# Analysis of the Influence of Water Plan Strategies on Inflows and Salinity in Galveston Bay

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## EXECUTIVE SUMMARY

This study investigates the influence of water plan strategies for the Trinity River Basin on the volume of freshwater inflow reaching Galveston Bay and subsequent effects on salinity conditions within the bay. The Texas Commission on Environmental Quality (TCEQ) regional water availability model (WAM) for the Trinity River basin was modified to reflect future conditions, considering both increased reservoir sedimentation and planned water supply strategies for the region (based on the 2007 Regional/State Water Plan). The WAM then was used to develop water-plan-strategy inflows to Galveston Bay under two management scenarios. The first scenario, designated as a modified WAM Run3 reflects a future condition in which all existing water rights are fully utilized, no return flows are provided, and no term rights occur. The second scenario, designated WAM Run9 (based on a modified WAM Run8), reflects a future condition with anticipated demands and strategies as outlined in the 2007 State Water Plan. These scenarios then were compared to an *existing condition* and to two recommended target inflow conditions that were developed jointly by the Texas Parks and Wildlife Department (TPWD) and Texas Water Development Board (TWDB) to achieve ecological productivity targets for Galveston Bay. In total, five scenarios are considered and compared in this report:

1) An *existing condition* based on observed inflows from 1980 to 1989;
2) Modified WAM Run3, a future inflow condition based on fully utilized water rights and no return flows;
3) WAM Run9, a future inflow condition with anticipated water demands and strategies implemented;
4) MaxH, a target inflow recommendation for Galveston Bay designed to maximize ecological productivity for a given flow volume; and,
5) MinQ, a target inflow recommendation for Galveston Bay designed to provide the minimum inflows necessary to meet identified salinity and ecological constraints.

Mean annual inflow into Galveston Bay for the historical period of record (1941 – 2005) is 11.3 million acre-feet, and mean annual inflow during the 1980 – 1989 *existing condition* (scenario 1) is 10.4 million acre-feet. However, under all four future inflow scenarios, simulated mean annual inflows are less than both the long-term historic mean and the *existing condition* mean inflow. Under WAM Run9 (scenario 3), average annual inflow is 9.1 million acre-feet which corresponds to the 58$^{th}$ percentile exceedance probability of historical inflows. Under a modified WAM Run3 (scenario 2), average annual inflows are 6.4 million acre-feet (78$^{th}$ percentile exceedance probability). The annualized recommended target inflows (*i.e.*, the sum of the individual monthly flows; scenarios 4 and 5) are less than either WAM scenario, a result of the management constraints which were applied to minimize inflow while simultaneously maintaining a desired salinity condition when determining target inflows to Galveston Bay. MaxH mean annual inflow is 5.2 million acre-feet (80$^{th}$ percentile exceedance probability of historical inflow events), and MinQ mean annual inflow is 4.2 million acre-feet (87$^{th}$ percentile exceedance probability inflow). Historically, three of the major sources of inflow (the Trinity River, San Jacinto River, and Buffalo Bayou) contribute 83 percent of freshwater inflows to the Galveston Bay system. WAM Run9 was most similar to the historical condition, with the "big

three" rivers contributing 82 percent of inflows. However, reduced inflows among all sources, but particularly the Trinity River, led to decreases in the percent contribution of these rivers to total bay inflow under the modified WAM Run3, MaxH, and MinQ target inflow scenarios.

Monthly inflows for the two WAM and two target inflow scenarios were converted to daily inflows and then distributed among the nine natural drainages to Galveston Bay. These then were provided as inputs to the Galveston Bay TxBLEND hydrodynamic and salinity transport model in order to simulate salinity conditions within the bay over a ten-year period. For comparison purposes, TxBLEND simulations also were conducted for an *existing condition* based on observed inflows to the bay for the period 1980 – 1989. Simulated salinities were evaluated at several locations in the bay in order to assess the impact of each scenario on salinity condition within the bay, particularly with respect to conditions known to be preferred by key estuarine species of the Galveston Bay system.

Compared to the modified WAM Run3 or target inflow scenarios, the WAM Run9 scenario has the least impact on salinity condition within the bay. Under WAM Run9 inflows, median daily salinity at all sites increases only about 1 ppt, and the frequency of occurrence of the desired 10 – 20 ppt salinity range remains consistent with that seen under *existing conditions*. However, under a modified WAM Run3, in which water rights are fully utilized and there are no return flows, daily inflows less than 100 cfs occur much more frequently, thus contributing to a 4 ppt increase in median daily salinity in Trinity Bay. While the frequency of events occurring within the desired 10 – 20 ppt salinity zone remains similarly consistent in the upper estuary, the number of low salinity events (<10 ppt) decreases under a WAM Run3 inflow scenario. This is not the case in the lower estuary where the number of events occurring within the desired salinity zone decreases, and the number of high salinity events (>25 ppt) increases.

For the two recommended target inflow cases of MaxH and MinQ, monthly target inflows were provided as recommended to the three major contributing rivers (Trinity, San Jacinto, and Buffalo Bayou) and repeated annually over the multi-year simulation period. This is a simplistic application of the target inflows, which results in the exclusion of high inflow events as compared to the *existing condition* and to the two WAM scenarios. This application was selected as one means to compare the relative effects of the target inflow recommendations versus potential future inflow conditions. As a result, this strict interpretation greatly reduces total bay inflow, as compared to the *existing condition* and the two WAM scenarios – except during relatively dry periods. In the upper and mid-estuary, overall salinity variation is reduced as the frequency of events ranging within the desired 10 – 20 ppt range greatly increases at a detriment to events <10 ppt. In the lower bay under the target inflow scenarios, the number of high salinity events (>20 ppt) increases by as much as 20 percent, and at Bolivar Roads salinities less than 20 ppt are effectively eliminated. Therefore throughout the estuary, under a strict interpretation of MinQ and MaxH inflows, salinity condition increases at all locations.

Overall, inflow reductions are most pronounced in the MinQ target inflow scenario where flows are reduced 60 percent from *existing condition* inflows. By comparison, inflows are reduced 50 percent under a MaxH scenario, 39 percent under a modified WAM Run3, and only 12 percent under a WAM Run9 scenario. The reduction of inflows from the four scenarios increases salinity conditions within in the bay in different ways. First, while the MinQ target inflow scenario has the biggest impact on total bay inflow, it does not have the greatest impact on median daily salinity. Instead, salinity increases more under a modified WAM Run3 scenario. However, the salinity impact of both scenarios is similar in the upper and lower estuary. In the upper estuary, these two scenarios increase median daily salinity by 4 ppt. The MaxH target inflow scenario increases median daily salinity by 1 to 3 ppt, which is more than the WAM Run9 scenario but less than the MinQ or modified Run3 scenarios. Finally, the WAM scenarios have little effect on the frequency of occurrence of salinities in the desired 10 – 20 ppt range in the upper estuary and only somewhat decrease the number of events in the lower estuary. In contrast, the target inflow scenarios, as applied here, increase the frequency of occurrence of events in the desired 10 – 20 ppt range in the upper estuary (by as much as 35 percent), and nearly equally decrease the frequency of such events in the lower estuary (by as much as 24 percent).

The results show that changes in overall quantity, as well as the geographic and temporal distribution, of inflows to the bay have a variety of impacts on salinity, ranging from increases in the average or median salinity value at locations throughout the bay to displacement or even loss of desired salinity zones. While the results are not meant to be conclusive or absolute, the results are meant to be indicative of possible future salinity conditions within the bay – conditions which are dependent on the application of the rules defining the quantity and pattern of inflows (both geographically and temporally). The results also serve to encourage and guide further exploration of future impacts to freshwater inflows, salinity condition, and estuarine ecology as a result of water plan strategies and environmental flow recommendations.

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## INTRODUCTION

The purpose of this study is to investigate the influence of water plan strategies for the Trinity River Basin on the quantity of freshwater inflows reaching Galveston Bay and on salinity condition within the receiving waters of the bay. Regional water availability models (WAM) for the Trinity River basin, obtained from the Texas Commission on Environmental Quality (TCEQ), were used to develop water plan strategy inflows to Galveston Bay for two management scenarios, Run3 and Run8. However to more accurately reflect future conditions, the scenarios were modified to include expected levels of reservoir sedimentation and planned water supply strategies as documented in the 2007 State Water Plan (TWDB 2007). The modified scenarios are designated as a modified WAM Run3 and a WAM Run9 (based on a modified WAM Run8). (*Note: At the time of study, these models were the most current in use; more recent WAM models are now available for this basin.*) These scenarios were compared to an *existing condition*, based on known inflows from 1980 – 1989. Finally, two target inflow conditions, MaxH and MinQ, which were developed jointly by the Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) to achieve productivity targets for Galveston Bay, were included in the comparison. Thus, the five scenarios considered are:

1) An *existing* freshwater inflow condition based on known inflows from 1980 to 1989;
2) Modified WAM Run3, a future inflow condition with fully utilized water rights and no return flows;
3) WAM Run9, a future inflow condition with anticipated demands and strategies implemented;
4) MaxH, a target inflow recommendation for Galveston Bay designed to maximize ecological productivity for a given inflow volume; and,
5) MinQ, a target inflow recommendation for Galveston Bay designed to provide the minimum inflows necessary to meet identified salinity and ecological constraints.

## METHODOLOGY

This study utilizes the TxBLEND hydrodynamic and salinity transport model to evaluate the effects of changes in total inflow on salinity within the Galveston Bay system (Matsumoto 1993, Matsumoto 2005). Several freshwater inflow scenarios are compared to an *existing* inflow condition for the period 1980 – 1989. To begin, historical inflows to the Galveston Bay system were determined for the Trinity River, San Jacinto River, Buffalo Bayou, and contributing coastal basins. These inflows were used as inputs to TxBLEND in order to simulate salinity at several locations in the bay under *existing* inflow conditions. These results then were compared to TxBLEND salinity results obtained from four other scenarios representing inflows generated by two WAM models and two target-inflow recommendations.

**Study System**

The Galveston Bay system, which includes Galveston Bay, Trinity Bay, East Bay, and West Bay, will be referred to throughout this report synonymously with the Trinity-San Jacinto Estuary (Figure 1). This estuary has several distinctive features. First, the primary sources of freshwater inflow are the Trinity River, San Jacinto River, and Buffalo Bayou, though streams and bayous draining the surrounding coastal basins also provide an important contribution. Second, a large man-made dike (the Texas City Dike) restricts circulation and exchange between Galveston Bay and West Bay. Third, the estuary has a several direct connections to the Gulf of Mexico. Bolivar Roads is the primary entrance channel, followed by San Luis Pass in West Bay, and Rollover Pass in East Bay. As with other Texas bays, the Galveston Bay system is transected east to west by the Gulf Intracoastal Waterway (GIWW), and again north to south by the Houston Ship Channel.

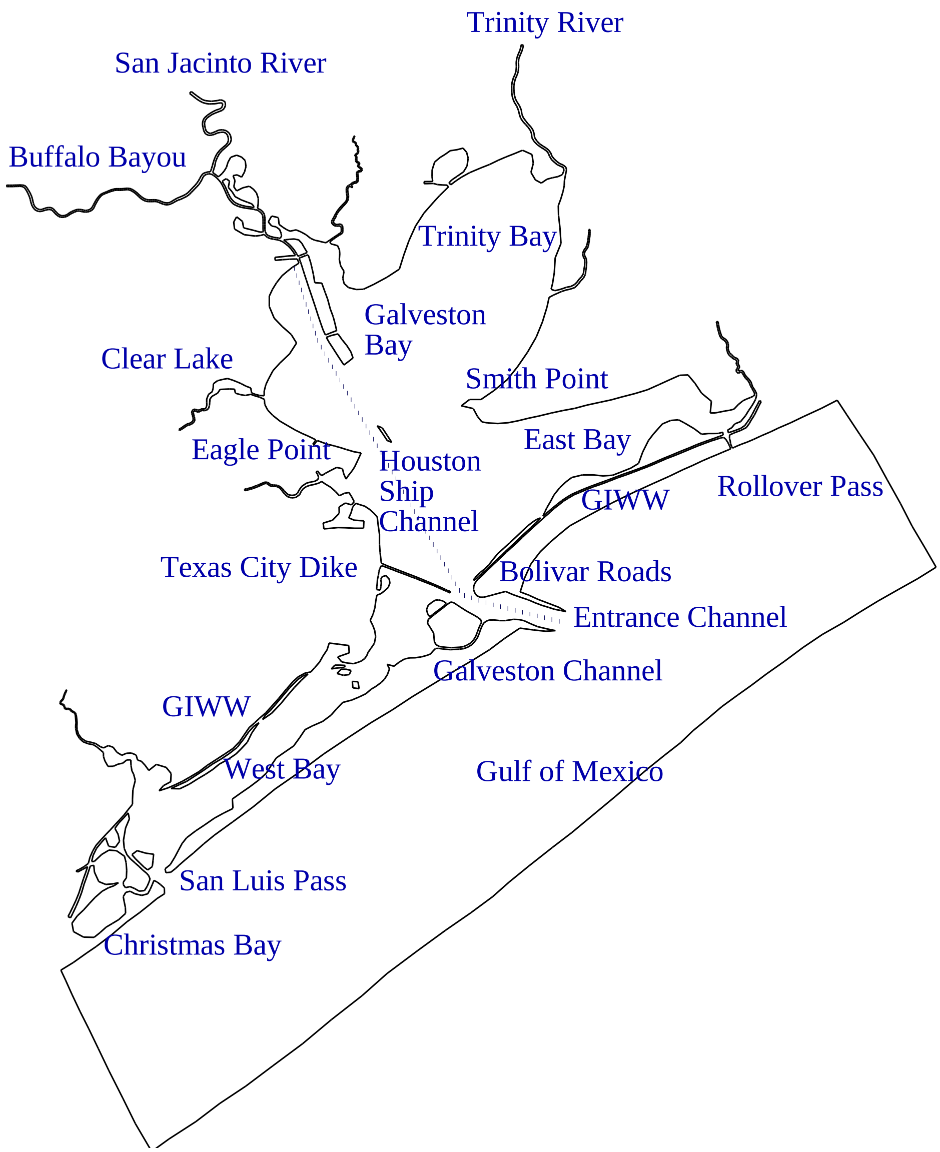



Figure 1. Key features of the Trinity-San Jacinto Estuary (Galveston Bay system).

*Historical Surface Inflows to Galveston Bay*

Average annual surface (freshwater) inflow to the Galveston Bay system for the 65 year period from 1941 – 2005 was 11.3 million acre-feet per year. Annual inflows during this period are presented in Figure 2 and Table 1. Table 1 also presents descriptive statistics and the rank order of inflows. Surface inflows were developed by summing gaged inflows, ungaged inflows, and return flows and by subtracting diversions. Gaged inflows include daily recorded inflows by the U.S. Geological Survey (USGS) and estimated flows over the Lake Houston spillway based on recorded lake levels. Ungaged inflows are estimated using a rainfall-runoff model to determine runoff in coastal basins lacking a stream gage. From 1977 to present, daily ungaged inflows are estimated using the Texas Rainfall-Runoff (TxRR) model (Matsumoto 1992). Prior to 1977, ungaged inflows are available only from archived records which provide monthly estimates of runoff (TDWR 1981). Reported monthly return flows and diversions are obtained from the Texas Commission on Environmental Quality (TCEQ). Recent updates of bay inflows are available from TWDB (http://midgewater.twdb.state.tx.us/bays_estuaries/hydrologypage.html). Earlier versions of coastal hydrology (such as that used in this study) or more detailed versions of hydrology are available upon request.

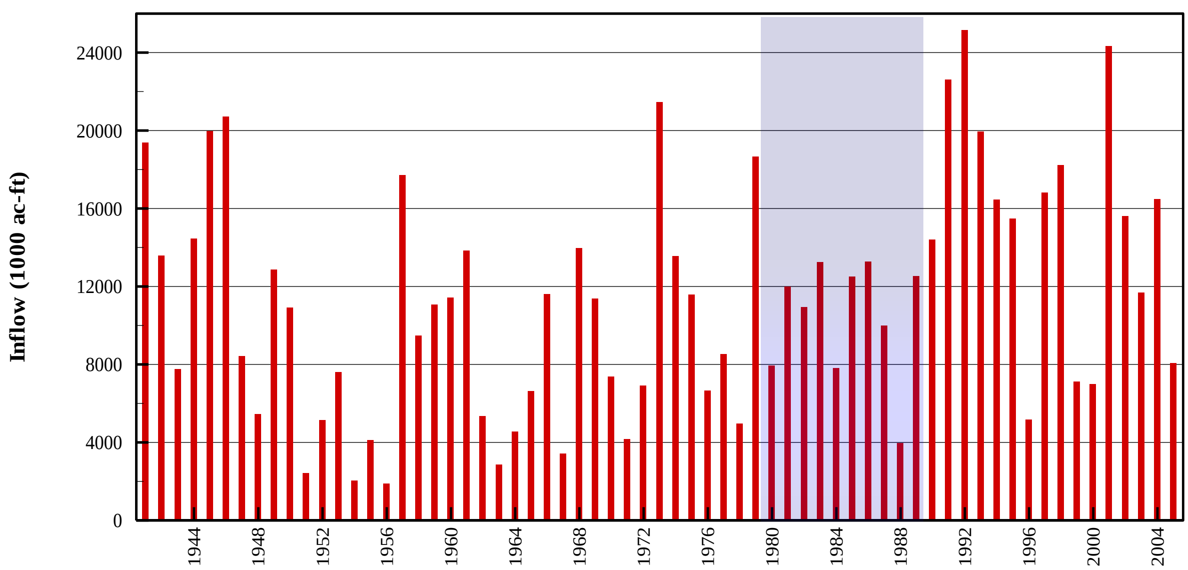



Figure 2. Total annual surface inflow (acre-feet) to Galveston Bay for the period 1941 – 2005. Also highlighted is the selected 1980 – 1989 *existing condition* study period used for evaluating model scenarios.

Table 1. Galveston Bay annual surface inflow (in 1,000 acre-feet) and rank, from highest inflow to lowest inflow, for 1941 – 2005. Descriptive statistics for this period are at bottom left.

| Year | Surface Inflow | Rank | Year | Surface Inflow | Rank | Year | Surface Inflow | Rank | Year | Surface Inflow | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1941 | 19,378 | 8 | 1961 | 13,820 | 20 | 1981 | 11,989 | 28 | 2001 | 24,325 | 2 |
| 1942 | 13,571 | 21 | 1962 | 5,344 | 53 | 1982 | 10,947 | 35 | 2002 | 15,610 | 15 |
| 1943 | 7,764 | 44 | 1963 | 2,860 | 62 | 1983 | 13,248 | 24 | 2003 | 11,666 | 29 |
| 1944 | 14,453 | 17 | 1964 | 4,562 | 57 | 1984 | 7,795 | 43 | 2004 | 16,487 | 13 |
| 1945 | 19,973 | 6 | 1965 | 6,630 | 51 | 1985 | 12,492 | 27 | 2005 | 8,059 | 41 |
| 1946 | 20,702 | 5 | 1966 | 11,593 | 30 | 1986 | 13,277 | 23 | | | |
| 1947 | 8,414 | 40 | 1967 | 3,410 | 61 | 1987 | 9,988 | 37 | | | |
| 1948 | 5,454 | 52 | 1968 | 13,973 | 19 | 1988 | 3,955 | 60 | | | |
| 1949 | 12,870 | 25 | 1969 | 11,375 | 33 | 1989 | 12,530 | 26 | | | |
| 1950 | 10,905 | 36 | 1970 | 7,362 | 46 | 1990 | 14,394 | 18 | | | |
| 1951 | 2,419 | 63 | 1971 | 4,162 | 58 | 1991 | 22,599 | 3 | | | |
| 1952 | 5,133 | 55 | 1972 | 6,898 | 49 | **1992** | **25,148** | **1** | | | |
| 1953 | 7,608 | 45 | 1973 | 21,455 | 4 | 1993 | 19,952 | 7 | | | |
| 1954 | 2,047 | 64 | 1974 | 13,560 | 22 | 1994 | 16,463 | 14 | | | |
| 1955 | 4,114 | 59 | 1975 | 11,565 | 31 | 1995 | 15,484 | 16 | | | |
| **1956** | **1,871** | **65** | 1976 | 6,660 | 50 | 1996 | 5,157 | 54 | | | |
| 1957 | 17,709 | 11 | 1977 | 8,522 | 39 | 1997 | 16,812 | 12 | | | |
| 1958 | 9,484 | 38 | 1978 | 4,958 | 56 | 1998 | 18,224 | 10 | | | |
| 1959 | 11,061 | 34 | 1979 | 18,671 | 9 | 1999 | 7,113 | 47 | | | |
| 1960 | 11,418 | 32 | 1980 | 7,937 | 42 | 2000 | 6,973 | 48 | | | |
| *Descriptive Statistics for 1941 - 2005* | | | | | | | | | | | |
| Min | 1,871 | | | | | | | | | | |
| 10% | 4,114 | | | | | | | | | | |
| 25% | 6,838 | | | | | | | | | | |
| Median | 11,375 | | | | | | | | | | |
| Mean | 11,267 | | | | | | | | | | |
| 75% | 14,711 | | | | | | | | | | |
| 90% | 19,952 | | | | | | | | | | |
| Max | 25,148 | | | | | | | | | | |

**TxBLEND Model of Galveston Bay**

TxBLEND is a two-dimensional, finite element, hydrodynamic and salinity transport model used for simulating water circulation and salinity distribution in bays and estuaries (Matsumoto 1993). The TxBLEND computational grid for the Galveston Bay model contains 5,070 nodes and 8,041 triangular elements (Figure 3; Matsumoto 2005) and includes the previously described distinctive features of this system, as well as nine inflow points corresponding to the nine rivers and bayous that flow into the bay: Trinity River, San Jacinto River, Buffalo Bayou, Clear Creek, Cedar Bayou, Dickinson Bayou, Double Bayou, Oyster Bayou, and Chocolate Bayou (Figure 3).

Inflows for each of the nine rivers and bayous were developed by TWDB as described above and applied as described in the next two sections. In addition to surface inflows, TxBLEND requires tide levels, wind, evaporation, precipitation, Gulf of Mexico salinity, and bay bathymetry as inputs. These data as well as historical inflow data were readily available for the period 1989 - 1996, because they had been compiled for a previous modeling study conducted for the Galveston Bay Estuary Program (Matsumoto 2005). For the sake of this study, wind, tides, and evaporation developed for the 2005 study were expanded to include 1980 - 1988 and then applied to the modeling period selected for this study.

TxBLEND was used to compare the effects of several freshwater inflow scenarios on salinity condition within the Galveston Bay system. Prior to simulating the various scenarios however, TxBLEND model performance was assessed by simulating conditions over an eight year period, 1989 – 1996 and then comparing simulated salinity values to long-term, field collected salinity data. This validation exercise was conducted for four locations: Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads (Figure 4). These locations correspond to four TWDB long-term water quality (Datasonde Program) monitoring stations in Galveston Bay. Model validation results are available in *Appendix A: Salinity Validation for TxBLEND.* These same four locations also are used to compare the results from the freshwater inflow modeling scenarios for target inflow recommendations and WAM future condition inflows (as described in *Model Scenarios*).

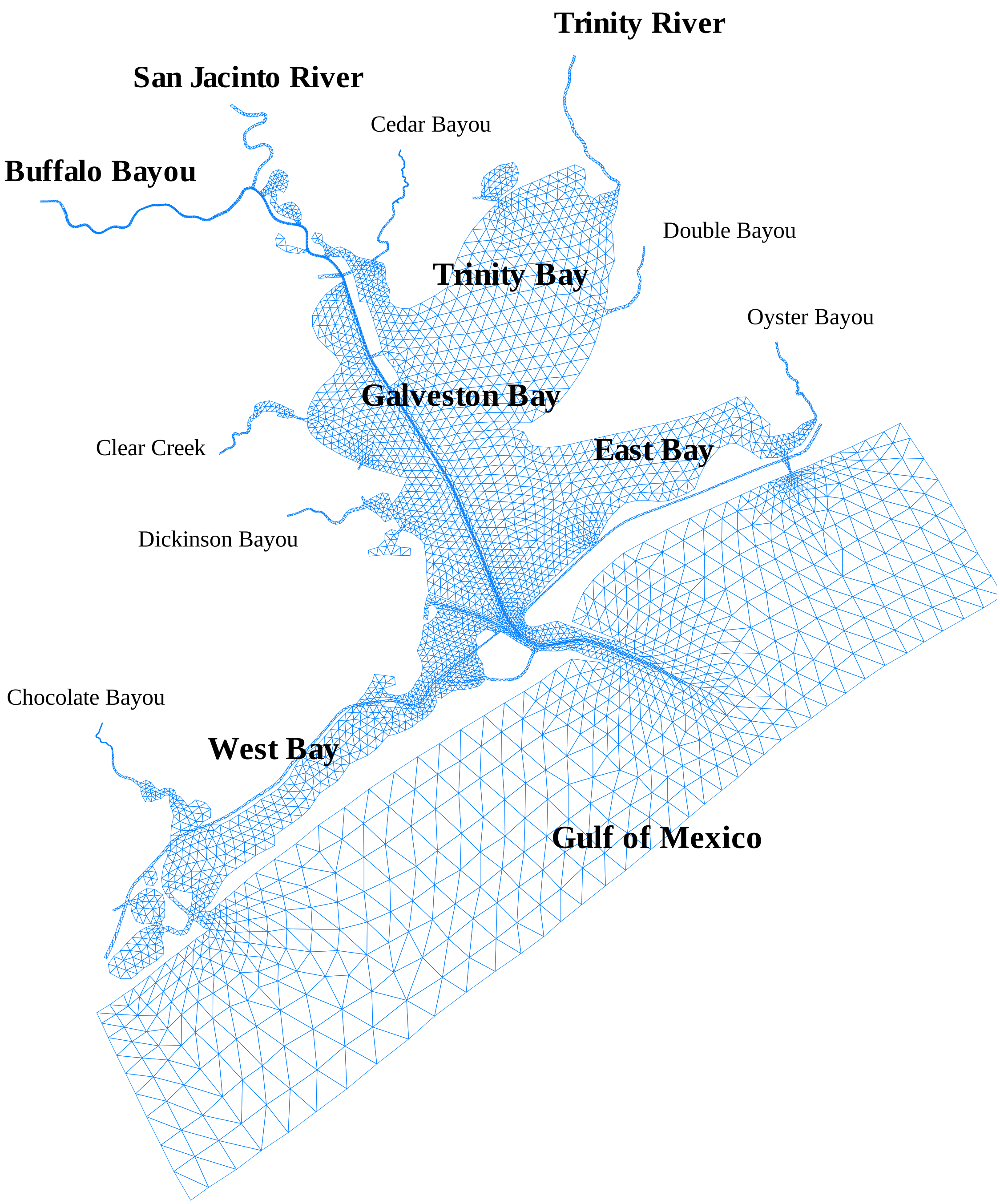



Figure 3. Computational grid for the TxBLEND hydrodynamic and salinity transport model of the Galveston Bay system. Major inflow points (Trinity River, San Jacinto River, and Buffalo Bayou), minor inflow points (Oyster Bayou, Double Bayou, Cedar Bayou, Clear Creek, Dickinson Bayou, and Chocolate Bayou), and subbays (Galveston Bay, Trinity Bay, East Bay, and West Bay) of Galveston Bay are identified as well the three direct connections to the Gulf of Mexico, including Rollover Pass in East Bay, Bolivar Roads in Galveston Bay, and San Luis Pass in West Bay. The Houston Ship Channel transects the bay north to south, from the entrance channel at Bolivar Roads up to Buffalo Bayou, and the Gulf Intracoastal Waterway transects the lower portion of the bay from east to west.

