Richard L. Watson, Ph.D., P.G.
Consulting Geologist
P.O. Box 1040   Port Aransas, Tx 78373
(361) 749-4152   (253) 981-0412 fax
(361) 332-9720 cell   TexasCoastGeology.com
Richard@TexasCoastGeology.com

Geologic framework of the eolian sand plain and the Central Flats of Laguna Madre and circulation between northern and southern Laguna Madre.

July 10, 2008

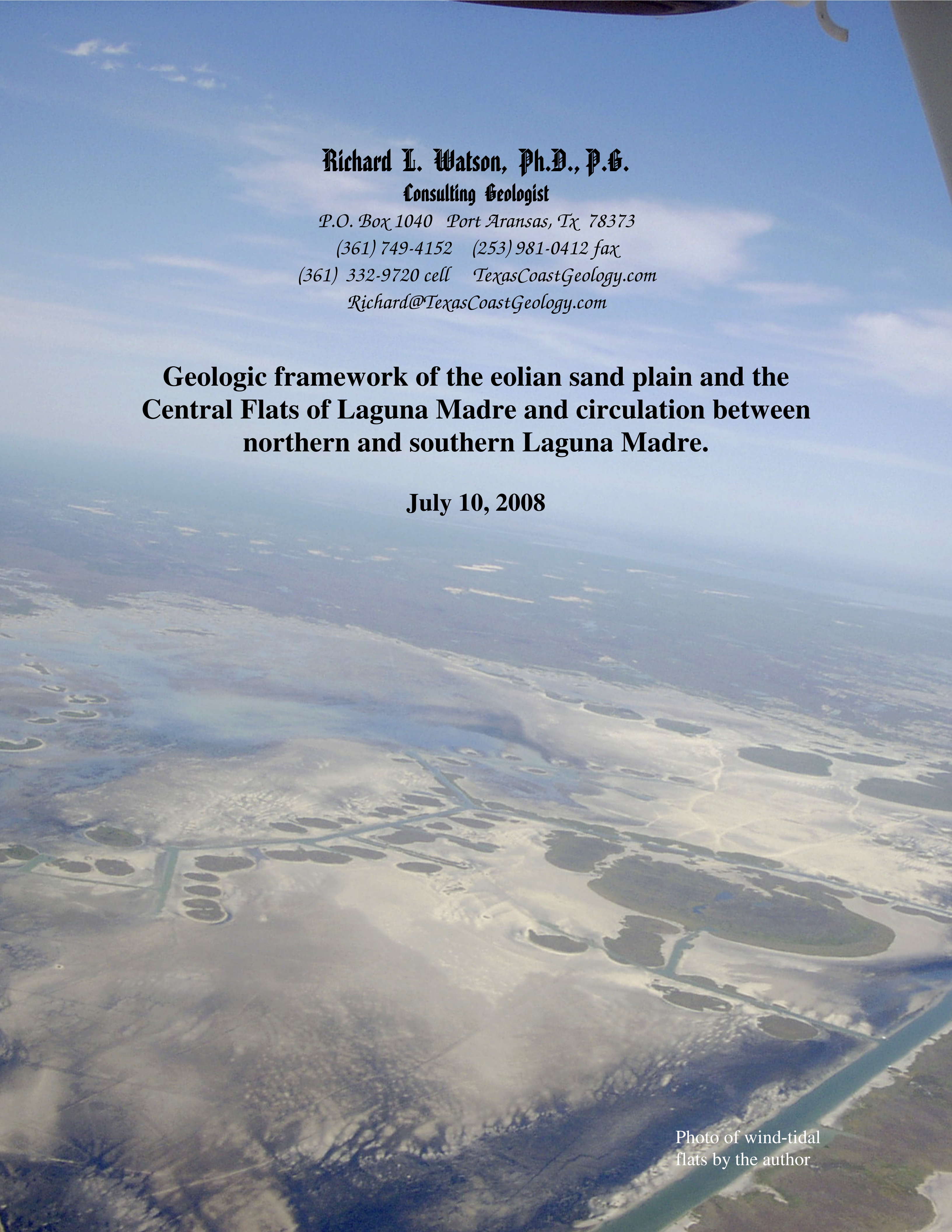

Photo of wind-tidal flats by the author

Richard L. Watson, Ph.D., P.G.
Consulting Geologist
P.O. Box 1040 Port Aransas, Tx 78373
(361) 749-4152 (253) 981-0412 fax
(361) 332-9720 cell TexasCoastGeology.com
Richard@TexasCoastGeology.com

Geologic framework of the eolian sand plain and the Central Flats of Laguna Madre and circulation between northern and southern Laguna Madre.

July 10, 2008

Prepared for:

Brown McCarroll, L.L.P.
Attorneys at Law
111 Congress Ave. Suite 1400
Austin, Tx. 78701

and

Baker Botts L.L.P.
1500 San Jacinto Center
98 San Jacinto Blvd.
Austin, TX 78701

STATE OF TEXAS
Richard L. Watson
Geology
10328
LICENSED
PROFESSIONAL GEOSCIENTIST

Richard L. Watson, Ph.D., P.G.
7/10/2008

2

Introduction

The plaintiffs contend that there is significant flow of fresh water or brackish water from the uplands passing under the Central Flats to the Gulf Intracoastal Waterway (GIWW) at the Land Cut and that flow reduces salinity in Laguna Madre. I will show that if flow exists, it is pushing extremely hypersaline water from salts concentrated in the Central Flats into the GIWW. Further, I will show that the wind-driven circulation transporting water between northern and southern Laguna Madre exceeds the most generous conceivable estimate of hypothetical flow of ground water from the uplands to the GIWW by a factor of 1000. In other words, I will show that even if fresh ground water from the uplands is flowing into the GIWW, it will take nearly three years for it to equal the amount of water that is flowing through the GIWW between northern and southern Laguna Madre in a single day. Since the GIWW at the Land Cut is an insignificant percentage of the total volume of Laguna Madre, this exceedingly small hypothetical volume of water flow into the GIWW at the land cut, no matter the salinity of that flow, whether fresh, brackish or hypersaline would have no measurable effect on Laguna Madre.

Geologic Framework

The eolian sand plain and banner dune complexes

The Gulf Wind and Penascal wind farm sites are located in the San Pedro and Sarita eolian sand lobes of the Eolian Sand Plain, also known as the South Texas Sand Sheet (STSS). It is composed of wind deposited sand and intervening wind deflated areas, which extend over a vast area of the South Texas coast (Fig. 1).

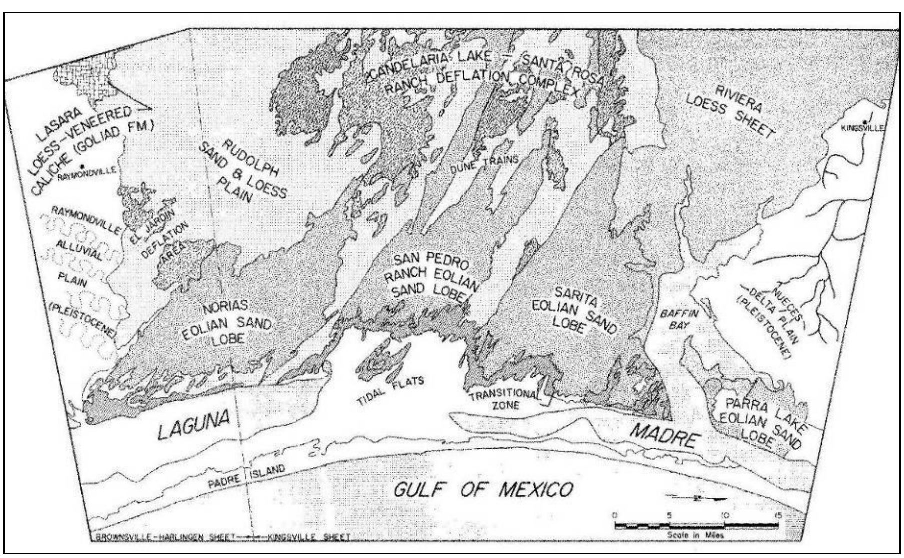

Figure 1. Principal elements within the South Texas eolian system (Brown, et al., 1977).

> *Sarita eolian sand lobe.* – This dune complex constitutes the largest eolian lobe within the South Texas System... It is composed of active sand dunes and blowout areas, as well as oak-covered relict (stabilized) dunes and base-leveled or stripped dune fields… Base-leveled dune fields display prominent textural and topographic "grain" on aerial photographs and topographic maps, respectively. This grain is produced by repeated eolian blowout, dune migration, and erosion. The unique texture and topography of the stripped plains are the "scars" of repeated dune development and eventual base-leveling by wind erosion as the dunes migrated downwind (Brown, et al., 1977, p. 74). [1]

Figure 2. Isolated banner dune and trailing base-leveled flat (photo by author).

Since the dominant winds that transport sand are the strong southeast winds, the long axis of the deflated areas extend from southeast to northwest. Figure 2 shows a banner dune (Price, 1958) with a triangular deflation area to the southeast and the active migrating dune as the white area to the northwest. These start as a small area at the apex of the triangle in the southeast, where erosion caused bare sand to be exposed and dune movement to initiate. As the dune migrates to the northwest, it leaves a flat base-leveled

[1] Text which is inset in a smaller font, such as this, is a long quote from the author cited and the end of the indented text.

area behind, where the surface is eroded down to damp sand. As the dune moves, it becomes wider by spilling laterally off the ends of the active face, forming the classic triangular shape of the banner dune (Fig. 3). This particular example is unusual in that it is isolated and it is easy to understand. Over most of the eolian sand plain, these banner dunes and trailing flats have run over the same area many times, creating the complex topography of low flats (which often become wetlands), active dune areas of bare, white sand, high hummocky areas of sand dunes that have become vegetated and stabilized by grasses and finally by oak mottes. Eventually another cycle will even have active dunes overrun old flats and oak mottes and kill the trees as dune ridges as high as 40 feet advance across them (Fig. 4).

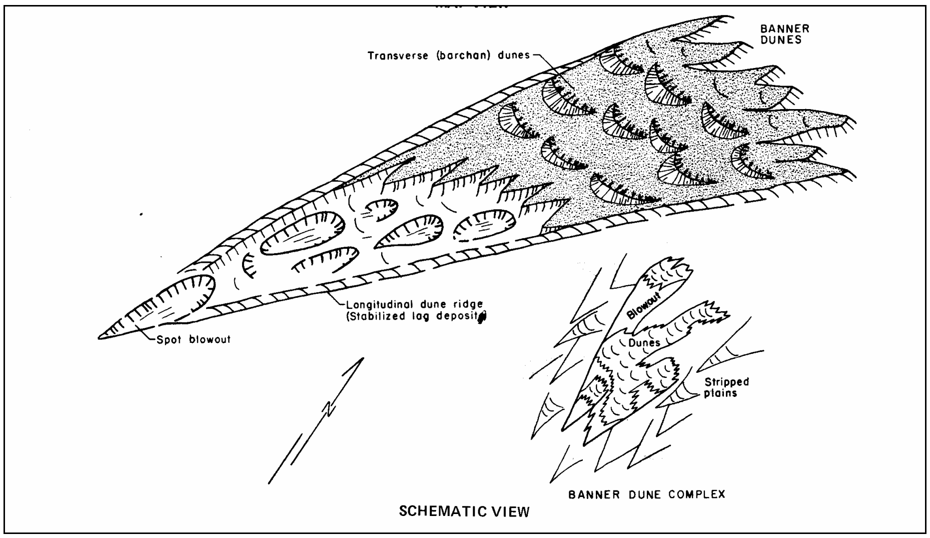

Figure 3. Schematic view of a banner dune and a dune complex produced by successive passage of multiple individual banner dunes (Brown, et al., 1977, p76).

"The San Pedro ranch lobe, located in the central part of the Kingsville map area, is composed of the same fundamental environments and eolian features that characterize the Sarita and Norias lobes..."(Brown, et al., 1977, p.77).

