Coastal Hydrology for the Laguna Madre Estuary, With Emphasis on the Lower Laguna Madre

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Purpose

This technical memo documents the procedure for estimating combined freshwater inflow data and the freshwater inflow balance for the Laguna Madre Estuary and the specifics related to producing TWDB hydrology datasets version #TWDB201101 for the Laguna Madre and #TWDB201101-L for the Lower Laguna Madre only.

Introduction

The goal of the Texas Water Development Board (TWDB) Coastal Hydrology program is to provide estimates of historical freshwater inflows into Texas bays and estuaries to support environmental and water planning studies. The earliest freshwater inflow estimates were compiled in a series of reports published by the Texas Department of Water Resources (TDWR) between 1980 and 1983. Monthly inflows to the seven major estuaries in Texas for the period 1941 - 1976 were estimated in those studies, with estimates for the Laguna Madre Estuary published in Chapter 4 of LP-182, *Laguna Madre Estuary: A Study of the Influence of Freshwater Inflows* (TDWR 1983, available on the TWDB website or upon request). These early estimates were not completed for each of the Upper and Lower Laguna Madre separately, but rather, were calculated for the Laguna Madre Estuary as a whole.

Inflow records for each estuary have been updated periodically since then in support of ongoing research and planning studies both within and external to TWDB. Additionally, subsequent updates are provided in daily as well as monthly formats. This report describes the

most recent update of freshwater inflow estimates for the Laguna Madre Estuary, and focuses on estimates for freshwater inflow to the Lower Laguna Madre after 1977. Therefore, two datasets are presented herein: (1) Complete hydrology for the entire Laguna Madre (upper and lower combined) from 1941 - 2010, with daily estimates of inflows available only after 1977, and (2) Complete hydrology for the Lower Laguna Madre from 1977 - 2010, available as daily, monthly, or annual estimates.

Estimates of Combined Freshwater Inflows

Detailed studies of hydrology of the areas draining to the Laguna Madre Estuary include gaged watersheds and ungaged portions of small coastal basins. The Rio Grande does not contribute freshwater inflow to the Laguna Madre because it is separated from the bay by a coastal land mass. The combination of Gaged Inflows + Ungaged Inflows + Return Flows - Diversions below the last gaging stations provide for estimates of ***Combined Freshwater Inflow*** to the estuary. The ***Freshwater Inflow Balance*** consists of Combined Inflows + Precipitation on the estuary – Evaporation from the estuary. Although inflow estimates are updated on an ongoing basis, there are two distinct periods of estimation. Before 1977, inflow estimates are available only in monthly intervals and only for the entire Laguna Madre (upper and lower combined). Starting in 1977 and thereafter, inflow estimates became available on a daily basis and can be provided for the entire estuary or for the upper and lower Laguna Madre separately.

1941 - 1976 Period of Record

This dataset used measurements from U.S. Geological Survey (USGS) and International Boundary and Water Commission (IBWC) stream gages, as well as rainfall-runoff estimates from a water yield model to determine flows in both gaged and ungaged watersheds, respectively (TDWR 1983). In most estimates of coastal hydrology, flows in ungaged areas were adjusted for known agricultural, municipal, and industrial return flows. Municipal and industrial return flows were obtained from the Texas Department of Water Resources self-reporting system (TDWR 1983), but were considered insignificant. Agricultural return flows also were calculated using agency data. LP-182 did not specifically address the use of diversions in estimating combined inflows to the estuary. Data on inflows to the Laguna Madre Estuary for 1941 - 1976 are available as monthly or annual estimates, but are available only for the estuary as a whole.

1977 - 2010 Period of Record

The 1977 – 2010 period of record used measurements from USGS and IBWC stream gages along with rainfall-runoff estimates from the Texas Rainfall-Runoff (TxRR) model, adjusted for known diversion and return flows obtained from the Texas Commission on Environmental Quality (TCEQ), the South Texas Water Master (STWM), and the TWDB Irrigation Water Use estimates. In some cases, diversion and return data may be obtained through other entities, such as in the TWDB report on *Coastal Hydrology for the Guadalupe Estuary: Updated Hydrology with Emphasis on Diversion and Return Flow Data for 2000 - 2009* (Guthrie and Lu 2010) where

recent diversion and return flow data were obtained from HDR, Inc. Data on inflows to the Laguna Madre Estuary for 1977 - 2010 are available as daily, monthly, or annual estimates, and also are available for the Upper and Lower Laguna Madre, separately.

Gaged Watersheds

Daily flow recorded at four stream gages was used to develop the gaged component of inflows to the Laguna Madre Estuary. Data from two USGS stream gages were used to estimate the gaged portion of the Upper Laguna Madre, and two gages maintained by the IBWC were used to estimate flows from the gaged portion of the Lower Laguna Madre. Approved USGS stream flow data was obtained through September 2010, but were provisional for October through December 2010. In some cases, there were missing gaged records, which instead were modeled using the Texas Rainfall-Runoff (TxRR) model. Table 1 lists the stream gages and corresponding period of record utilized in estimating combined freshwater inflows to the estuary.

Table 1. USGS and IBWC stream gage number, location, and period of record used to develop the gaged inflow component of combined inflows to the Laguna Madre Estuary from 1941 - 2010. Gaged flows were modeled using TxRR where gaged data was missing, as shown by the modeled period.

Estuary	Segment	Gage Station Number	Gage Location	Utilized Period of Record	Modeled Period
Laguna Madre	Upper	USGS 08211900	San Fernando Creek at Alice	1965 - 1987 and 1999 - 2010	3/6/87 - 4/2/99
		USGS 08212400	Los Olmos Creek at Falfurrias	1967 - 1982 and 1999 - 2010	7/1/82 - 3/31/99
	Lower	IBWC 08470200	North Floodway near Sebastian	1941 - 1978 and 1982 - 1997	11/1/78 - 12/31/1981 and 1/1/98 - 6/30/10
		IBWC 08470400	Arroyo Colorado at Harlingen	1958 - present	None

Ungaged Watersheds

The number of ungaged watersheds for which ungaged inflows are estimated has changed through time as gages became available or unavailable. Initial inflow estimates for 1941 – 1976 were determined for 11 ungaged watersheds that contribute flow to Baffin Bay and Upper Laguna Madre and six watersheds that contribute flow into the Lower Laguna Madre. For a period of time when the two USGS gages were non-operational (before 1965, see Table 1), estimates were based on 13 ungaged watersheds that contribute to Baffin Bay and the Upper

Laguna Madre and six watersheds that contribute to the Lower Laguna Madre. Current estimates for 1977 - 2010 use 12 divisions of watersheds that contribute to Baffin Bay and Upper Laguna Madre flows and nine ungaged watersheds for the Lower Laguna Madre. Figures 1 - 3 show the delineation of watershed boundaries and their changes over the period from 1941 to 2010. Watershed delineation changes also included changes in watershed areas between the watershed delineation in LP-182 (TDWR 1983) and the current watershed delineation, as shown in Table 2.

The ungaged inflow component of combined inflows is estimated using a rainfall-runoff model. Before 1977, stream flows in ungaged watersheds were obtained using a *water yield model* which required daily precipitation, Soil Conservation Service average curve numbers, and soil depletion index (TDWR 1980). This water yield model provided for monthly estimates of ungaged inflows – not daily. TWDB does not have daily estimates of ungaged inflows for the period prior to 1977.

Since 1977, however, TWDB has used the Texas Rainfall-Runoff (TxRR) model to estimate daily stream flows in ungaged watersheds. This model is conceptually similar to the Agricultural Research Service (ARS) rainfall-runoff model which is based on the Soil Conservation Service's curve number method to estimate direct runoff from a precipitation event. TxRR, however, has three key differences: (1) Use of simpler and more straightforward mathematics, (2) Introduction of 12 monthly depletion factors, instead of a single depletion factor as used in the ARS Model, and (3) Introduction of a base flow component into the model. TxRR has been used to estimate daily stream flows from over 50 coastal ungaged watersheds as a part of the TWDB Bays & Estuaries Coastal Hydrology program to study freshwater inflows to Texas bays and estuaries.

Table 2. Comparison of ungaged watershed area from LP-182 (TDWR 1983) estimates to current estimates. These changes affect inflow estimates for the ungaged flow component. Note that watershed numbers in the Lower Laguna Madre do not correspond geographically between the LP-182 watershed delineation and the current watershed delineation.

Segment	Watershed ID Number	LP-182 (Square Miles) 1941-1976	Watershed ID Number	Current Area (Square Miles) 1977-2009
Upper Laguna Madre	22020	134	22020	141.94
	22021	191	22021	227.33
	22022	228	22022	290.94
	22023	91	22023	121.2
	22024	84	22024	90.02
	22025	89	22025	41.94
	22026	Not Applicable	22026	36.88
	22030	64	22030	99.1
	22031	274	22031	277.06
	22032	434	22032	426.08
	22040	255	22040	313.62
	22041	162	22041	304.9
	UPPER TOTAL	**2,006**	**UPPER TOTAL**	**2,371.01**
Lower Laguna Madre	22050	122	22900	591.45
	22057	102	22901	45.84
	22060	97	22902	226.65
	22079	64	22903	398.8
	22080	181	22904	161.21
	22090	114	22905	377.32
	-	-	22906	28.55
	-	-	22907	50.25
	-	-	22908	34.79
	LOWER TOTAL	**680**	**LOWER TOTAL**	**1,914.86**
Upper and Lower Combined	**Combined Total**	**2,686**	**Combined Total**	**4,285.87**