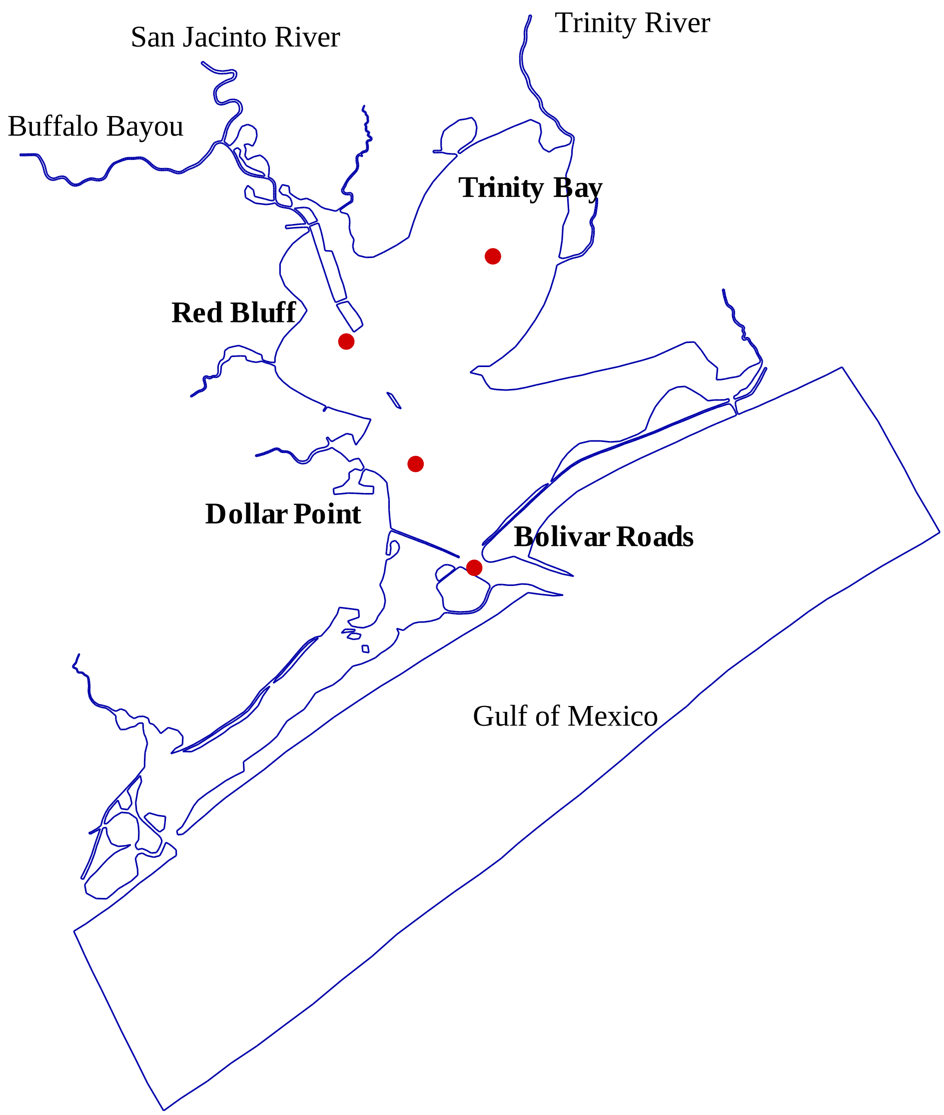



Figure 4. Four TWDB long-term water quality (Datasonde Program) monitoring stations in Galveston Bay, as indicated by red markers for Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads.

*Selection of a Modeling Period Representative of Existing Conditions*

A ten-year period was chosen in order to allow for model simulations to be long enough to include varying conditions but not exceed computer processing limitations. One goal in selecting an appropriate modeling period was to choose a ten-year period in which mean annual surface inflow was similar to the 1941 – 1990 mean annual inflow of 10.0 million acre-feet, which was the period used to set inflow constraints in the development of target inflow recommendations for Galveston Bay (*described below*, TPWD 2001). The period between 1991 and 2001 included some years with extremely high inflows (*e.g.*, 1991, 1992, 2001; Table 2, Selections 1 - 3) and so were not considered representative of inflows typical for the 1941 – 1990 period of record. However, since the period from 1980 – 1989 had a mean annual inflow of 10.4 million acre-feet (Table 2, Selection 4), it was selected as the period most representative of *existing conditions* and therefore used to compare model scenarios of future inflow conditions versus target inflow recommendations. Additional information on monthly inflows for 1980 – 1989 and for the *full period of record* 1941 – 2005 is available in *Appendix B: Monthly Inflows to Galveston Bay*.

Table 2. Mean surface inflows (in 1,000 acre-feet) for four selected ten-year periods were compared to a long-term average of 10.0 million acre-feet (1941 – 1990) in order to determine a period most representative of *existing conditions* for model analysis. The period 1980 – 1989 (Selection 4) was selected as being the most representative with a mean inflow of 10.4 million acre-feet.

| Selection 1 | | | Selection 2 | | | Selection 3 | | | Selection 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Inflow | Rank | Year | Inflow | Rank | Year | Inflow | Rank | Year | Inflow | Rank |
| 1995 | 15,484 | 16 | 1996 | 5,157 | 54 | 1987 | 9,988 | 37 | 1980 | 7,937 | 42 |
| 1996 | 5,157 | 54 | 1997 | 16,812 | 12 | 1988 | 3,955 | 60 | 1981 | 11,989 | 28 |
| 1997 | 16,812 | 12 | 1998 | 18,224 | 10 | 1989 | 12,530 | 26 | 1982 | 10,947 | 35 |
| 1998 | 18,224 | 10 | 1999 | 7,113 | 47 | 1990 | 14,394 | 18 | 1983 | 13,248 | 24 |
| 1999 | 7,113 | 47 | 2000 | 6,973 | 48 | 1991 | 22,599 | 3 | 1984 | 7,795 | 43 |
| 2000 | 6,973 | 48 | 2001 | 24,325 | 2 | 1992 | 25,148 | 1 | 1985 | 12,492 | 27 |
| 2001 | 24,325 | 2 | 2002 | 15,610 | 15 | 1993 | 19,952 | 7 | 1986 | 13,277 | 23 |
| 2002 | 15,610 | 15 | 2003 | 11,666 | 29 | 1994 | 16,463 | 14 | 1987 | 9,988 | 37 |
| 2003 | 11,666 | 29 | 2004 | 16,487 | 13 | 1995 | 15,484 | 16 | 1988 | 3,955 | 60 |
| 2004 | 16,487 | 13 | 2005 | 8,059 | 41 | 1996 | 5,157 | 54 | 1989 | 12,530 | 26 |
| Mean Inflow | 13,785 | | | 13,043 | | | 14,567 | | | 10,416 | |

*Calculation of Daily Inflows for Application to TxBLEND*

The TxBLEND model for Galveston Bay requires the input of daily inflows at nine freshwater inflow points. However, the target inflow recommendations for ecological productivity and the estimated WAM inflows are given only as monthly inflows which must be converted into a daily time-series for use in TxBLEND. One way to convert monthly inflows into daily inflows is to divide a given monthly inflow by the number of days in that month. Another approach is to distribute the monthly inflows according to a distribution pattern exhibited in the existing daily flow record provided either by a reference USGS stream gage station or by modeled runoff using TxRR. In this method, if the ratio (*Rm)* is calculated as the monthly observed (or modeled by TxRR) inflow ($Qm_O$) divided by the monthly WAM inflow ($Qm_{WAM}$), then a daily WAM inflow ($Qd_{WAM}$) can be calculated as *Rm* * daily observed inflow ($Qd_O$).

Therefore, if $\mathrm{Rm} = \mathrm{Qm_O} / \mathrm{Qm_{WAM}}$, then $\mathrm{Qd_{WAM}} = \mathrm{Rm} * \mathrm{Qd_O}$.

Monthly target inflow recommendations and monthly estimated WAM inflows were converted to daily inflows by the latter method which distributes flows temporally according to patterns observed in the gaged records or in the ungaged estimates generated by the TxRR model. Observed daily flow patterns for the Trinity River, San Jacinto River, and Buffalo Bayou were based on gaged flows for the Trinity River using the USGS stream gage at Romayor (#08066500), the San Jacinto River at Lake Houston (USGS #08072000), and gage #08074000 at Buffalo Bayou, respectively. Daily flow patterns for ungaged streams were based on TxRR daily modeled flows; this included Oyster Bayou, Double Bayou, Cedar Bayou, Clear Creek, Dickinson Bayou, and Chocolate Bayou during the period 1/1/1997 to 12/31/2005.

*Distribution of Surface Inflows to Galveston Bay*

TWDB compiled surface inflows for each of the subwatersheds contributing to Galveston Bay for the *recent period* of record, 1977 – 2005. (Surface inflow data at the subwatershed level is not available prior to 1977.) Table 3 lists the individual contribution of inflows for the nine rivers, creeks, and bayous draining into Galveston Bay. Based on this hydrologic record, the Trinity River is the largest provider of inflows (55 percent), followed by the San Jacinto River (16 percent), and then Buffalo Bayou (12 percent). Contributions from the remaining six subwatersheds total 17 percent of inflows and, individually, are significantly smaller. For TxBLEND modeling purposes, estimated inflows from WAM simulations and the recommended target inflows were geographically distributed among the nine TxBLEND inflow points (which correspond to natural drainages, *e.g.*, rivers, creeks, and bayous) based on these inflow ratios.

For comparison purposes, average inflow and the ratio of inflows were calculated for the *existing condition* study period (1980 – 1989; shown as shaded area, Table 3). Inflows during this ten-year period were distributed similarly to those over the recent historical record with the Trinity River contributing 56 percent of inflows, the San Jacinto River contributing 13 percent, Buffalo Bayou contributing 14 percent, and the remaining six subwatersheds contributing 17 percent. Note that in both periods of record, approximately 30 percent of surface inflows to the bay originate from the coastal watersheds, including Buffalo Bayou, that surround Galveston Bay.

Table 3. Total annual surface inflow (in 1,000 acre-feet) and average annual inflow, by contributing subwatershed, into Galveston Bay for the *recent period*, 1977 – 2005. Also included is the average percent contribution of each subwatershed to total bay inflow, as well as the same information for the selected *existing condition* study period 1980 – 1989.

| Year | Trinity River | San Jacinto River | Buffalo Bayou | Clear Creek | Dickinson Bayou | Chocolate Bayou | Double Bayou | Oyster Bayou | Cedar Bayou | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 5,505 | 930 | 920 | 186 | 153 | 226 | 159 | 306 | 140 | 8,525 |
| 1978 | 2,022 | 741 | 1,153 | 174 | 153 | 301 | 98 | 185 | 126 | 4,954 |
| 1979 | 8,884 | 3,155 | 2,216 | 861 | 541 | 1,306 | 380 | 776 | 513 | 18,632 |
| 1980 | 4,180 | 1,108 | 1,177 | 196 | 164 | 262 | 231 | 482 | 161 | 7,961 |
| 1981 | 6,581 | 1,425 | 1,749 | 363 | 235 | 421 | 321 | 594 | 334 | 12,023 |
| 1982 | 7,225 | 1,289 | 1,129 | 194 | 147 | 231 | 188 | 412 | 165 | 10,978 |
| 1983 | 5,989 | 2,362 | 2,035 | 456 | 316 | 599 | 360 | 745 | 388 | 13,250 |
| 1984 | 4,018 | 1,379 | 1,254 | 210 | 180 | 324 | 93 | 217 | 122 | 7,797 |
| 1985 | 6,970 | 1,758 | 1,559 | 380 | 257 | 477 | 272 | 563 | 273 | 12,507 |
| 1986 | 7,742 | 2,069 | 1,632 | 348 | 197 | 382 | 211 | 431 | 291 | 13,301 |
| 1987 | 5,809 | 798 | 1,517 | 337 | 221 | 368 | 220 | 456 | 275 | 10,001 |
| 1988 | 1,926 | 457 | 758 | 131 | 158 | 177 | 86 | 180 | 64 | 3,938 |
| 1989 | 7,941 | 1,171 | 1,485 | 311 | 220 | 367 | 269 | 548 | 237 | 12,548 |
| 1990 | 11,154 | 896 | 1,026 | 223 | 168 | 218 | 190 | 404 | 130 | 14,408 |
| 1991 | 10,370 | 7,008 | 2,111 | 534 | 376 | 600 | 399 | 847 | 359 | 22,604 |
| 1992 | 13,414 | 6,507 | 2,346 | 515 | 422 | 801 | 241 | 475 | 406 | 25,127 |
| 1993 | 9,655 | 5,938 | 1,886 | 415 | 253 | 624 | 274 | 543 | 373 | 19,962 |
| 1994 | 10,446 | 2,385 | 1,658 | 321 | 144 | 320 | 258 | 513 | 479 | 16,524 |
| 1995 | 9,251 | 2,069 | 1,410 | 389 | 378 | 597 | 310 | 636 | 426 | 15,468 |
| 1996 | 1,751 | 874 | 982 | 217 | 280 | 329 | 167 | 319 | 232 | 5,150 |
| 1997 | 9,115 | 2,206 | 2,437 | 549 | 366 | 817 | 272 | 589 | 437 | 16,787 |
| 1998 | 11,304 | 1,440 | 2,314 | 440 | 397 | 752 | 367 | 713 | 474 | 18,202 |
| 1999 | 4,257 | 840 | 966 | 190 | 166 | 216 | 114 | 201 | 169 | 7,120 |
| 2000 | 3,453 | 945 | 1,216 | 264 | 234 | 302 | 123 | 220 | 210 | 6,967 |
| 2001 | 12,992 | 2,673 | 2,849 | 873 | 569 | 1,051 | 862 | 1,765 | 688 | 24,321 |
| 2002 | 7,908 | 2,341 | 1,891 | 513 | 467 | 828 | 311 | 674 | 606 | 15,539 |
| 2003 | 5,378 | 2,251 | 1,583 | 287 | 237 | 380 | 337 | 814 | 357 | 11,624 |
| 2004 | 9,907 | 1,993 | 2,227 | 351 | 253 | 509 | 249 | 565 | 417 | 16,470 |
| 2005 | 4,174 | 1,611 | 1,263 | 143 | 163 | 178 | 101 | 243 | 151 | 8,027 |
| *Recent Period of Record (1977 – 2005)* | | | | | | | | | | |
| Mean Inflow | 7,218 | 2,090 | 1,612 | 358 | 270 | 482 | 257 | 532 | 310 | 13,128 |
| Inflow Ratio | 0.55 | 0.16 | 0.12 | 0.03 | 0.02 | 0.04 | 0.02 | 0.04 | 0.02 | 1.00 |
| *Existing Condition Period of Record (1980 – 1989)* | | | | | | | | | | |
| Mean Inflow | 5,838 | 1,382 | 1,430 | 293 | 210 | 361 | 225 | 463 | 231 | 10,430 |
| *Existing Condition* Ratio | 0.56 | 0.13 | 0.14 | 0.03 | 0.02 | 0.03 | 0.02 | 0.04 | 0.02 | 1.00 |

## Model Scenarios

The purpose of this study is (1) to investigate the influence of water plan strategies for the Trinity River Basin on inflows reaching Galveston Bay and on salinity condition in the receiving waters of the bay and (2) to compare the effect of these strategies to the *existing condition* as well as to target inflow recommendations developed to protect the health and productivity of the Galveston Bay ecosystem. To accomplish this, five scenarios are considered and compared in this report:

1) An *existing* freshwater inflow condition based on known inflows from 1980 to 1989;
2) Future inflows estimated by a modified WAM Run3, which represents a future inflow condition with fully utilized water rights and no return flows;
3) Future inflows estimated by a WAM Run9, which represent a future inflow condition with anticipated water demands and strategies implemented;
4) Inflows estimated by the MaxH target inflow recommendation for Galveston Bay, designed to maximize ecological productivity for a given inflow volume; and,
5) Inflows estimated by the MinQ target inflow recommendation for Galveston Bay, designed to provide the minimum inflows necessary to meet identified salinity and ecological constraints.

The *existing condition* was simulated first using input data, including tide, wind, precipitation, evaporation, inflows, and salinity at the Gulf boundary, for a representative period 1980 – 1989. The *existing condition* is distinguished from all other scenarios in that the freshwater inflows used as inputs to the model were obtained from observed records of inflows or from computed inflows based on observed rainfall data estimated by the TWDB Coastal Hydrology Program. All other scenarios are based on inflows obtained from either the WAM models (*i.e.*, modified WAM Run3 or WAM Run9) or the State's target inflow recommendations for Galveston Bay (*i.e.*, MaxH or MinQ). Additionally, for this study, both WAM models were modified to reflect future conditions including increased reservoir sedimentation and implementation of planned water supply strategies for the region.

### *Future Inflow Conditions Based on Water Availability Modeling Analyses*

The Texas Commission on Environmental Quality's (TCEQ) water availability models (WAM) for Run8 and Run3 are able to estimate the expected volume of water passing a control point within a river given current and future patterns of water use and infrastructure. Run8 represents current conditions by applying water right demands equal to the maximum diversion for a recent ten-year period (which was 1995 – 2004 at the time of model development), return flows based on current levels, and term (temporary) water rights. Run3 represents a future condition in which there is full use of permitted diversions with no return flows and no term water rights. At the time of this study, these two models were capable of simulating expected water availability based on observed hydrology from the period 1940 – 1996. However, in order to evaluate the influence of water plans and future conditions (target year 2060) on freshwater inflows to

Galveston Bay, several modifications were made to these models in an attempt to make the simulations more realistic of future scenarios by considering reductions in the capacity of reservoir storage due to sedimentation, changes in system operations, and inter-basin transfers consistent with strategies described in the 2007 Texas Water Plan (TWDB 2007). The modified runs are identified as Run9 (a modified version of Run8) and as modified Run3; details are described in Table 4.

Table 4. Model versions used to generate WAM Run8, WAM Run3, modified WAM Run9, and modified WAM Run3 for this study. Water demands and strategies applied to the WAM were based on the 2007 State Water Plan (TWDB 2007).

| WAM Run8 | WAM Run3 |
|---|---|
| Trinity version 2004<br>San Jacinto version 2003<br>Neches-Trinity version 2004<br>Brazos version 2004, with inflow data updated to 2008 | Trinity version 2004<br>San Jacinto version 2003<br>Neches-Trinity version 2004<br>Brazos version 2007 |
| **WAM Run9 (a modified Run8)** | **Modified WAM Run3** |
| Reservoir capacities of major reservoirs are changed based on predictions for 2060, when data are available. Plus, all water management strategies developed by the Water Planning Regions are modeled, including but not limited to: new water permits, reuse, reservoir system operation, scalping, *etc*. | All water management strategies developed by the Water Planning Regions are modeled, including but not limited to: new reservoirs and new diversion permits, reuse, reservoir system operation, scalping, *etc*. |

Surface inflows estimated by the WAM enter Galveston Bay via defined control points (Figure 5). Control Point *Trinity* passes inflows from the Trinity River basin; whereas, NT-TB is a control point near the mouth of Double Bayou (east side of Trinity Bay), and NT-EB is a control point near the mouth of Oyster Bayou (east end of East Bay). T-SJ is a control point near the mouth of Cedar Bayou. Inflows from the San Jacinto Basin, including Buffalo Bayou, pass through control point SJA. SJGBC3 is a control point for the basins of Clear Creek and Dickinson Bayou, and SJGMC4 is a control point for Chocolate Bayou and local drainages around West Bay. WAM inflows from these seven control points were distributed to represent inflows from each of the five surrounding river basins. WAM inflows also were divided accordingly among the nine TxBLEND inflow points. Both are described below.

To represent inflows from the five major basins surrounding Galveston Bay, WAM inflows from the control points are combined as follows:

<u>Trinity Basin</u> (Trinity) – Includes the Trinity River as the primary source and is represented by all inflows passing the *Trinity* control point.

<u>Neches-Trinity Basin</u> (N-T) – Includes Double Bayou and Oyster Bayou and is represented by the combined inflows passing the NT-TB and NT-EB control points.

Trinity-San Jacinto Basin (T-SJ) – Includes only Cedar Bayou and so is represented by all inflows passing the T-SJ control point.

San Jacinto Basin (SJA) – Includes San Jacinto River and Buffalo Bayou and is represented by all inflows passing the SJA control point.

Brazos-San Jacinto Coastal Basin (BSJC) – Includes Clear Creek, Dickinson Creek, and Chocolate Bayou and is represented by the combined inflows passing SJGBC3 and SJGBC4.

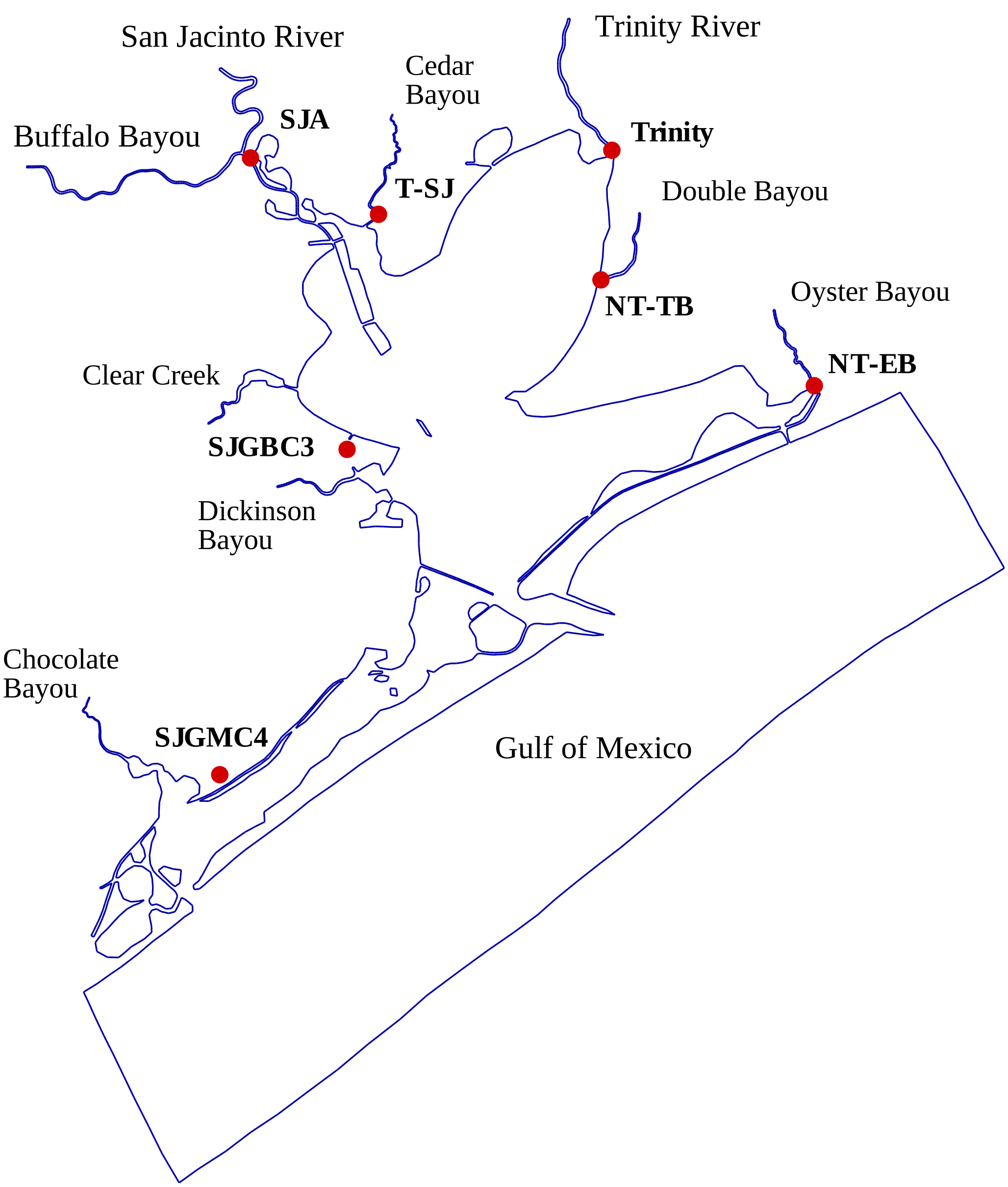



Figure 5. Seven WAM control points (*red circles*) for surface inflows entering the Galveston Bay system.

The seven WAM control points do not correspond in location to the natural drainages to Galveston Bay, which are specified as nine inflow points in the TxBLEND hydrodynamic and salinity transport model. Therefore for application to TxBLEND, inflows from the seven WAM control points were distributed among the nine TxBLEND inflow points for Galveston Bay (as seen in Figure 3) according to the percentages shown in Figure 6. Percent distributions between Buffalo Bayou and San Jacinto River and between Clear Creek and Dickinson Bayou were determined based on the relative contribution of average inflow for each river or bayou during the *recent period of record* (as identified by the inflow ratios reported in Table 3).

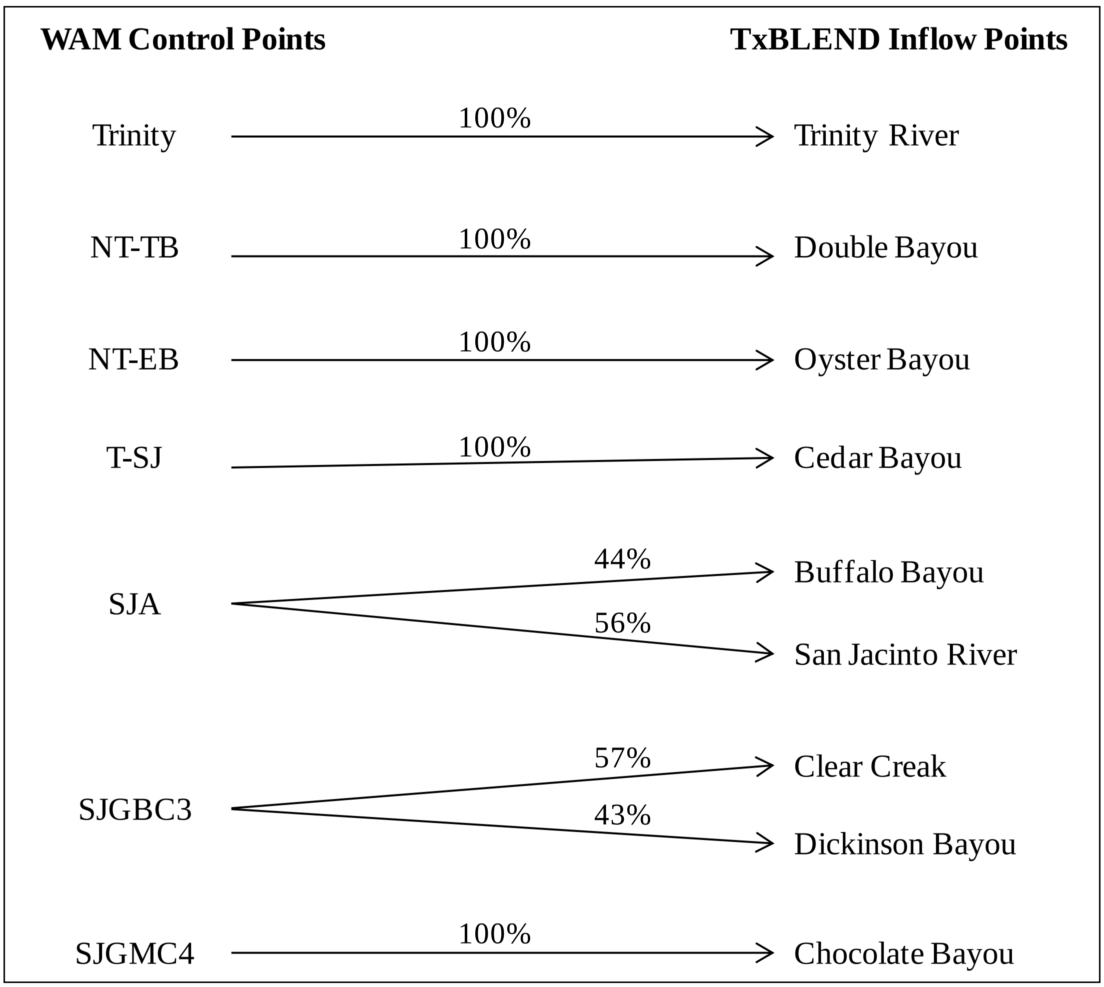



Figure 6. Distribution of flows from seven WAM control points to nine natural drainages to Galveston Bay, which also corresponds to the nine TxBLEND inflow points.

