Development of a Galveston Bay TxBLEND Hydrodynamic and Salinity Transport Model Through the Historic Drought of the 1950's

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Introduction

In Texas, a variety of approaches have been applied to the evaluation and management of freshwater inflow needs for the State's major estuaries. While early efforts focused on determining the optimal inflows for supporting economically important fisheries species, more recent efforts through the Texas Senate Bill 3 (2007) process for developing environmental flow regime recommendations as well as other independent studies (T-SJ BBEST 2009, Espey Consultants, Inc. 2009, Johns 2009, C-L BBEST 2011, G-SA BBEST 2011, Nueces BBEST 2011, RG BBEST 2012, Johns 2012) seek to determine the role of the timing and volume of freshwater inflow in sustaining the broader estuarine ecosystem. This modern focus on determining suitable freshwater inflow regimes includes understanding the importance of inflows for sediment and nutrient supply, retaining suitable habitat areas, and for limiting disease and parasites of key estuarine species, for example.

Many of these efforts rely on understanding the effects of historically dynamic inflow conditions, including droughts and flood cycles, on salinity patterns in the bay. One of the principal tools for examining such salinity patterns is TWDB's TxBLEND hydrodynamic and salinity transport model, which produces high-resolution, dynamic simulations of estuarine conditions over long periods of time. Presently, the TxBLEND model for the Trinity-San Jacinto Estuary (Galveston Bay) has been calibrated and validated for simulating the period of record from 1987 – 2005 (Guthrie *et al.* 2012). At the request of the National Wildlife Federation (NWF) in order to better understand long-term patterns of salinity and drought impacts to Texas estuaries, TWDB extended the TxBLEND simulation for Galveston Bay back 64 years to cover the drought of the 1950's, which historically has been recognized as the worst in Texas recorded history.

This report focuses on work elements for developing data and model parameters to extend the period of TxBLEND simulation for Galveston Bay back in time to cover the period from 1949 - 1986 as well as to extend it forward for the period 2006 - 2012 in order to provide the capability to simulate salinity patterns from 1950 - 2012. This TxBLEND model for Galveston Bay was not developed to aid in any specific analysis, but rather, was intended to be a proof of concept. Any applications of this model should take into consideration the evaluation of model performance as discussed in this report. Due to the exploratory nature of the project and the short time period in which to complete the work, future efforts should include further refinement of the methodology used to modify the TxBLEND model and the acquisition of additional historical salinity data, particularly during the drought of the 1950's, to provide for a more robust validation. Additional sources of historical data may exist that are not available electronically (*i.e.*, in archives maintained by Texas A&M University at Galveston) and would require significant effort to discover and digitize.

Methodology

TxBLEND Modifications

The TxBLEND hydrodynamic and salinity transport model is designed to simulate water level, water circulation, and salinity condition in estuaries. TWDB has developed and maintained this model for the Trinity-San Jacinto Estuary (Galveston Bay system) with the most recent model (Version S8HH.f; July 20, 2009) capable of simulating the period from 1987 – 2005 (Guthrie *et al*. 2012). Therefore, this TxBLEND version was utilized and modified for this effort to expand simulations to cover the period 1949 – 2012. Though parameter values for Manning's *n* and the dispersion coefficients remained the same, the computational model grid was modified to reflect the changing geometry of Galveston Bay since 1949. While many changes both subtle and substantial have occurred to the bay during the past 60+ years, for this study four distinct periods were identified and modeled based on changes in the opening of Rollover Pass and the deepening and widening of the Houston Ship Channel.

1949 - 1954: Houston Ship Channel (HSC) at 250 feet wide x 38 feet deep and Rollover Pass closed (Model designation CHN250NR; Figures 1, 2a, and 3a)

1955 - 1963: HSC at 250 feet wide x 38 feet deep and Rollover Pass open (Model designation CHN250; Figures 2b and 3a)

1964 - 2004: HSC at 400 feet wide x 40 feet deep and Rollover Pass open (Model designation CHN400; Figures 2b and 3b)

2005 - 2012: HSC at 530 feet wide x 45 feet deep and Rollover Pass open (Model designation CHN530; Figures 2b and 3c)

Three branches of the HSC (Entrance Channel, Texas City Channel, and the Galveston Channel) and the upper portion of the HSC were modified over the years and so also were included in the modifications. All details are presented in Table 1, and dimensions were provided by Mark Vincent, Port of Houston Authority (*pers. comm.*) based on information in Alperin 1977 (citation unavailable). Measurements for the channel dimensions of Barbour Cut to Boggy Bayou, Boggy Bayou to Sims Bayou, and Sims Bayou to the Turning Basin also are based on values provided by Mark Vincent (Appendix A). All four grids used in this model extension project represent the HSC with two rows of nodes, rather than three rows as in the most recent TxBLEND model version (used in simulations for the Senate Bill 3 process to establish environmental flow regime recommendations). Until 1963, the HSC was only 250 feet wide, less than half its present width. Therefore, to adequately model the earlier period yet still retain the same number of nodes throughout all four periods (grids), the HSC was modeled with only two rows of nodes for this study.

Table 1. Channel dimensions used in the extended Galveston Bay TxBLEND model. All channel dimensions are based on values from Alperin 1977 (via Mark Vincent, Port of Houston Authority, *pers. comm.*). Dimensions of the Entrance Channel, Galveston Channel, and Texas City Channel were estimated to be consistent with HSC development.

Model Designation	Entrance Channel	Houston Ship Channel	Barbour Cut to Boggy Bayou	Boggy Bayou to Sims Bayou	Sims Bayou to Turning Basin	Galveston Channel	Texas City Channel
CHN250NR	250' x 38'	250' x 38'	250' x 38'	250' x 38'	250' x 38'	500' x 37'	250' x 38'
CHN250	250' x 38'	250' x 38'	250' x 38'	250' x 38'	250' x 38'	500' x 37'	250' x 38'
CHN400	800' x 42'	400' x 42'	400' x 42'	300' x 42'	300' x 38'	1100' x 42'	400' x 42'
CHN530	800' x 47'	530' x 47'	400' x 47'	300' x 42'	300' x 38'	1100' x 42'	400' x 42'

Note: Channel width is design width; channel depth is design depth plus two feet.

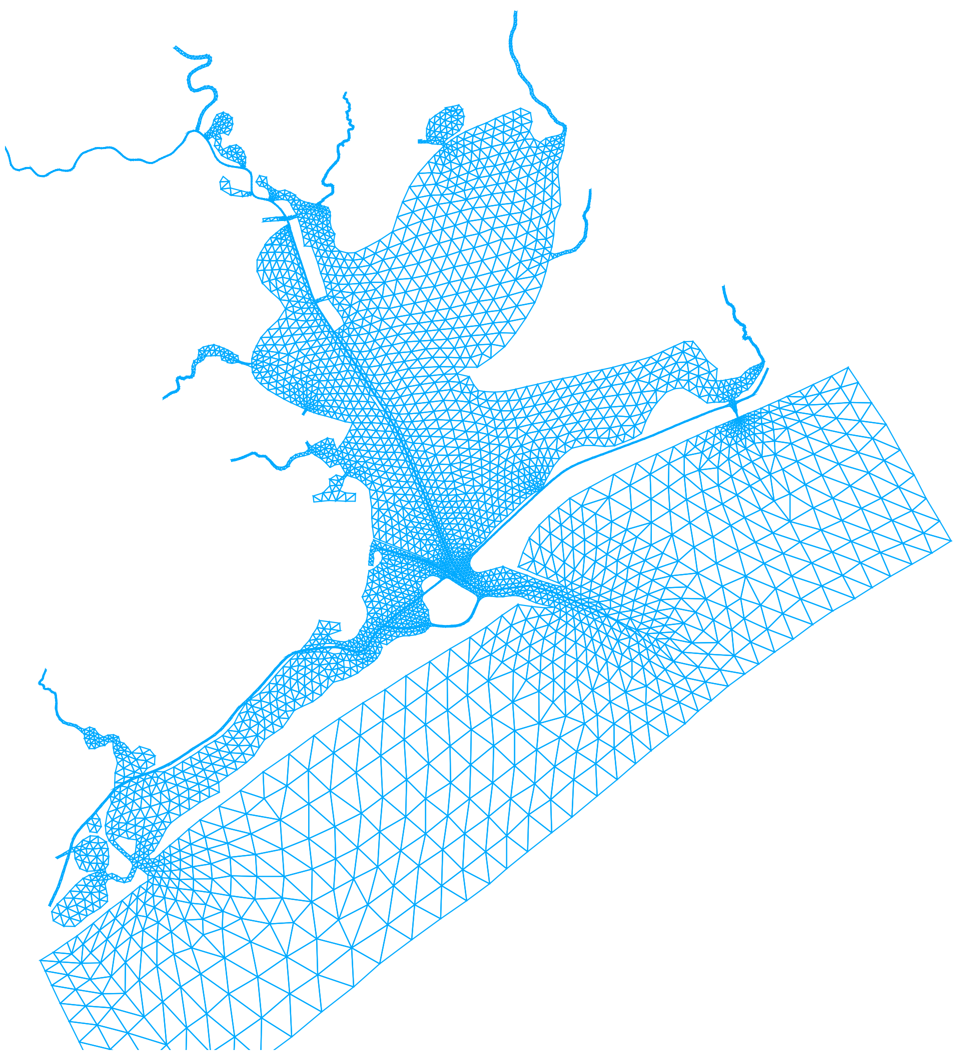

Figure 1. TxBLEND computational grid. Specific modifications were made to represent changes in bathymetry through time. All model grids have 4,826 nodes and 7,514 elements.

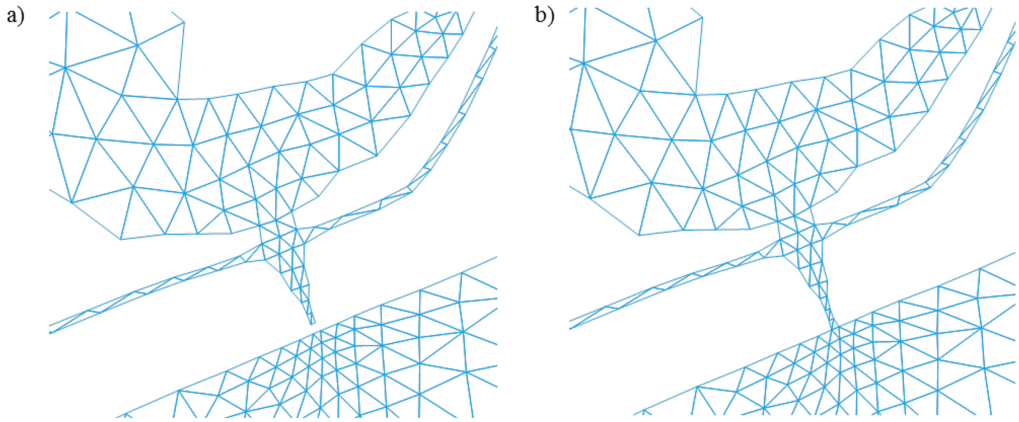

Figure 2. Computational grid for (a) CHN250NR with Rollover Pass closed and for (b) model designations with Rollover Pass opened. Rollover Pass and the Gulf are separated or joined by the absence or presence, respectively, of connecting elements.

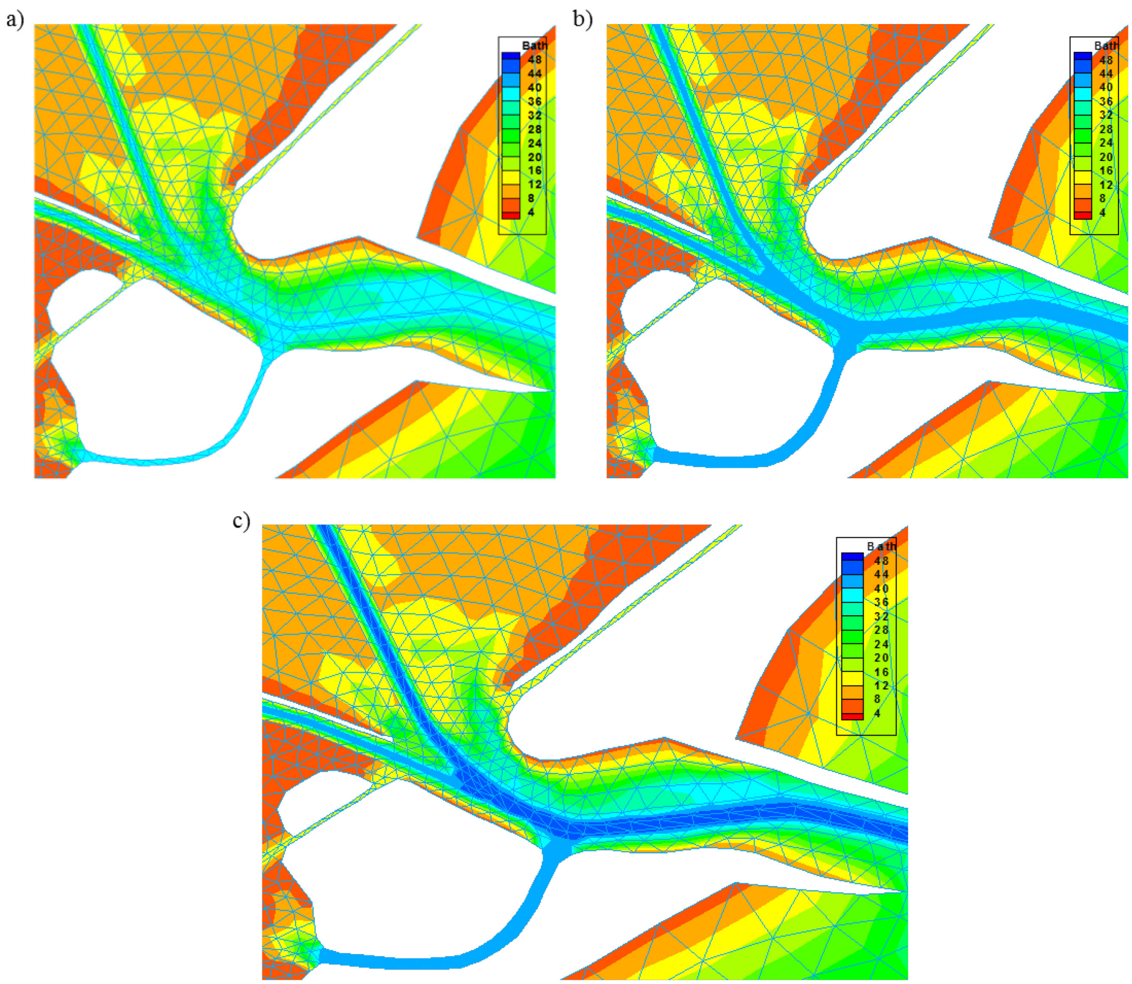

Figure 3. Computational grid and bathymetry along the Entrance Channel for model designations (a) CHN250NR and CHN250, (b) CHN400, and (c) CHN530.

Development of Model Inputs for the Extended Period

TxBLEND requires inputs for hydrology, meteorology, tides, and salinity which were compiled to cover the extension of the simulation period from 1949 – 1986 and for 2006 – 2012. Previously compiled datasets were available for 1987 – 2005, a period in which the Galveston Bay TxBLEND model was calibrated and validated (Guthrie *et al*. 2012).

Hydrology

TWDB estimates of daily freshwater inflow to the Galveston Bay system were distributed and applied among nine TxBLEND model inflow points (Figure 4 and Table 2) for the 1949 – 2012 period of simulation. For 1977 – 2012, inflow estimates were based on the current methodology for estimating coastal hydrology (Schoenbaechler *et al.* 2012) which relies on daily flows measured from gaged watersheds (Figure 5 and Table 3), estimated daily flows from ungaged watersheds using the Texas Rainfall-Runoff (TxRR) model, and monthly reports of diversion and return flows (distributed into daily amounts) provided by the Texas Commission on Environmental Quality (TCEQ).

Figure 4. Nine TxBLEND inflow points, Oyster Bayou, Double Bayou, Trinity River, Cedar Bayou, San Jacinto River, Buffalo Bayou, Clear Creek, Dickinson Bayou, and Chocolate Bayou and four power plant intake and discharge sites including: *A*, intake site at Cedar Bayou; *B*, discharge site near upper Galveston Bay; *C*, intake site at Dickinson Bay; *D*, discharge site near Bacliff.

Prior to 1977, however, TWDB records of ungaged, diversion, and return flows are only available as monthly, whole-bay estimates. Therefore to provide inflows as a model input for the nine TxBLEND inflow points, new daily estimates of stream flows, diversions, and returns were developed for each ungaged watershed. Stream flows for all ungaged watersheds were estimated with TxRR, several of which had not previously been modeled, *i.e.* watersheds #10020, #10030, #10100, #10110, #10063, #10065, #10066, #10074, #11081. This required developing watershed specific input files for TxRR that described the unique characteristics such as watershed number and area, TxRR model parameters, and simulation start and end dates for each watershed. Given the abbreviated time for completing this project, input files for newly modeled watersheds were based on TxRR model parameters of a previously modeled, nearby, similarly sized and shaped watershed. These watersheds and their representative counterpart are noted in Table 3 along with the period of record for stream flows (gaged or modeled) for all watersheds in the Galveston Bay drainage basin.

Flows for 12 watersheds upstream of Lake Houston were treated differently due to the completion of Lake Houston Dam in 1954 (Figure 5). For example, three USGS gages (#08070500, #08071000, and #08069500) were active upstream of the current Lake Houston Dam from 1949 to 1954. Using the active USGS gages, flows for watersheds #10101 and #10111 were determined using USGS gages #08070500 and #08071000, respectively. Flows from gage #08069500 represented flows from six watersheds (10040, 10080, 10081, 10090, 10091, and 10120) for which the flow was split evenly. Also, four ungaged watersheds upstream of the current Lake Houston Dam (watersheds #10020, #10030, #10100, #10110) required TxRR modeling to estimate flow prior to April 1954. TxRR input files were created using previously modeled watershed input files as described above.

Flow estimation for watershed #08020 was not included in the total freshwater inflow estimation due to unknown Lake Anahuac release and pumping data. TWDB contacted the Trinity Bay Conservation District for information regarding Lake Anahuac elevation and/or release data. Based on phone conversations with a Trinity Bay Conservation District representative, the Lake Anahuac outfall is an overflow structure and was damaged during Hurricane Ike. During reconstruction, the outfall design was modified and a new rating curve is needed in order to estimate flow calculations from Lake Anahuac to Trinity Bay. Furthermore, Lake Anahuac is primarily a water supply reservoir for Anahuac and the surrounding agricultural area. Thus, incomplete and missing pumping information to the adjacent canal system and unknown outfall/release data from Lake Anahuac prevented accurate freshwater inflow estimations from watershed #08020 into Trinity Bay.

Daily, watershed-specific diversion and return flow data were estimated by first calculating the ratio of a watershed's diversion (or return flow) contribution relative to the whole-bay value, based on data from 1977 – 2009. Next, these watershed-specific ratios were used to spatially assign monthly diversion and return flow values among each watershed for the period 1949 – 1976. Then, each monthly watershed value was divided by the number of days per month to yield a daily value.

Generally, permitted diversions and return flows are aggregated on a watershed level as inputs to the TxBLEND model, but two water rights permits relating to the P.H. Robinson Power Plant (permit #5363) and the Cedar Bayou Power Plant (permit #3926) were specifically assigned as diversion and return flow points in the TxBLEND model during the period 1949 - 2012 (Figure 4). These power plants divert large volumes of bay water on a daily basis for cooling purposes from one watershed before returning it to a different bay watershed. Specifically, the Robinson Power Plant diverts water from Salt Bayou, west of Dickinson Bay and San Leon (watershed #24390), and discharges water into Upper Galveston Bay near Bacliff (watershed #24210). The Cedar Bayou Power Plant in Baytown diverts water from Cedar Bayou (watershed #09010) and releases water into the northern side of Trinity Bay (watershed #07070). Monthly diversion and return flow values were available for both permitted uses from 1980 – 2001 (Matsumoto *et al*. 2005). For years 1949 – 1979 and 2002 – 2012, the Robinson and Cedar Bayou Power Plant return and diversion data was derived from TCEQ water use information (available at http://www.tceq.texas.gov/permitting/water_rights/wr_databases.html). Pertinent data was identified based on the water right number.

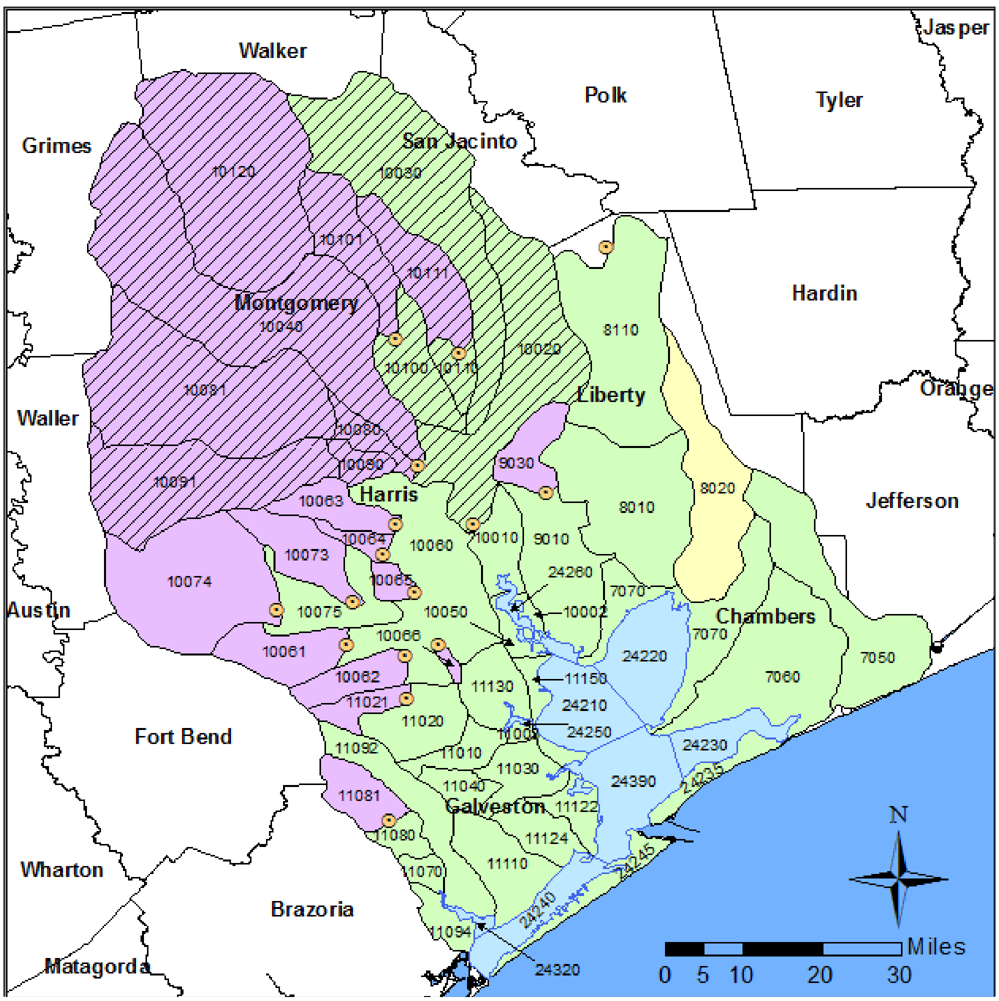

Figure 5. Lower Galveston Bay Basin gaged (*purple*) and ungaged (*green*) watersheds. Lake Houston watersheds are represented with cross-hatching and those colors are based on years 1949 – 1954, prior to construction of the dam. Watershed #08020 (*yellow*) was not included in the freshwater inflow estimations due to unknown Lake Anahuac release and pumping data.

Table 2. Distribution of inflows from surrounding river basins and coastal watersheds to the nine inflow points of the Trinity-San Jacinto Estuary TxBLEND model (Figure 4). 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

Table 3. Watersheds and the period of record in which stream flow data was either gaged by a USGS stream gaging station or modeled using TxRR. In some cases, newly modeled watersheds were assigned the characteristics of a similar (representative) watershed.

Watershed Number	USGS Gage Station Number	Gaged Period of Record	TxRR Modeled Period of Record	Representative Watershed
07050	n/a	n/a	1/1/1949 – 12/31/2012	n/a
07060	n/a	n/a	1/1/1949 – 12/31/2012	n/a
07070	n/a	n/a	1/1/1949 – 12/31/2012	n/a
08010	n/a	n/a	1/1/1949 – 12/31/2012	n/a
08110	n/a	n/a	1/1/1949 – 12/31/2012	n/a
09010	n/a	n/a	1/1/1949 – 12/31/2012	n/a
10010	n/a	n/a	1/1/1949 – 12/31/2012	n/a
10060	n/a	n/a	1/1/1949 – 12/31/2012	n/a
09030	8067500	10/1/1971 – 9/30/1991 & 10/1/2001 – 12/31/2012	1/1/1949 – 9/30/1971 & 10/1/1999 – 9/30/2001	n/a
10061	8075000	1/1/1949 – 12/31/2012	n/a	n/a
10062	8075500	10/1/1952 – 9/30/1995	1/1/1949 – 9/30/1952 & 9/30/1995 – 12/31/2012	
10063	8076000	10/1/1952 – 12/31/2012	1/1/1949 – 9/30/1952	10064
10064	8076500	10/1/1952 – 9/30/1993 & 10/1/2000–12/31/2012	1/1/1949 – 9/30/1952 & 10/1/1993 - 9/30/2000	n/a
10065	8075770	4/14/1964 – 9/30/2004 10/1/2005 – 12/31/2012	1/1/1949 – 4/14/1964 & 10/1/2004 – 9/30/2005	10064
10066	8075730	10/1/1971 – 12/31/2012	1/1/1949 – 9/30/1971	10062
10073	8074500	1949 – 2012		n/a
10074	8073600	9/1/1971 – 12/31/2012	1/1/1949 – 9/1/1971	10075
11021	8077000	1/1/1949 -12/31/1959 & 4/1/1963 – 9/4/1994	1/1/1960 – 3/31/1963 & 9/5/1994 – 12/31/2012	n/a
11081	8078000	3/1/1959 – 12/31/2012	1/1/1949 – 2/28/1959	11080
Trinity	8066500	1949 – 2012	n/a	n/a
Lake Houston	8072000	4/1/1954 – 12/31/2012	* (see below)	n/a
10120*,10040*, 10080*,10081*, 10090*, 10091*	8069500	1/1/1949 – 3/31/1954	n/a	n/a
10020*	n/a	n/a	1/1/1949 – 3/31/1954	10062
10030*	n/a	n/a	1/1/1949 – 3/31/1954	10062
10100*	n/a		1/1/1949 – 3/31/1954	10062
10101*	8070500	1/1/1949 – 3/31/1954	n/a	n/a
10110*	n/a		1/1/1949 – 3/31/1954	10062
10111*	8071000	1/1/1949 – 3/31/1954	n/a	n/a

* Indicates watershed upstream of Lake Houston Dam

Meteorology

As with previous TxBLEND models, time-varying and spatially uniform meteorology data (wind, air temperature, precipitation, and evaporation) was used to drive the model (refer to Guthrie *et al*. 2012 for more information). Wind speed, direction, and air temperature were obtained for Sholes International Airport in Galveston from the National Climatic Data Center (www.ncdc.noaa.gov). Missing data were filled in using measurements from Ellington Air Force Base near Houston. Precipitation data was downloaded from the National Weather Service (NWS; http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/) for use in developing coastal hydrology for ungaged watersheds, as previously described, and for determining daily precipitation across the bay (which was based on precipitation over watershed #24390). Precipitation also was used to estimate and apply daily net evaporation across the model domain.

Net evaporation is calculated as evaporation minus precipitation, such that a positive net evaporation equates to a water loss and a negative net evaporation equates to a water gain within the system. Daily evaporation data was calculated based on the Harbeck equation which considers air temperature, dew point temperature, and wind speed (Brandes and Mash 1972). Calculated daily evaporation estimates were summed and compared to the monthly estimates from QUAD#813 of the TWDB Evaporation Program for quality control purposes. If the difference was large, the calculated daily data was adjusted, usually by 10 – 20%, so that the calculated monthly values were similar to the monthly estimates generated from the TWDB Evaporation Program (Appendix B). The annual average evaporation (based on the period 1949 - 2012) for QUAD#813 as generated by the TWDB Evaporation Program is 3.84 feet, whereas the calculated (and adjusted) annual average evaporation based on the Harbeck equation is 3.64 feet.

Tides

Tide (water level) data is used to activate water movement applied at the Gulf boundary of the TxBLEND model. Most of the tide input came from measured and predicted hourly tide (water level) data at the Galveston Pleasure Pier gage station, a station within the National Oceanic and Atmospheric Administration (NOAA) network of tide gages. NOAA deactivated the Pleasure Pier Station in July 2011, so input also was derived from a nearby gage, the Galveston Bay Entrance North Jetty station for the period July 2011 – December 2012. The North Jetty station is part of the Texas Coastal Ocean Observation Network (TCOON) which is operated by the Conrad Blucher Institute (CBI) of Texas A&M University – Corpus Christi.

Measured and predicted hourly tide (water level) data were downloaded from the NOAA website (http://tidesandcurrents.noaa.gov) for the Pleasure Pier Station (ID: 8771510) from 1949 through June 30, 2011 (Figures 6 - 8). Measured data began August 21, 1957 and ended on July 20, 2011 when Pleasure Pier was closed to repair damages from 2008's Hurricane Ike. From 1949 through July of 1957, only predicted values were available, and they were downloaded and used for TxBLEND model input. There also were periods where sequential months had no measured data (*i.e.*, 1965 and 1979, Table 4), so the predicted values again were used. However, during some of these data gaps between 1957 and 2002, predicted water levels were adjusted to better match the levels measured on nearby dates. Forecasts are based on harmonics of the moon's gravity and sun's gravity interacting with the earth's oceans and do not take meteorological conditions into account. Therefore, while the observed tide typically follows the pattern of the forecasted tide, there is often a shift up or down in the absolute water level due to weather. Figure 9 shows where the predicted levels were shifted downwards to fill in missing measurements the week of June 2 -7, 1964. While the harmonic prediction is shown as a black line, available measured data is displayed with a blue "+" sign. The green line, with an absence of these marks, shows where the predicted values (*black line*) were shifted downward to match measured data from nearby dates. This green curve represents the information used in the TxBLEND simulations. There were no missing measurements from NOAA for the period 2003 through June 2011.

Water levels from the North Jetty Station (CBI ID: 529, http://www.cbi.tamucc.edu/dnr/station) were used to simulate water levels at Pleasure Pier after July 2011. The North Jetty Station began collecting data on March 17, 2011. Therefore, Pleasure Pier and North Jetty stations operated continuously and concurrently from March 17 to July 20, 2011. Four months of overlapping data collection allowed for a comparison of the tide signals and for a derivation of factors to simulate the Pleasure Pier tide from North Jetty data. All final water level data applied in the TxBLEND simulations were reported in feet, were vertically referenced to Mean Sea Level (MSL = 4.61 feet (1.404 meters)) for the station's datum, and referenced to Central Standard Time (CST).

Table 4. Percentage of time within each month that measured water levels were available from the Galveston Pleasure Pier Gage Station (ID: 8771510), shown only for years with incomplete data while the gage was in operation from 1957 – 2011. Data gaps were filled by shifting NOAA's predicted values according to measured levels nearest the missing data. Months with no data (nd) designate the period before and after the gage was in operation at this site.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	nd	nd	nd	nd	nd	nd	nd	34.7	100	100	100	100
1963	100	100	81.5	58.3	100	100	100	100	100	100	100	100
1964	100	100	100	100	100	53.3	77.7	100	100	100	100	100
1965	100	3.3	0	0	0	0	0	63.7	100	100	100	81.5
1966	99.2	82.1	67.7	100	100	100	100	100	100	71	100	82.7
1967	100	89.9	100	100	100	100	100	100	100	100	100	100
1968	100	100	100	100	100	21.1	63.7	100	100	100	100	100
1972	100	100	100	100	100	100	100	100	100	100	100	96.8
1973	96	97.6	94.5	96	97.7	100	76.3	23.9	100	100	100	100
1974	99.6	100	85.3	100	100	100	100	100	100	100	100	100
1976	100	100	100	100	100	100	100	0.8	38.5	78.9	100	100
1977	100	100	100	100	100	96.4	99.7	100	100	100	100	100
1978	100	100	94.2	100	100	98.6	100	100	100	100	100	99.2
1979	0	0	0	0	0	0	0	99.2	96.7	100	100	100
1981	100	100	64.9	74.2	100	100	100	100	100	100	100	100
1991	100	100	100	100	48	100	100	100	100	100	100	100
1995	100	100	84.4	100	100	100	100	100	100	100	100	100
2002	100	100	100	99.7	100	100	100	100	100	100	100	100
2011	100	100	100	100	100	100	nd	nd	nd	nd	nd	nd

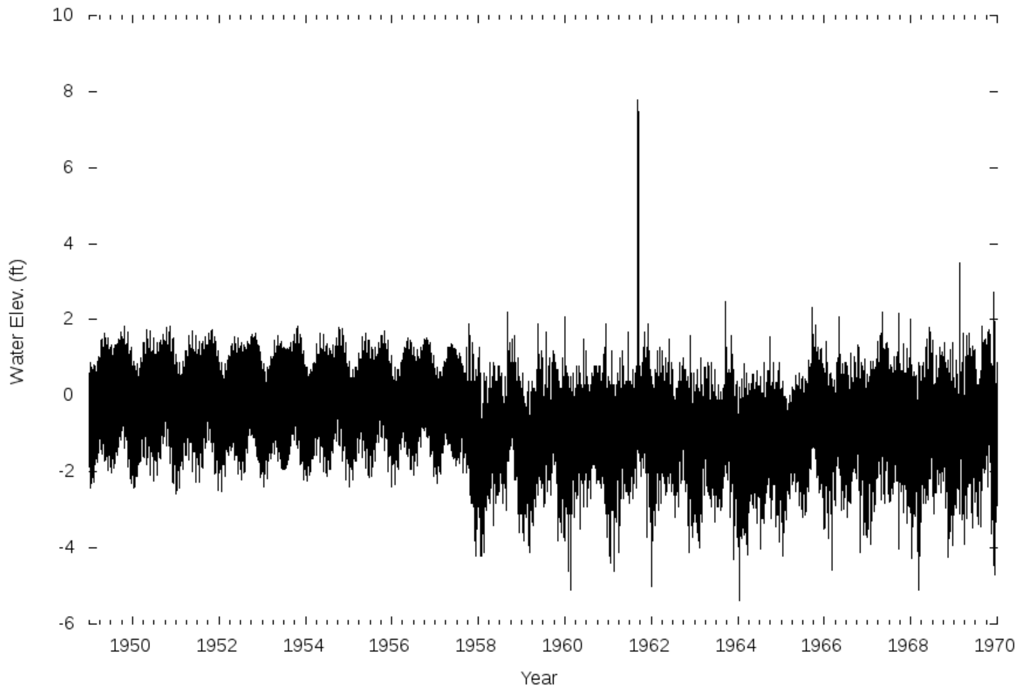

Figure 6. Measured and predicted hourly tides (water level) at the Galveston Pleasure Pier gage station (NOAA ID: 8771510) from 1950 – 1970. *Note*: The spike in 1961 corresponds to the impact of Hurricane Carla on Galveston Bay.

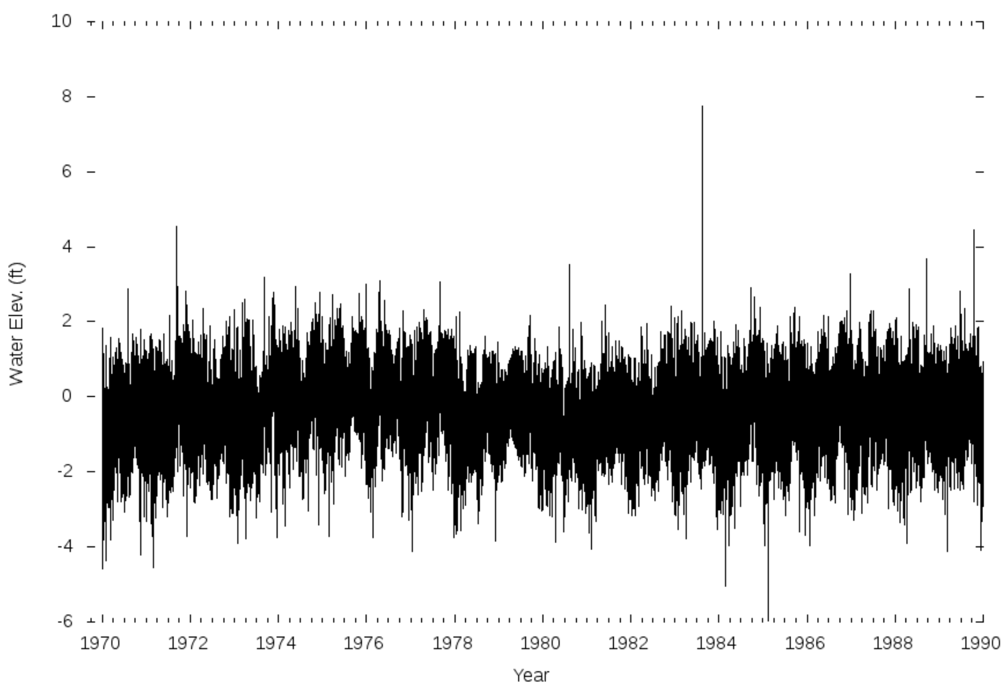

Figure 7. Measured and predicted hourly tides (water level) at the Galveston Pleasure Pier gage station (NOAA ID: 8771510) from 1970 – 1990. *Note*: The spike in 1983 corresponds to the impact of Hurricane Alicia on Galveston Bay.

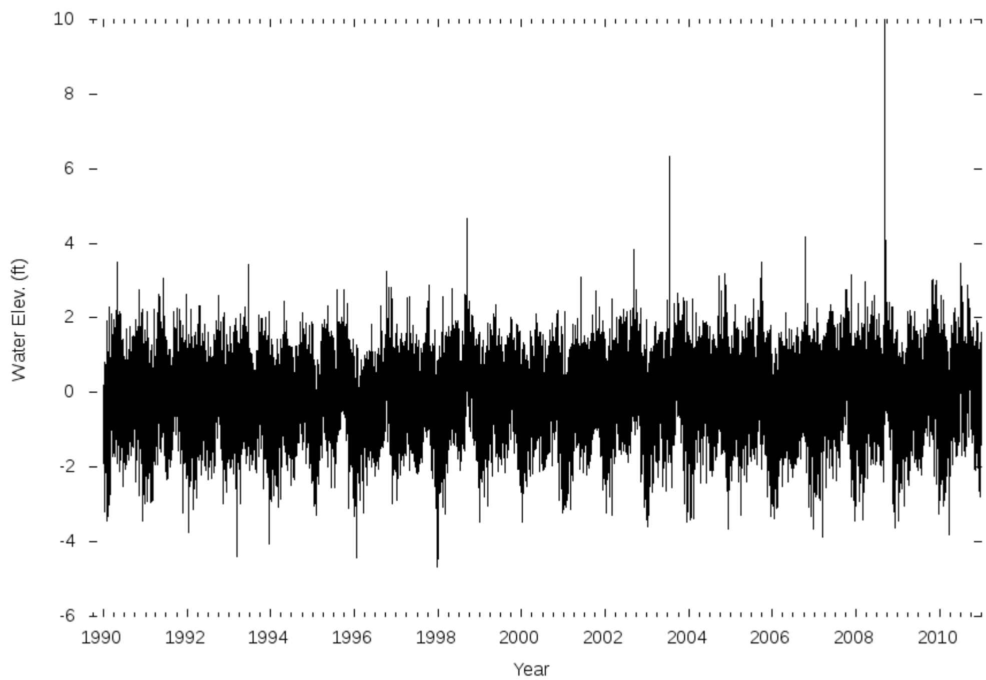

Figure 8. Measured and predicted hourly tides (water level) at the Galveston Pleasure Pier gage station (NOAA ID: 8771510) and the nearby Galveston Bay North Jetty gage station (CBI ID: 529) from 1990 – 2011. *Note*: The spike in 2008 corresponds to the impact of Hurricane Ike on Galveston Bay.

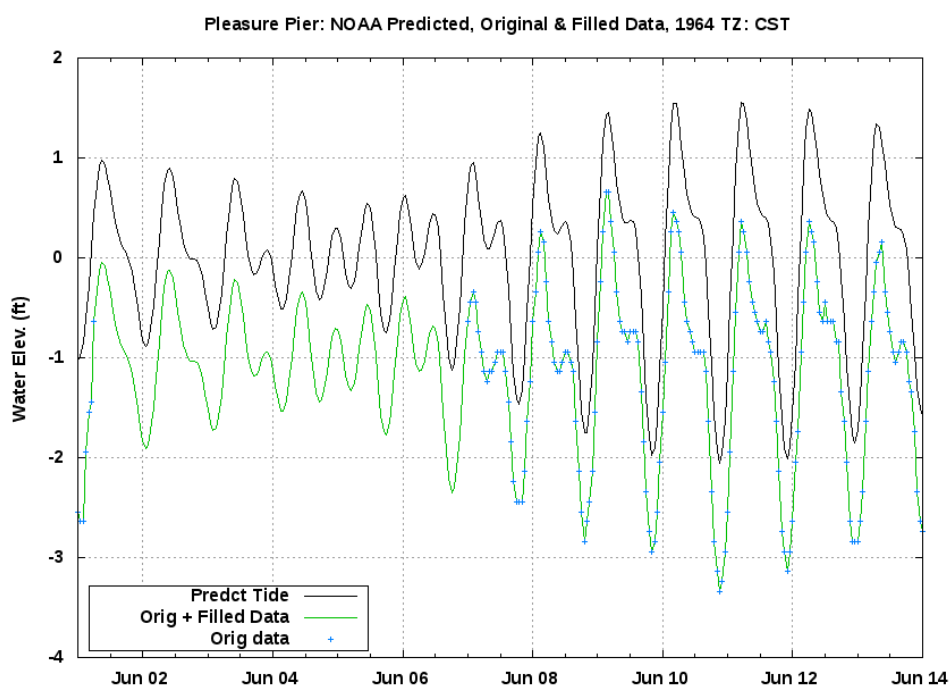

Figure 9. Predicted tides (*black line*) were shifted as necessary (*green line*), and in this example for June 2 – 7, 1964, were shifted downwards, to correspond with measured levels (*blue* +) from days nearest the missing data.

Offshore Salinity Boundary Condition

Gulf of Mexico offshore salinity condition influences within-bay salinities, and therefore is considered as a boundary condition within the TxBLEND model. For this exercise, the offshore salinity boundary condition was developed using Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Monitoring Program salinity measurements recorded from 1986 – 2012 in the vicinity of Bolivar Pass (Figure 10). Discrete salinity samples collected at various offshore locations within the model domain were applied at the ocean boundary assuming spatially uniform offshore salinity in the model domain. The salinity samples were typically collected twice a month and were interpolated to daily frequency needed by TxBLEND using cubic spline interpolation. However, when there were multiple records per day, they were averaged before the interpolation. No data was available from 1949 – 1985 (Figure 11); therefore, for this period offshore salinity was estimated using a multiple linear regression analysis that accounted for the influence of freshwater inflow into the Gulf of Mexico from the Mississippi, Atchafalaya, Sabine-Neches, and Trinity-San Jacinto river basins. Previous modeling studies (http://pong.tamu.edu/~rob/mch/) have shown that near-shore salinities in the Galveston Bay region are affected by outflows from the Mississippi and Atchafalaya rivers. While inflows from these four regions were considered, analyses which also incorporated a long-shore current did not return an improvement and so was not used in this effort.

