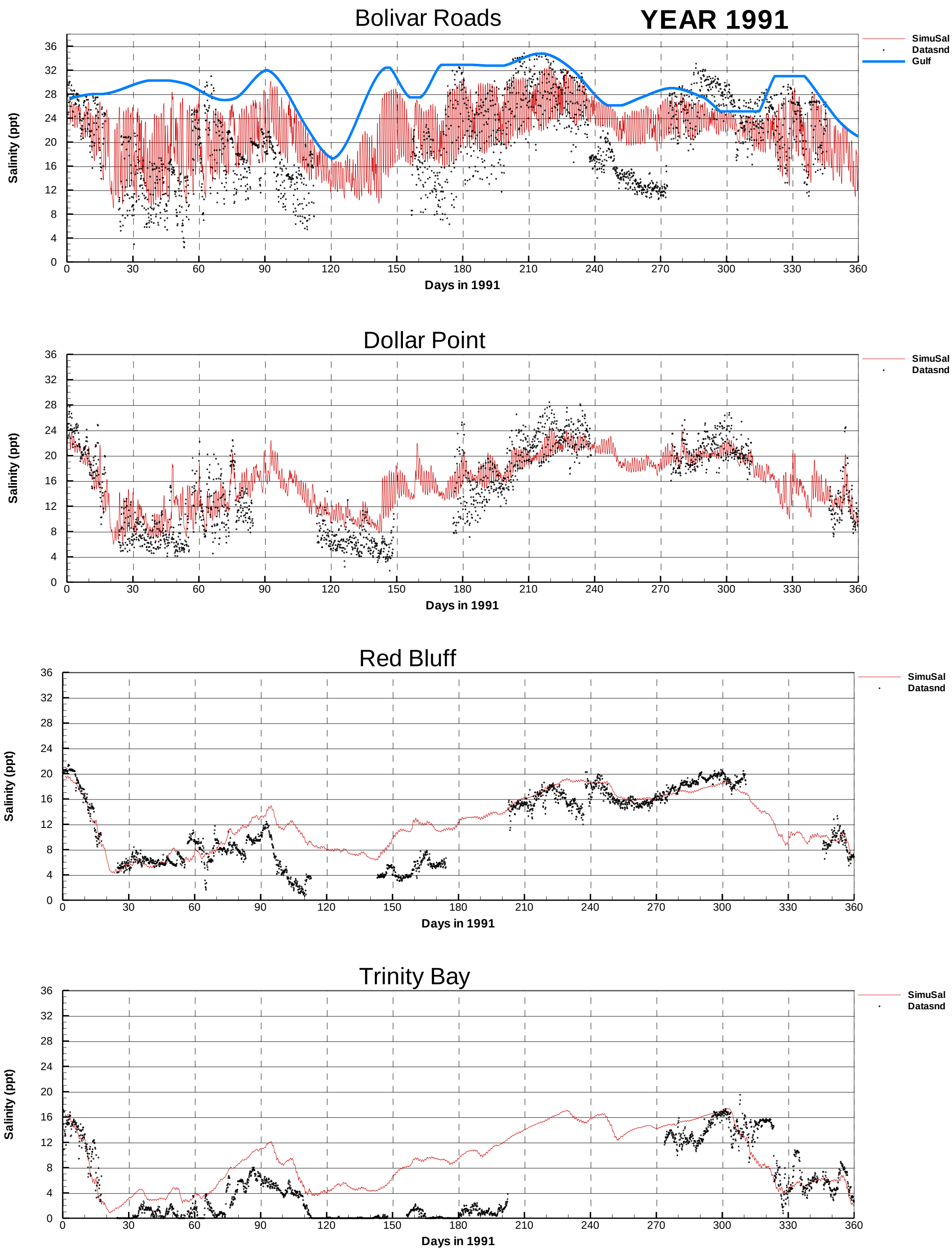


Figure 26. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1991. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

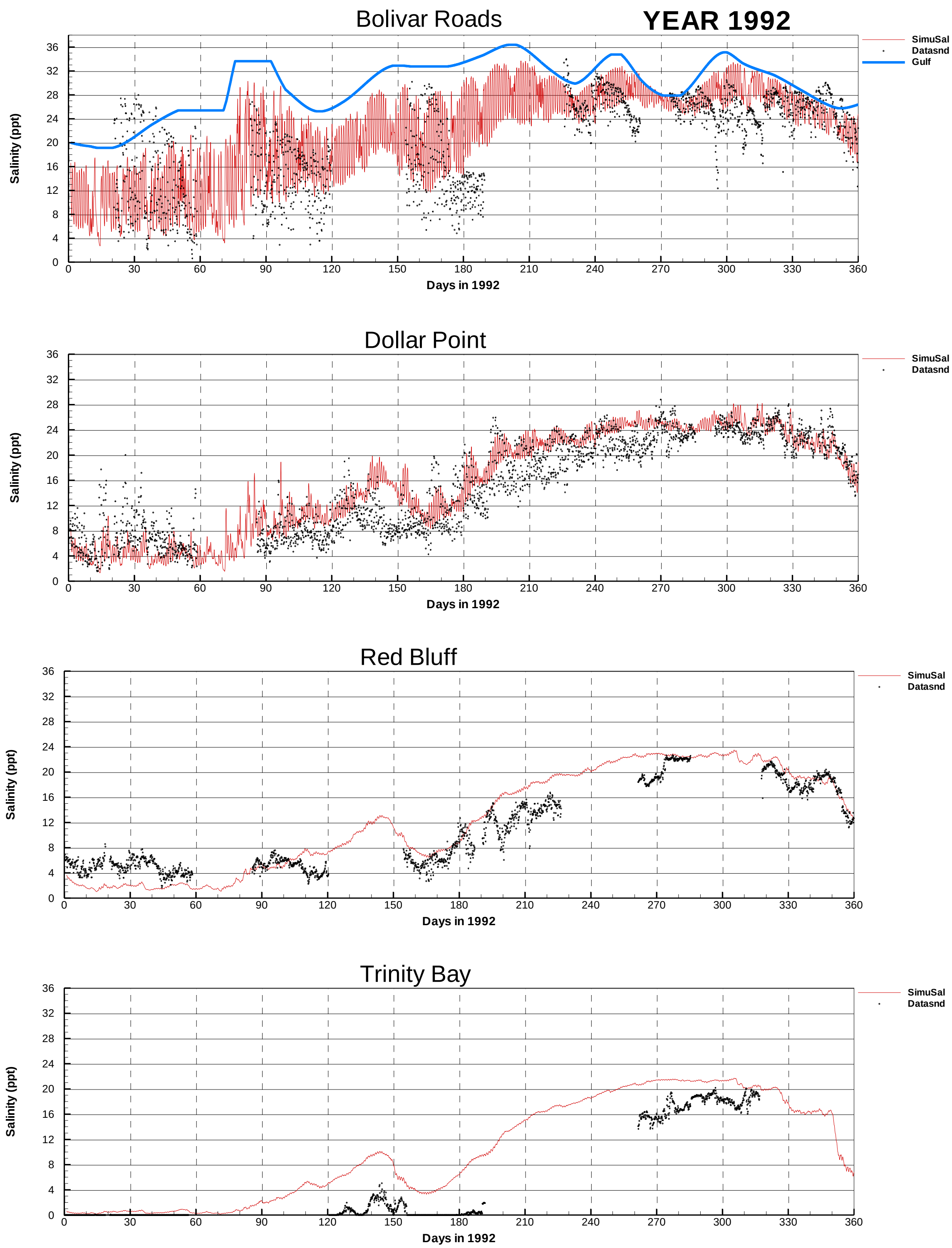


Figure 27. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1992. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