*Selection of WAM Run9 and Modified Run3 for Comparison of Future Conditions*

The WAM Run3 and WAM Run8 models are capable of simulating surface inflows based on hydrology for the period 1940 to 1996. However, in order to determine inflows under future expected conditions, the WAM models were modified as previously described. To allow for a comparison of estimated future surface inflows between the base and modified WAM models, WAM analyses were conducted for four models (Run8, Run9, Run3, and modified Run3). Total inflow to Galveston Bay under Run8 is 9.3 million acre-feet and under Run3 is 7.7 million acre-feet (Table 5). There is a slight increase of 301,000 acre-feet or 3.2 percent under Run9, as compared to Run8, while there is a noticeable decrease of 808,000 acre-feet or 10.5 percent under modified Run3 as compared to Run3. Table 5 also shows estimated inflows for each of the five major river basins for each WAM model.

Table 5. Mean annual inflow (1,000 acre-feet), as estimated by four WAM scenarios using hydrology from the period 1940 – 1996, from the five major river basins surrounding Galveston Bay and total mean annual inflow to Galveston Bay for each WAM scenario.

| Scenario | Trinity | SJA | BSJC | N-T | T-SJ | Total |
|---|---|---|---|---|---|---|
| Run 8 | 5,349 | 2,234 | 1,147 | 361 | 186 | 9,276 |
| Run 9 | 5,321 | 2,448 | 1,261 | 361 | 186 | 9,577 |
| Run 3 | 4,317 | 1,701 | 1,137 | 361 | 168 | 7,684 |
| Modified Run 3 | 3,358 | 1,852 | 1,137 | 361 | 168 | 6,876 |

Table 6 lists the ratios of inflows from each river basin under the various WAM scenarios. The Trinity River basin supplies 49 percent to 58 percent of inflows depending on the scenario, with Run8 providing the highest percentage and modified Run3 providing the lowest percentage of inflows. The San Jacinto River basin is the next largest contributor of inflows to Galveston Bay, ranging from 22 percent to 27 percent of the total inflow contribution depending on the WAM scenario. In contrast to the Trinity River basin, modified WAM Run3 provided the greatest percentage contribution from the San Jacinto River basin. WAM Run9 also provided a relatively greater percentage contribution from the San Jacinto basin than either of the base run scenarios. The shift in ratios reflects the effect of water supply strategies, such as the transfer of a portion of Trinity River basin flow into the San Jacinto River basin which is most evident in modified Run3. The remaining coastal basins, together, contribute 18 percent to 24 percent of inflows. The Trinity-San Jacinto (T-SJ) and Neches-Trinity (N-T) basins vary little among the scenarios, providing approximately 2 percent and 5 percent, respectively. The Brazos-San Jacinto coastal basin (BSJC) however varies among the WAM scenarios, providing between 12 percent and 17 percent of inflows to Galveston Bay, with the greatest percent contribution occurring under a modified WAM Run3.

For the purpose of this report, TxBLEND simulations and salinity comparisons were conducted only for two WAM scenarios, WAM Run9 and a modified WAM Run3. Run8 and Run3 were not included in the comparison, because the modified runs reflect expected future conditions more accurately than the base cases.

Table 6. Ratios of mean annual inflow by river basin for each WAM scenario, including base and modified runs. Only Run9 and modified Run3 were selected for use in further comparison of effects on freshwater inflows and bay salinity conditions.

| Scenario | Trinity | SJA | BSJC | N-T | T-SJ |
|---|---|---|---|---|---|
| Run8 | 0.58 | 0.24 | 0.12 | 0.04 | 0.02 |
| Run9 | 0.56 | 0.26 | 0.13 | 0.04 | 0.02 |
| Run3 | 0.56 | 0.22 | 0.15 | 0.05 | 0.02 |
| Modified Run3 | 0.49 | 0.27 | 0.17 | 0.05 | 0.02 |

*Target Freshwater Inflow Recommendations for Maintaining Ecological Productivity*

TPWD and TWDB conducted a joint study to determine the freshwater inflows needs of the Trinity-San Jacinto Estuary (TPWD 2001). In this study, target monthly inflows were identified in order to maintain productivity levels of economically important and ecologically significant species. Target inflows were determined by using an optimization approach to meet a set of constraints and management objectives. The complete analysis generated a performance curve relating commercial fisheries harvest to annual inflows, where annual inflow was based on a specified series of monthly inflows. From this curve, two target inflows, MaxH and MinQ, were identified. MaxH target inflows represent a series of monthly inflows which provide for the maximum harvest (fisheries productivity) of the species evaluated. MinQ target inflows represent the minimum monthly inflows necessary to meet the constraints specified for inflow, salinity, harvest, and other biological conditions. Each target has a different distribution of monthly inflows (Table 7). It is important to remember that some parameters in the methodology depend on the statistics of the observed data used in the study. For example, lower and upper constraints on monthly inflow solutions were based on the median and 10$^{th}$ percentile historical monthly flows for the period 1941 – 1990. As a result, no monthly target inflow could exceed the historical median value of inflow. Similar lower and upper constraints were set for salinity condition as well. This served to guide the target inflow solutions into providing desired salinity conditions based on pre-determined management goals.

Herein, two target inflows, MaxH and MinQ, are evaluated and compared to the results generated by inflows for the *existing condition* and for WAM model runs of future conditions. The question of *how best to implement* the target inflow recommendations is not considered in this report. Instead, the target inflow recommendations are applied in the strictest sense, by repeatedly applying the monthly inflows shown in Table 7 from one year to the next. Though this lack of monthly and annual inflow variation is unrealistic, it at least provides a means for comparing the relative effects of the target inflow recommendations versus potential future conditions as described by the WAM analyses.

Unlike the WAM scenarios, where simulated inflows were distributed among the nine TxBLEND inflow points according to the inflow ratios, the target inflows first were adjusted to remove the effect of the average inflow coming from the six coastal streams and bayous (1.783 million acre-feet) during the study period (1980 – 1989). This decision considers that inflows from these six sources are not regulated and therefore cannot be controlled. The remainder for each target inflow then was geographically distributed among the three major sources of inflow based on a proportional adjustment to the *recent period* inflow ratios. The adjusted ratios are: Trinity River (0.66), San Jacinto River (0.19), and Buffalo Bayou (0.15). Therefore, for MaxH, after subtracting out coastal inflows, the remaining 3.4 million acre-feet was distributed to provide 2.3 million acre-feet to the Trinity River, 662 thousand acre-feet to the San Jacinto River, and 498 thousand acre-feet to Buffalo Bayou. For MinQ, the remaining 2.4 million acre-feet was distributed to provide 1.6 million acre-feet to the Trinity River, 458 thousand acre-feet to the San Jacinto River, and 345 thousand acre-feet to Buffalo Bayou. Finally, daily surface inflows for the Trinity River, San Jacinto River, and Buffalo Bayou were determined from the adjusted target monthly inflows using the methodology previously described in the section *Calculation of Daily Inflows for Application to TxBLEND*. The adjusted monthly target inflows were repeated each year over the 1980 – 1989 simulation period, though the daily inflow amounts within each month varied across years according to the pattern in the observed record. Observed daily inflows from 1980 – 1989 were applied to the six unregulated creeks and bayous.

Table 7. Target monthly inflow recommendations for MinQ and MaxH (in 1,000 acre-feet) for the Trinity-San Jacinto Estuary (TPWD 2001).

| Month | MinQ | MaxH |
|---|---|---|
| January | 150.5 | 150.5 |
| February | 216.7 | 155.2 |
| March | 363.9 | 652.8 |
| April | 352.6 | 632.5 |
| May | 679.7 | 1,273.7 |
| June | 448.1 | 839.7 |
| July | 232.7 | 211.5 |
| August | 154.0 | 140.0 |
| September | 330.2 | 103.0 |
| October | 251.9 | 78.6 |
| November | 351.5 | 351.5 |
| December | 626.8 | 626.8 |
| Annual Total | 4,158.6 | 5,215.8 |

## RESULTS

### WAM Run9 Inflow Simulations

Future surface inflows, as estimated by WAM Run9, in which anticipated demands and strategies are implemented, were obtained from the WAM for the seven control points to Galveston Bay (as seen in Figure 5) for the study period 1980 – 1989 (Table 8). Mean total bay inflow for this scenario is 9.1 million acre-feet, with 7.5 million acre-feet (or 82 percent) being delivered by the Trinity, San Jacinto, and Buffalo Bayou rivers. This represents a decrease of nearly 1.3 million acre-feet as compared to observed *existing condition* inflows, with 90 percent of the decrease resulting from reduced flows in the three major contributing rivers.

For application to the TxBLEND circulation and salinity transport model, inflows from these seven control points were distributed among the nine TxBLEND inflow points for Galveston Bay. These distributed inflows are shown in Table 9, along with the percent contribution of mean inflow for each of the nine sub-basins. In addition, future inflows, as simulated by WAM Run9, were compared to the *existing condition* by calculating the ratio of WAM Run9 mean annual inflow to the *existing condition* mean annual inflow (Table 9). The ratio of mean annual total bay inflow for this ten-year period is 0.88, meaning that simulated inflows from WAM Run9 are roughly 12 percent lower than observed inflows from the *existing condition*.

There is a slight discrepancy in the ratio calculated for Chocolate Bayou in Table 9, in that it appears that WAM Run9 provides more than twice the flow as compared to the existing condition. However, this is likely caused by a difference in the method of calculating inflows at the control point SJGMC4 as compared to the method of calculation used by the Texas Rainfall-Runoff Model (TxRR) to estimate inflows for Chocolate Bayou. Although the discrepancy appears large, the overall influence to total bay inflows is approximately 4 percent (refer to Table 3). Additionally, because inflows to Chocolate Bayou influence West Bay and not the main body of Galveston Bay (where the salinity comparison is made), the discrepancy was considered insignificant for this exercise.

Table 8. WAM Run9 simulated inflows (in 1,000 acre-feet) to Galveston Bay for the period 1980 – 1989 at seven WAM control points.

| Year | Trinity | SJA | SJGBC3 | SJGMC4 | NT-TB | NT-EB | T-SJ | Total |
|---|---|---|---|---|---|---|---|---|
| 1980 | 3,150 | 1,796 | 349 | 584 | 110 | 278 | 166 | 6,433 |
| 1981 | 5,726 | 2,268 | 505 | 958 | 164 | 383 | 333 | 10,337 |
| 1982 | 6,273 | 2,252 | 316 | 501 | 72 | 191 | 223 | 9,828 |
| 1983 | 4,509 | 3,866 | 547 | 1,061 | 126 | 319 | 315 | 10,743 |
| 1984 | 3,341 | 2,179 | 359 | 606 | 38 | 105 | 82 | 6,710 |
| 1985 | 5,764 | 2,844 | 455 | 837 | 93 | 246 | 243 | 10,482 |
| 1986 | 6,982 | 2,483 | 429 | 774 | 86 | 225 | 285 | 11,264 |
| 1987 | 5,293 | 2,489 | 343 | 567 | 99 | 253 | 311 | 9,355 |
| 1988 | 1,235 | 997 | 198 | 217 | 42 | 111 | 60 | 2,860 |
| 1989 | 9,143 | 2,203 | 438 | 799 | 134 | 320 | 279 | 13,316 |
| Mean | 5,142 | 2,338 | 394 | 690 | 96 | 243 | 230 | 9,133 |

Table 9. Simulated WAM Run9 inflows (in 1,000 acre-feet) from the seven WAM control points distributed and applied to the nine TxBLEND inflow points for the period 1980 - 1989. The distribution of inflows from the seven control points to the nine inflow points is shown in the first row and was based on the distribution presented in Figure 6. Mean inflows from Run9 for each of the TxBLEND inflow points are provided along with the ratio of inflows among the nine inflow points. Finally, a ratio of estimated mean inflows from Run9 to *existing condition* inflows for the period 1980 – 1989 (as in Table 3) is provided for each subbasin and total bay inflow.

| | WAM Control Points (and Percent Contribution) | Trinity (100%) | SJA (56%) | SJA (44%) | SJGBC3 (57%) | SJGBC3 (43%) | SJGMC4 (100%) | NT-TB (100%) | NT-EB (100%) | T-SJ (100%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TxBLEND Inflow Points | Trinity River | San Jacinto River | Buffalo Bayou | Clear Creek | Dickinson Bayou | Chocolate Bayou | Double Bayou | Oyster Bayou | Cedar Bayou | Total Inflow |
| Year | 1980 | 3,150 | 1,006 | 790 | 199 | 150 | 584 | 110 | 278 | 166 | 6,433 |
| | 1981 | 5,726 | 1,270 | 998 | 288 | 217 | 958 | 164 | 383 | 333 | 10,337 |
| | 1982 | 6,273 | 1,261 | 991 | 180 | 136 | 501 | 72 | 191 | 223 | 9,828 |
| | 1983 | 4,509 | 2,165 | 1,701 | 312 | 235 | 1,061 | 126 | 319 | 315 | 10,743 |
| | 1984 | 3,341 | 1,220 | 959 | 205 | 154 | 606 | 38 | 105 | 82 | 6,710 |
| | 1985 | 5,764 | 1,593 | 1,251 | 259 | 196 | 837 | 93 | 246 | 243 | 10,482 |
| | 1986 | 6,982 | 1,390 | 1,093 | 245 | 184 | 774 | 86 | 225 | 285 | 11,264 |
| | 1987 | 5,293 | 1,394 | 1,095 | 196 | 147 | 567 | 99 | 253 | 311 | 9,355 |
| | 1988 | 1,235 | 558 | 439 | 113 | 85 | 217 | 42 | 111 | 60 | 2,860 |
| | 1989 | 9,143 | 1,234 | 969 | 250 | 188 | 799 | 134 | 320 | 279 | 13,316 |
| | Run9 Mean Inflow | 5,142 | 1,309 | 1,029 | 225 | 169 | 690 | 96 | 243 | 230 | 9,133 |
| | Inflow Ratio | 0.56 | 0.14 | 0.11 | 0.02 | 0.02 | 0.08 | 0.01 | 0.03 | 0.03 | 1.0 |
| | Ratio Run9 to *Existing Condition* | 0.88 | 0.95 | 0.72 | 0.77 | 0.80 | 1.91 | 0.43 | 0.52 | 1.0 | 0.88 |

## Modified WAM Run3 Inflow Simulations

Future surface inflows, as simulated by a modified WAM Run3 in which water rights are fully utilized with no return flows, were obtained for the seven WAM control points to Galveston Bay (as seen in Figure 5) for the study period 1980 – 1989 (Table 10). Mean total bay inflow for this scenario is 6.4 million acre-feet, with 4.9 million acre-feet (or 76 percent) being delivered by the Trinity, San Jacinto, and Buffalo Bayou rivers. This represents a decrease of nearly 4.1 million acre-feet as compared to observed *existing condition* inflows, with nearly all of the decrease resulting from reduced flows in the three major contributing rivers.

Similar to Table 9, WAM inflows were distributed among the nine inflow points for application in the TxBLEND model, according to the distribution described in Figure 6. Newly distributed inflows and their percent contribution to total bay inflow are shown in Table 11. Also provided is a ratio of mean simulated Run3 inflows to mean observed *existing condition* inflows during the study period. This ratio of the ten-year average inflow between the two scenarios is 0.61, suggesting that inflows simulated by a modified WAM Run3 are, on average, 39 percent lower in a given year than observed inflows from the *existing condition*. In particular, inflows from the Trinity River are reduced by 46 percent in comparison to *existing* inflows; San Jacinto River inflows are reduced by about 30 percent. Similar to the WAM Run9 scenario, there is a slight discrepancy in the ratio calculated for Chocolate Bayou in that the modified WAM Run3 provides more than twice the flow as compared to the *existing condition*. However, the overall influence to total bay inflows is approximately 4 percent (refer to Table 3), and because these inflows do not influence the main body of Galveston Bay (where the salinity comparison is made), the discrepancy was considered insignificant for this exercise.

Table 10. Modified WAM Run3 simulated inflows (in 1,000 acre-feet) for the period 1980 – 1989 at seven control points to Galveston Bay.

| Year | Trinity | SJA | SJGBC3 | SJGMC4 | NT-TB | NT-EB | T-SJ | Total |
|---|---|---|---|---|---|---|---|---|
| 1980 | 2,323 | 1,229 | 243 | 566 | 110 | 278 | 148 | 4,897 |
| 1981 | 2,623 | 1,674 | 398 | 938 | 164 | 383 | 316 | 6,496 |
| 1982 | 3,836 | 1,627 | 209 | 482 | 72 | 191 | 205 | 6,622 |
| 1983 | 2,778 | 3,249 | 440 | 1,041 | 126 | 319 | 297 | 8,250 |
| 1984 | 1,701 | 1,544 | 253 | 587 | 38 | 105 | 64 | 4,292 |
| 1985 | 3,847 | 2,253 | 348 | 818 | 93 | 246 | 225 | 7,830 |
| 1986 | 4,794 | 1,864 | 322 | 757 | 86 | 225 | 268 | 8,316 |
| 1987 | 3,110 | 1,901 | 236 | 550 | 99 | 253 | 293 | 6,442 |
| 1988 | 460 | 459 | 92 | 201 | 42 | 111 | 42 | 1,407 |
| 1989 | 5,792 | 1,576 | 332 | 783 | 134 | 320 | 261 | 9,198 |
| Mean | 3,126 | 1,738 | 287 | 672 | 96 | 243 | 212 | 6,375 |

Table 11. Modified WAM Run3 inflows (in 1,000 acre-feet) simulated at the seven WAM control points, distributed and applied to the nine TxBLEND inflow points for the period 1980 – 1989. The distribution of inflows from the seven control points to the nine inflow points is shown in the first row and was based on the distribution of flows presented in Figure 6. Mean inflows from Run3 for each of the TxBLEND inflow points are provided along with the ratio of inflows among the nine inflow points. Finally, a ratio of estimated mean inflows from Run3 to *existing condition* inflows for the period 1980 – 1989 (as in Table 3) is provided for each subbasin and total bay inflow.

| | WAM Control Points (and Percent Contribution) | Trinity (100%) | SJA (56%) | SJA (44%) | SJGBC3 (57%) | SJGBC3 (43%) | SJGMC4 (100%) | NT-TB (100%) | NT-EB (100%) | T-SJ (100%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TxBLEND Inflow Points | Trinity River | San Jacinto River | Buffalo Bayou | Clear Creek | Dickinson Bayou | Chocolate Bayou | Double Bayou | Oyster Bayou | Cedar Bayou | Total Inflow |
| Year | 1980 | 2,323 | 688 | 541 | 139 | 104 | 566 | 110 | 278 | 148 | 4,897 |
| | 1981 | 2,623 | 937 | 737 | 227 | 171 | 938 | 164 | 383 | 316 | 6,496 |
| | 1982 | 3,836 | 911 | 716 | 119 | 90 | 482 | 72 | 191 | 205 | 6,622 |
| | 1983 | 2,778 | 1,819 | 1,430 | 251 | 189 | 1,041 | 126 | 319 | 297 | 8,250 |
| | 1984 | 1,701 | 865 | 679 | 144 | 109 | 587 | 38 | 105 | 64 | 4,292 |
| | 1985 | 3,847 | 1,262 | 991 | 198 | 150 | 818 | 93 | 246 | 225 | 7,830 |
| | 1986 | 4,794 | 1,044 | 820 | 184 | 138 | 757 | 86 | 225 | 268 | 8,316 |
| | 1987 | 3,110 | 1,065 | 836 | 135 | 101 | 550 | 99 | 253 | 293 | 6,442 |
| | 1988 | 460 | 257 | 202 | 52 | 40 | 201 | 42 | 111 | 42 | 1,407 |
| | 1989 | 5,792 | 883 | 693 | 189 | 143 | 783 | 134 | 320 | 261 | 9,198 |
| | Modified Run3 Mean Inflow | 3,126 | 973 | 765 | 164 | 124 | 672 | 96 | 243 | 212 | 6,375 |
| | Inflow Ratio | 0.49 | 0.15 | 0.12 | 0.03 | 0.02 | 0.11 | 0.02 | 0.04 | 0.03 | 1.00 |
| | Ratio modified Run3 to *Existing Condition* | 0.54 | 0.70 | 0.53 | 0.56 | 0.59 | 1.86 | 0.43 | 0.52 | 0.92 | 0.61 |

**MaxH Target Inflow Simulations**

MaxH target inflows were applied fairly strictly; nonetheless, a table similar to that given for the two WAM scenarios (refer to Tables 9 and 11) is provided for clarity and to show the distribution of MaxH target inflows among the three major TxBLEND inflow points and the observed inflows for the six minor inflow points (Table 12). Even though observed coastal inflows were applied for 1980 – 1989, total bay inflow was adjusted to be *on average* equal to the MaxH target inflow of 5.2 million acre-feet. Therefore, under this scenario, the geographic distribution of inflows among the nine sources to Galveston Bay changes such that inflow from the Trinity River, San Jacinto River, and Buffalo Bayou represents only 66 percent of total bay inflows (Table 12) – as compared to their recent historical contribution of 83 percent of total bay inflows (Table 3).

Table 12 also shows the effect of the target inflows as compared to observed flows recorded for the 1980 – 1989 *existing condition*. When MaxH is applied, the ratio of the ten-year average inflow between the two scenarios (MaxH inflows versus *existing condition*) is 0.50, suggesting that MaxH inflows, when strictly applied, are on average 50 percent lower than observed inflows for the 1980 – 1989 *existing condition*. In particular, inflows from the Trinity River are reduced by 61 percent (or 3.6 million acre-feet) in comparison to *existing* inflows. Being the largest contributor of inflows to Galveston Bay, this results in the greatest reduction in volume of inflow to the bay. The second largest contributor, the San Jacinto River, is reduced by 52 percent (or 720,000 acre-feet). Buffalo Bayou inflows however experience the greatest percent reduction in inflows at 65 percent, which corresponds to a decrease of approximately 931,500 acre-feet.

The decision to represent MaxH target inflows in this manner is based on the idea that MaxH represents the complete inflow need for the bay to produce a maximum fisheries harvest given a set of management constraints related to salinity and inflow condition. The scenario does not allow for uncontrolled high flow pulses or flushing flows which would occur naturally. Also, the scenario assumes that the volume and timing of coastal inflows from unregulated streams will remain the same in the future – whereas regulated streams would be subject to following the target inflow recommendations. By assuming coastal inflows are on average the same in the future as they are now, then water managers could deliver less water to the bay via the Trinity, San Jacinto, and Buffalo rivers and still meet the MaxH recommendation under this scenario.

Table 12. MaxH target inflows (in 1,000 acre-feet) distributed and applied to the three major inflow points of the TxBLEND model to evaluate the effects on freshwater inflows and bay salinity conditions during the period 1980 – 1989. Inflows for the minor six inflow points are based on the observed record as reported in Table 3. Mean inflows by basin and for total bay inflow show that on average inflows met the MaxH recommended target of 5.2 million acre-feet. The inflow ratio shows the geographic distribution of inflows among the nine inflow points for the MaxH inflow scenario. Also, mean MaxH inflows by subbasin and total bay are compared to mean inflows obtained under the *existing condition* period of 1980 – 1989 (as in Table 3).

| | TxBLEND Inflow Points | Trinity River | San Jacinto River | Buffalo Bayou | Clear Creek | Dickinson Bayou | Chocolate Bayou | Double Bayou | Oyster Bayou | Cedar Bayou | Total Inflow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1980 | 2,273 | 662 | 498 | 196 | 164 | 262 | 231 | 482 | 161 | 4,929 |
| | 1981 | 2,273 | 662 | 498 | 363 | 235 | 421 | 321 | 594 | 334 | 5,701 |
| | 1982 | 2,273 | 662 | 498 | 194 | 147 | 231 | 188 | 412 | 165 | 4,770 |
| | 1983 | 2,273 | 662 | 498 | 456 | 316 | 599 | 360 | 745 | 388 | 6,297 |
| | 1984 | 2,273 | 662 | 498 | 210 | 180 | 324 | 93 | 217 | 122 | 4,579 |
| | 1985 | 2,273 | 662 | 498 | 380 | 257 | 477 | 272 | 563 | 273 | 5,655 |
| | 1986 | 2,273 | 662 | 498 | 348 | 197 | 382 | 211 | 431 | 291 | 5,293 |
| | 1987 | 2,273 | 662 | 498 | 337 | 221 | 368 | 220 | 456 | 275 | 5,310 |
| | 1988 | 2,273 | 662 | 498 | 131 | 158 | 177 | 86 | 180 | 64 | 4,229 |
| | 1989 | 2,273 | 662 | 498 | 311 | 220 | 367 | 269 | 548 | 237 | 5,385 |
| | Mean Inflow | 2,273 | 662 | 498 | 293 | 210 | 361 | 225 | 463 | 231 | **5,215** |
| | Inflow Ratio | 0.44 | 0.13 | 0.10 | 0.06 | 0.04 | 0.07 | 0.04 | 0.09 | 0.04 | 1.00 |
| | Ratio MaxH to *Existing Condition* Inflows | 0.39 | 0.48 | 0.35 | 0.43 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.50 |

**MinQ Target Inflow Simulations**

As with the MaxH target inflow scenario, MinQ inflows were adjusted to remove the influence of average inflow from the coastal basins and then were apportioned and strictly applied to the three major inflow sources (Table 13). Thus for the 1980 – 1989 simulation period, MinQ inflows were on average consistent with the recommended inflow target of 4.2 million acre-feet. Similar to the MaxH scenario, the geographic distribution of inflows to Galveston Bay changes such that inflow from the Trinity River, San Jacinto River, and Buffalo Bayou represents only 57 percent of total bay inflows (Table 13) – as compared to their recent historical contribution of 83 percent of total bay inflows (Table 3).

Also shown is a comparison of the target inflows to observed flows recorded for the 1980 – 1989 period. The ratio of the ten-year average inflow between the two scenarios (MinQ inflows versus *existing condition*) is 0.40, suggesting that MinQ inflows, when strictly applied, are on average 60 percent lower than the observed inflows from the *existing condition*. In particular, inflows from the Trinity River are reduced by 73 percent (or 4.3 million acre-feet) in comparison to *existing* inflows. Being the largest contributor of inflows to Galveston Bay, this results in the greatest reduction in volume of inflow to the bay. The second largest contributor, the San Jacinto River, is reduced by 67 percent (or 923,600 acre-feet). Buffalo Bayou has the greatest percent reduction of inflows at 76 percent, which corresponds to a decrease of approximately 1.08 million acre-feet.