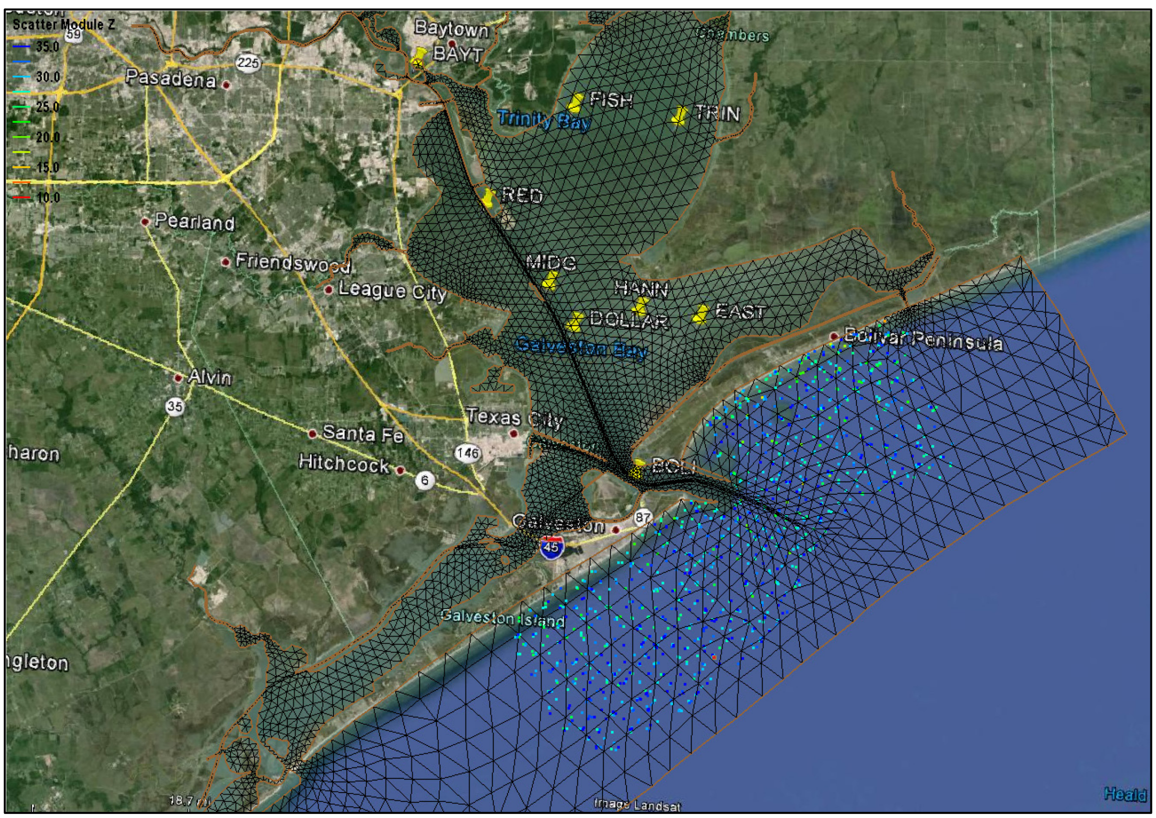

Figure 10. Location of available TPWD Coastal Fisheries offshore salinity data (*blue and green circles*) with respect to the Galveston Bay TxBLEND model grid which were used to develop the offshore salinity boundary condition for the period 1986 – 2012. Also shown are TWDB Datasonde locations (*yellow markers*) within Galveston Bay.

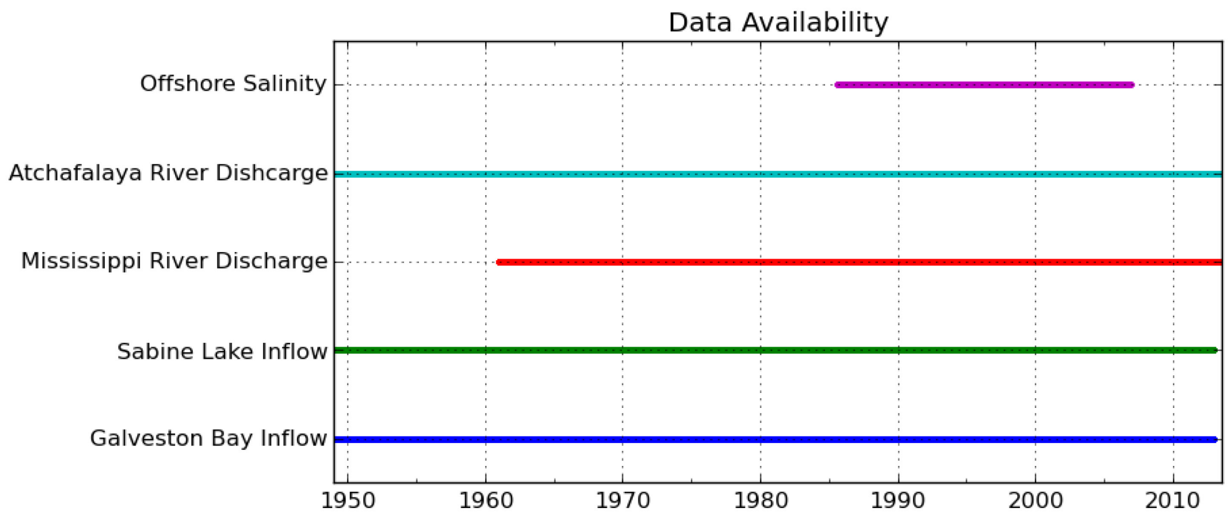

Figure 11. Availability of TPWD Coastal Fisheries offshore salinity data near Bolivar Pass (purple) and availability of freshwater inflow records for four Gulf Coast river basins, Atchafalaya (turquoise), Mississippi (red), Sabine-Neches (green), Trinity-San Jacinto (dark blue).

The regression equation was developed using a period of 20 years (1986 – 2006) when all data was available. Mississippi and Atchafalaya river flows were obtained from the United States Army Corps of Engineers (http://www2.mvn.usace.army.mil/eng/edhd/wcontrol/discharge.asp). Sabine Lake inflows from the Sabine and Neches rivers were obtained from United States Geological Survey gage records (Gages #08041780 and #08030500, found at (http://waterservices.usgs.gov/nwis/dv/?endDT=2012-12-31&startDT=1949-01-01&site=08041780&format=waterml and http://waterservices.usgs.gov/nwis/dv/?endDT=2012-12-31&startDT=1949-01-01&site=08030500&format=waterml). Galveston Bay inflows were obtained from TWDB's Coastal Hydrology dataset which included gaged and ungaged estimates of inflows discussed in the hydrology section of this report.

The equation which best predicted salinity offshore (RMS = 3.53 ppt) was:

$$S = 55.12 - 0.37\ln(Q_M) - 1.11\ln(Q_A) - 0.33\ln(Q_{SN}) - 0.57\ln(Q_{TSJ})$$

where, Q_M = Mississippi River outflow
Q_A = Atchafalaya River outflow
Q_{SN} = Sabine Lake inflows based on gaged inflows from Sabine and Neches Rivers
Q_{TSJ} = Galveston Bay inflows based on TWDB Coastal Hydrology estimates.

This equation was used to predict salinity and to determine the offshore boundary condition for the period 1961 – 1985, when Mississippi River inflow data was available. When Mississippi River inflows were not available, a different equation that similarly predicted salinity (RMS = 3.49 ppt) was used to develop offshore salinity condition for the period 1949 – 1960.

This secondary equation was:

$$S = 54.74 - 1.47\ln(Q_A) - 0.33\ln(Q_{SN}) - 0.57\ln(Q_{TSJ})$$

The combination of TPWD Coastal Fisheries data, along with the data developed by the two salinity regression equations then, provided offshore salinity boundary condition for the full model simulation period from 1950 – 2012.

Model Simulations

The Galveston Bay TxBLEND model simulated salinity and water currents from 1949 – 2012. However in order to capture the bathymetric changes associated with the reoccurring deepening and widening of the Houston Ship Channel and the opening of Rollover Pass, four sequential simulations were run to cover the 64-year period, beginning with a simulation of model CHN250NR from 1/1/1949 to 12/31/1954. At the end of this simulation, computed values for surface water elevation (z), velocity (u and v), and salinity (c) were saved and used to initiate the simulation of model CHN250 from 1/1/1955 to 12/31/1963. The next sequential simulation was for model CHN400, which covered the longest period, from 1/1/1964 – 12/31/2004, and was similarly started with the data from the prior simulation. The final simulation used model CHN530 and covered the most recent period from 1/1/2005 to 12/31/2012. Due to differences in channel bathymetry, the four model grids differ somewhat but were made to have the same number of nodes to facilitate utilizing each model's simulation output as the initial condition for the next sequential model run. Model runs allowed for a one-year ramp-up period during 1949, prior to running simulations for model validation for 1950 -2012, to allow the model to distribute salinity appropriately.

Model Validation

The Galveston Bay TxBLEND model used for this study was previously calibrated and validated for salinity performance for the period 1987 – 2005 at four TWDB Datasonde stations, Bolivar Roads (BOLI), Dollar Point (DOLLAR), Red Bluff (RED), and Trinity Bay (TRIN) (Figure 12; Guthrie *et al*. 2012). Point measurements from TPWD's Coastal Fisheries Monitoring Program database, TCEQ's Surface Water Quality Monitoring database, and the Texas Department of State Health Services Shell Fish Safety Program database also were used in those validation efforts. Since previously acquired and applied salinity data used in model validation covered only the period from 1987 – 2005, salinity data used to validate model performance was compiled from a variety of sources in order to cover the entire 1950 – 2012 simulation period (Appendix B), including TPWD's historical Coastal Fisheries Project Reports (*e.g.*, Hofstetter 1959, Martinez 1971, Moffett 1964, etc.) and a compilation of databases prepared for the Galveston Bay Estuary Program (Ward and Armstrong 1992). Finally, TWDB's Datasonde data was used to validate the model for the more recent period of 2006 – 2012.

Model validation for this study included an assessment of salinity performance during the period 1950 – 1986 and 2006 – 2012 for the four TWDB Datasonde sites previously assessed, as well as an assessment for the entire period at other locations of interest throughout the bay. In total, thirteen sites of interest were identified for validation purposes. Apart from the four TWDB Datasonde stations listed above, six additional Datasonde locations were evaluated: Houston Ship Channel at Baytown (BAYT), Mid-Galveston Bay (MIDG), East Bay (EAST), Fisher's Reef (FISH), and Hanna's Reef (HANN). Three other areas of interest also were evaluated: Trinity River Mouth (TRINM), Houston Point near San Jacinto River Mouth (HOUSPT), and West Bay (WEST).

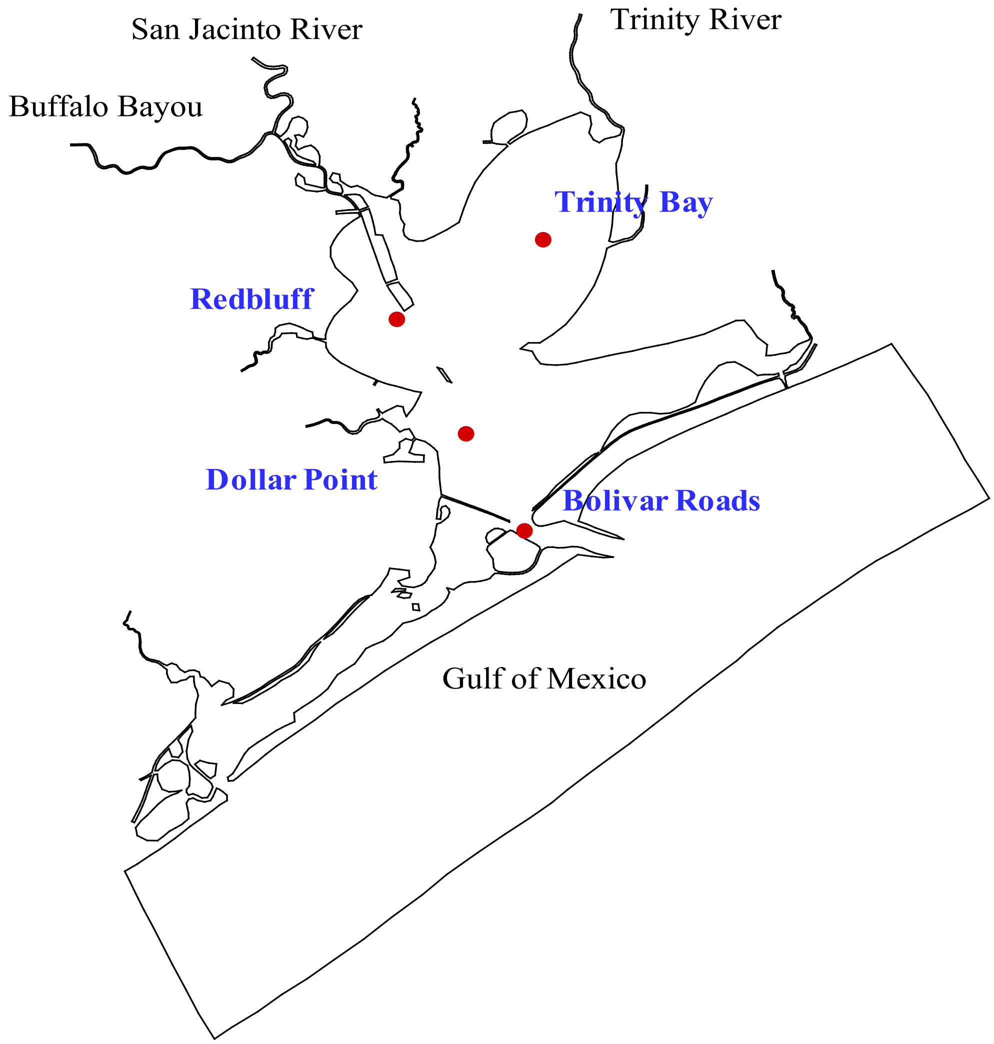

Figure 12. Locations of TWDB Datasonde stations, Bolivar Roads (BOLI), Dollar Point (DOLLAR), Red Bluff (RED), and Trinity Bay (TRIN), where salinity performance was previously evaluated for the period 1987 – 2005.

Historical Salinity Data Compilation and Manipulation

Salinity data were extracted and compiled from historic documents to allow for model validation during the early period from 1950 – 1986. As aforementioned, two valuable sources of historical data were used in this model validation exercise: (1) the historical Coastal Fisheries Project Reports generated by TPWD and stored in an archive maintained by Texas A&M University - Galveston and (2) a water quality dataset compiled for Galveston Bay by Ward and Armstrong (1992).

The historical Coastal Fisheries Project Reports reported salinity values in a variety of inconsistent formats, including instantaneous point measurements, monthly average salinity, non-specified monthly salinity (a value that was not specified to be either an average of multiple samples or a singular point-measurement taken during a given month), seasonal averages, and salinity ranges. In sum, these reports span a period of record from 1958 – 1978. By far, most of these reports presented data as either a monthly average value or a non-specified monthly value, resulting in approximately 3,800 observations. These data were collected throughout Galveston Bay and provide broad spatial coverage (Figure 13).

Tabular data presented in the TPWD reports were manually compiled into one database. Typically, data from the reports did not contain geographic coordinates of sampling locations, but rather hand-drawn maps that show approximate locations of sampling stations. The hand-drawn maps were geo-referenced in a GIS environment in order to determine geographic coordinates of salinity sampling stations. In some cases, sampling locations were not specified, and these salinity data were omitted from the validation exercise. Additionally, only the non-specified monthly and monthly average salinity values were used for comparison in the validation exercise, because this was the most common type of data compiled from the reports and too few data points of the other types of salinity values were reported. Due to many unknowns associated with this dataset, the data was not used in statistical tests, but rather for aid in visual comparison.

Ward and Armstrong (1992) compiled one of the most comprehensive water quality datasets ever assembled for Galveston Bay. Geo-referenced salinity data from over twenty-five sampling programs were collected and organized into a standardized, consistent format that span a period of record from 1950 – 1991 at numerous locations throughout the bay, which total approximately 77,000 observations. This dataset provides extensive spatial coverage across the entirety of Galveston Bay (Figure 13). Other than converting the coordinate data from degrees/minutes/seconds to decimal degrees, the data was not altered from its original format as compiled by Ward and Armstrong (1992).

In order to provide an adequate, yet manageable number of data points for comparison in this validation exercise, a subset of salinity data compiled from the Coastal Fisheries Project reports and Ward and Armstrong (1992) were used. Groupings of salinity data were established for each data source by designating a circular region with a radius of one mile around identified center points in each area of interest (Figure 14). Circular regions of this size were chosen based on the assumption that salinity variation is minimal in an area of this size. All ten TWDB Datasondes that have been deployed in Galveston Bay at some point in history were used as center points, while center points for the other three areas of interest were randomly chosen (Table 5). Only salinity data extracted from these groups were used to validate the model for the early period of model simulation from 1950 – 1986.

This period was separated into five-year intervals to ensure that historical data from at least two distinct geographic locations and from at least two distinct points in time (separated by at least a month) were used in model validation. In fact, in most five-year intervals, more than four data points were available for comparison. However, data from the Coastal Fisheries Project Reports were not always included in the designated circular salinity groupings at every location because that dataset is so much smaller compared to Ward and Armstrong (1992) and in many cases data points did not fall within the designated area. After employing this methodology to extract a manageable number of data points for validation, 233 observations were used from the Coastal Fisheries Project Reports and 5,514 observations were used from Ward & Armstrong (1992).

Although an extensive dataset was generated for this validation exercise, there is limited salinity data during the period of most interest - the drought of record during the 1950's. Data availability plots (Figures 15 - 17) show that less data is available during the period 1950 – 1960 across all sites compared to other time periods. However, data is available during the drought of record at locations other than those chosen for validation in this study (Figures 18 and 19). Future investigations may include validating the model at other locations that have more salinity observations during the drought of record.

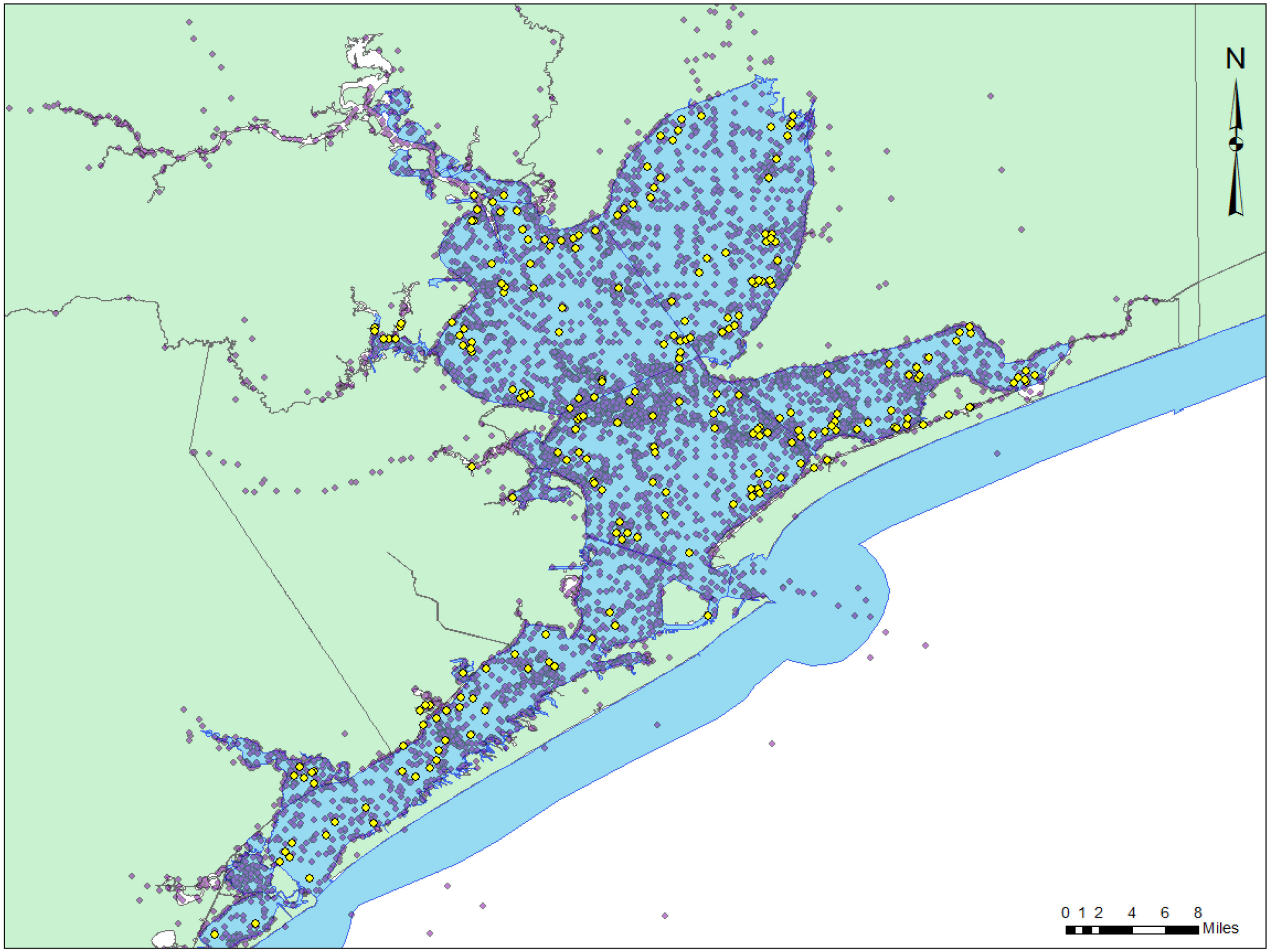

Figure 13. Sampling locations of historical salinity data, as compiled by Ward & Armstrong 1992 (*purple circles*) and TPWD Coastal Fisheries Project Reports (*yellow circles*).

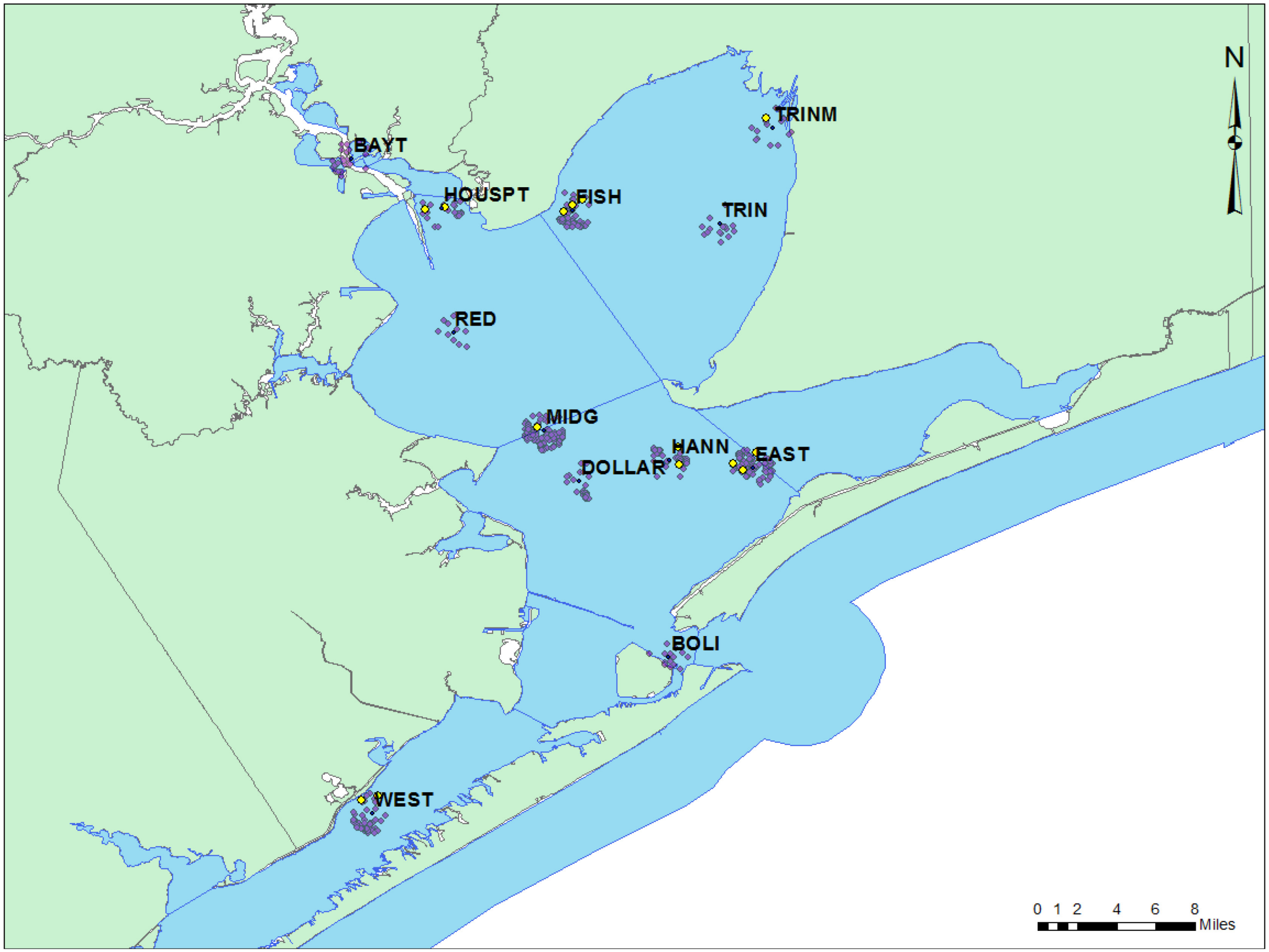

Figure 14. Locations (consisting of circular area with a one mile radius) of historical salinity data used for model validation for the period 1950 – 1986. *Purple circles* represent data that was compiled by Ward & Armstrong (1992), and *yellow circles* represent data compiled from TPWD Coastal Fisheries Project Reports.

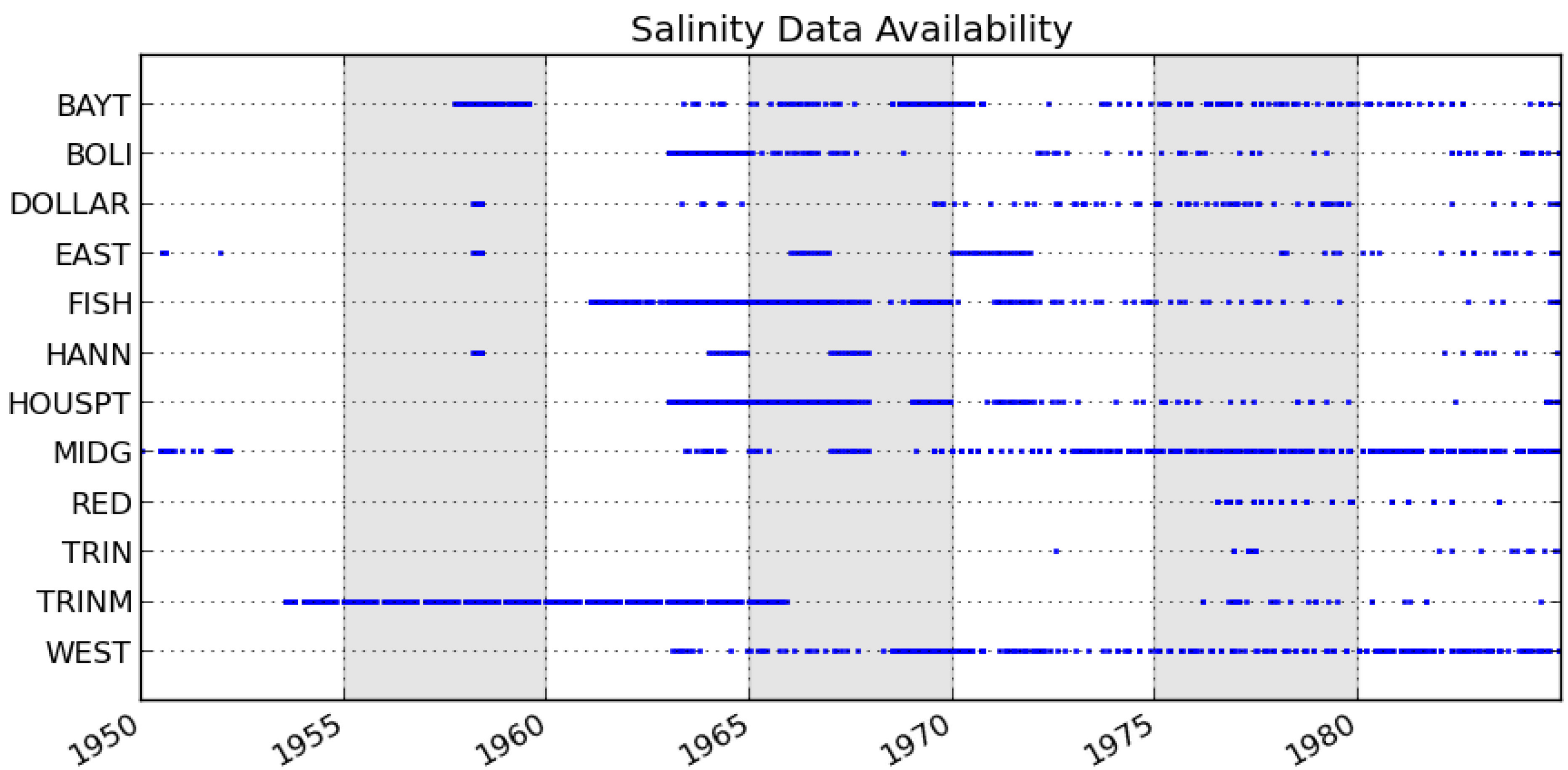

Figure 15. Historical salinity data availability from 1950 – 1985 at thirteen locations in Galveston Bay, including Baytown (BAYT), Bolivar Roads (BOLI), Dollar Point (DOLLAR), East Bay (EAST), Fisher's Reef (FISH), Hanna's Reef (HANN), Houston Point (HOUSPT), Mid-Galveston Bay (MIDG), Old River (OLDR), Redbluff (RED), Trinity Bay (TRIN), Trinity River Mouth (TRINM), and West Bay (WEST). Data sources include Coastal Fisheries Reports and Ward & Armstrong 1992.

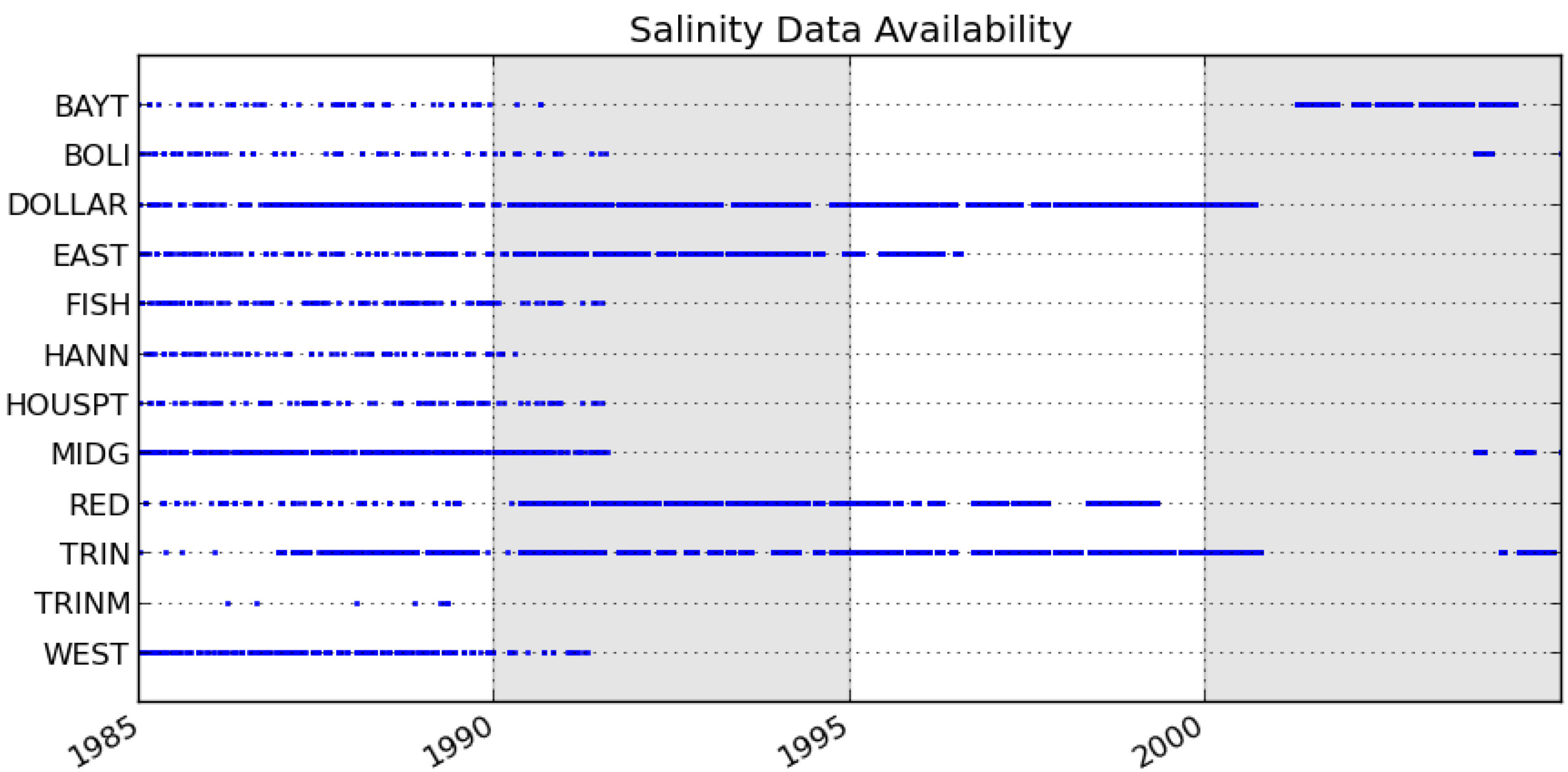

Figure 16. Historical salinity data availability from 1985 – 2005 at thirteen locations in Galveston Bay, including Baytown (BAYT), Bolivar Roads (BOLI), Dollar Point (DOLLAR), East Bay (EAST), Fisher's Reef (FISH), Hanna's Reef (HANN), Houston Point (HOUSPT), Mid-Galveston Bay (MIDG), Old River (OLDR), Redbluff (RED), Trinity Bay (TRIN), Trinity River Mouth (TRINM), and West Bay (WEST). Data sources include Coastal Fisheries Reports and Ward & Armstrong 1992.

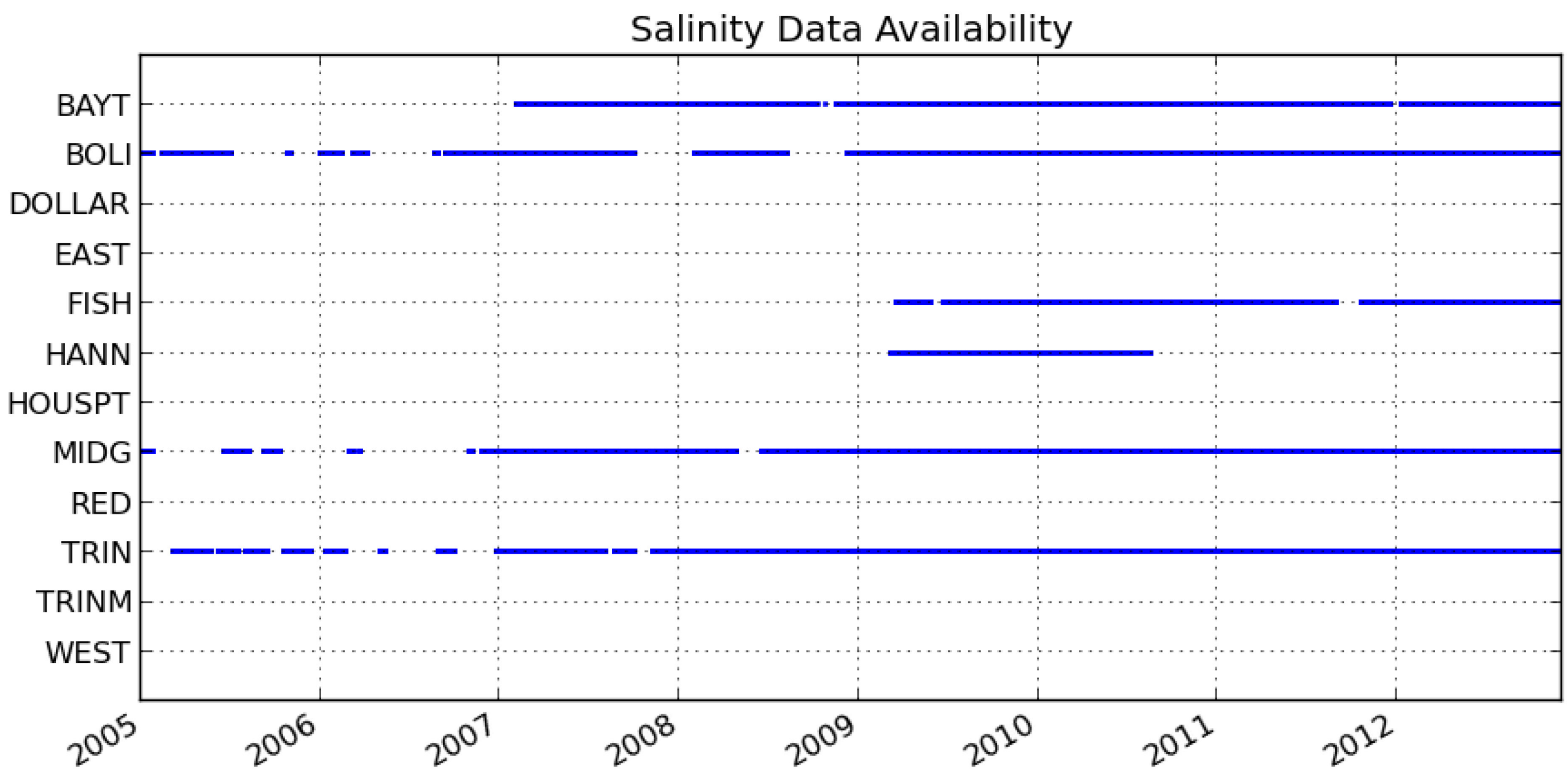

Figure 17. Historical salinity data availability from 2005 – 2012 at thirteen locations in Galveston Bay, including Baytown (BAYT), Bolivar Roads (BOLI), Dollar Point (DOLLAR), East Bay (EAST), Fisher's Reef (FISH), Hanna's Reef (HANN), Houston Point (HOUSPT), Mid-Galveston Bay (MIDG), Old River (OLDR), Redbluff (RED), Trinity Bay (TRIN), Trinity River Mouth (TRINM), and West Bay (WEST). Data sources include Coastal Fisheries Reports and Ward & Armstrong 1992.

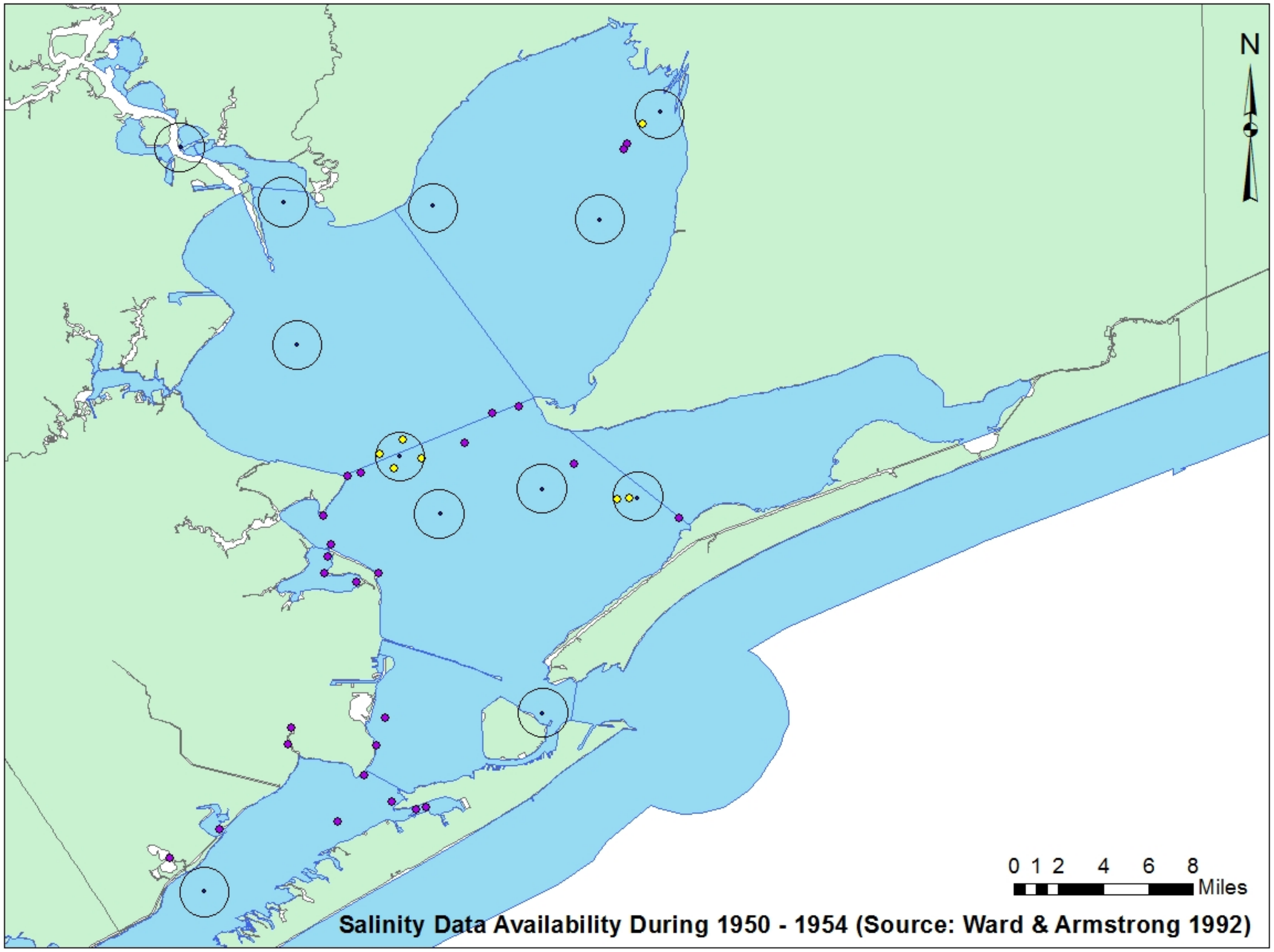

Figure 18. Locations of historical salinity data (compiled by Ward & Armstrong 1992) available for the drought of record period 1950 – 1954. *Purple circles* represent data that is available during this period but was not used in model validation and *yellow circles* represent data that was used in model validation, as these observations fell within the circle of one-mile radius designation near TWDB Datasonde sites (*open black circles*). *Purple* and *yellow circle* symbols may represent multiple observations.