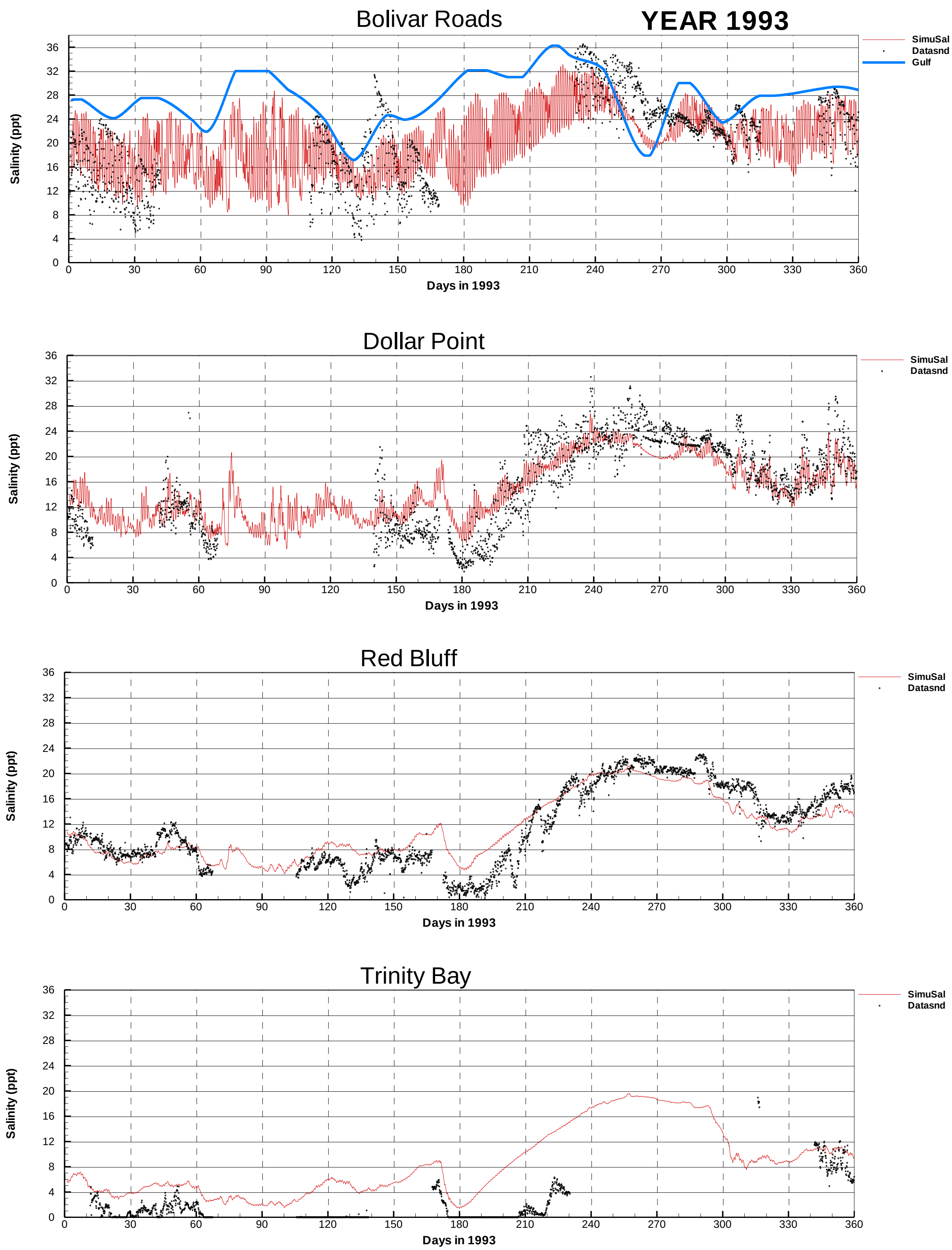


Figure 28. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1993. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

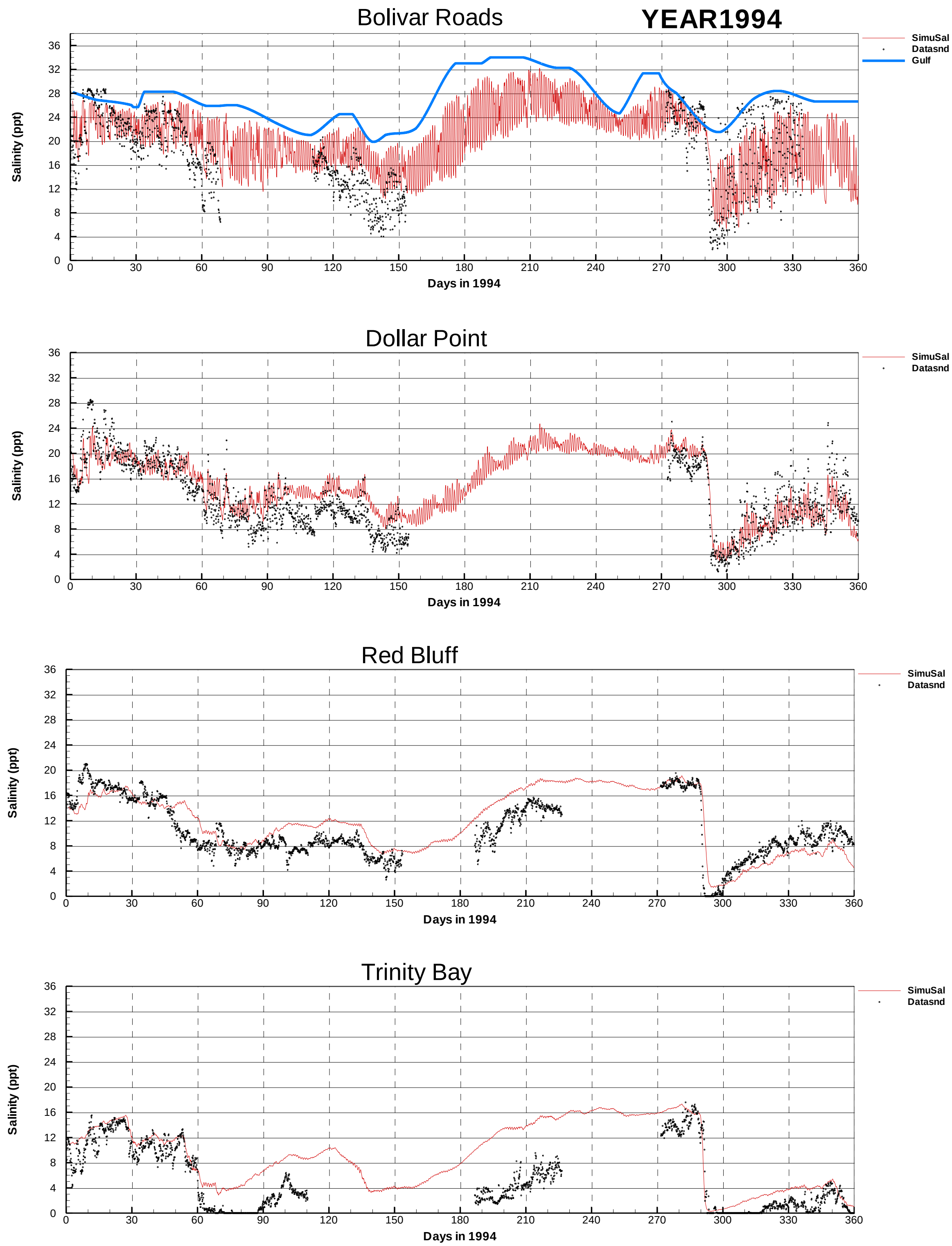


Figure 29. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1994. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