It has long been known that there is a convergence of longshore sediment transport on Central Padre Island adjacent to Kenedy County (Watson, 1971). This has brought an excess of sand to the beaches of Kenedy County and over thousands of years has provided the huge source of sand required to fill Laguna Madre in the Central Flats and to supply the vast dune fields of the Eolian Sand Plain. Even though most of the Texas Gulf beaches are now eroding, there is a short stretch on Padre Island at the convergence area where Padre Island is still accreting seaward. The existence of relict lithified shell Gulf beaches on the mainland shore of Laguna Madre just south of Baffin Bay indicates that the same convergence of sediment transport occurred when they were deposited during the last high stand of sea level, perhaps 75,000 years ago. Sand has been abundantly supplied to Kenedy County for a very long time.

The huge area of tidal flats east of the San Pedro lobe represent massive wind erosion by this same process (Fig. 1, cover photo, and Fig. 16). Mesquite Rincon and some of the other highs on the Central Flats are remnants left behind as highs and longitudinal dune ridges along the sides of old blowout areas (Fig. 4). This provided a major source of sand for the San Pedro lobe. The wind-tidal flats east of the San Pedro lobe are several thousand years old. They are flooded by wind-tides generated by strong south and southeast winds and by major storms.

Figure 4. Banner dunes overrunning and killing oak trees (photo by author).

Ground Water in the Eolian Sand Plain

> The south Texas eolian plain deposits consist of tan to white, unfossiliferous, massive, fine to very fine sand, greenish-gray sandy clay, highly calcareous clay, caliche, marl, and thin-bedded clayey sand. Maximum thickness of the deposits is not known but is in excess of 60 feet in some places.
>
> The eolian deposits yield small quantities of slightly saline water to a few stock wells in Kenedy County. Well RD-88-10-303 in central Kenedy County yielded water having a chloride content of 1,410 mg/l from a depth of 40 feet. Shallow test wells from 19 to 24 feet deep which were drilled for observation purposes near Armstrong, reveal that in this area the eolian deposits contain brine with chloride concentrations as high as 28,000 mg/l. Fresh water is not known to be present anywhere in the deposits…[2]
>
> Most of the flowing wells in the area covered by this report are in Kenedy County. The Goliad Sand is the principal artesian aquifer, whereas water contained in eolian and barrier island deposits is under water-table conditions (Shafer and Baker, 1973, p. 18).

[2] The Armstrong Ranch is near highway 77 about 18 miles from the GIWW at the Land Cut.

The Penescal project drilled a 1200 ft. deep well to obtain water for their cement batch plant. It is obtaining water from the Goliad Sand, an artesian aquifer deep beneath the Kenedy Ranch.[3]

Shallow subsurface geology

In the late 1940s Harold Fisk did a massive study of the Central Flats area for the Humble Oil and Refining Company in conjunction with a lawsuit concerning the ownership of the Central Flats and thus the mineral rights beneath them (Fisk, H.N., 1949) *Sun Oil Co. v. Humble Oil & Refining Co.* 190 F.2d 71 (Tex. 1944). This study included collecting thousands of deep and shallow cores, topographic and hydrologic studies. Some of the results were published by Fisk in 1959.

Fisk's cores revealed Pleistocene river valleys below the flats that were incised during the latest low stand of sea level and are now buried beneath the wind-tidal flats of the Central Flats (Fig. 5). Note the location of cross-section. The cross section, B-B' goes from the upland and the eolian sand plain on the west to Padre Island on the east (Fig. 6).

Note that on the west, the closed lagoon (wind-tidal flat sediments) of the Central Flats overlie the eolian sand plain sediments from the upland edge to about 5 miles to the east. It is the upper part of this eolian plain complex that was nearly completely blown inland to form the San Pedro lobe. They are not labeled as such, but Pleistocene sediments underlie the eolian sand plain complex sediments.

The wind-tidal flat sediments of the Central Flats accreted upward at a rate of 0.1 to 0.2 feet per century, along with rising sea level over the past several thousand years (Miller, 1974, Watson, 1995).

[3] Personal communication, Mike W. Robbins, Ecologist, CH2M Hill

Figure 5. Late Pleistocene streams and location of cross sections (Fisk, 1959, p. 147).

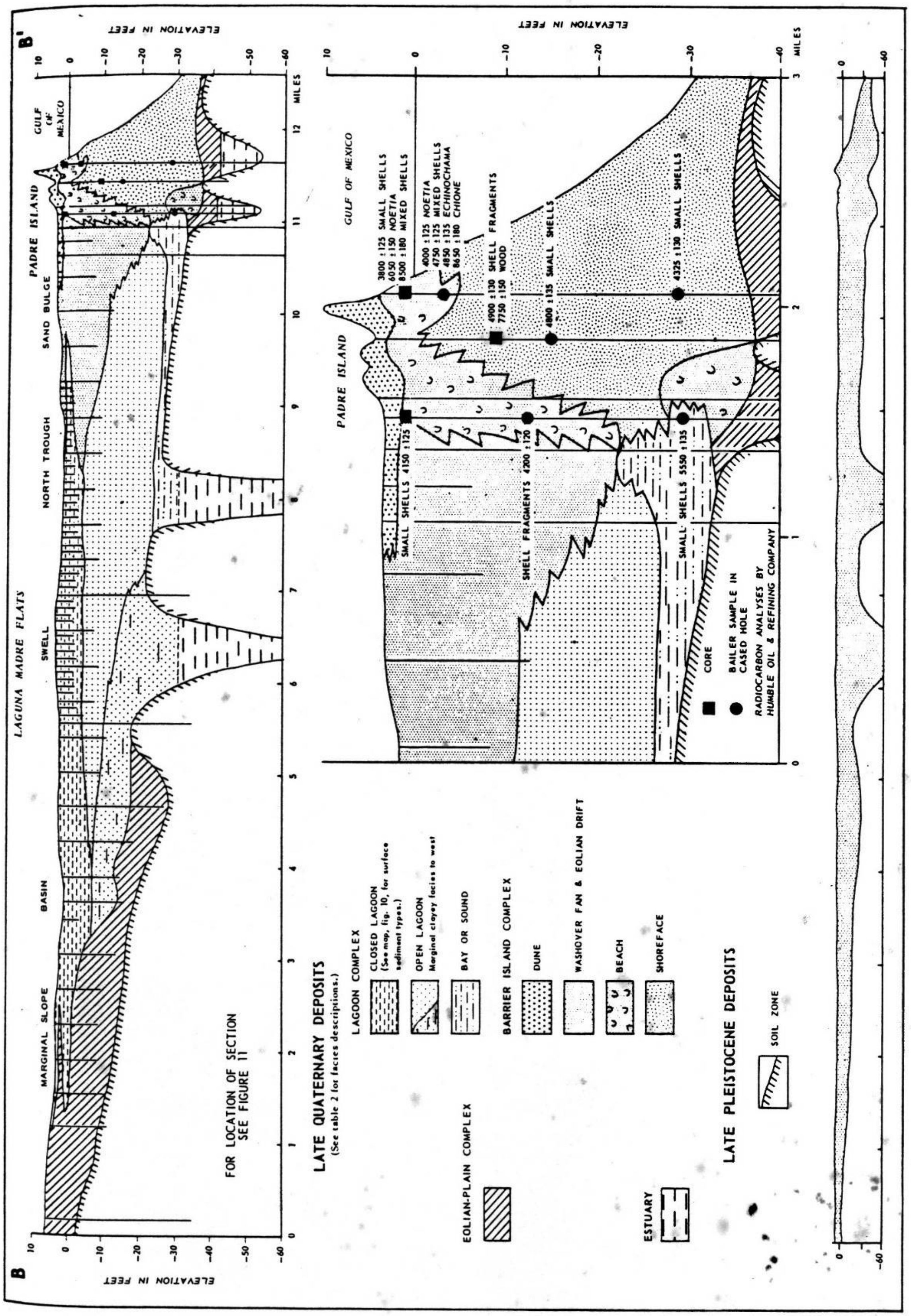

Figure 6. Cross section from eolian sand plain, across flats to Padre Island (Fisk, 1959).

Fresh and salt water supply & circulation in Laguna Madre

Sources of fresh water and normal salinity sea water for Laguna Madre.

Laguna Madre is composed of Northern Laguna Madre, Southern Laguna Madre and the Land Cut between them (Fig. 7). The total length of the combined lagoon is about 120 miles and its water body effectively includes Baffin Bay. There are several connections to the Gulf of Mexico where Laguna Madre can exchange water with the Gulf. From north to south, these include Aransas Pass via Corpus Christi Bay, Packery Channel, Mansfield Pass and Brazos Santiago Pass. Freshwater sources include direct rainfall, water from the Nueces River via Corpus Christi Bay, sporadic inflow from the streams flowing into Baffin Bay, discharge from the Arroyo Colorado and, during floods, Rio Grande water from the North Floodway, just north of Arroyo Colorado.

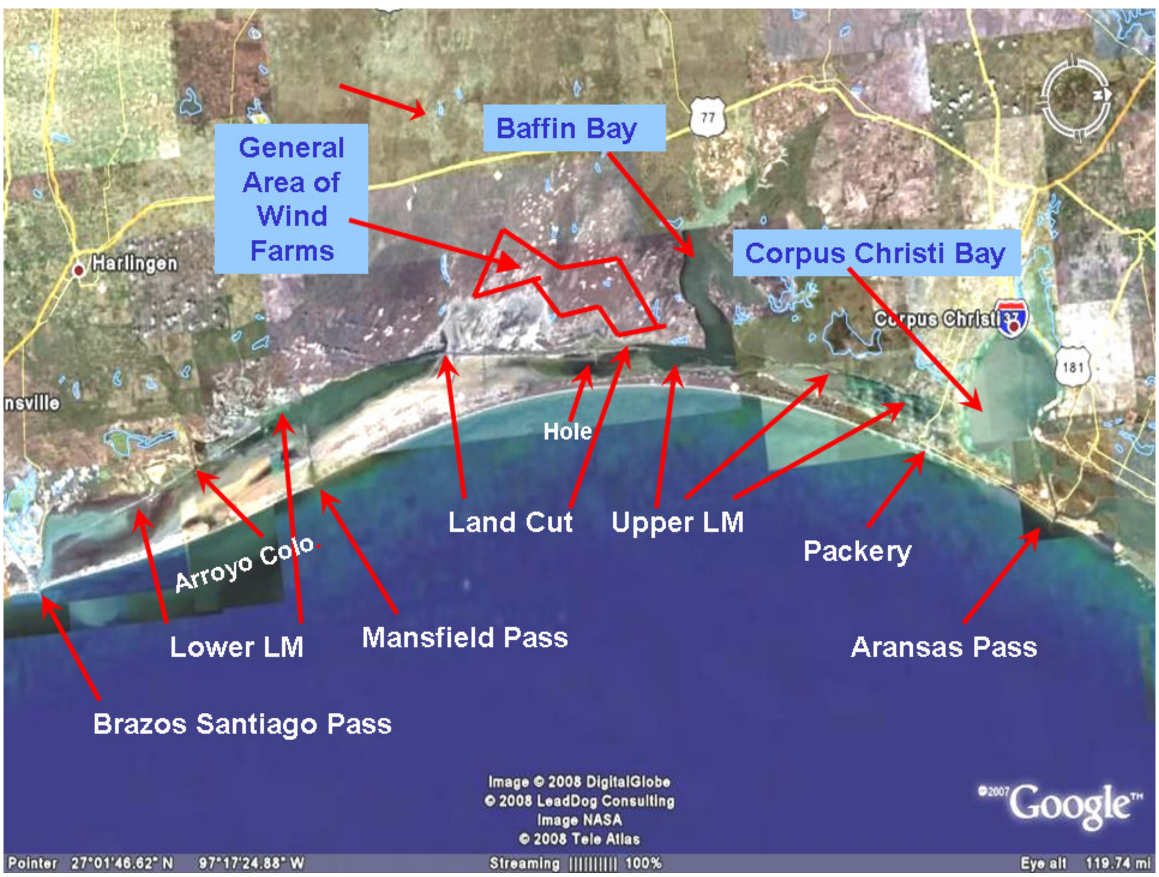

Figure 7. Sources of water for Laguna Madre (photo from Google Earth)

Until the Central Flats were cut by the Gulf Intracoastal Waterway (GIWW) in 1949, there was little circulation between northern and southern Laguna Madre and between Laguna Madre and the Gulf of Mexico (Fisk, 1959, Brown, et al., 1977, Quammen and

Onuf, 1993). Construction of Mansfield Pass in 1962 further increased circulation in Laguna Madre (Quammen and Onuf, 1993).

