

A Tide and Circulation Study of Upper Laguna Madre

May 1, 1974 to April 30, 1975

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Preface

The Laguna Madre of Texas has been the subject of considerable interest for many years. The biology of the waters is unique in many respects in that the native flora and fauna must be capable of tolerating a wide range of salinity, between mid summer, when evaporation increases salinities to 60 parts per thousand or more, and the fall months, when the annual precipitation curve is at its highest values and the waters may become nearly fresh.

In spite of these harsh environmental conditions, fish populations of Laguna Madre are both abundant and diverse, and the waters are heavily fished by sportsmen and commercial fishermen. Unlike many coastal waters, Laguna Madre is not simply a nursery ground for juvenile forms of fish and invertebrates, but rather supports adult populations year around.

The scientific interest and commercial value of the waters of Laguna Madre has stimulated studies over the past thirty years. Most of the published accounts deal with the biology or general ecology of the region. Two phases of a three-part survey conducted by the Texas Game and Fish Commission were carried out in Laguna Madre north of the Land Cut. Breuer (1957) reported on an ecological survey of Baffin and Alazan Bays, and Simmons (1957) has published a report of a similar survey of the ecology of Laguna Madre between Baffin Bay and Corpus Christi Bay. This latter report is of a more general nature and includes information relating to the local circulation and tides. Simmons notes that wind directions and water levels are interrelated, but no quantitative data are presented. Hedgpeth (1947) included remarks dealing with the hydrography of Laguna Madre in a general study

of the area. Some evidence for a wind-induced flushing of Laguna Madre waters is presented, using salinity as a natural tracer.

The only purely hydrographic study of the area was that conducted by Collier and Hedgpeth (1950). A separate section is devoted to the Laguna Madre, but the data presented were collected before the construction of the Intracoastal Waterway, and thus are largely of historical interest.

These previous studies provide a good background for a more specific tide and circulation study in Upper Laguna Madre. The research described above not only suggests the best approach to a circulation study, but also indicates something of what might be expected in the data collected. This simplified the experimental design. It has been shown qualitatively that tidal variations in water level are small and often dominated by wind effects. It is also implied that because Laguna Madre is largely an enclosed basin the circulation is directly related to the changing water levels.

The 1974-75 Tide and Circulation Study of Upper Laguna Madre was initiated in May, 1974, to fill the hiatus left by the previous biological, ecological and hydrographic studies. The purpose was to provide a quantitative set of baseline data on the characteristics of tidal and wind-induced water level variations, from which could be postulated the characteristics of the internal circulation of the area. Specifically, the research objectives as set forth in the proposal were as follows:

- a. to determine, from time series of water level records, the volume of water moving into and out of the study site--the flushing due to surface windstress, surface pressure gradients and tidal forces;

- b. to determine, from field surveys, the primary inflow and outflow channels, and thus the most and least flushed sections of the study site;
- c. to determine, from observations and from first-order computations, characteristic current speeds associated with wind drift and tidal motions; and
- d. to determine the characteristics of the local tides, i.e., quantitatively differentiate between the "wind tides" and the true astronomical tides.

With these as the primary goals, the first year's study was begun with a field exercise in August and September of 1974, designed to monitor the study site during typical summer conditions. This was followed approximately four months later with a second one-month field study to record the effects of frontal passages in flushing the study site. For the purpose of this investigation, the study site was arbitrarily defined as the area between the Kennedy Causeway on the north and latitude $27^{\circ}36'N$ on the south, passing through Pita Island. The open-ended nature of the study site was not ideal, but represented a necessary compromise given the overall scope of the study.

Over 11,800 hourly water levels were used in this first year's study to define the characteristics of the tides and internal circulation of Upper Laguna Madre. The results of the investigation are summarized in the following section.

Summary

Results of the 1974-75 Tide and Circulation Study indicate that tidal motions move into the study site from the Gulf of Mexico at Port Aransas in anywhere from seven to nine hours, depending on the period of the tidal constituent. In the process of moving the 35 kilometers from the coast to the study site, tidal amplitudes are reduced to less than 10% of their values at the coast. Tidal motions in Upper Laguna Madre are predominantly diurnal.

The total variance computed from water level fluctuations measured in Upper Laguna Madre is largely accounted for by meteorological effects. Only 10-30% of the variance occurs at tidal periodicities. The dominant rise and fall of water levels occurs at periods of several days and longer.