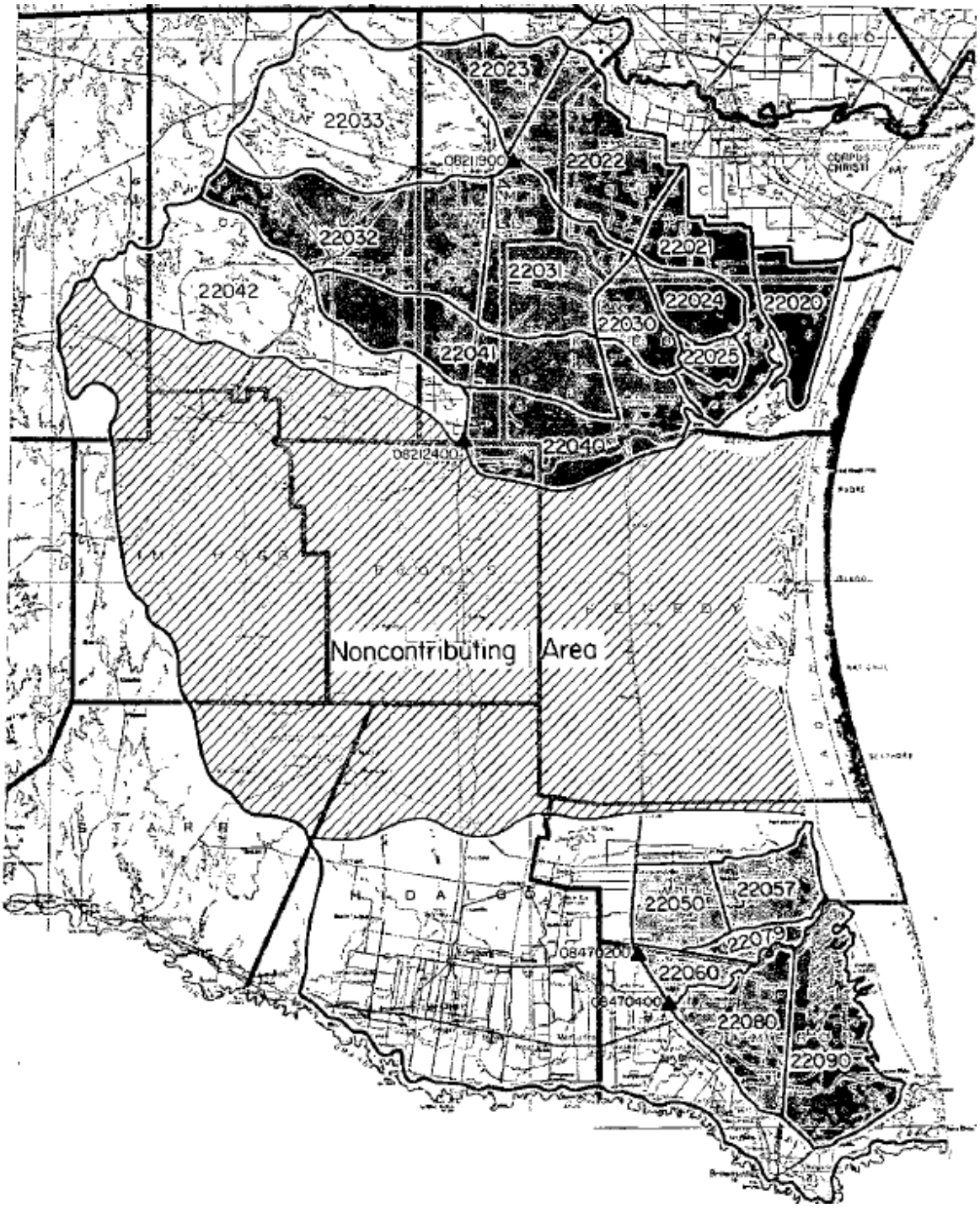

Figure 1. Ungaged watershed delineation used to determine ungaged inflows to the Laguna Madre Estuary from 1941 - 1976. Ungaged watersheds are highlighted in dark ink. Eleven ungaged watersheds contributed to Baffin Bay and the Upper Laguna Madre, while six ungaged watersheds contributed to the Lower Laguna Madre. Watershed #22033 became gaged in 1965; watershed #22042 became gaged in 1967.

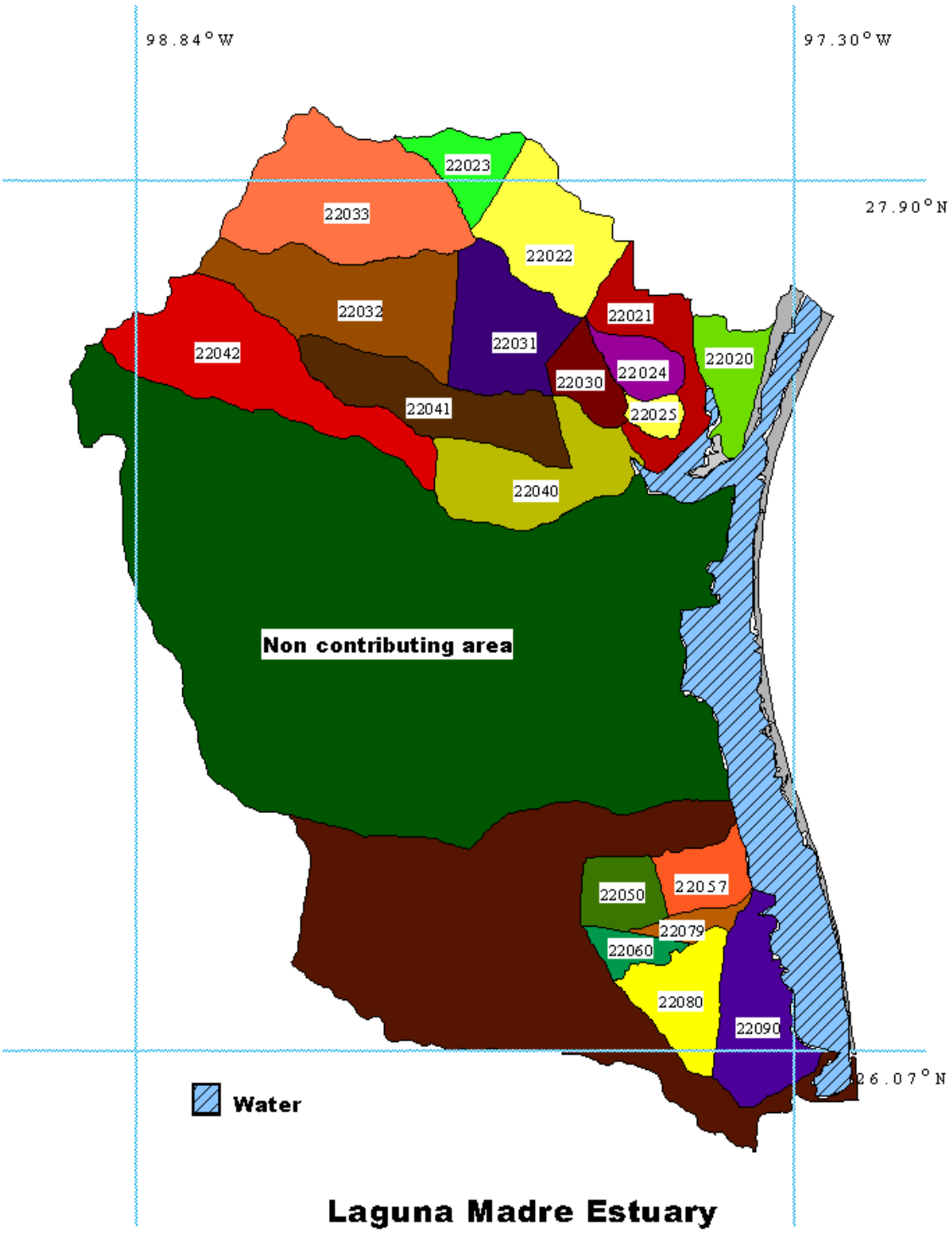

Figure 2. Ungaged watershed delineation used to determine ungaged inflows in the Laguna Madre Estuary when two USGS gages (San Fernando Creek at Alice and Los Olmos Creek at Falfurrias) in the Upper Laguna Madre were not installed (before 1965). During this period, 13 ungaged watersheds contributed inflows to Baffin Bay and the Upper Laguna Madre, while six ungaged watersheds contributed to the Lower Laguna Madre.