The Central Flats separated Laguna Madre into two basins for a very long time. Work by this author and by Dr. Robert Morton, then of the Bureau of Economic Geology of the University of Texas at Austin, in conjunction with a coastal boundary trial between the John G. and Marie Stella Kenedy Memorial Foundation and the State of Texas determined the age of the Central Flats. In both of our studies and that of Miller, 1975, radiocarbon age dates of buried algal mats showed that the flats accreted upward at a rate of only 0.1 to 0.2 ft. per century (Watson, 1995). Their thickness implied that Laguna Madre had been separated into two hypersaline basins for at least 1000 years and probably longer.

Before 1949, when the Gulf Intracoastal Waterway (GIWW), a 12 ft. deep, 125 ft. wide channel was dredged through the Central Flats, both northern and southern Laguna Madre were extremely hypersaline. The Central Flats prevented any flow between northern Laguna Madre and southern Laguna Madre, except during tropical storms and very high wind events, such as strong northers or the strong southerly winds that precede northers. There was, and still is, very little astronomical tide in Laguna Madre, with the major influence of astronomical tides being the seasonal changes in Gulf water level with highs in the fall and spring.

The main influence on the water level over any short time period throughout the year is the wind. The wind blowing along the length of Laguna Madre during either strong southerly winds or strong northerly winds blows the water along in the wind direction. Before the construction of the GIWW, strong north winds would push water up onto the north end of the flats. At the same time, the north winds would blow the water away from the south end of the flats to the south in lower Laguna Madre. Strong southerly winds produced the opposite results. Before the GIWW was built, strong southerly winds would blow the water to the north in northern Laguna Madre and would blow the portion of Laguna Madre adjacent to the Kenedy Trust Ranch dry. This killed a lot of fish, and at that time, this shallow basin was called "The Fish Graveyard Basin." The Fish Graveyard Basin is now renamed, "The Hole," because it is an excellent fishing location, and is never completely dry.

Opening the GIWW, in 1949, totally transformed Laguna Madre (Fig 8). Before it was opened, salinities frequently exceeded 100 ppt (parts per thousand of dissolved salts) in northern Laguna Madre. (Normal seawater is 35 ppt). The high salinities in northern Laguna Madre prevented growth of sea grasses, and only the most salt-resistant organisms could live in northern Laguna Madre. Since opening the GIWW, salinities have not exceeded 60 ppt and rarely rise above the 50s (Fig. 9). Northern Laguna Madre is full of seagrasses, and fishing is excellent everywhere. In addition, "The Hole" is now never blown dry, because the drain provided to the wind-tides, in both directions, by the GIWW. The Land Cut of the GIWW has reduced the frequency and height of both the high wind-tides and the low wind-tides, because the Central Flats are no longer an effectively impenetrable barrier to the wind-tides.

At the present time, there is robust wind-driven circulation along the length of Laguna Madre by the wind, forcing water north on strong southerly winds and south on strong northerly winds. This is the main normal control of salinity within the entire Laguna Madre system. The system was further improved by opening Mansfield Pass in 1962.

Figure 8. Land Cut Channel Looking North from Mesquite Rincon. The body of water on the upper right is “The Hole” (photo by the author).

What controls salinity of Laguna Madre?

Quammen and Onuf (1993) describe the salinity changes in Laguna Madre.

> Moderation of hypersalinity was a necessary condition for the major shift in community that has occurred in Laguna Madre over the last 25 yr. In the brief period in the 1940s for which data are available, salinities > 100 ppt were recorded in the upper laguna (Fig. 3a: Fig. 9 in this document) and > 60 ppt in the lower laguna (Fig. 3b: Fig. 10 in this document)… Since 1967, even at the

stations where hypersalinity was most pronounced in the 1940s, salinities have not risen much above 40 ppt and are rarely that high.

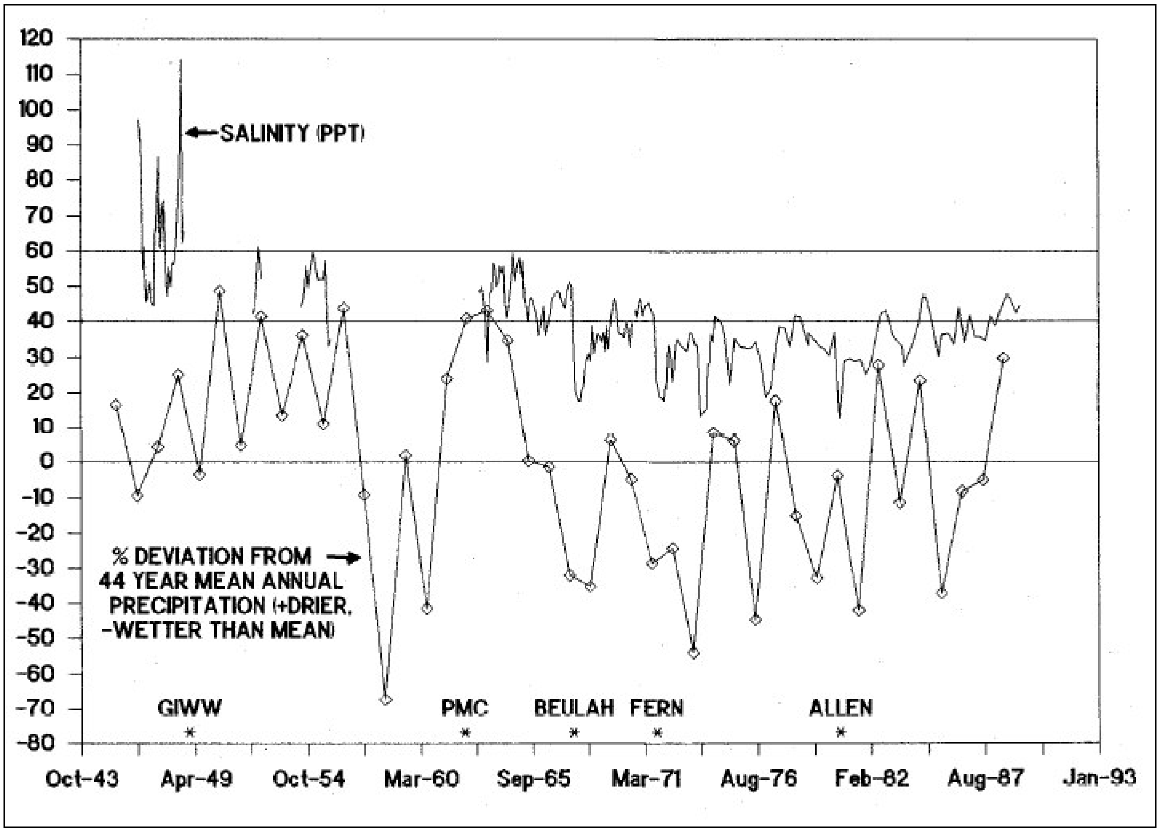

Figure 9. Salinities in upper Laguna Madre, from Quammen and Onuf, 1993

Three factors working in concert appear to be responsible for the moderation of hypersaline conditions in the laguna: increased exchange with the Gulf of Mexico resulting from channel dredging, increased precipitation since 1965 compared to the period 1945 to 1965, and increased flow into the laguna from the Arroyo Colorado and North Floodway, the principal drainage networks serving the lower Rio Grande agricultural district and its main population centers (Quammen and Onuf, 1993, p.305).

The relative contributions of climatic change, increased exchange with the Gulf of Mexico and agricultural drains on the salinity regime are hard to quantify; however, the aggregate effect of the hydrological changes is demonstrable. In approximately monthly sampling at four stations in the lower laguna during 1946-1948, before completion of the Gulf Intracoastal Waterway, salinity exceed 50ppt for 29 of 76 observations compared to 19 of 684 observations at the same stations 1952-1958 and 1964-1967. In the period after dredging of the Intracoastal Waterway, nine years were drier than the driest in the period before dredging.

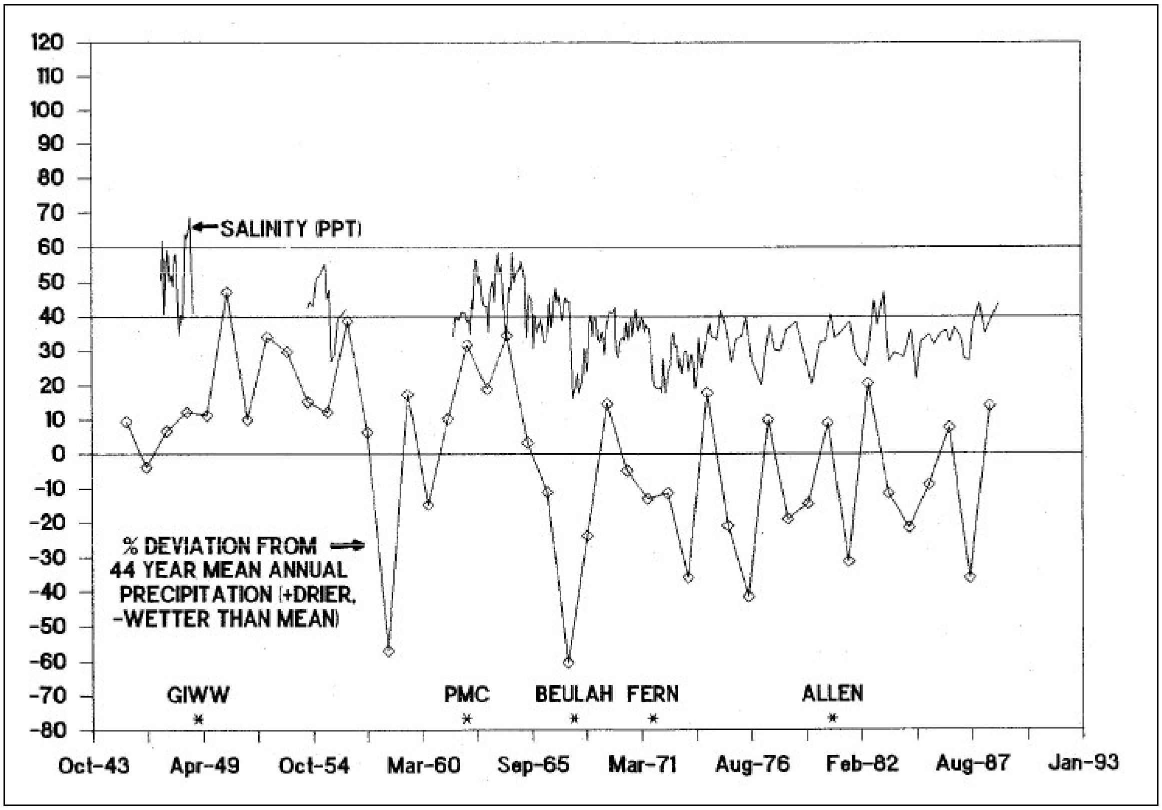

Figure 10. Salinities in lower Laguna Madre (Quammen and Onuf, 1993, p. 306)

At four stations in the upper laguna over approximately the same time periods, salinity exceeded 60 ppt for 37 of 112 observations before channel dredging, compared to 17 of 632 after. Six years in the post-dredging period were drier than the driest in the pre-dredging period…

The Intracoastal Waterway has a moderating influence on the salinity regime of Laguna Madre; the navigation channel provides the only permanent water connection between the upper laguna and the lower laguna. This allows circulation (driven by prevailing southeasterly winds) of Gulf water entering at Brazos Santiago Pass the length of the laguna, into Corpus Christi Bay, and ultimately back out to the Gulf at Aransas Pass. Exchange in the lower laguna was enhanced further when an artificial cut across Padre Island at Port Mansfield was made permanent in 1962.