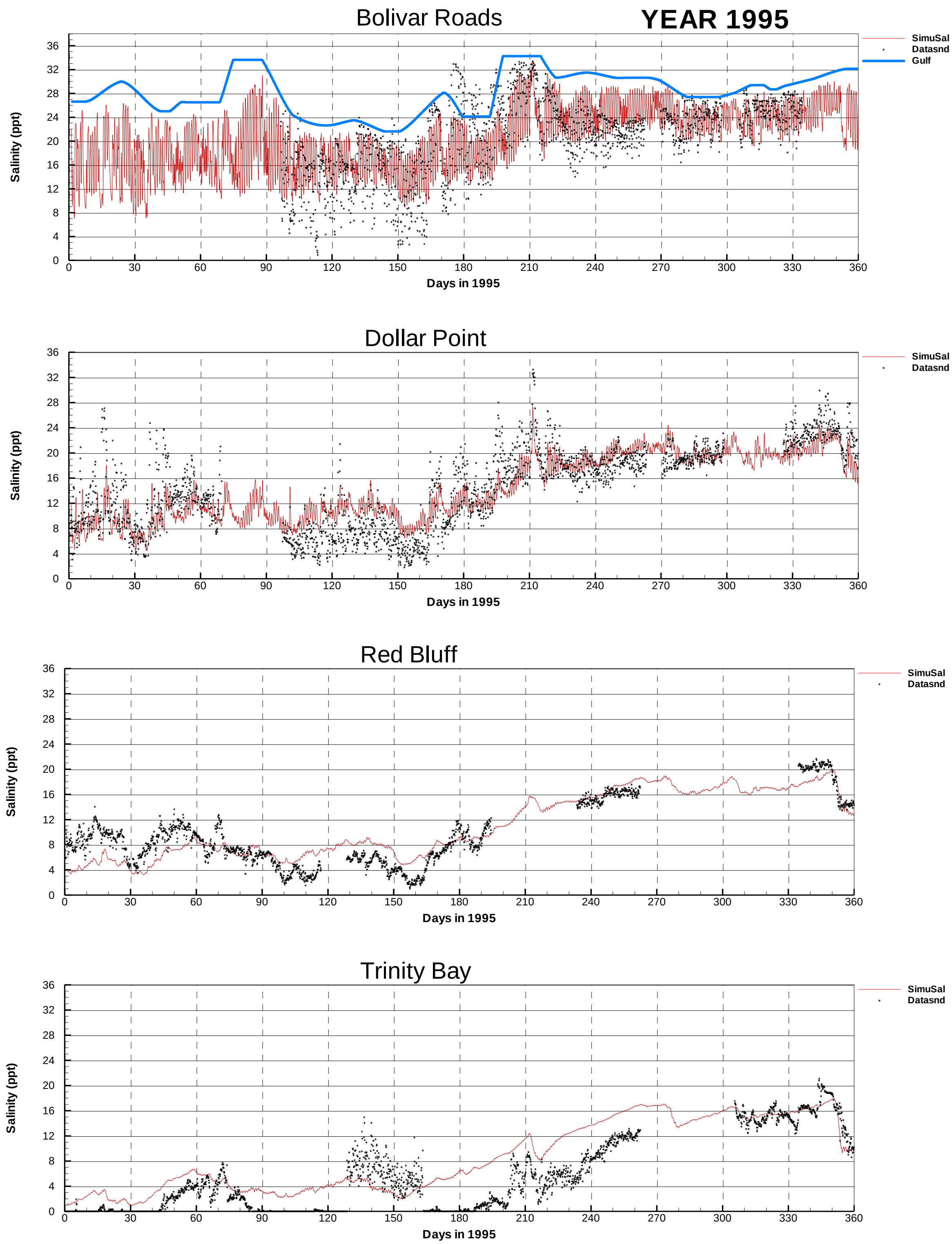


Figure 30. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1995. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

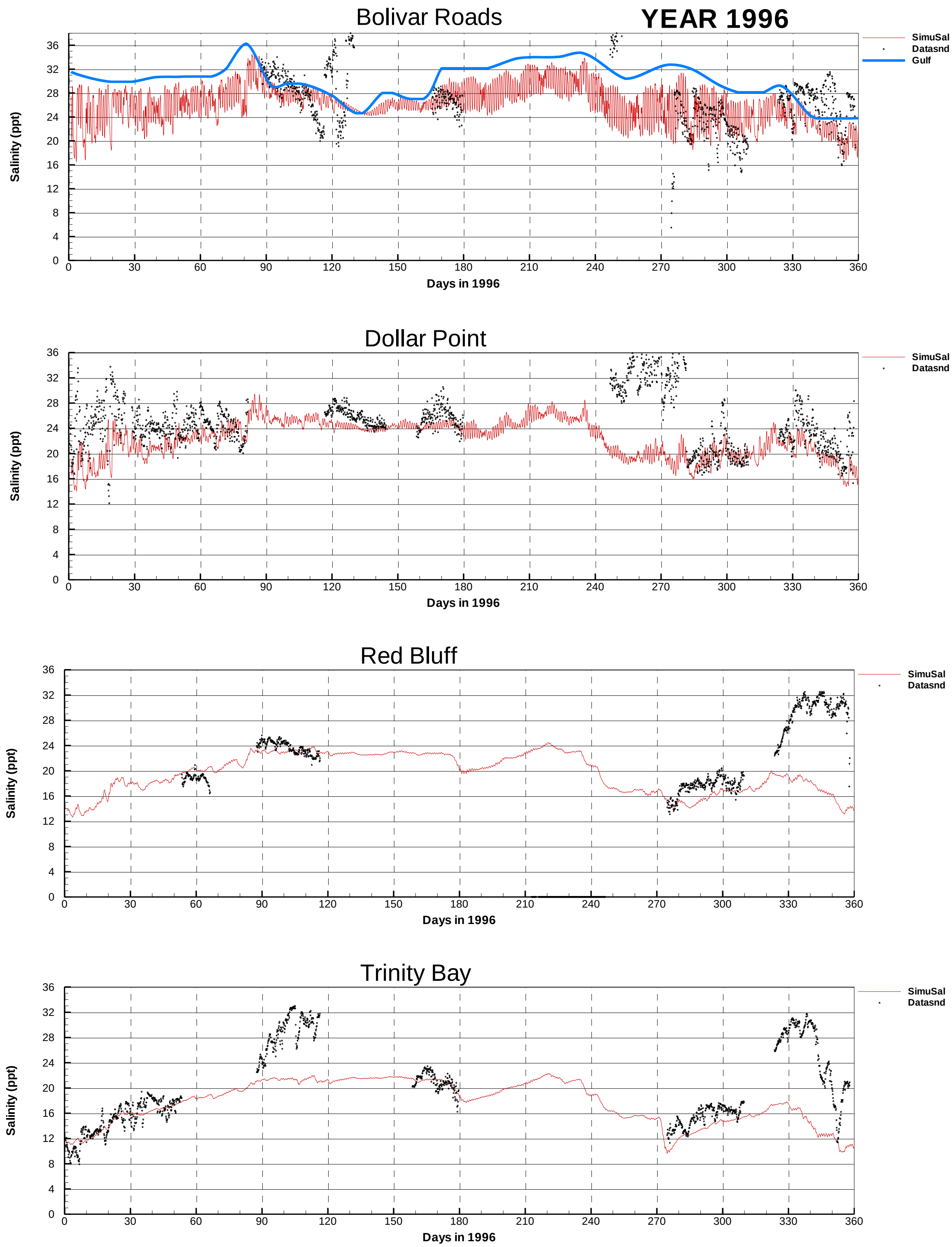


Figure 31. Simulated (*red*) versus observed *(black)* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites in the Trinity-San Jacinto Estuary during 1996. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

Model Validation

To verify the validity of the calibrated Galveston Bay TxBLEND model for salinity, a second model run was conducted to simulate salinities for the period 1997 - 2005. Salinity initial conditions were determined the same as during model calibration. Salinity at the river inflow points was set at 0 ppt and time-varying salinity boundary conditions were obtained from the TPWD Coastal Fisheries database to specify salinity at the Gulf boundary. Model simulated salinity values then were compared to observed salinities obtained from the TWDB Datasonde Program for four monitoring sites: Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads (refer to Figure 6). TxBLEND model validation results also were compared to point-measurement data obtained from *Spotcheck* measurements collected by TPWD when retrieving datasondes at the four established stations, and from TPWD's Coastal Fisheries database, the Texas Commission on Environmental Quality (TCEQ) Surface Water Quality Monitoring database, and the Texas Department of State Health Services (TDH) Shell Fish Safety Program for sites located within the vicinity of the established TWDB monitoring stations. These datasets provided additional point measurements representing local conditions.

Validation statistics (Table 8) were similar to the calibration statistics (Table 7), indicating that the model performed reasonably well in terms of salinity prediction. The mean difference between simulated and observed salinity ranged from 0.4 ppt to 4.2 ppt. Model performance, as indicated by r^2 values ranging from 0.61 to 0.73, with lower values occurring in the upper estuary sites, was reasonably good. Similarly, Nash-Sutcliffe Efficiency Criterion values show that the model is a better predictor at the lower bay sites (NSEC = 0.71 and 0.70), than at the upper bay sites (NSEC = 0.21 and 0.31). Figures 32 through 41 show comparisons of simulated and observed salinities, both as scatter plots for the period 1997 - 2005 and as time-series plots for each year at the four sites in Galveston Bay. Similar to the calibration results, the model was less-representative of observed salinities and high-frequency fluctuations in salinity at the upper estuary sites at Red Bluff (r^2 = 0.61) and Trinity Bay (r^2 = 0.63). In contrast, the model performed reasonably well at the lower estuary sites, Bolivar Roads (r^2 = 0.71) and Dollar Point (r^2 = 0.73), and simulated long-term trends in salinity variation well.