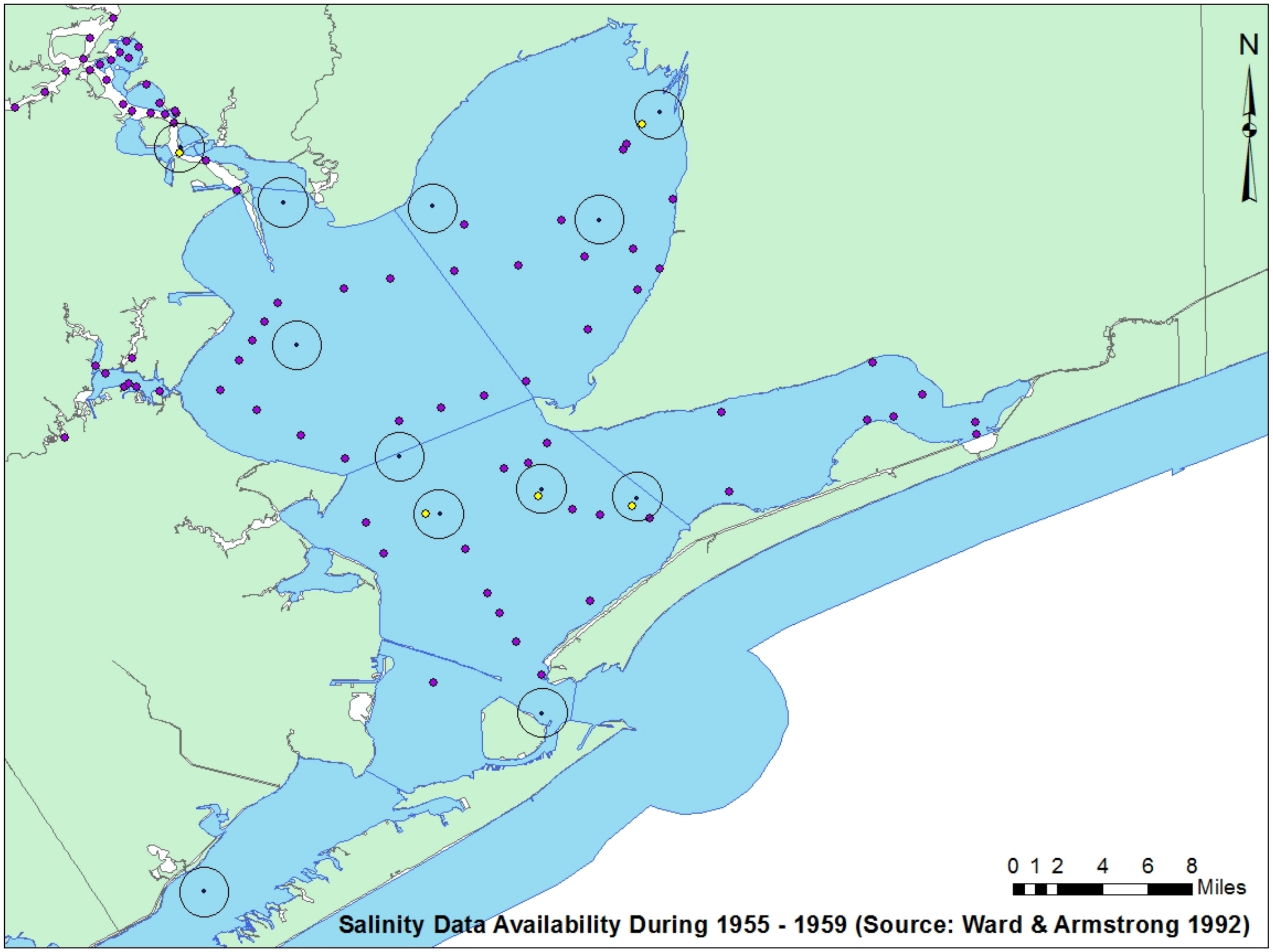

Figure 19. Locations of historical salinity data (compiled by Ward & Armstrong 1992) available for the drought of record period 1955 – 1959. *Purple circles* represent data that is available during this period but was not used in model validation and *yellow circles* represent data that was used in model validation, as these observations fell within the circle of one-mile radius designation near TWDB Datasonde sites. *Purple* and *yellow circle* symbols may represent multiple observations.

Results

Model simulated, daily-average salinity data was compared to the observed historical, daily average salinity data for the period 1950 – 1986 and to TWDB Datasonde data for the period 2006 – 2012, at several locations throughout the bay. In the Ward and Armstrong (1992) dataset, multiple records for a given day were usually measurements taken at different depths (vertical profiles) and so a depth-averaged salinity was computed and compared to the TxBLEND simulated salinity.

Model performance is evaluated by a variety of standard regression, dimensionless, and error index statistical measures, including Coefficient of determination (r^2), Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency Criterion (NSEC), and Percent Bias (PBIAS). The NSEC index describes model performance, where E=1 represents a match between model output and observed data and E<0 represents a poor match between model output and observed data. Values between zero and one are generally viewed as acceptable levels of performance. Percent Bias is a measure of the average tendency of simulated values to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low magnitude values representative of accurate model simulation. Positive values indicate model under-estimation and negative values indicate model over-estimation (Moriasi *et al.* 2007). Visualizations of PBIAS are presented in Figures 20 - 22.

Data from the TPWD Coastal Fisheries reports were not included in statistical tests for two reasons: (1) the number of data points was too small compared to the dataset compiled by Ward and Armstrong (1992) thus the data were statistically insignificant, and (2) the data could not be directly compared to model output because in most cases, there was not a specific time-stamp associated with the measurement or it was unclear whether the value was an average or a point-measurement. Data from the reports is however, included in the figures to allow for a visual comparison between observed and modeled salinities.

Table 5 shows comparison statistics for simulated and observed salinity for the periods 1950 – 1985, 1987 – 2005, and 2006 – 2012. Figures 23 - 51 show comparisons of simulated and observed salinities, both as scatter plots and time-series plots for the simulation period. Time-series plots do not exist for every location for the entire simulation period, because observed data was not always available for comparison. Additionally, numerous time-series plots in five-year intervals for the period of 1950 – 1990 also were created in order to more closely visualize the comparisons as well as to ensure the availability of at least four data points per five-year interval for validation purposes (Appendix C). Five-year interval plots were not included for the period of time after 1990 because plots for 1987 – 2012 are included in the results section of this report. Daily average salinity at 50 selected nodes and monthly average salinity at all model nodes also were produced during this exercise (Appendix D).

Validation Results for 1950 – 1986

For the period 1950 – 1986, the magnitude of the difference between mean simulated salinity and mean observed salinity ranged from 0.1 ppt at Mid-Galveston Bay to 10.3 ppt at the Trinity River mouth. Based on r^2 values, the model performed better at Houston Point (r^2 = 0.8) than at East Bay (r^2 = 0.32). NSEC values ranged from -5.9 at the Trinity River mouth, indicating the model is a poor predictor in this location, to 0.72 at Houston Point, indicating that the model predicted salinity well at this location. In fact, the model did not predict salinity well at any location in Trinity Bay, including Trinity Bay (r^2 = 0.5, NSEC = -2.0, PBIAS = -57.09), Trinity River mouth r^2 = 0.5, NSEC = 0.-5.9, PBIAS = -346.03), and Fisher's Reef (r^2 = 0.75, NSEC = 0.33, PBIAS = -42.85) but did perform well in the upper reaches of Galveston Bay near Houston Point (r^2 = 0.8, NSEC = 0.72, PBIAS = -14.8), and at Hanna's Reef (r^2 = 0.78, NSEC = 0.71, PBIAS = -14.57). During this time period, the model over-predicted salinity at more locations than it under-predicted salinity, particularly in Trinity Bay. Additionally, the extent of over- or under-prediction was greater in the upper estuary sites, as compared to those in the lower bay (Figure 20). Although several factors may be contributing to patterns of over- or under-prediction throughout the bay, over-prediction in Trinity Bay may be consistent with the absence of inflows from watershed #08020. The inclusion of inflows from this watershed and their effect on modeled salinity patterns requires further investigation.

Gradually increasing salinities from 1950 through 1956 were represented at all locations across the bay (Figures 27, 29, 32, 34, 36, 38, 40, 42, 45, 47, 50, 51). During that time, model results indicate that high salinities were sustained and there were fewer instances of low salinity events compared to the period of record. Although in most cases there is limited data available for comparison, some data confirm the model's ability to simulate increasing salinities during the 1950's drought at East Bay and Mid-Galveston Bay (Figures 34 and 42, respectively), as well as decreased salinity that occurred during higher inflows in 1957 - 1958 at Baytown, Dollar Point, and Hanna's Reef (Figures 27, 32, and 38, respectively). Although the model does not predict the magnitude of salinity values well at the Trinity River mouth location, the model did simulate the pattern of reduced salinities due to higher inflows in 1957 (Figure 50). Overall with the exception of upper Trinity Bay, the model generally predicted long-term salinity patterns reasonably well.

Validation Results for 1987 – 2005

For a more in-depth evaluation of model performance during the 1987 – 2005 time period, refer to the report entitled, *TxBLEND Model Calibration and Validation for the Trinity-San Jacinto Estuary* by Guthrie *et al.* (2012). Validation statistics reveal that the TxBLEND model for Galveston Bay performed better during the period 1987 – 2005 than in the extended period covered by this report. The magnitude of the difference between mean simulated salinity and mean observed salinity was less during this period, ranging from 0.3 ppt at Bolivar Roads to 3.5 ppt at East Bay. R^2 values were higher, ranging from 0.49 at Baytown to 0.77 at Dollar Point. The model did not predict salinity as well in the upper reaches of the estuary at Baytown (r^2 = 0.49, NSEC = -0.12, PBIAS = 33.71) and Trinity Bay (r^2 = 0.68, NSEC = 0.48, PBIAS = -39.25) but was a better predictor at other locations, such as Dollar Point (r^2 = 0.77, NSEC = 0.77, PBIAS = 3.66) and Red Bluff (r^2 = 0.69, NSEC =0.67, PBIAS = -4.64). Again, the model over-predicted salinity in more instances than it under-predicted salinity, especially at Trinity Bay (PBIAS = -39.25) and East Bay (PBIAS = -25.11). Although high-frequency variation in salinity was difficult for the model to simulate, long-term patterns of salinity variation were well simulated at most locations across the bay and were representative of the higher variation that occurs near the

Gulf of Mexico pass compared to lower variation that occurs in the upper estuary near river mouths (Figures 30, 33, 35, 41, 43, 46, 48).

Validation Results for 2006 – 2012

The model predicted salinity accurately at most locations during the period 2006 – 2012. The magnitude of the difference between mean simulated and mean observed salinity was small, ranging from 0.1 ppt at Bolivar Roads to 3.1 ppt at Baytown. R^2 values also reflected good performance, ranging from 0.6 at Bolivar Roads to 0.82 at Hanna's Reef. NSEC values were higher for this period, ranging from 0.42 at Baytown to 0.74 at Hanna's Reef. The model over- and under-predicted salinity an equal amount of times, but most over-predicted salinity at Trinity Bay (PBIAS = -10.73) and most under-predicted salinity at Baytown (PBIAS = 23.13). However, the model did not over-predict salinity as much compared to the previous simulation periods. The model generally captured salinity patterns very well. For instance, TxBLEND captured the rapid increase in salinity during low inflows in the summer of 2009 and the steady increase in salinity beginning in 2010 that marks the onset of the 2011 drought at all locations across the bay (Figures 28, 31, 37, 39, 44, 49), although the pattern is less obvious at Bolivar Roads due to the moderating effect of Gulf salinity.

Table 5. Comparison statistics for simulated and observed daily-average salinities for three distinct time periods that span 1950 – 2012.

Site	Number of data	R^2	RMS* (ppt)	Observed Mean	Simulated Mean	Difference (Simulated minus Observed)	NSEC**	PBIAS†
1950 – 1986 (Data Source: Ward & Armstrong 1992)								
BAYT	199	0.61	4.9	11.2	7.8	-3.4	0.23	27.17
BOLI	115	0.47	4.5	25.9	25.3	-0.6	0.45	2.04
DOLLAR	97	0.59	4.7	14.8	16.7	1.9	0.52	-15.41
EAST	48	0.32	6.9	14.3	16.6	2.3	0.24	-18.13
FISH	228	0.75	5.2	9.6	13.7	4.1	0.33	-42.85
HANNA	30	0.78	3.3	14.6	15.4	0.8	0.71	-14.57
HOUSPT	162	0.80	3.2	13.6	15.2	1.6	0.72	-14.8
MIDG	256	0.49	5.4	15.2	15.1	-0.1	0.49	-1.14
RED	26	0.52	4.5	18.7	15.5	-3.2	0.02	12.51
TRIN	16	0.50	7.0	5.4	11.7	6.3	-2.00	-57.09
TRINM	1151	0.50	11.3	3.0	13.3	10.3	-5.90	-346.03
WEST	200	0.44	5.3	22.9	24.3	1.4	0.38	-7.48
1987 – 2005 (Data Source: TWDB Datasonde)								
BAYT	828	0.49	4.2	9.2	6.1	-3.1	-0.12	33.71
BOLI	2735	0.59	4.0	21.0	21.3	0.3	0.59	-1.72
DOLLAR	3527	0.77	3.4	17.6	17.0	-0.6	0.77	3.66
EAST	1658	0.66	5.0	13.6	17.1	3.5	0.36	-25.11
MIDG	649	0.65	3.9	15.9	13.3	-2.6	0.29	16.62
RED	2197	0.69	3.5	11.9	12.4	0.5	0.67	-4.64
TRIN	3667	0.68	5.4	8.4	11.8	3.4	0.48	-39.25
2006 – 2012 (Data Source: TWDB Datasonde)								
BAYT	2051	0.71	4.3	13.3	10.2	-3.1	0.42	23.13
BOLI	2140	0.60	3.3	24.6	24.5	-0.1	0.56	0.36
FISH	1310	0.69	4.1	14.2	15.4	1.2	0.66	-8.1
HANNA	530	0.82	3.1	16.1	17.5	1.4	0.74	-8.52
MIDG	2188	0.64	4.0	18.8	17.2	-1.6	0.56	8.63
TRIN	2198	0.69	4.8	12.2	13.5	1.3	0.65	-10.73

*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.

†PBIAS is Percent Bias, a measure of the average tendency of simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0, with low magnitude values representative of accurate model simulation. Positive values indicate under-estimation and negative values indicate over-estimation.

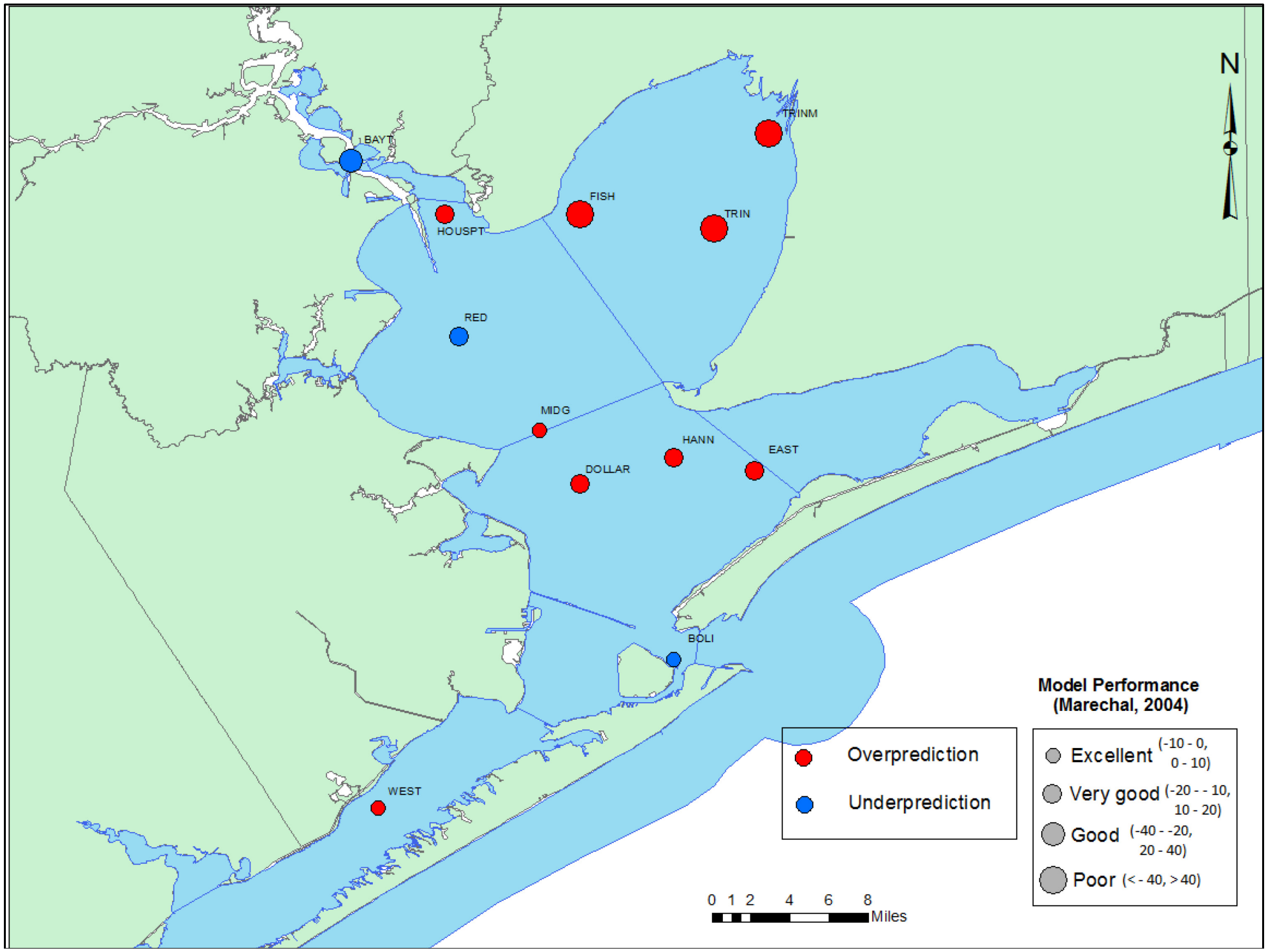

Figure 20. Percent Bias for eleven locations in Galveston Bay (BAYT, BOLI, DOLLAR, EAST, FISH, HANN, MIDG, RED, TRIN, TRINM, and WEST) during the extended period from 1950 – 1986. The optimal value of Percent Bias is 0, with low magnitude values (*small circles*) representative of accurate model simulation and large magnitude values (*large circles*) representative of less accurate model simulation. Positive values (*blue*) indicate under-estimation and negative values (*red*) indicate over-estimation.

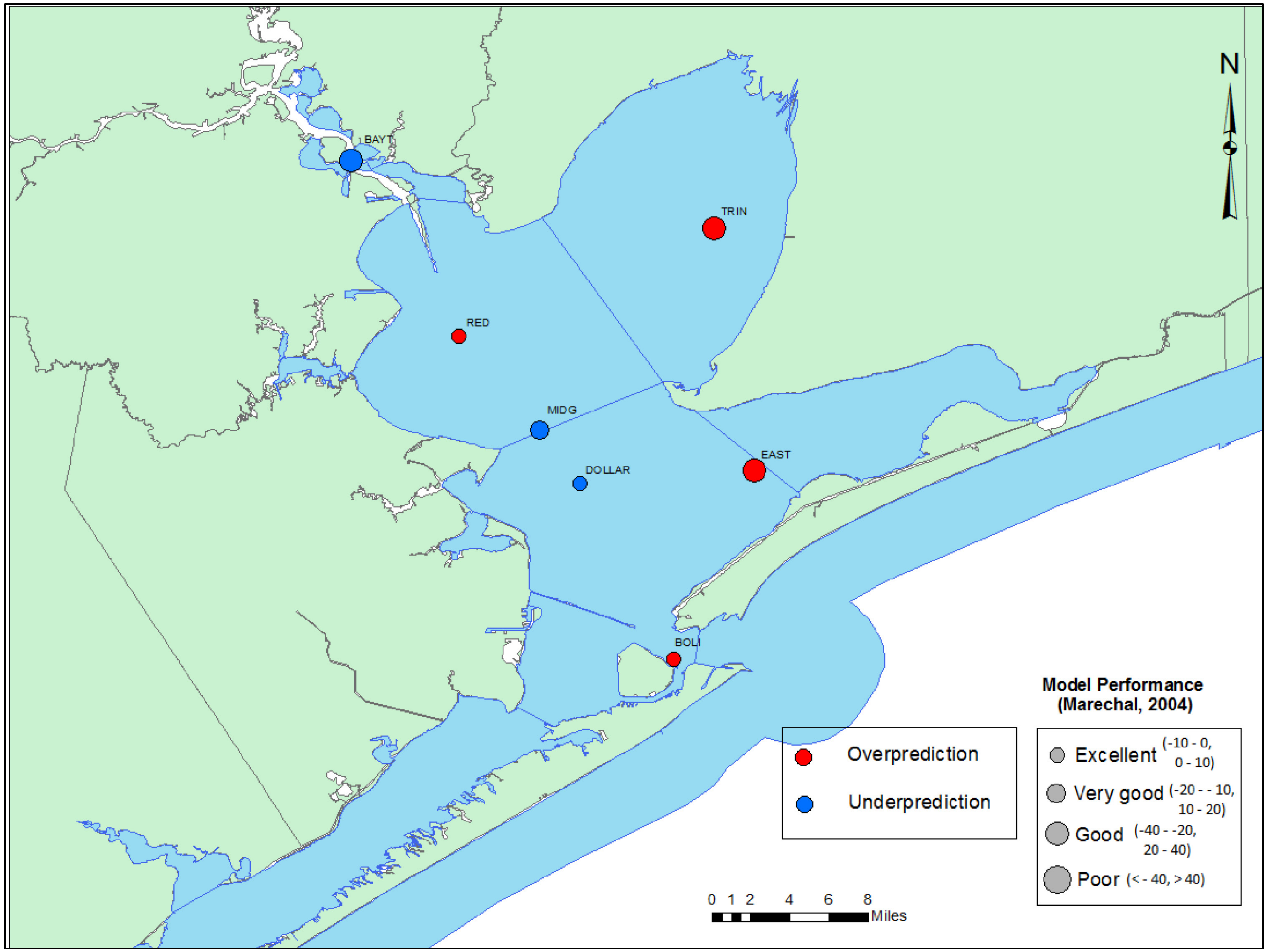

Figure 21. Percent Bias for seven locations in Galveston Bay (BAYT, BOLI, DOLLAR, EAST, MIDG, RED, TRIN) during the period 1987 - 2005. The optimal value of Percent Bias is 0, with low magnitude values (*small circles*) representative of accurate model simulation and high magnitude values (*large circles*) representative of less accurate model simulation. Positive values (*blue*) indicate under-estimation and negative values (*red*) indicate over-estimation.

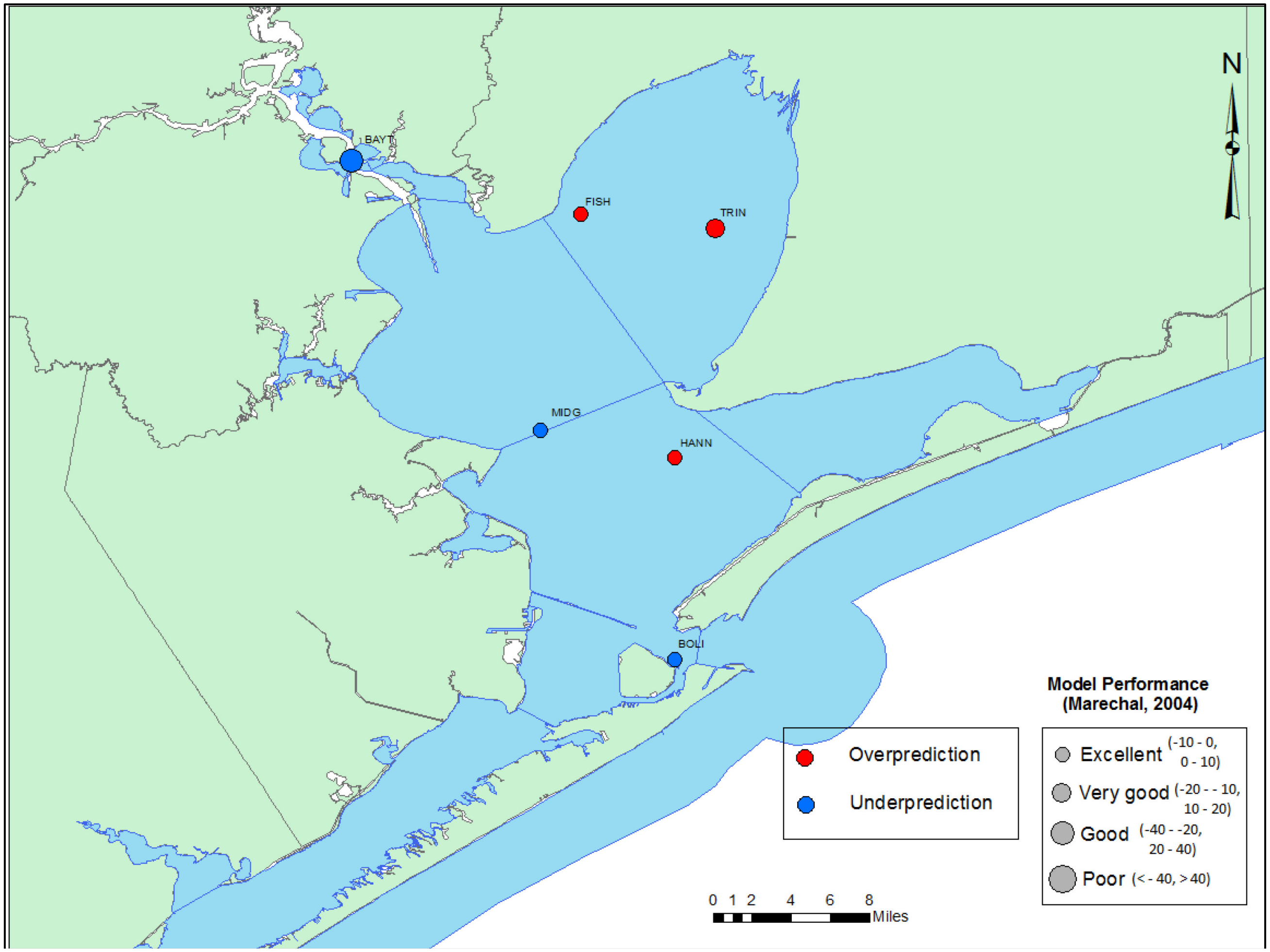

Figure 22. Percent Bias for six locations in Galveston Bay (BAYT, BOLI, FISH, HANN, MIDG, TRIN) during the period 2006 – 2012. The optimal value of Percent Bias is 0, with low magnitude values (*small circles*) representative of accurate model simulation and high magnitude values (*large circles*) representative of less accurate model simulation. Positive values (*blue*) indicate under-estimation and negative values (*red*) indicate over-estimation.

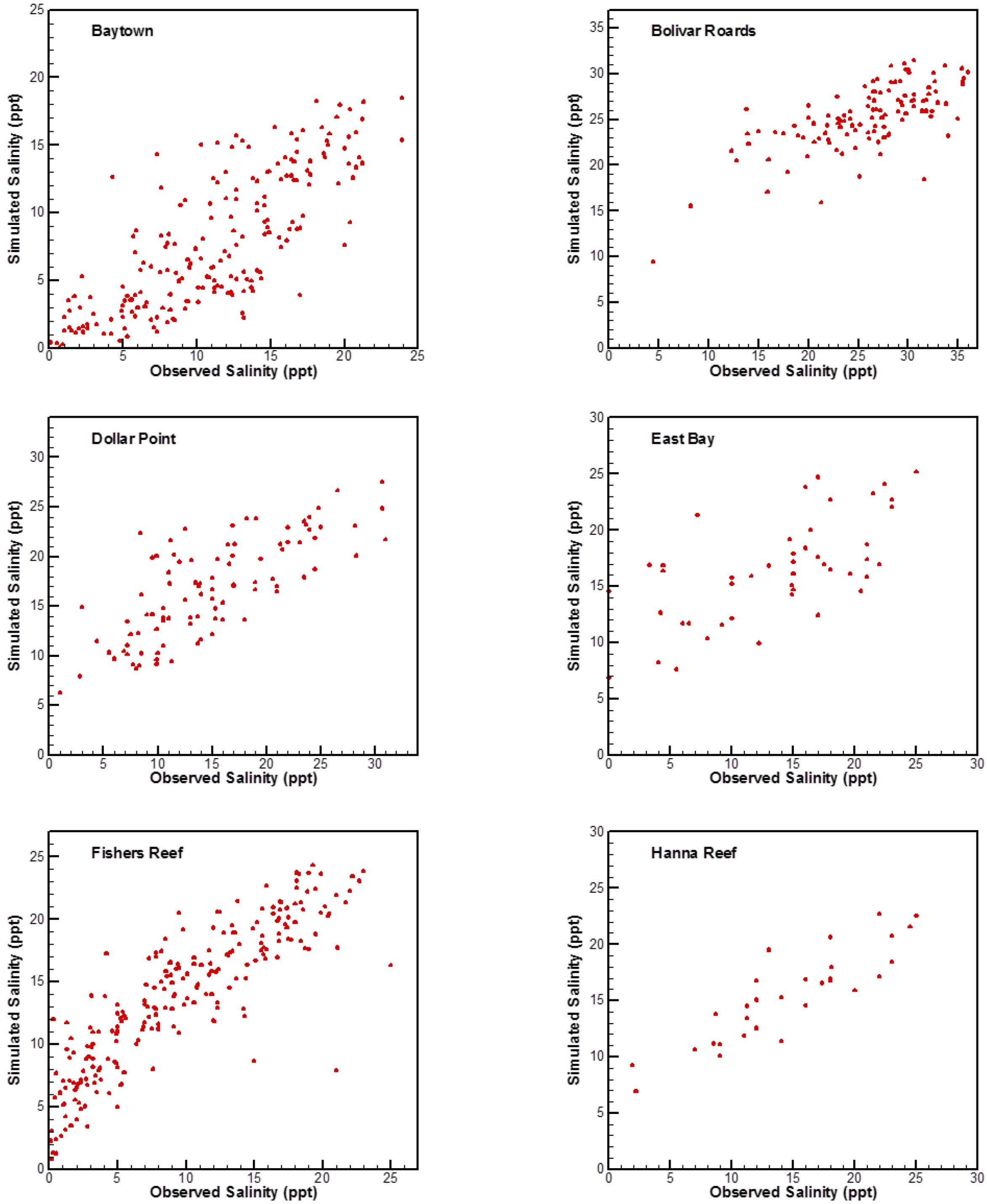

Figure 23. Scatter plots comparing simulated and observed salinity at six sites (BAYT, BOLI, DOLLAR, EAST, FISH, and HANNA) for the validation period 1950 - 1986.

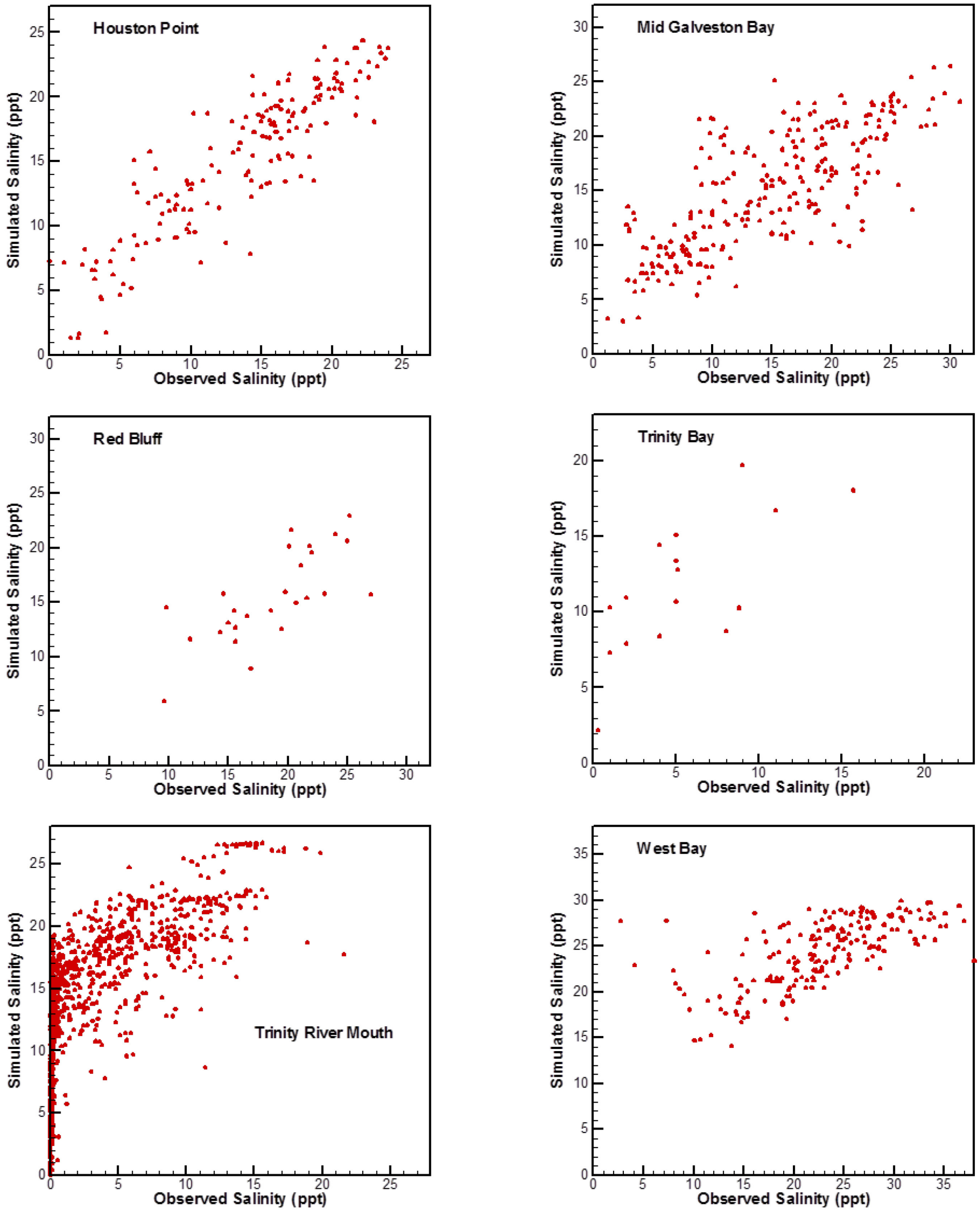

Figure 24. Scatter plots comparing simulated and observed salinity at six sites (HOUSPT, MIDG, RED, TRIN, TRINM, and WEST) for the validation period 1950 - 1986.

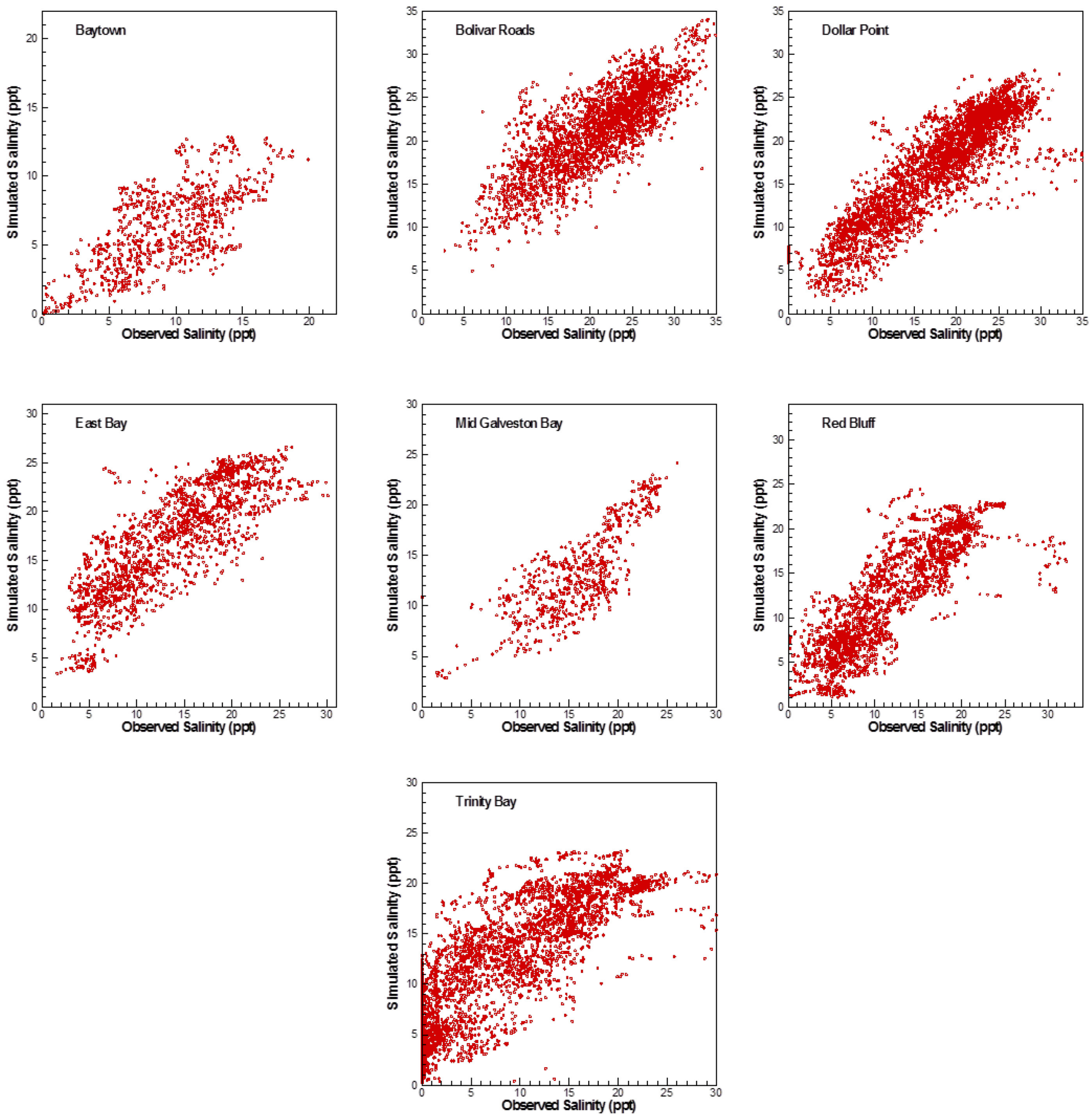

Figure 25. Scatter plots comparing simulated and observed salinity at seven sites (BAYT, BOLI, DOLLAR, EAST, MIDG, RED, and TRIN) for the validation period 1987 - 2005.

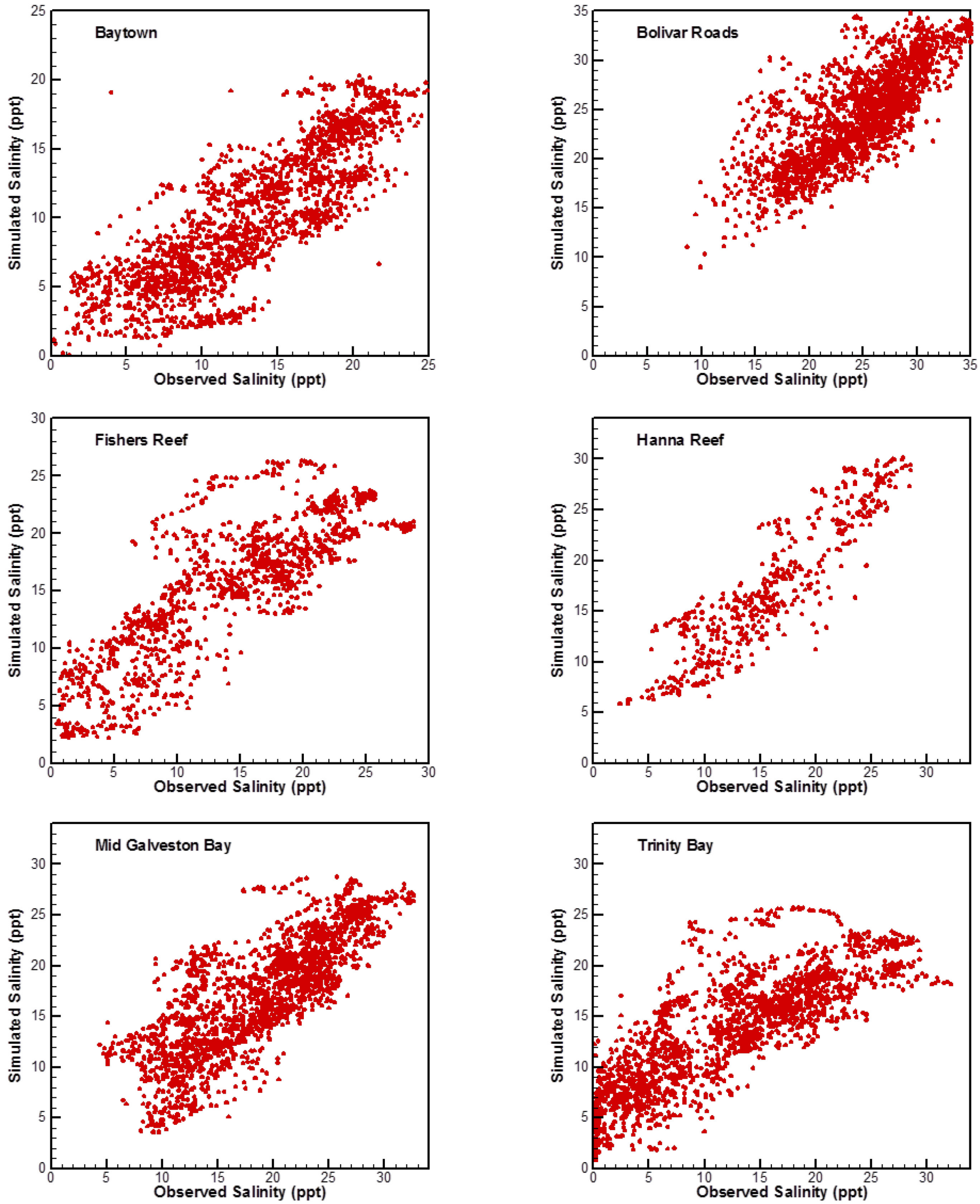

Figure 26. Scatter plots comparing simulated and observed salinity at six sites (BAYT, BOLI, FISH, HANNA, MIDG, and TRIN) for the validation period 2006 - 2012.

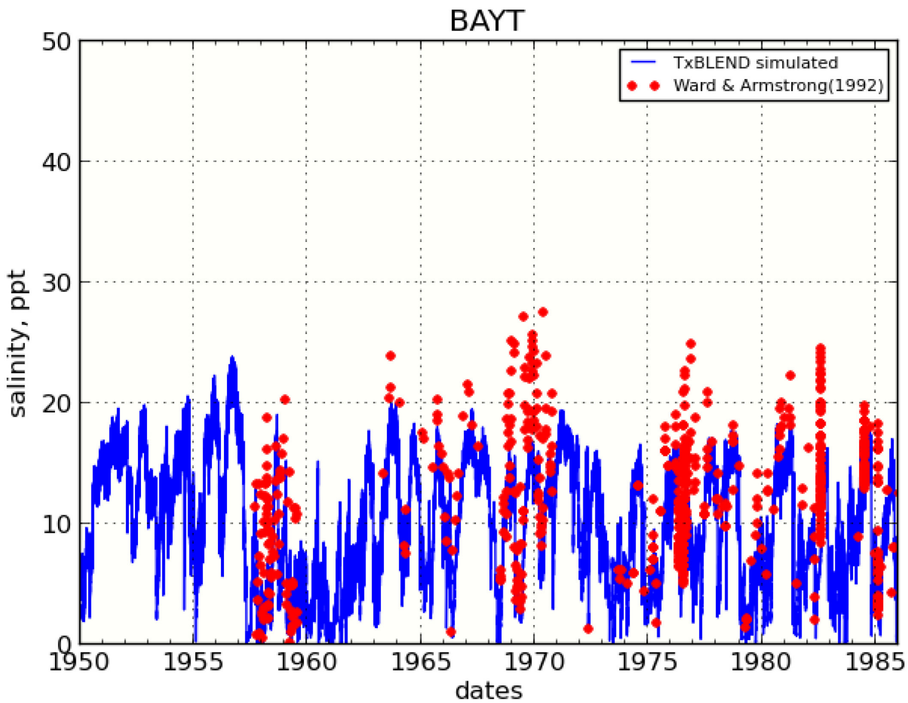

Figure 27. Simulated (*blue*) versus observed (*red*) salinity at the Houston Ship Channel near Baytown in Galveston Bay for 1950 – 1985.