Under this scenario, inflows are greatly reduced for the three major rivers but not for the coastal streams; because it was assumed that in meeting the whole bay target inflow of 4.2 million acre-feet, the coastal streams would on average contribute as much in the future as under current conditions. Given this interpretation of the target inflow recommendation, inflows from the Trinity River, San Jacinto River, and Buffalo Bayou could be greatly reduced yet still meet the overall target inflow. However, for both target inflow scenarios, this study evaluates only the impact on salinity conditions within Galveston Bay. It does not address the effects of such reduced flows on sediment or nutrient delivery to the bay.

Table 13. MinQ target inflows (in 1,000 acre-feet) distributed and applied to the three major inflow points of the TxBLEND model to evaluate the effects on freshwater inflows and bay salinity conditions during the period 1980 – 1989. Inflows for the minor six inflow points are based on the observed record as reported in Table 3. Mean inflows by basin and for total bay inflow show that on average inflows met the MinQ recommended target of 4.2 million acre-feet. The inflow ratio shows the geographic distribution of inflows among the nine inflow points for the MinQ inflow scenario. Also, mean MinQ inflows by subbasin and total bay are compared to mean inflows obtained under the *existing condition* period of 1980 – 1989 (as in Table 3).

| | TxBLEND Inflow Points | Trinity River | San Jacinto River | Buffalo Bayou | Clear Creek | Dickinson Bayou | Chocolate Bayou | Double Bayou | Oyster Bayou | Cedar Bayou | Total Inflow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1980 | 1,573 | 458 | 345 | 196 | 164 | 262 | 231 | 482 | 161 | 3,872 |
| | 1981 | 1,573 | 458 | 345 | 363 | 235 | 421 | 321 | 594 | 334 | 4,644 |
| | 1982 | 1,573 | 458 | 345 | 194 | 147 | 231 | 188 | 412 | 165 | 3,713 |
| | 1983 | 1,573 | 458 | 345 | 456 | 316 | 599 | 360 | 745 | 388 | 5,240 |
| | 1984 | 1,573 | 458 | 345 | 210 | 180 | 324 | 93 | 217 | 122 | 3,522 |
| | 1985 | 1,573 | 458 | 345 | 380 | 257 | 477 | 272 | 563 | 273 | 4,598 |
| | 1986 | 1,573 | 458 | 345 | 348 | 197 | 382 | 211 | 431 | 291 | 4,236 |
| | 1987 | 1,573 | 458 | 345 | 337 | 221 | 368 | 220 | 456 | 275 | 4,253 |
| | 1988 | 1,573 | 458 | 345 | 131 | 158 | 177 | 86 | 180 | 64 | 3,172 |
| | 1989 | 1,573 | 458 | 345 | 311 | 220 | 367 | 269 | 548 | 237 | 4,328 |
| Mean Inflow | | 1,573 | 458 | 345 | 293 | 210 | 361 | 225 | 463 | 231 | 4,158 |
| Inflow Ratio | | 0.38 | 0.11 | 0.08 | 0.07 | 0.05 | 0.09 | 0.05 | 0.11 | 0.06 | 1.00 |
| Ratio Min Q to *Existing Condition* Inflows | | 0.27 | 0.33 | 0.24 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.40 |

## Comparison of Model Scenarios for Inflows

Historic inflows over the *full period of record* (1941 – 2005) range from 1.9 million acre-feet to 25.1 million acre-feet, with a mean inflow of 11.3 million acre-feet. An evaluation of mean annual inflow simulated from the two WAM scenarios and the two target inflow recommendations for the 1980 – 1989 study period shows that historically 60 percent of inflows to Galveston Bay have been greater than the mean inflows generated by these scenarios (Figure 7, Table 14), though the individual scenarios differ in their exceedance probabilities. It also is worth noting the difference in mean annual inflow among the various periods of record mentioned throughout this report. Whereas the *full period of record* has an exceedance probability of 51 percent, the *recent period of record* (1977 – 2005), with a mean of 13.1 million acre-feet, has an exceedance probability of 37 percent. Recall that the *recent period* of record was used to determine the relative contribution of inflows from the nine rivers, streams and bayous draining into Galveston Bay, because this was the period for which subwatershed inflow values were available. Overall, inflows during this recent period were considerably higher than the historic record. To avoid the influence of these high inflows, a study period lacking abnormally high inflows was selected for model simulations. This study period or *existing condition* (1980 – 1989) has a mean annual inflow of 10.4 million acre-feet with an exceedance probability of 55 percent.

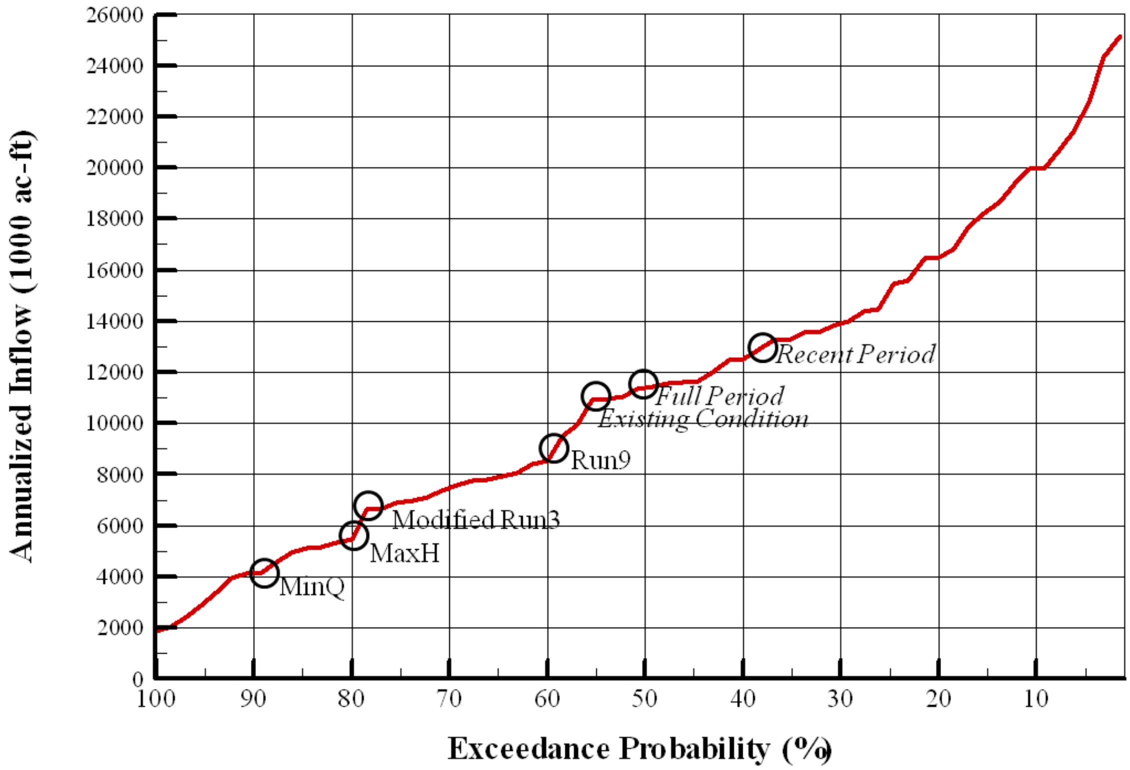



Figure 7. Exceedance probability of annual inflows for Galveston Bay for the period 1941 – 2005 (*blue line*) with mean annual observed and simulated inflows identified (*red circles*), including the *recent period* (1977 – 2005), *full period* of record (1941 – 2005), *existing condition* (1980 - 1989), and for the *WAM Run9*, *modified WAM Run3*, *MaxH*, and *MinQ* simulation period of 1980 - 1989.

Both the WAM and target inflow recommendation scenarios take into account future inflow conditions in which river flows are limited either by increased water demand or the need to achieve management guidelines which accommodate human uses of water. As a result, mean annual inflows from these four scenarios are lower than the observed mean inflows from the various periods of record, including that of the *existing condition*. Mean inflow from WAM Run9, however, most closely approximates the observed mean inflow for the *existing condition*, with a mean inflow of 9.1 million acre-feet and an exceedance probability of 58 percent. All other scenarios had much lower mean annual inflow and much higher probabilities of exceedance. Mean annual inflow under a Modified WAM Run3 was 6.4 million acre-feet corresponding to a 78$^{th}$ percentile exceedance probability, and annual inflow for MaxH and MinQ target inflows were 5.2 million acre-feet (80$^{th}$ percentile level) and 4.2 million acre-feet (87$^{th}$ percentile level), respectively.

Table 14. Exceedance probability and rank (from highest to lowest) for total annual inflow (1,000 acre-feet) to Galveston Bay, 1941 – 2005. These values are the same as those presented in Table 1 only exceedance probability is included here along with the relative position of observed mean (full period of record (1941 – 2005), recent period of record (1977 – 2005), and *existing condition* (1980 – 1989)) and simulated mean (modified WAM Run3, WAM Run9, MaxH, and MinQ) inflows to Galveston Bay.

| Year | Inflow | Rank | % Exceedance |
|---|---|---|---|
| 1956 | 1,871 | 65 | 100.0 |
| 1954 | 2,047 | 64 | 98.5 |
| 1951 | 2,419 | 63 | 96.9 |
| 1963 | 2,860 | 62 | 95.4 |
| 1967 | 3,410 | 61 | 93.8 |
| 1988 | 3,955 | 60 | 92.3 |
| 1955 | 4,114 | 59 | 90.8 |
| 1971 | 4,162 | 58 | 89.2 |
| | *4,258* | *MinQ Mean Inflow* | |
| 1964 | 4,562 | 57 | 87.7 |
| 1978 | 4,958 | 56 | 86.2 |
| 1952 | 5,133 | 55 | 84.6 |
| 1996 | 5,157 | 54 | 83.1 |
| 1962 | 5,344 | 53 | 81.5 |
| | *5,215* | *MaxH Mean Inflow* | |
| 1948 | 5,454 | 52 | 80.0 |
| | *6,375* | *Modified Run3 Mean Inflow* | |
| 1965 | 6,630 | 51 | 78.5 |
| 1976 | 6,660 | 50 | 76.9 |
| 1972 | 6,898 | 49 | 75.4 |
| 2000 | 6,973 | 48 | 73.8 |
| 1999 | 7,113 | 47 | 72.3 |
| 1970 | 7,362 | 46 | 70.8 |
| 1953 | 7,608 | 45 | 69.2 |
| 1943 | 7,764 | 44 | 67.7 |
| 1984 | 7,795 | 43 | 66.2 |
| 1980 | 7,937 | 42 | 64.6 |
| 2005 | 8,059 | 41 | 63.1 |
| 1947 | 8,414 | 40 | 61.5 |
| 1977 | 8,522 | 39 | 60.0 |
| | *9,133* | *Run9 Mean Inflow* | |
| 1958 | 9,484 | 38 | 58.5 |
| 1987 | 9,988 | 37 | 56.9 |
| | *10,430* | *Existing Condition Mean Inflow* | |
| 1950 | 10,905 | 36 | 55.4 |
| 1982 | 10,947 | 35 | 53.8 |
| 1959 | 11,061 | 34 | 52.3 |
| | *11,267* | *Full Period Mean Inflow* | |
| 1969 | 11,375 | 33 | 50.8 |
| 1960 | 11,418 | 32 | 49.2 |
| 1975 | 11,565 | 31 | 47.7 |
| 1966 | 11,593 | 30 | 46.2 |
| 2003 | 11,666 | 29 | 44.6 |
| 1981 | 11,989 | 28 | 43.1 |
| 1985 | 12,492 | 27 | 41.5 |
| 1989 | 12,530 | 26 | 40.0 |
| 1949 | 12,870 | 25 | 38.5 |
| | *13,128* | *Recent Period Mean Inflow* | |
| 1983 | 13,248 | 24 | 36.9 |
| 1986 | 13,277 | 23 | 35.4 |
| 1974 | 13,560 | 22 | 33.8 |
| 1942 | 13,571 | 21 | 32.3 |
| 1961 | 13,820 | 20 | 30.8 |
| 1968 | 13,973 | 19 | 29.2 |
| 1990 | 14,394 | 18 | 27.7 |
| 1944 | 14,453 | 17 | 26.2 |
| 1995 | 15,484 | 16 | 24.6 |
| 2002 | 15,610 | 15 | 23.1 |
| 1994 | 16,463 | 14 | 21.5 |
| 2004 | 16,487 | 13 | 20.0 |
| 1997 | 16,812 | 12 | 18.5 |
| 1957 | 17,709 | 11 | 16.9 |
| 1998 | 18,224 | 10 | 15.4 |
| 1979 | 18,671 | 9 | 13.8 |
| 1941 | 19,378 | 8 | 12.3 |
| 1993 | 19,952 | 7 | 10.8 |
| 1945 | 19,973 | 6 | 9.2 |
| 1946 | 20,702 | 5 | 7.7 |
| 1973 | 21,455 | 4 | 6.2 |
| 1991 | 22,599 | 3 | 4.6 |
| 2001 | 24,325 | 2 | 3.1 |
| 1992 | 25,148 | 1 | 1.5 |

*WAM Inflow Scenarios and the Big Three Rivers*

During the *recent period* of record (1977 – 2005) and also for the shortened *existing condition* study period (1980 – 1989), the Trinity River, San Jacinto River, and Buffalo Bayou together contributed 83 percent of annual surface inflow to Galveston Bay (Table 3). However, under a modified WAM Run3 scenario with full utilization of water rights, the combined contribution decreases to 76 percent, primarily due to reduced flows in the Trinity River (Table 11). This reduction is not as great under a WAM Run9 scenario, where the combined inflow is 82 percent of total bay inflow (Table 9) and also similar to the observed record.

Examination of daily inflow exceedance probability curves generated for the Trinity River and for the San Jacinto River (plus Buffalo Bayou) reveals that patterns of inflow differ between the two basins depending on the WAM scenario. In the Trinity River, inflow reduction is more pronounced in the lower range of flows (<1,000 cfs; Figure 8) under both scenarios, but more so under a modified Run3 where inflows remain depressed below 100 cfs. In the *existing condition*, flows are rarely less than 100 cfs (99 percent exceedance), but under a modified Run3 this level of inflow has an exceedance probability of 63 percent. Similarly, under the *existing condition* 1,000 cfs has an exceedance probability of 80 percent, but a 45 percent probability under a modified Run3. This large reduction of flows from the Trinity River is a contributing factor for the simulated increase in salinity in the upper estuary and Trinity Bay, as presented in the next section. Interestingly under a WAM Run 9 scenario, mid-range to high inflows are conserved as compared to the *existing condition*, but a different pattern occurs in the San Jacinto River/ Buffalo Bayou system.

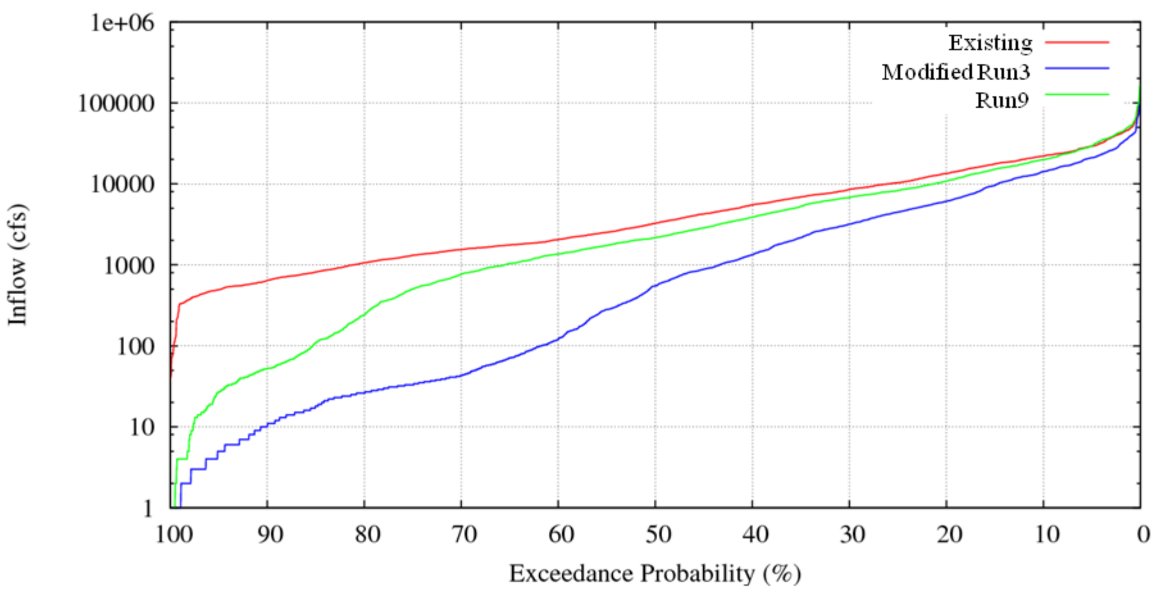



Figure 8. Exceedance probability of daily inflows (cfs) from the Trinity River under *existing condition* (*red*), modified WAM Run3 (*blue*), and WAM Run9 (*green*) inflows for the ten-year period 1980 – 1989.

The San Jacinto River plus Buffalo Bayou exceedance probability curve shows that daily inflows are somewhat uniformly reduced across all levels of inflow in the modified Run3 and Run9 scenarios as compared to the *existing condition* (Figure 9). However, similar to the changes noted for the Trinity River under a modified WAM Run3 scenario, inflows from the San Jacinto/Buffalo Bayou are reduced more relative to the Run9 scenario and particularly so for lower flow values where minimum daily inflows decrease greatly. It is important to note that the minimum daily inflow of about 600 cfs has a 100 percent exceedance probability in the *existing condition* (Figure 9, *red line*), but under the two WAM scenarios this level of daily inflow has an exceedance probability between 50 and 36 percent depending on the scenario. Focusing on the *existing condition* median daily inflow value of 1,000 cfs, this value not only decreases but the exceedance probability shifts from 50 percent (in the *existing condition*) to between 25 and 30 percent under future inflow scenarios. In contrast, high inflow events are relatively unchanged between the scenarios.

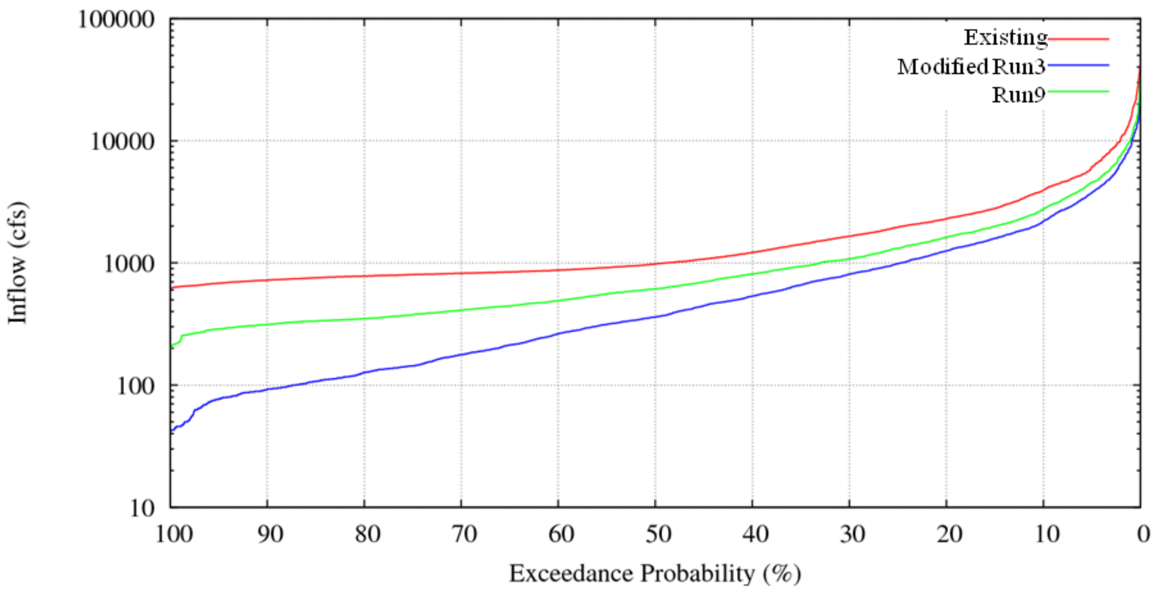



Figure 9. Exceedance probability of daily inflows (cfs) from the San Jacinto River (including Buffalo Bayou) under *existing condition* (*red*), modified WAM Run3 (*blue*), and WAM Run9 (*green*) inflows for a ten-year period, 1980 – 1989.

*Target Inflow Scenarios and the Big Three Rivers*

As noted above the Trinity River, San Jacinto River, and Buffalo Bayou together contribute 83 percent of annual surface inflow to Galveston Bay (Table 3). However, under the target inflow scenarios, the combined contribution decreases to 67 percent and 57 percent for the MaxH and MinQ scenarios, respectively (Tables 12 and 13). Exceedance probability curves for daily inflow show changes in the pattern of freshwater inflow between the two target inflow scenarios. For both the Trinity River and the San Jacinto River plus Buffalo Bayou, the frequency of all levels of daily inflow is reduced in comparison to the *existing condition* (Figures 10 and 11), though the pattern is stronger in the San Jacinto/Buffalo Bayou system. In the Trinity River, flows are rarely less than 500 cfs and never below 50 cfs under the *existing condition*. However as implemented in the target inflow scenarios, daily inflow rates less than 500 cfs may occur as much as 8 percent of the time and inflows less than 50 cfs appear some of the time (Figure 10). Generally, the frequency of occurrence of flows less than 1,000 cfs increases about 15 percent under the target inflow scenarios, while flows greater than 10,000 cfs decrease by about 20 percent – as compared to the *existing condition*.

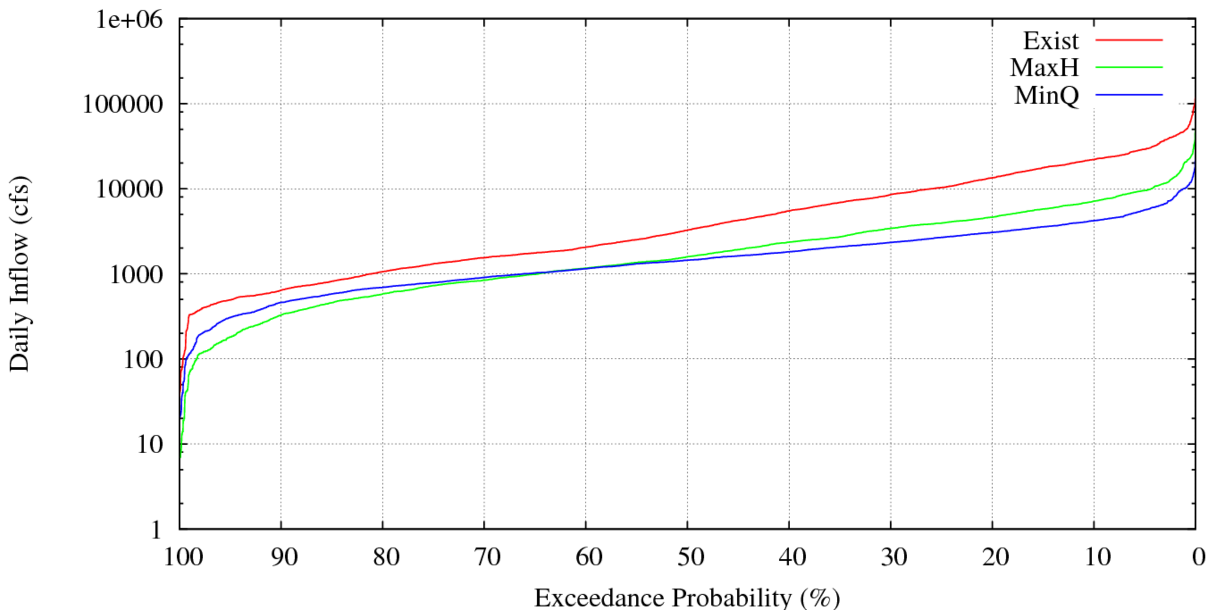



Figure 10. Exceedance probability of daily inflows (cfs) from the Trinity River under *existing condition* (*red*), MaxH (*green*), and MinQ (*blue*) inflows for a ten-year period, 1980 – 1989.

A comparison between the two target inflow scenarios shows that the frequency of occurrence of daily inflows less than 1,000 cfs (*i.e.*, low flows) increases under a MaxH target inflow scenario, relative to the MinQ scenario (Figure 10). This pattern switches for flows above 1,000 cfs, such that the frequency of occurrence of "high flows" is greater under a MaxH scenario. The reduced occurrence of very high inflows is a direct result of the strict application of the target inflow recommendations which do not include opportunities for high flow pulses to enter the bay. Generally though, the exceedance probability curves show that the MaxH scenario increases the frequency of low flow events, and the MinQ scenario decreases the frequency of high inflow events, relative to each other. A similar pattern exists for the San Jacinto/Buffalo Bayou system, but the transition occurs at a lower inflow value (~300 cfs; Figure 11, *intersection of blue and green lines*).

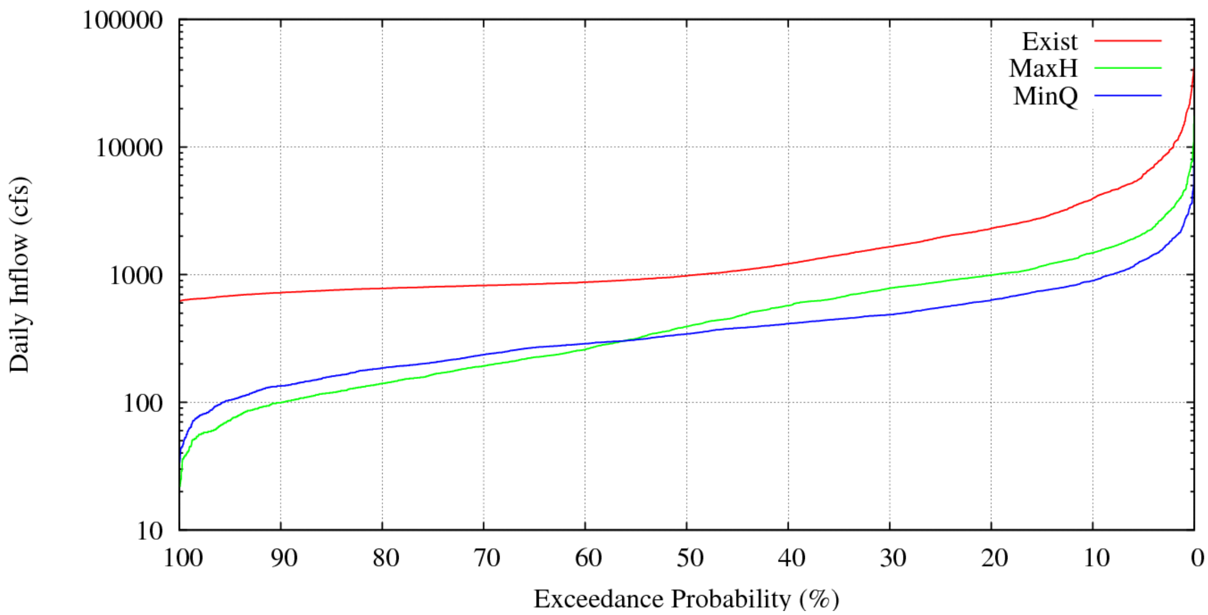



Figure 11. Exceedance probability of daily inflows (cfs) from the San Jacinto River (including Buffalo Bayou) under *existing condition* (*red*), MaxH (*green*), and MinQ (*blue*) inflows for a ten-year period, 1980 – 1989.