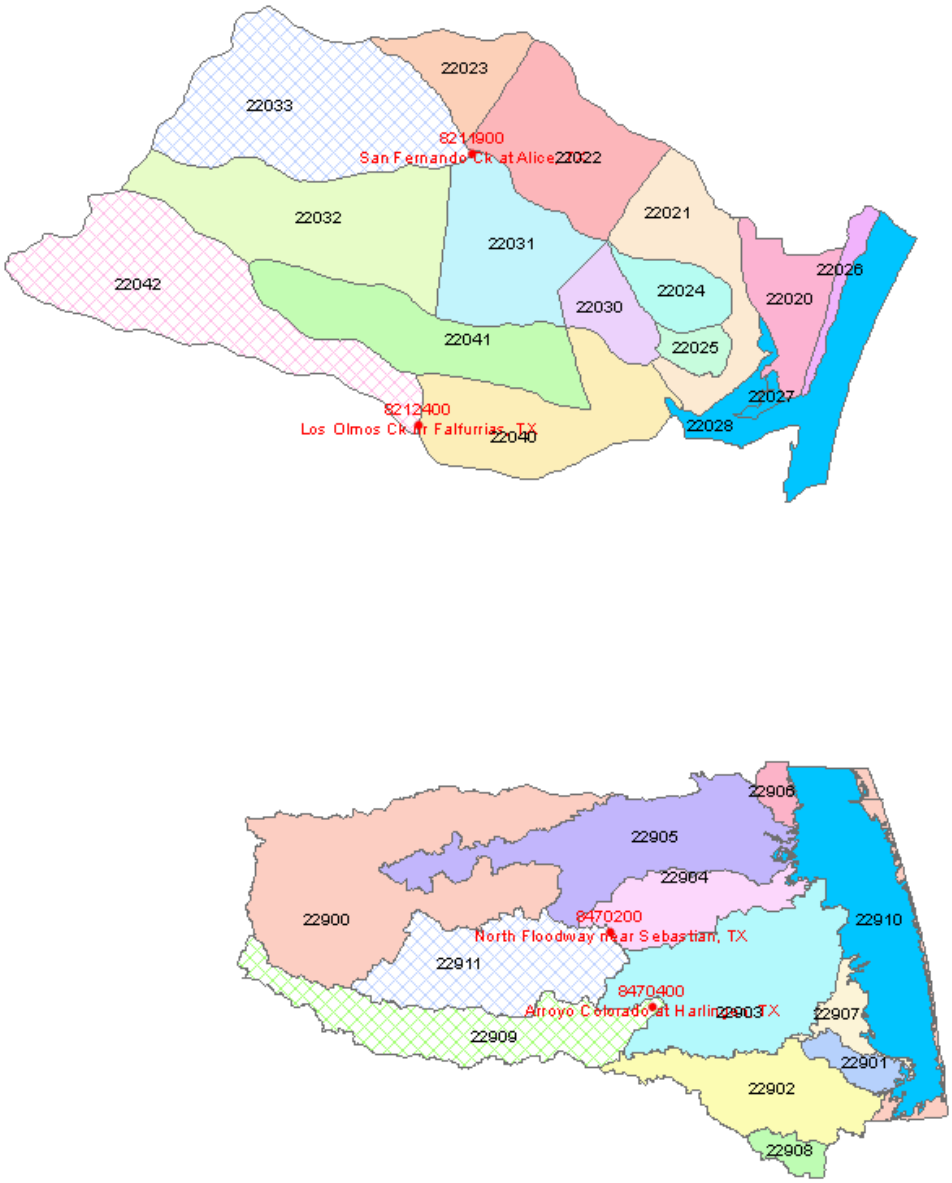

Figure 3. Ungaged watershed delineation used to determine ungaged inflows in the Laguna Madre Estuary from 1977 to present. Currently, 12 ungaged watersheds contribute to Baffin Bay and the Upper Laguna Madre, while nine ungaged watersheds contribute to the Lower Laguna Madre. Watershed #22026 was added to the subdivision of watersheds in the Upper Laguna Madre for better estimation of ungaged inflows. Similarly, three ungaged watersheds were further subdivided in the Lower Laguna Madre re-delineation, and previous watershed numbers were re-numbered. Gaged watersheds are indicated by cross-hatching. Note that in the Upper Laguna Madre, gaged watershed #22033 was ungaged from 1987 - 1999, gaged watershed #22042 was ungaged from 1982 - 1999, and in the Lower Laguna Madre gaged watershed #22911 was ungaged from 1978 - 1981 and 1998 - 2010, during which time flows were modeled using TxRR.

Diversion and Return Points

Diversion and return flows within the ungaged watersheds are accounted for when estimating total freshwater inflow to the estuary. While the major water rights and holders and the major discharge permits and dischargers in the Laguna Madre Estuary are listed in Table 3, with locations of these permits shown in Figure 4, TWDB is not always able to obtain complete records of diversions and return flows when estimating Combined Freshwater Inflows. As such, this contributes to some of the error in estimating total inflow to an estuary.

Table 3. Major water rights and discharge permits in the Laguna Madre basin below the lowest USGS/IBWC stream gages. *Note:* there are currently no diversions in the watersheds contributing to the Lower Laguna Madre; Owners of diversions listed in Appendix E are unknown at this time.

Upper Laguna Madre		
DIVERSION	**Water Right Number**	**Owner**
	4147	City of Alice
	4271	John H & Edith L Burris
	4507	Texas A&M University
	5465	Circle C Cattle Co Ltd
RETURNS	**NPDES Number***	**Owner**
	TX0006025	Ticona Polymers Inc.
	TX0020397	City of Orange Grove
	TX0023019	City of Bishop
	TX0023418	City of Kingsville
	TX0033201	US Dept of The Navy
	TX0033367	City of Agua Dulce
	TX0034002	City of Alice
	TX0047121	City of Corpus Christi
	TX0054291	Nueces County WCID 5
	TX0064408	Teen Challenge of South Texas
	TX0069884	Bishop Consolidated ISD
	TX0094145	City of Driscoll
	TX0102857	Kleberg County
	TX0104400	Us Ecology Texas LP
	TX0112763	Riviera WCID
	TX0113981	Kleberg County
	TX0117978	City of Kingsville
	TX0125636	Coil Tubing Services LLC
	TX0129607	LCS Corrections Services Inc.

Lower Laguna Madre		
	NPDES Number*	**OWNER**
RETURNS	TX0003611	La Palma WLE, LP
	TX0006564	Brownsville Navigation District
	TX0023621	Laguna Madre Water District
	TX0023639	Laguna Madre Water District
	TX0023647	Laguna Madre Water District
	TX0024546	City of Raymondville
	TX0027782	City of Rio Hondo
	TX0047929	City of Harlingen
	TX0055484	Brownsville Public Utilities Board
	TX0056821	Us Dept of Justice
	TX0071340	Brownsville Public Utilities Board
	TX0072133	County of Hidalgo
	TX0074047	Brownsville Navigation District
	TX0076392	Port Mansfield PUD And Willacy CO Navigation District
	TX0084719	City of Lyford
	TX0087441	Harlingen Shrimp Farms Ltd
	TX0091243	City of Los Fresnos
	TX0093106	City of McAllen
	TX0100242	Brownsville Navigation District
	TX0103811	Taiwan Shrimp Village Assoc Inc.
	TX0108197	Southern Star Inc.
	TX0113875	Olmito WSC
	TX0114031	North Alamo WSC
	TX0116751	Calpine Corp.
	TX0117072	Laguna Madre Water District
	TX0117731	Valley MUD 2
	TX0119024	North Alamo WSC
	TX0119423	Calpine Hidalgo Energy Center LP
	TX0124664	Southmost Regional Water Authority
	TX0125148	Lone Star Hatchery Inc. and Advanced Marine
	TX0125156	North Alamo WSC
	TX0125971	City of San Benito
	TX0127086	East Rio Hondo WSC

*National Pollutant Discharge Elimination System (NPDES)

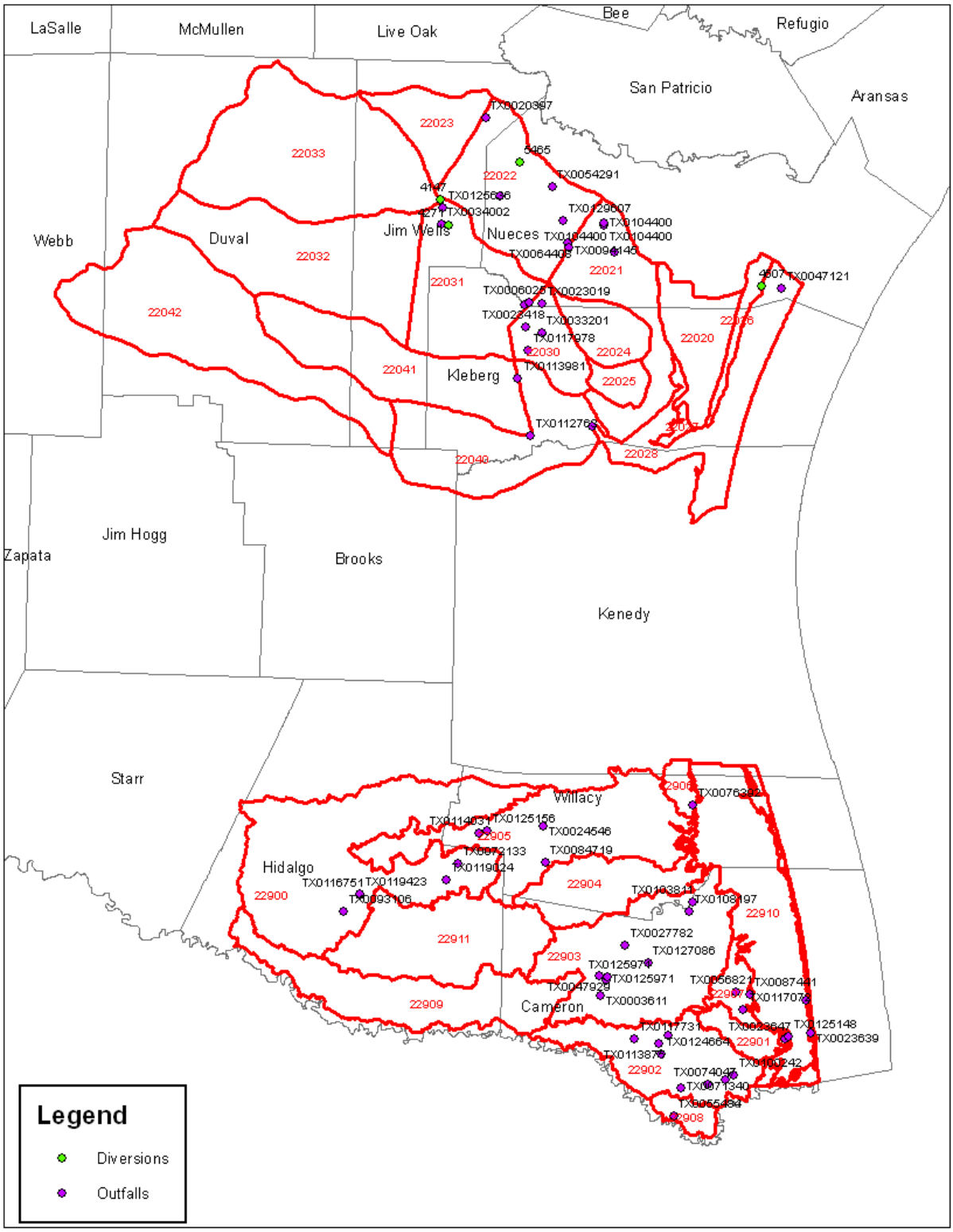

Figure 4. Location of permitted diversion points (*green*) and wastewater outfalls (*purple*) in the Laguna Madre Estuary. Note there are currently no diversions in the Lower Laguna Madre basin.

Estimates of Freshwater Inflow Balance

Total Freshwater Inflow to the estuary may include estimates of ***Combined Freshwater Inflow*** to the estuary + Precipitation on the Estuary. The ***Freshwater Inflow Balance***, then, considers the effect of evaporation from the estuary. Due to limitations on the ungaged inflows prior to 1977 and on estimates of evaporation throughout the period of record, estimates of the freshwater inflow balance are available only in monthly intervals.

The bay surface area which was used to calculate precipitation onto and evaporation from the estuary has changed over time. Prior to 1977, the total bay (upper and lower combined) surface area was estimated to be 885 square miles; whereas, after 1977, the total bay surface area was estimated to be 620.3 square miles (Table 4). Using a smaller bay surface area then, results in a decrease in the annual estimates for precipitation and evaporation from the estuary after 1977. Note however that these annual estimates are rarely used in freshwater inflow analyses. They are presented for descriptive purposes only, but when applied for modeling analyses (such as in the TxBLEND hydrodynamic and salinity transport model) a rate of evaporation or precipitation is used. The bay surface area change does not affect estimates for the separated Upper and Lower Laguna Madre datasets, since those datasets began in 1977, after the new surface areas were already being used in coastal hydrology estimates.

Table 4. Estimates of bay surface area from LP-182 (TDWR 1983) and current estimates.