Table 8. Summary statistics for observed and simulated salinities for a period from 1997 - 2005 for four sites in the Trinity-San Jacinto Estuary. State agency's data (TWDB, TCEQ, TDH, TPWD) for 1997 - 2005 are combined.

Site	n	r^2	RMS* (ppt)	Observed Mean	Simulated Mean	Difference	NSEC**
Bolivar Roads	1156	0.71	3.4	20.3	20.7	0.4	0.71
Dollar Point	1047	0.73	3.6	18.2	18.9	-0.7	0.70
Red Bluff	528	0.61	4.6	11.3	13.4	-2.1	0.21
Trinity Bay	1291	0.63	6.3	9.2	13.4	-4.2	0.31

*RMS is root mean square error.

**NSEC is the Nash-Sutcliffe Efficiency Criterion (E) and describes model performance, where E = 1.0 represents a match between model output and observed data, and E < 0 suggests the model is a poor predictor.

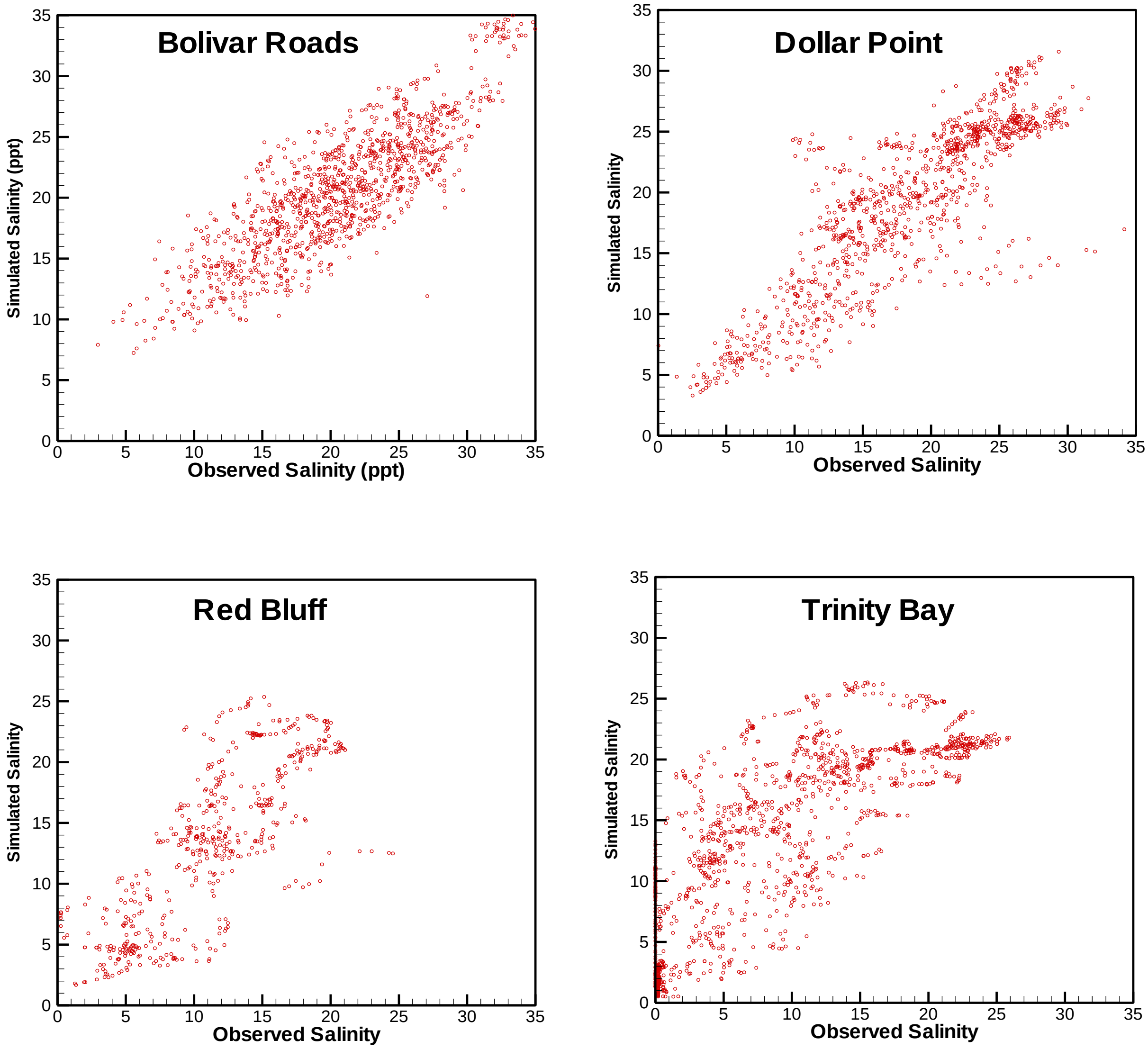


Figure 32. Scatter plots comparing simulated to observed salinities at four sites in the Trinity-San Jacinto Estuary, including Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay, for the validation period of 1997 - 2005.

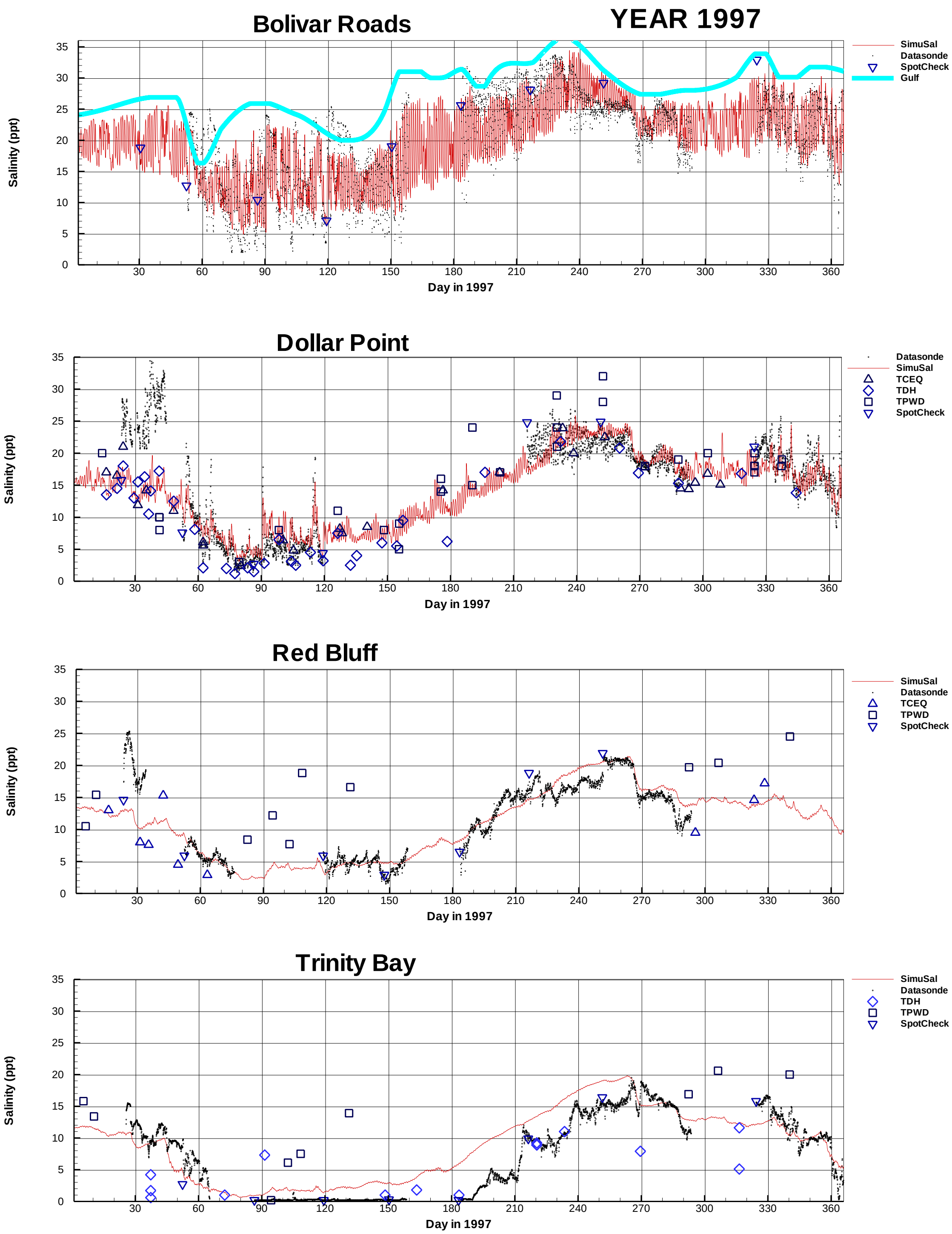


Figure 33. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 1997. Gulf salinities *(blue)* at Bolivar Roads were used to set the Gulf boundary salinity condition.