The other major hydrological alteration of the Laguna Madre ecosystem is the drainage network of the lower Rio Grande agricultural district. Flows in Arroyo Colorado and the North Floodway the two main drains, have increased over time. Their combined flows were greater than 10 cubic meters per second only 8% of the time during 1941-1952, compared to 35% of the time during 1966-1975, and 72% of the time during 1976-1986 (Quammen and Onuf, 1993, p.305).

Quammen and Onuf attribute the post 1965 decrease in salinity of southern Laguna Madre to increased population, installation of subsurface drainage of agricultural lands, and increased acreage of irrigated cropland. The subsurface drainage prevents accumulation of salts in the soils by evaporation and the excess water goes into the drainage system and ultimately Laguna Madre via the Arroyo Colorado.

> A flow of 10 cubic meters per second for a month corresponds to a 4 cm layer of fresh water over the surface of lower laguna. About half the time the direct input of precipitation to the surface of the laguna is less than this… Perhaps the most important property of this input of fresh water as an influence on salinity in the laguna is its timing. Drain flows are driven much of the time by human usage or water additions in irrigation. The former is relatively constant over time and the latter is greatest at times of greatest moisture stress imposed by the natural hydrological cycle. Therefore, the drains deliver when natural processes push most strongly toward hypersalinity. As a result, drain flows may have a moderating effect on hypersalinity out of proportion to their modest volume (Quammen and Onuf, 1993, p.305).

It has long been recognized that opening the GIWW radically transformed Laguna Madre, by allowing wind-driven through flow from Brazos Santiago Pass at one end and Aransas Pass at the other. Circulation and salinity reduction was further improved when Mansfield Pass was opened in 1962. Finally, Quammen and Onuf show that increased farming along with buried drain pipes and greater sewage outfall, along with discharge from the North Floodway have brought important additions of fresh water to southern Laguna Madre where the wind-driven circulation can carry it throughout the entire lagoon system, both north and south.

Additional salinity data were published by PBS&J and George Ward. Refer to Table 1. Station ULM3 is located in northern Laguna Madre adjacent to the Penascal site and just north of the north end of the Land Cut.

> Almost all of the average monthly salinities in the Lower Laguna exceed 30 ppt but rarely exceed 36 ppt until the first three months of 1998. The uniformly low standard deviations testify to the stability of the salinity structure during the study period. Salinities in the Upper Laguna are somewhat higher, with monthly average values easily exceeding 40 ppt, especially during summer 1996 (PBS&J and George Ward, 1999, p. 4-45).

STATISTICS OF SALINITY DATA - UPPER LAGUNA MADRE

Time	Station ULM1						Station ULM2						Station ULM3					
	Monthly Average (‰) of Daily				Monthly		Monthly Average (‰) of Daily				Monthly		Monthly Average (‰) of Daily				Monthly	
	Min	Mean	Max	St Dev	Mean	St Dev	Min	Mean	Max	St Dev	Mean	St Dev	Min	Mean	Max	St Dev	Mean	St Dev
Sep-94																		
Oct-94																		
Nov-94	30.4	30.9	32.1	0.4	30.9	0.5												
Dec-94	27.8	28.7	29.4	0.3	28.4	1.8	33.4	38.1	39.6	1.4	37.8	1.9	38.4	38.6	38.8	0.1	38.6	0.5
Jan-95	26.4	26.9	27.6	0.3	26.8	2.7	30.0	34.8	36.8	1.5	34.9	4.1	36.5	37.0	37.7	0.3	37.0	3.3
Feb-95	30.9	33.3	34.0	0.3	33.3	1.3	37.2	42.1	43.2	1.0	42.2	2.0	42.1	44.3	44.8	0.3	44.3	1.7
Mar-95	28.6	30.4	30.9	0.3	30.4	1.0	34.4	37.5	38.6	0.6	37.4	1.6	30.9	39.8	31.7	2.7	26.0	13.7
Apr-95	28.2	30.0	30.5	0.3	30.0	0.8	35.2	37.9	38.7	0.4	37.9	1.8	35.0	38.8	39.2	0.2	38.8	0.7
May-95	28.7	30.3	31.3	0.4	30.3	0.8	37.5	39.5	40.2	0.4	39.5	1.3	35.1	37.4	38.2	0.5	37.3	2.4
Jun-95	31.1	33.0	34.4	0.6	33.0	1.5	33.5	36.1	37.0	0.6	36.2	2.2	32.8	34.3	34.7	0.2	34.3	1.5
Jul-95	31.3	33.8	35.1	0.6	33.7	1.2	32.9	34.8	35.8	0.6	34.8	3.3	30.8	32.6	33.4	0.3	32.6	1.6
Aug-95	33.1	34.6	35.4	0.2	34.6	0.6	35.0	37.3	38.2	0.5	37.3	1.1	32.8	34.8	35.6	0.3	35.0	2.2
Sep-95	33.0	34.5	34.9	0.2	34.5	1.0	35.2	38.6	39.2	0.6	38.5	2.2	34.7	36.3	36.7	0.2	36.0	1.6
Oct-95	29.7	32.4	32.8	0.2	32.4	1.3	35.8	37.9	38.5	0.3	37.8	1.1	36.6	38.2	38.6	0.2	38.1	1.5
Nov-95	29.6	30.7	32.0	0.6	31.1	1.4	35.8	38.6	39.0	0.3	38.6	0.7	36.0	38.2	38.5	0.2	38.1	1.1
Dec-95	29.2	31.4	32.4	0.4	31.4	0.8	36.0	38.0	38.4	0.3	38.0	1.0						
Jan-96	31.7	32.1	32.7	0.2	32.1	0.6	36.9	37.5	38.0	0.3	37.5	0.9	37.7	38.2	38.6	0.2	38.2	0.7
Feb-96	31.0	32.8	33.3	0.2	32.7	0.6	35.0	37.2	37.8	0.1	37.2	0.8	36.1	38.0	38.5	0.3	38.0	1.6
Mar-96	31.9	33.8	34.3	0.3	33.9	0.5	39.1	41.1	41.6	0.3	41.2	1.1	39.0	40.9	41.5	0.3	40.9	1.6
Apr-96	31.7	34.1	35.0	0.5	34.1	1.6	38.3	41.7	42.5	0.6	41.6	1.0	38.8	41.0	41.5	0.3	41.0	2.0
May-96	33.5	35.7	36.4	0.3	35.7	1.4	38.2	40.4	41.5	0.5	40.4	0.8	37.7	38.1	38.4	0.2	38.0	1.1
Jun-96	35.6	38.4	38.5	0.5	38.2	1.7	40.3	42.3	43.0	0.3	42.3	0.7	38.4	40.2	40.5	0.2	40.2	0.6
Jul-96	38.4	41.5	42.7	0.5	41.5	1.1	40.2	44.9	46.6	1.1	44.8	2.8	37.3	42.7	44.0	1.1	42.7	2.6
Aug-96							45.8	48.7	49.4	0.4	48.7	1.3						
Sep-96							43.8	46.6	48.0	0.7	46.6	2.8	39.7	43.0	44.8	0.8	43.0	2.5
Oct-96							42.6	46.4	48.1	1.1	46.4	2.3	40.4	43.2	44.9	0.8	43.2	2.0
Nov-96							43.4	46.8	47.0	0.6	45.8	2.1	39.0	40.6	42.1	0.7	40.4	2.4
Dec-96							46.3	48.6	49.3	0.3	48.7	1.2						
Jan-97	34.4	35.3	36.3	0.5	35.3	1.7	45.1	47.6	49.7	1.3	47.6	2.7	44.2	45.7	47.1	0.8	45.7	4.5
Feb-97	30.5	33.6	34.1	0.4	33.5	1.2	38.7	43.6	45.6	1.2	43.5	3.1	38.7	43.6	45.6	1.2	43.5	3.1
Mar-97																		
Apr-97																		
May-97																		
Jun-97																		
Jul-97																		
Aug-97																		
Sep-97																		
Oct-97																		
Nov-97							22.2	23.3	24.0	0.5	23.2	1.5						
Dec-97	27.0	27.2	27.4	0.1	27.3	0.4	19.2	22.2	22.7	0.4	22.2	0.8	24.3	24.8	25.2	0.2	24.8	1.0
Jan-98	27.3	27.4	27.6	0.1	27.8	0.6	24.6	25.2	25.9	0.4	25.2	0.8	24.8	25.3	25.8	0.3	25.3	1.1
Feb-98	26.0	28.6	29.0	0.2	28.7	2.0							22.0	23.4	23.8	0.2	23.4	0.8
Mar-98	22.0	24.8	25.3	0.3	24.7	1.3	22.3	24.2	25.2	0.6	24.2	1.3	20.4	23.6	24.1	0.2	23.6	0.6
Apr-98	26.1	26.5	27.0	0.3	26.5	2.5	22.8	27.6	27.9	0.2	27.6	0.3						
May-98	21.5	25.8	26.9	0.5	25.5	1.8												

Table 1. Northern Laguna Madre Salinities 1994 to 1998
(PBS&J and Ward, 1999, p. 4-52)

Plaintiffs contend that fresh ground water flows from the upland of the Kenedy Ranches under or through the wind-tidal flat sediments and affects Laguna Madre.

In his Exhibit B, A Brief Inquiry into the Ecohydrology of the South Texas Sand Sheet, Dr. Jacob states the following on page 7:

> Because of the high coverage of wetlands on the STSS and the regional dip of the landscape, it is highly probable that much of the water flowing on and in the STSS moves through the wetlands and into the tidal flats and the LM … These wetlands thus likely play an important role in the overall aquatic integrity of the Laguna Madre, given that very little if any water enters the upper LM through streams or arroyos... The complexity of this landscape does not lend itself well to facile dismissals of how water might flow through this system into the wind flats and the Laguna Madre. The presence of hypersaline mineral deposits in soils and sediments near the Land Cut or the Laguna Madre is not an indication

> that water is not moving into this environment from the wetland, and may in fact be an indication of flow through a discharge wetland. The fact that receiving waters may be hypersaline does not mean that the STSS wetlands do not have an impact on the LM system. We cannot presume to understand the full suite of interactions between the STSS wetlands and the LM. Given the array of evidence of water moving in this landscape, a hydrologic connection between the STSS wetlands and the LM should be assumed until proven otherwise (Jacob, J.S., July 1, 2008).

Dr. Sass prepared additional comments for the plaintiffs, attempting to show that ground water flows from the upland into Laguna Madre.

> The area is semi-arid. Precipitation averages about 26 inches annually and is generally in short supply. The Sand Sheet is however an effective water collector and a significant portion of rainwater easily percolates through it rather than evaporating. It can then be transported as sub-surface or ground water (Amdurer and Land, 1982). Because the elevation of the watershed drops toward the Laguna Madre, this unconfined sub-surface water then flows in a sheet to the Laguna Madre. The clay-like Beaumont formation just below the sand sheet and the denser salt water table extending at sea level from the Gulf restricts runoff fresh water from percolating too deeply. As it approaches the Laguna Madre it comes very near or above the surface of the sand in the area closest to the Laguna Madre… This sheet flow thus replenishes the exposed fresh water wetlands and is of significant importance to the salinity and ecology of Laguna Madre (Sass, July 1, 2008, p. 10).