	Segment ID Number	**LP-182 (Square Miles) 1941 - 1976**	**Segment ID Number**	**Current Area (Square Miles) 1977 - 2009**
Upper Laguna Madre	n/a	n/a	22027	11.83
	n/a	n/a	22028	242.93
Lower Laguna Madre	n/a	n/a	22910	365.54
Upper & Lower Laguna Madre Combined	**Total**	**885.0**	**Total**	**620.3**

<u>Precipitation</u>

Direct precipitation onto the surface of the Laguna Madre Estuary is calculated using Thiessen-weighted precipitation techniques as described in LP-182 (TDWR 1983). Station based rainfall data are obtained from the National Weather Service (NWS) and processed using Arc/Info Macro Language. Bay segments (#22027, #22028 for Upper Laguna Madre and #22910 for Lower Laguna Madre) are used to calculate precipitation on the bay by summing the area-weighted rainfall of the Thiessen polygon fragments within the bay watershed. Figure 5 shows the Thiessen polygons that were drawn to be coincident with rainfall stations to calculate watershed rainfall.

Annual estimates of precipitation onto the surface of the bay, as prepared for hydrology version #TWDB201101 for the entire Laguna Madre Estuary, are shown in Figure 6. Since precipitation estimates were affected by the decrease in bay surface area, Figure 7 shows annual estimates

of precipitation on the surface of the bay adjusted for the change in bay area. Specifically, precipitation values from the earlier period of record, from 1941 - 1976, were adjusted with the ratio 620.3/885 to provide for comparable estimates between the two time periods. Hydrology version #TWDB201101 for the Laguna Madre Estuary does *not* reflect these adjustments.

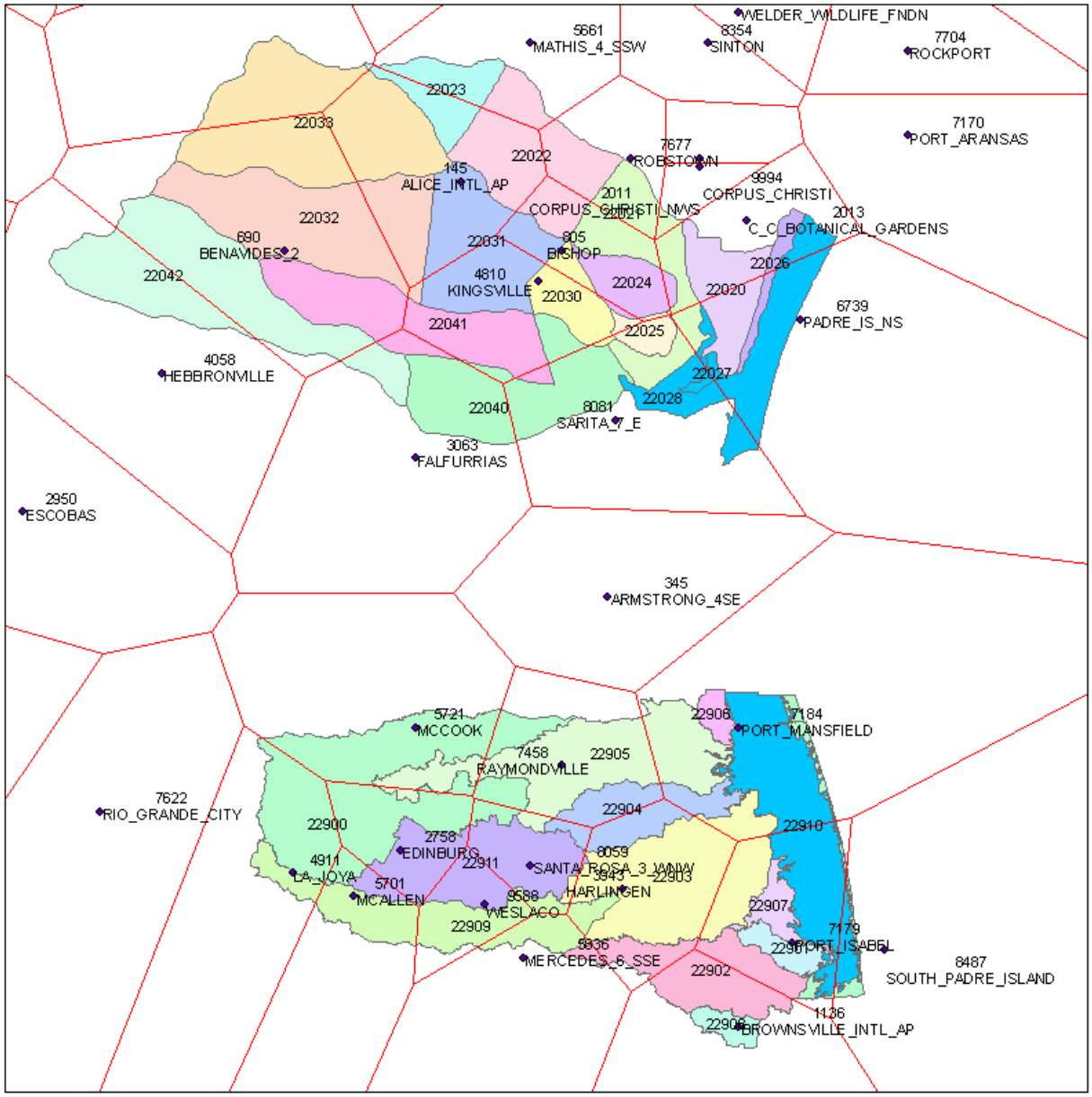

Figure 5. Rainfall stations (♦) and Thiessen polygons (red lines) used to estimate direct precipitation onto the Laguna Madre Estuary and associated ungaged watersheds.

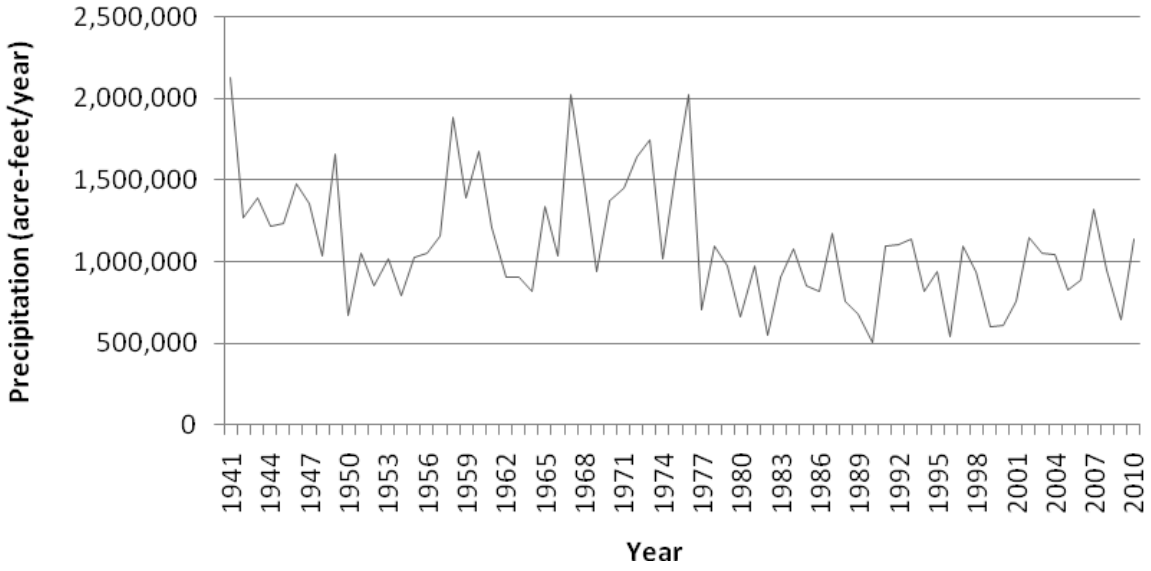

Figure 6. Annual estimates of precipitation (in acre-feet/year) for the entire Laguna Madre from 1941 - 2010. Precipitation estimates prior to 1977 were based on a larger bay surface area of 885 mi.^{2} versus the current estimate of 620.3 mi.^{2}, hence the apparent decline in precipitation after 1976. *Note*: These are the values presented in hydrology version #TWDB201101 for the Laguna Madre Estuary.

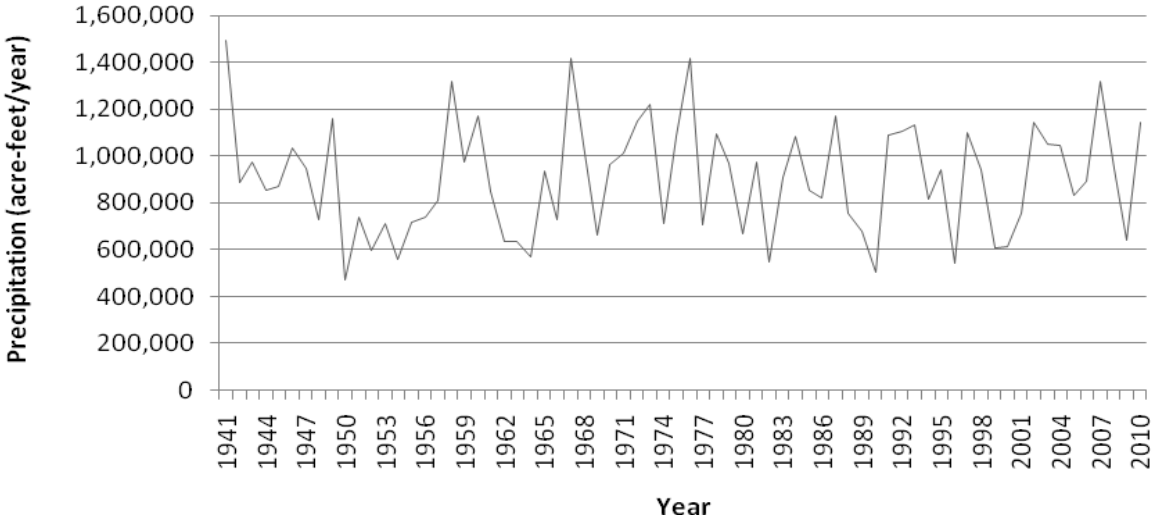

Figure 7. Area-adjusted estimates of annual precipitation on the estuary (in acre-feet/year) over the period 1941 - 2010. Values for 1941 - 1976 were adjusted based on current estimates of bay area using the ratio of 620.3/885.