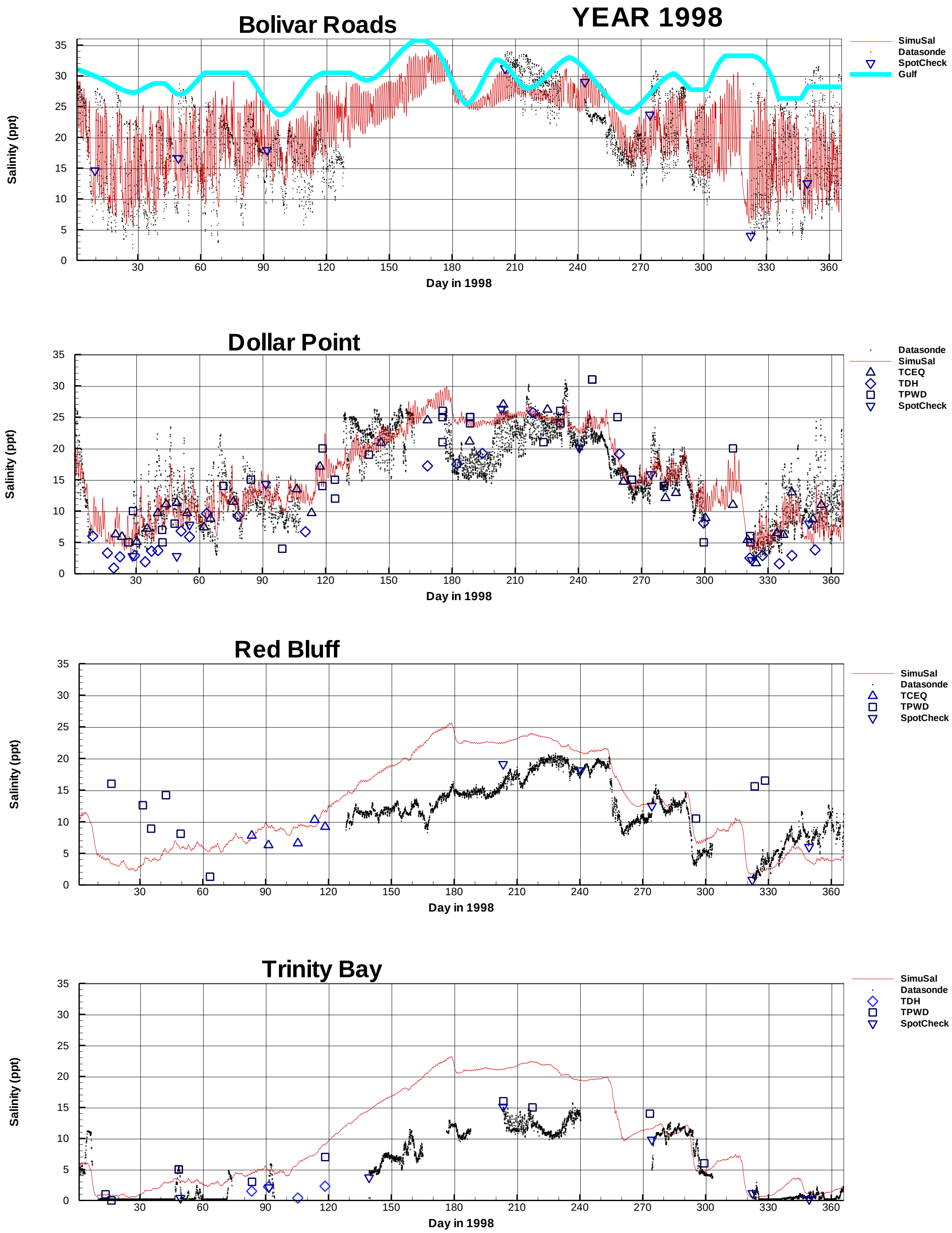


Figure 34. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 1998. Gulf salinities *(blue)* at Bolivar Roads were used to set the Gulf boundary salinity condition.

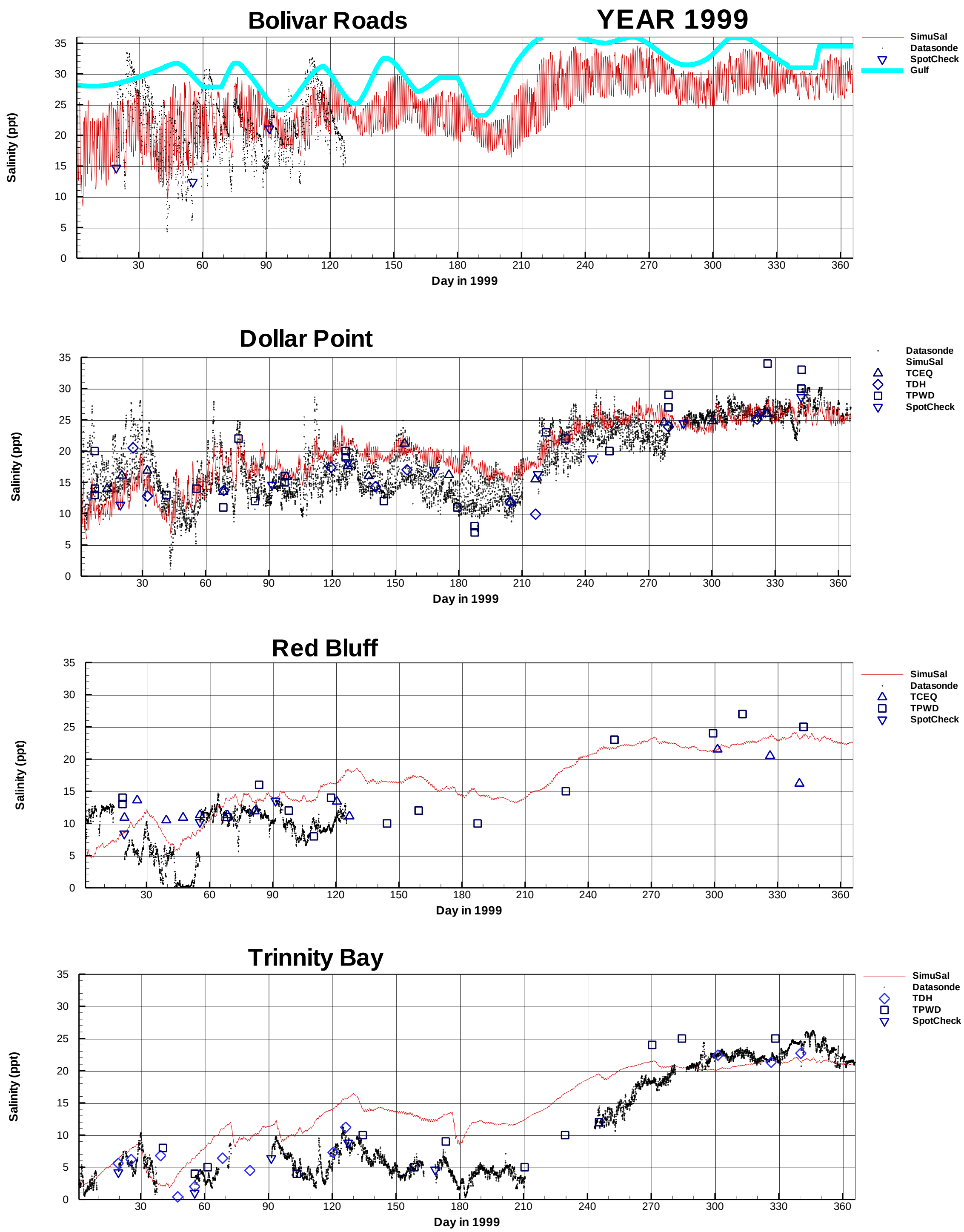


Figure 35. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 1999. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

