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

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Bays & Estuaries Program
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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.

<table>
<thead>
<tr>
<th>Estuary</th>
<th>Segment</th>
<th>Gage Station Number</th>
<th>Gage Location</th>
<th>Utilized Period of Record</th>
<th>Modeled Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IBWC 08470400</td>
<td>Arroyo Colorado at Harlingen</td>
<td>1958 - present</td>
<td>None</td>
</tr>
</tbody>
</table>

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-operative (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.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Watershed ID Number</th>
<th>LP-182 (Square Miles) 1941-1976</th>
<th>Watershed ID Number</th>
<th>Current Area (Square Miles) 1977-2009</th>
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</thead>
<tbody>
<tr>
<td>Upper Laguna Madre</td>
<td>22020</td>
<td>134</td>
<td>22020</td>
<td>141.94</td>
</tr>
<tr>
<td></td>
<td>22021</td>
<td>191</td>
<td>22021</td>
<td>227.33</td>
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<tr>
<td></td>
<td>22022</td>
<td>228</td>
<td>22022</td>
<td>290.94</td>
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<tr>
<td></td>
<td>22023</td>
<td>91</td>
<td>22023</td>
<td>121.2</td>
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<tr>
<td></td>
<td>22024</td>
<td>84</td>
<td>22024</td>
<td>90.02</td>
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<td></td>
<td>22025</td>
<td>89</td>
<td>22025</td>
<td>41.94</td>
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<td></td>
<td>22026</td>
<td>Not Applicable</td>
<td>22026</td>
<td>36.88</td>
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<tr>
<td></td>
<td>22030</td>
<td>64</td>
<td>22030</td>
<td>99.1</td>
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<td></td>
<td>22031</td>
<td>274</td>
<td>22031</td>
<td>277.06</td>
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<td></td>
<td>22032</td>
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<td>22032</td>
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<tr>
<td></td>
<td>22040</td>
<td>255</td>
<td>22040</td>
<td>313.62</td>
</tr>
<tr>
<td></td>
<td>22041</td>
<td>162</td>
<td>22041</td>
<td>304.9</td>
</tr>
<tr>
<td></td>
<td><strong>UPPER TOTAL</strong></td>
<td><strong>2,006</strong></td>
<td><strong>UPPER TOTAL</strong></td>
<td><strong>2,371.01</strong></td>
</tr>
<tr>
<td>Lower Laguna Madre</td>
<td>22050</td>
<td>122</td>
<td>22900</td>
<td>591.45</td>
</tr>
<tr>
<td></td>
<td>22057</td>
<td>102</td>
<td>22901</td>
<td>45.84</td>
</tr>
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<td></td>
<td>22060</td>
<td>97</td>
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<td>226.65</td>
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<tr>
<td></td>
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<td>-</td>
<td>-</td>
<td>22908</td>
<td>34.79</td>
</tr>
<tr>
<td></td>
<td><strong>LOWER TOTAL</strong></td>
<td><strong>680</strong></td>
<td><strong>LOWER TOTAL</strong></td>
<td><strong>1,914.86</strong></td>
</tr>
<tr>
<td>Upper and Lower Combined</td>
<td>Combined Total</td>
<td>2,686</td>
<td>Combined Total</td>
<td>4,285.87</td>
</tr>
</tbody>
</table>
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.*

<table>
<thead>
<tr>
<th>Upper Laguna Madre</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIVERSION</strong></td>
</tr>
<tr>
<td>Water Right Number</td>
</tr>
<tr>
<td>Owner</td>
</tr>
<tr>
<td>4147</td>
</tr>
<tr>
<td>4271</td>
</tr>
<tr>
<td>4507</td>
</tr>
<tr>
<td>5465</td>
</tr>
</tbody>
</table>

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

*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.

<table>
<thead>
<tr>
<th>Segment ID Number</th>
<th>LP-182 (Square Miles) 1941 - 1976</th>
<th>Segment ID Number</th>
<th>Current Area (Square Miles) 1977 - 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Laguna Madre</td>
<td>n/a</td>
<td>n/a</td>
<td>22027</td>
</tr>
<tr>
<td>Lower Laguna Madre</td>
<td>n/a</td>
<td>n/a</td>
<td>22028</td>
</tr>
<tr>
<td>Upper &amp; Lower Laguna Madre Combined</td>
<td>Total</td>
<td>885.0</td>
<td>Total</td>
</tr>
</tbody>
</table>

**Precipitation**

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](image-url)  
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. Diversion data 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**


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

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

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<th>Ungaged Flows</th>
<th>Diversions</th>
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**Appendix B.** Annual hydrology for the Laguna Madre Estuary (upper and lower combined) as calculated by version #TWDB201101. Included are estimates of gaged and unaged (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.

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<th>Diversion</th>
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<th>Combined Surface Inflow*</th>
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<td>Combined Surface Inflow*</td>
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*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.

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<th>Return*</th>
<th>Combined Surface Inflow*</th>
<th>Evaporation</th>
<th>Precipitation</th>
<th>Freshwater Balance*</th>
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*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 unaged (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.

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<th>Diversion</th>
<th>Return</th>
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<td>405,134</td>
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<td>1,181,079</td>
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<td>2,225,448</td>
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</table>

*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.

<table>
<thead>
<tr>
<th>Year</th>
<th>Gage</th>
<th>Ungaged</th>
<th>Diversion*</th>
<th>Return*</th>
<th>Combined Surface Inflow*</th>
<th>Evaporation</th>
<th>Precipitation</th>
<th>Freshwater Balance*</th>
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<td>144,403</td>
<td>37,132</td>
<td>19</td>
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<td>766,585</td>
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</tbody>
</table>

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