Evaporation

Evaporation is calculated for the surface area of the bays using TWDB and NWS pan evaporation data to estimate evaporation rates. Bay segments used to calculate evaporation include segments #22027 and #22028 for Upper Laguna Madre and #22910 for the Lower Laguna Madre, which are located within quadrangle 1010, 1110, and 1210 (Figure 8). Total water evaporated from these bay segments is calculated by multiplying the segment's area by the observed evaporation rates obtained from TWDB. Evaporation rates are determined with a GIS-based program, *ThEvap*, using TWDB and NWS pan evaporation data. The *ThEvap* program replaced an older program, *WD0300*, previously run by the Texas Department of Water Resources (http://midgewater.twdb.state.tx.us/Evaporation/evap.html).

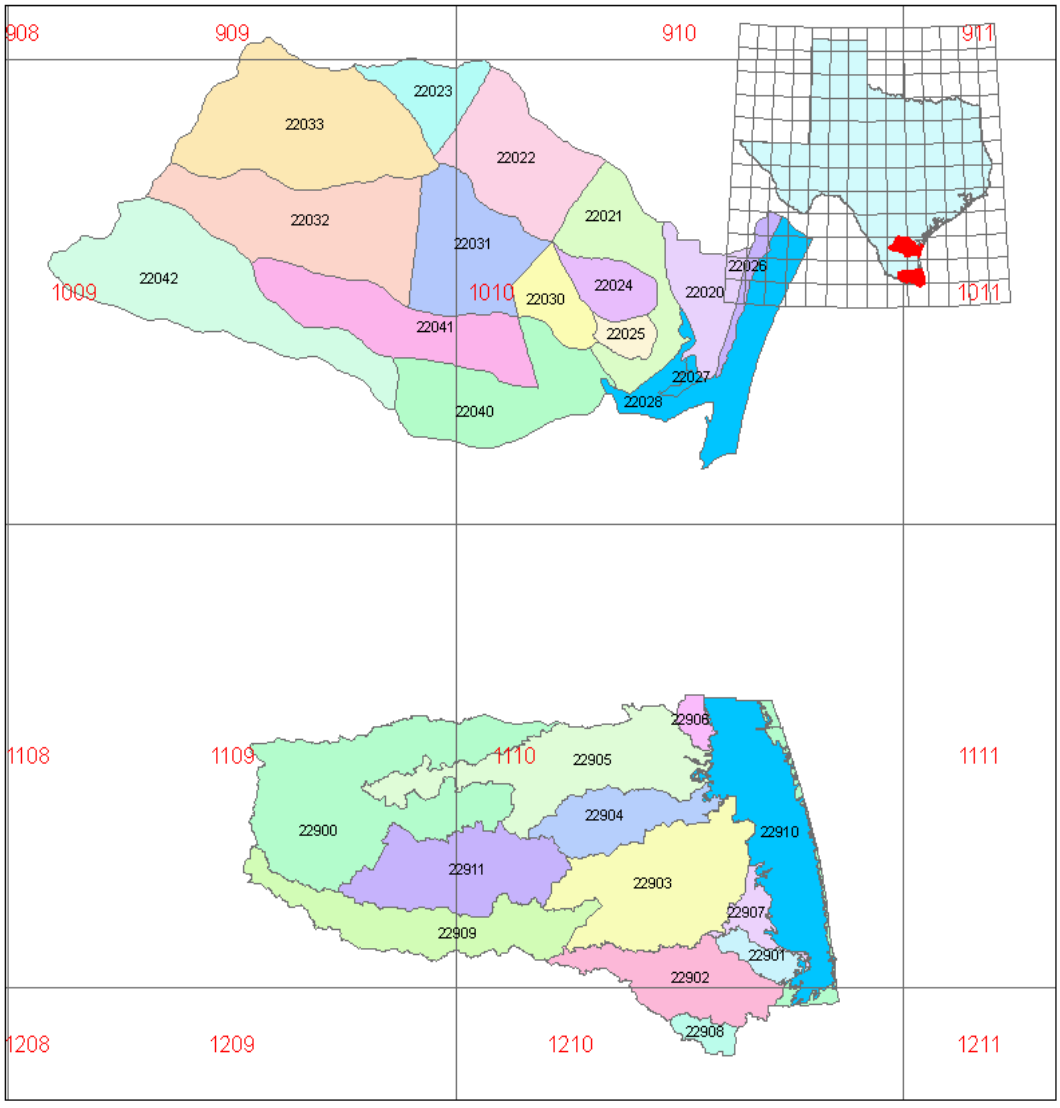

Figure 8. TWDB evaporation quadrangles used to estimate evaporation. Quadrangles 1010, 1110, and 1210 are used to estimate evaporation from the Laguna Madre bay segments #22027, #22028, and #22910.

Annual estimates of evaporation from the surface of the estuary, as prepared for hydrology version #TWDB201101 for the combined Laguna Madre Estuary, are shown in Figure 9. The decrease in evaporation estimates after 1976 is due to the use of decreased bay surface area estimates. Figure 10 shows the pre-1977 evaporation estimates adjusted for the more recent approximation of bay surface area by using a ratio of 620.3/885. However, hydrology version #TWDB201101 for the Laguna Madre Estuary, as presented in Appendix B, does not reflect these adjustments. Hydrology version #TWDB201101-L for the Lower Laguna Madre is not affected by the change in bay surface area because that dataset began in 1977, when the more accurate estimate for surface area became available.

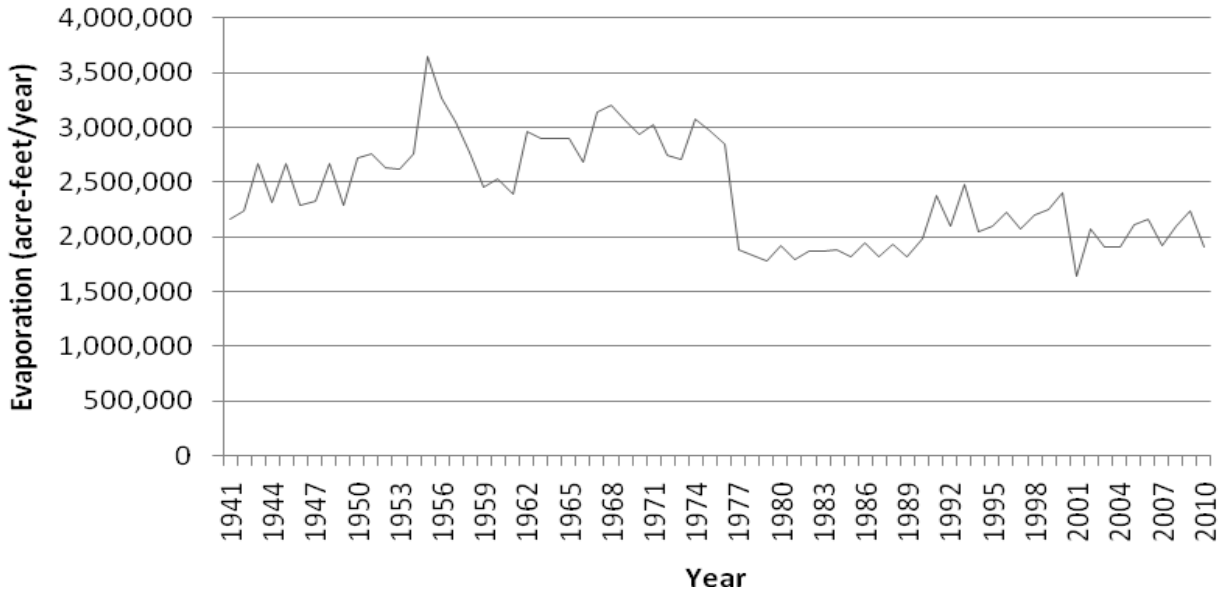

Figure 9. Annual estimates of evaporation (in acre-feet) for the combined Laguna Madre from 1941 - 2010. Evaporation estimates prior to 1977 are based on a larger bay surface area of 885 mi.^{2} versus the current estimate of 620.3 mi.^{2}, hence the apparent decline in evaporation after 1976. *Note*: These are the values presented in hydrology version #TWDB201101 for the Laguna Madre Estuary.

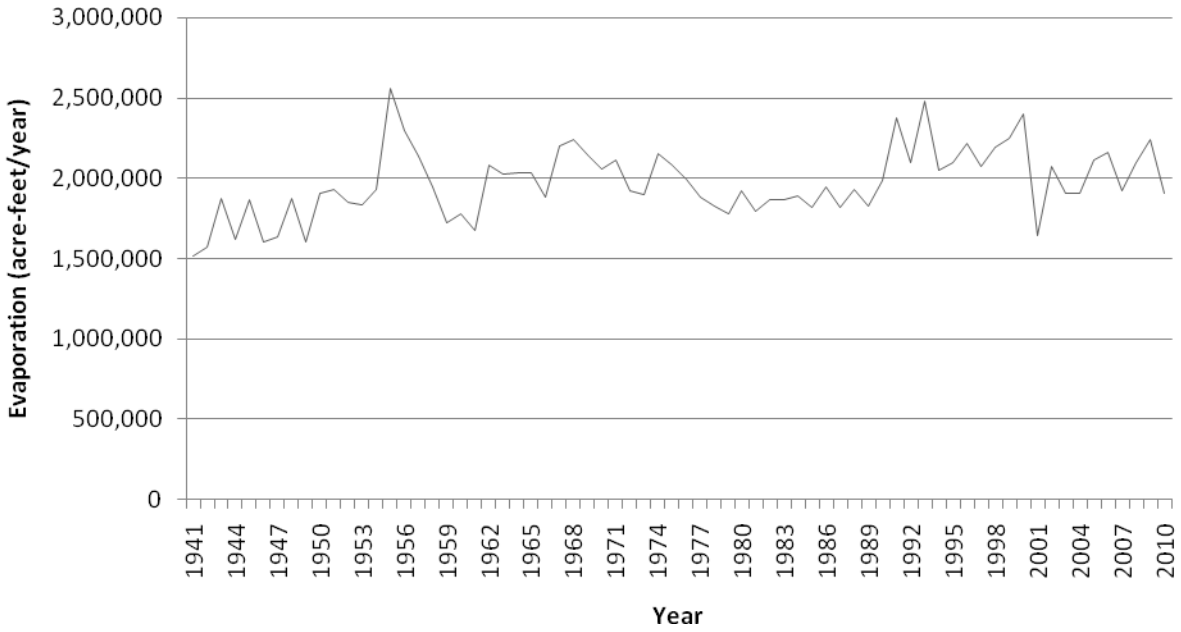

Figure 10. Area-adjusted estimates of annual evaporation from the estuary (in acre-feet/year) over the period 1941 - 2010. Values for 1941 - 1976 were adjusted based on current estimates of bay area using the ratio of 620.3/885.