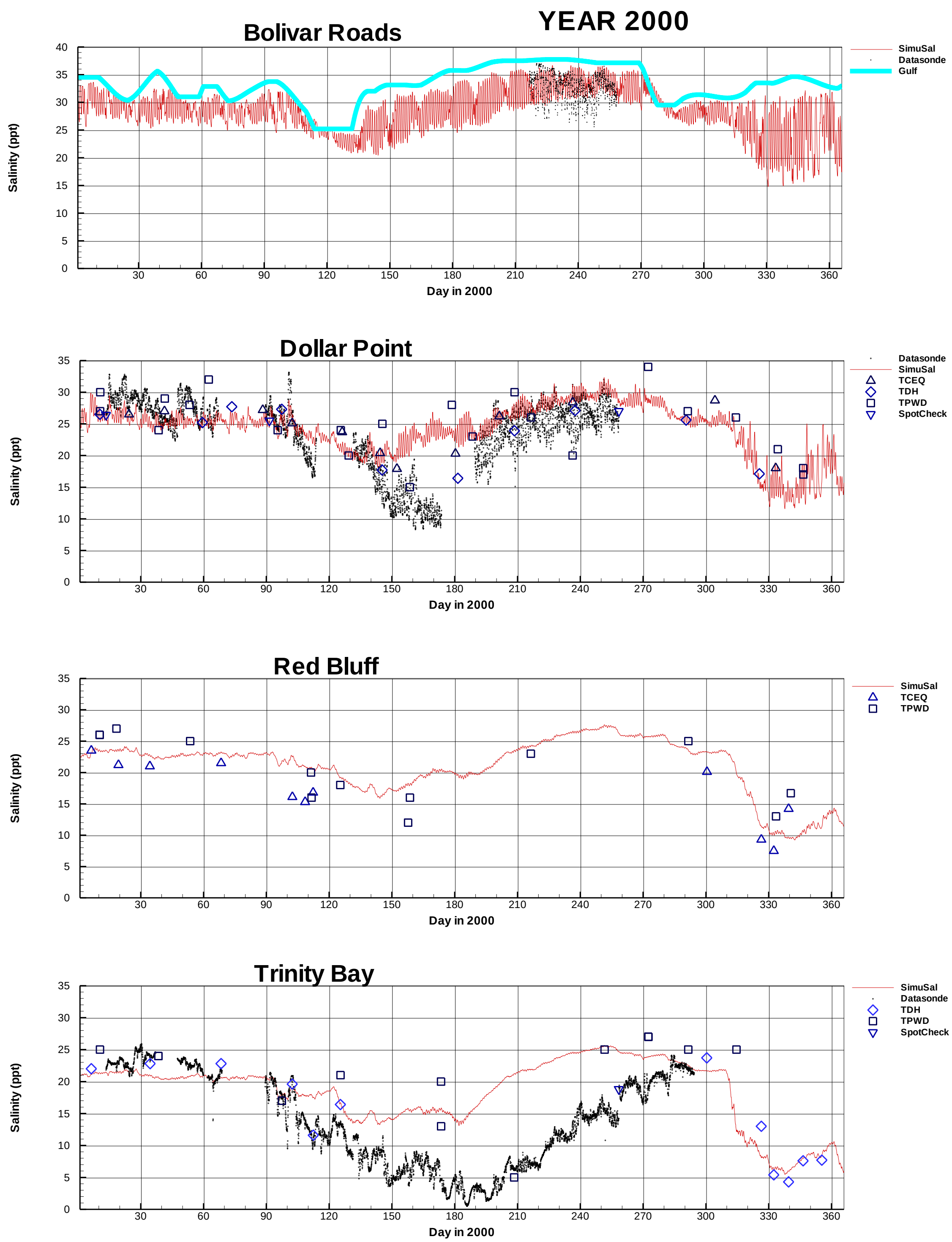


Figure 36. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2000. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

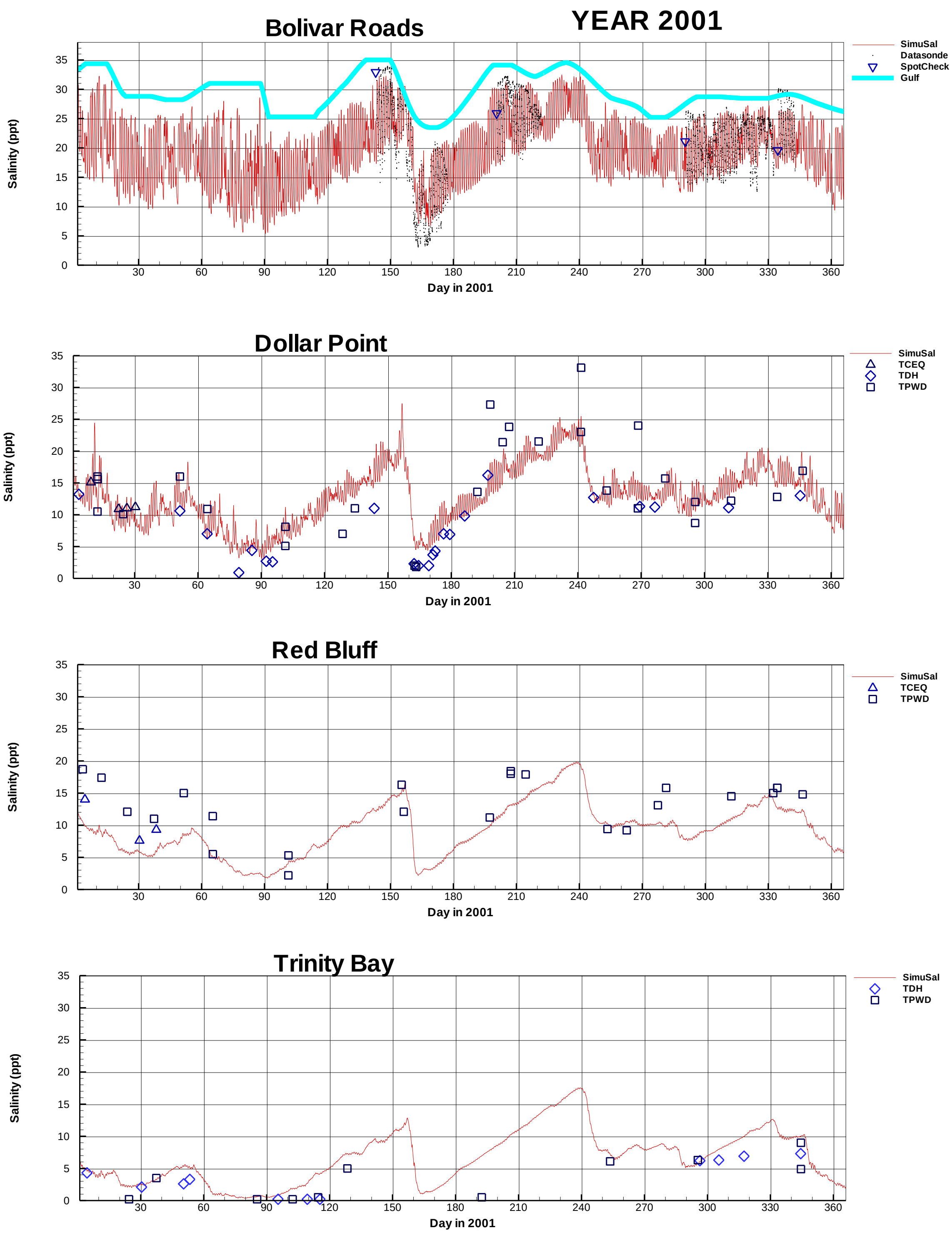


Figure 37. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2001. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