Amdurer's master's thesis contains data from his test wells on the Central Flats west of the GIWW (Amdurer, 1978). Figures 11 and 16 show the location of that sample well, number 33. Well 33 is about 3 miles from the GIWW, but is located near an oil field channel. The base of Amdurer's well 33 is about 2.7 meters or 9 feet below sea level. Amdurer found the following.

> There the 3-m piezometer, which penetrated a sandy stratum below an impermeable clay layer (Amdurer, 1978), contained lower salinity water than the shallower piezometers, and water in the pipe rose to an elevation of 21 cm *above* the sabkha. This could only be due to confining of the regional coastal plain aquifer by the impermeable Holocene clays present in this area (Amdurer and Land, 1982, p. 709).

Figure 12 shows a cross section of the wells in Figure 11. Note: Even though the salinity decreased with depth, it was still over 90 ppt at the base of well 33, the well that was pressurized from beneath. What this means is that even if ground water from the upland is pushing water toward the GIWW and Laguna Madre, it is hypersaline water of nearly three times the salinity of normal sea water and is certainly not reducing salinity in Laguna Madre. There is no direct evidence of fresh or brackish ground water flow from the upland of the Kenedy Ranches to the GIWW or Laguna Madre.

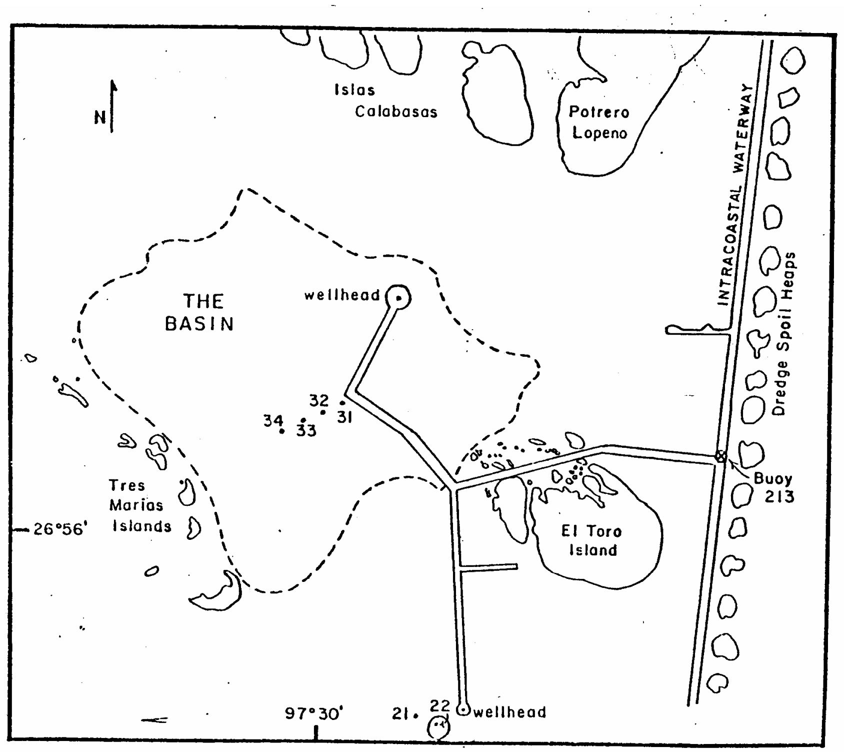

Figure 11. Location of Amdurer sample wells west of the GIWW (Amdurer, 1978)

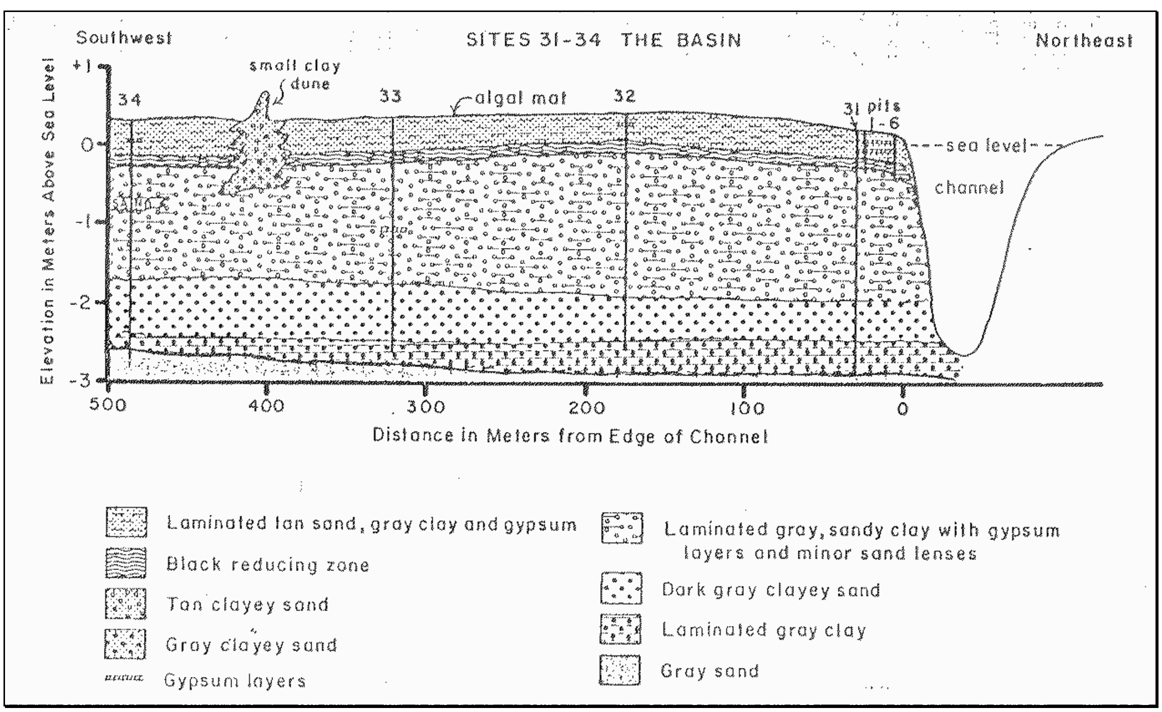

Figure 12. Cross section showing Amdurer well 33. The salinity at the bottom of well 33 is over 90 ppt. (Amdurer, 1978)

The Central Flats on both the east and west sides of the GIWW are flooded with Laguna Madre water from time to time when high wind-tides are generated by strong winds. The portion of the flood water that does not drain back off of the flats slowly evaporates and becomes a concentrated brine. Some of the salt deposits are left behind on the surface as the ever more concentrated brine sinks into the wind-tidal flat sediments where it precipitates calcium carbonate and gypsum minerals. Figure 13 shows a concentration of salt around a drying pond on the surface of the flats adjacent to the Kenedy Foundation Ranch.

> Tidal fluctuations in Laguna Madre are small, but persistent winds from either the southeast or the northeast periodically drive lagoonal waters onto the flats. During the summer months, the area frequently is covered by several inches of water. During dry periods the water table may drop as much as one and one-half feet below the surface. It is readily apparent that these thin sheets of windblown water, fed without recirculation from Laguna Madre become highly enriched in dissolved salts as a result of evaporation…. No complete analysis of water from the moving windblown sheets on the flats surface is available, but the chloride content of one sample was found to be 79,650 ppm (Masson, 1955).

Note: 79,650 ppm chlorinity = 79.6 ppt chlorinity, which is equal to a salinity of 145 ppt.

Figure 13. Salt precipitated on the surface of the Central Flats (photo by author)

James A. Miller working under the supervision of Dr. Alan J. Scott at the University of Texas collected extensive samples in the Central Flats west of the GIWW. This work was toward a Ph.D. dissertation that was never completed. The following information is from a draft of that dissertation.

A total of 93 interstitial water samples was collected from 21 sampling locations on the Laguna Madre Flats between September 1969 and June 1970 (FIGURE (sic) 25: Figure 14, this report)… Chloride, which varies from 35,600 to 137,000 ppm (normal seawater = 18,900 ppm), is probably the best indicator of interstitial water concentration because of its high solubility and the absence of chloride minerals in the sediments…The greatest variations in chloride concentration tend to occur in the upper 30-40 cm of sediment, where the values are influenced by surface water, and may fluctuate by as much as 60,000 ppm. Below this zone, chloride concentration remains relatively uniform to a depth of 1.5 to 2.0 meters…Laterally, chloride tends to increase in concentration from the lagoon axis to the mainland (Figure 26b: Figure 15, this report), indicating that there is a progressive concentration of interstitial brines, and that the ground water system for the Eolian Sand Plain affects only the surficial sediments along the margin of the wind-tidal flat (Miller, 1974).

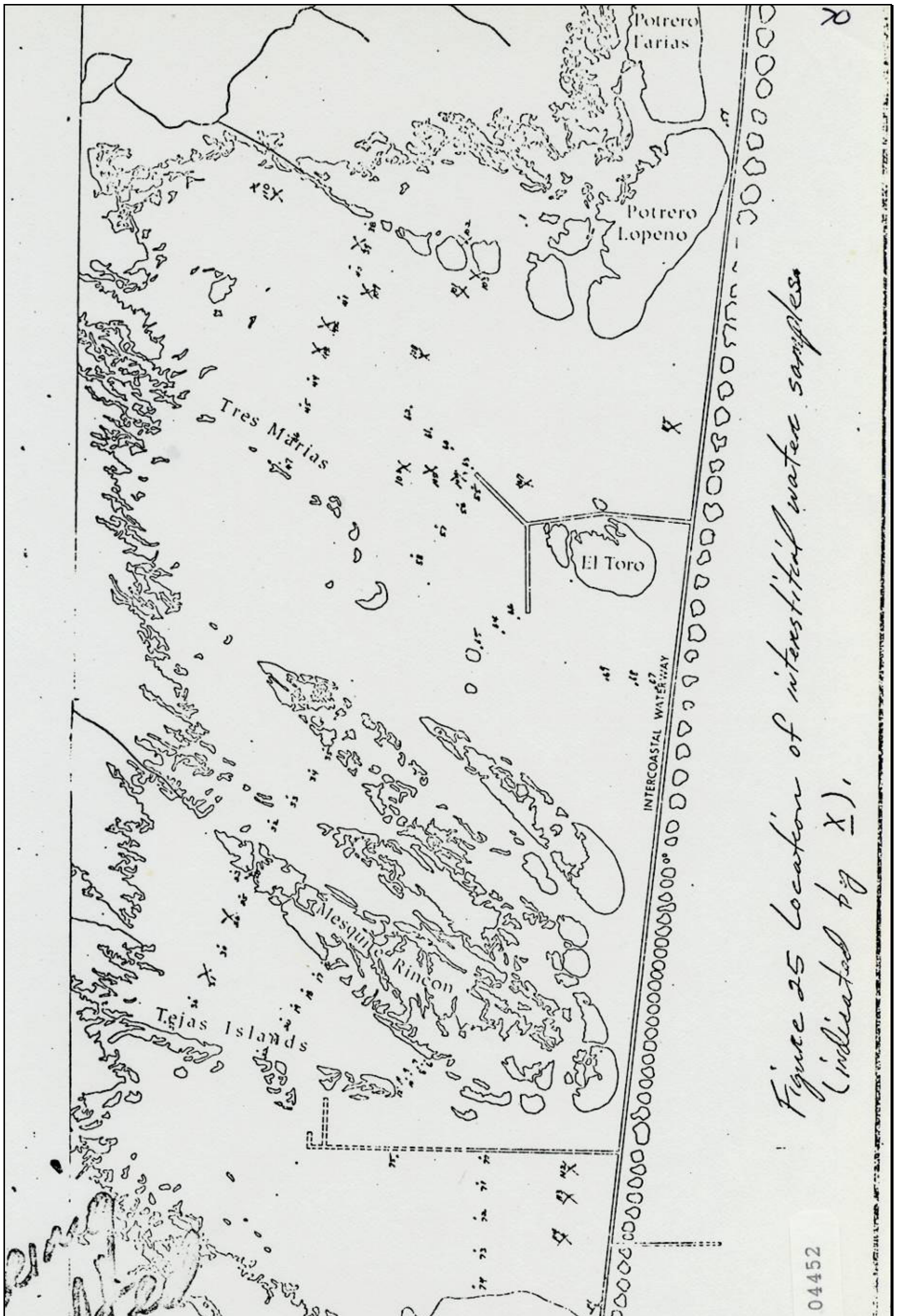

Figure 14. Location of Miller interstitial water samples (indicated by X)