## Evaluation of Salinity Effects

*Evaluation of WAM Inflow Scenarios*

Salinity was evaluated at four locations (Figure 4, Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads) for a ten-year period for the five model scenarios considered in this study. Here, salinities simulated from the *existing condition* scenario are compared to salinities simulated from inflows estimated by two WAM models. At all sites, from Trinity Bay in the upper estuary to the pass at Bolivar Roads, salinity levels were higher under the WAM scenarios as compared to the *existing condition* (Figures 12 – 15), with modified WAM Run3 inflows having a greater effect on salinity than those of WAM Run9. Modified Run3 inflows raise the median salinity value by about 1.5 ppt in the lower bay, 3 ppt at mid-bay and 4 ppt in Trinity Bay. WAM Run9 raises median salinity by about 1 ppt in the lower bay and by 1.4 ppt in mid- and upper bay (Table 15). Under both scenarios, the effect of reduced inflows is most pronounced in the upper estuary where salinity increases the most. Another effect of reduced inflow is shown in Figure 16. This comparison of bay salinity, simulated for the month of February 1988, shows that under the *existing condition* salinity throughout much of the bay ranges from 14 – 22 ppt. However, under a modified Run3, salinity values increase (ranging 20 – 26 ppt) and overall spatial variability decreases.

Table 15. Median daily salinity (ppt) and the difference in salinity between the *existing condition* and WAM Run9 and modified WAM Run3.

| Site | Simulated Median Daily Salinity (ppt.) | | | Difference in ppt. \|*Existing* – WAM scenario\| | |
|---|---|---|---|---|---|
| | *Existing* | Run9 | Run3 | Run9 | Run3 |
| Trinity Bay | 12.3 | 13.7 | 16.5 | 1.4 | 4.2 |
| Red Bluff | 15.0 | 16.4 | 18.6 | 1.4 | 3.6 |
| Dollar Point | 18.7 | 19.9 | 21.6 | 1.2 | 2.9 |
| Bolivar Roads | 23.9 | 24.7 | 25.6 | 0.8 | 1.7 |

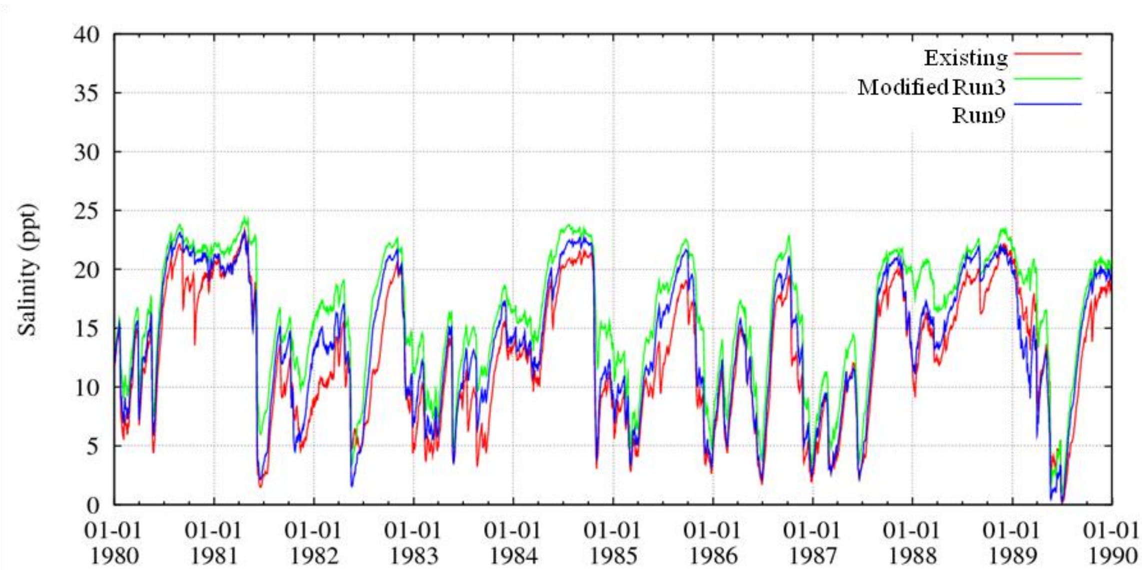



Figure 12. Simulated daily salinity in Trinity Bay under observed inflows for the *existing condition* (*red*) and for simulated inflows from modified WAM Run3 (*green*) and WAM Run9 (*blue*) for the period 1980 – 1989.

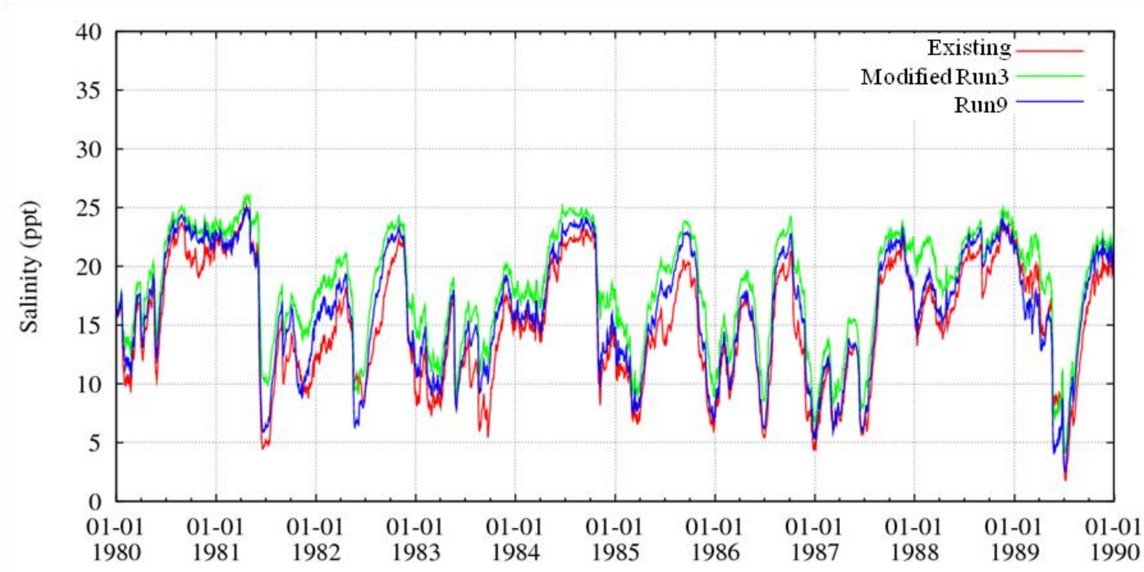



Figure 13. Simulated daily salinity near Red Bluff under observed inflows for the *existing condition* (*red*) and for simulated inflows from modified WAM Run3 (*green*) and WAM Run9 (*blue*) for the period 1980 – 1989.

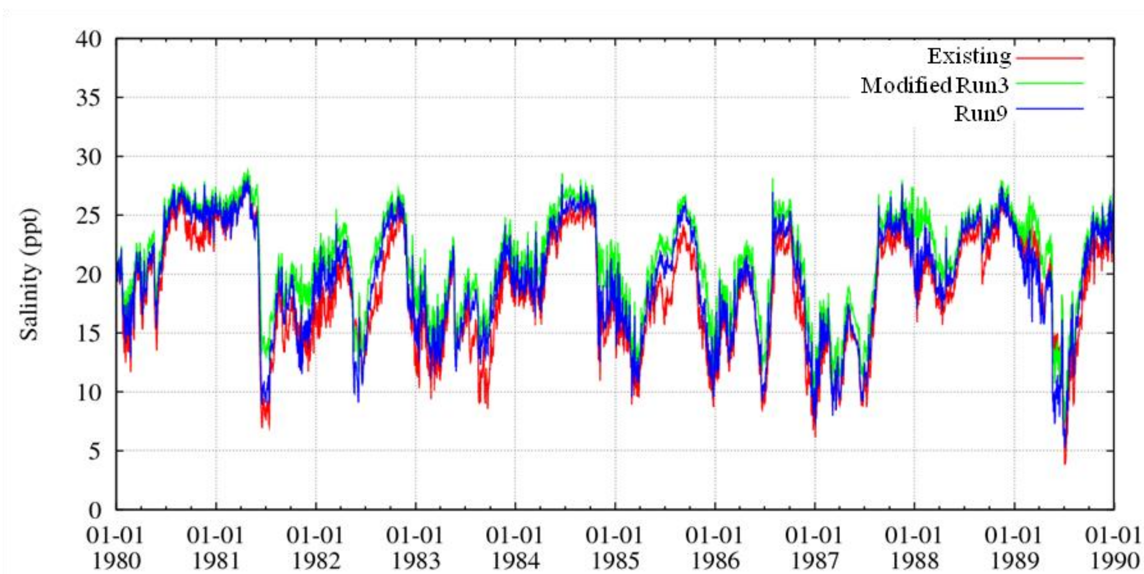



Figure 14. Simulated daily salinity near Dollar Point under observed inflows for the *existing condition* (*red*) and for simulated inflows from modified WAM Run3 (*green*) and WAM Run9 (*blue*) for the period 1980 – 1989.

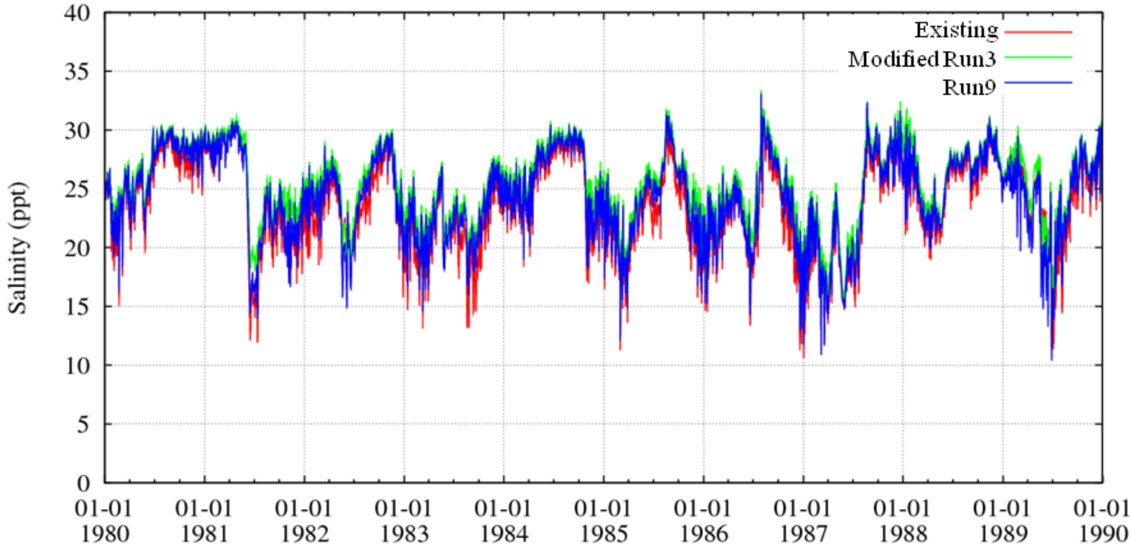



Figure 15. Simulated daily salinity at Bolivar Roads under observed inflows for the *existing condition* (*red*) and for simulated inflows from modified WAM Run3 (*green*) and WAM Run9 (*blue*) for the period 1980 – 1989.

In order to better quantify the effects of the WAM scenarios, daily simulated salinities at each reference location were assigned exceedance probabilities (Figures 17 – 20). These curves are similar to those shown previously for inflows, but instead represent computed salinity for different freshwater inflow scenarios. In the Texas Parks and Wildlife Department's freshwater inflow recommendations report for the Galveston Bay estuary, salinity ranging between 10 – 20 ppt is recognized as being important for maintaining key estuarine species throughout much of the estuary (Lee *et al*. 2001). However, under future expected inflow conditions, the frequency of occurrence of this ideal range of salinity changes at all locations and decreases for mid- and lower bay locations. Table 16 shows a change in the range of exceedance probabilities for the desired 10 – 20 ppt salinity zone at each location.

Under the *existing condition*, Trinity Bay is most often between 10 – 20 ppt. Less than 10 percent of salinity events are higher than 20 ppt, and 35 percent of salinity events are less than 10 ppt (Figure 17). However, under the WAM scenarios, the frequency of higher salinity events (those greater than 20 ppt) increases as a result of reduced freshwater inflows. Also while approximately 55 percent of events remain in the preferred 10 – 20 ppt salinity range regardless of the future inflow scenario, fewer low salinity (< 10 ppt) events occur. This reduction in the occurrence of low salinity events, from 35 percent to 15 percent, could be problematic for Trinity Bay as some species benefit from having very low salinity conditions at least some of the time (*e.g*., La Peyre *et al*. 2009, Posey *et al*. 2005, Sklar and Browder 1998).

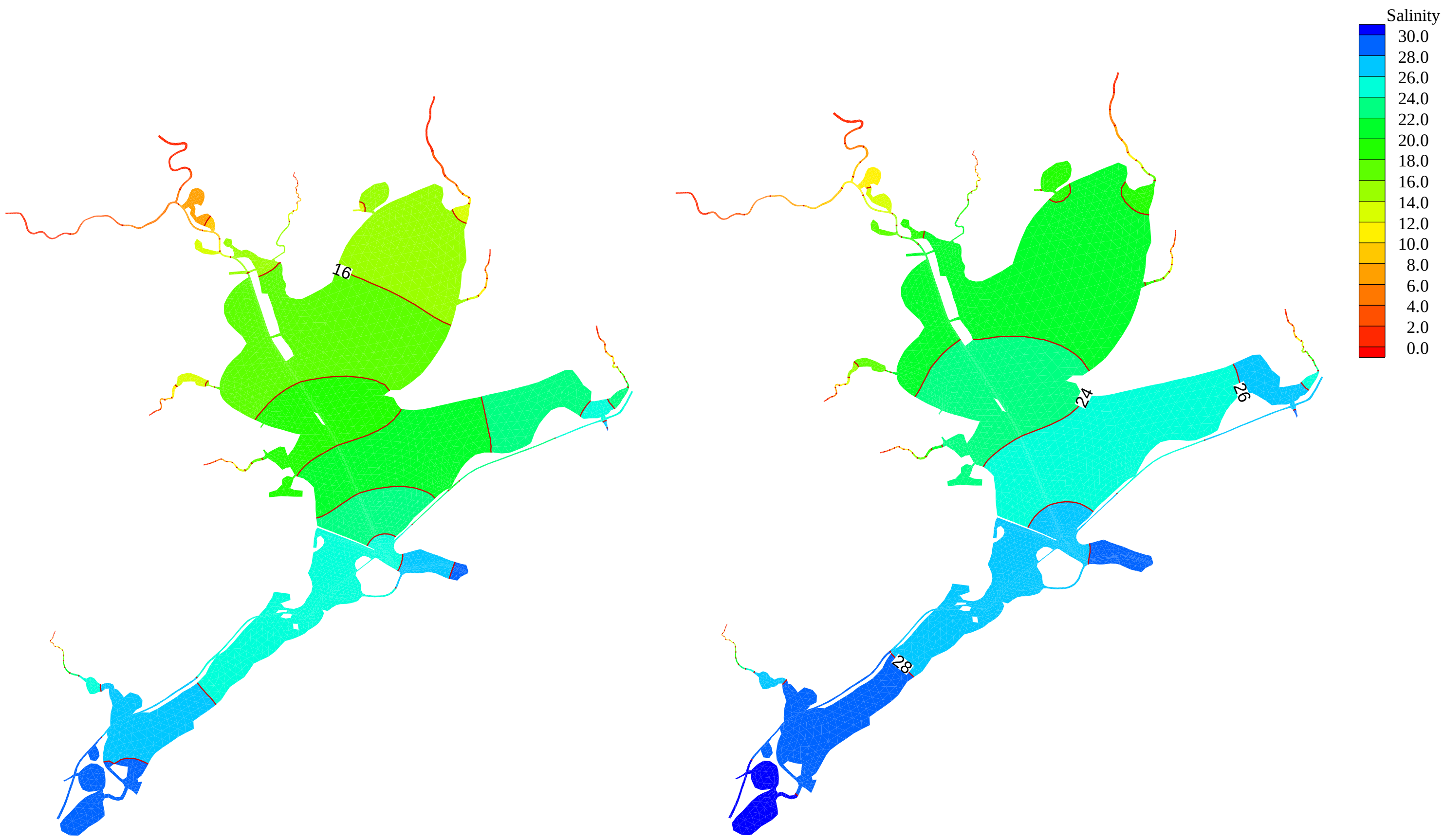



Figure 16. Simulated average monthly salinity for February 1988 under observed inflows for the *existing condition* (*left*) and under a modified WAM Run3 scenario (*right*).

A similar trend is seen at the other bay locations, though the impact of WAM inflows on salinity condition is most pronounced in Trinity Bay and at the mid-bay location of Red Bluff, where even though salinity continues to range between 0 – 25 ppt, reduced inflows decrease the occurrence of low salinity events (those less than 10 ppt). At the Dollar Point and Bolivar Roads locations, salinity rarely or never is less than 10 ppt under *existing conditions*, but can range above 25 ppt. However, as inflows decrease under the WAM scenarios, the number of high salinity events ($\geq$ 25 ppt) increases from 6 percent to 25 percent at Dollar Point and from 41 percent to 55 percent at Bolivar Roads (Figures 19 – 20).

Table 16. Exceedance probabilities for the desired 10 – 20 ppt salinity zone under *existing conditions*, WAM Run9, and modified WAM Run3.

| | Exceedance Probability (%) for a Salinity Occurrence from 10 – 20 ppt. | | |
|---|---|---|---|
| Location | *Existing Conditions* | Run9 | Modified Run3 |
| Trinity Bay | 65 – 10 | 74 – 20 | 85 – 31 |
| Red Bluff | 83 – 24 | 87 – 31 | 95 – 42 |
| Dollar Point | 96 – 42 | 97 – 51 | 99 – 65 |
| Bolivar Roads | 100 – 83 | 100 – 87 | 100 – 92 |

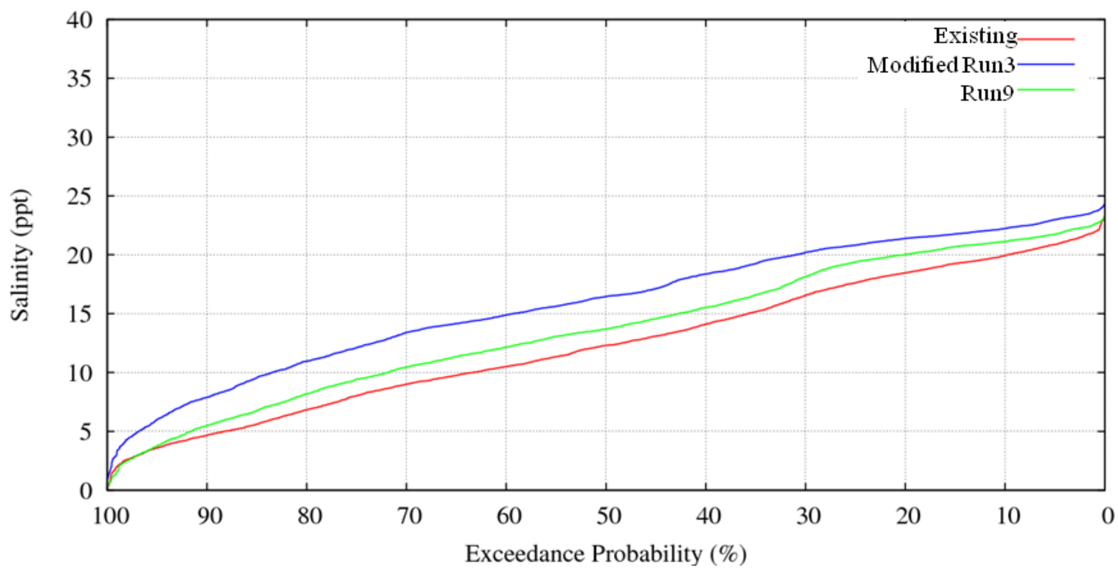



Figure 17. Exceedance probability of simulated daily salinity in Trinity Bay under *existing conditions*, modified WAM Run3, and WAM Run9 inflows for a ten-year period 1980 – 1989.

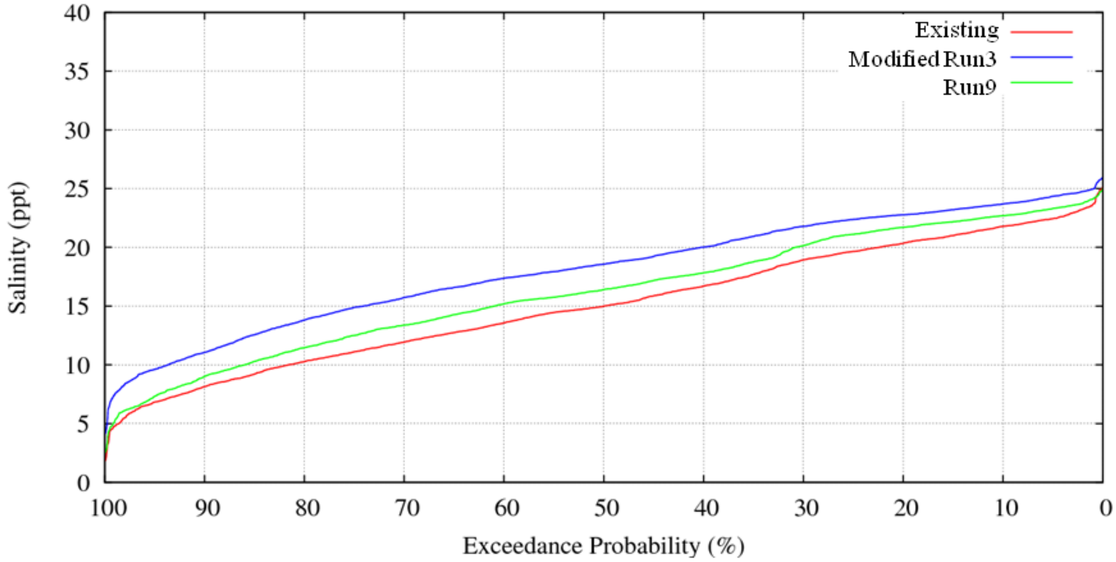



Figure 18. Exceedance probability of simulated daily salinity at Red Bluff under *existing conditions*, modified WAM Run3, and WAM Run9 inflows for a ten-year period 1980 – 1989.

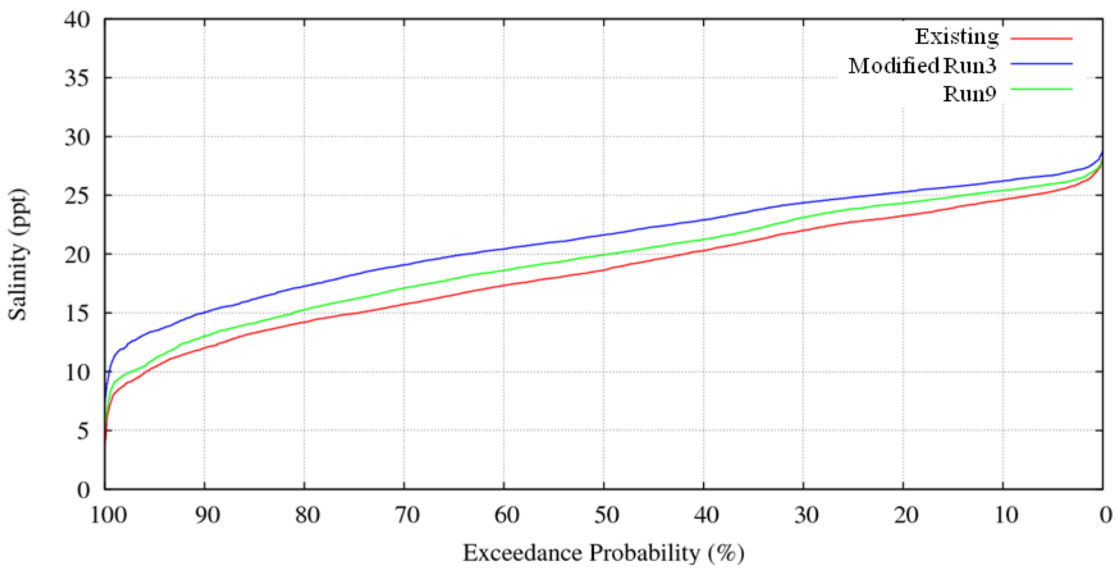



Figure 19. Exceedance probability of simulated daily salinity at Dollar Point under *existing conditions*, modified WAM Run3, and WAM Run9 inflows for a ten-year period 1980 – 1989.

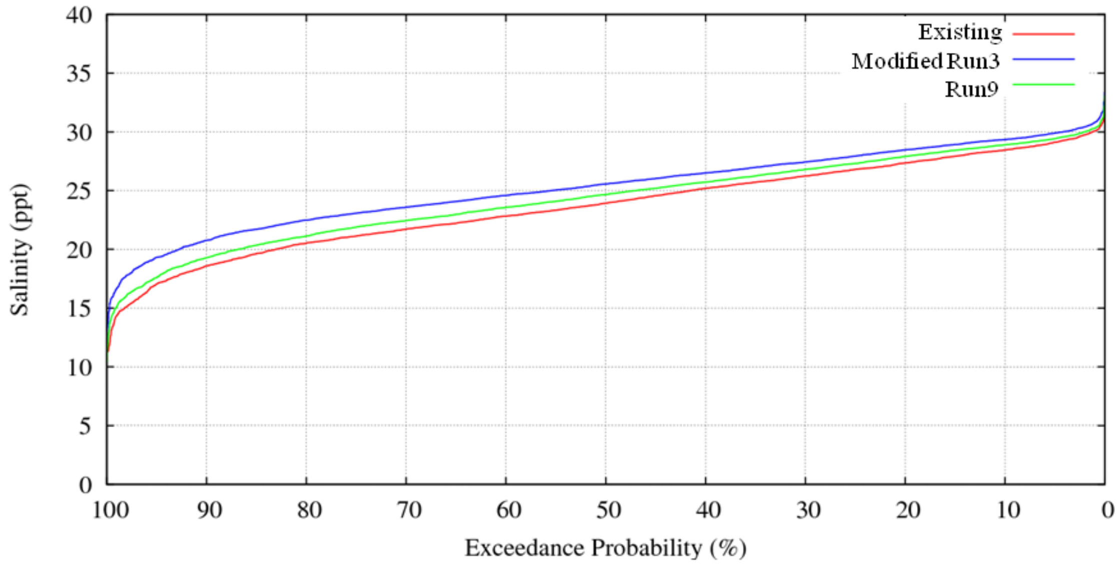



Figure 20. Exceedance probability of simulated daily salinity at Bolivar Roads under *existing conditions*, modified WAM Run3, and WAM Run9 inflows for a ten-year period 1980 – 1989

*Evaluation of Target Inflow Scenarios*

Salinities simulated from the *existing condition* scenario also were compared to salinities generated for the MaxH and MinQ target inflow scenarios (Figures 21 – 24). However when comparing target inflows such as MaxH and MinQ, a few points must be considered. First, the target inflows are given as monthly targets for a representative single year period. In this study, the monthly target inflows were exactly repeated year-after-year for the three major contributing rivers (Trinity, San Jacinto, and Buffalo Bayou). However, since these inflows are designed to be met as targets, they are not expected to occur with such regularity in reality. Targets may be met some of the time and not at other times. While it is desirable to conduct a detailed system's operational simulation over a long period of time to predict likely outcomes, this was not possible for this study. Thus, we examined the target inflows as recommended, without operational consideration. This consistent repetition year-after-year is unrealistic, because, for example, large flooding inflows which could not now be controlled still were excluded from simulation.