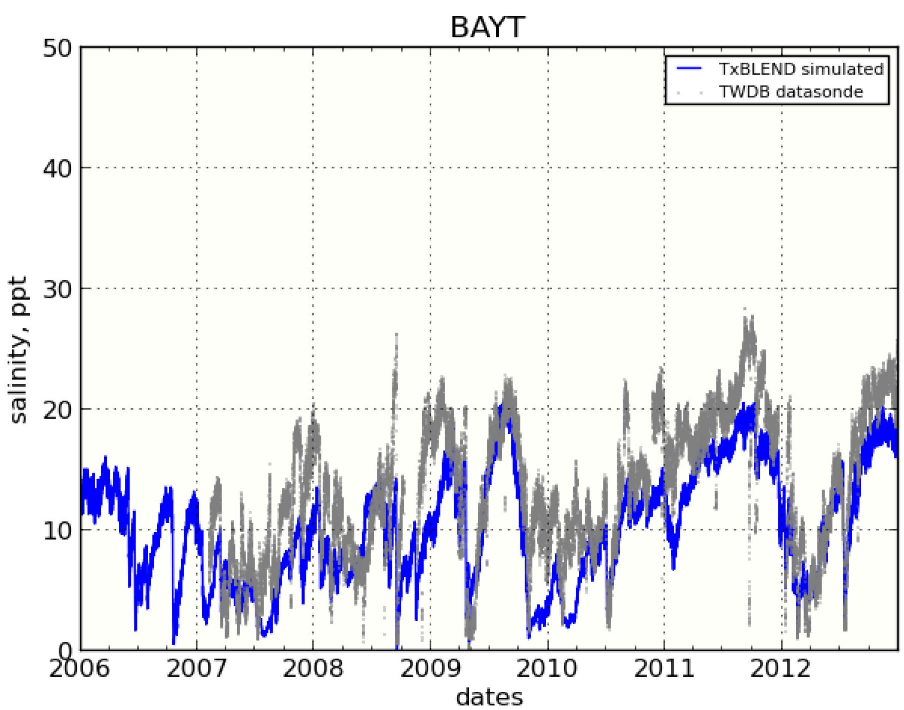

Figure 28. Simulated (*blue*) versus observed (*grey*) salinity at the Houston Ship Channel near Baytown in Galveston Bay for 2006 – 2012.

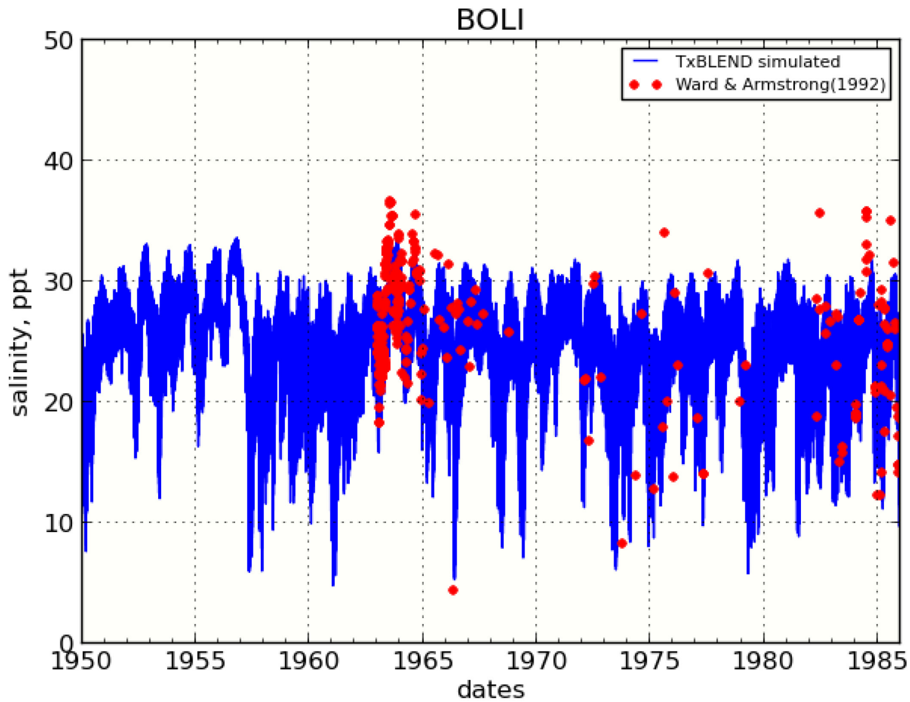

Figure 29. Simulated (*blue*) versus observed (*red*) salinity at Bolivar Roads in Galveston Bay for 1950 – 1985.

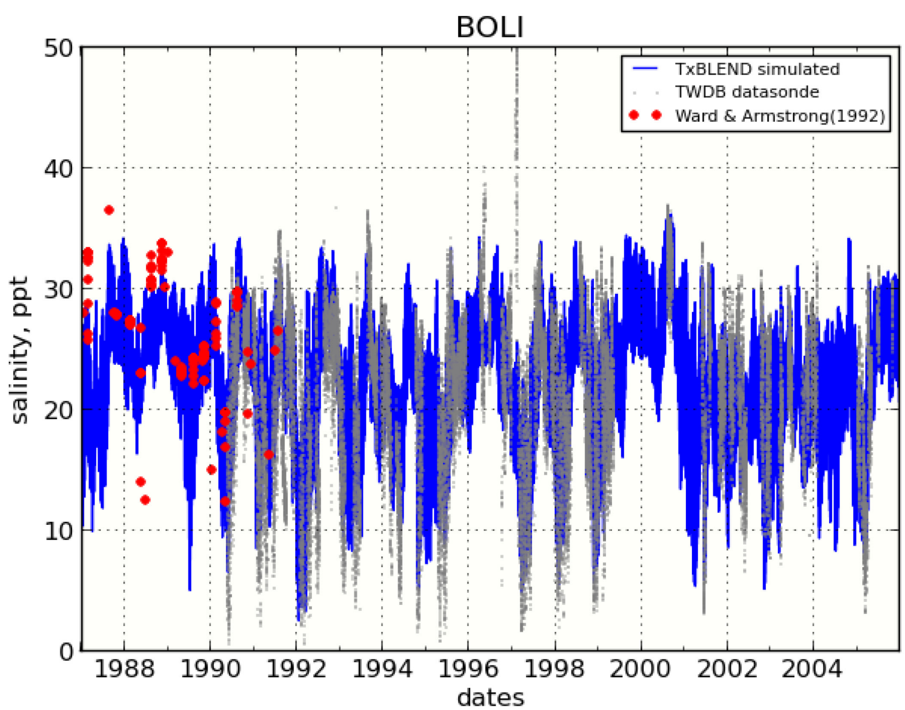

Figure 30. Simulated (*blue*) versus observed (*red* and *grey*) salinity at Bolivar Roads in Galveston Bay for 1987 – 2005.

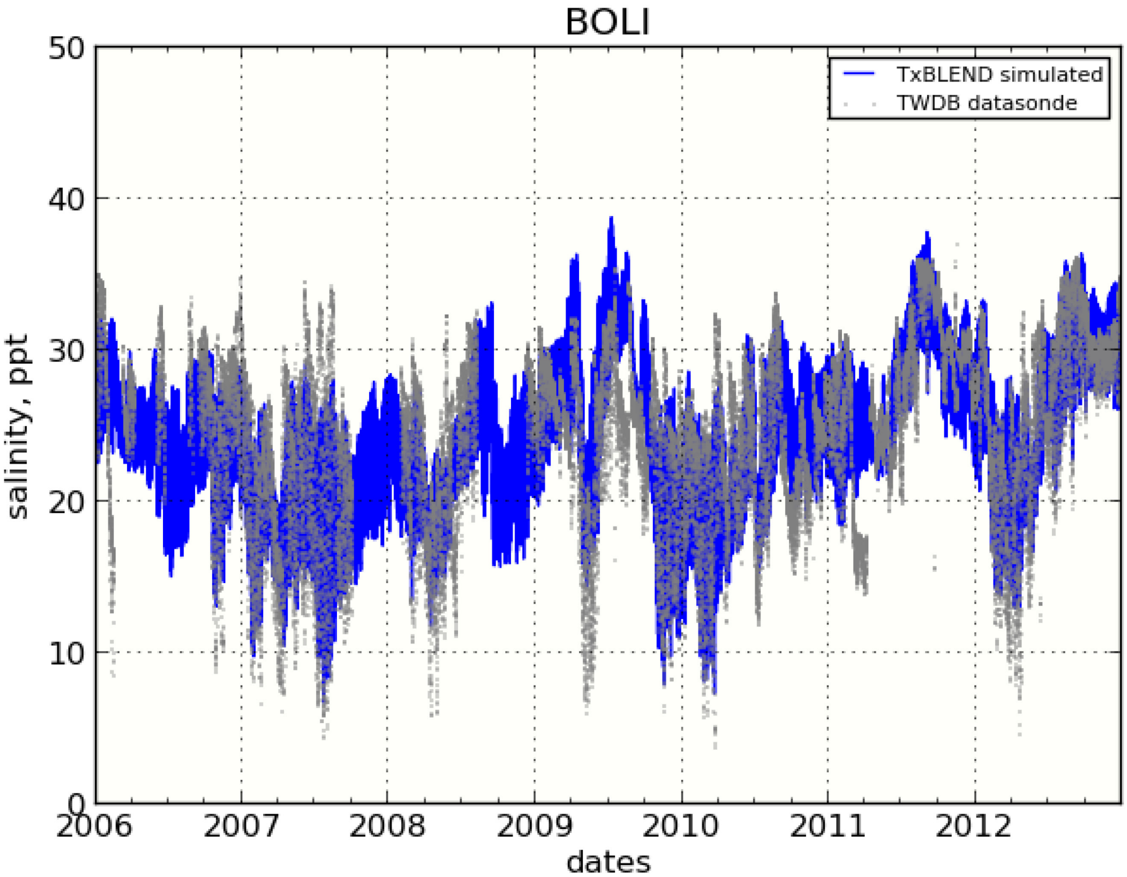

Figure 31. Simulated (*blue*) versus observed (*grey*) salinity at Bolivar Roads in Galveston Bay for 2006 - 2012.

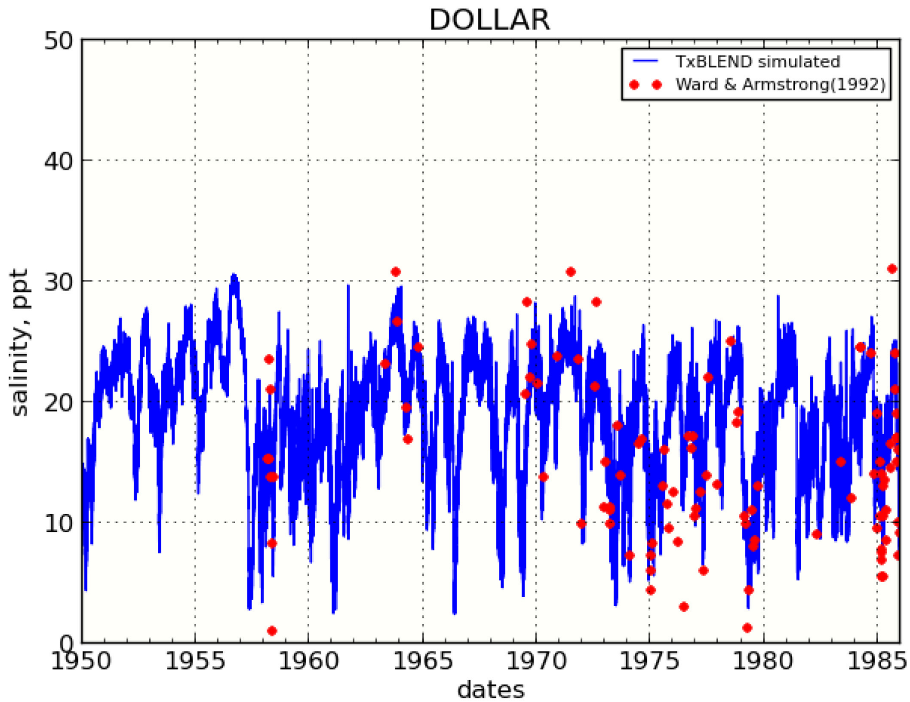

Figure 32. Simulated (*blue*) versus observed (*red*) salinity at Dollar Reef in Galveston Bay for 1950 – 1985.

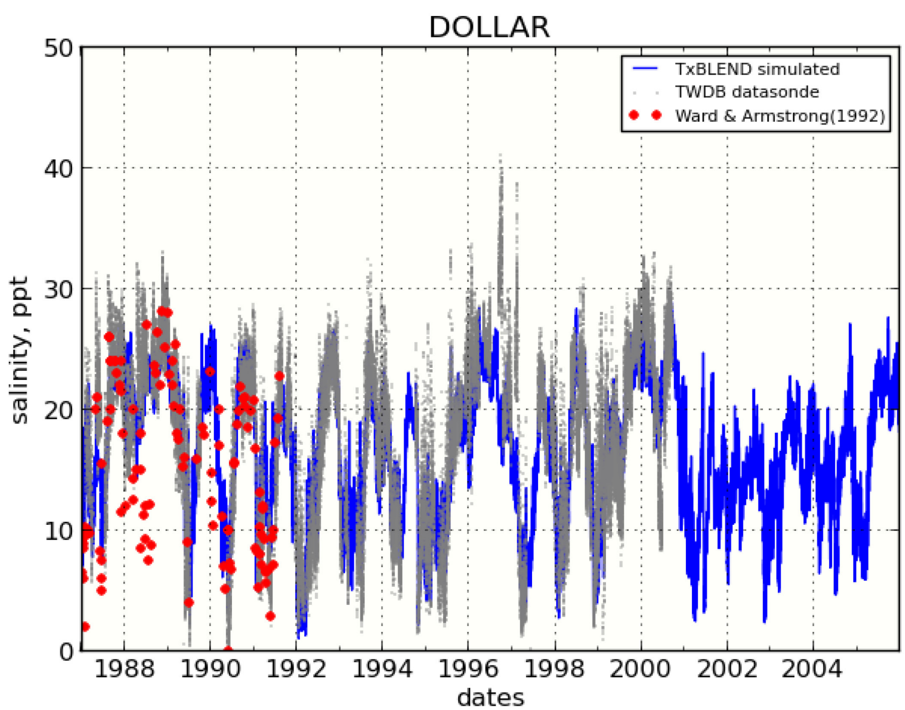

Figure 33. Simulated (*blue*) versus observed (*red* and *grey*) salinity at Dollar Reef in Galveston Bay for 1987 – 2005.

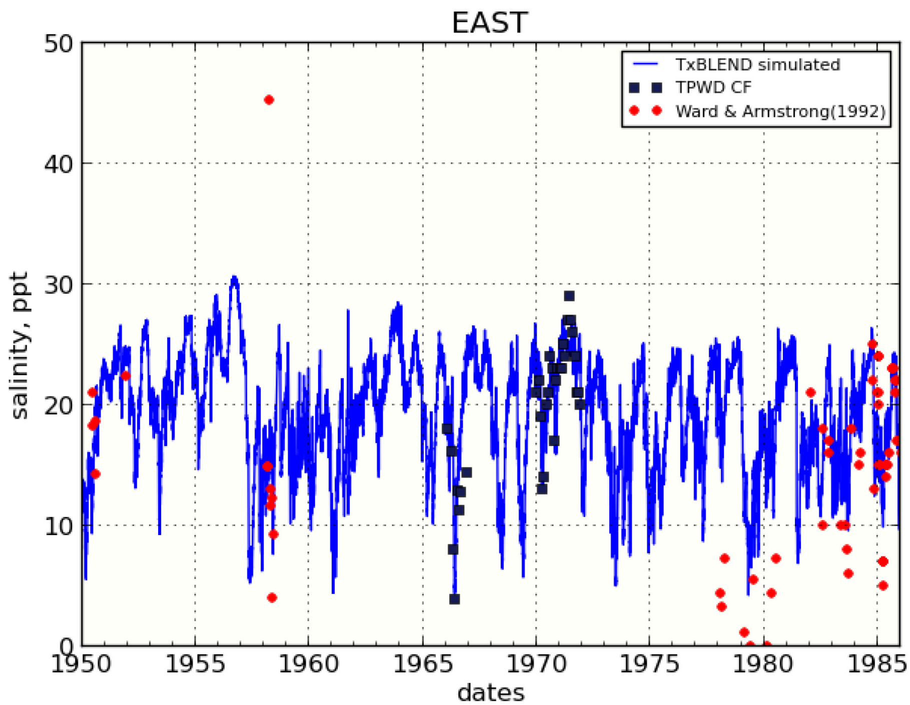

Figure 34. Simulated (*blue*) versus observed (*red* and *black*) salinity at East Bay in Galveston Bay for 1950 – 1985.

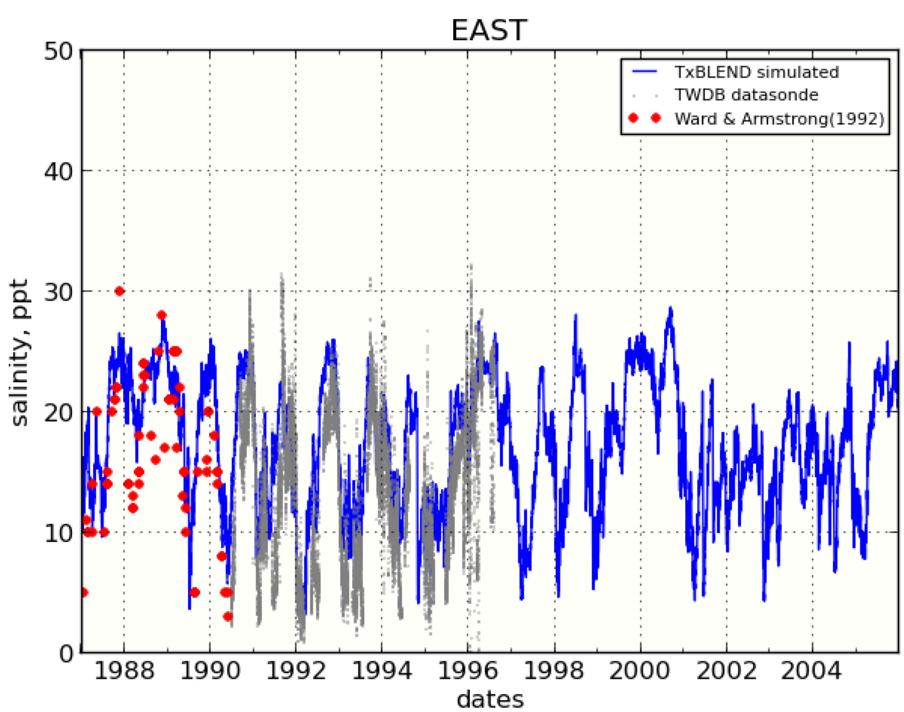

Figure 35. Simulated (*blue*) versus observed (*red and grey*) salinity at East Bay in Galveston Bay for 1987 – 2005.

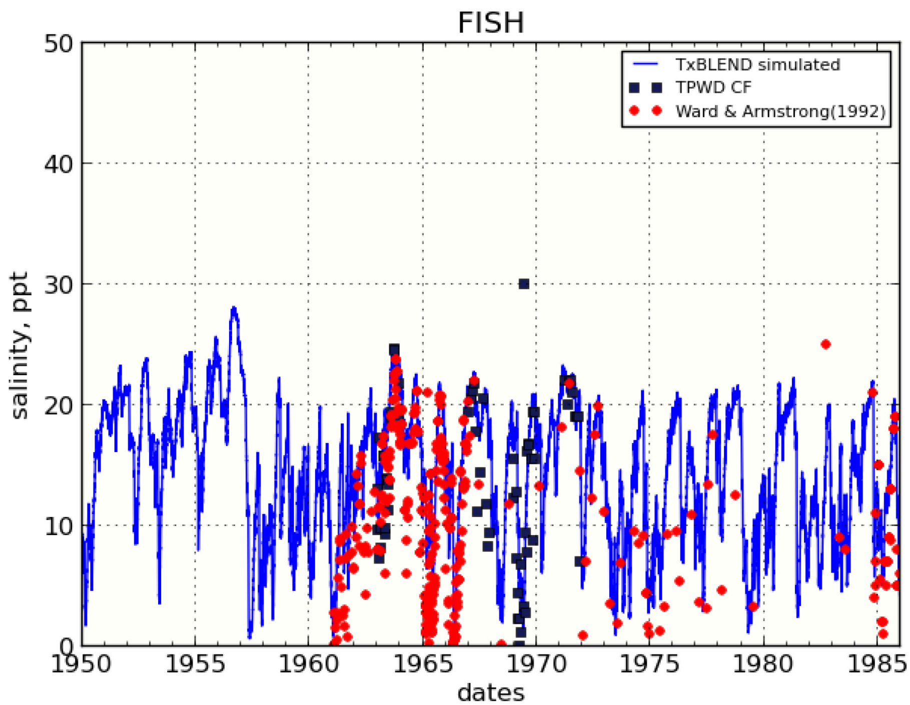

Figure 36. Simulated (*blue*) versus observed (*red* and *black*) salinity at Fisher's Reef for 1950 – 1985.

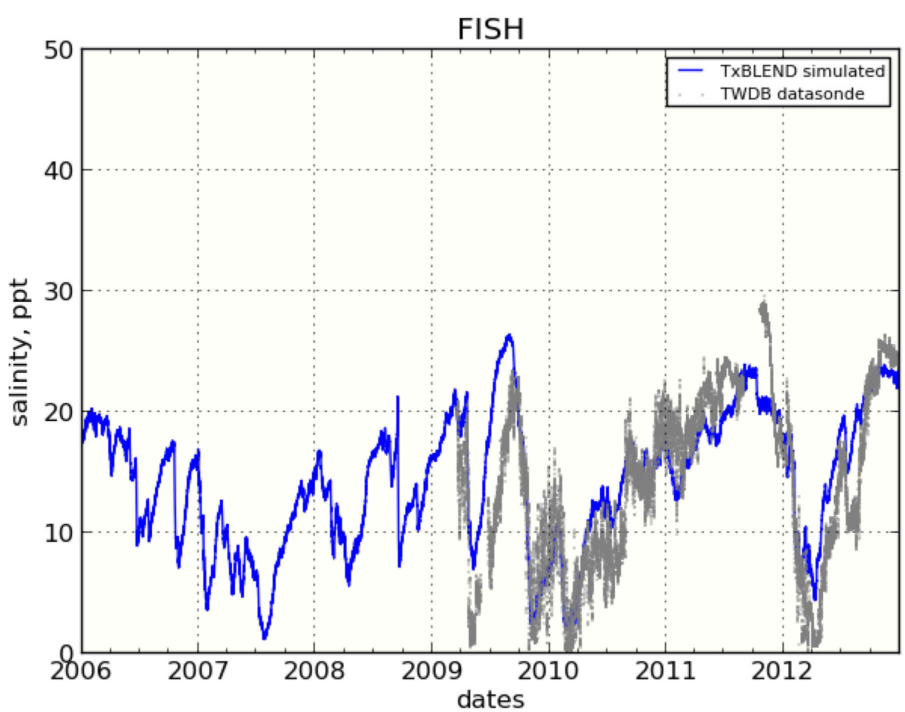

Figure 37. Simulated (*blue*) versus observed (*grey*) salinity at Fisher's Reef for 2006 – 2012.

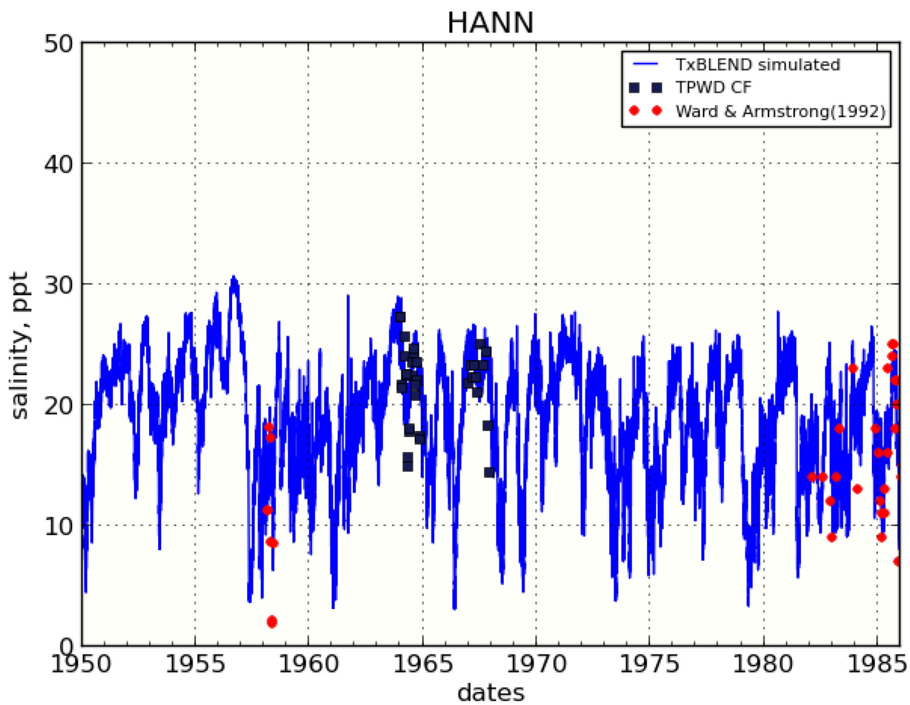

Figure 38. Simulated (*blue*) versus observed (*red* and *black*) salinity at Hanna's Reef for 1950 – 1985.

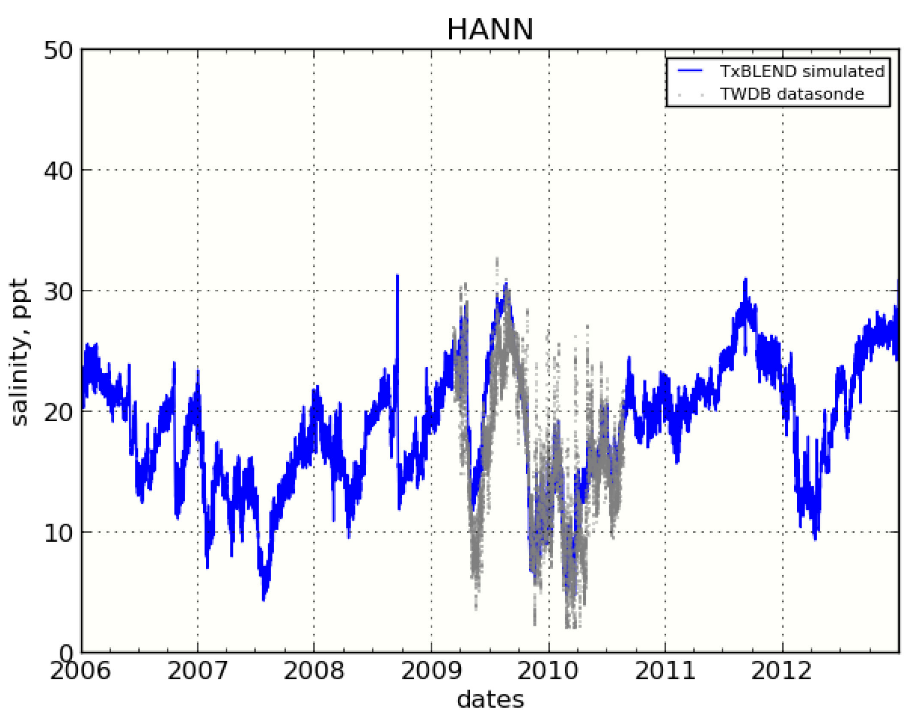

Figure 39. Simulated (*blue*) versus observed (*grey*) salinity at Hanna's Reef for 2006 – 2012.

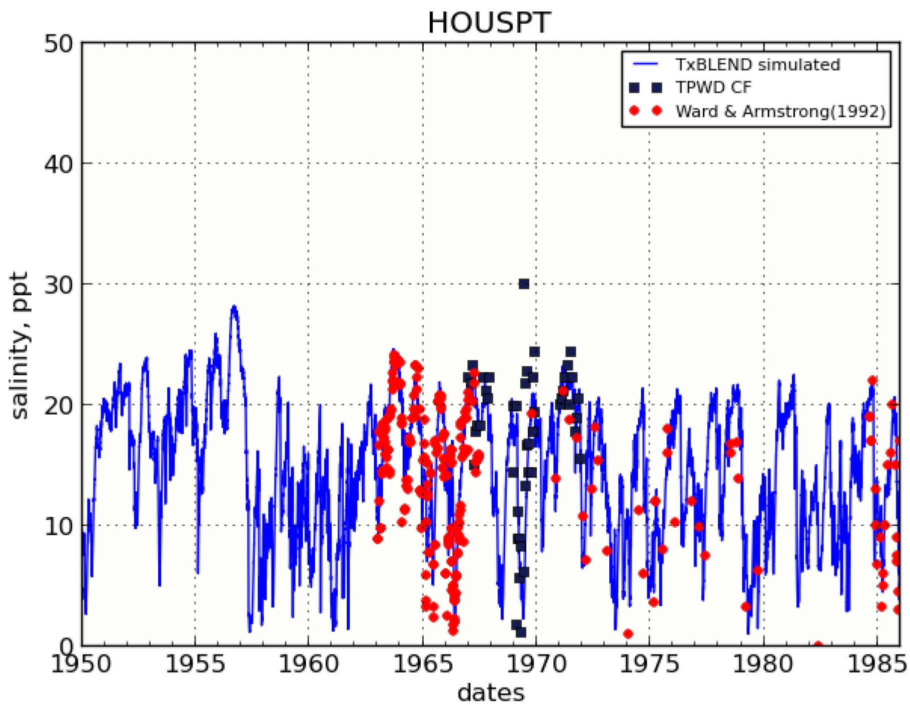

Figure 40. Simulated (*blue*) versus observed (*red* and *black*) salinity at Houston Point for 1950 – 1985.

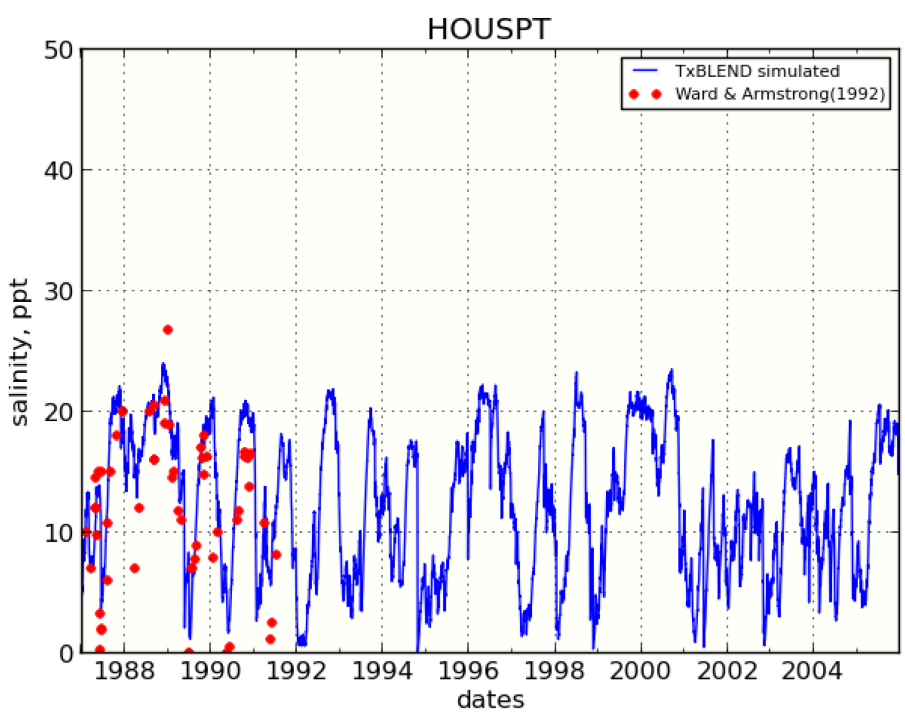

Figure 41. Simulated (*blue*) versus observed (*red* and *black*) salinity at Houston Point for 1987 – 2005.

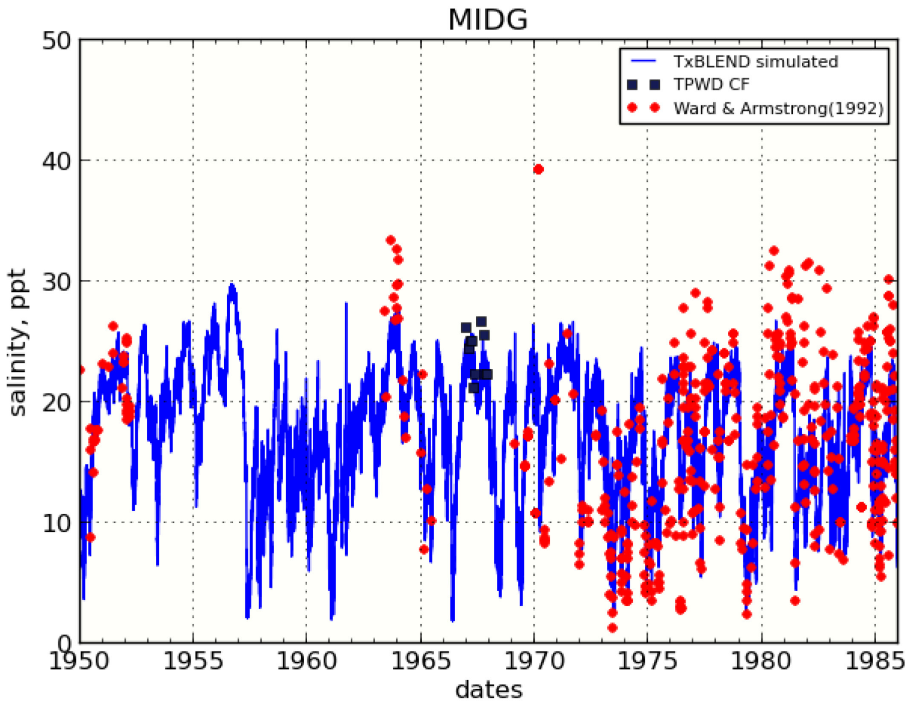

Figure 42. Simulated (*blue*) versus observed (*red* and *black*) salinity at Mid Galveston Bay for 1950 – 1985.

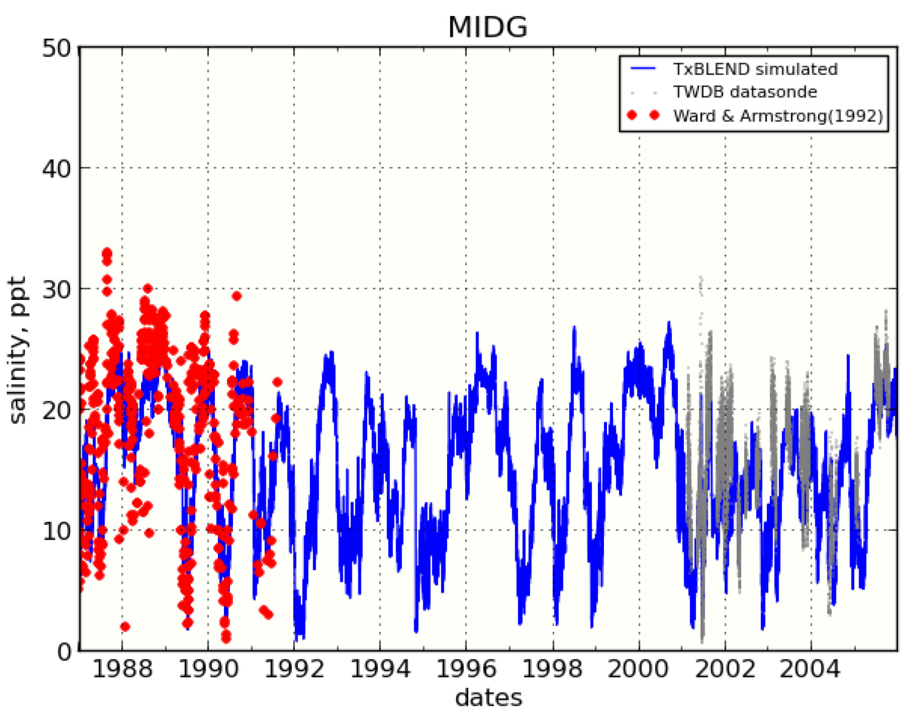

Figure 43. Simulated (*blue*) versus observed (*red* and *grey*) salinity at Mid Galveston Bay for 1987 – 2005.

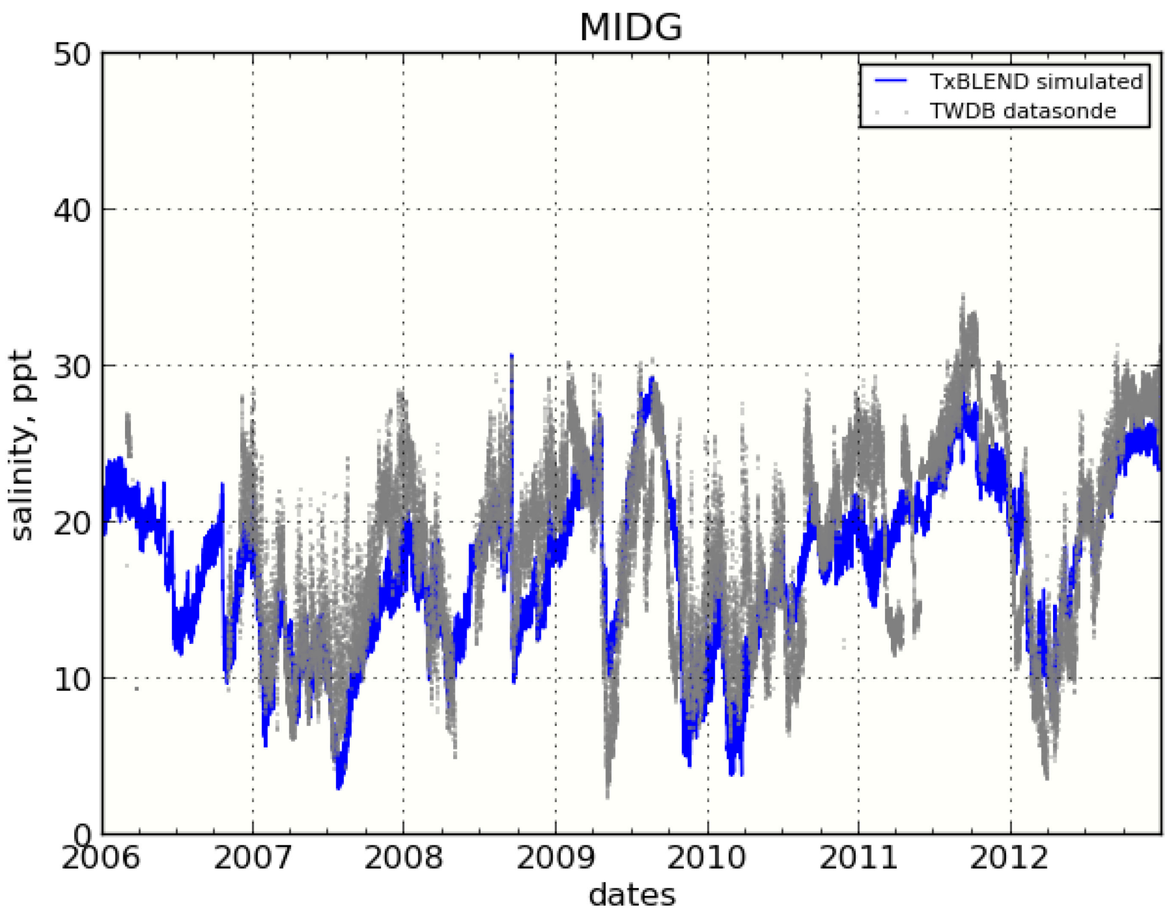

Figure 44. Simulated (*blue*) versus observed (*grey*) salinity at Mid-Galveston Bay for 2006 – 2012.

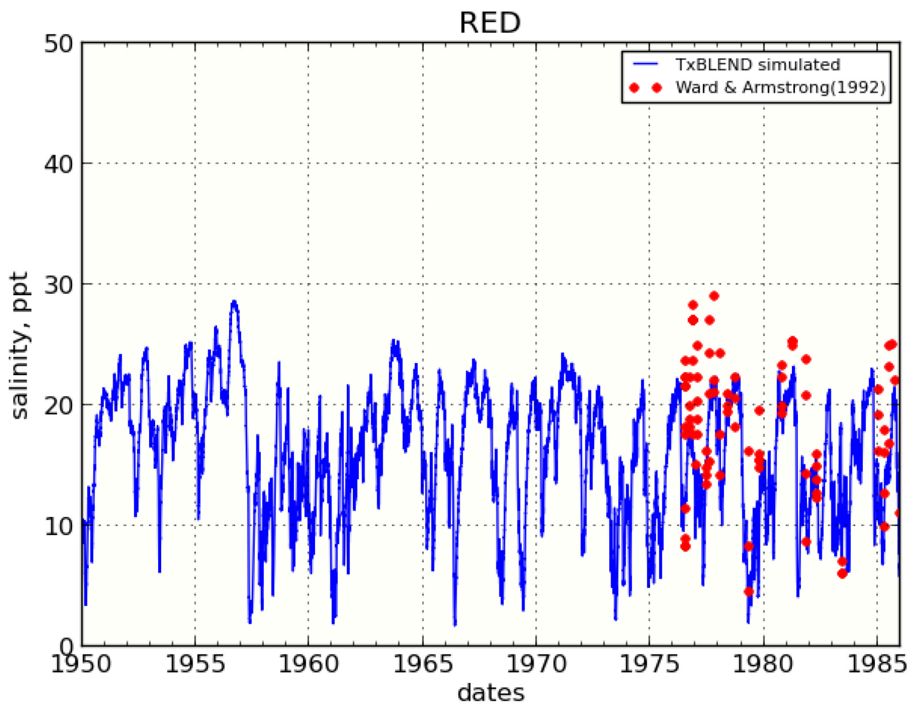

Figure 45. Simulated (*blue*) versus observed (*red)* salinity at Red Bluff for 1950 – 1985.

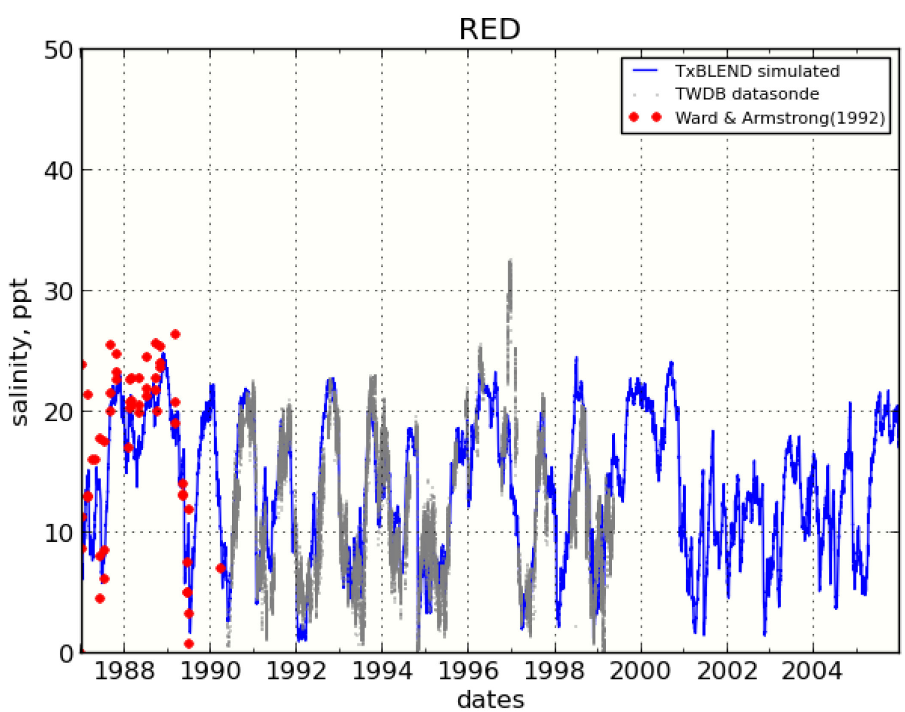

Figure 46. Simulated (*blue*) versus observed (*red* and *grey*) salinity at Red Bluff for 1987 – 2005.