Laguna Madre Estuary Hydrology Datasets (Upper + Lower)

Hydrology: Version #TWDB201001

TWDB coastal hydrology version #TWDB201001 for the entire Laguna Madre Estuary (upper and lower combined) included gaged and ungaged inflows through December 2008, with all estimates prior to 1977 coming from those reported in LP-182 (TDWR 1983). In cases where the USGS gaged record was missing data, TWDB modeled gaged flows for that period of time (refer to Table 1). Gaged flow data for the Lower Laguna Madre were obtained from the International Boundary and Water Commission (IBWC). Ungaged inflows were estimated using National Weather Service (NWS) precipitation data from 1941 – 2008. Diversion and return data prior to 1977 derived from LP-182, although the report did not specify diversion data for the period 1941 through 1976. After 1976, raw diversion data were obtained from TCEQ for the period from 1977 to 1988 and from the STWM for the period from 1989 through October 2005. Industrial and municipal return flow data were obtained from the TDWR self-reporting system from 1941 through 1976 and from TCEQ for the period from 1977 to 2007, and agricultural return flows also were calculated using agency data. However, LP-182 stated that industrial and municipal return flows were insignificant, and do not appear to be included in the 1941 – 1976 estimates. Additional return flow data were obtained from TWDB's agricultural return flow estimates through December 2005. Note that while this version of hydrology extends estimates of freshwater inflow from 1941 through 2008, not all components were

updated through 2008. Specifically, diversion and return flow estimates are not considered complete for the 2005 - 2008 period.

Hydrology version **#TWDB201002** and version **#TWDB201003** do not exist, due to the way in which the past versioning system was designed. TWDB is in the process of converting to a versioning system that will result in sequential versions for coastal hydrology datasets.

Hydrology: Version #TWDB201004

TWDB coastal hydrology version #TWDB201004 for the entire Laguna Madre Estuary (upper and lower) extended gaged inflow data (as reported in version #TWDB201001) through November 2009 and used provisional data for December 2009. In cases where the USGS gaged record was missing data (i.e. watershed 22911 was missing data for 1998 – 2010), TWDB modeled gaged flows for that period of time. Additional gaged flow data for the Lower Laguna Madre were obtained from the IBWC. Ungaged inflows were updated from coastal hydrology version #TWDB201001 using approved daily precipitation data from the NWS through November 2009, with provisional data for December 2009. Diversions were the same as in version #TWDB201001 which included non-specified data from LP-182 and TCEQ/STWM data through 2005. Diversion data obtained from HDR, Inc. extended the dataset through 2009, though missing diversion data remains for 2006. Prior to 2006, return flows were the same as in version #TWDB201001, but additional data obtained from TCEQ extended the data through December 2009, and agricultural return flow data obtained from TWDB were extended to December 2007. Note that while this version of hydrology extended estimates of freshwater inflow from 1941 through 2009, not all components were updated through 2009. Gaged inflows and precipitation data were provisional for December 2009, and agricultural return flows were not available after 2007.

Hydrology: Version #TWDB201101

TWDB hydrology version #TWDB201101 for the Laguna Madre Estuary was updated from version #TWDB201004 to extend gaged, ungaged, evaporation, and precipitation data through 2010. However, diversion and return flow data were not available to be updated. Gaged flow data were considered provisional from October through December 2010, as were precipitation data for September through December 2010. While this version of hydrology extends estimates of freshwater inflow from 1941 through 2010, not all components were updated through 2010. Specifically, diversion and return flow estimates are not considered complete for 2010. Figure 11 shows the combined annual surface inflow to the Laguna Madre Estuary as calculated for version #TWDB201101.

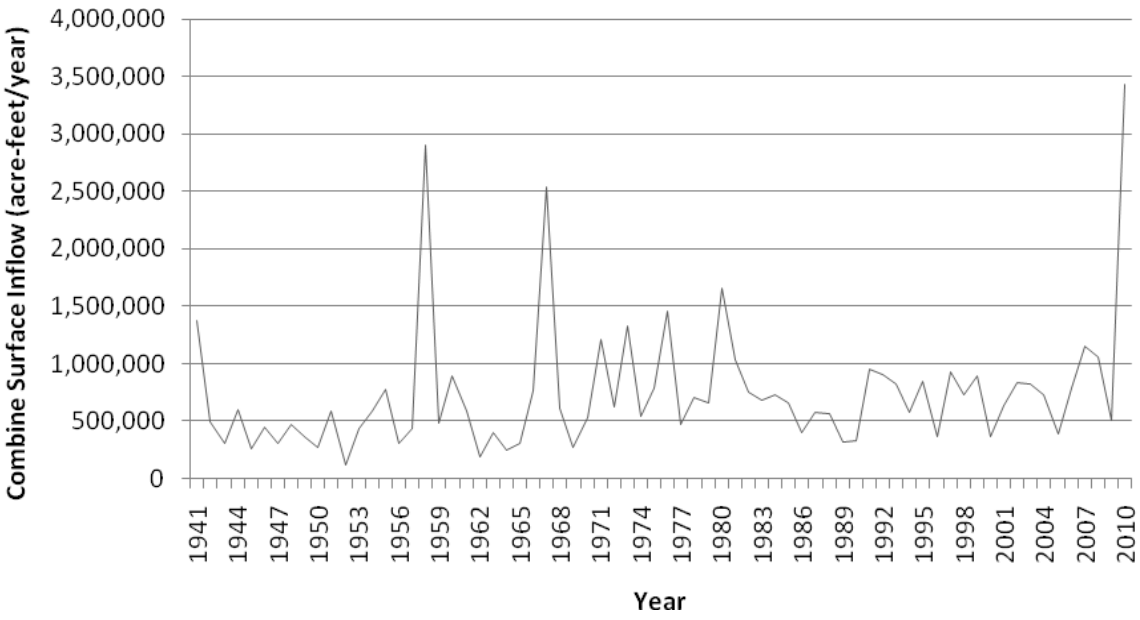

Figure 11. Annual estimates of combined surface inflow to the Laguna Madre Estuary (upper and lower) as calculated for version #TWDB201101 for the period from 1941 - 2010. *Note:* diversions and returns were not updated for 2010.

Lower Laguna Madre Hydrology Datasets

Hydrology: Version #TWDB201004 – L

TWDB coastal hydrology version #TWDB201004-L for the Lower Laguna Madre was extracted from version #TWDB201004, and includes only data for the Lower Laguna Madre watershed. This dataset is only available for the time period from 1977 - 2009.

Hydrology: Version #TWDB201101 – L

This version of coastal hydrology for the Lower Laguna Madre was updated from version #TWDB201004-L to extend gaged, ungaged, evaporation, and precipitation estimates through 2010. Diversion and return flow data were not updated for 2010, and thus are not considered complete. Gaged flow data were considered provisional from October through December 2010, and precipitation data were provisional for September through December 2010. Figure 12 shows total annual surface inflow to the Lower Laguna Madre Estuary as calculated for version #TWDB201101-L for the period from 1977 - 2010.

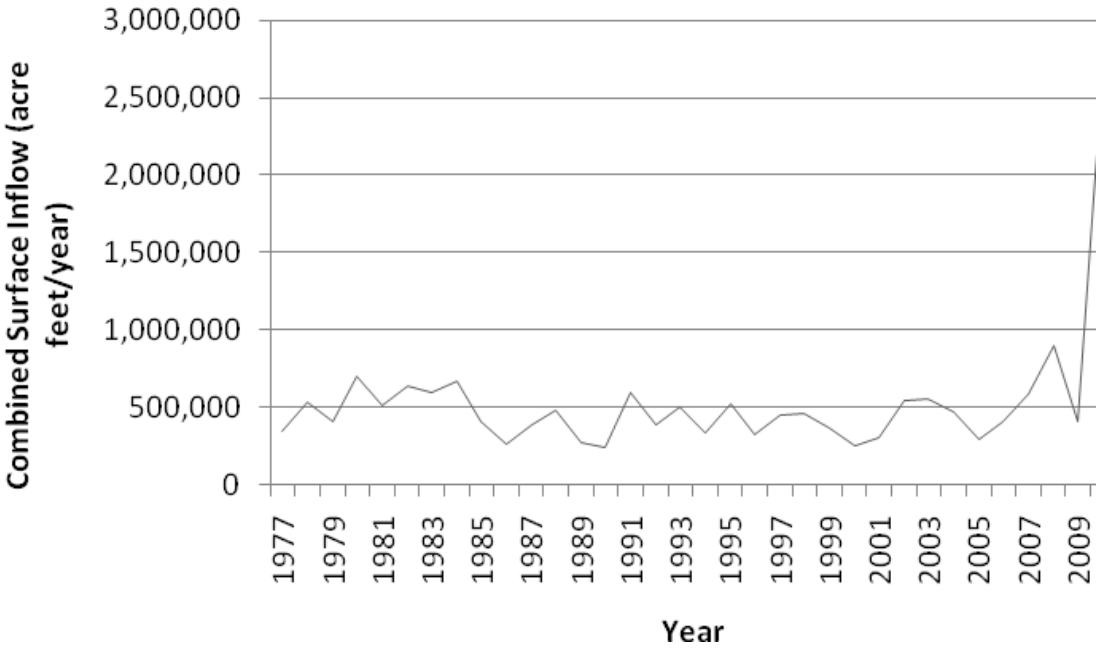

Figure 12. Annual estimates of combined surface inflow to the Lower Laguna Madre Estuary as calculated for version #TWDB201101-L for the period from 1977 - 2010. *Note:* diversions and returns were not updated for 2010.