Second, without large inflow events, annual volumes for the target inflows are rather low, occurring at about the 80 percent exceedance probability of historical inflows (Figure 7). Model simulations demonstrated that this smaller volume of inflow, as compared to the *existing condition*, resulted in increased salinity throughout the estuary, except during relatively dry periods (*e.g.*, early 1981, mid 1984, and late 1988; Figure 21) when the target inflow volumes exceeded measured inflows. Despite the fact that the monthly target inflows are repeated year after year for the major contributing rivers (Trinity, San Jacinto, and Buffalo Bayou), simulated salinities under MaxH and MinQ inflows do not show repeated salinity patterns, because the daily inflows for the major rivers varied in a pattern consistent with the pattern of the observed record, daily inflows for coastal streams varied based on amounts in the observed record, the salinity boundary condition imposed at the Gulf boundary varied with time based on observed offshore salinity values, and evaporation and precipitation varied with time.

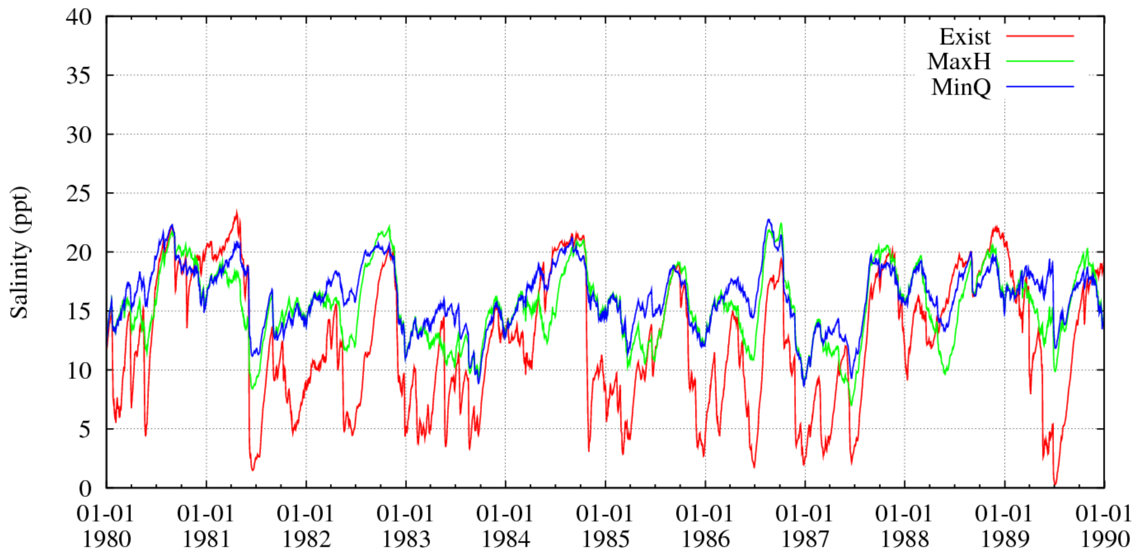



Figure 21. Simulated daily salinity in Trinity Bay under *existing conditions*, MaxH, and MinQ inflows for the ten-year period 1980 – 1989.

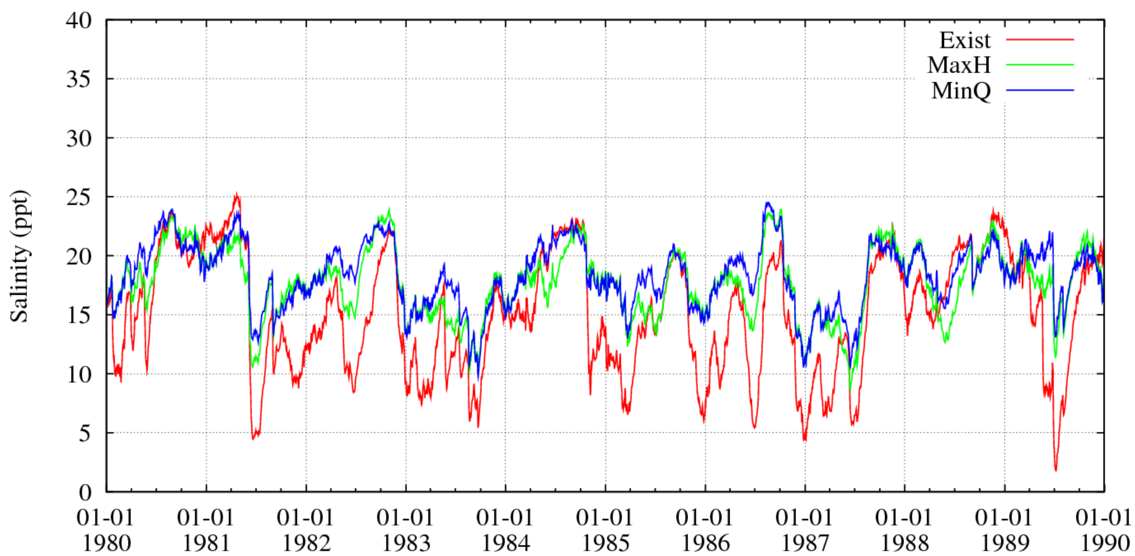



Figure 22. Simulated daily salinity at Red Bluff under *existing conditions*, MaxH, and MinQ inflows for the ten-year period 1980 – 1989.

The target inflow scenarios exhibit a similar pattern of change in salinity as that observed under the WAM inflow scenarios. At all sites, salinity levels were elevated as compared to the *existing condition*, with the effect being most pronounced in the upper and mid-estuary sites. At the Trinity Bay and Red Bluff sites, *existing condition* inflows frequently result in salinity conditions less than 10 ppt, but such low salinities rarely occur under the target inflow scenarios (Figures 21 and 22). MinQ inflows have a slightly greater impact on salinity than MaxH inflows; yet neither inflow scenario substantially increases the maximum salinity observed at each site (Figures 21 – 24). However, at Dollar Point, the target inflow scenarios result in elevated salinity conditions which frequently exceed the preferred 10 – 20 ppt range recognized by TPWD as being important for fisheries species (Figure 23; Lee *et al*. 2001). This range is almost entirely exceeded at Bolivar Roads under the target inflow scenarios (Figure 24).

Table 17 summarizes median daily salinity as simulated by TxBLEND under *existing condition* inflows and under the MaxH and MinQ target inflow recommendations. In the upper bay, median salinity increases approximately 3.0 to 4.0 ppt under the target inflow scenarios. This increase likely is due to the exclusion of high inflow events, which are not part of the target inflow recommendations. In the lower bay, median salinity increases by 1.0 to 3.0 ppt as a result of the increased frequency of higher salinity values (those greater than 20 ppt).

Table 17. Median daily salinity (ppt) and the difference in salinity between MaxH and MinQ target inflow recommendations with the *existing condition*.

| Site | Simulated Median Daily Salinity (ppt.) | | | Difference in ppt. \|*Existing* – Target scenario\| | |
|---|---|---|---|---|---|
| | *Existing* | MaxH | MinQ | MaxH | MinQ |
| Trinity Bay | 12.3 | 15.3 | 16.2 | 3.0 | 3.9 |
| Red Bluff | 15.0 | 17.8 | 18.4 | 2.8 | 3.4 |
| Dollar Point | 18.7 | 20.9 | 21.5 | 2.2 | 2.8 |
| Bolivar Roads | 23.9 | 25.2 | 25.5 | 1.3 | 1.6 |

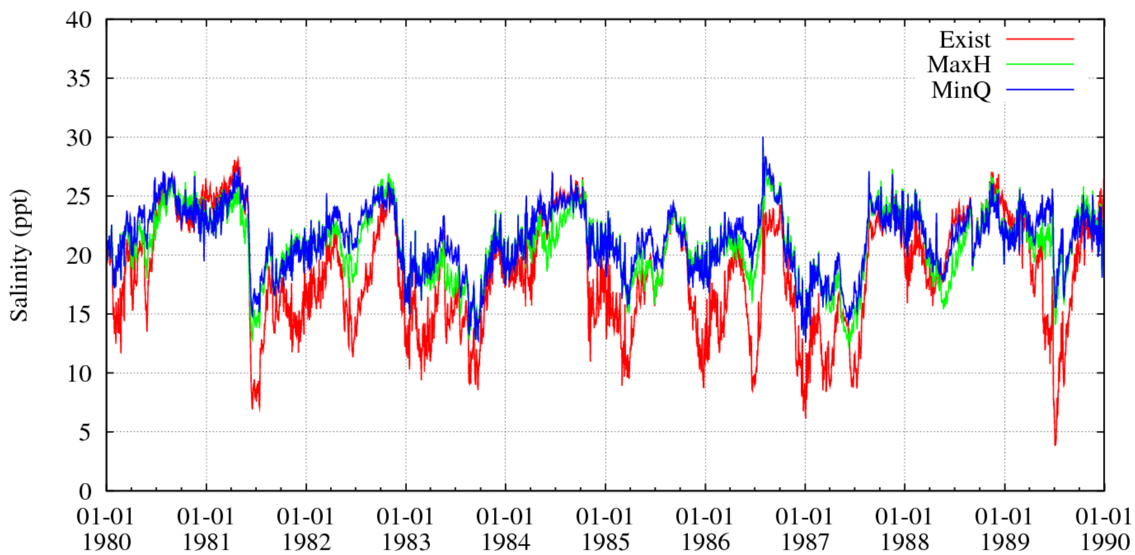



Figure 23. Simulated daily salinity at Dollar Point under *existing conditions*, MaxH, and MinQ inflows for the ten-year period 1980 – 1989.

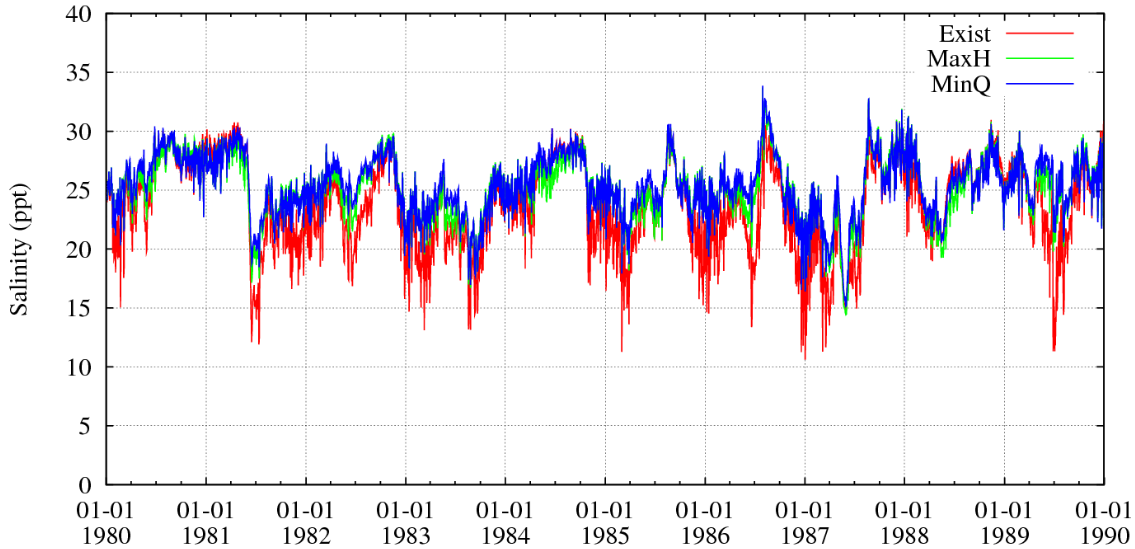



Figure 24. Simulated daily salinity at Bolivar Roads under *existing conditions*, MaxH, and MinQ inflows for the ten-year period 1980 – 1989.

To better quantify salinity changes among the scenarios, particularly within the desired 10 – 20 ppt salinity range, exceedance probability plots were calculated for daily salinity at each reference location (Figures 25 – 28). This evaluation shows that the target freshwater inflows for MaxH and MinQ – *as applied in this analysis* – result in considerable change to the frequency of occurrence of salinity events in Trinity Bay and at Red Bluff. The most notable change is an increase to the number of events occurring in the 10 – 20 ppt range, which occur at the expense of lower salinity events which are virtually eliminated under the target inflow scenarios (Table 18, Figures 25 and 26). For example in Trinity Bay under *existing conditions*, 55 percent of salinity events range between 10 – 20 ppt, with lower salinity events occurring 35 percent of the time (Figure 25, Table 18). However, under the target inflow recommendations, salinity variation decreases such that nearly 90 percent of salinity events now fall within the 10 – 20 ppt range. This drastic reduction in low salinity events is likely an artifact of the strict application of the freshwater inflow target recommendations and the exclusion of high inflow events. This trend, however, reverses at lower bay locations (*e.g.*, Dollar Point and Bolivar Roads) where salinity rarely is less than 10 ppt, even under *existing conditions*. At these locations, the target inflow scenarios increase the number of salinity events above 20 ppt and reduce the number of events occurring in the desired 10 – 20 ppt range (Figures 27 and 28, Table 18).

Table 18. Exceedance probabilities for the desired 10 – 20 ppt salinity zone under *existing conditions*, MaxH, and MinQ inflows.

| | Exceedance Probabilities (%) for a Salinity Range from 10 – 20 ppt. | | |
|---|---|---|---|
| Location | Existing Conditions | MaxH | MinQ |
| Trinity Bay | 65 – 10 | 97 – 10 | 99 – 10 |
| Red Bluff | 83 – 24 | 100 – 25 | 100 – 33 |
| Dollar Point | 96 – 42 | 100 – 64 | 100 – 70 |
| Bolivar Roads | 100 – 83 | 100 – 96 | 100 – 97 |

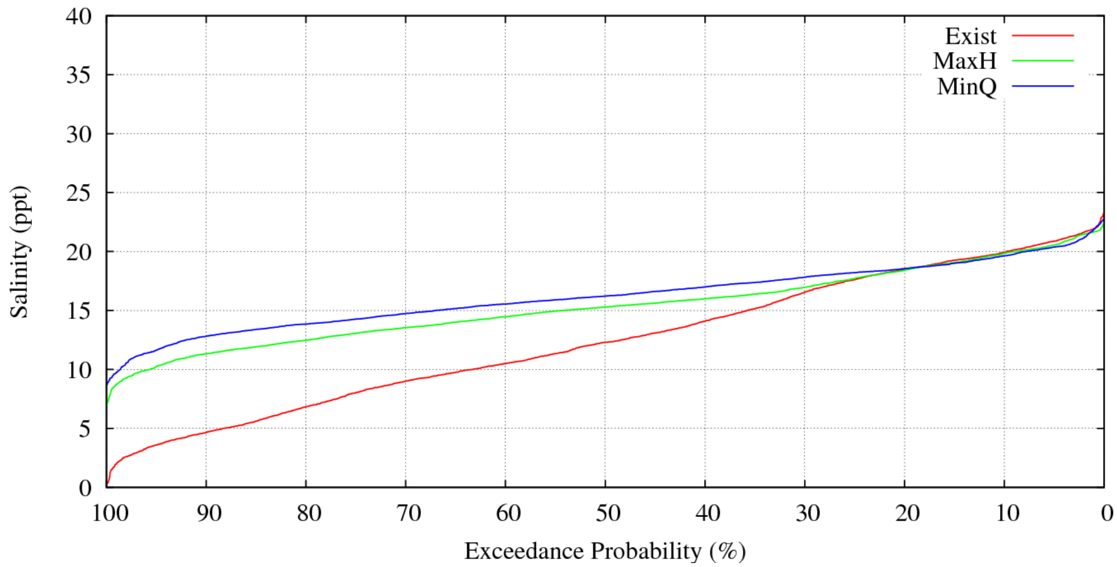



Figure 25. Exceedance probability of simulated daily salinity in Trinity Bay under *existing conditions*, MaxH and MinQ inflows for a ten-year period 1980 – 1989.

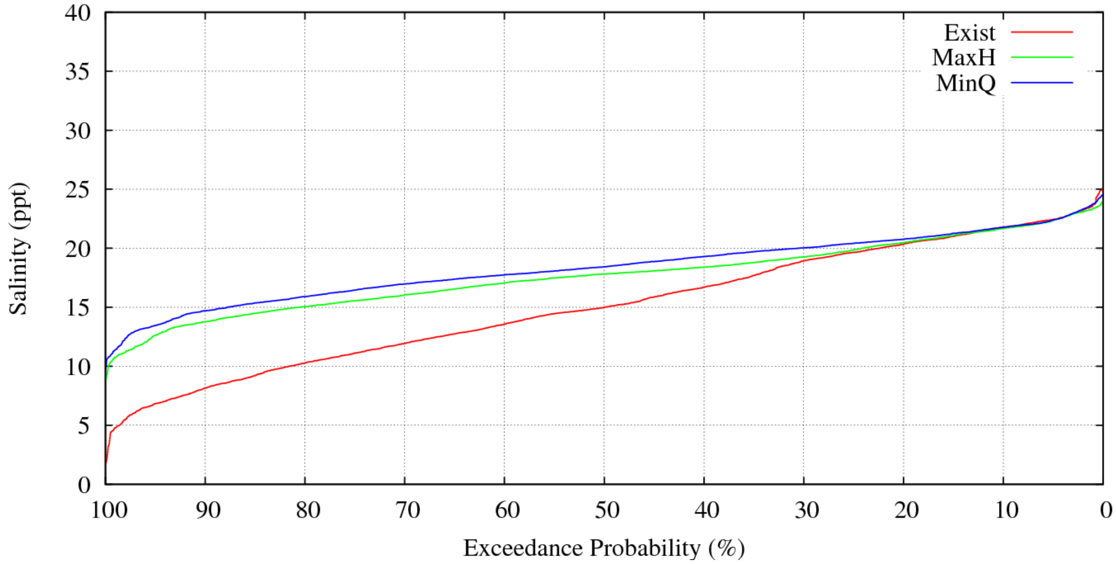



Figure 26. Exceedance probability of simulated daily salinity at Red Bluff under *existing conditions*, MaxH and MinQ inflows for a ten-year period 1980 – 1989.

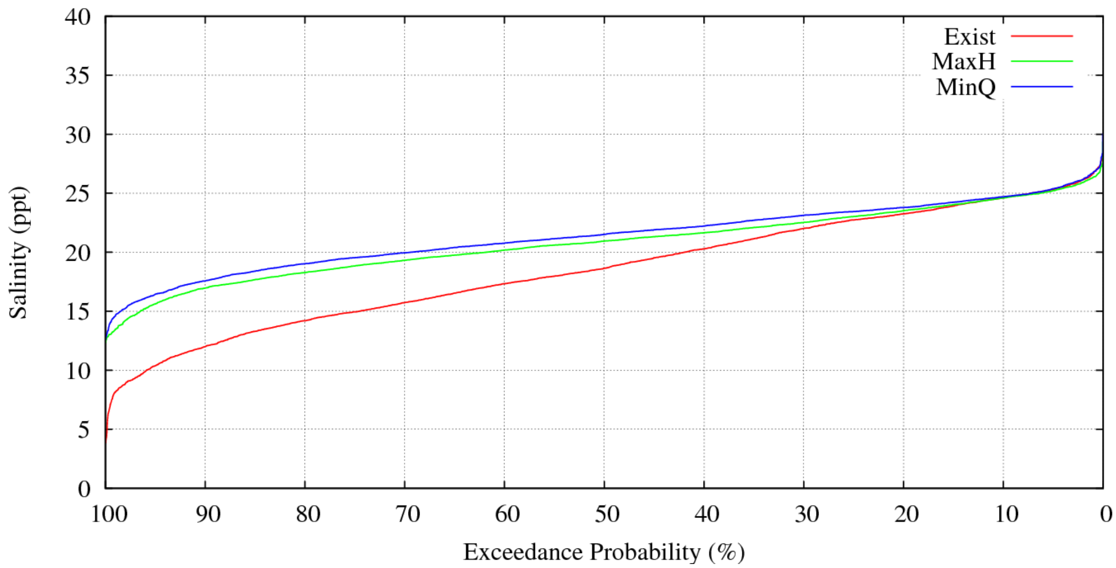



Figure 27. Exceedance probability of simulated daily salinity at Dollar Point under *existing conditions*, MaxH and MinQ inflows for a ten-year period 1980 – 1989.

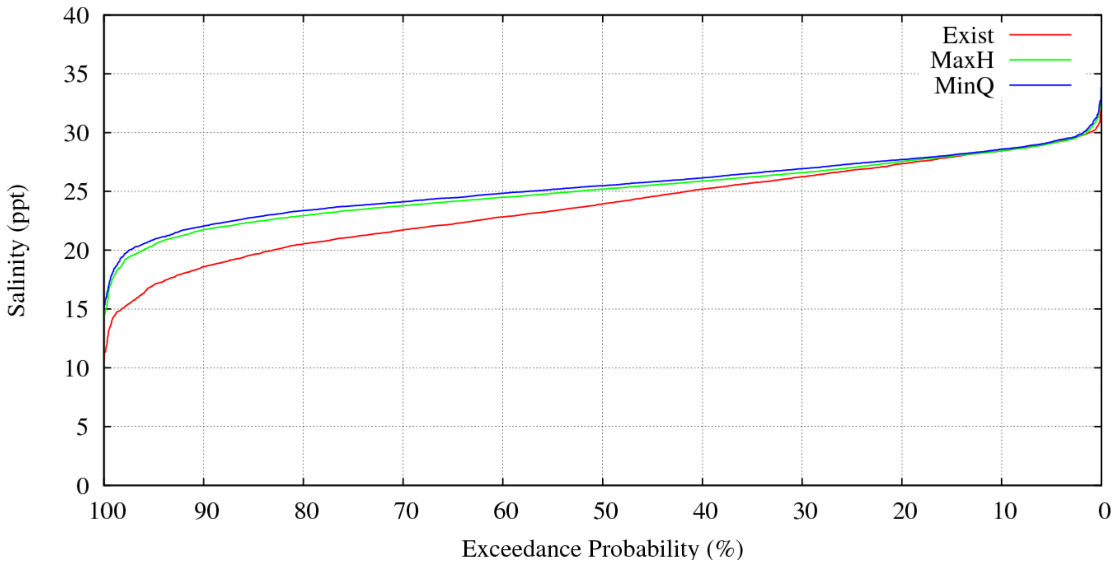



Figure 28. Exceedance probability of simulated daily salinity at Bolivar Roads under *existing conditions*, MaxH and MinQ inflows for a ten-year period 1980 – 1989.

## DISCUSSION

This modeling study investigated the influence of future freshwater inflow scenarios on flow volume and resulting salinity conditions within the Galveston Bay estuary. Three categories of scenarios were considered and compared: (1) the influence of water plan strategies in the Trinity River Basin for the year 2060; (2) the influence of the Texas Parks and Wildlife Department's target freshwater inflow recommendations for Galveston Bay; and, (3) an *existing condition* based on known inflows for a ten-year period from 1980 – 1989. This ten-year period was chosen for several reasons, including that the time-frame could be modeled with in-house computing resources, it avoided extreme high inflow years, and it closely matched mean annual inflow for the time period used in developing the target freshwater inflow recommendations.

A regional water availability model (WAM) for the Trinity River basin was used to simulate water plan strategy inflows to Galveston Bay for two management scenarios, a modified WAM Run3 and a WAM Run9. The two scenarios reflect a future condition in which either all Trinity Basin water rights are fully utilized, with no return flows and no term water rights (*i.e.*, WAM Run3) or all Trinity Basin water rights have anticipated demands and strategies (as outlined in the 2007 State Water Plan (TWDB 2007); *i.e.*, WAM Run9). Simulated inflows obtained from these scenarios then were applied to the TxBLEND hydrodynamic and salinity transport model to predict resulting salinity conditions within the bay. A comparison of these results to those for an *existing condition* based on known inflows from 1980 – 1989 reveals that under both future inflow scenarios, salinity in the upper and mid-bay occurs at similar frequencies within the 10 – 20 ppt preferred salinity range for key estuarine species. However, low salinity events (<10 ppt) are fewer in number, especially under modified WAM Run3 inflows. Additionally, Trinity Bay sees a 4 ppt increase in median daily salinity under Run3. Inflow conditions under this scenario could impact estuarine populations which rely on low salinity events for part of their life cycle (*e.g.*, La Peyre *et al.* 2009, Posey *et al.* 2005, Sklar and Browder 1998). As it is, low salinity events are infrequent under *existing conditions* in the bay near the Gulf pass. Under future scenarios of decreased inflows to the bay, the number of high salinity events ($\geq$ 25 ppt) would increase in frequency by 10 to 20 percent. Overall, the modified WAM Run3 scenario, in which water rights are fully utilized and there are no return flows, greatly increases the frequency of occurrence of low inflows (those <100 cfs) and thus impacts bay salinity conditions. The WAM Run 9 scenario in contrast has less of an impact on daily inflows across all ranges of flows and thus less of an impact on salinity conditions throughout the estuary, as compared to the modified WAM Run3.

Finally, the two recommended target inflow conditions, MaxH and MinQ, which were developed jointly by the Texas Parks and Wildlife Department and Texas Water Development Board (Lee *et a*l. 2001), were included in the comparison. For these scenarios, monthly target inflows were assigned to the three major contributing rivers (Trinity, San Jacinto, and Buffalo Bayou) as recommended and repeated annually over the multi-year simulation period. This simplistic application of the target inflows was necessary to allow for a means to compare among the scenarios. As a result, this strict interpretation of the target inflows does not allow for the occurrence of high inflow events and thus greatly reduces total bay inflow, as compared to the *existing condition* and the two WAM scenarios – except during relatively dry periods. The effect on salinity conditions in Trinity Bay and mid-Galveston Bay is that overall salinity variation is reduced, nearly eliminating salinities less than 10 ppt in favor of an increased number of salinity events in the 10 – 20 ppt range. In the lower bay under the target inflow scenarios, the number of high salinity events (>20 ppt) increases by as much as 20 percent (*e.g.*, Figure 27), and at Bolivar Roads salinities less than 20 ppt are effectively eliminated. Therefore, throughout the estuary, under a strict interpretation of MinQ and MaxH inflows, in which large inflows are excluded, salinity condition increases at all locations. These noted increases, particularly within the 10 – 20 ppt range, are consistent with the objectives of the optimization procedure to provide inflows to manage for a desired salinity condition.

Mean annual inflow under all four scenarios is less than that observed in the historical hydrology for Galveston Bay from 1941 – 2005, which had a median annual inflow of 11.4 million acre-feet and an average annual inflow of 11.3 million acre-feet. WAM Run9 was the most similar yielding an average annual inflow of 9.1 million acre-feet which corresponds to the 58$^{th}$ percentile exceedance probability of historical inflows. Inflows for the remaining scenarios are much less. The modified WAM Run3 yields an average annual inflow of 6.4 million acre-feet, a 78$^{th}$ percentile inflow. MaxH and MinQ target inflows yield average annual inflows of 5.2 million acre-feet, an 80$^{th}$ percentile inflow, and 4.2 million acre-feet, an 87$^{th}$ percentile inflow, respectively. However, these reductions were not uniformly consistent among all sources of inflow to the bay. In this study, inflows were distributed among nine contributing rivers, streams, and bayous. Historically, three of these sources (the Trinity River, San Jacinto River, and Buffalo Bayou) contribute 83 percent of freshwater inflow to the Galveston Bay system. Under the scenarios, this relative percent contribution decreased from 83 percent to as low as 57 percent under a MinQ target inflow scenario. WAM Run9 again was most similar to the historical condition, with the “big three” contributing 82 percent of inflows. Modified WAM Run3 contributed 76 percent, and MaxH scenario contributed 67 percent. These decreases occur in large part due to reduced inflows from the Trinity River. Additionally, under the target inflow scenarios, there is an increased reliance of inflows from the smaller coastal watersheds to support total bay inflow.