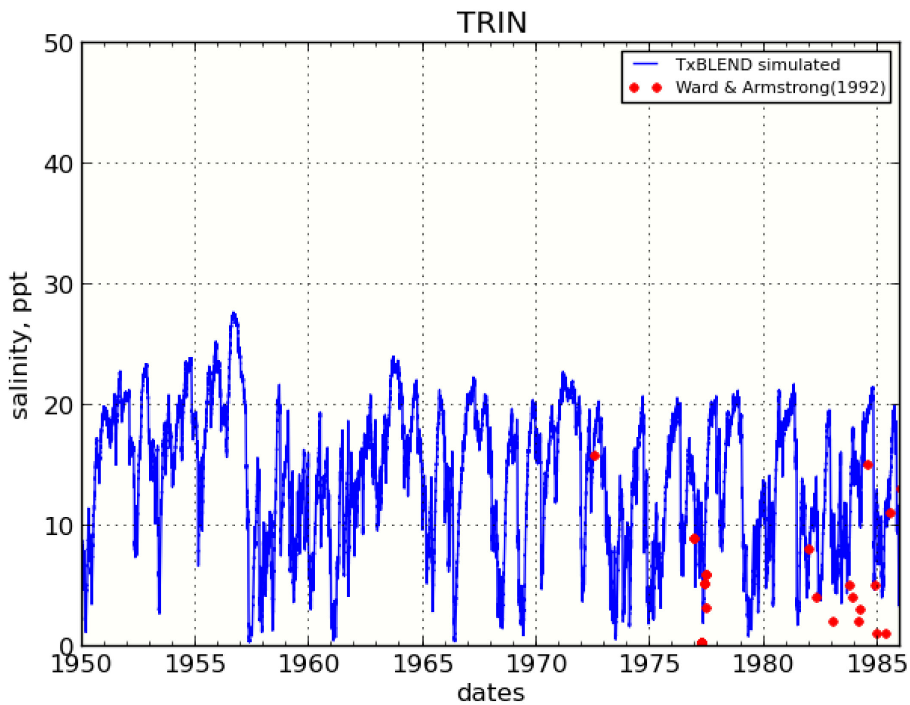

Figure 47. Simulated (*blue*) versus observed (*red*) salinity at Trinity Bay for 1950 – 1985.

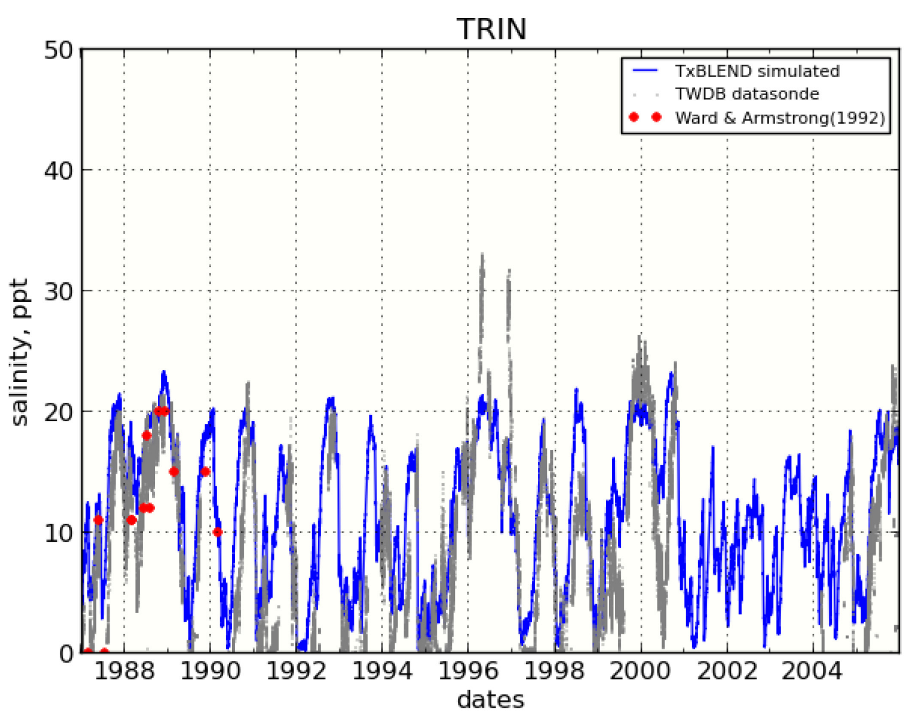

Figure 48. Simulated (*blue*) versus observed (*red* and *grey*) salinity at Trinity Bay for 1987 – 2005.

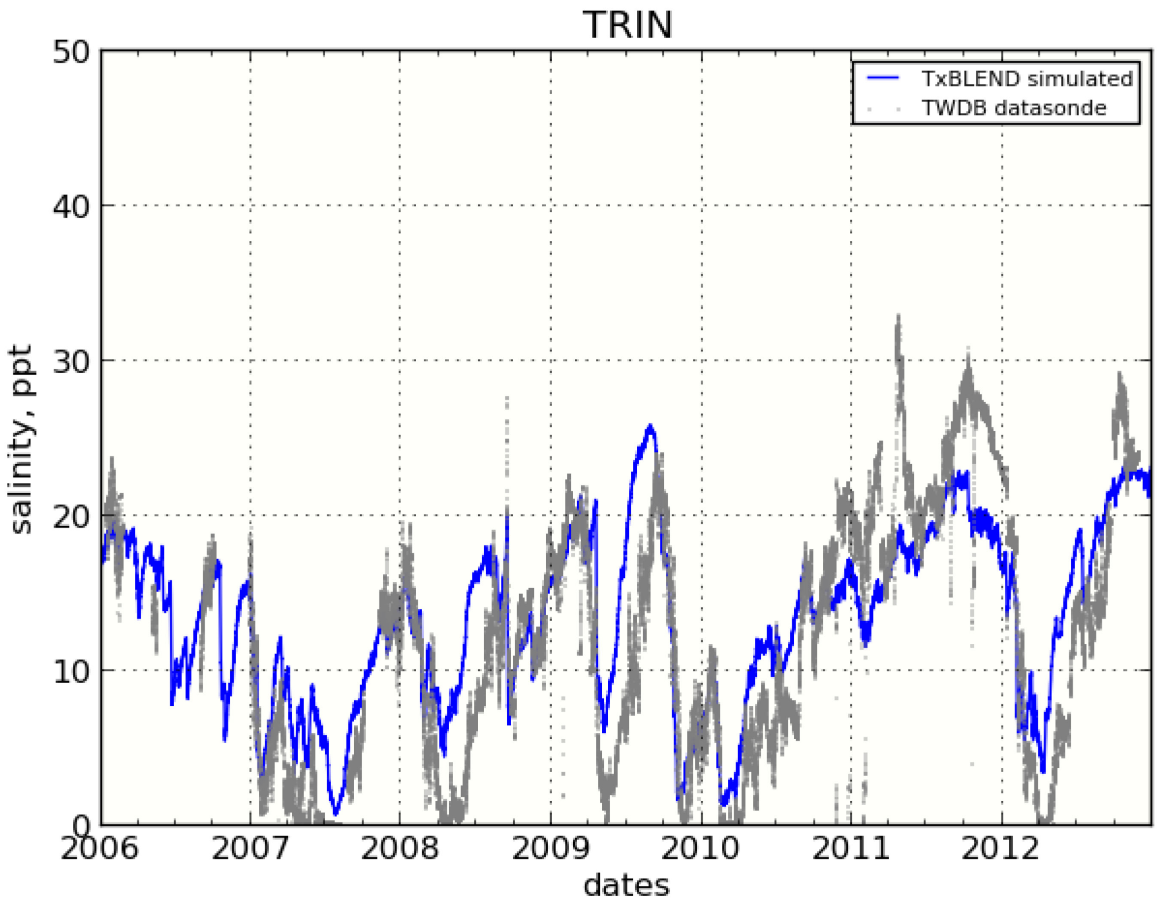

Figure 49. Simulated (*blue*) versus observed (*grey*) salinity at Trinity Bay for 2006 – 2012.

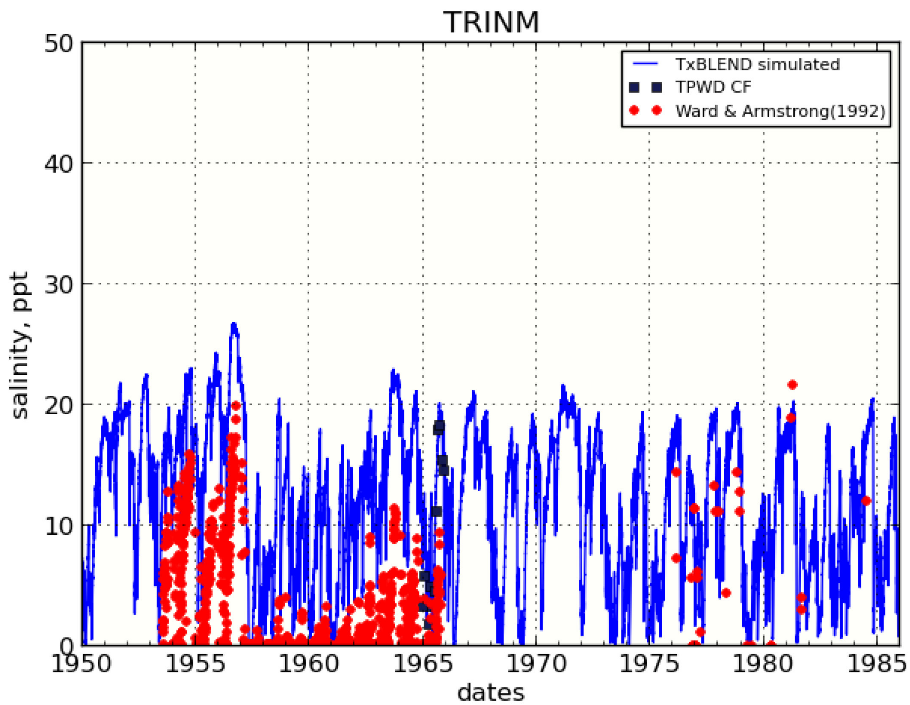

Figure 50. Simulated (*blue*) versus observed (*red* and *black*) salinity at Trinity Bay for 1950 – 1985.

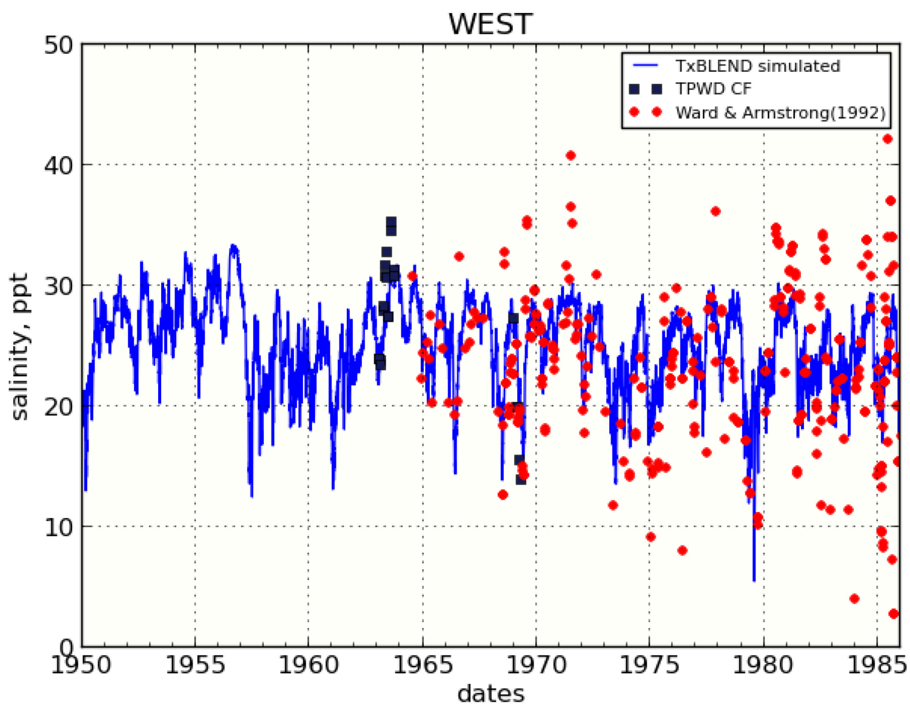

Figure 51. Simulated (*blue*) versus observed (*red* and *black*) salinity at West Bay for 1950 – 1985.

Discussion

The extended TxBLEND model for the Trinity-San Jacinto Estuary was generally representative of observed salinities and trends, although limited data was available for comparison during the period of greatest interest, the drought of the 1950's. Model performance for the extended period from 1950 – 1985 (as indicated by r^2 values ranging from 0.32 to 0.8 and by a mean salinity difference between simulated and observed data ranging from 0.1 ppt to 10.3 ppt) was reasonable, but the model had difficulty simulating conditions in Trinity Bay, particularly near the Trinity River mouth during this period. As expected, the model simulated gradually increasing and sustained high salinities during the early 1950's drought, but as previously mentioned, limited data was available to validate model behavior. Validation statistics for the extended period of 1950 – 1985 indicate the model was a poorer predictor compared to the other simulation periods, but general model performance was acceptable.

Validation statistics indicating poor model performance, particularly in Trinity Bay, may be attributed to a variety of factors. The limited number of measured data points available for comparison (n = 16 at TRIN for 1950 – 1986) may be one factor affecting statistical tests. Acquiring additional historical salinity data for validation during the extended period would allow for a more robust evaluation of model simulation during this time. Also, evaluation of model performance at the Trinity River mouth location may be influenced by the selection of observed data for validation. For example, observed salinity data extracted from within the designated circular grouping may have included enough spatial variation in salinity to make comparison with simulated salinity output at only one model node incompatible. This could be a factor affecting model performance at other locations as well. Another factor that may introduce error and influence model performance is the use of regression-based calculated offshore salinity data rather than measured data to set the offshore salinity boundary condition.

Furthermore, the Galveston Bay TxBLEND model was calibrated over the period 1987 – 1996, which then was applied to the full simulation period. Galveston Bay's flow regimes, channel dimensions, bottom friction, and other properties were different between the calibration period and the extended period. Though different channel dimensions were accounted for, there were flow regimes that occurred in the drought of the 1950's and 1960's that did not occur in the calibration period, which may have influenced the model's ability to accurately predict salinity during that time. Calibration of the extended model may improve model performance, but it is an unlikely effort without the acquisition of extensive data with which to calibrate the model.

Model performance for the more recently simulated period of 2006 – 2012 (as indicated by r^2 values ranging from 0.6 to 0.8 and a mean salinity difference between simulated and observed data ranging from 0.1 ppt to 3.1 ppt) was good. TxBLEND accurately simulated the pattern of increasing salinities beginning in 2010 and throughout 2011 due to the onset and duration of low inflows during this time.

Overall, the model performed similar to other TxBLEND simulations and applications, where long-term trends were simulated more accurately than short-term, high frequency variability and instances of under- or over-prediction occur at all sites, particularly in the upper reaches of the estuary. Furthermore, the extent of over- or under-prediction tends to be greater in the upper estuary. TxBLEND captured across bay changes in observed salinity behavior, such as greater daily variation at the Bolivar Roads site which occur with changes in the tidal cycle, as compared to the Trinity Bay site. Additionally, short-term, high inflow events and longer-term, seasonal, shifts in salinity (a function of seasonal changes in inflows) also were simulated well.

Conclusion

This TxBLEND model for the Trinity-San Jacinto Estuary (Galveston Bay) was not developed to aid in any specific analyses, but rather, was intended to be a proof of concept. Applications of the model should take into consideration the evaluation of model performance as discussed in this report. The model is somewhat limited in its ability to accurately predict salinity in the upper reaches of Trinity Bay, especially near the mouth of the Trinity River, for the extended period, as well as for the entire simulation period. However, increasing the one-mile radius of observed salinity data used for model validation may improve our ability to measure performance. Model improvements are necessary to simulate salinity in this part of the bay with confidence and could include improvements associated with the model grid or distribution of inflows as represented by the model, particularly with regards to the inclusion of inflows from watershed #08020. With increasing interest by stakeholders to model freshwater inflow effects on wetlands, deltas, and other upper estuarine habitats, TWDB staff continues to work on improving TxBLEND model performance in this area.

Extending TxBLEND back in time to simulate historical periods of interest depended heavily on access to historical datasets which were surprisingly more available than initially perceived. However, to truly conduct a robust model validation or even a model calibration, it is necessary to acquire additional sets of observed data. Further refinements to the methodologies described herein to modify TxBLEND, to prepare historical data, and to evaluate performance should be explored as well (*e.g.*, validating the model at other locations in the bay that may have more historical salinity observations). Future efforts such as these will aid in better understanding of long-term patterns of freshwater inflow and drought influences on Galveston Bay and will allow for the possibility of developing extended models for other Texas estuaries.

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Appendix A. Documentation of Historical Dimensions of the Houston Ship Channel, Provided by Mark Vincent, Channel Development Director at Port of Houston Authority.

Table A-1. Chronology of Houston Ship Channel (HSC) dimensions based on information provided by Mark Vincent, but reproduced from Alperin 1977. The dates represent the construction completion date.

Date	Min Depth (ft)	Max Width (ft)
1851	4	-
1870	4	70
1874	9	120
1889	12	100
1893	14	100
1903	18.5	150
1914	25	150
1926	30	250
1932	32	250
1935	34	250
1948	36	250
1964	40*	400*
2005	45*	530*

*These depths are given as the authorized channel depth to be maintained for navigation. The channel is constructed to a slightly deeper depth, which enables silt to accumulate before minimum authorized depths become limiting (when maintenance dredging is then scheduled). This additional advance maintenance, plus dredge equipment tolerance currently totals 4 feet throughout the channel. For instance, the 45’ channel section was initially dredged to 49’ (45’ plus 2’ advance maintenance + 2’ dredge tolerance), but is thereafter dredged to a minimum of 47’ during maintenance dredging.

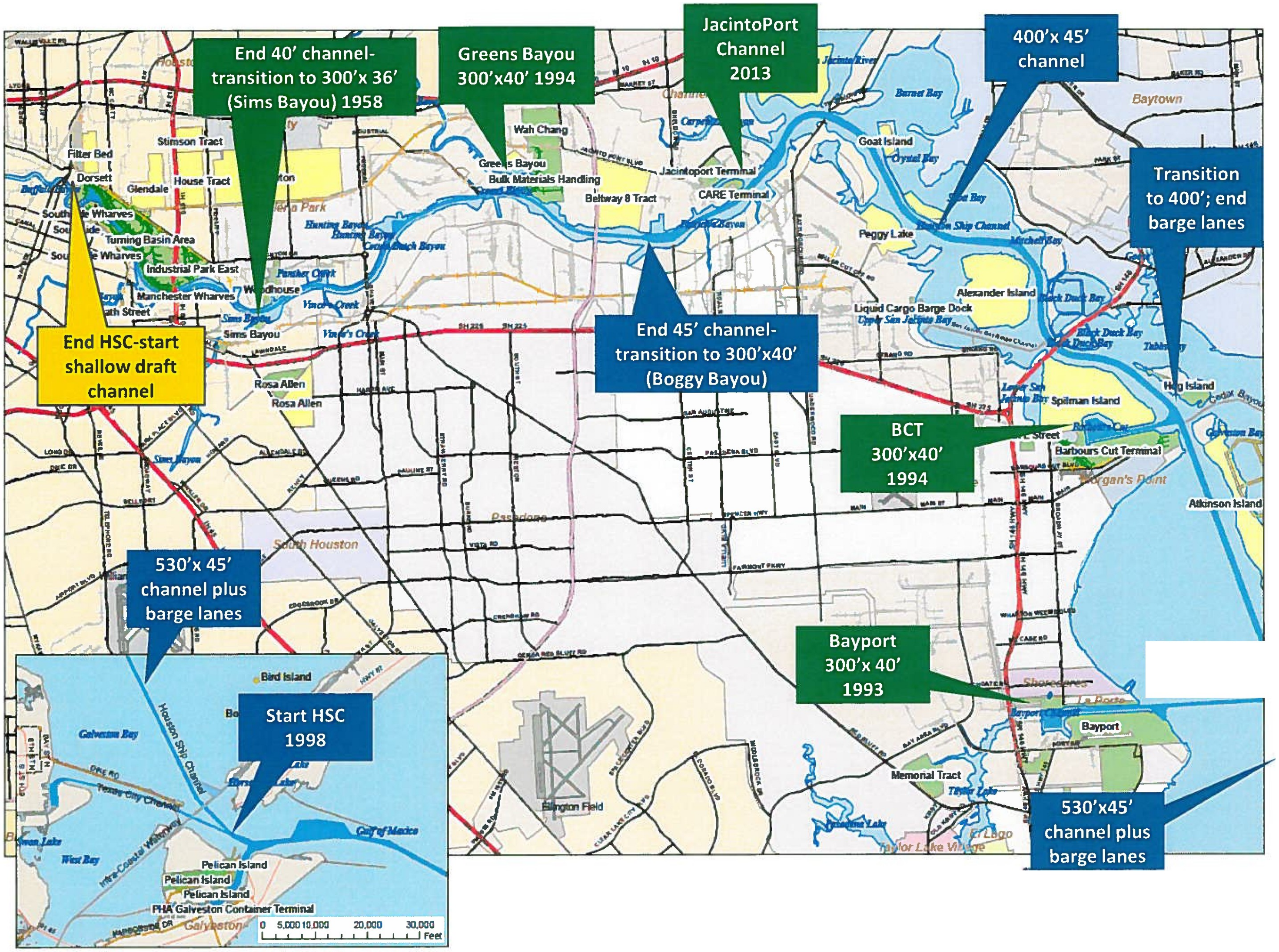

Figure A-1. Map of the Houston Ship Channel (HSC) showing historical depths and widths and the Congressional authorization date of the improvement. Map provided to TWDB by Mark Vincent on June 11, 2013.

Appendix B. Monthly Evaporation Data

Table B-1. Monthly evaporation estimates (in inches) from QUAD#813 of the TWDB Evaporation Program (http://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp).

QUAD	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL	in feet
813	1954	1.27	2.86	3.26	3.65	3.96	5.40	5.54	4.90	3.97	3.20	2.47	3.16	43.66	3.64
813	1955	2.01	1.55	3.21	2.94	3.82	4.74	4.39	3.77	3.24	4.37	2.86	2.00	38.89	3.24
813	1956	1.88	2.00	2.83	3.13	3.98	4.86	5.54	4.60	4.52	3.74	3.22	2.15	42.44	3.54
813	1957	2.04	2.09	3.49	3.73	3.95	3.71	4.71	5.22	3.64	3.68	2.41	2.34	41.01	3.42
813	1958	1.86	2.07	2.73	3.07	4.02	5.17	4.89	4.84	3.05	3.18	2.10	2.39	39.37	3.28
813	1959	1.87	1.44	3.16	3.05	3.26	6.39	4.46	4.00	3.98	3.23	2.64	1.73	39.23	3.27
813	1960	1.62	1.66	2.39	3.20	3.94	4.62	3.94	3.38	3.86	3.67	1.88	1.53	35.69	2.97
813	1961	1.65	1.92	2.57	3.53	4.21	4.19	3.64	3.55	3.34	3.63	2.63	2.00	36.84	3.07
813	1962	1.92	2.00	3.11	3.14	3.88	3.47	4.45	5.40	3.44	3.76	2.60	1.89	39.06	3.26
813	1963	1.50	1.84	2.63	3.38	3.78	4.15	3.95	4.43	3.23	3.18	2.55	1.90	36.53	3.04
813	1964	1.72	1.89	3.17	3.88	4.58	5.72	5.70	5.34	4.19	4.31	2.62	1.86	44.98	3.75
813	1965	2.45	2.25	3.26	3.78	4.13	5.33	5.93	4.96	4.75	3.80	2.14	1.44	44.21	3.68
813	1966	1.15	1.92	3.49	3.71	3.82	5.53	5.40	4.94	4.62	3.62	2.78	2.00	42.98	3.58
813	1967	1.99	2.48	4.21	4.15	4.98	6.64	6.03	5.37	4.31	4.29	2.88	1.88	49.23	4.10
813	1968	1.67	2.05	2.93	3.19	4.18	3.87	4.86	5.32	2.28	3.28	2.51	2.12	38.27	3.19
813	1969	2.04	1.81	3.09	3.03	4.07	5.11	5.99	5.65	5.00	4.04	2.94	1.93	44.69	3.72
813	1970	1.63	2.74	2.72	3.93	4.04	5.23	5.41	6.49	4.26	3.23	3.03	2.28	44.98	3.75
813	1971	2.21	2.61	3.42	4.49	4.20	6.02	6.30	5.02	3.62	3.36	2.62	1.37	45.24	3.77
813	1972	2.13	2.33	3.66	4.28	4.48	5.17	4.98	4.63	3.69	3.53	2.07	1.36	42.32	3.53
813	1973	1.39	2.02	2.71	3.13	4.86	3.38	4.53	4.46	3.11	2.73	3.17	2.41	37.91	3.16
813	1974	1.81	2.85	2.92	4.48	4.35	4.68	6.35	4.36	3.28	3.96	1.71	2.35	43.11	3.59
813	1975	2.38	2.10	2.88	3.30	4.19	4.66	4.30	4.10	3.89	3.90	2.87	2.13	40.70	3.39
813	1976	2.47	3.24	2.95	3.94	4.50	5.26	4.44	6.07	4.60	3.31	2.07	1.89	44.73	3.73
813	1977	1.70	2.85	3.07	4.10	4.86	6.08	6.09	4.60	4.43	3.86	2.49	2.53	46.66	3.89
813	1978	2.04	1.84	3.65	4.66	5.40	5.45	5.66	5.60	4.11	4.31	2.45	1.80	46.97	3.91
813	1979	1.67	2.02	3.62	3.78	4.48	5.98	5.63	5.08	4.60	5.12	3.15	2.39	47.52	3.96
813	1980	1.74	2.36	2.90	4.93	4.75	7.07	7.39	6.53	5.05	4.22	2.74	2.38	52.05	4.34
813	1981	2.53	2.23	3.92	4.53	5.30	5.42	5.91	5.96	4.89	3.81	3.01	2.58	50.07	4.17
813	1982	2.22	2.29	3.39	3.83	4.95	5.76	6.58	5.85	6.06	4.50	2.68	2.55	50.68	4.22
813	1983	2.30	2.87	4.23	4.28	4.74	5.47	6.24	5.22	4.62	3.91	3.03	2.25	49.16	4.10
813	1984	1.52	3.04	3.67	5.44	5.18	6.57	6.25	5.80	5.15	3.95	3.24	2.53	52.34	4.36
813	1985	2.13	1.58	3.26	4.90	5.30	6.24	5.98	6.23	5.57	3.93	2.68	1.81	49.62	4.14
813	1986	2.52	2.71	4.39	4.51	4.78	4.70	6.67	5.86	4.23	3.81	2.11	1.40	47.69	3.97
813	1987	1.97	2.28	4.09	5.79	4.18	4.90	5.83	6.45	4.76	4.50	3.06	1.62	49.43	4.12
813	1988	2.24	2.29	3.66	4.56	5.75	6.14	6.42	6.00	5.00	4.44	3.75	2.41	52.66	4.39
813	1989	1.85	1.82	3.26	4.58	4.97	5.28	5.71	5.36	5.57	4.51	2.80	1.95	49.15	4.10
813	1990	2.23	2.45	3.26	4.40	4.75	6.42	5.60	6.67	4.56	4.14	2.66	1.85	50.44	4.20
813	1991	1.86	2.32	3.68	3.18	4.76	6.53	6.54	6.06	4.94	5.47	3.09	3.62	52.05	4.34

Table B-1., *continued*.

QUAD	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL	in feet
813	1992	2.21	3.10	3.51	4.27	4.88	5.50	5.64	5.44	4.74	4.39	2.69	1.87	48.23	4.02
813	1993	2.88	2.79	3.07	3.97	6.28	4.98	7.30	7.83	7.00	4.76	3.06	3.62	57.53	4.79
813	1994	2.33	2.52	3.17	3.78	5.44	5.12	7.34	4.81	5.91	5.02	3.75	2.74	51.94	4.33
813	1995	2.69	2.35	2.79	3.84	4.83	6.16	5.71	5.47	4.86	4.83	2.83	2.39	48.75	4.06
813	1996	2.01	3.05	3.58	5.04	6.02	5.79	6.15	5.70	4.29	3.71	2.34	2.89	50.57	4.21
813	1997	1.80	2.53	3.60	4.72	4.61	5.78	6.61	6.39	5.50	4.62	3.01	2.96	52.12	4.34
813	1998	2.48	2.64	4.31	5.30	6.08	8.00	7.77	6.43	4.99	4.20	2.75	2.56	57.51	4.79
813	1999	1.99	2.30	3.31	4.01	4.61	5.39	5.66	5.34	4.42	3.98	2.71	2.20	45.98	3.83
813	2000	2.19	2.53	3.64	4.41	5.07	5.93	6.23	5.87	4.86	4.38	2.99	2.42	50.51	4.21
813	2001	2.03	2.36	3.92	5.10	6.30	5.42	5.74	6.17	5.00	4.40	3.11	2.39	51.94	4.33
813	2002	2.45	2.94	3.93	5.05	5.88	6.37	6.05	6.44	4.49	2.68	2.38	1.70	50.35	4.20
813	2003	1.90	1.51	2.59	3.49	4.10	4.30	4.18	4.23	3.50	3.31	2.51	2.13	37.77	3.15
813	2004	1.69	1.60	3.01	3.71	3.84	4.91	4.67	4.73	4.24	3.23	1.89	1.81	39.36	3.28
813	2005	1.80	1.50	3.56	4.48	4.30	4.96	6.81	5.00	4.99	4.92	3.22	2.24	47.79	3.98
813	2006	3.06	2.45	3.80	4.95	4.77	5.44	4.47	4.78	4.54	3.99	2.99	2.11	47.35	3.95
813	2007	1.80	1.65	3.69	3.78	4.46	5.03	4.11	4.94	4.57	4.32	2.90	2.29	43.56	3.63
813	2008	2.00	2.37	3.91	4.28	4.64	4.91	5.34	4.56	4.18	4.33	3.68	1.97	46.18	3.85
813	2009	2.62	2.57	3.50	4.52	4.62	5.95	5.99	4.93	3.38	3.27	2.75	1.72	45.82	3.82
813	2010	2.04	1.78	3.59	4.43	5.11	5.02	4.68	5.06	4.22	5.07	2.69	2.62	46.31	3.86
813	2011	2.06	2.09	3.60	4.89	5.32	6.32	5.35	6.14	5.14	4.60	3.18	1.90	50.59	4.22
Mo. Average (in)		2.02	2.26	3.36	4.10	4.66	5.39	5.59	5.32	4.42	3.99	2.74	2.18		
Mo. Average (ft)		0.17	0.19	0.28	0.34	0.39	0.45	0.47	0.44	0.37	0.33	0.23	0.18		

Table B-2. Monthly evaporation estimates calculated based on the Harbeck equation.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL	feet
1949	1.64	1.24	2.99	3.21	5.50	7.67	6.00	6.65	5.80	3.39	2.94	1.82	48.85	4.07
1950	1.36	1.98	3.62	3.41	4.65	4.79	6.34	5.57	4.76	4.37	3.57	2.27	46.69	3.89
1951	1.94	1.51	3.40	3.85	5.01	5.96	6.97	6.89	4.33	4.56	2.82	2.21	49.45	4.12
1952	2.44	3.06	2.88	3.06	4.12	4.11	4.62	6.29	4.74	4.49	2.61	2.11	44.53	3.71
1953	2.76	1.83	2.44	3.71	3.97	6.37	6.18	5.04	5.49	4.29	2.73	2.41	47.22	3.94
1954	1.39	3.55	3.02	3.07	4.46	5.85	6.62	6.28	5.22	5.07	4.08	3.35	51.96	4.33
1955	2.19	2.00	3.01	3.52	4.94	5.14	6.26	6.41	6.00	8.36	5.41	3.29	56.53	4.71
1956	3.15	3.06	3.04	4.82	5.84	8.38	8.39	7.26	7.23	5.25	4.18	2.31	62.91	5.24
1957	1.82	2.00	3.19	3.29	5.59	6.65	6.96	7.12	5.19	4.72	3.07	2.92	52.52	4.38
1958	2.72	2.29	2.83	3.67	5.94	7.79	9.63	7.41	4.16	3.36	1.81	1.71	53.32	4.44
1959	1.81	1.75	3.65	3.37	5.27	6.94	5.30	5.60	5.01	4.23	2.63	2.26	47.82	3.98
1960	1.72	2.04	1.87	3.18	4.96	5.67	5.60	5.16	4.71	3.63	2.94	1.88	43.36	3.61
1961	1.59	1.63	3.24	4.37	5.90	5.60	5.95	5.02	6.17	5.04	2.86	2.34	49.71	4.14
1962	1.73	1.98	3.24	3.37	6.34	5.35	6.50	6.80	6.44	6.07	3.65	1.77	53.24	4.44
1963	1.55	1.90	2.75	4.41	4.81	5.43	6.36	5.61	4.74	2.38	2.28	1.71	43.93	3.66
1964	1.54	1.67	2.84	3.57	4.44	5.70	4.23	4.22	2.55	2.72	2.01	1.61	37.10	3.09
1965	2.21	1.84	2.90	3.18	4.78	4.29	4.11	3.14	3.84	2.41	2.07	1.55	36.32	3.03
1966	1.22	1.44	3.44	3.33	2.59	3.25	3.56	3.57	3.02	2.89	2.30	1.86	32.47	2.71
1967	1.93	1.87	3.13	3.31	3.52	3.45	3.72	2.90	2.65	2.97	2.39	1.50	33.34	2.78

Table B-2., *continued.*

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL	feet
1968	1.46	1.50	1.81	2.45	2.89	2.50	2.18	2.86	1.83	2.20	2.30	1.66	25.64	2.14
1969	1.36	1.43	2.30	2.27	2.33	3.74	3.94	3.85	2.71	2.68	2.07	1.38	30.06	2.50
1970	1.47	1.96	2.45	3.29	4.03	4.05	3.30	3.91	3.17	2.42	2.20	1.65	33.90	2.83
1971	1.97	2.51	3.19	3.14	3.04	3.66	4.10	2.20	2.44	2.47	2.48	1.09	32.29	2.69
1972	2.02	2.32	3.56	4.40	3.15	4.32	3.12	2.64	2.16	2.50	2.10	1.66	33.95	2.83
1973	1.76	1.43	2.60	3.04	4.18	4.39	5.23	5.03	4.63	4.54	2.84	2.47	42.14	3.51
1974	0.90	3.11	2.16	4.53	4.84	7.20	6.44	6.18	5.31	4.54	3.17	1.83	50.21	4.18
1975	2.16	2.28	3.28	3.83	5.28	5.56	5.93	4.87	3.83	3.29	2.96	1.65	44.92	3.74
1976	2.06	2.42	2.90	3.07	4.59	5.27	4.63	4.62	4.29	3.38	1.80	1.60	40.63	3.39
1977	1.38	2.32	2.54	3.43	4.32	5.52	5.35	5.47	5.18	4.41	2.63	3.10	45.65	3.80
1978	1.51	1.26	2.29	2.96	4.51	5.27	5.15	5.21	5.03	4.43	2.75	2.14	42.51	3.54
1979	2.03	1.33	3.05	3.18	4.21	5.90	5.59	4.64	4.46	5.03	2.97	1.80	44.19	3.68
1980	1.56	1.60	2.59	3.53	3.70	5.66	5.86	8.01	4.32	4.31	2.13	1.62	44.89	3.74
1981	1.54	1.68	2.80	3.01	4.87	6.14	4.92	5.37	3.89	4.28	2.13	2.33	42.96	3.58
1982	1.86	1.50	2.64	3.41	4.56	5.26	6.81	5.62	6.25	3.70	2.39	1.93	45.93	3.83
1983	1.54	1.77	2.86	3.17	3.49	4.59	5.30	4.21	4.36	3.87	3.31	2.33	40.80	3.40
1984	1.71	2.58	3.06	4.82	5.96	5.58	6.16	5.50	5.44	3.77	3.58	2.24	50.40	4.20
1985	1.72	1.33	2.47	4.05	5.16	5.16	4.43	6.25	6.54	4.13	2.56	1.76	45.56	3.80
1986	2.20	2.21	3.17	4.11	4.49	5.47	7.03	6.81	6.66	4.34	2.37	1.64	50.50	4.21
1987	2.14	2.84	3.57	4.52	5.32	6.80	7.05	8.11	6.53	5.35	3.46	2.28	57.97	4.83
1988	2.60	2.25	3.39	4.38	5.48	6.45	6.22	6.83	6.01	5.21	4.80	2.28	55.90	4.66
1989	1.68	1.65	2.57	3.37	5.21	6.48	5.41	5.12	6.13	4.64	3.42	1.71	47.39	3.95
1990	1.44	2.02	2.52	3.71	5.03	7.27	6.36	6.39	4.81	4.76	2.79	2.14	49.24	4.10
1991	1.26	2.35	3.37	3.00	4.32	5.07	5.58	5.31	5.07	4.40	2.81	2.28	44.82	3.73
1992	1.80	2.08	2.94	3.46	4.79	5.26	7.72	7.54	6.89	4.65	3.10	1.67	51.90	4.32
1993	1.84	2.12	3.14	3.75	5.27	5.80	7.66	7.57	6.43	4.24	2.53	2.77	53.12	4.43
1994	2.09	1.57	2.85	2.62	4.70	5.51	7.54	5.71	4.88	4.13	3.67	2.18	47.45	3.95
1995	2.64	2.15	2.65	4.61	6.09	8.52	8.53	7.72	7.27	6.29	3.61	2.46	62.54	5.21
1996	2.70	2.84	3.94	4.20	5.68	6.47	7.11	5.30	4.25	3.79	2.87	1.57	50.72	4.23
1997	1.54	1.25	1.80	3.22	3.64	3.72	4.46	5.60	4.31	3.81	2.00	1.70	37.05	3.09
1998	1.32	1.51	2.43	3.51	3.40	4.78	4.71	3.34	3.06	3.72	1.59	1.31	34.68	2.89
1999	1.72	1.81	2.26	3.27	3.17	1.89	3.16	4.10	3.00	2.01	0.48	0.53	27.40	2.28
2000	2.22	1.82	2.22	3.09	4.41	5.44	5.54	4.74	3.97	2.20	1.31	1.17	38.13	3.18
2001	1.14	1.09	1.75	2.98	3.42	3.60	3.38	3.96	2.58	2.34	1.44	1.16	28.84	2.40
2002	1.19	1.41	1.92	2.82	4.04	3.07	3.19	3.21	2.88	1.77	1.53	0.89	27.92	2.33
2003	1.14	0.94	1.53	2.26	3.92	3.27	3.60	2.89	2.35	2.33	2.37	1.55	28.15	2.35
2004	1.09	0.96	1.77	1.76	3.73	3.13	3.23	3.59	3.24	3.55	1.76	1.44	29.25	2.44
2005	1.49	1.05	2.24	3.20	3.34	4.92	3.89	3.12	4.97	3.31	2.08	1.78	35.39	2.95
2006	2.80	2.38	3.65	3.88	5.61	4.88	4.73	5.12	4.85	4.33	2.92	2.20	47.35	3.95
2007	1.55	1.98	2.71	3.11	4.18	4.29	3.53	4.36	3.98	4.12	2.32	2.29	38.42	3.20
2008	2.04	2.17	3.20	4.07	4.94	6.54	5.66	4.27	2.75	3.05	2.49	2.35	43.53	3.63
2009	1.79	2.30	2.18	3.57	4.68	5.75	5.97	5.63	3.32	2.66	2.03	1.38	41.26	3.44
2010	1.37	1.28	2.40	3.09	3.75	4.78	4.72	5.67	5.05	5.09	2.49	2.25	41.94	3.49
2011	1.39	1.45	2.40	5.60	6.34	7.45	6.89	7.43	6.97	4.83	3.49	1.63	55.87	4.66
2012	1.96	1.76	2.34	4.11	4.44	4.96	4.44	5.72	4.24	3.87	2.38	1.80	42.02	3.50
Avg (in)	1.79	1.91	2.76	3.51	4.55	5.31	5.45	5.29	4.60	3.92	2.67	1.93		
Avg (ft)	0.15	0.16	0.23	0.29	0.38	0.44	0.45	0.44	0.38	0.33	0.22	0.16		

Appendix C. Sources of Salinity Data Used for Model Validation

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Appendix D. Time - Series Plots of Simulated Salinity Versus Observed Salinity at Selected Locations for Five - Year Intervals.

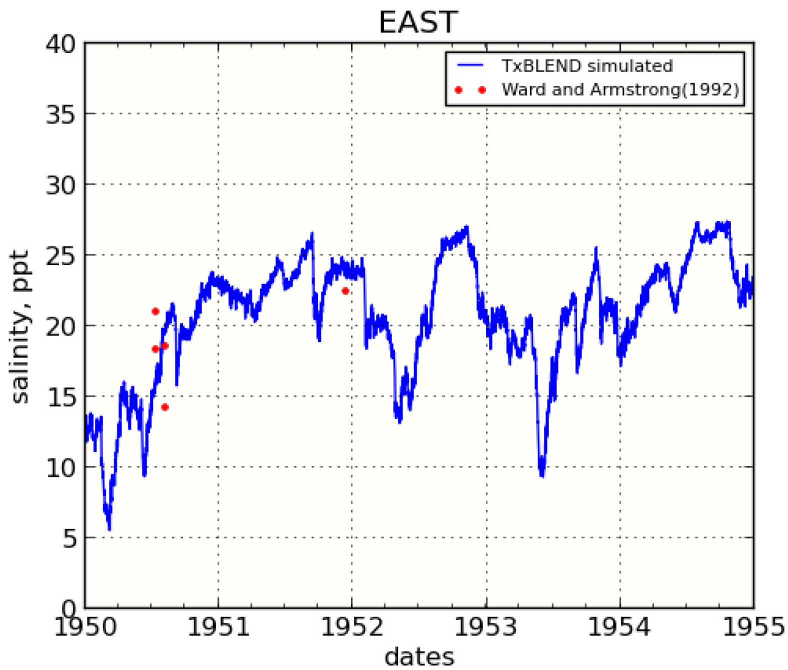

Figure D-1. Simulated (*blue*) versus observed (*red*) salinities at East Bay for the period 1950 – 1954.