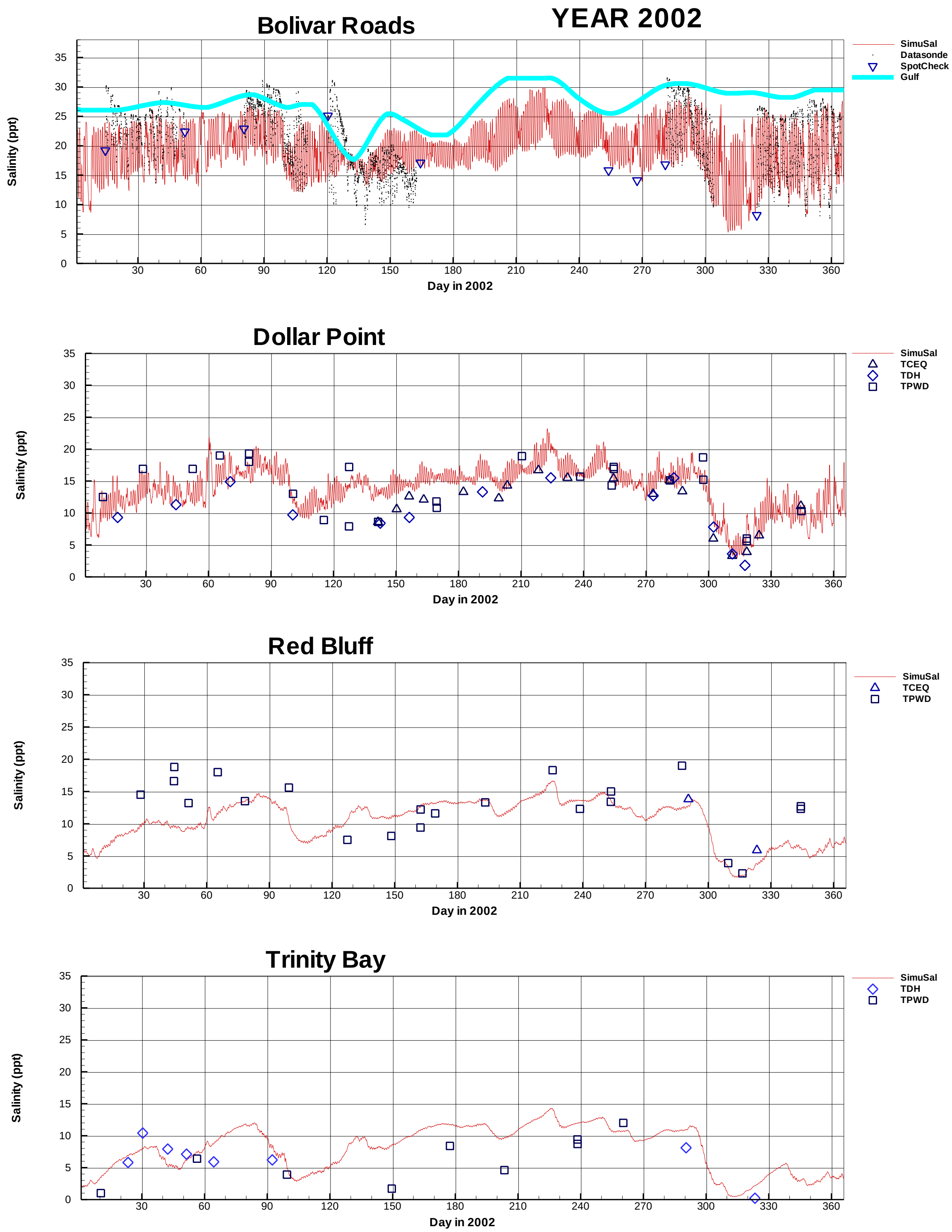


Figure 38. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2002. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

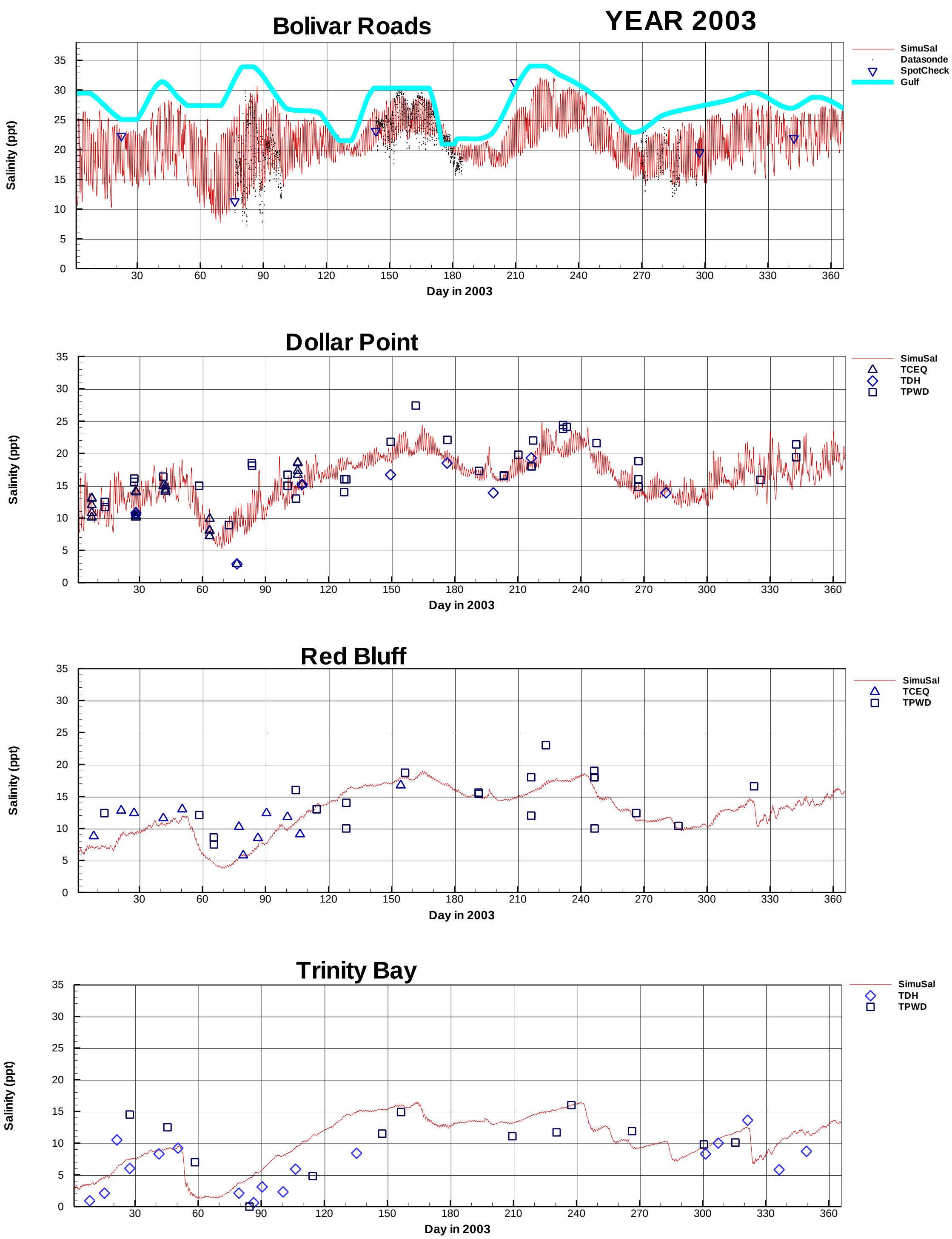


Figure 39. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2003. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