In 2009, the Texas regional water planning group for Region H completed a study describing a qualitatively similar impact of proposed management strategies on Galveston Bay inflows (Region H 2009), though their study reported that WAM Run3 inflows were less than the State's target inflow values for MaxH and MinQ – a key difference. This difference may be due in part to the fact that the present study prevents inflows greater than and lesser than the target value; whereas, the Region H study allowed for larger inflows by setting achievement guidelines for the target inflows (*e.g*., a 50 percent attainment frequency for MaxH and a 60 percent attainment for MinQ). While their study did not assess impacts to bay salinity condition, the two studies taken together highlight the importance of evaluating the effect of various model assumptions and conditions when trying to interpret the impacts of future changes in freshwater inflows to bays.

Overall, inflow reductions are most pronounced in the MinQ scenario where flows are reduced 60 percent from *existing condition* inflows. By comparison, inflows are reduced 50 percent under a MaxH scenario, 39 percent under a modified WAM Run3, and only 12 percent under a WAM Run9 scenario. Not surprisingly, the reduction of inflows from the four scenarios increases salinity conditions within in the bay, but perhaps not as expected. First, while the MinQ target inflow scenario has the biggest impact on total bay inflow, it does not have the greatest impact on median daily salinity. Instead, salinity increases more under a modified WAM Run3 scenario. However, the MinQ and modified Run3 scenarios were similar to one another in terms of impacting median daily salinity in the upper and lower estuary. In the upper estuary, these two scenarios increase salinity by 4 ppt. The MaxH target inflow scenario increases median daily salinity by 1 to 3 ppt, which is more than the WAM Run9 scenario but less than the MinQ or modified Run3 scenarios. Finally, the WAM scenarios have little effect on the frequency of occurrence of salinity in the desired 10 – 20 ppt range in the upper estuary and only somewhat decrease the number of events in the lower estuary. In contrast, the target inflow scenarios, as applied here, increase the frequency of occurrence of events in the desired 10 – 20 ppt range in the upper estuary (by as much as 35 percent), and nearly equally decrease the frequency of such events in the lower estuary (by as much as 24 percent).

## CONCLUSIONS

The implementation of future water plans will affect the quantity and timing of freshwater inflows to coastal estuaries. Therefore, to better understand the potential impacts of such changes on salinity condition in the Galveston Bay system, this demonstration study interpreted and applied expected 2060 inflows based on water plan strategies for the Trinity River Basin. The study also assessed a singular interpretation of the State's target freshwater inflow recommendations for Galveston Bay which were developed to meet specific goals but were not developed to serve as a freshwater inflow regime covering all ranges of inflows. The results show that changes in overall quantity as well as the geographic and temporal distribution of inflows to the bay has a variety of impacts on salinity, ranging from increases in the average or median salinity value at locations throughout the bay to displacement or even loss of desired salinity zones. While the results are not meant to be conclusive or absolute, the results are meant to be indicative of possible future salinity conditions within the bay – conditions which are dependent on the application of the rules defining the quantity and pattern of inflows (both geographically and temporally). The results also serve to encourage and guide further exploration of future impacts to freshwater inflows, salinity condition, and estuarine ecology as a result of water plan strategies and environmental flow recommendations.

## REFERENCES


La Peyre, M.K., B. Gossman, J.F. La Peyre. 2009. Defining optimal freshwater flow for oyster production: Effects of freshet rate and magnitude of change and duration on eastern oysters and *Perkinsus marinus* infection. *Estuaries and Coasts* 32: 522 – 534.

Lee, W., D. Buzan, P. Eldridge, and W. Pulich, Jr. 2001. *Freshwater Inflow Recommendation for the Trinity-San Jacinto Estuary of Texas.* Texas Parks and Wildlife Department, Austin, Texas.

Matsumoto, J. 2005. *Effects of structures and practices on the circulation and salinity patterns of Galveston Bay, Texas.* Texas Water Development Board, Austin, Texas.

Matsumoto, J. 1993. *User's manual for the Texas Water Development Board's hydrodynamic and salinity model, TxBLEND.* Texas Water Development Board, Austin, Texas.

Matsumoto, J. 1992. *User's manual for the Texas Water Development Board's Rainfall-Runoff Model, TxRR.* Texas Water Development Board, Austin, Texas.

Posey, M.H., T.D. Alphin, H. Harwell, B. Allen. 2005. Importance of low salinity areas for juvenile blue crabs, *Callinectes sapidus* Rathbun, in river-dominated estuaries of the southeastern United States. *Journal of Experimental Marine Biology and Ecology* 319: 81 – 100.

Region H. 2009. *Region H Water Planning Group Environmental Flow Study*. Prepared by AECOM USA Group, Inc., Kellogg Brown & Root Services, Inc., LBG-Guyton Associates, and Ekistics Corporation. July 2009. pp. 112.

Sklar, F.H., and J.A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* 22(4): 547 – 562.

TDWR. 1981. *Trinity-San Jacinto Estuary: A study of the influence of freshwater inflows*. LP-113. Texas Department of Water Resources, Austin, Texas.

TWDB. 2007. *Water for Texas 2007*. Texas Water Development Board, Austin, Texas.

## APPENDIX A: Salinity Validation for TxBLEND

This study utilized the TxBLEND hydrodynamic and salinity transport model to compare the effect of several freshwater inflow scenarios on salinity conditions within the Galveston Bay system. Prior to simulating the various scenarios however, TxBLEND model performance was assessed by simulating conditions over an eight year period, 1989 – 1996, and then comparing simulated salinity values to long-term, field collected salinity data. This validation exercise was conducted for four locations: Trinity Bay, Red Bluff, Dollar Point, and Bolivar Roads (Figure 4). These locations correspond to four of TWDB's long-term water quality data collection (Datasonde Program) sites in Galveston Bay.

Figures A1 through A8 are time-series plots comparing TxBLEND simulated salinity against observed salinity at the four bay locations for each year in the eight year study period, 1989 – 1996. Observed data consists of salinity recorded at hourly frequencies by *in situ* water quality meters deployed and maintained as part of the TWDB Datasonde Program. As can be seen in the comparison plots, simulated salinity approximates but does not always match observed data. However, the model seems to replicate daily variation and long-term trends reasonably well. At the Bolivar Roads site, daily salinity variation is much greater than at the Trinity Bay site reflecting, Bolivar's proximity to the Gulf of Mexico and faster water velocity. All four sites exhibit responses to large inflow events whereby salinity rapidly decreases and then gradually recovers over a period of weeks or months. Of particular interest is October 1994 in which a large flood event on the Trinity River, with an estimated daily inflow of 244,000 cubic feet per second, occurred on October 19, 1994 causing a sudden drop in salinity. This effect in both observed and simulated data can be seen in Figure A6.

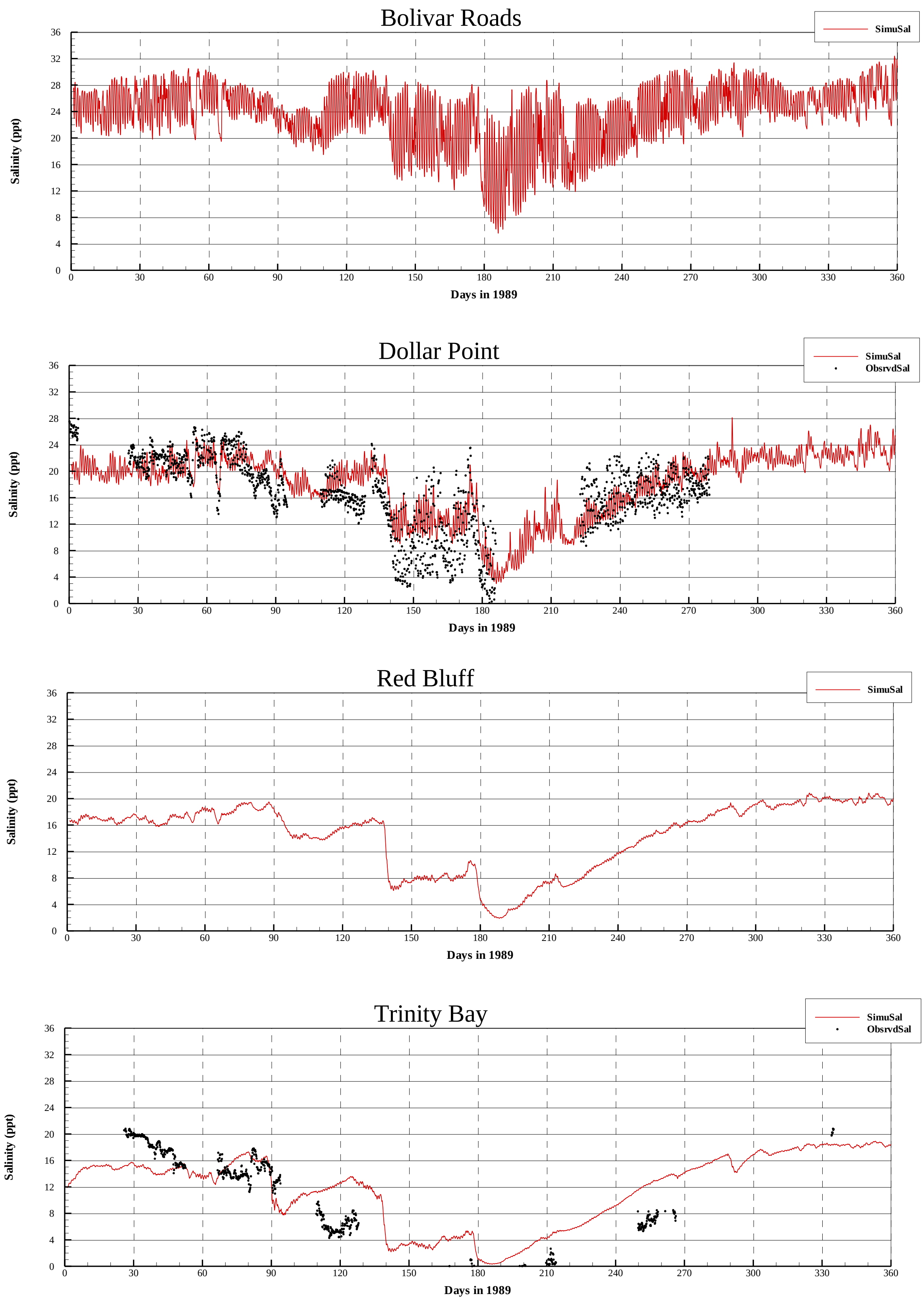



Figure A1. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1989 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

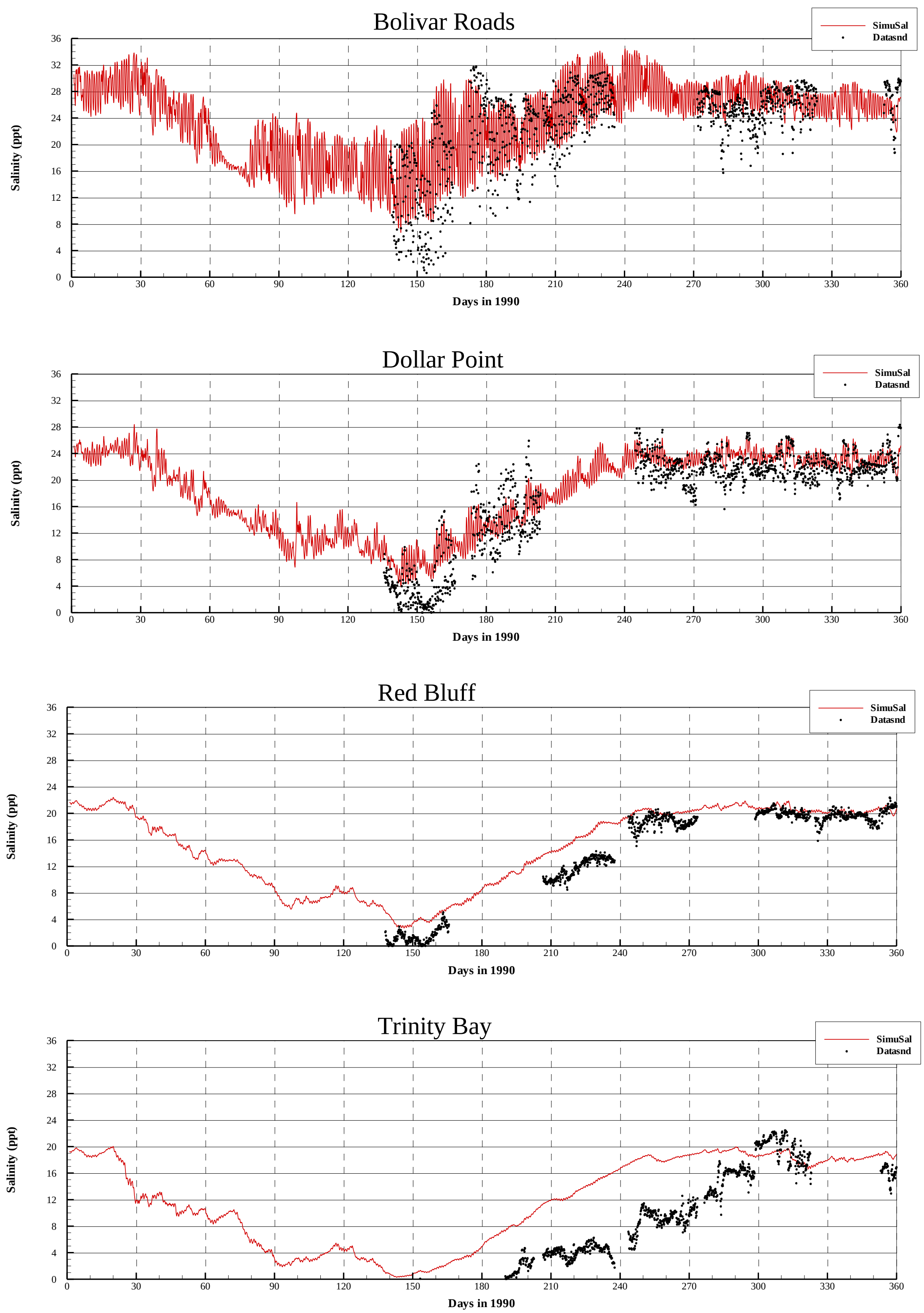



Figure A2. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1990 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

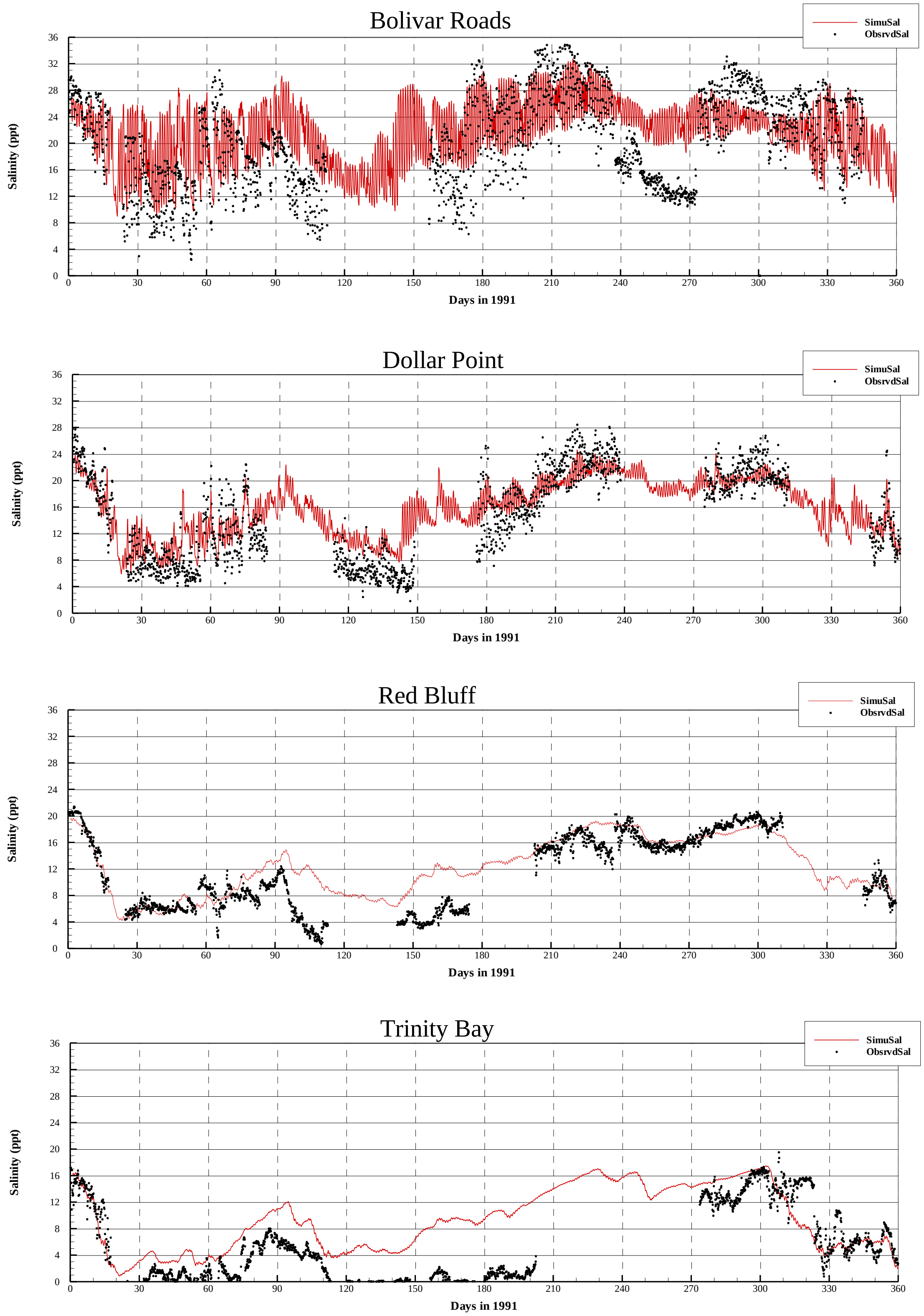



Figure A3. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1991 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

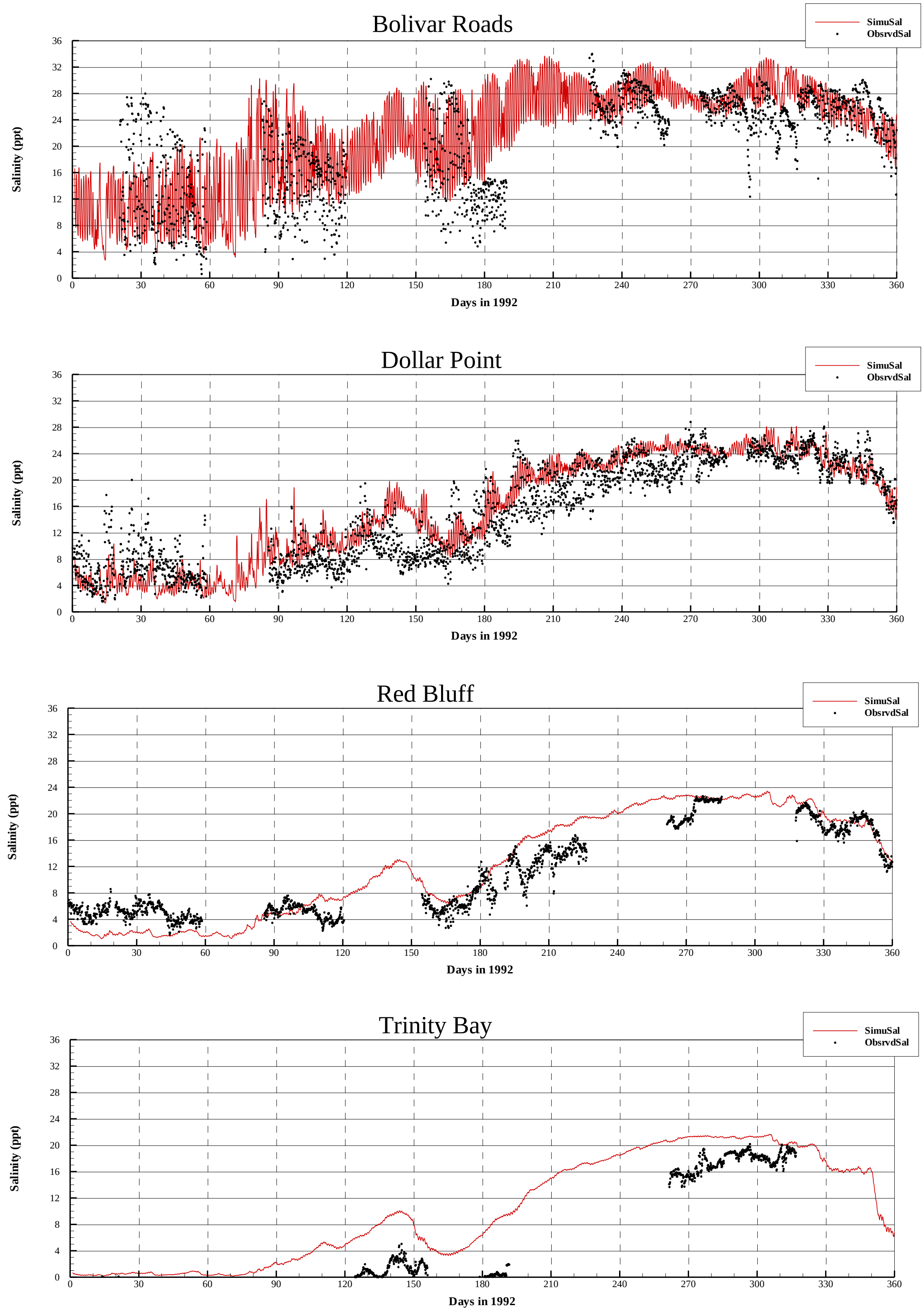
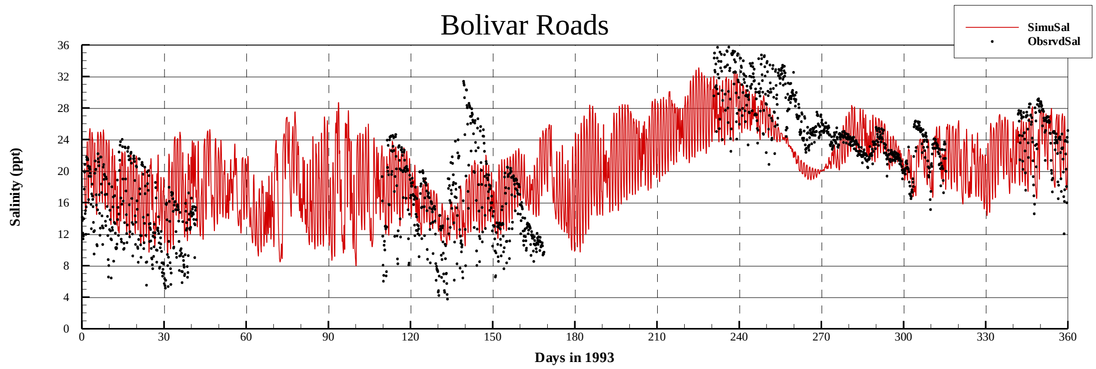
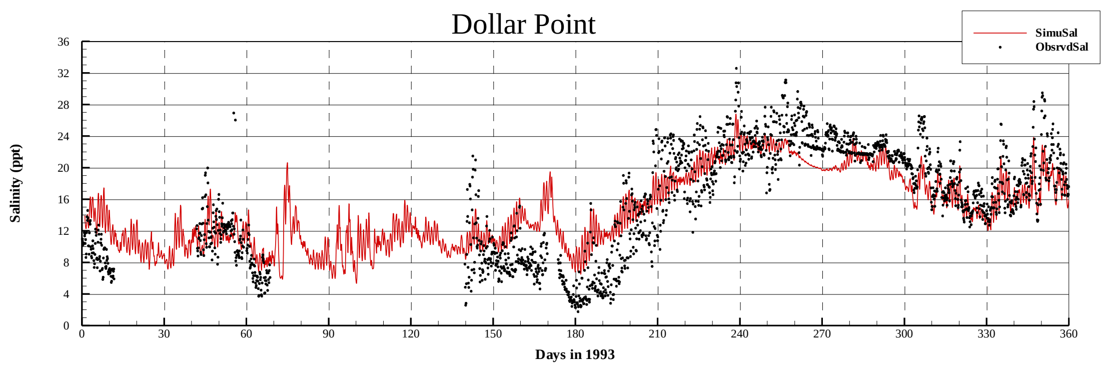
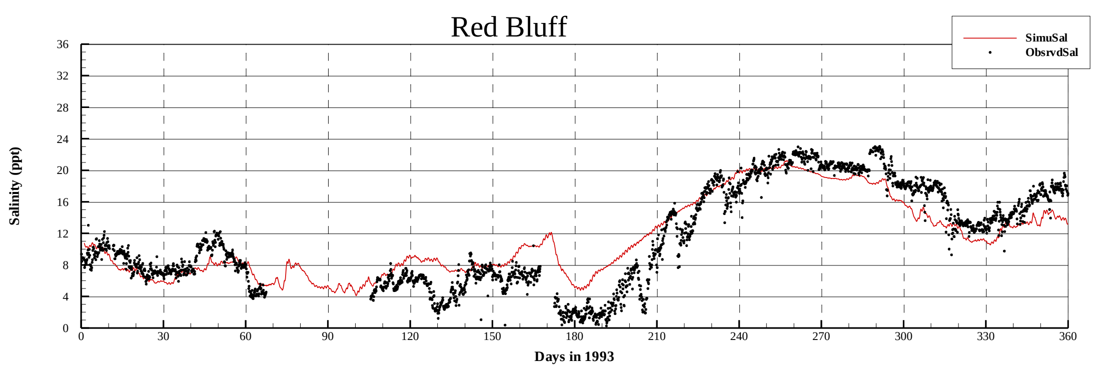



Figure A4. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1992 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.