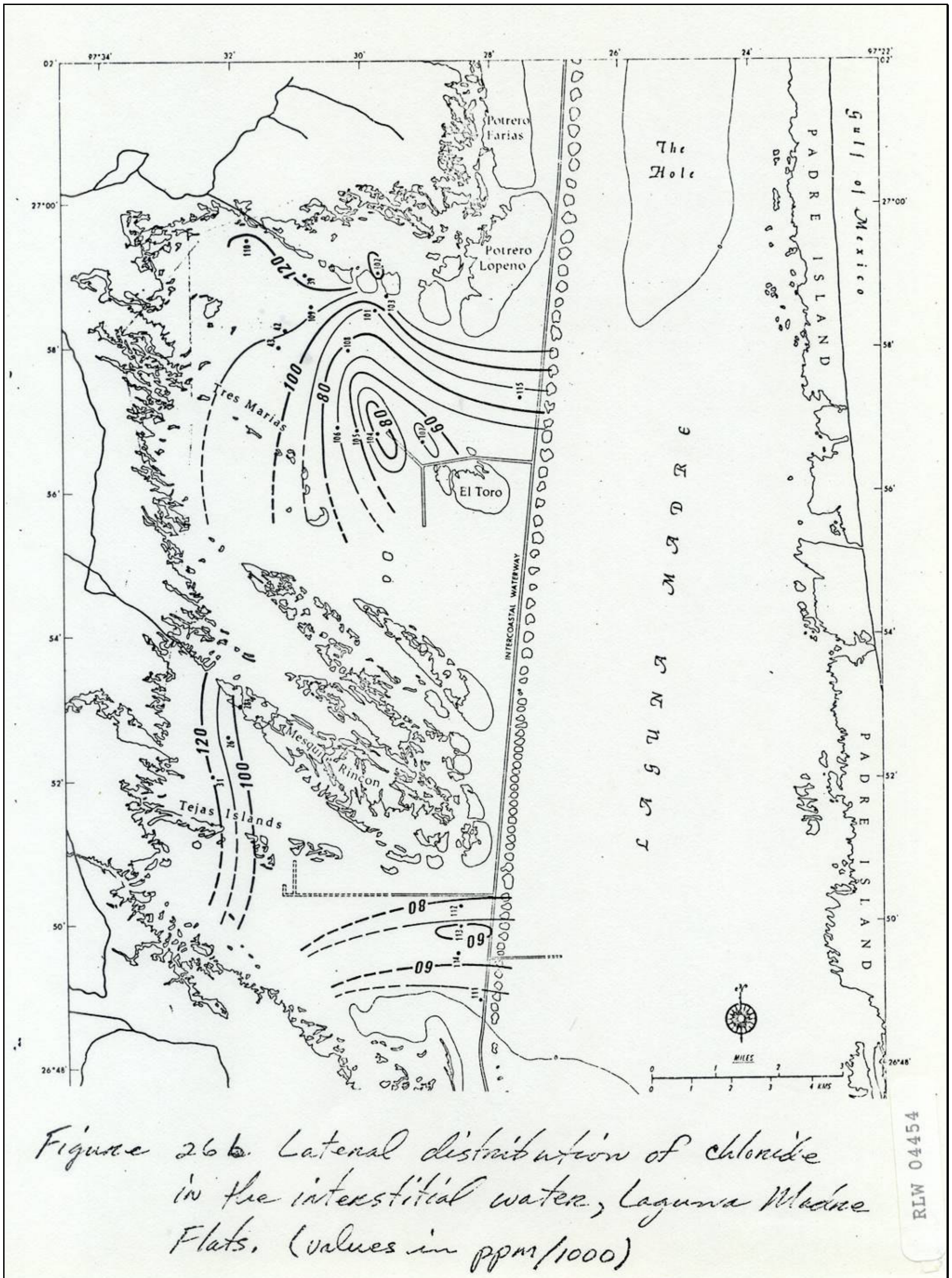

Figure 15. Miller's lateral distribution of chloride in the interstitial water, Laguna Madre flats (values in ppm/1000)

Though the plaintiffs hypothesize that fresh or brackish ground water is moving through the subsurface from the upland to the GIWW and then to Laguna Madre, the only data that actually exists (Miller and Amdurer) show only extremely hypersaline water in those sediments. Since fresh water is less dense, it floats is on top of salt water. It is very unlikely that fresh water is flowing below the very hypersaline ground water in the flats to Laguna Madre, especially since Amdurer found water with a salinity over 90 ppt at a depth within a few feet of the depth of the bottom of the GIWW and far deeper than the deepest parts of Laguna Madre itself.

What is the actual current velocity and volume of water moving through the Land Cut between northern Laguna Madre and southern Laguna Madre?

In 1991, the Conrad Blucher Institute for Surveying and Science at Texas A&M University, Corpus Christi, Texas operated water level recorders (tide gauges) near El Toro island and Rincon del San Jose in the middle and south end of the Land Cut (Fig. 16).

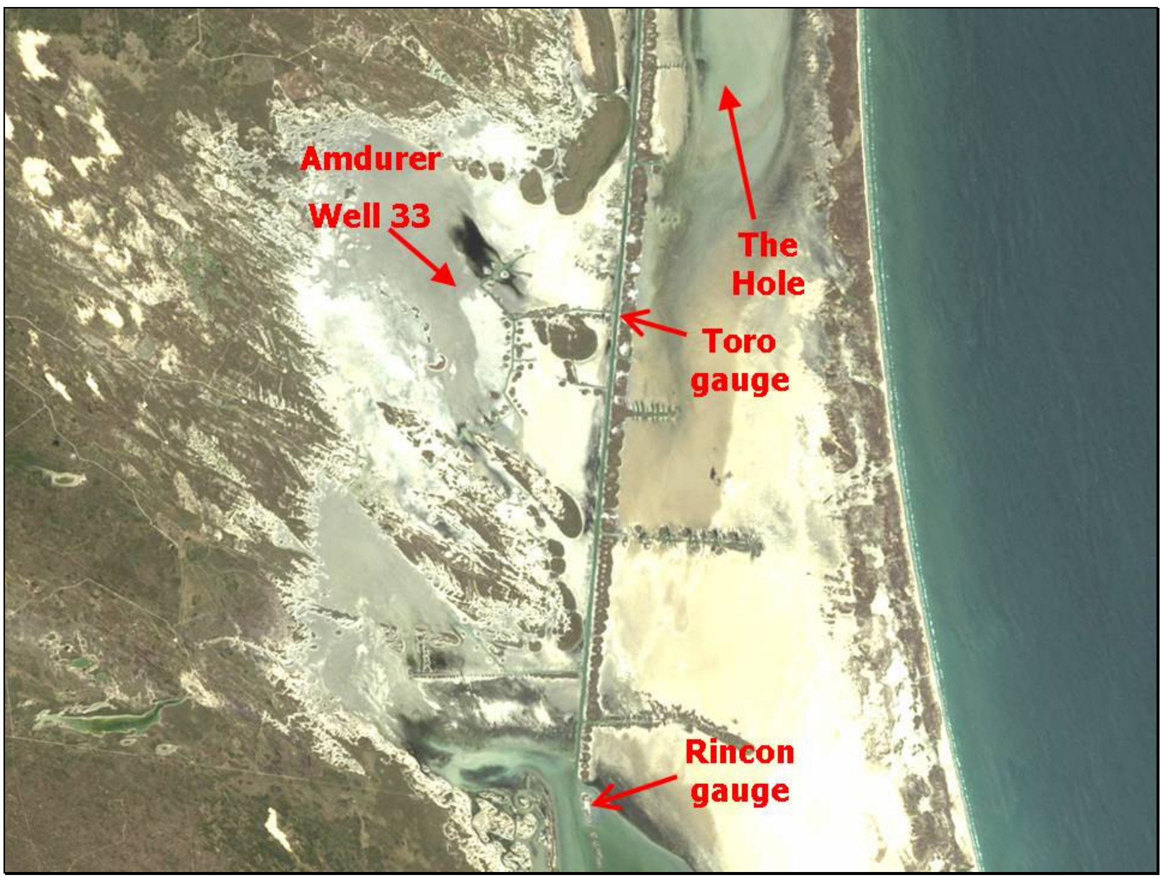

Figure 16. Location of the El Toro and Rincon del San Jose gauges, and Amdurer well 33.

Knowing the relative elevations of the two water level recorders, I used the records from the water level recorders to compute the current velocity in the Land Cut channel for an extended period of time using the Manning equation. The Manning equation is designed to calculate the average velocity of flow across the cross section of open channels such as the Land Cut channel.

The Manning equation is presented below (Watson and Behrens, 1976, p. 30).

Manning Equation $$V = \frac{k}{n} R_h^{2/3} S^{1/2}$$

Hydraulic Radius $$R_h = \frac{A}{P}$$

V is the cross-sectional average velocity (ft/sec)
k is a constant equal to 1.49 for US units
n is the Manning friction coefficient = 0.022 for a smooth earth channel
S is the slope of the water surface (ft/ft)
A is the cross sectional area of the channel (ft^2) = 1788 ft^2.
P is the wetted perimeter of the channel (the length of the bottom and sides) (ft) = 179 ft
R_h is the hydraulic radius (ft) = 1788/179 = 9.99

The channel length between the El Toro water level recorder and the Rincon del San Jose water level recorder is 51,200 ft. The water surface slope at any time is the difference in the water level at the two gauges divided by 51,200 feet, the distance between them.

The Manning equation along with water level data for the El Toro gauge and the Rincon del San Jose gauge were used to compute the flow velocity through the Land Cut channel every six hours for all data that existed for 1991 (TCOON, 2008). The second half of November and all of December have no data. There were 1081 complete 6 hour data sets for the year 1991.

The average flow velocity calculated for the water in the Land Cut without regard to whether it was flowing to the north or to the south was 0.6 ft/sec. This results in an average discharge of 2.77 billion ft^3/mo through the Land Cut.

In addition, the component of the wind energy that is north or south and thus nearly parallel with the Land Cut channel, was calculated and plotted for every six hours in 1991 as well. Since the energy of the wind is a function of wind velocity squared, that is what was used to compute the north/south wind vector. The wind data were obtained from the Blucher Institute. It was collected at the El Toro station simultaneously with the water level data in 1991. [4]

[4] From January 1, 1991 till the end of June, 1991, it appears that the wind velocities reported for the El Toro station are only ½ of what they should be. Personnel at the Blucher Institute investigated this problem. They agree that the wind velocities reported from January through June appear to be ½ of the actual wind velocities. A search of their records does not turn up any concrete coefficient that may be incorrect. They are unable to repair the wind velocity data (Personal communication, John S. Adams, Conrad Blucher Institute for Surveying and Science, Texas A&M University, Corpus Christi, Texas). For this reason, I am not adjusting their data. The conclusions are the same regardless of whether the reported wind velocity is correct or if it is actually twice what was reported. The correlation between current

Figure 17 shows the current velocity and the wind that created the current in the Land Cut in January and February of 1991.