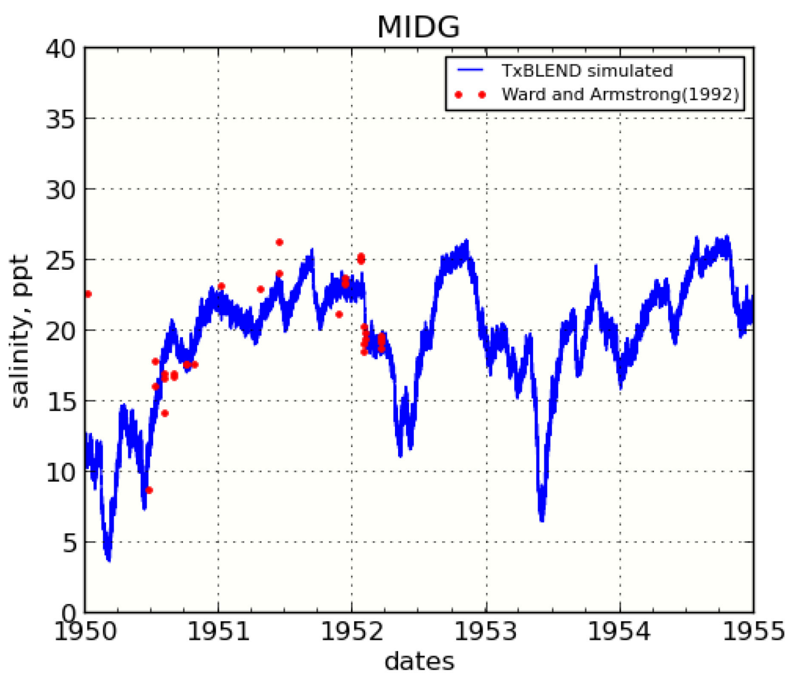

Figure D-2. Simulated (*blue*) versus observed (*red*) salinities at Mid-Galveston Bay for the period 1950 – 1954.

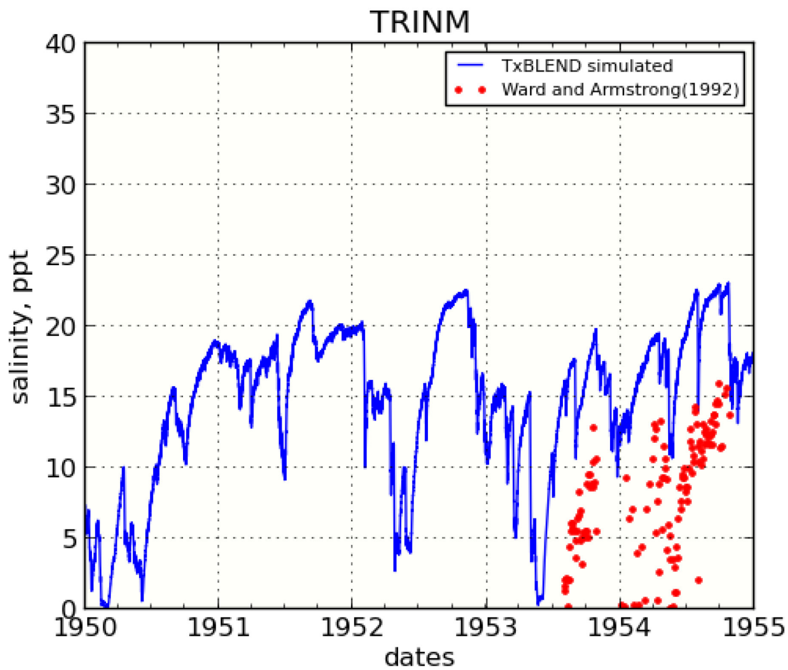

Figure D-3. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1950 – 1954.

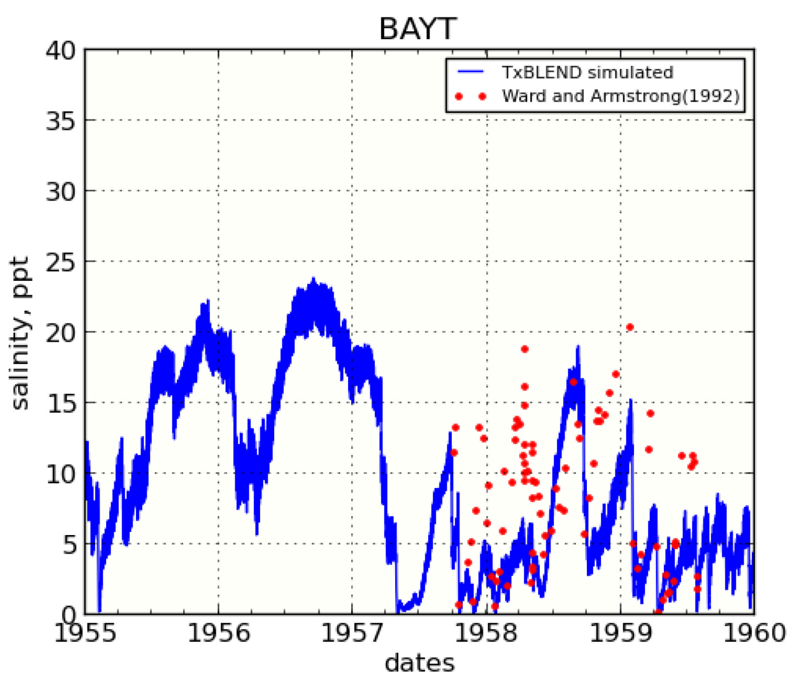

Figure D-4. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1955 - 1959.

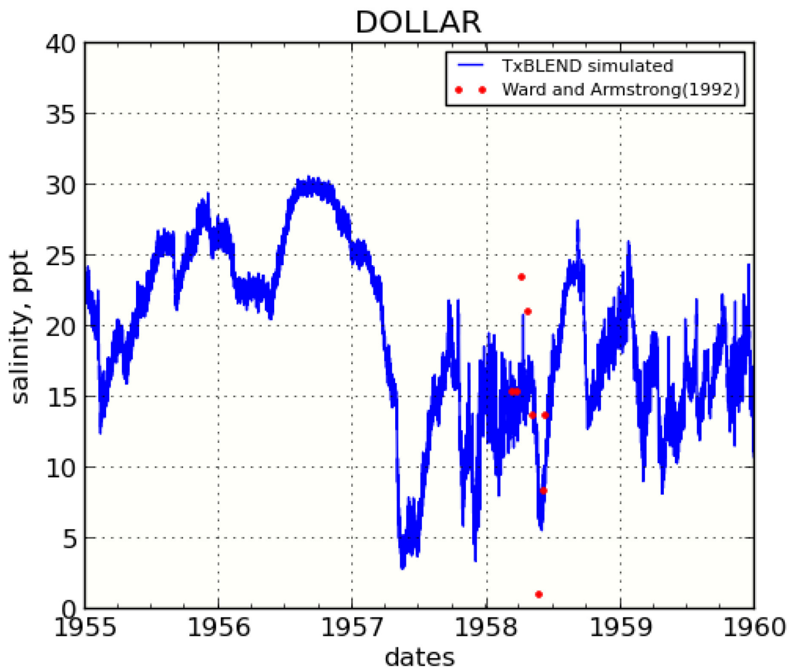

Figure D-5. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1955 - 1959.

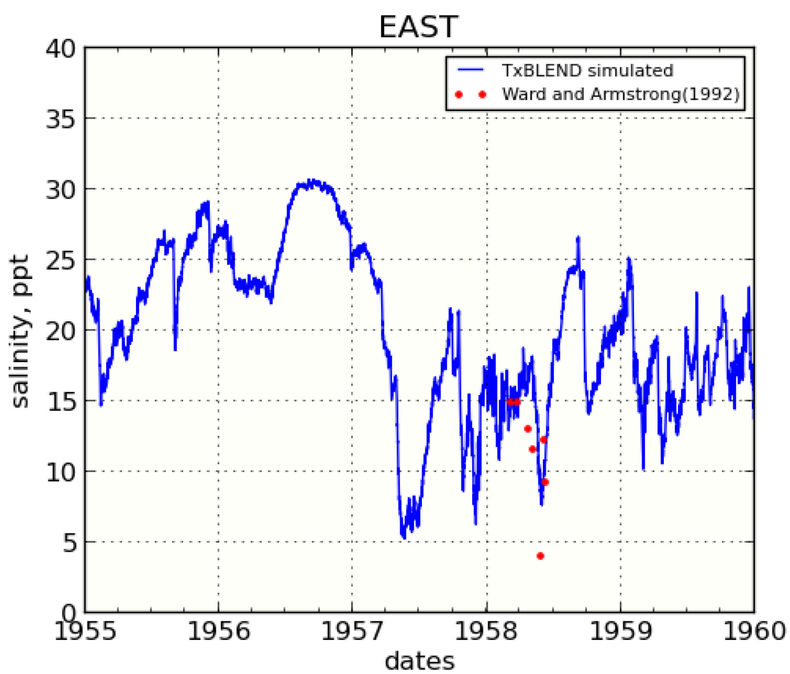

Figure D-6. Simulated (*blue*) versus observed (*red*) salinities at East Bay for the period 1955 – 1959.

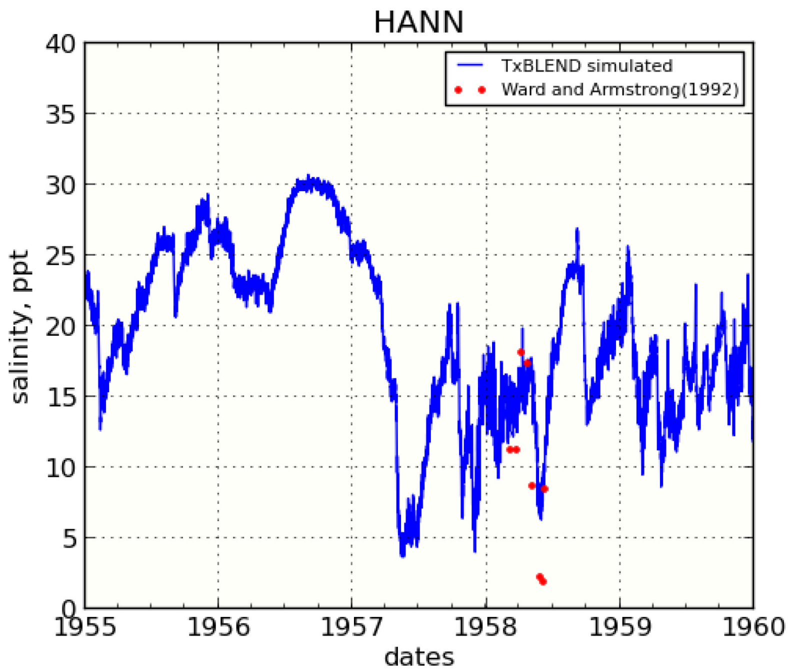

Figure D-7. Simulated (*blue*) versus observed (*red*) salinities at Hanna's Reef for the period 1955 - 1959.

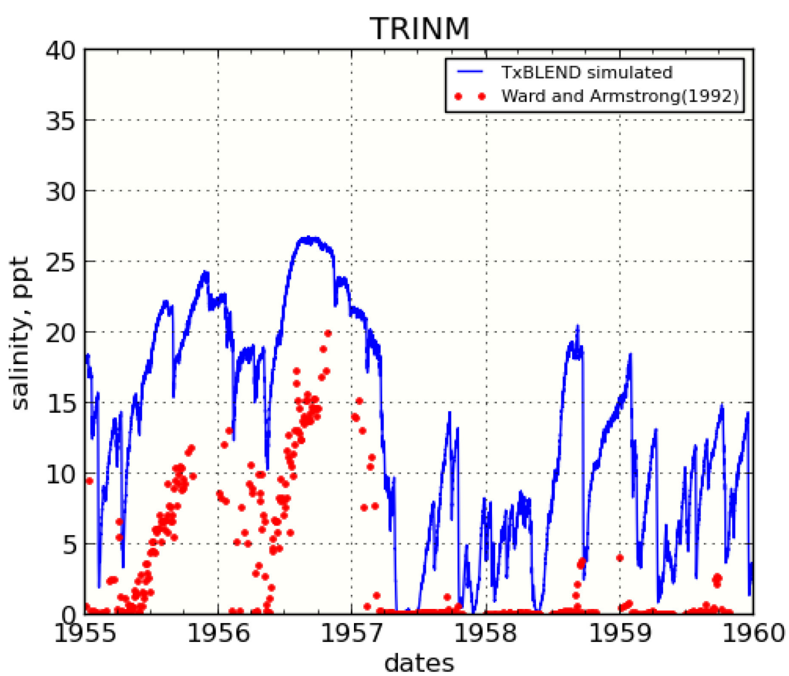

Figure D-8. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1955 - 1959.

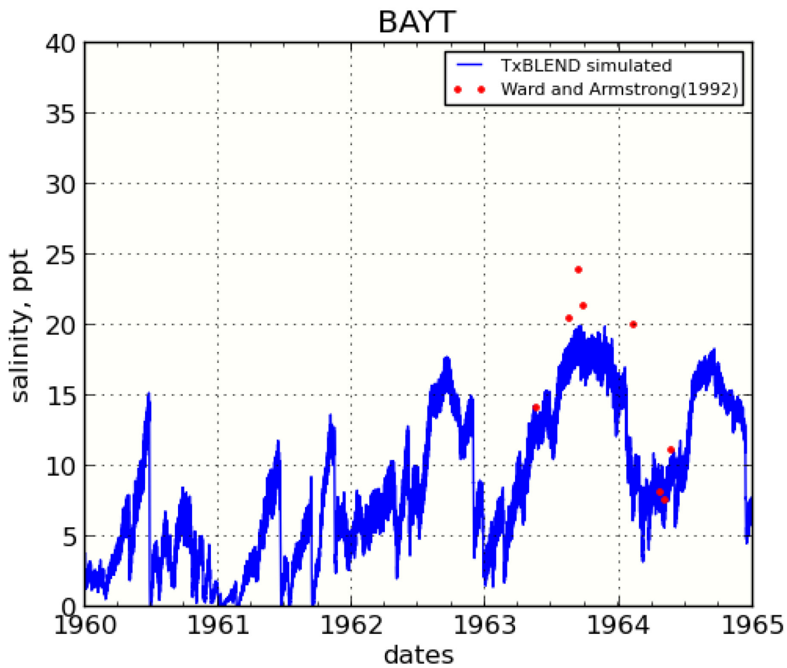

Figure D-9. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1960 - 1964.

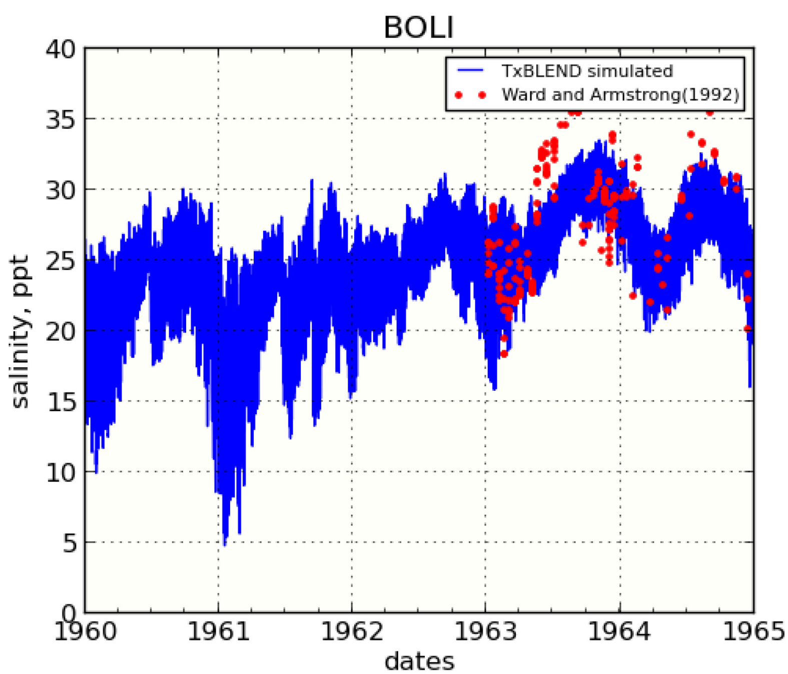

Figure D-10. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Road for the period 1960 - 1964.

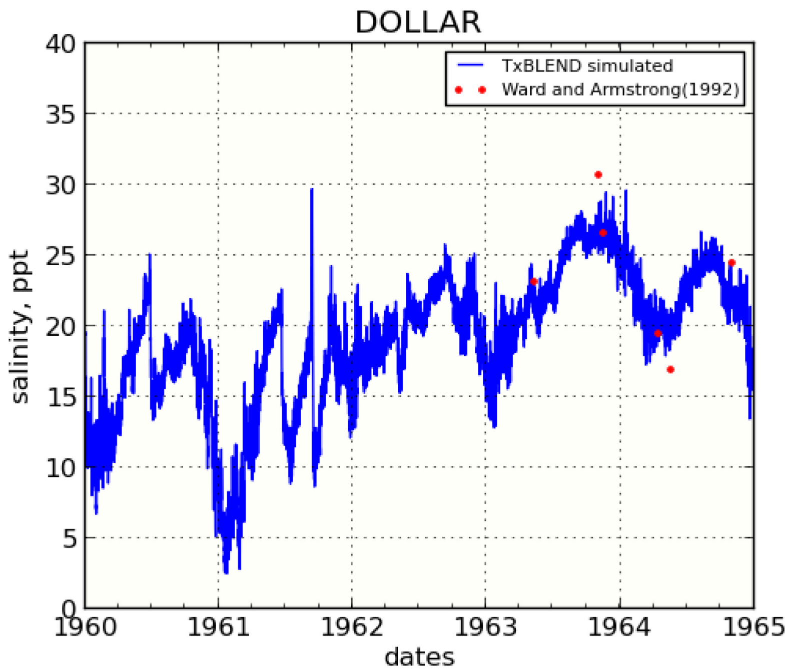

Figure D-11. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1960 - 1964.

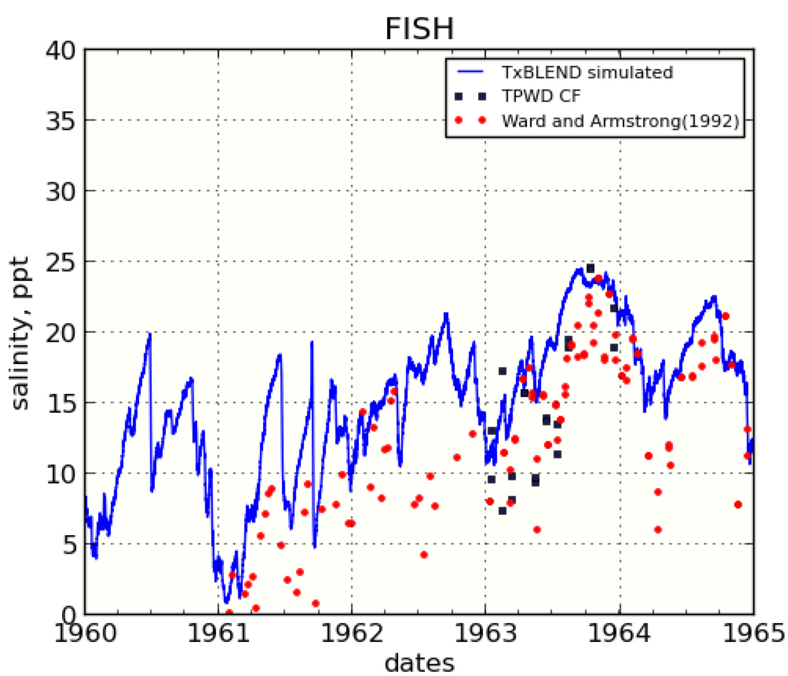

Figure D-12. Simulated (*blue*) versus observed (*red and black*) salinities at Fisher's Reef for the period 1960 - 1964.

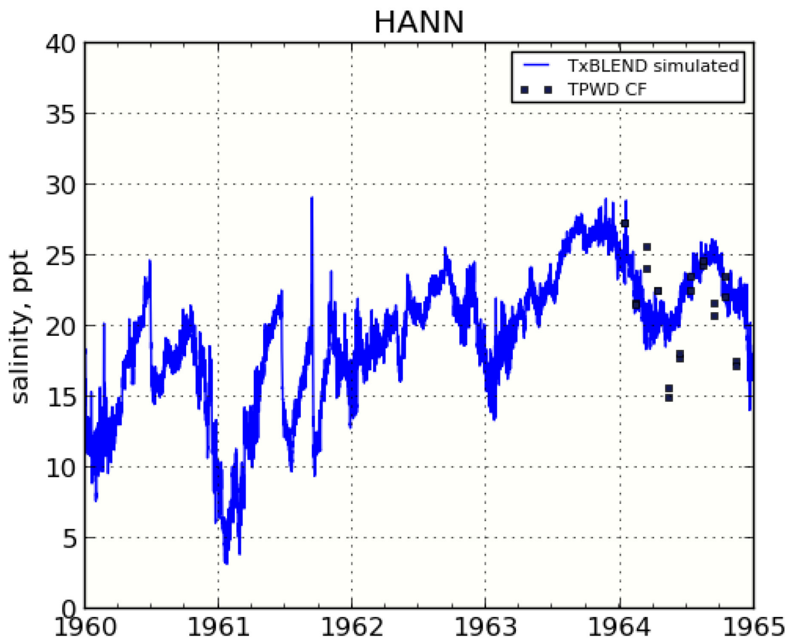

Figure D-13. Simulated (*blue*) versus observed (*black*) salinities at Hanna's Reef for the period 1960 - 1964.

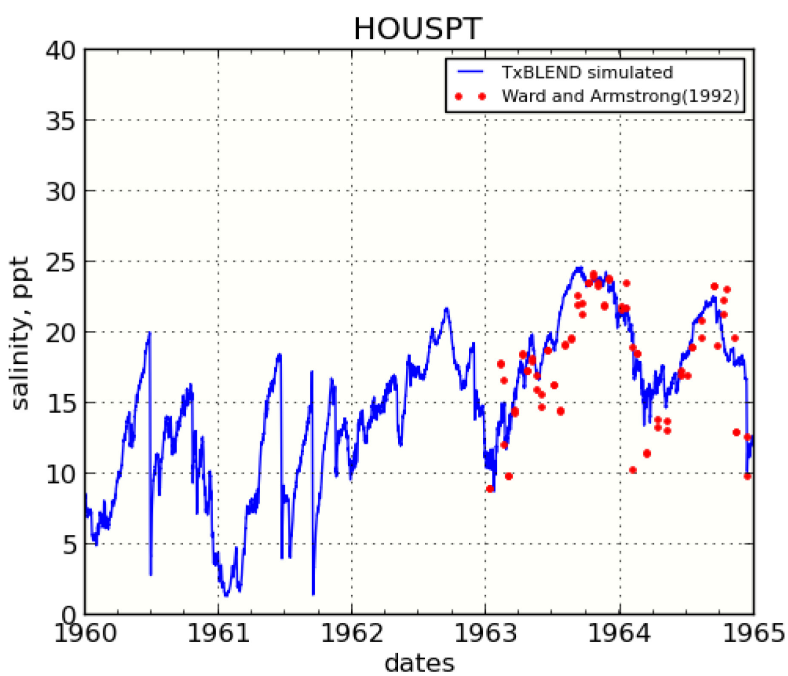

Figure D-14. Simulated (*blue*) versus observed (*red*) salinities at Houston Point for the period 1960 - 1964.

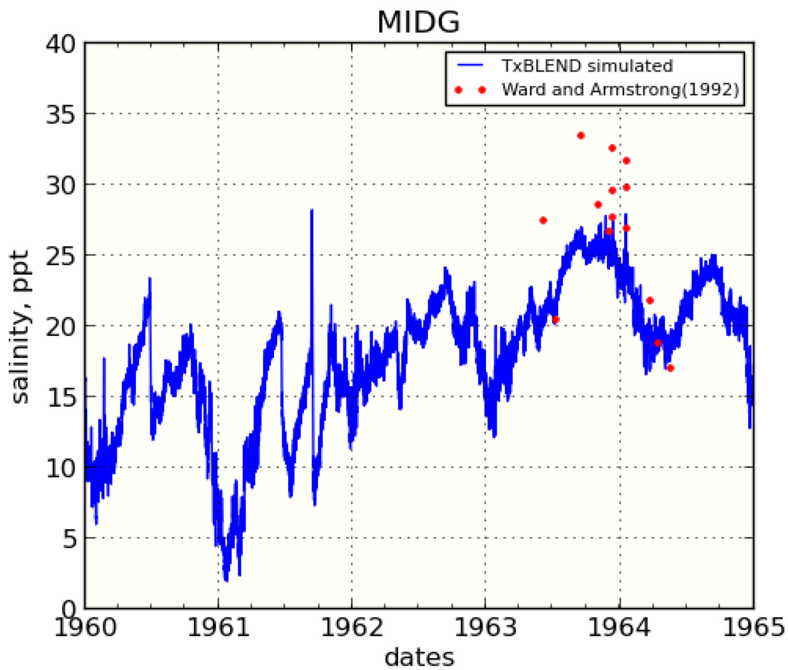

Figure D-15. Simulated (*blue*) versus observed (*red*) salinities at Mid Galveston Bay for the period 1960 - 1964.

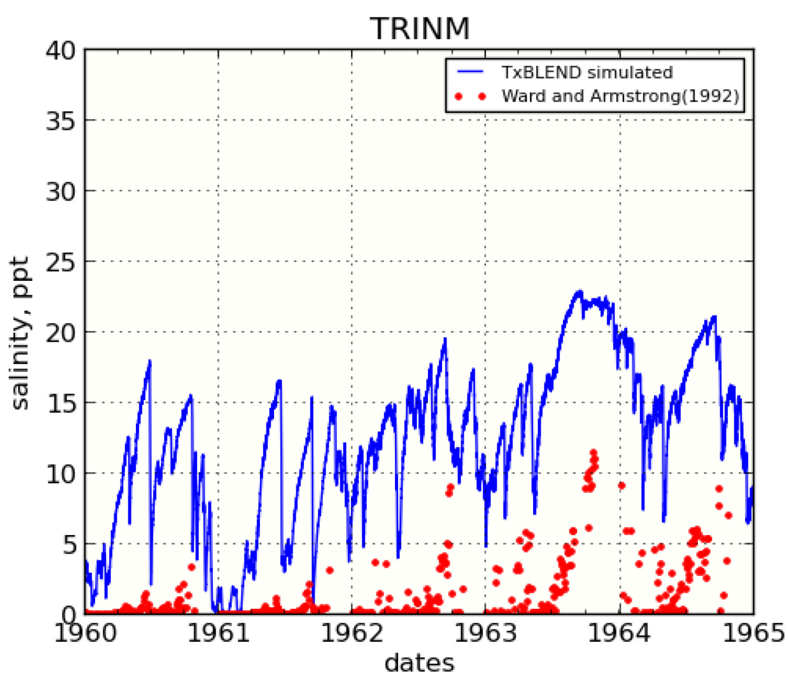

Figure D-16. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1960 - 1964.

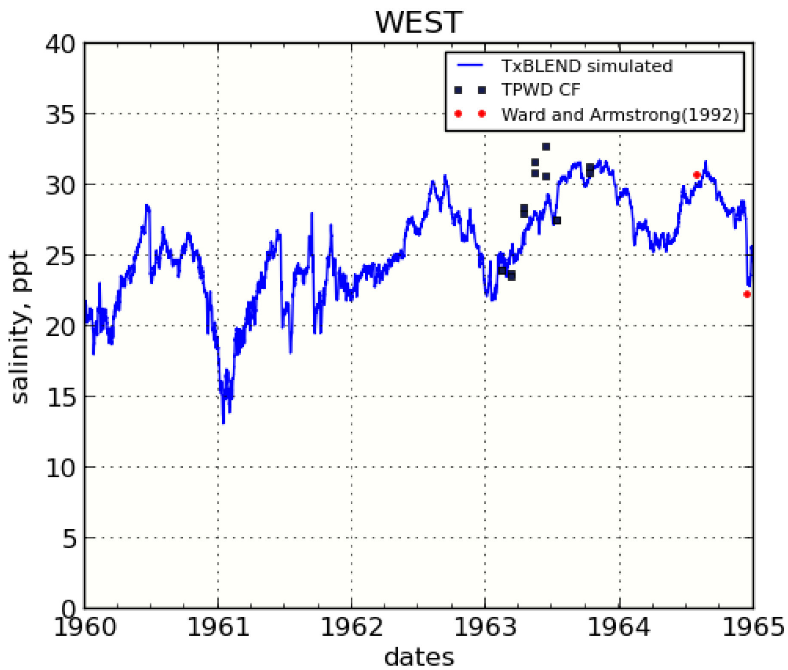

Figure D-17. Simulated (*blue*) versus observed (*red and black*) salinities at West Bay for the period 1960 - 1964.

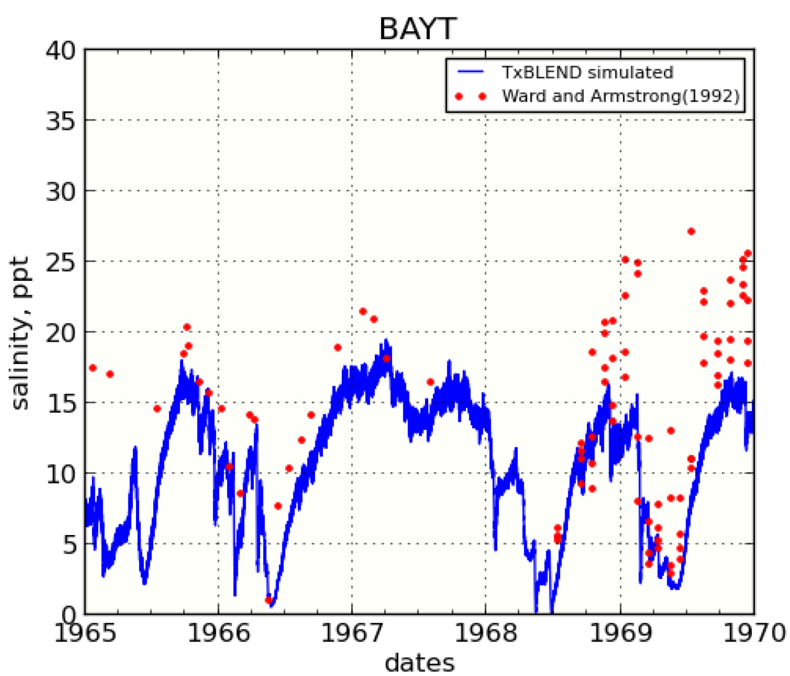

Figure D-18. Simulated (*blue*) versus observed (*red*) salinities at Houston Ship Channel near Baytown for the period 1965 – 1969.

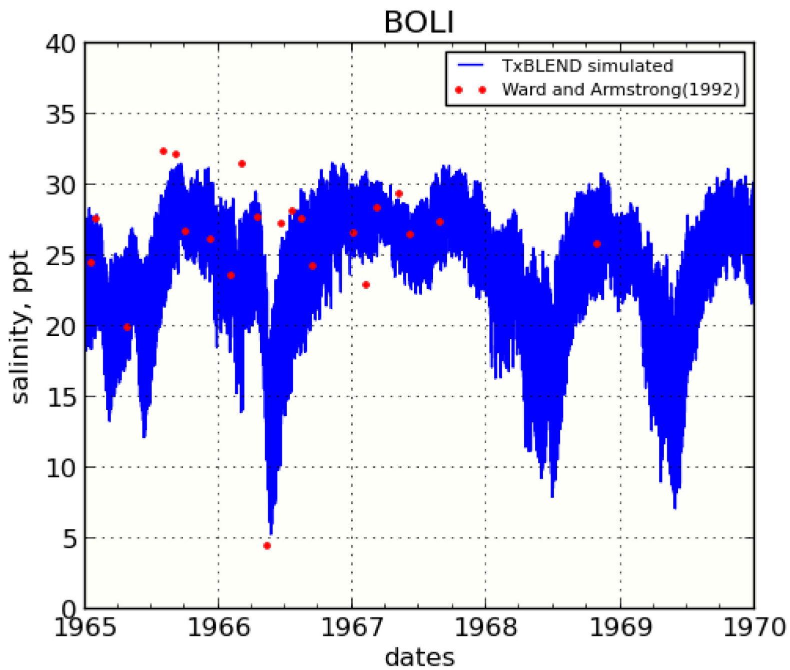

Figure D-19. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Road for the period 1965 - 1969.

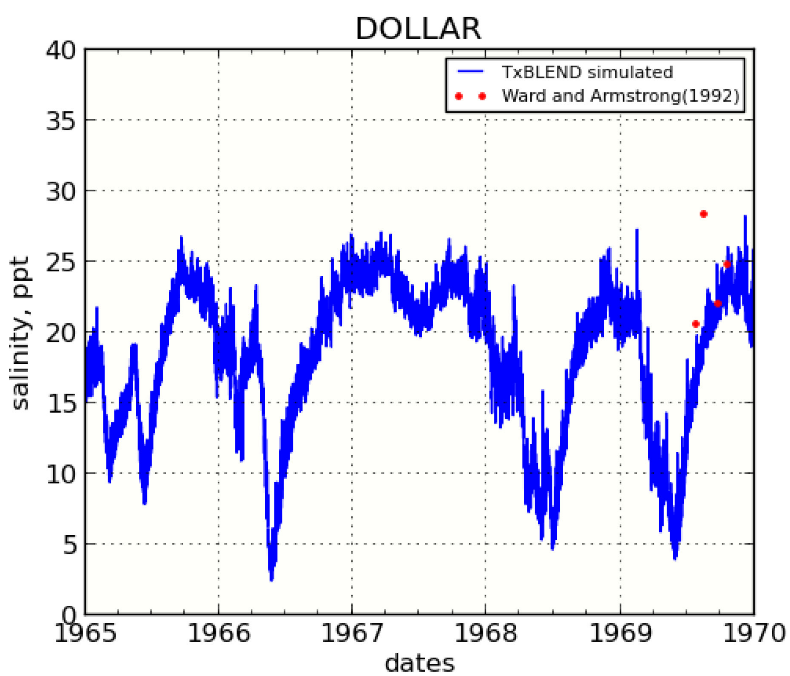

Figure D-20. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1965 - 1969.

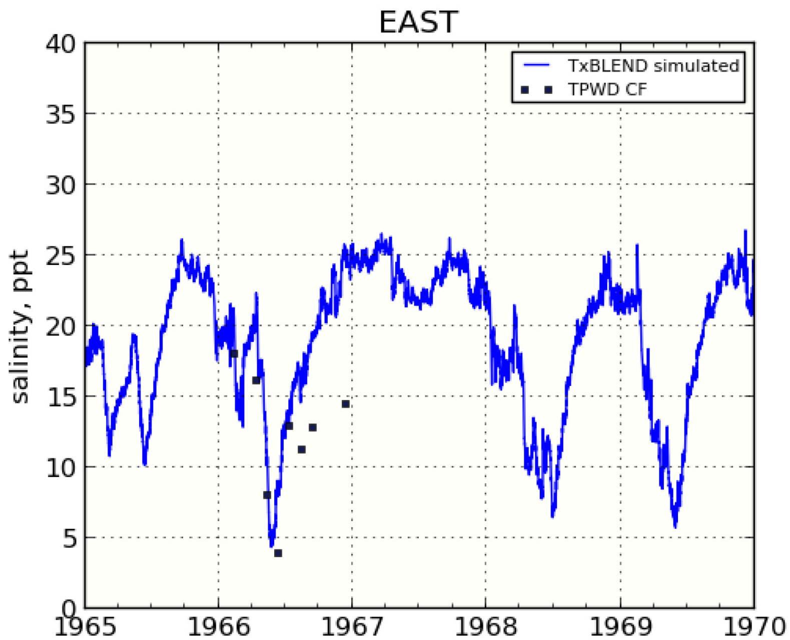

Figure D-21. Simulated (*blue*) versus observed (*black*) salinities at Dollar Point for the period 1965 - 1969.

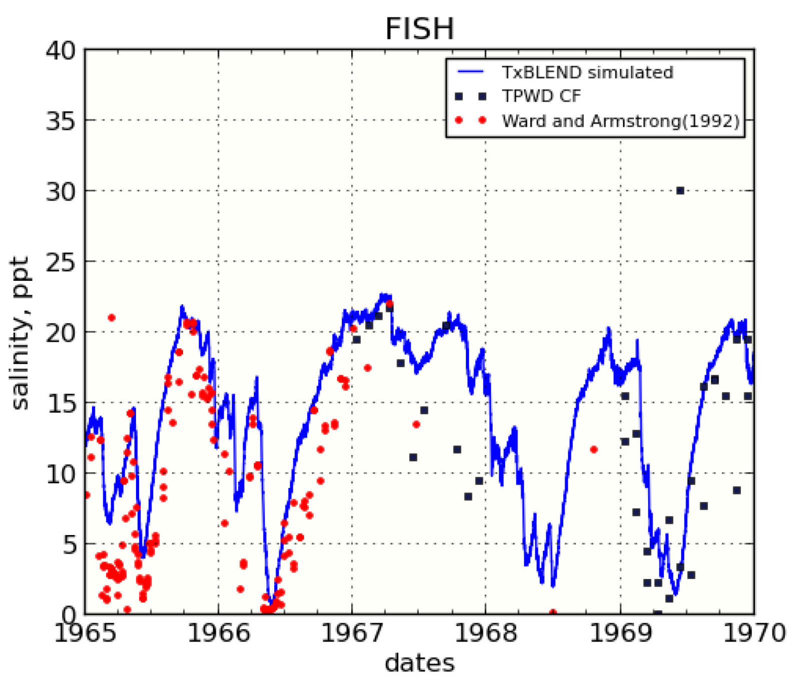

Figure D-22. Simulated (*blue*) versus observed (*red and black*) salinities at Fisher's Reef for the period 1965 – 1969.

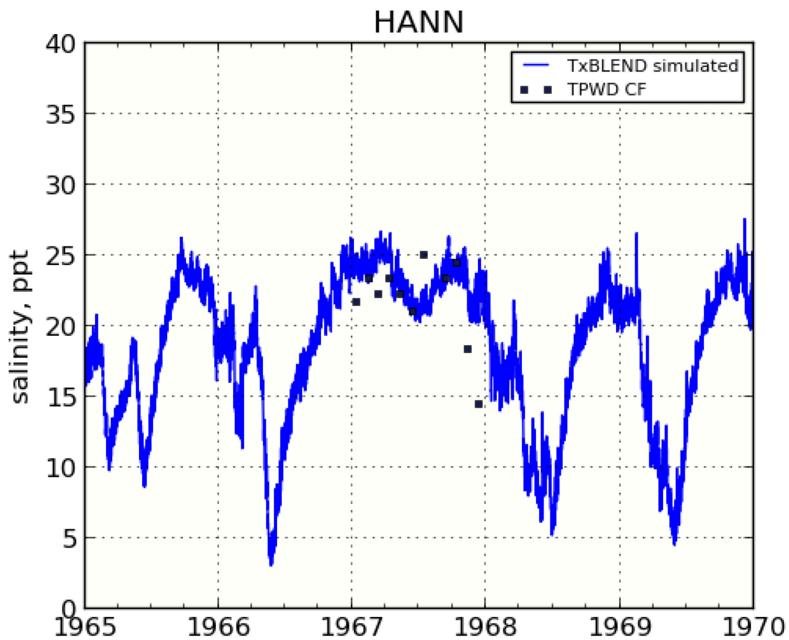

Figure D-23. Simulated (*blue*) versus observed (*black*) salinities at Hanna's Reef for the period 1965 - 1969.

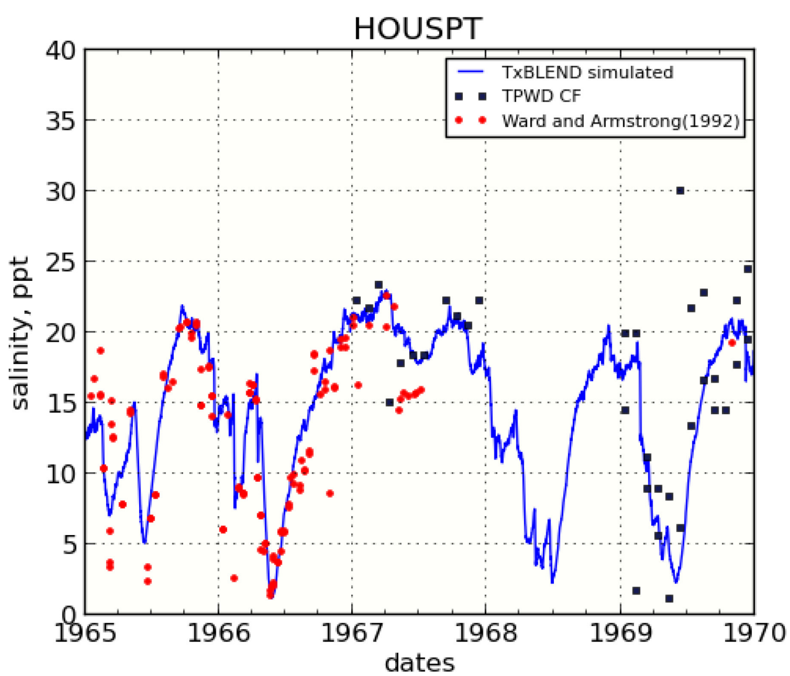

Figure D-24. Simulated (*blue*) versus observed (*red and black*) salinities at Houston Point for the period 1965 - 1969.

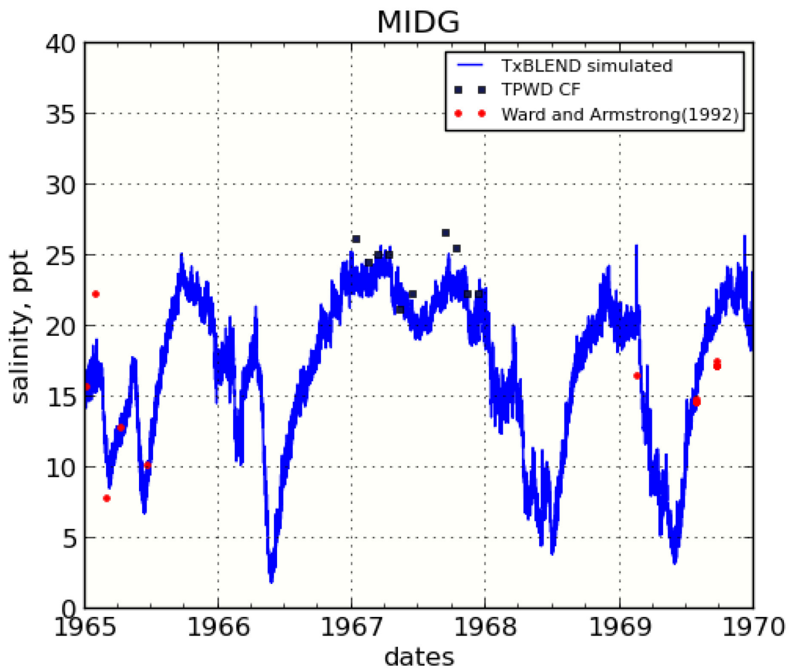

Figure D-25. Simulated (*blue*) versus observed (*red and black*) salinities at Mid- Galveston Bay for the period 1965 - 1969.

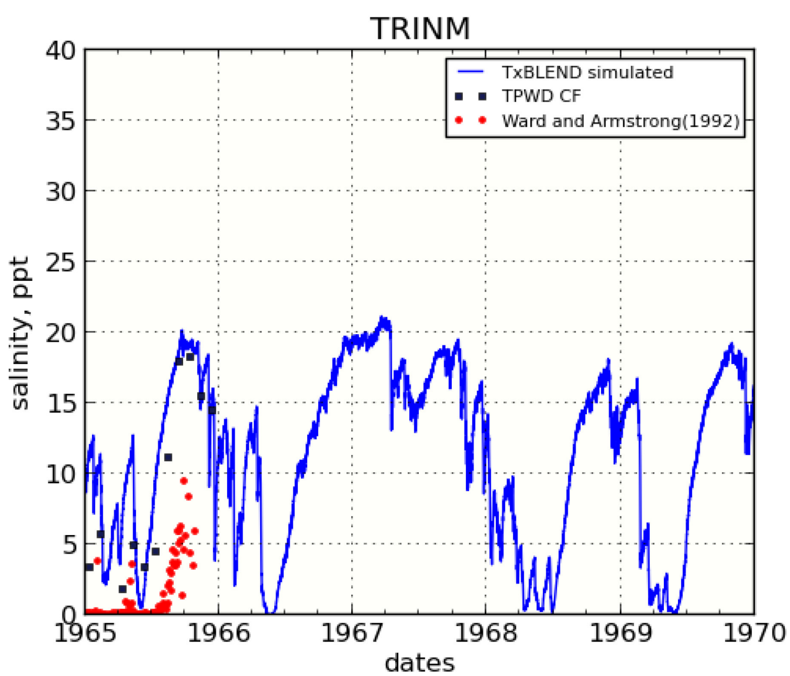

Figure D-26. Simulated (*blue*) versus observed (*red and black*) salinities at Trinity River Mouth for the period 1965 - 1969.