Discussion

Versions #TWDB201101 and #TWDB201101-L of coastal hydrology for the Laguna Madre Estuary, presented herein, are the most up-to-date data sets representing not only combined freshwater inflows but also the individual components of inflows (*i.e*., gaged flows, ungaged flows, diversions, return flows) for the whole estuary for 1941 - 2010 and for the Lower Laguna Madre for 1977 - 2010, respectively. Appendix A summarizes recent updates, by version, to the estimates of hydrology for the Laguna Madre Estuary and the Lower Laguna Madre. Appendix B lists annual combined inflow along with the four components, as well as estimates for evaporation and precipitation on the estuary and the total freshwater inflow balance of the entire Laguna Madre Estuary. Appendix C lists summary statistics for the inflow components for the period 1941 - 2010 for the entire Laguna Madre. Appendix D lists annual combined inflow along with the four components, as well as estimates for evaporation and precipitation on the estuary and the total freshwater inflow balance of the Lower Laguna Madre. Appendix E lists summary statistics for the inflow components for 1977 - 2010 for the Lower Laguna Madre.

Laguna Madre Estuary (Upper + Lower)

During the period from 1941 to 2010, gaged inflow to the Laguna Madre Estuary accounted for approximately 45 percent of combined surface inflows, while ungaged flows accounted for 51 percent and net diversions accounted for four percent. Specifically, average annual diversions totaled almost one percent of combined freshwater inflows, and average annual return flows totaled nearly 5 percent of inflows. Average combined surface inflow to the Laguna Madre Estuary over the study period was 743,924 acre-feet per year, and ranged from a minimum of 123,000 acre-feet in 1952 to 3,428,875 acre-feet in 2010.

When considering total freshwater inflow balance, evaporation from and precipitation onto the surface of the estuary must be taken into account. In 60 out of 70 years, there was a negative freshwater inflow balance, which indicates that evaporation exceeded precipitation and combined inflow to the estuary. During this period of record, average annual evaporation was approximately 2,395,299 acre-feet, while average annual precipitation was 1,102,724 acre-feet over the surface of the Laguna Madre estuary. Thus, average freshwater inflow balance for the Laguna Madre estuary was approximately -548,652 acre-feet per year. However, as Appendix B shows, wide variations from the mean freshwater inflow balance occurred, ranging from a minimum of -1,919,000 acre-feet in 1956 to a maximum of 2,661,555 acre-feet in 2010.

Lower Laguna Madre Estuary

During the period from 1977 to 2010, gaged inflow to the Lower Laguna Madre accounted for approximately 60 percent of combined inflow, while ungaged flows accounted for about 38 percent and net diversions accounted for two percent. Specifically, average annual diversions totaled less than one percent of combined freshwater inflows, and average annual return flows totaled almost three percent of inflows. Average combined surface inflow to the Lower Laguna Madre Estuary over the study period was approximately 523,602 acre-feet per year, and ranged from a minimum of 234,158 acre-feet in 1990 to 2,726,325 acre-feet in 2010.

Evaporation from and precipitation onto the surface of the estuary also were considered in order to determine the total freshwater inflow balance. In 30 out of 34 years, there was a negative freshwater inflow balance, indicating that evaporation exceeded precipitation and combined inflow to the estuary. During this period of record, average annual evaporation was approximately 1,554,580 acre-feet, while average annual precipitation was 664,629 acre-feet over the surface of the Lower Laguna Madre Estuary. Thus, the average freshwater inflow balance for the Lower Laguna Madre estuary was -366,348 acre-feet per year. However, as Appendix F shows, wide variations from the mean freshwater inflow balance occurred, ranging from a minimum of -1,092,699 acre-feet in 1996 to a maximum of 2,225,448 acre-feet in 2010.

Literature Cited

TDWR. 1983. *Laguna Madre Estuary: A study of the Influence of Freshwater Inflows*. LP-182. Texas Department of Water Resources, Austin, Texas.

Guthrie, C.G. and Q. Lu. 2010. *Coastal Hydrology for the Guadalupe Estuary: Updated Hydrology with Emphasis on Diversion and Return Flow Data for 2000 - 2009*. Texas Water Development Board, Austin, Texas.

Appendix A. Record of coastal hydrology versions developed by the TWDB Bays & Estuaries Program for the Laguna Madre Estuary.

Estuary	Version	Date Range	Gaged Flows	Ungaged Flows	Diversions	Return Flows	Creation Date
Laguna Madre (Upper and Lower Combined)	TWDB201001	1941-2008	1941-2008	1941-2008	1941-2005 TCEQ 1977-1988 STWM 1989-2005	1941-2007 TDWR 1941-1976 TCEQ 1977-2007 TWDB 1977-2005 (Agricultural)	Jan 2010
	TWDB201002	Dataset does not exist.					
	TWDB201003	Dataset does not exist.					
	TWDB201004	1941-2009	1941-2009 USGS & IBWC USGS provisional 12/09	1941-2009 Precipitation data provisional for 12/09	1941 -2009 TCEQ 1977 -1988 STWM 1989-2005 HDR 2007-2009	1941-2009 TDWR 1941-1976 TCEQ 1977-2009 TWDB 1977-2007 (Agricultural)	Sep 2010
	TWDB201101	1941-2010	1941-2010 USGS & IBWC USGS provisional for 10/2010 – 12/2010	1941-2010 Precipitation data provisional 9/10 – 12/10	1941 -2009 TCEQ 1977 -1988 STWM 1989-2005 HDR 2007-2009	1941-2009 TDWR 1941-1976 TCEQ 1977-2009 TWDB 1977-2007 (Agricultural)	May 2011

Appendix A *Continued*. Record of coastal hydrology versions developed by the TWDB Bays & Estuaries Program for the Lower Laguna Madre Estuary.

Estuary	Version	Date Range	Gaged Flows	Ungaged Flows	Diversions	Return Flows	Creation Date
Lower Laguna Madre	TWDB201004 - L	1977-2009	1977-2009 USGS & IBWC, USGS provisional 12/09	1977-2009 Precipitation data provisional for 12/09	1977-2009, TCEQ 1977 -1988 STWM 1989-2005 HDR 2007 - 2009	1977-2009 TCEQ 1977-2007 (Agricultural)	May 2011
	TWDB201101 - L	1977-2010	1977-2010 USGS & IBWC, USGS provisional 10/2010 – 12/2010	1977-2010 Precipitation data provisional 9/10 – 12/10	1977-2009, TCEQ 1977 -1988 STWM 1989-2005 HDR 2007 - 2009	1977-2009, TCEQ TWDB 1977-2007 (Agricultural)	May 2011

Appendix B. Annual hydrology for the Laguna Madre Estuary (upper and lower combined) as calculated by version #TWDB201101. Included are estimates of gaged and ungaged (modeled) inflows, diversions, and return flows, combined surface inflow to the estuary, as well as evaporation and direct precipitation on the estuary and the total freshwater balance of the estuary. All values are in units of acre-feet.

Year	Gage	Ungaged (Modeled)	Diversion	Return	Combined Surface Inflow*	Evaporation	Precipitation	Freshwater Balance**
1941	211,000	1,148,000	n/a	14,000	1,373,000	2,165,000	2,128,000	1,336,000
1942	200,000	262,000	n/a	32,000	494,000	2,240,000	1,267,000	-479,000
1943	93,000	157,000	n/a	54,000	304,000	2,669,000	1,392,000	-973,000
1944	297,000	278,000	n/a	29,000	604,000	2,312,000	1,219,000	-489,000
1945	93,000	121,000	n/a	43,000	257,000	2,668,000	1,238,000	-1,173,000
1946	165,000	241,000	n/a	43,000	449,000	2,286,000	1,475,000	-362,000
1947	134,000	119,000	n/a	47,000	300,000	2,328,000	1,354,000	-674,000
1948	244,000	177,000	n/a	47,000	468,000	2,670,000	1,036,000	-1,166,000
1949	206,000	108,000	n/a	53,000	367,000	2,288,000	1,658,000	-263,000
1950	165,000	56,000	n/a	53,000	274,000	2,717,000	668,000	-1,775,000
1951	273,000	255,000	n/a	56,000	584,000	2,758,000	1,055,000	-1,119,000
1952	41,000	25,000	n/a	57,000	123,000	2,637,000	849,000	-1,665,000
1953	245,000	108,000	n/a	82,000	435,000	2,616,000	1,015,000	-1,166,000
1954	506,000	22,000	n/a	57,000	585,000	2,758,000	794,000	-1,379,000
1955	394,000	326,000	n/a	53,000	773,000	3,656,000	1,024,000	-1,859,000
1956	148,000	90,000	n/a	62,000	300,000	3,274,000	1,055,000	-1,919,000
1957	231,000	159,000	n/a	47,000	437,000	3,047,000	1,152,000	-1,458,000
1958	1,941,000	921,000	n/a	40,000	2,902,000	2,773,000	1,882,000	2,011,000
1959	284,000	174,000	n/a	23,000	481,000	2,453,000	1,390,000	-582,000
1960	372,000	484,000	n/a	40,000	896,000	2,537,000	1,672,000	31,000
1961	300,000	247,000	n/a	44,000	591,000	2,396,000	1,211,000	-594,000
1962	122,000	11,000	n/a	53,000	186,000	2,967,000	909,000	-1,872,000
1963	291,000	71,000	n/a	43,000	405,000	2,894,000	908,000	-1,581,000
1964	181,000	24,000	n/a	47,000	252,000	2,906,000	815,000	-1,839,000
1965	149,000	84,000	n/a	67,000	300,000	2,901,000	1,336,000	-1,265,000
1966	332,000	413,000	n/a	19,000	764,000	2,682,000	1,038,000	-880,000
1967	1,164,000	1,313,000	n/a	58,000	2,535,000	3,142,000	2,025,000	1,418,000
1968	210,000	373,000	n/a	33,000	616,000	3,200,000	1,502,000	-1,082,000
1969	170,000	42,000	n/a	57,000	269,000	3,065,000	942,000	-1,854,000
1970	181,000	293,000	n/a	57,000	531,000	2,932,000	1,373,000	-1,028,000
1971	639,000	513,000	n/a	53,000	1,205,000	3,021,000	1,447,000	-369,000
1972	300,000	288,000	n/a	31,000	619,000	2,741,000	1,643,000	-479,000
1973	410,000	885,000	n/a	37,000	1,332,000	2,704,000	1,742,000	370,000
1974	360,000	131,000	n/a	53,000	544,000	3,074,000	1,017,000	-1,513,000