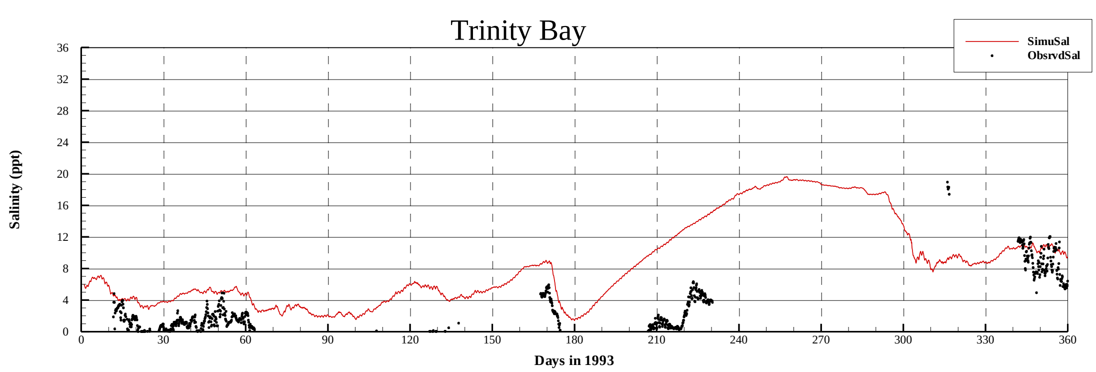




Figure A5. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1993 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

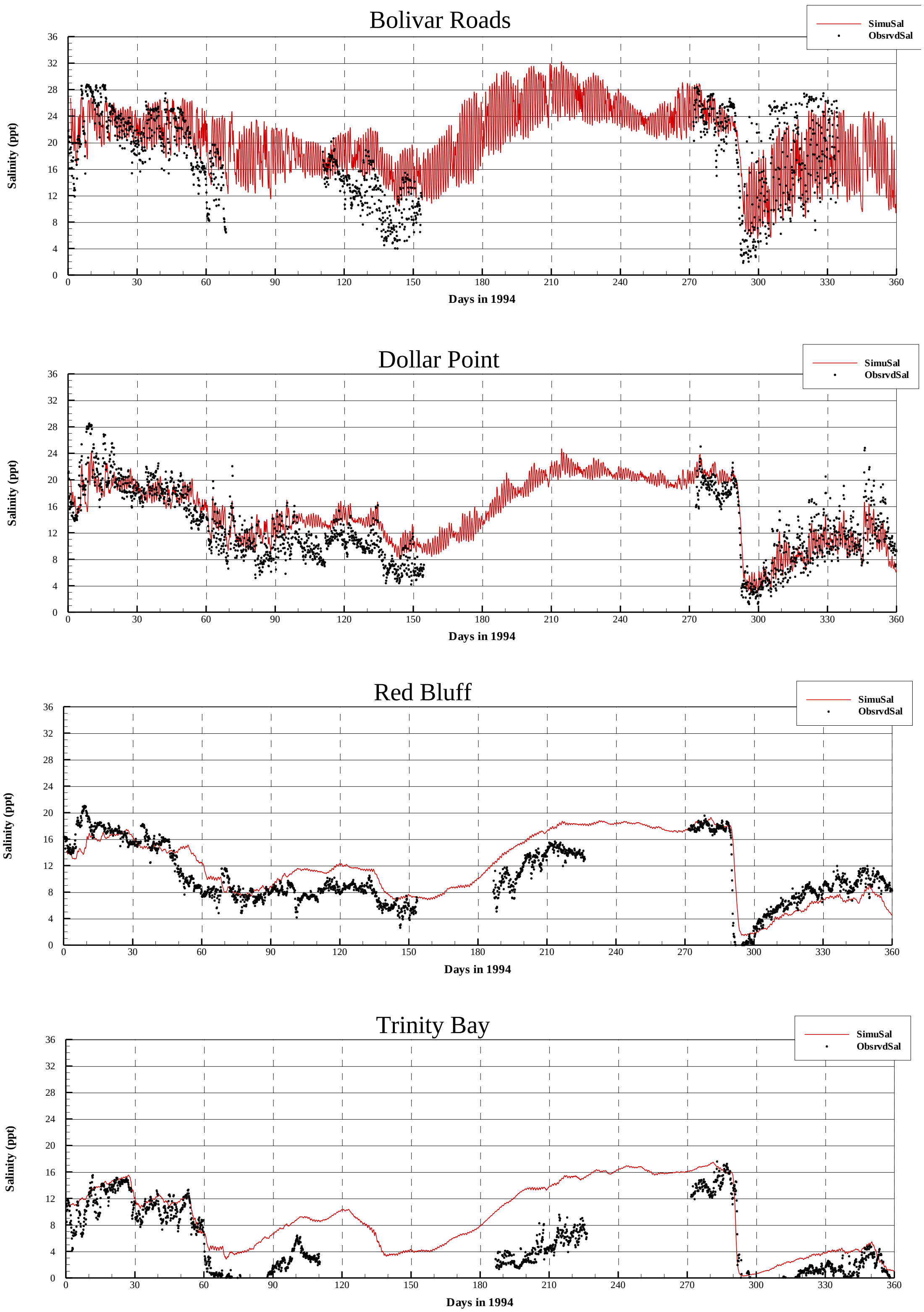



Figure A6. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1994 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

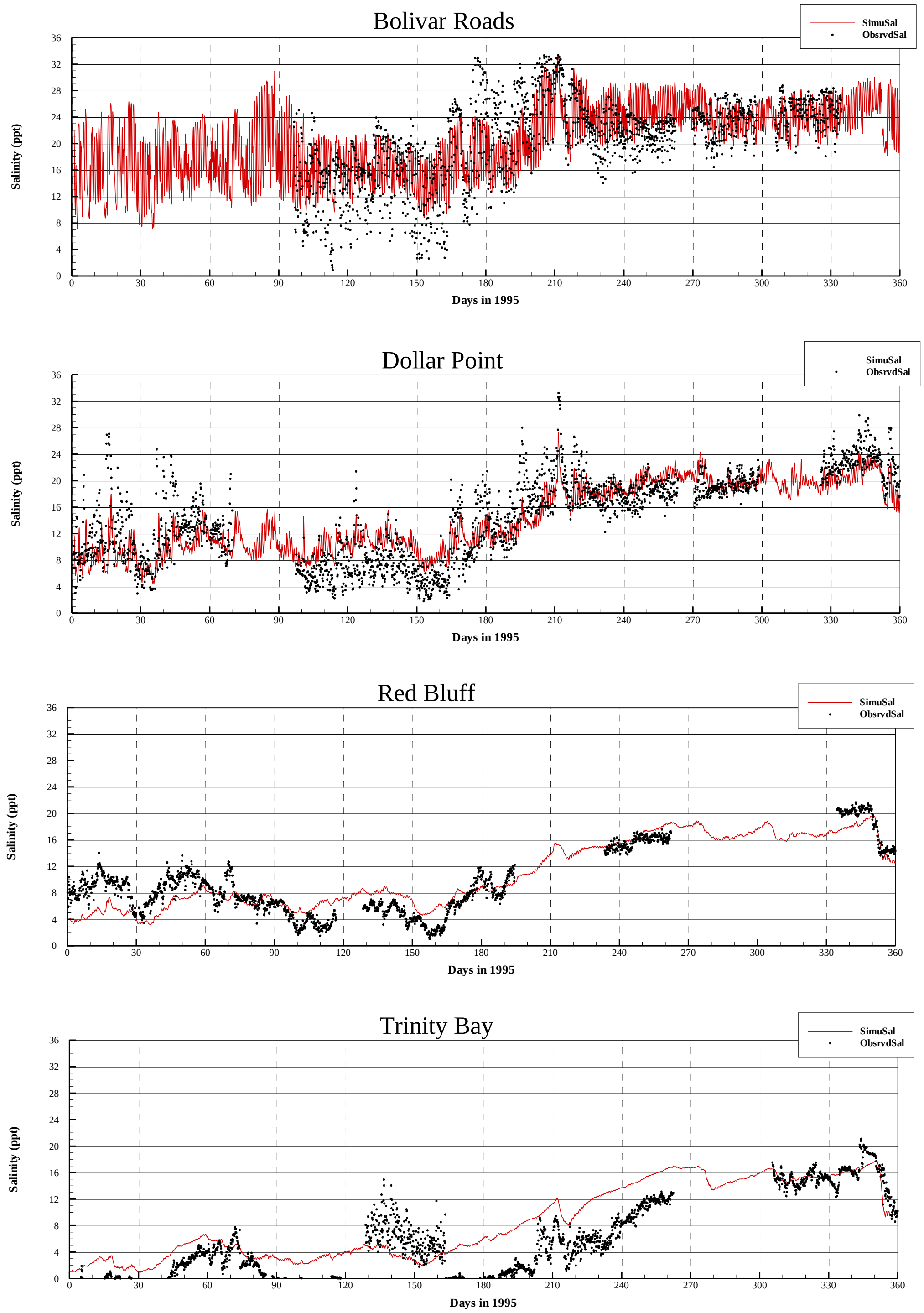



Figure A7. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1995 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

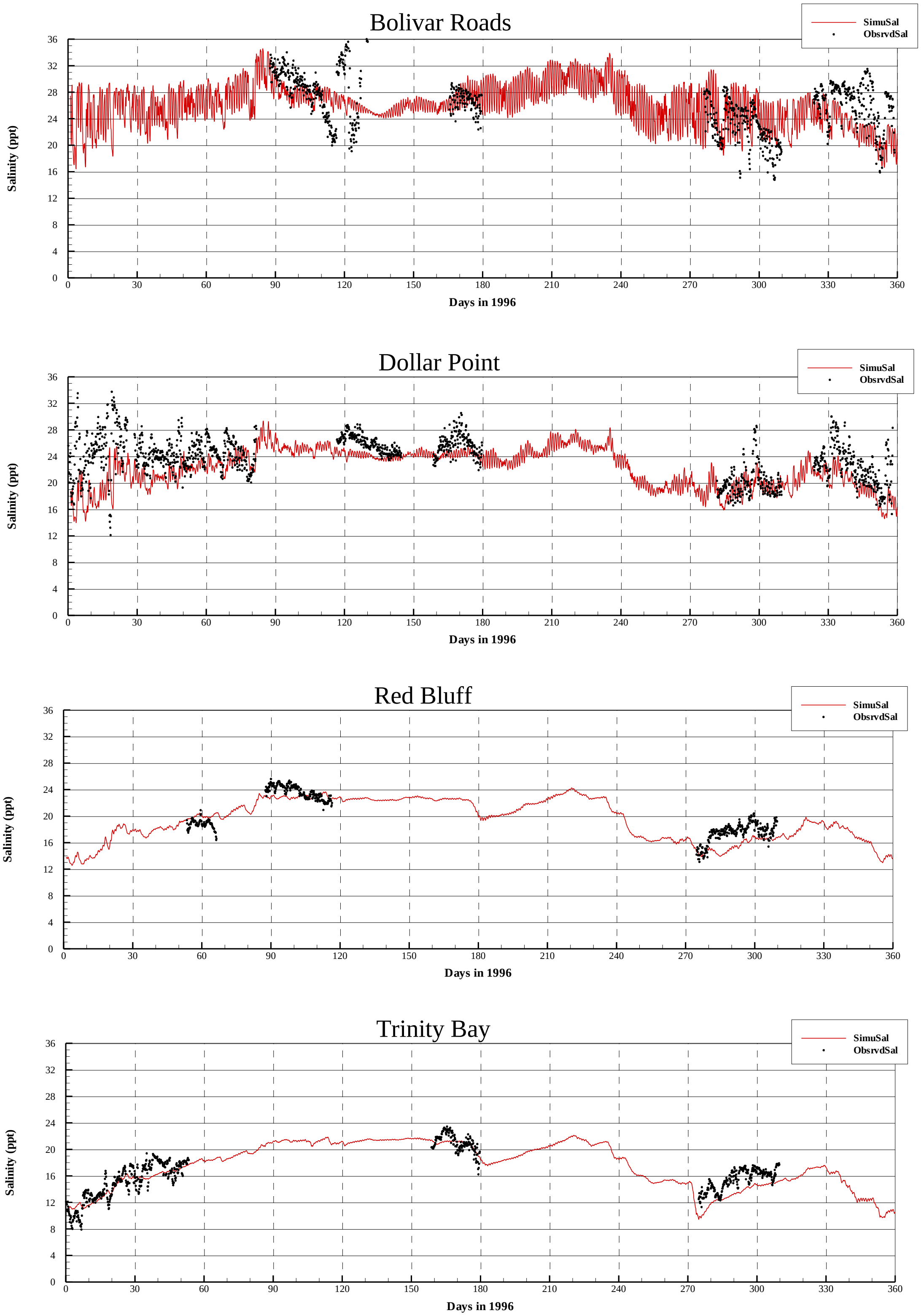



Figure A8. Observed (*black*) and TxBLEND simulated (*red*) salinities (ppt) for 1996 at four locations in Galveston Bay; from top to bottom, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

Scatter plots of observed versus simulated salinity, and the corresponding statistics, indicate that TxBLEND more accurately predicts salinities at the mid-estuary sites of Dollar Point and Red Bluff than at the Bolivar Roads and Trinity Bay sites (Figure A9 and Table A1). Nonetheless, the difference in observed versus simulated mean daily salinity among all sites is less than 3 ppt.

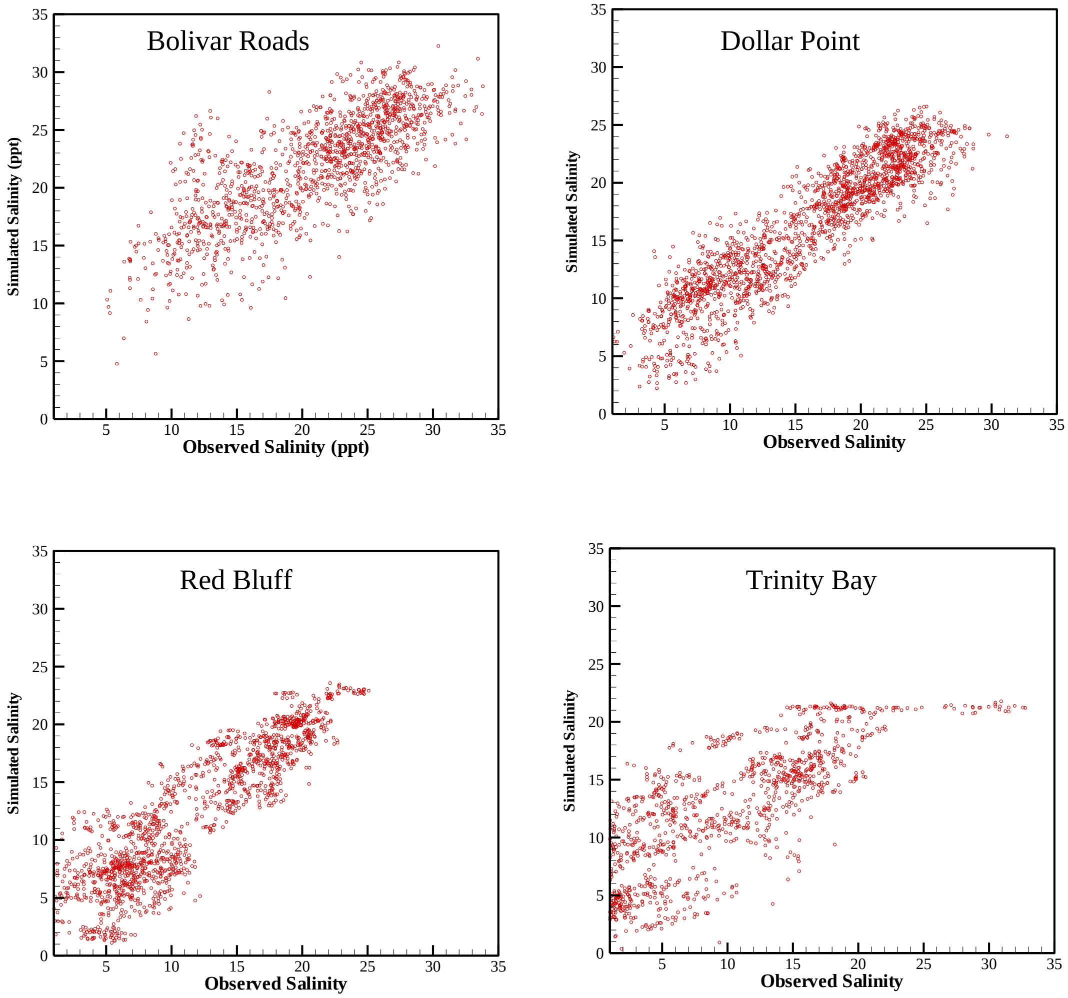



Figure A9. Scatter plots of simulated versus observed daily salinity (ppt.) for the period 1989 – 1996 at four Datasonde locations in Galveston Bay; clockwise from top left, Bolivar Roads, Dollar Point, Red Bluff, and Trinity Bay.

Table A1. Simulated and observed mean daily salinity (ppt) for the period 1989 – 1996 at four Datasonde locations in Galveston Bay.

| Site | Days | $r^2$ | RMS (ppt) | Observed Mean | Simulated Mean | Difference |
|---|---|---|---|---|---|---|
| Bolivar Roads | 1,438 | 0.62 | 3.9 | 20.8 | 21.4 | -0.6 |
| Dollar Point | 1,767 | 0.84 | 2.8 | 16.0 | 15.7 | 0.3 |
| Red Bluff | 1,604 | 0.80 | 2.8 | 11.7 | 11.4 | 0.3 |
| Trinity Bay | 1,573 | 0.69 | 4.8 | 6.9 | 8.9 | -2.0 |

## APPENDIX B: Monthly Inflows to Galveston Bay from 1980 – 1989

This period was selected to be representative of *existing conditions*, and monthly inflows for the full period of record (1941 – 2005)

Table B1. Monthly surface inflow (in 1,000 acre-feet) to Galveston Bay for the period 1980 – 1989.

| Year | Month | Inflow | Year | Month | Inflow | Year | Month | Inflow | Year | Month | Inflow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980 | 1 | 1,451 | 1983 | 1 | 807 | 1986 | 1 | 312 | 1989 | 1 | 358 |
| 1980 | 2 | 1,038 | 1983 | 2 | 1,865 | 1986 | 2 | 1,340 | 1989 | 2 | 446 |
| 1980 | 3 | 951 | 1983 | 3 | 1,505 | 1986 | 3 | 370 | 1989 | 3 | 560 |
| 1980 | 4 | 771 | 1983 | 4 | 383 | 1986 | 4 | 401 | 1989 | 4 | 820 |
| 1980 | 5 | 1,709 | 1983 | 5 | 1,732 | 1986 | 5 | 1,561 | 1989 | 5 | 2,535 |
| 1980 | 6 | 322 | 1983 | 6 | 792 | 1986 | 6 | 2,958 | 1989 | 6 | 3,616 |
| 1980 | 7 | 247 | 1983 | 7 | 1,139 | 1986 | 7 | 605 | 1989 | 7 | 2,446 |
| 1980 | 8 | 137 | 1983 | 8 | 1,988 | 1986 | 8 | 237 | 1989 | 8 | 929 |
| 1980 | 9 | 584 | 1983 | 9 | 1,794 | 1986 | 9 | 616 | 1989 | 9 | 209 |
| 1980 | 10 | 425 | 1983 | 10 | 225 | 1986 | 10 | 981 | 1989 | 10 | 314 |
| 1980 | 11 | 136 | 1983 | 11 | 349 | 1986 | 11 | 1,728 | 1989 | 11 | 193 |
| 1980 | 12 | 166 | 1983 | 12 | 670 | 1986 | 12 | 2,169 | 1989 | 12 | 104 |
| 1981 | 1 | 189 | 1984 | 1 | 626 | 1987 | 1 | 998 | | | |
| 1981 | 2 | 144 | 1984 | 2 | 635 | 1987 | 2 | 911 | | | |
| 1981 | 3 | 161 | 1984 | 3 | 928 | 1987 | 3 | 1,560 | | | |
| 1981 | 4 | 234 | 1984 | 4 | 356 | 1987 | 4 | 396 | | | |
| 1981 | 5 | 919 | 1984 | 5 | 528 | 1987 | 5 | 541 | | | |
| 1981 | 6 | 3,675 | 1984 | 6 | 294 | 1987 | 6 | 2,536 | | | |
| 1981 | 7 | 1,312 | 1984 | 7 | 315 | 1987 | 7 | 1,122 | | | |
| 1981 | 8 | 347 | 1984 | 8 | 210 | 1987 | 8 | 154 | | | |
| 1981 | 9 | 1,053 | 1984 | 9 | 233 | 1987 | 9 | 326 | | | |
| 1981 | 10 | 1,279 | 1984 | 10 | 1,795 | 1987 | 10 | 123 | | | |
| 1981 | 11 | 1,783 | 1984 | 11 | 905 | 1987 | 11 | 408 | | | |
| 1981 | 12 | 893 | 1984 | 12 | 970 | 1987 | 12 | 913 | | | |
| 1982 | 1 | 729 | 1985 | 1 | 1,092 | 1988 | 1 | 581 | | | |
| 1982 | 2 | 655 | 1985 | 2 | 1,379 | 1988 | 2 | 416 | | | |
| 1982 | 3 | 628 | 1985 | 3 | 2,015 | 1988 | 3 | 805 | | | |
| 1982 | 4 | 960 | 1985 | 4 | 659 | 1988 | 4 | 466 | | | |
| 1982 | 5 | 2,002 | 1985 | 5 | 902 | 1988 | 5 | 290 | | | |
| 1982 | 6 | 1,551 | 1985 | 6 | 863 | 1988 | 6 | 204 | | | |
| 1982 | 7 | 937 | 1985 | 7 | 352 | 1988 | 7 | 262 | | | |
| 1982 | 8 | 554 | 1985 | 8 | 277 | 1988 | 8 | 268 | | | |
| 1982 | 9 | 193 | 1985 | 9 | 462 | 1988 | 9 | 359 | | | |
| 1982 | 10 | 147 | 1985 | 10 | 900 | 1988 | 10 | 112 | | | |
| 1982 | 11 | 788 | 1985 | 11 | 1,763 | 1988 | 11 | 88 | | | |
| 1982 | 12 | 1,806 | 1985 | 12 | 1,827 | 1988 | 12 | 103 | | | |

Table B2. Galveston Bay monthly inflow statistics (in 1,000 acre-feet) for 1980 - 1989.

| Month | Min | $25^{th}$% | Median | Mean | $75^{th}$% | Max |
|---|---|---|---|---|---|---|
| January | 189 | 414 | 678 | 714 | 950 | 1,451 |
| February | 144 | 493 | 783 | 883 | 1,265 | 1,865 |
| March | 161 | 577 | 867 | 948 | 1,367 | 2,015 |
| April | 234 | 386 | 434 | 545 | 743 | 960 |
| May | 290 | 631 | 1,240 | 1,272 | 1,726 | 2,535 |
| June | 204 | 440 | 1,207 | 1,681 | 2,853 | 3,675 |
| July | 247 | 324 | 771 | 874 | 1,135 | 2,446 |
| August | 137 | 217 | 273 | 510 | 502 | 1,988 |
| September | 193 | 256 | 411 | 583 | 608 | 1,794 |
| October | 112 | 167 | 370 | 630 | 961 | 1,795 |
| November | 88 | 232 | 598 | 814 | 1,522 | 1,783 |
| December | 103 | 292 | 903 | 962 | 1,597 | 2,169 |

Table B3. Galveston Bay monthly inflow statistics (in 1,000 acre-feet) for 1941 - 2005.

| Month | Min | $25^{th}$% | Median | Mean | $75^{th}$% | Max |
|---|---|---|---|---|---|---|
| January | 42 | 357 | 818 | 1,121 | 1,526 | 5,044 |
| February | 71 | 432 | 1,041 | 1,071 | 1,418 | 4,560 |
| March | 74 | 384 | 805 | 1,142 | 1,654 | 4,444 |
| April | 136 | 406 | 659 | 1,149 | 2,028 | 5,290 |
| May | 139 | 455 | 1,312 | 1,475 | 2,107 | 4,571 |
| June | 57 | 370 | 891 | 1,275 | 1,833 | 4,012 |
| July | 44 | 231 | 461 | 649 | 943 | 2,446 |
| August | 21 | 167 | 277 | 420 | 649 | 2,111 |
| September | 16 | 211 | 359 | 610 | 666 | 2,564 |
| October | 21 | 123 | 286 | 639 | 912 | 4,288 |
| November | 31 | 236 | 414 | 780 | 1,007 | 4,565 |
| December | 55 | 313 | 765 | 936 | 1,375 | 3,427 |

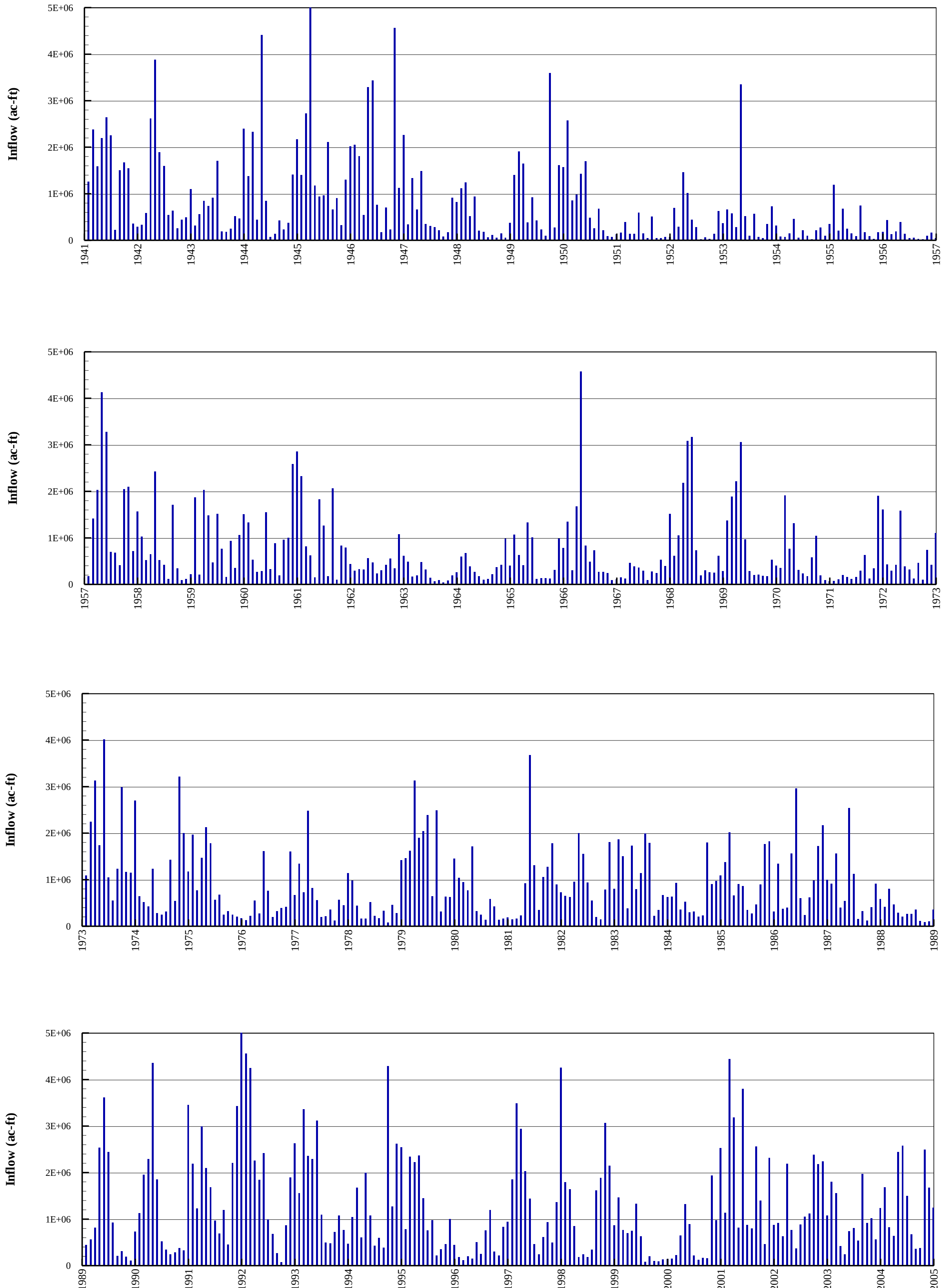



Figure B1.  Galveston Bay monthly inflows over the full period of record, 1941 – 2005.