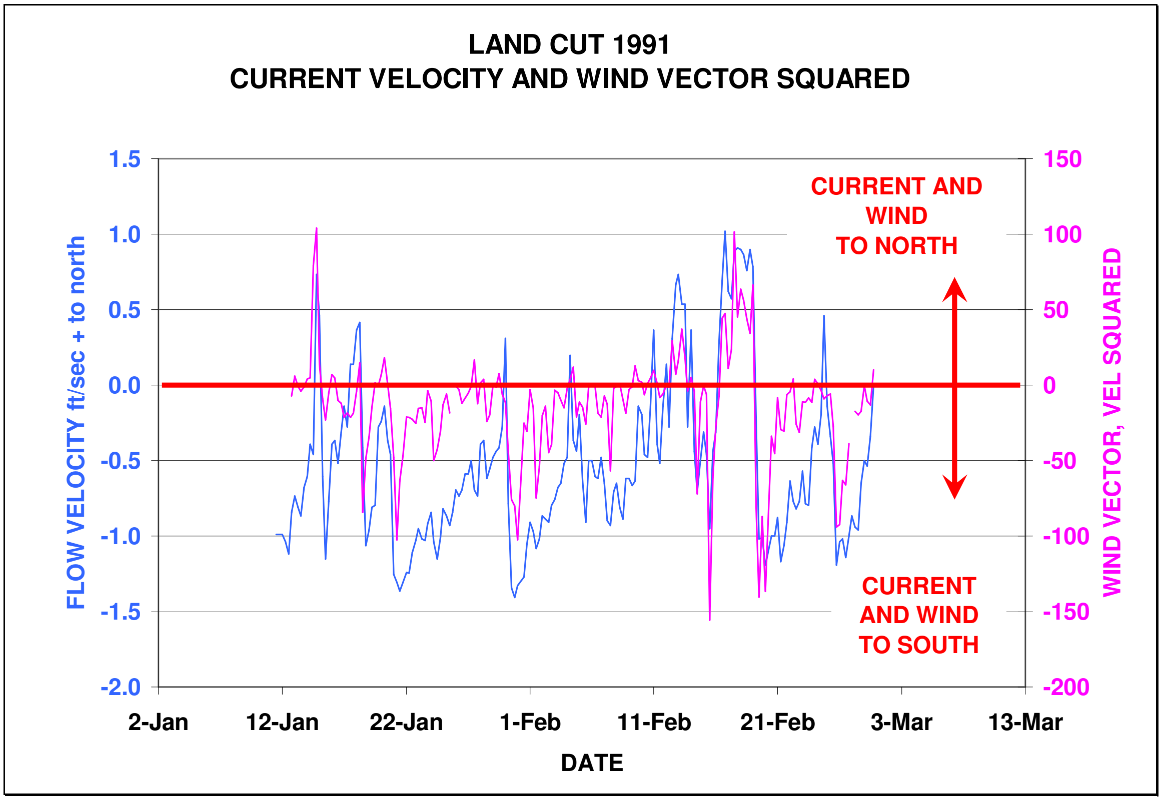

Figure 17. Wind-driven current in the Land Cut, Jan.-Feb. 1991

Note that nearly all of the time the wind was to the south, the current flowed to the south as well. When the wind was to the north, so was the current, and the harder that the wind blew, indicated by a larger vector of wind velocity squared, the faster the current flowed. I believe that this study is the first time that this well-known phenomenon of the wind driving the flow between northern Laguna Madre and Southern Laguna Madre has ever actually been calculated in the channel by using a channel flow equation. It has been shown in a more general sense by large scale models.

Figure 18 shows the same type of graph for the months July and August 1991. Note that the current is flowing to the north, nearly all of the time as would be expected since it is driven by the predominant SE winds of the summer months. Again there is a close correlation between the north-south component of the wind energy as would be expected.

---

direction and the wind vector is the same regardless of the value for the wind velocity reported. The calculated current velocity is accurate; it is dependent only on the water level recorded at El Toro and Rincon del San Jose and those data are excellent.

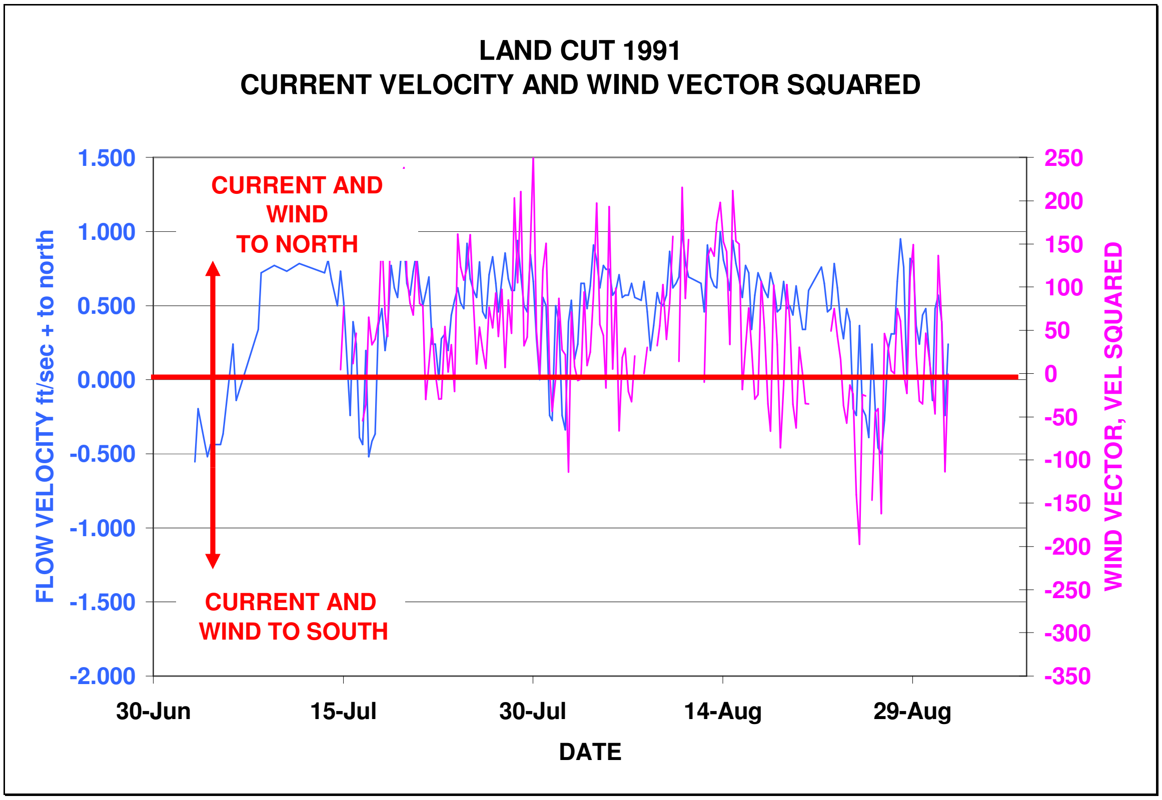

Figure 18. Wind-driven current in the Land Cut, Jul.-Aug. 1991

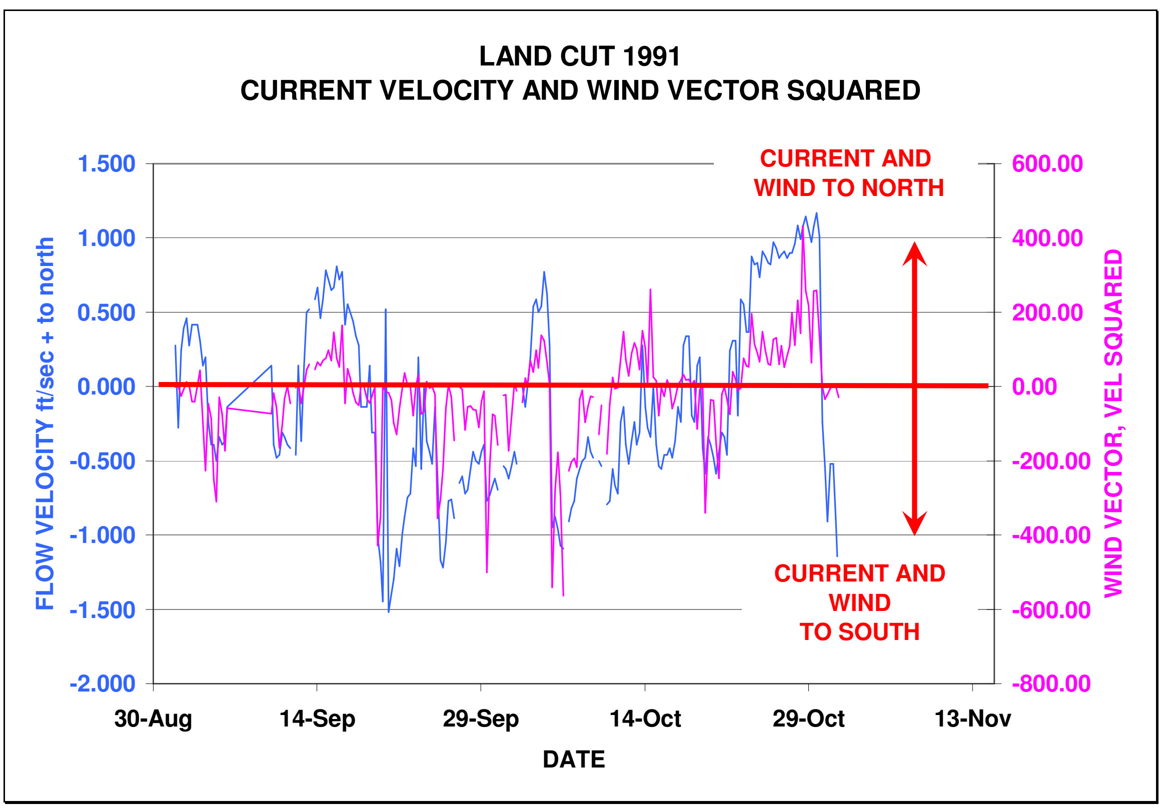

Figure 19. Wind-driven current in the Land Cut, Sep.-Oct. 1991

September and October 1991 show the beginning of the winter northers with wind and current alternating between north and south in the Land Cut (Figure 19).

The entire 1991 year of the calculated wind-driven current is shown in Figure 20. There are no data for the second half of November nor any part of December. It is easy to see that even though the average flow velocity for the year is 0.6 ft/sec, there are many days when the flow velocity is much higher and can even reach more than 1.0 ft/sec.
Note that the wind vector from January through June appears to be lower than in the latter half of the year. That is because the wind data appears to be only half of its actual velocity. However, the direction of current flow still agrees with the direction of the wind (see footnote 4, p. 24).