Year	Gage	Ungaged (Modeled)	Diversion	Return	Combined Surface Inflow*	Evaporation	Precipitation	Freshwater Balance**
1975	368,000	371,000	n/a	48,000	787,000	2,967,000	1,548,000	-632,000
1976	667,000	768,000	n/a	25,000	1,460,000	2,844,000	2,021,000	637,000
1977	207,558	246,989	90	14,469	468,926	1,878,843	706,841	-703,076
1978	414,967	273,861	400	15,963	704,391	1,829,334	1,095,391	-29,552
1979	236,940	410,718	90	15,708	663,276	1,780,760	970,654	-146,830
1980	301,653	1,340,084	869	14,740	1,655,608	1,925,237	666,536	396,907
1981	272,759	747,762	85	13,559	1,033,995	1,798,507	971,595	207,083
1982	404,759	338,240	150	13,043	755,892	1,864,832	548,030	-560,910
1983	444,845	225,221	340	12,905	682,631	1,863,898	906,691	-274,576
1984	320,832	394,303	90	13,149	728,194	1,888,187	1,082,553	-77,440
1985	296,962	353,168	185	11,680	661,625	1,822,172	853,539	-307,008
1986	209,810	181,563	2,965	11,287	399,695	1,946,407	822,581	-724,131
1987	249,262	311,201	1,231	12,064	571,296	1,816,257	1,172,464	-72,497
1988	341,681	207,466	1,192	13,768	561,723	1,930,217	755,298	-613,196
1989	226,520	77,487	2,567	12,984	314,424	1,823,416	676,679	-832,313
1990	217,596	103,560	7,730	13,501	326,927	1,987,516	504,793	-1,155,796
1991	412,675	523,766	106	15,446	951,781	2,380,472	1,091,500	-337,191
1992	334,528	559,070	116	16,271	909,753	2,099,296	1,105,299	-84,244
1993	310,513	490,528	53	16,911	817,899	2,480,419	1,134,999	-527,521
1994	284,872	276,754	107	16,406	577,925	2,047,924	815,418	-654,581
1995	365,515	465,274	111	20,457	851,135	2,098,985	939,874	-307,976
1996	207,272	142,003	80	21,165	370,360	2,220,110	542,836	-1,306,914
1997	213,463	704,066	n/a	12,037	929,566	2,074,699	1,099,005	-46,128
1998	190,100	522,096	n/a	13,256	725,452	2,194,269	941,277	-527,540
1999	159,755	720,164	n/a	10,415	890,334	2,250,312	605,236	-754,742
2000	146,974	185,935	28	32,341	365,222	2,401,347	612,291	-1,423,834
2001	219,252	380,931	248	37,171	637,106	1,645,660	754,959	-253,595
2002	239,771	555,529	248	44,475	839,527	2,072,431	1,144,542	-88,362
2003	209,295	564,002	248	50,021	823,070	1,907,619	1,052,081	-32,468
2004	249,851	441,664	68	41,702	733,149	1,909,235	1,047,067	-129,019
2005	190,281	156,045	29	40,562	386,859	2,116,261	830,209	-899,193
2006	225,991	520,795	n/a	43,791	790,577	2,159,729	890,122	-479,030
2007	259,320	853,836	188	43,479	1,156,447	1,920,920	1,320,633	556,160
2008	341,824	673,069	301	41,600	1,056,192	2,097,728	947,145	-94,391
2009	229,569	233,274	323	40,330	502,850	2,241,158	641,050	-1,097,258
2010	2,355,774	1,073,101	n/a	n/a	3,428,875	1,908,793	1,141,473	2,661,555

*Combined Surface Inflow = Gage + Model - Diversion + Return

**Freshwater Balance = Surface Inflow – Evaporation + Precipitation

Appendix C. Summary statistics for annual freshwater inflow (in acre-feet) for the period 1941 - 2010 for the Laguna Madre Estuary (combined Upper and Lower) based on hydrology version #TWDB201101.

Year	Gage	Model	Diversion*	Return*	Combined Surface Inflow*	Evaporation	Precipitation	Freshwater Balance*
MIN	41,000	11,000	28	10,415	123,000	1,645,660	504,793	-1,919,000
5th%ile	127,400	32,650	39	12,048	262,400	1,818,919	608,411	-1,847,250
10th%ile	148,900	76,838	65	13,031	300,000	1,860,442	667,854	-1,589,400
25th%ile	206,318	156,284	90	15,708	412,500	1,956,684	850,135	-1,146,597
MEDIAN	247,131	283,000	185	40,000	610,000	2,300,000	1,049,574	-571,455
MEAN	333,996	375,879	698	34,836	743,924	2,395,299	1,102,724	-548,652
75th%ile	339,893	518,846	340	48,000	835,413	2,753,750	1,307,225	-103,048
90th%ile	417,955	776,584	1,498	57,000	1,217,700	3,023,600	1,644,500	372,691
95th%ile	654,400	1,004,656	2,806	57,600	1,567,584	3,111,400	1,819,000	1,021,450
MAX	2,355,774	1,340,084	7,730	82,000	3,428,875	3,656,000	2,128,000	2,661,555
TOTAL	23,379,739	26,311,525	20,238	2,403,656	52,074,682	167,670,950	77,190,661	-38,405,607

*2010 estimates do not include diversion and return data, which may affect combined surface inflow and freshwater balance estimates.

Appendix D. Annual hydrology for the Lower Laguna Madre Estuary based on version #TWDB201101-L. Included are estimates of gaged and ungaged (modeled) inflows, diversions, and return flows, combined surface inflows to the estuary, as well as evaporation and direct precipitation on the estuary and the total freshwater balance of the estuary. All values are in units of acre-feet.

Year	Gage	Ungaged	Diversion	Return	Combined Surface Inflow*	Evaporation	Precipitation	Freshwater Balance**
1977	205,041	136,157	n/a	5,081	346,279	1,588,213	597,749	-644,185
1978	412,174	117,321	310	6,055	535,240	1,546,362	913,864	-97,258
1979	228,400	175,997	n/a	6,138	410,535	1,505,301	789,892	-304,874
1980	270,175	418,846	469	6,688	695,240	1,627,432	529,313	-402,879
1981	262,032	238,035	n/a	5,600	505,667	1,520,306	803,839	-210,800
1982	393,485	240,503	n/a	5,735	639,723	1,576,370	450,350	-486,297
1983	438,105	153,466	n/a	4,991	596,562	1,575,578	737,252	-241,764
1984	318,574	341,635	n/a	5,813	666,022	1,596,110	975,189	45,101
1985	266,774	138,618	n/a	5,522	410,914	1,540,308	673,550	-455,844
1986	201,188	59,541	2,515	5,472	263,686	1,645,328	671,971	-709,671
1987	221,836	152,893	761	6,510	380,478	1,535,309	1,033,363	-121,468
1988	325,077	142,578	585	7,401	474,471	1,631,642	658,288	-498,883
1989	222,258	46,038	657	6,976	274,615	1,541,362	592,486	-674,261
1990	196,909	37,132	7,640	7,757	234,158	1,680,076	416,655	-1,029,263
1991	312,988	268,189	72	9,465	590,570	2,012,247	869,118	-552,559
1992	261,561	118,455	26	9,223	389,213	1,774,566	935,706	-449,647
1993	272,082	224,005	19	8,751	504,819	2,096,734	904,909	-687,006
1994	248,515	80,501	28	8,845	337,833	1,731,138	678,287	-715,018
1995	275,599	238,156	111	4,737	518,381	1,774,304	790,946	-464,977
1996	206,245	113,315	22	4,365	323,903	1,876,693	460,091	-1,092,699
1997	212,511	236,538	n/a	3,494	452,543	1,753,773	926,229	-375,001
1998	184,982	265,028	n/a	6,682	456,692	1,854,846	793,838	-604,316
1999	154,928	202,450	n/a	3,134	360,512	1,902,221	505,627	-1,036,082
2000	144,403	81,720	n/a	26,146	252,269	1,497,000	347,802	-896,929
2001	166,080	107,734	n/a	29,765	303,579	894,440	357,355	-233,506
2002	197,165	309,878	n/a	36,114	543,157	1,337,379	662,267	-131,955
2003	195,794	316,971	n/a	41,464	554,229	1,218,900	558,165	-106,506
2004	229,560	201,245	n/a	33,231	464,036	1,188,177	503,578	-220,563
2005	184,285	76,872	n/a	35,216	296,373	1,341,942	470,239	-575,330
2006	214,509	151,542	n/a	39,083	405,134	1,382,558	514,880	-462,544
2007	241,477	301,332	n/a	37,020	579,829	1,230,027	804,393	154,195
2008	340,377	522,161	n/a	36,546	899,084	1,317,974	617,430	198,540
2009	228,712	146,478	n/a	35,217	410,407	1,380,016	372,566	-597,043
2010	2,304,477	421,848	n/a	n/a	2,726,325	1,181,079	680,202	2,225,448

*Combined Surface Inflow = Gage + Model - Diversion + Return

**Freshwater Balance = Surface Inflow – Evaporation + Precipitation

Appendix E. Summary statistics for annual freshwater inflow (in acre-feet) for the period 1977 - 2010 for the Lower Laguna Madre, version #TWDB201101-L.

Year	Gage	Ungaged	Diversion*	Return*	Combined Surface Inflow*	Evaporation	Precipitation	Freshwater Balance*
MIN	144,403	37,132	19	3,134	234,158	894,440	347,802	-1,092,699
5th%ile	162,177	54,815	21	4,017	259,690	1,185,693	367,242	-1,031,650
10th%ile	184,494	77,961	23	4,788	281,142	1,222,238	426,764	-842,356
25th%ile	202,151	117,605	28	5,600	349,837	1,380,652	507,940	-634,218
MEDIAN	229,136	164,732	310	6,976	454,618	1,560,970	667,119	-459,194
MEAN	309,949	199,505	1,017	14,977	523,602	1,554,580	664,629	-366,348
75th%ile	274,720	258,897	657	29,765	551,461	1,718,373	801,339	-213,241
90th%ile	377,553	334,236	2,164	36,460	658,132	1,870,139	922,520	2,393
95th%ile	421,250	419,897	4,565	37,845	766,585	1,940,730	949,525	169,716
MAX	2,304,477	522,161	7,640	41,464	2,726,325	2,096,734	1,033,363	2,225,448
TOTAL	10,538,278	6,783,178	13,215	494,237	17,802,478	52,855,711	22,597,389	-12,455,844

*2010 estimates do not include diversion and return data, which may affect combined surface inflow and freshwater balance estimates.