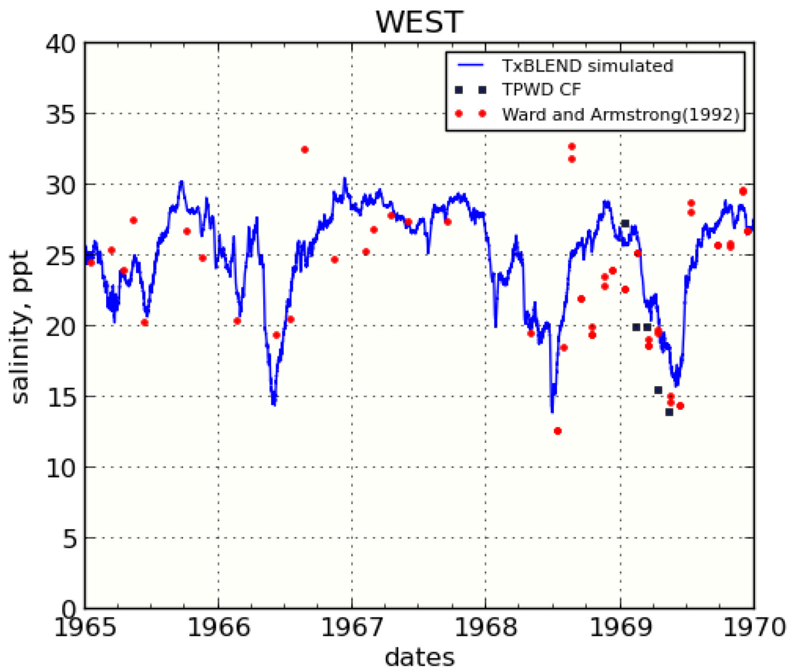

Figure D-27. Simulated (*blue*) versus observed (*red and black*) salinities at West Bay for the period 1965 - 1969.

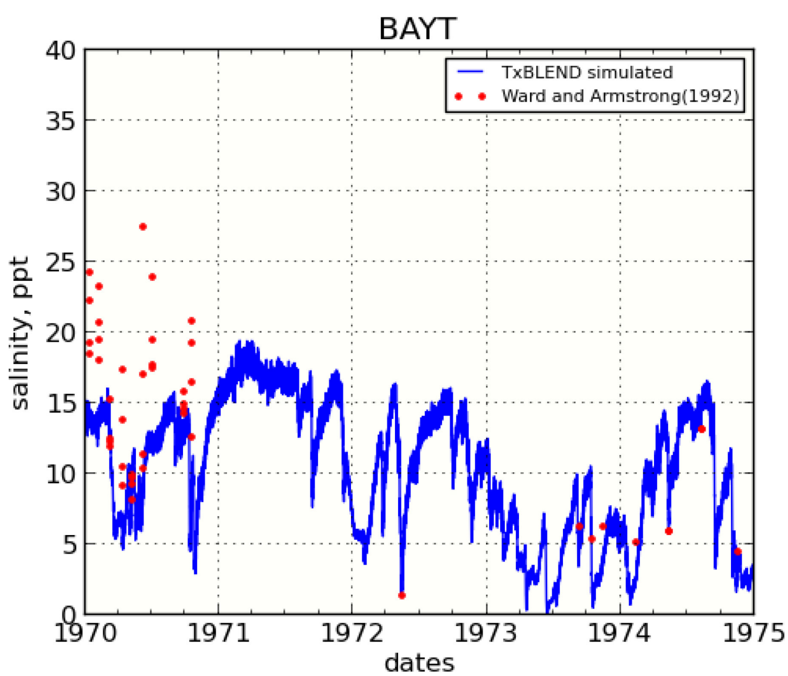

Figure D-28. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1970 - 1974.

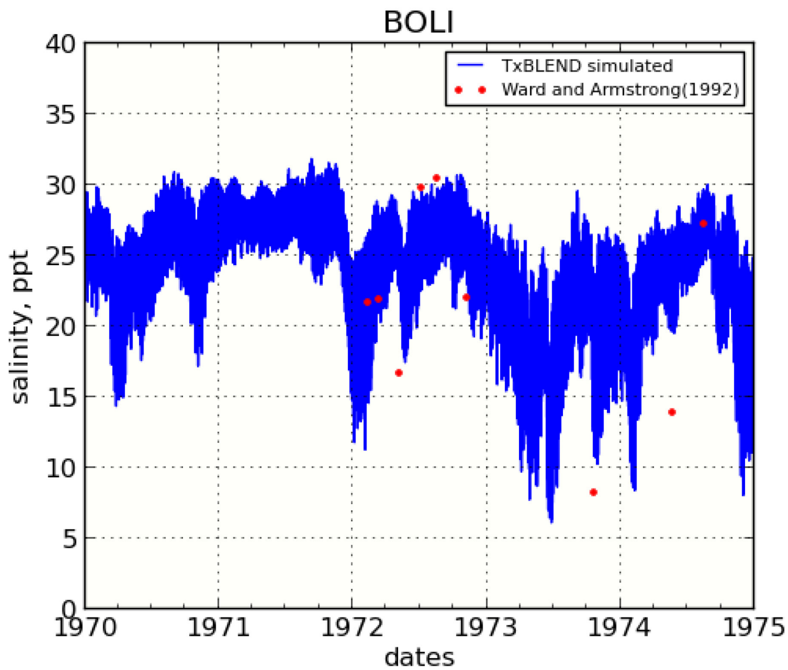

Figure D-29. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Roads for the period 1970 - 1974.

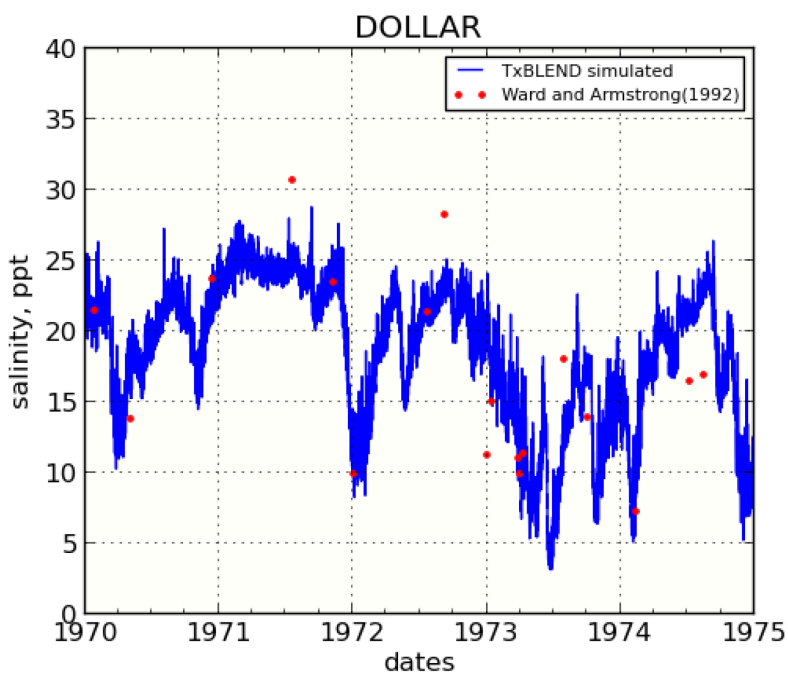

Figure D-30. Simulated (*blue*) versus observed (*red)* salinities at Dollar Point for the period 1970 - 1974.

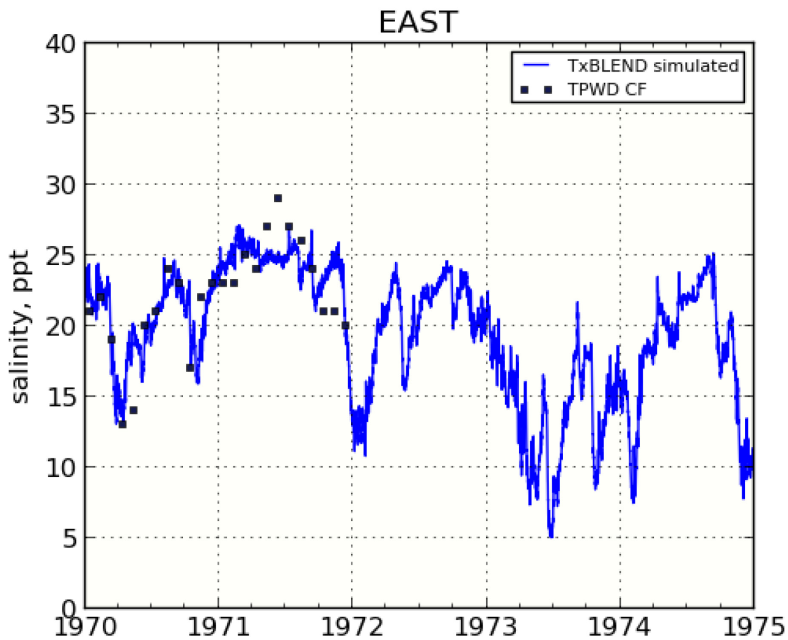

Figure D-31. Simulated (*blue*) versus observed (*black*) salinities at East Bay for the period 1970 - 1974.

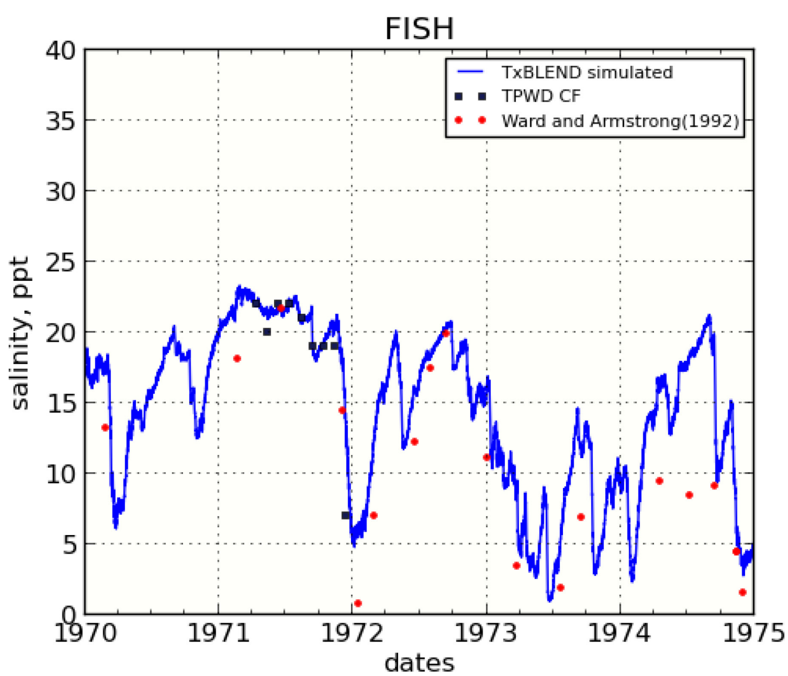

Figure D-32. Simulated (*blue*) versus observed (*red and black*) salinities at Fisher's Reef for the period 1970 - 1974.

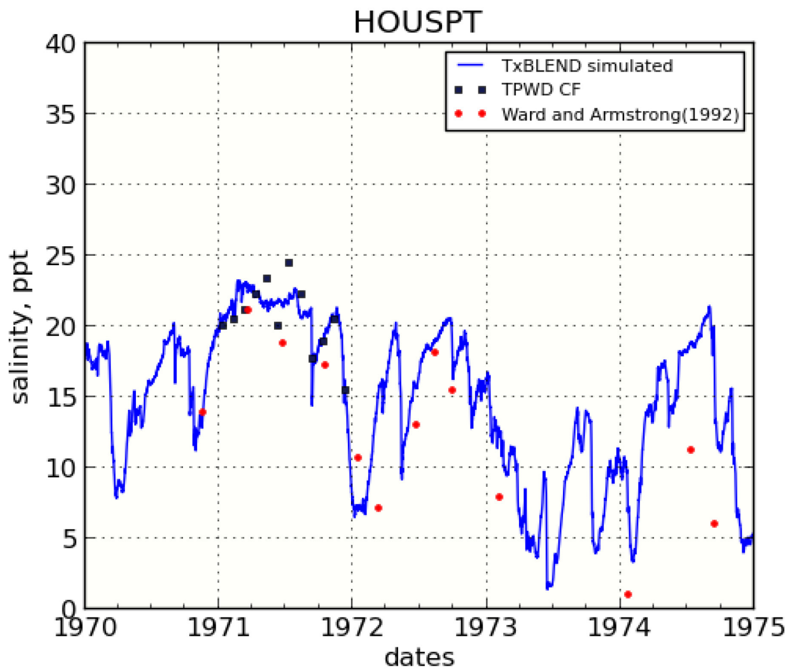

Figure D-33. Simulated (*blue*) versus observed (*red and black*) salinities at Houston Point for the period 1970 – 1974.

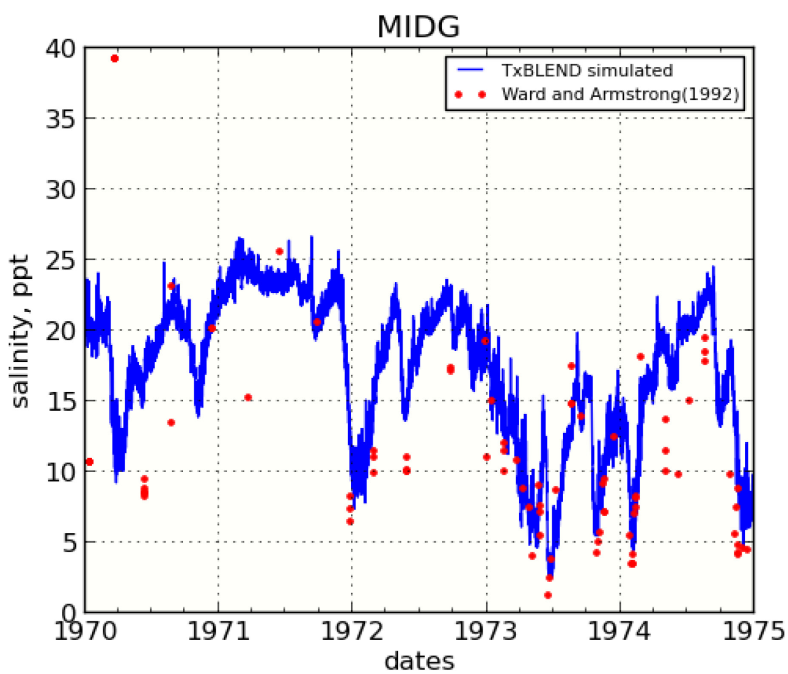

Figure D-34. Simulated (*blue*) versus observed (*red*) salinities at Mid Galveston Bay for the period 1970 - 1974.

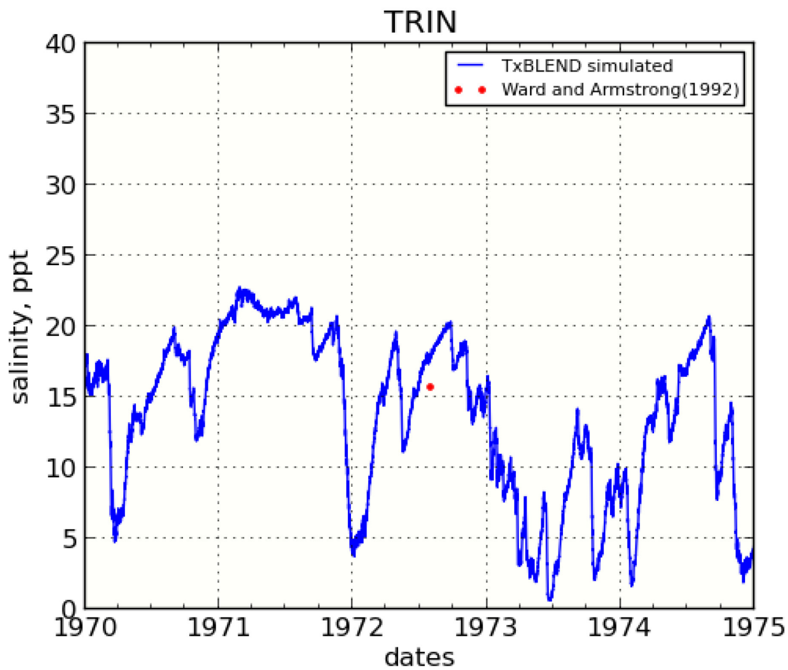

Figure D-35. Simulated (*blue*) versus observed (*red*) salinities at Trinity Bay for the period 1970 - 1974.

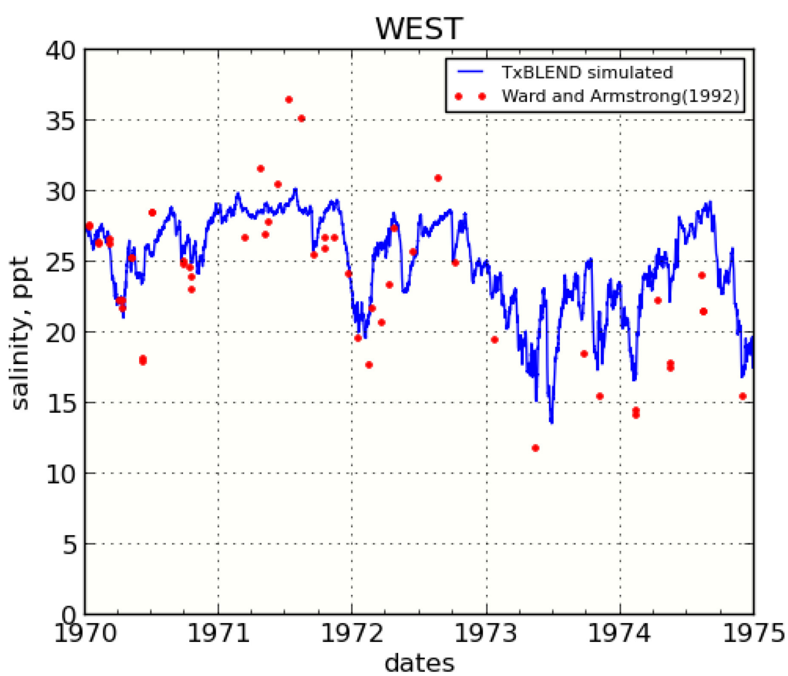

Figure D-36. Simulated (*blue*) versus observed (*red*) salinities at West Bay for the period 1970 - 1974.

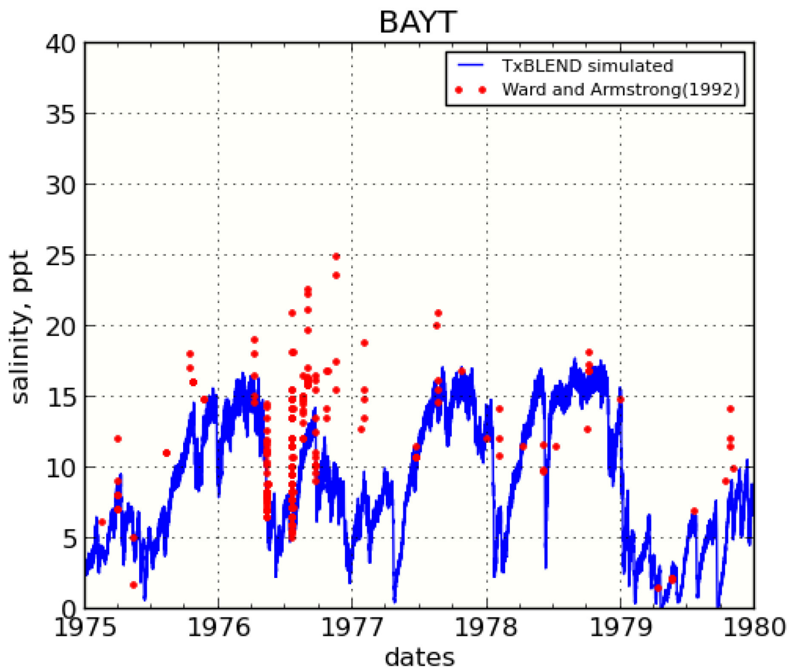

Figure D-37. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1975 - 1979.

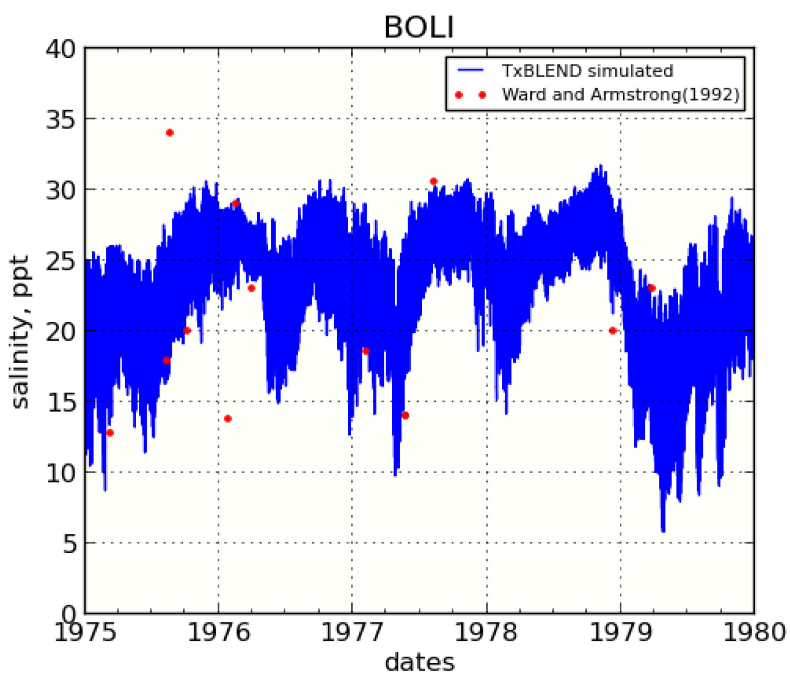

Figure D-38. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Road for the period 1975 - 1979.

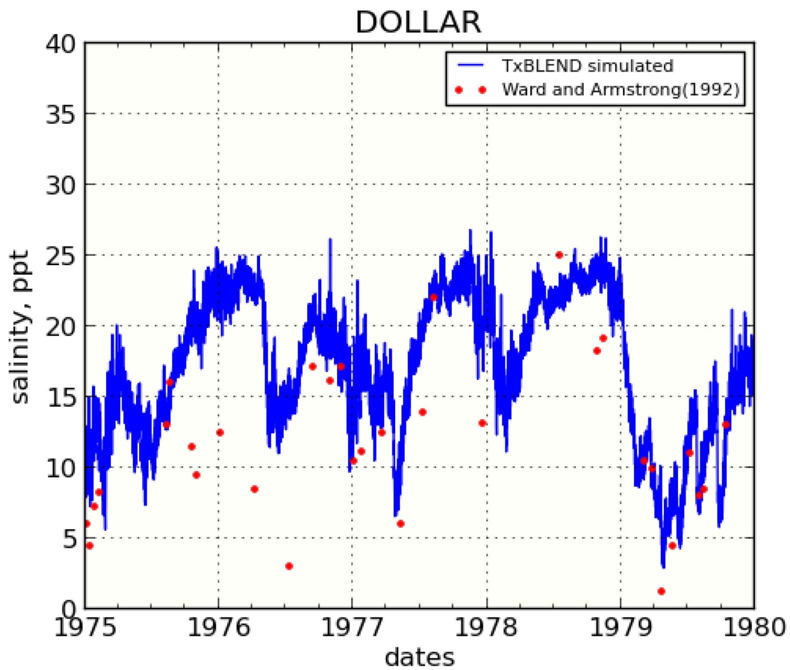

Figure D-39. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1975 - 1979.

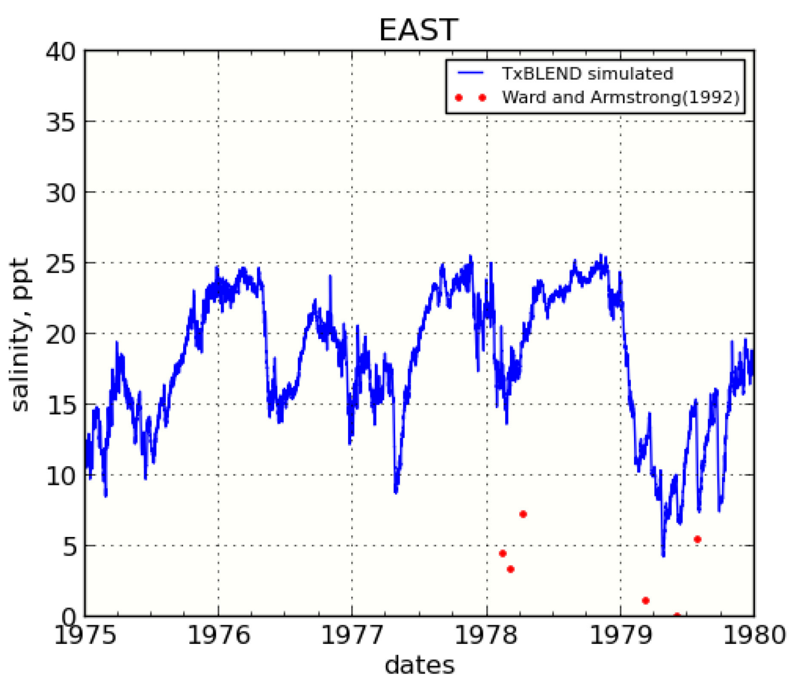

Figure D-40. Simulated (*blue*) versus observed (*red*) salinities at East bay for the period 1975 – 1979.

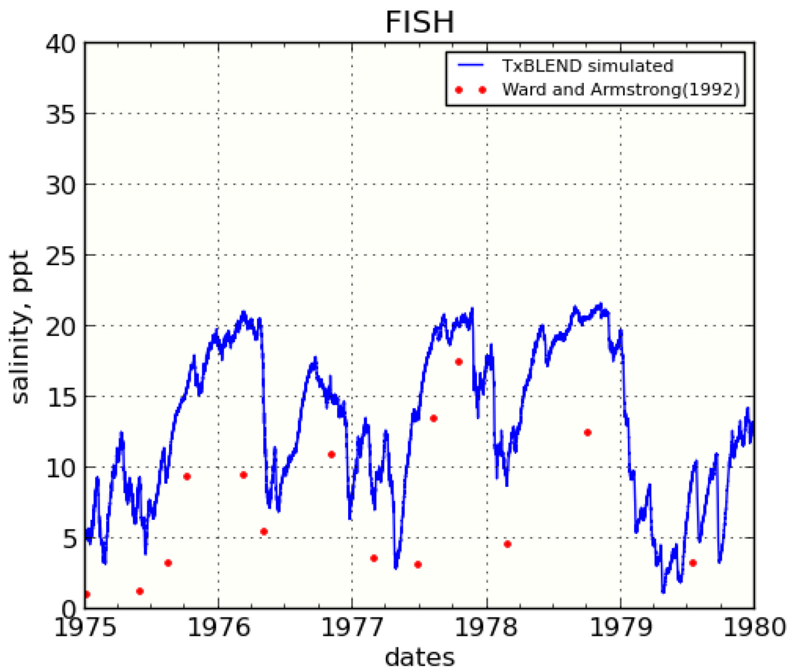

Figure D-41. Simulated (*blue*) versus observed (*red*) salinities at Fisher's Reef for the period 1975 - 1979.

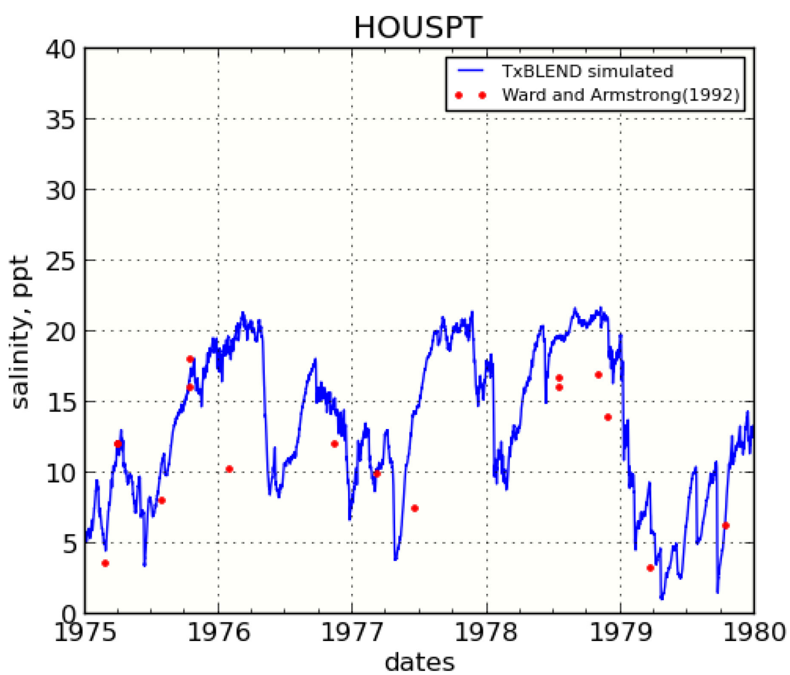

Figure D-42. Simulated (*blue*) versus observed (*red*) salinities at Houston Point for the period 1975 - 1979.

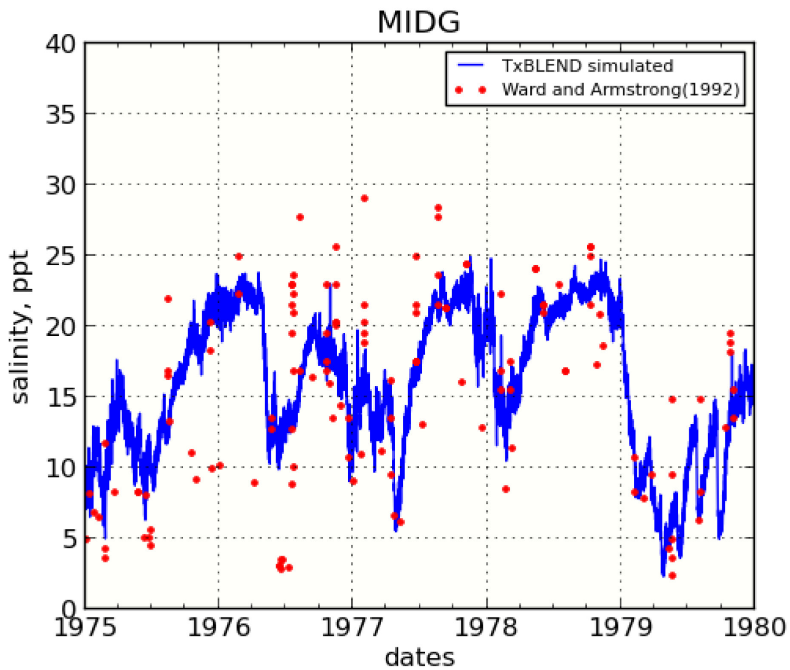

Figure D-43. Simulated (*blue*) versus observed (*red*) salinities at Mid Galveston Bay for the period 1975 - 1979.

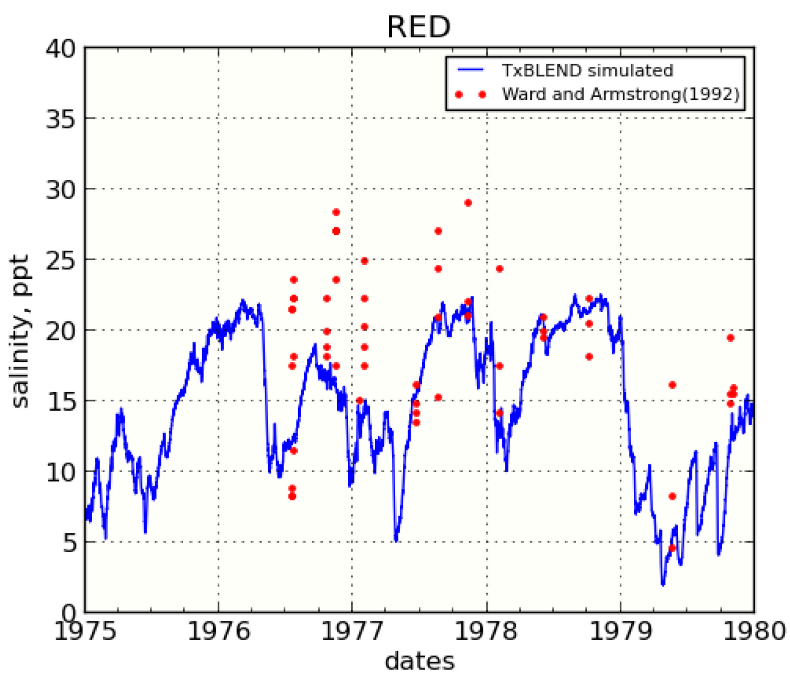

Figure D-44. Simulated (*blue*) versus observed (*red*) salinities at Red Bluff for the period 1975 - 1979.

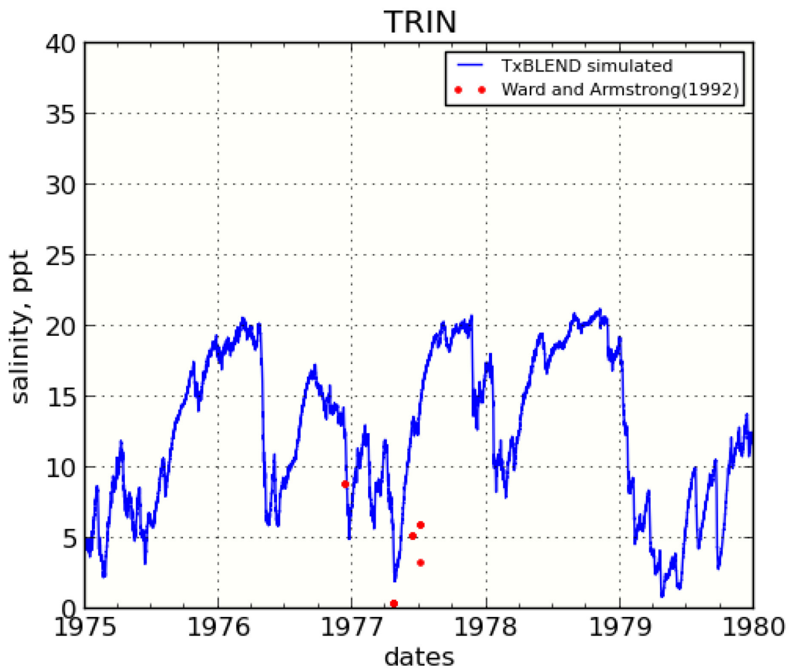

Figure D-45. Simulated (*blue*) versus observed (*red*) salinities at Trinity Bay for the period 1975 - 1979.

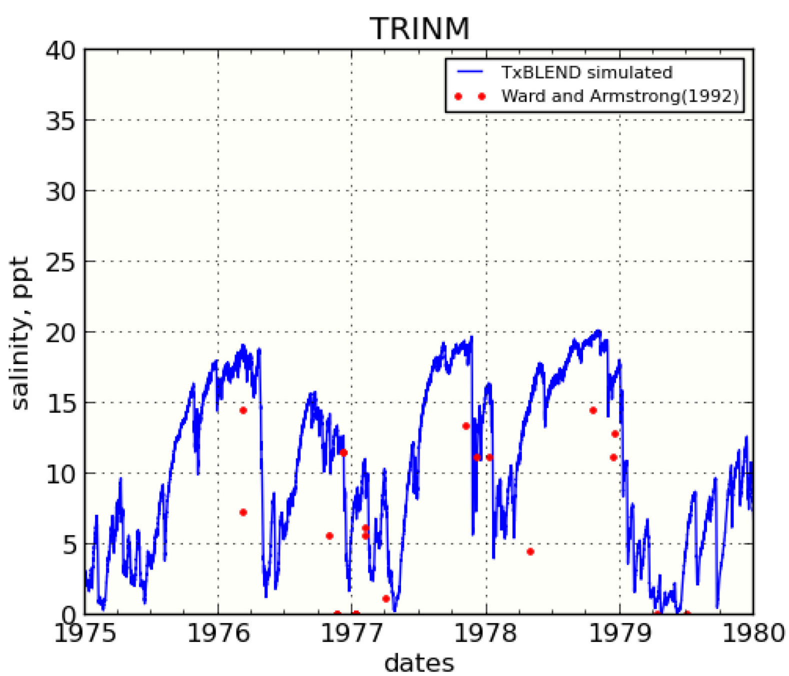

Figure D-46. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1975 - 1979.

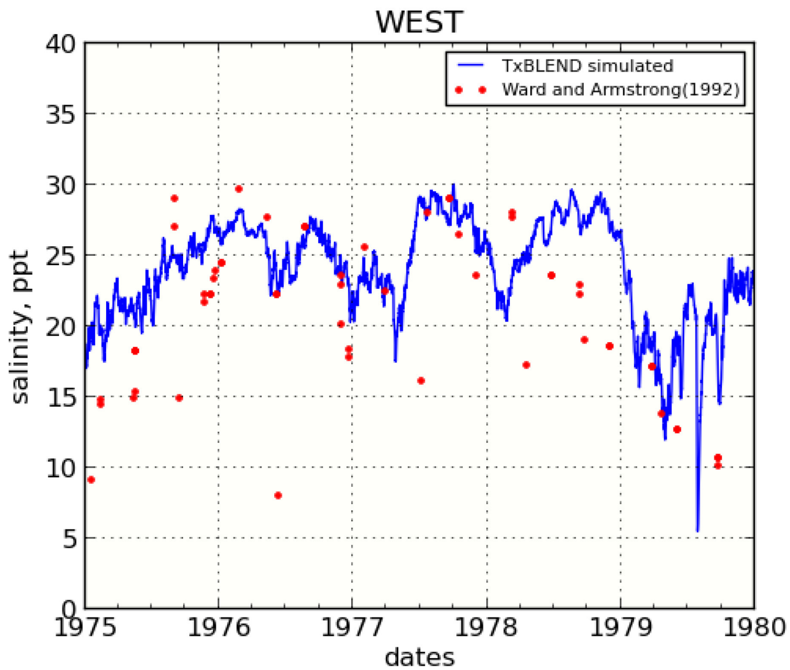

Figure D-47. Simulated (*blue*) versus observed (*red*) salinities at West Bay for the period 1975 - 1979.

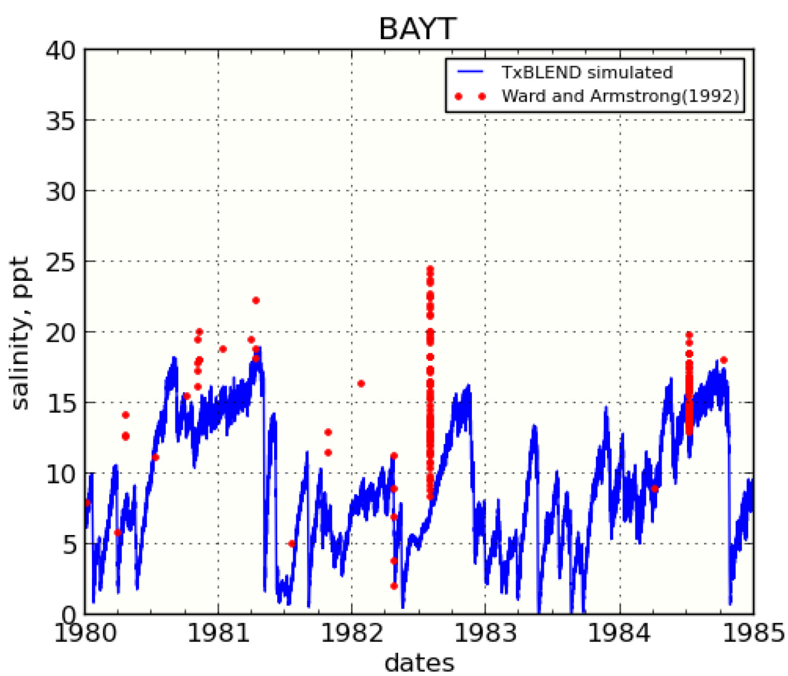

Figure D-48. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1980 - 1984.

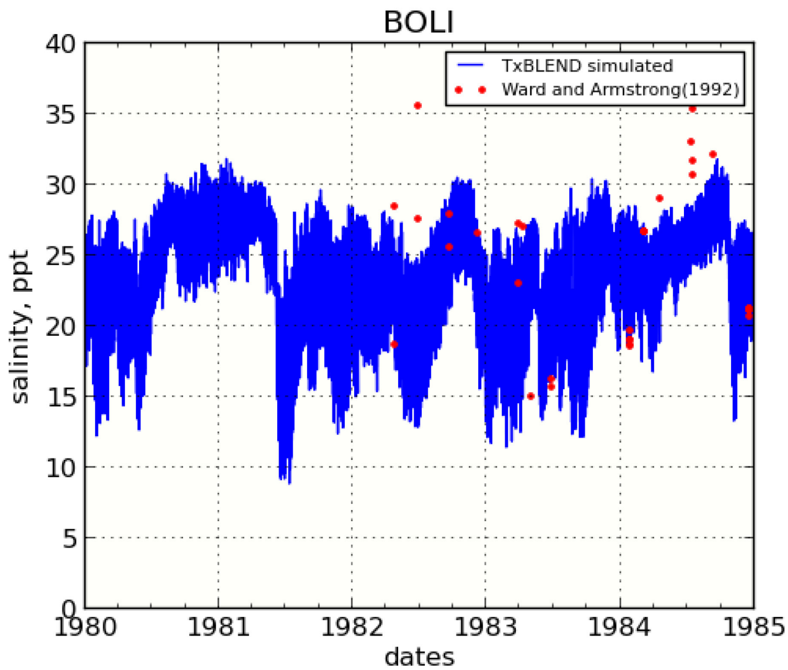

Figure D-49. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Road for the period 1980 - 1984.

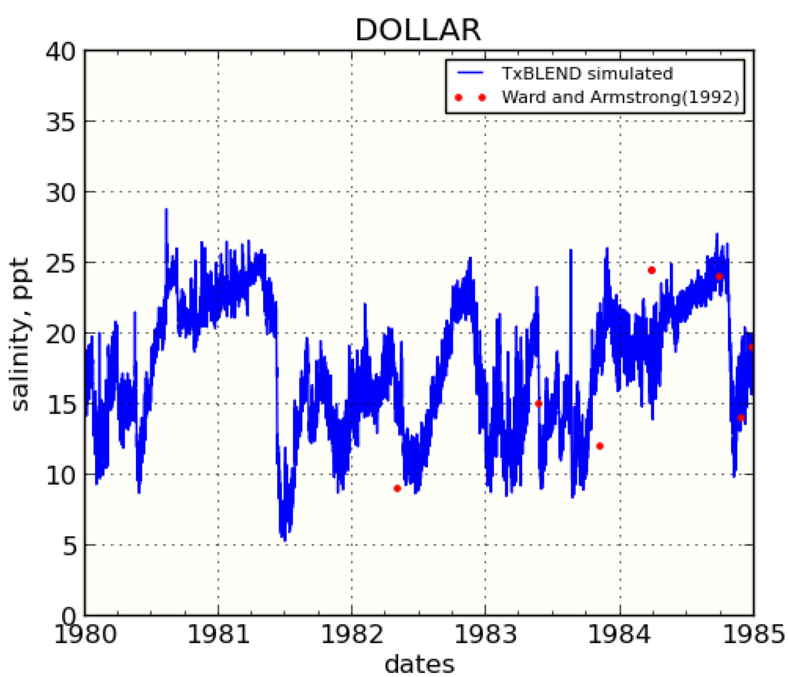

Figure D-50. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1980 - 1984.