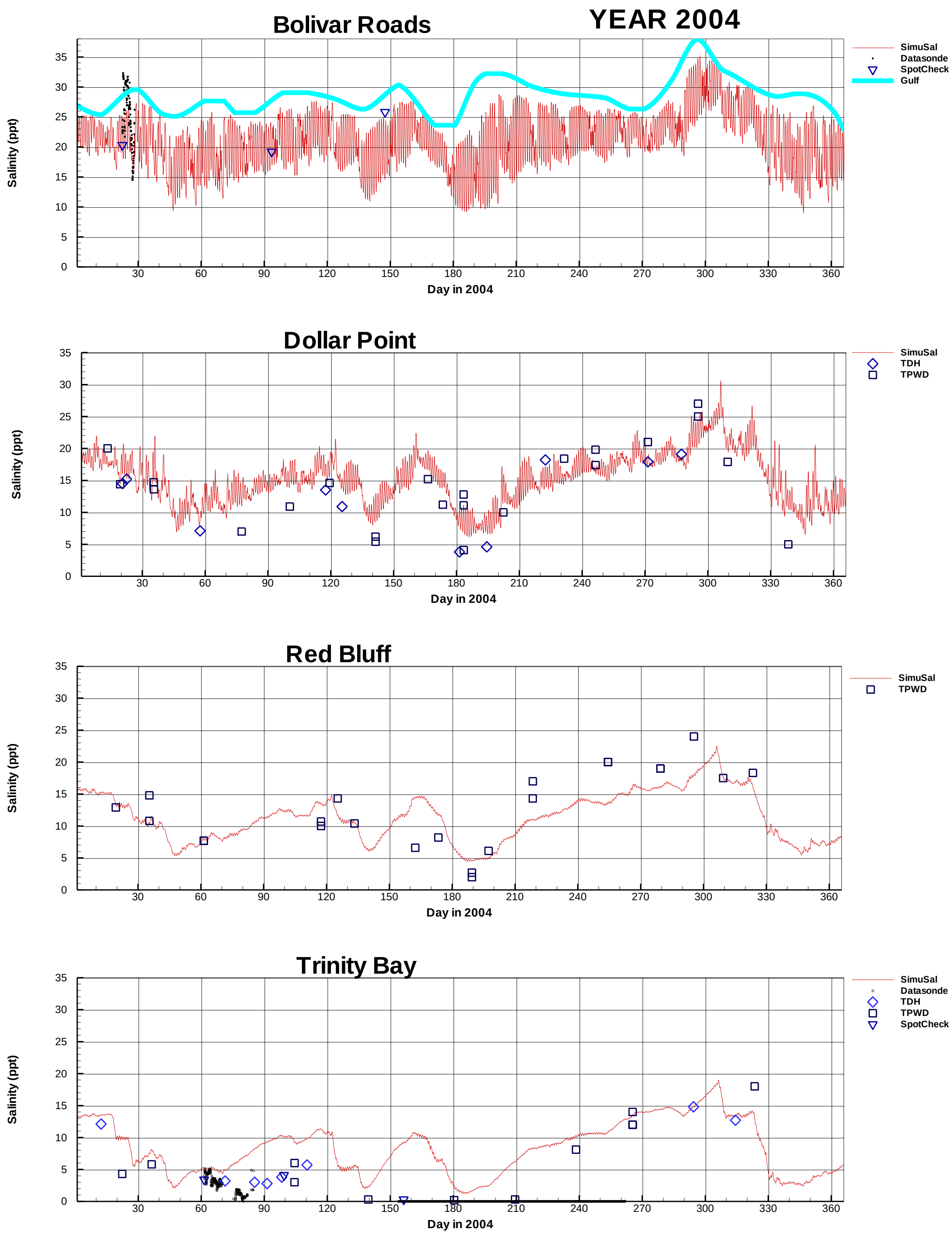


Figure 40. Simulated *(red)* and observed *(black (TWDB), inverted triangle (Spotcheck), small triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2004. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

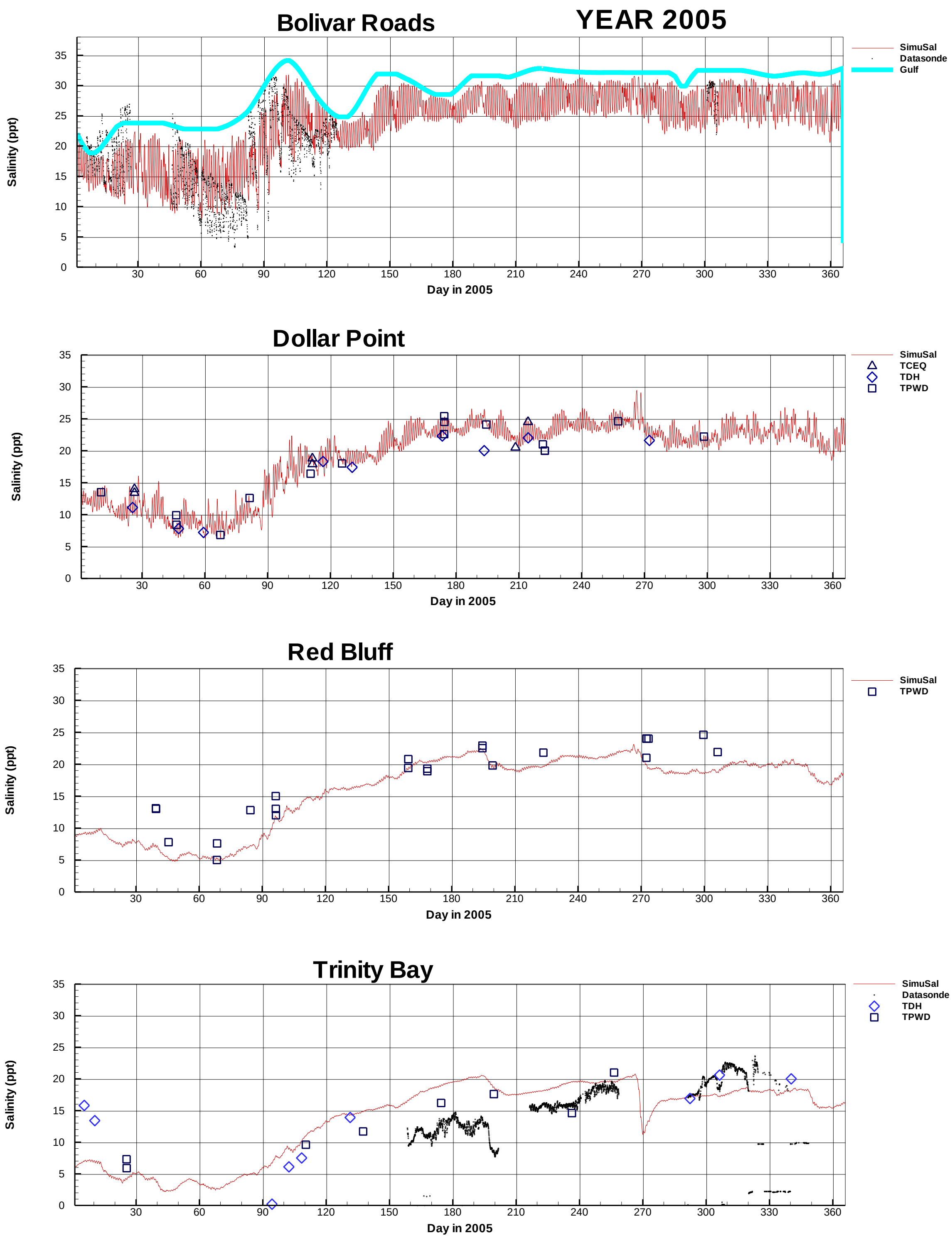


Figure 41. Simulated *(red)* and observed *(black (TWDB), inverted triangle (TCEQ), diamond (TDH), or square (TPWD))* salinities at Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay sites for 2005. Gulf salinities (*blue*) at Bolivar Roads were used to set the Gulf boundary salinity condition.

Discussion

Model calibration for velocity and surface elevation showed that the model was representative of observed conditions at most sites. The model simulated swift tidal currents in deep channels as well as reduced currents in shallow parts of the bay and accurately simulated water surface elevation throughout the system. Results for salinity calibration demonstrated that the TxBLEND model for the Trinity-San Jacinto Estuary was generally representative of observed salinities and trends, though long-term trends were simulated more accurately than short-term, high frequency variability, particularly in the upper estuary. The model also tended to over-predict salinity in the upper estuary, near sources of freshwater inflow and away from the Gulf passes. Nonetheless, overall model performance for salinity (as indicated by r^2 values ranging from 0.61 to 0.84 and a mean salinity difference between simulated and observed data ranging from 0.3 ppt to 3 ppt) was good. TxBLEND also captured across bay changes in observed salinity behavior, such as greater daily variation at the Bolivar Roads site as compared to the Trinity Bay site. Short-term, high inflow events and longer-term, seasonal, shifts in salinity (a function of seasonal changes in inflows) also were simulated well. The salinity validation exercise revealed that model performance for salinity simulation was similar to that observed during calibration. The model continued to perform reasonably well throughout the estuary, though simulated salinities again tended to be higher than observed values in the upper estuary and long-term trends were again more representative of bay conditions than short-term, high-frequency variations.

Model calibration improved TxBLEND's ability to simulate velocity, surface elevation, and salinity throughout the estuary. Overall, the model simulates long-term trends, though instances of over- or under-prediction occur at all sites. Short-term, high-frequency variations, such as those which occur with changes in the tidal cycle, are simulated by the model but are not as well represented. Additionally, the model has greater difficulty simulating conditions in the upper estuary. Recognizing the increasing interest by stakeholders in modeling freshwater inflow effects on wetlands, deltas, and other upper estuarine habitats, TWDB staff is working to improve model performance in this area. Additionally, TWDB staff continues to explore the use of three-dimensional hydrodynamic models in order to expand modeling capabilities in the Galveston Bay system.

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