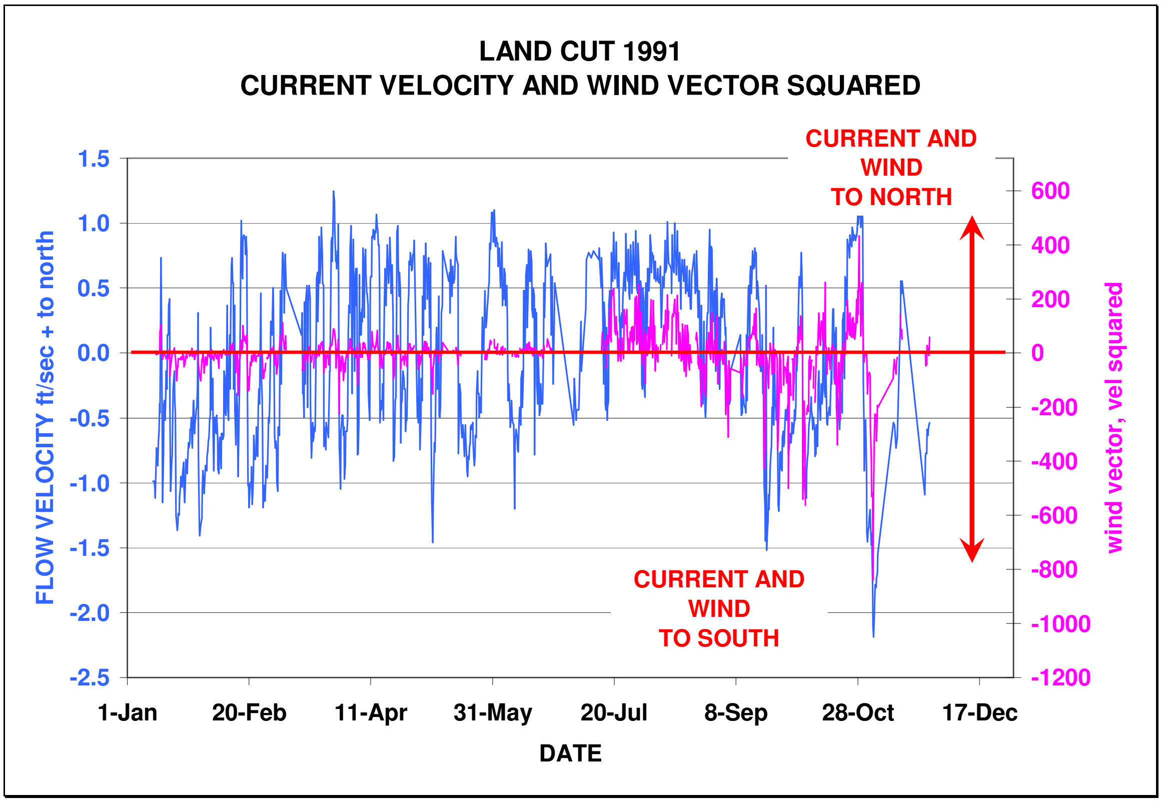

Figure 20. Wind-driven current in the Land Cut for the year 1991

Table 2 shows the monthly average flow speed and velocity in the Land Cut. The average speed is calculated without regard to direction, north or south, while the average velocity of the current takes direction into account. Positive numbers indicate a net flow direction to the north for the month and negative numbers a net flow direction to the south for the month. The gross discharge, or volume of water that flowed through the Land Cut for each month without regard to direction is shown as well. The lowest average speed of the current for every month was always 0.5 ft/sec or higher. The lowest monthly discharge through the channel was 2.33 billion cuft/mo. The net monthly discharge is the discharge with direction of flow considered. Note that when it is low, that is because there were nearly equal durations of flow to the north and to the south for the month. In spite of that, the gross discharge which does not consider direction of flow is still high. The average current speed for the year is 0.6 ft/sec and the gross discharge is 2.77 billion cuft/mo (30 days x average gross discharge/day).

Month in 1991	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV
DATA POINTS	80	111	100	116	113	92	76	118	105	124	39
AVG SPEED ft/sec	0.74	0.64	0.59	0.56	0.58	0.50	0.59	0.53	0.55	0.58	1.07
AVG VELOCITY ft/sec	-0.68	-0.40	0.01	0.27	-0.03	0.14	0.44	0.47	-0.25	-0.05	-0.98
GROSS DISCHARGE billion cuft/mo	3.55	2.79	2.85	2.61	2.76	2.33	2.80	2.55	2.53	2.77	4.97
NET DISCHARGE billion cuft/mo	-3.25	-1.92	0.04	1.31	-0.16	0.67	2.11	2.25	-1.18	-0.23	-4.69

Table 2. Land Cut Average Velocity and Discharge by Month in 1991, positive numbers are flow to the north, negative numbers are flow to the south.

What is the maximum conceivable flow of ground water into the 120,000 ft. long section of GIWW in the Land Cut and is it significant?

Using an assumption that the entire 12 foot high, 120,000 foot long vertical wall of the GIWW in the Land Cut is receiving fresh ground water at the rate of 75 ft/yr of flow and an effective porosity of 30%.[5] That will result in a daily flow of ground water into the GIWW at the Land Cut of 88,767 ft^3/day (75x0.3x12x120000/365). That is a hypothetical ground water discharge into the GIWW at the Land Cut of 0.09 million cubic feet/day.

At 0.6 ft/sec, the average daily discharge of wind-driven water through the GIWW is 92 million cubic feet per day (0.6x1788x60x60x24). Based on the parameters above, the daily discharge of ground water (0.09) million cubic feet per day is only $1/1000^{th}$ of the wind-driven flow through the Land Cut channel. It would take nearly three years for the ground water flow into the GIWW to equal one day of the wind-driven flow, either north or south through the Land Cut channel.

Remember that this calculation assumed that ground water was flowing through the entire 12 ft high side of the 120,000 ft long land cut at the rate of 75 ft/year. There is no chance this is true. In fact, there is no evidence that any fresh or even low salinity ground water is flowing into the GIWW from the uplands. There is evidence, however, that if any ground water is flowing into the GIWW, it is hypersaline concentrated brine produced by sinking of saline brines into the surface of the Central Flats bordering the GIWW (Masson, 1955, Miller, 1974, Amdurer, 1978). So, in the unlikely and undemonstrated

[5] The ground water flow rate of 75 ft/year and porosity of 30% were provided by Roger W. Lee, Ph.D. of ERM and by David K. Harkins, Ph.D., P.E. of Espey Consultants, Inc.

event that fresh or low salinity ground water were flowing under or through the Central Flats and reaching the GIWW, it would take nearly three years of that flow to equal one day of the daily wind-driven flow of Laguna Madre water through the Land Cut. Ground water flow from the uplands to Laguna Madre is insignificant, if it occurs at all.

Conclusions

Before the Gulf Intracoastal Waterway (GIWW) was dredged from Corpus Christi Bay to Port Isabel, and the Land Cut channel was dredged through the Central Flats, there was little exchange of water between northern and southern Laguna Madre except during extreme events such as tropical storms. As a result, Laguna Madre was very hypersaline, with salinities in the northern Lagoon sometimes exceeding 100 ppt or nearly three times the salinity of normal seawater of 35 ppt. After construction of the GIWW in 1949, salinities have rarely reached 60 ppt due to the wind-driven flow between northern and southern Laguna Madre and ultimately exchange with lower salinity water from the Gulf of Mexico at Aransas Pass and Brazos Santiago Pass.

The circulation of Laguna Madre with the Gulf of Mexico was further improved when Mansfield Channel was dredged in 1962 completing another connection with the Gulf of Mexico. Increased treated sewage outfall and agricultural irrigation along with flood waters from the Rio Grande via the North Floodway further reduced salinity in southern Laguna Madre. This helps northern Laguna Madre, as well, via the exchange through the Land Cut channel and salinities have rarely exceeded 50 ppt after 1965.

Previous studies have shown that there is significant exchange of water between northern and southern Laguna Madre via the Land Cut Channel. In this study, I have calculated that flow for most of the year 1991 when there were recording water level gauges installed along that channel. There is an average current of 0.6 ft/sec through the land cut channel, which carries an average of 2.77 billion cubic feet of water between the northern and southern parts of Laguna Madre every month.

The plaintiffs contend that there is significant flow of fresh water or brackish water from the uplands passing under or through the Central Flats to the Gulf Intracoastal Waterway (GIWW) at the Land Cut and that flow reduces salinity in Laguna Madre. I have calculated this hypothetical flow using generous assumptions. Even though there is no physical evidence that fresh or brackish ground water is able to flow into the GIWW at the Land Cut, I have calculated that the maximum conceivable volume of that flow is only 0.09 million cubic feet per day, which is only 1/1000 the daily wind-driven flow through that channel between northern and southern Laguna Madre. In the unlikely event that fresh or brackish ground water from the upland is able to reach the Land Cut, it would take nearly three years for that flow to equal the amount of water flowing through the Land Cut between northern and southern Laguna Madre in a single day.

Since the GIWW at the Land Cut is an insignificant percentage of the total volume of Laguna Madre, this exceedingly small hypothetical volume of water flow into the GIWW at the land cut, no matter the salinity of that flow, whether fresh, brackish or hypersaline, would have no measurable effect on Laguna Madre.

REFERENCES

Amdurer, Michael, 1978. Geochemistry, Hydrology, and mineralogy of noncarbonate coastal sabkha, Laguna Madre, Texas, MS thesis, The University of Texas at Austin, supervisor, Lynton Land, 171p.

Amdurer, Michael, and Lynton Land, 1982. Geochemistry, hydrology, and mineralogy of the Sand Bulge area, Laguna Madre Flats, South Texas. Jour. Sedimentary Petrology, v. 52, no. 3, p 0703-0716.

Brown, L.F.,Jr., Mcgowen, J.H., Evans, T.J., Groat, C.G., and Fisher, W.L., 1977. Environmental geologic atlas of the Texas coastal zone – Kingsville Area. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, 131p. and maps.

Fisk, H.N., 1949. Geological Investigation of the Laguna Madre flats, Humble Oil and Refining Company Exploration Department, Houston, Texas.

Fisk, H.N., 1959. Padre Island and the Laguna Madre flats, coastal south Texas: La. State Univ., 2nd Coastal Geography Conf., April 1959, p. 103-151.

Jacob, John S., July 1, 2008. A brief inquiry into the ecohydrology of the South Texas Sand Sheet

Masson, P.H., 1955. An occurrence of gypsum in southwest Texas. Jour. Sedimentary Petrology, v. 25, No. 1, p. 72-77.

Miller, James A., 1974. Depositional and diagenetic facies of a terrigenous clastic wind-tidal flat, Laguna Madre, Texas. University of Texas at Austin, Alan J. Scott, supervisor. Unfinished Ph.D. dissertation on the geochemistry of the Central Flats on the west side of the GIWW adjacent to the Kenedy Foundation Property

Miller, James A., 1975. Facies characteristics of Laguna Madre wind-tidal flats., *in* Tidal Deposits, a casebook of recent examples and fossil counterparts. Robert N. Ginsberg, ed., Springer-Verlag, p.67-73.

PBS&J and George Ward, 1999. Hydrographic monitoring in the Laguna Madre: Reduction, analysis and interpretation of data collected by the Conrad Blucher Institute, 1994-1998.

Price, W.A., 1958. Sedimentology and Quaternary geomorphology of south Texas: Gulf Coast Assoc. Geol. Soc. Trans., v. 8, p. 41-75.

Quammen, Milicent L., and C.P. Onuf, 1993. Laguna Madre: seagrass changes continue decades after salinity reduction. Estuaries, v. 16, No. 2, p. 302-310.

Sass, Ronald L., July 1, 2008. The ecohydrology of Laguna Madre estuarine system and adjacent wetlands.

Shafer, G.H., and Baker, E.T., Jr., 1973. Ground-water resources of Kleberg, Kenedy, and Southern Jim Wells Counties, Texas. Texas Water Development Board. This report was prepared by the U.S. Geological Survey under cooperative agreement with the Texas Water Development Board.

TCOON, 2008. Data obtained from the Texas Coastal Ocean Observation Network, Division of Nearshore Research, Conrad Blucher Institute for Surveying and Science, Texas A&M University-Corpus Christi. http://lighthouse.tamucc.edu/TCOON/HomePage

Watson, R.L., 1971. Origin of shell beaches, Padre Island, Texas: Journal of Sedimentary Petrology, v.41, No. 4, 1105-1111. http://www.texascoastgeology.com/papers/shellbeaches.pdf

Watson, R. L., 1995. Revision of radiocarbon age dates and sedimentation rates based on latest radiocarbon age calibration methods. Unpublished paper written in conjunction with the following lawsuit (The John G. and Marie Stella Kenedy Memorial Foundation and Corpus Christi Diocese of the Roman Catholic Church, Petitioners v. David Dewhurst, Commissioner of the General Land Office and the State of Texas, Respondents*, 90 S.W. 3d 268 (Tex. 2002)).*

Watson, R.L., and Behrens, E.W., 1976. Hydraulics and dynamics of New Corpus Christi Pass, Texas: A case history, 1973-75. GITI Report 9, for U.S. Army Coastal Engineering Research Center under contract DACW72-74-C-0017 by University of Texas Marine Science Institute, Port Aransas, Texas, 175p.