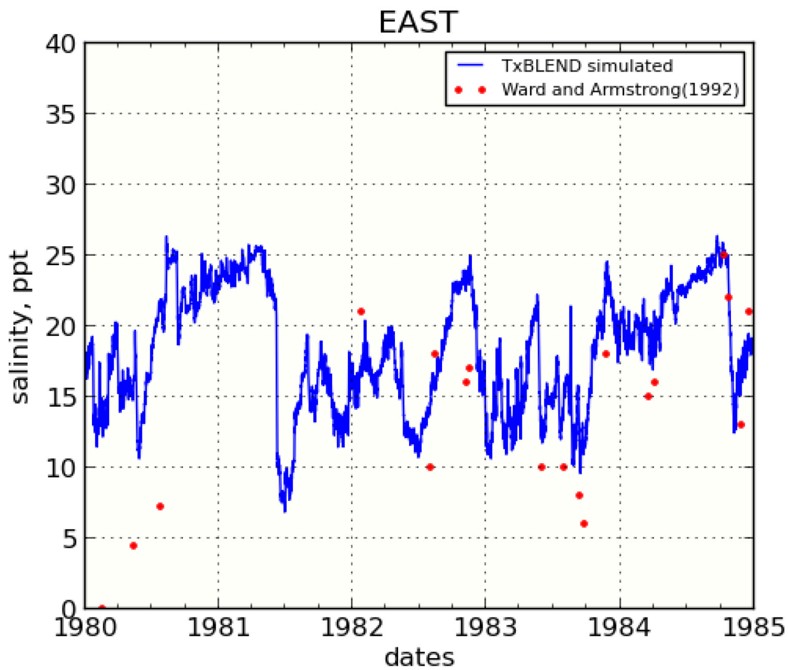

Figure D-51. Simulated (*blue*) versus observed (*red*) salinities at East Bay for the period 1980 - 1984.

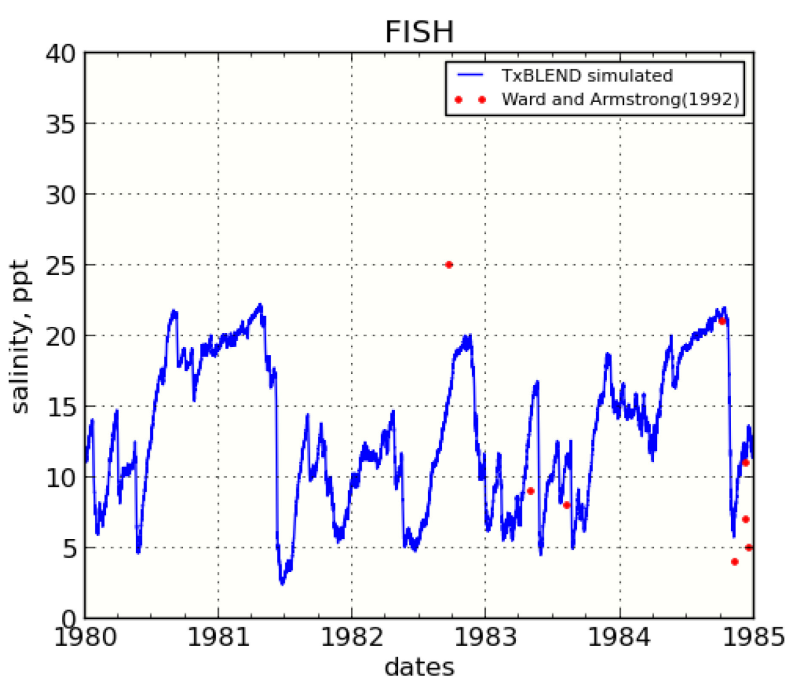

Figure D-52. Simulated (*blue*) versus observed (*red*) salinities at Fisher's Reef for the period 1980 - 1984.

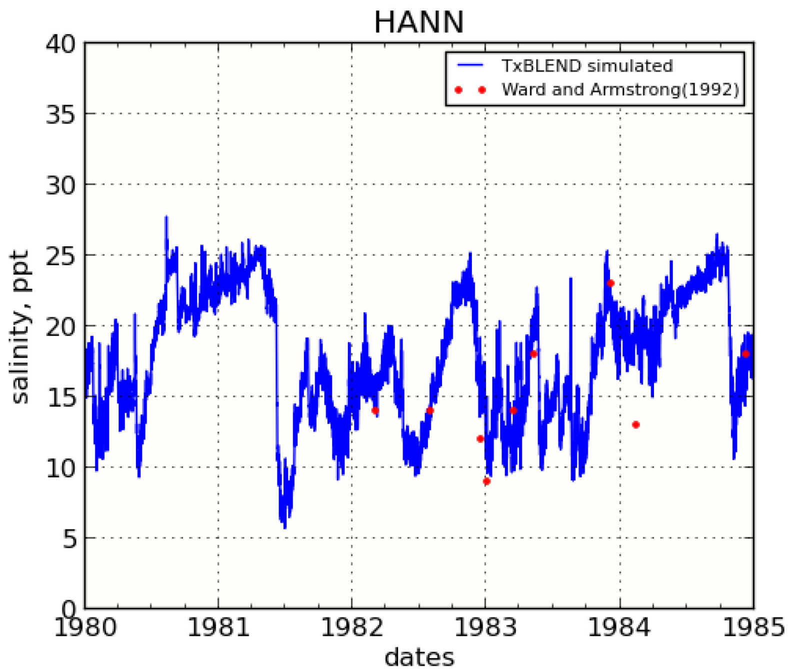

Figure D-53. Simulated (*blue*) versus observed (*red*) salinities at Hanna's Reef for the period 1980 - 1984.

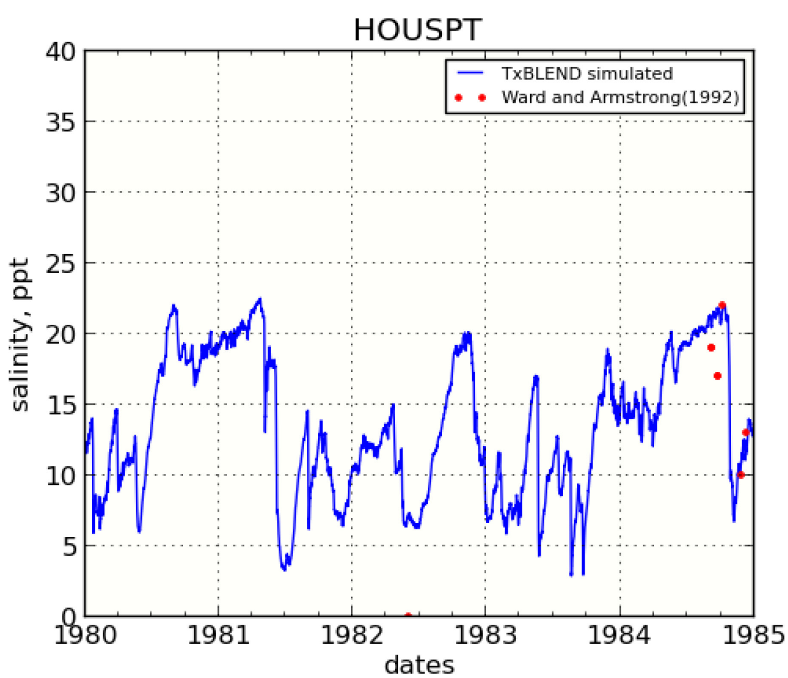

Figure D-54. Simulated (*blue*) versus observed (*red*) salinities at Houston Point for the period 1980 – 1984.

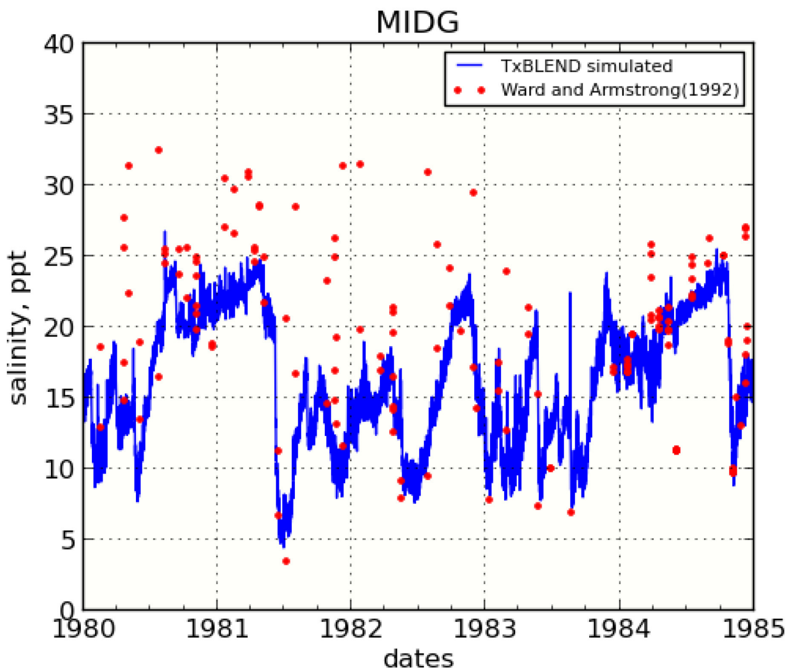

Figure D-55. Simulated (*blue*) versus observed (*red*) salinities at Mid Galveston Bay for the period 1980 – 1984.

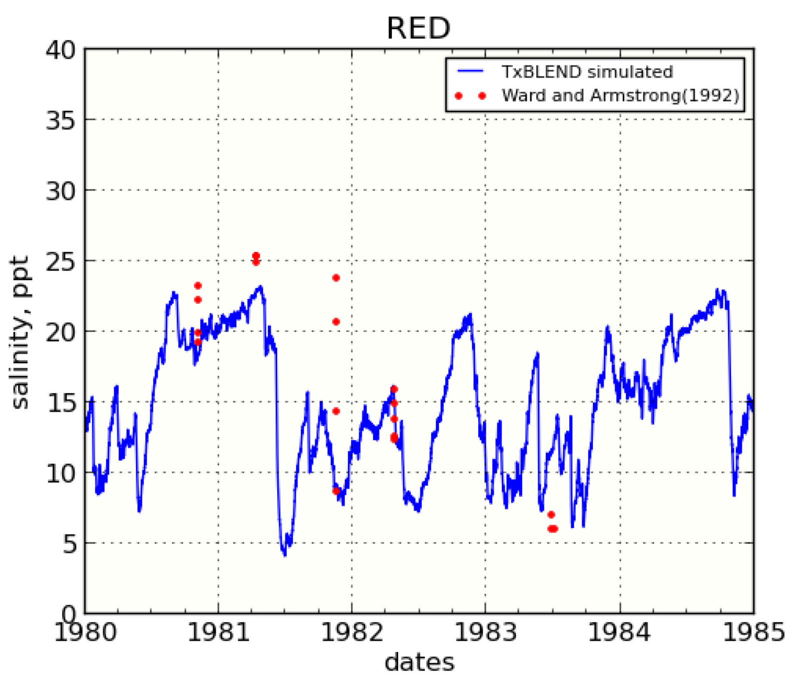

Figure D-56. Simulated (*blue*) versus observed (*red*) salinities at Red Bluff for the period 1980 – 1984.

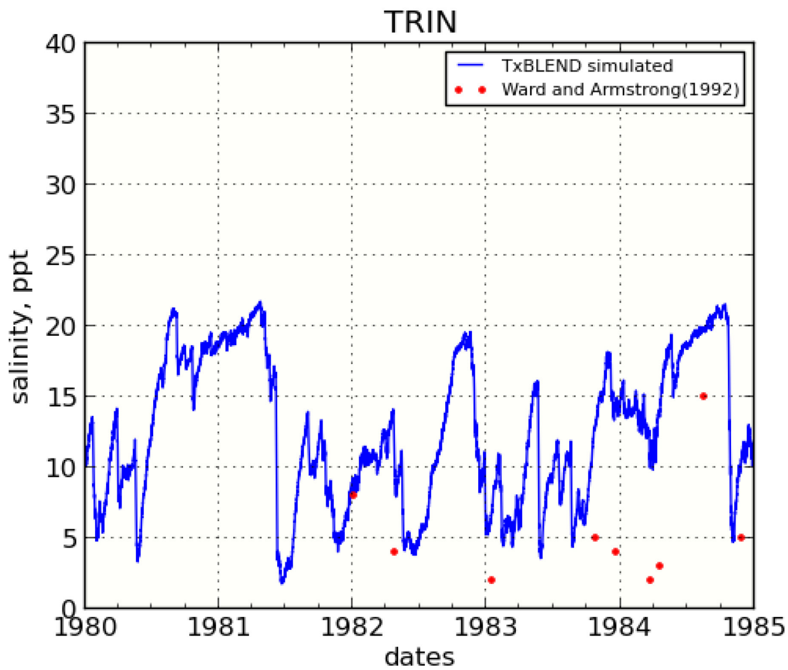

Figure D-57. Simulated (*blue*) versus observed (*red*) salinities at Trinity Bay for the period 1980 – 1984.

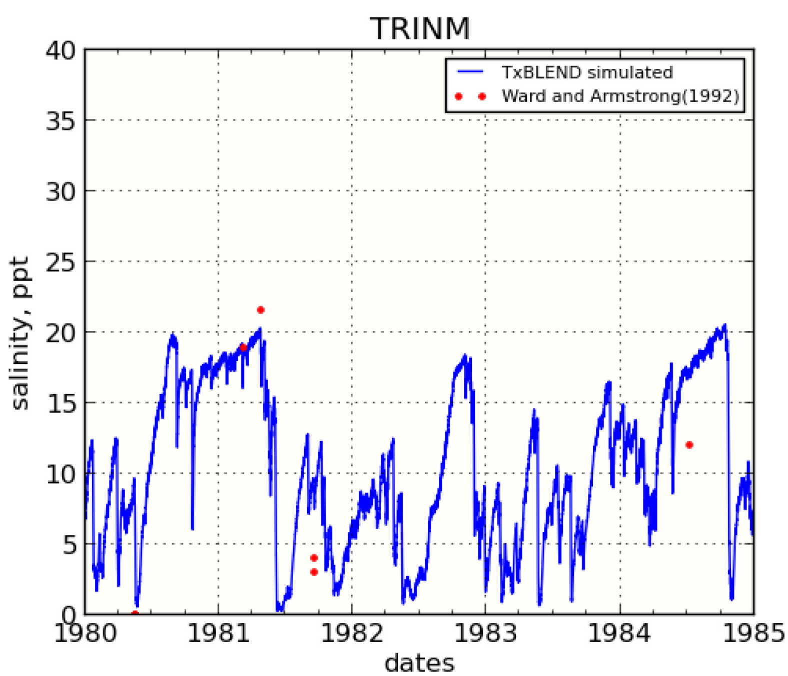

Figure D-58. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1980 – 1984.

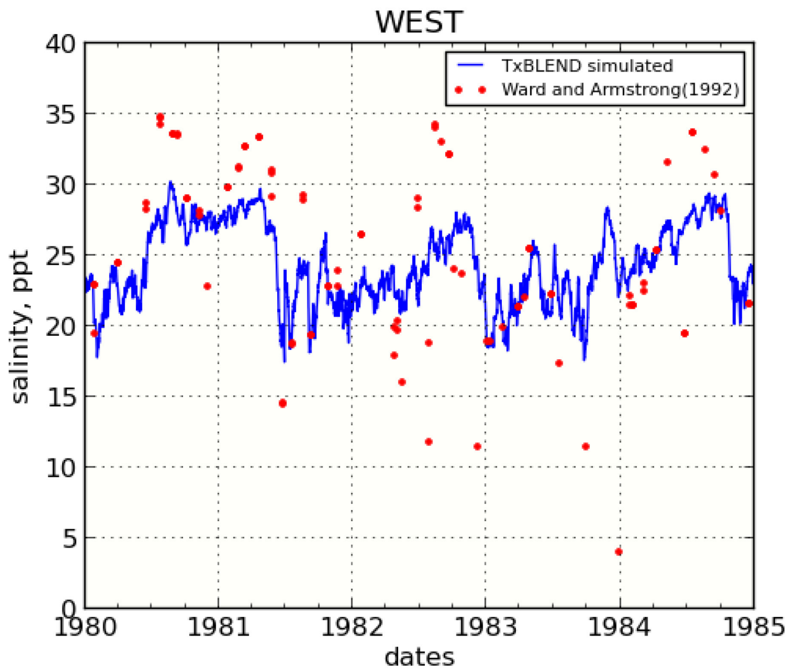

Figure D-59. Simulated (*blue*) versus observed (*red*) salinities at West Bay for the period 1980 – 1984.

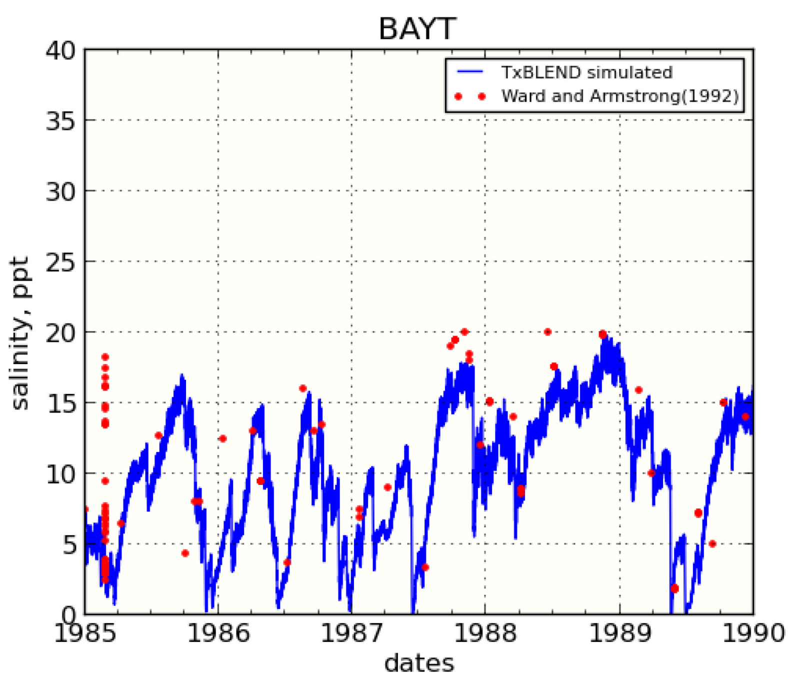

Figure D-60. Simulated (*blue*) versus observed (*red*) salinities at Baytown for the period 1985 – 1989.

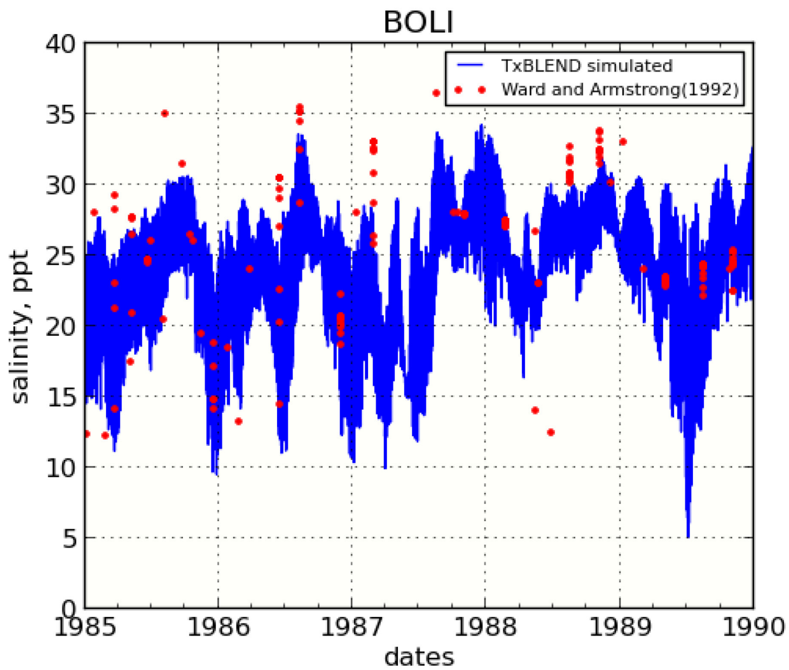

Figure D-61. Simulated (*blue*) versus observed (*red*) salinities at Bolivar Road for the period 1985 – 1989.

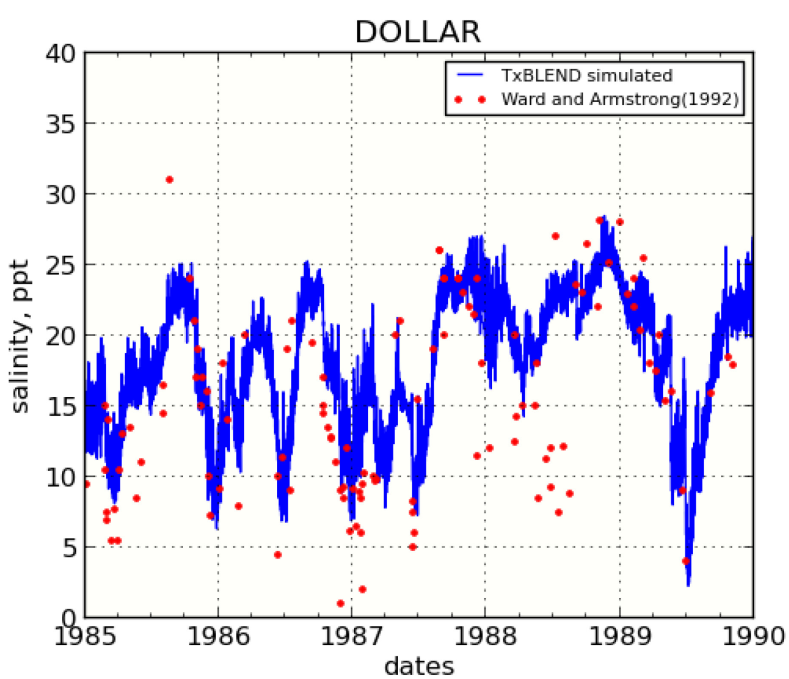

Figure D-62. Simulated (*blue*) versus observed (*red*) salinities at Dollar Point for the period 1985 – 1989.

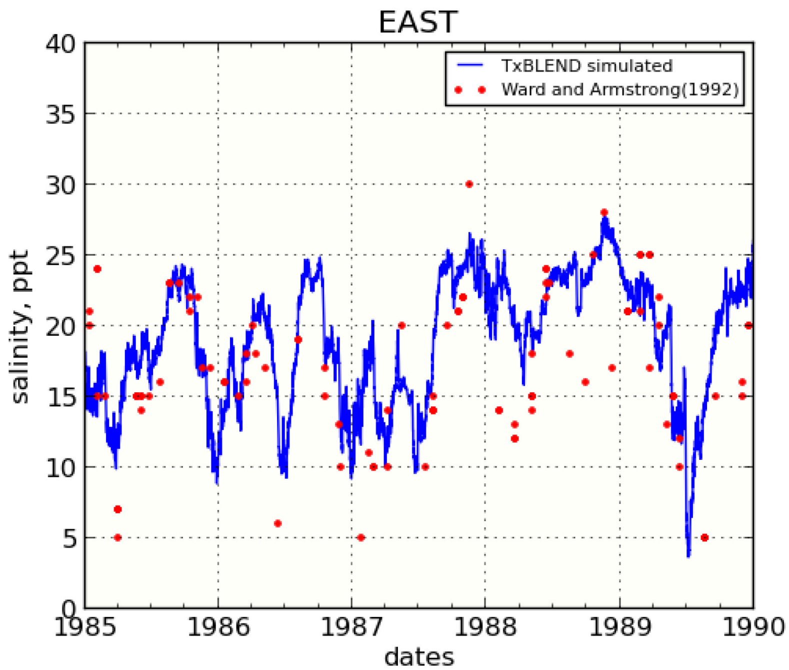

Figure D-63. Simulated (*blue*) versus observed (*red*) salinities at East Bay for the period 1985 – 1989.

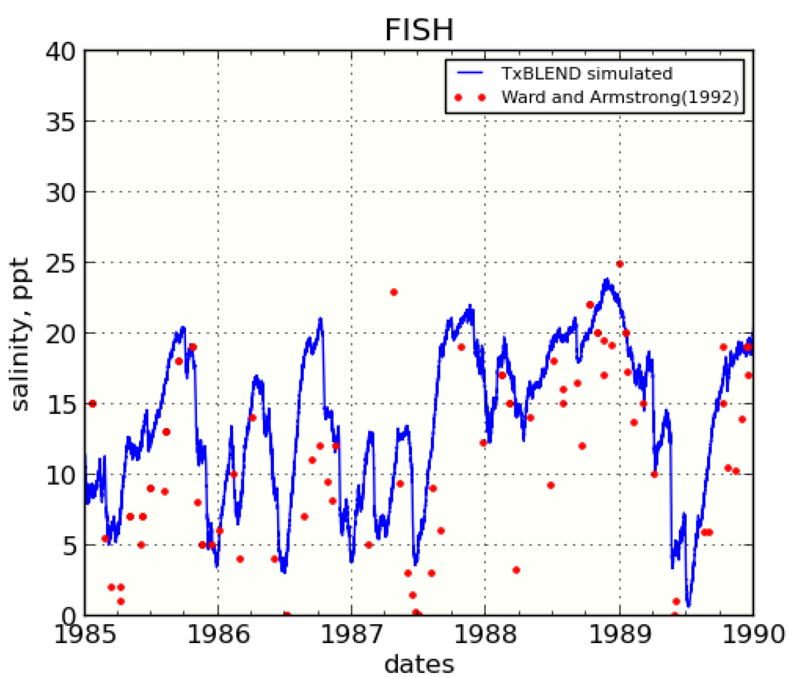

Figure D-64. Simulated (*blue*) versus observed (*red*) salinities At Fisher's Reef for the period 1985 – 1989.

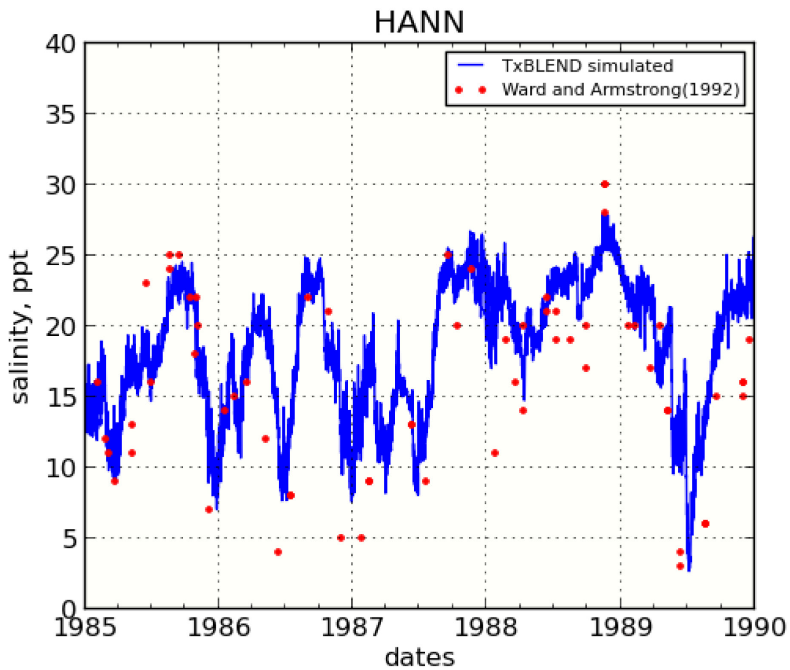

Figure D-65. Simulated (*blue*) versus observed (*red*) salinities at Hanna's Reef for the period 1985 – 1989.

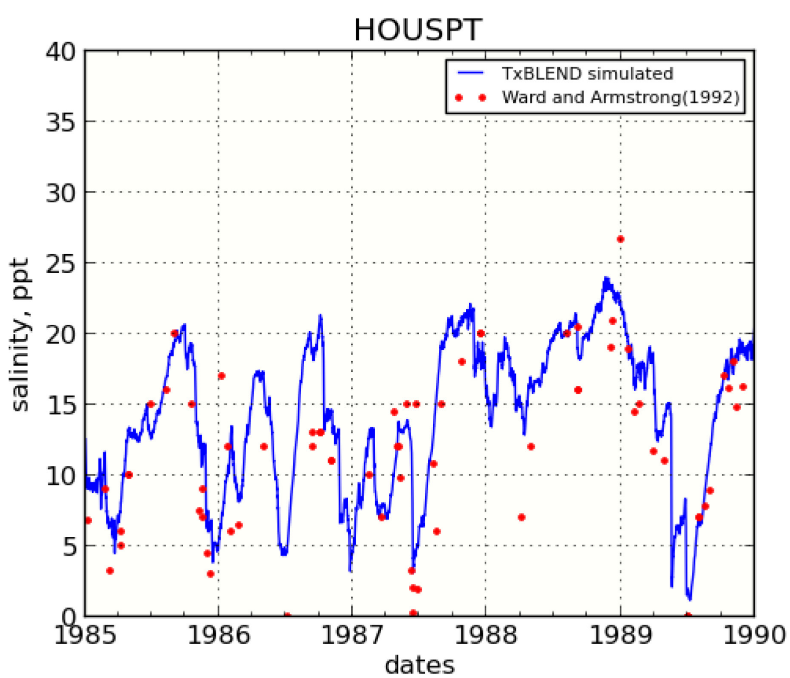

Figure D-66. Simulated (*blue*) versus observed (*red*) salinities at Houston Point for the period 1985 – 1989.

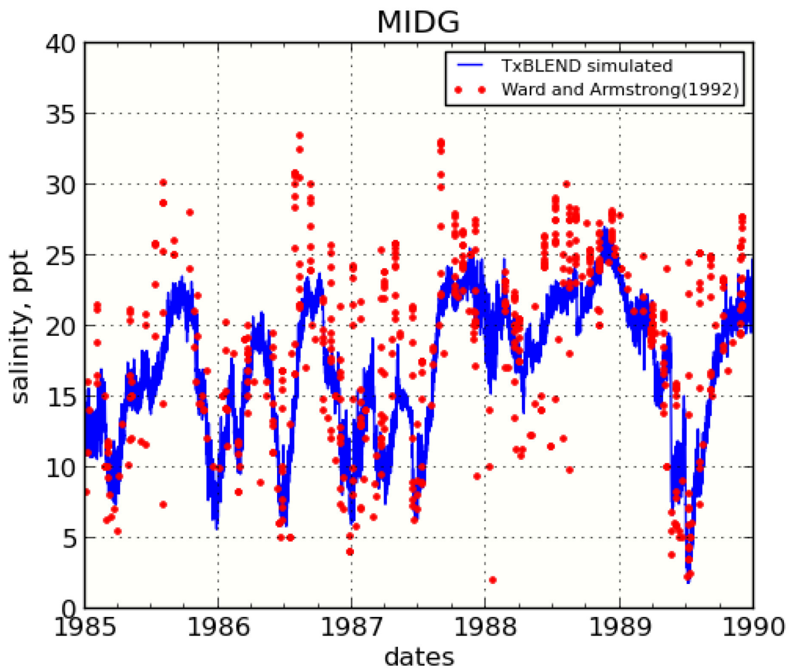

Figure D-67. Simulated (*blue*) versus observed (*red*) salinities at Mid-Galveston Bay for the period 1985 – 1989.

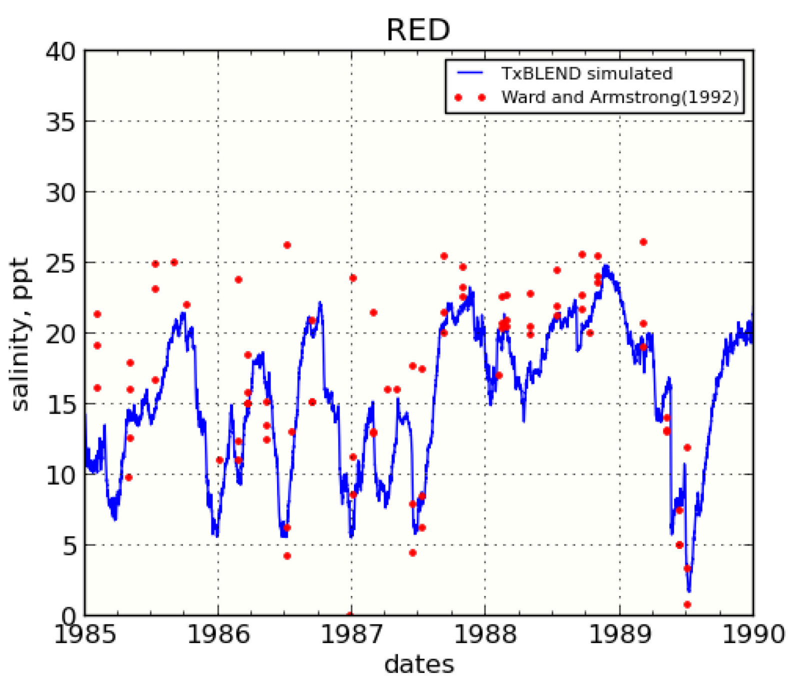

Figure D-68. Simulated (*blue*) versus observed (*red*) salinities at Red Bluff for the period 1985 – 1989.

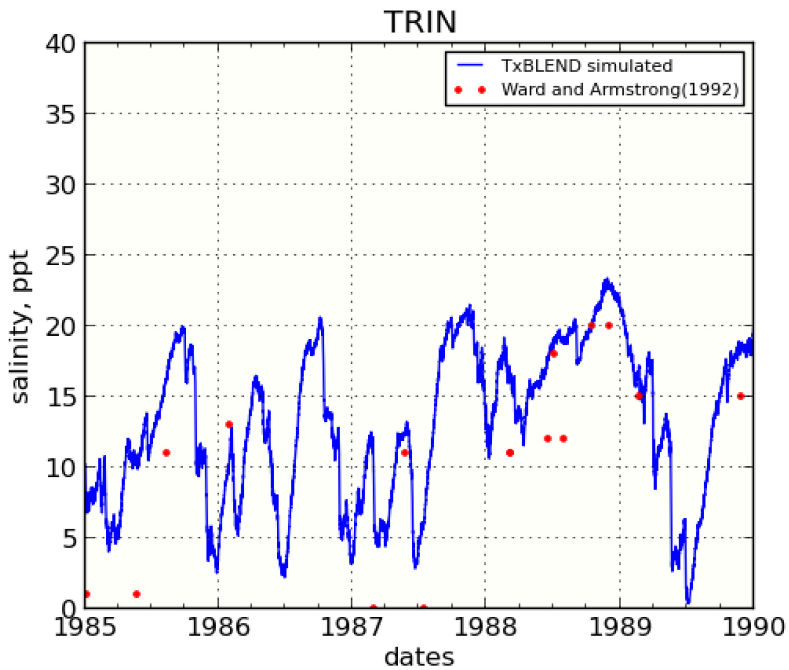

Figure D-69. Simulated (*blue*) versus observed (*red*) salinities at Trinity Bay for the period 1985 – 1989.

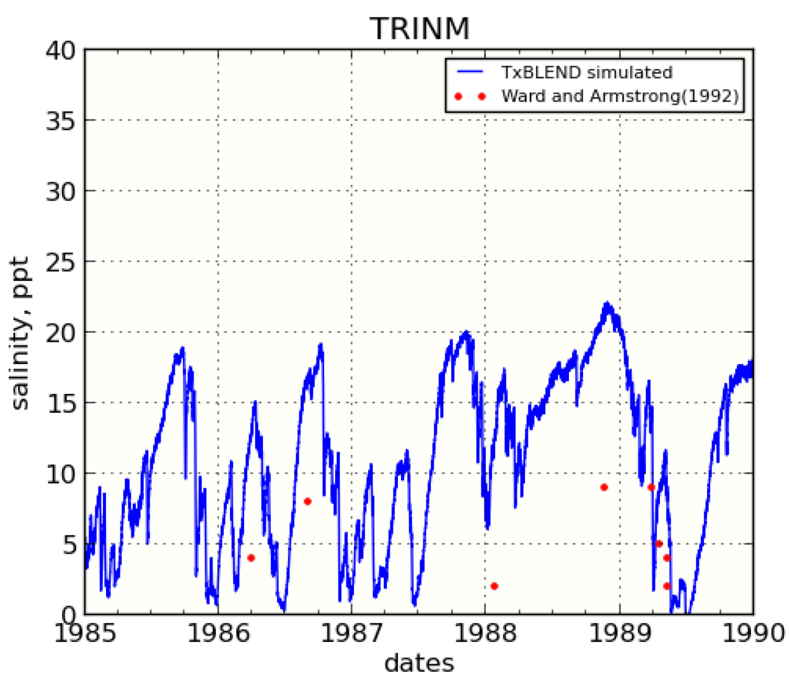

Figure D-70. Simulated (*blue*) versus observed (*red*) salinities at Trinity River Mouth for the period 1985 – 1989.

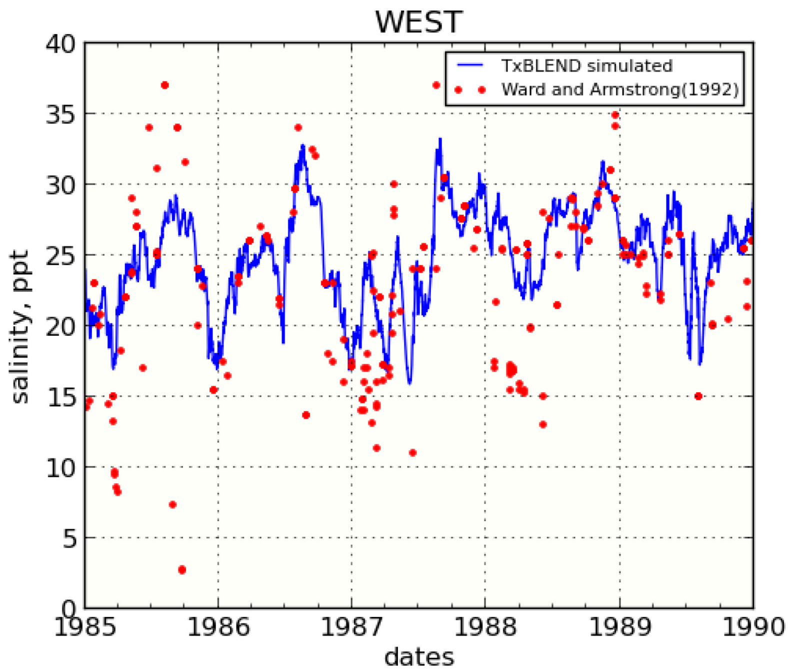

Figure D-71. Simulated (*blue*) versus observed (*red*) salinities at West Bay for the period 1985 – 1989.

Appendix E. Production of Daily and Monthly Average Salinity

Simulated daily average salinity was produced for fifty selected nodes (Table 1). There are four output files transmitted with this report: 1) avesalD-CHN250NR, 2) avesalD-CHN250, 3) avesalD-CHN400, and 4) avesalD-CHN530. They are written in a column-wise format with the following headers: Year, Month, Day, Salinity. Also, there are four files for monthly average salinity at all model nodes: 1) avesalM-CHN250NR, 2) avesalM-CHN250, 3) avesalM-CHN400, and 4) avesalM-CHN530. A Fortran statement writes these files: write(iwr,'(10(1x,f5.2))')(avec(i),i=1,nn), after year and month numbers are written.

Table D-1. Fifty specified nodes for recording a simulated daily average salinity. NWF specified these fifty nodes using the previous Galveston Bay model (NWFnode). They were translated into the nodes of this new model by finding the closest NWFnode to the node in CHN400 (newNode). Since all four grids used in this new model use the same nodes and node numbers, the translated node numbers are the same among all four model grids and time periods. Distance is the difference between the NWFnode and newNode. They are mostly the same location, but a few nodes are slightly different.

Number	NWFnode	xNWF	yNWF	newNode	xNEW	yNEW	Distance (m)
1	4295	331167.9	3302138	4184	331167.9	3302138	0
2	3047	331249.5	3281941	2992	331249.5	3281941	0
3	2706	320706.7	3261581	2656	320706.7	3261581	0
4	2801	318373.4	3265587	2749	318341.4	3265573	35.2
5	3487	311830.4	3273735	3382	311830.4	3273735	0
6	4241	304643.9	3288210	4145	304606.8	3288214	37.3
7	1198	326975.8	3247322	1174	326975.8	3247322	0
8	2083	333506.8	3262469	2042	333506.8	3262469	0
9	3194	319989.1	3282837	3139	319989.1	3282837	0
10	2521	326558.3	3263463	2475	326558.3	3263463	0
11	3993	308467.4	3284708	3917	308426.1	3284699	42.4
12	3314	334597.5	3288248	3260	334597.5	3288248	0
13	2780	326514.6	3272182	2728	326514.6	3272182	0
14	2955	322652	3276940	2900	322652	3276940	0
15	3610	329299.4	3293741	3553	329299.4	3293741	0
16	2740	320118.9	3264450	2689	320118.9	3264450	0
17	1393	347298.2	3268393	1364	347298.2	3268393	0
18	2407	317640.2	3248290	2363	317640.2	3248290	0
19	3617	336213.1	3293098	3560	336213.1	3293098	0
20	3784	309731.2	3279473	3683	309731.2	3279473	0
21	3790	310157.2	3285878	3721	310157.2	3285878	0
22	3924	307128.1	3281041	3816	307128.1	3281041	0
23	1584	342827.4	3266052	1551	342827.4	3266052	0
24	3242	314115.1	3277164	3188	314115.1	3277164	0
25	3093	327408.6	3282321	3038	327408.6	3282321	0

Table 1. *continued*

Number	NWFnode	xNWF	yNWF	newNode	xNEW	yNEW	Distance (m)
26	2961	331656.1	3279051	2906	331656.1	3279051	0
27	3032	316186.3	3272539	2977	316186.3	3272539	0
28	2837	318817.4	3268508	2785	318817.4	3268508	0
29	2980	315964.2	3265800	2886	315964.2	3265800	0
30	2645	325018.9	3267773	2597	325018.9	3267773	0
31	2726	317933.8	3257933	2676	317933.8	3257933	0
32	3740	309031.4	3277458	3632	309031.4	3277458	0
33	1661	309245.2	3237863	1627	309245.2	3237863	0
34	3149	333229	3285198	3094	333229	3285198	0
35	2920	329397.5	3277052	2866	329397.5	3277052	0
36	3504	326051	3290820	3448	326051	3290820	0
37	3305	323688.4	3286801	3251	323688.4	3286801	0
38	3137	316746.1	3280551	3082	316746.1	3280551	0
39	3446	312119.5	3282055	3390	312119.5	3282055	0
40	3410	332187.4	3290652	3354	332187.4	3290652	0
41	3309	329240.7	3287857	3255	329240.7	3287857	0
42	3413	334803.8	3290659	3357	334803.8	3290659	0
43	3710	328656.3	3295157	3652	328656.3	3295157	0
44	3514	335286.8	3292268	3458	335286.8	3292268	0
45	3560	332592.9	3293494	3504	332592.9	3293494	0
46	3663	332320.2	3294991	3605	332320.2	3294991	0
47	668	293291.7	3219029	662	293291.7	3219029	0
48	7	308664	3201268	7	308664	3201268	0
49	22	345589.5	3230644	22	345589.5	3230644	0
50	35	368282.7	3247381	35	368282.7	3247381	0