The circulation of Upper Laguna Madre is comprised of three components. There is a convergent flow, totalling $926,666 \text{ m}^3/\text{day}$, into the Central Power and Light generating station; a predominantly diurnal period tidal oscillation, involving an exchange of water with Corpus Christi Bay; and a similar long period oscillatory flow in response to meteorological forces, including winter frontal passages. The internal circulation of Upper Laguna Madre is a highly variable wind drift with some return flow guided by navigation channels, principally the Intracoastal Waterway.

The flushing of Upper Laguna Madre is directly related to the internal circulation and exchanges with Corpus Christi Bay and the Gulf. It is estimated that volumes of water equal to

that contained within the study site move through Upper Laguna Madre in as little as eight days due to tidal forces, two weeks due to the intake of the Central Power and Light station, and 2-3 days in response to occasional frontal passages.

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Data

The data used in the Tide and Circulation Study were of two forms: Water level data, obtained from the Aransas Pass at Port Aransas (see Fig. 1) and from four locations within the study site, and wind data from the U. S. Coast Guard Station at Port Aransas.

The Port Aransas water level data were obtained from a Corps of Engineers recording tide gage located on the Aransas Pass Channel ($27^{\circ}50'15''\text{N}$, $97^{\circ}03'00''\text{W}$), approximately six hundred yards in from the coast and 1,900 yards in from the ends of the jetties. These water levels are taken to represent the Gulf tides, which serve as the forcing mechanism for the tidal variations observed at the study site. Water level data from a 155 day, 4 hour period (0800, 23 January to 1200, 27 June, 1974) were used to characterize conditions as they exist at the coast. An overlapping, 148 day, 13 hour water level record (2100, 29 January to 1000, 27 June, 1974) was obtained from the Corps of Engineers tide gage at Marker 21 of the Intracoastal Waterway in Laguna Madre ($27^{\circ}37'06''\text{N}$, $97^{\circ}14'49''\text{W}$) to investigate water level variations occurring in Upper Laguna Madre in response to Gulf forcing.

Two additional study sites were chosen at which to monitor water level variations during both the late summer and winter field studies. In the late summer study, temporary recording tide gages were installed at the Coburn Marina ($27^{\circ}37'48''\text{N}$, $97^{\circ}17'14''\text{W}$) and at the Laguna Ranger Station ($27^{\circ}36'50''\text{N}$, $97^{\circ}18'02''\text{W}$), both along the west shore of the study site. These gages provided data lasting from 19 August to 4 October, 1974. In the winter

study, tide gages were installed again at the Laguna Ranger Station and near an Exxon Gas Well in the extreme northwestern corner of the study site (27°39'34"N, 97°16'15"W). This study was carried out between 15 January and 15 February, 1975.

To complement the data obtained along the west shore of the study site, water level data were obtained from Corps of Engineers recording tide gage along the Intracoastal Waterway on the east side of the study site. Values obtained between 20 August and 4 October, 1974, and between 15 January and 15 February, 1975, were used in the late summer and winter field studies, respectively.

The Corps of Engineers tide gages record water level variations continuously in analog form through a mechanical linkage on a chart which moves at a rate of 2.55 mm (0.1 inch) per hour. A tidal range of one meter corresponds to 16.66 cm (6.56 inches) on the chart. The chart paper is scaled in feet, with 20 divisions per foot. Water level values were read to the nearest 0.01 foot. High frequency variations in water levels were minimal at the study site, occurring only in response to barge traffic or pleasure boats moving along the Intracoastal Waterway. It is felt that digitized water level values are accurate to ± 0.01 foot relative to the datum. All water levels from Corps of Engineers tide gages were read relative to a datum plane one foot below mean sea level. The datum planes at Port Aransas and at Marker 21 were assumed accurate and were not relevelled.

The two tide gages obtained for this study and installed along the west shore of the study site were manufactured by Hovenga Instrumentation. These instruments sense water level

variations through a standard float/counterweight system, but the revolution of the sprocket wheel is monitored by a 10-turn potentiometer, which converts changes in water level to analog electrical signals. High frequency variations due to surface waves and boat wakes are exponentially filtered to pass only the lower frequency signals of interest. The response of an exponential filter as a function of period, T , is given by

$$R(T) = [1 + (4\pi^2\lambda^2/T)]^{-\frac{1}{2}},$$

where λ is the time constant of the filter, in this case 56 seconds, and T is the period of the variation. The associated phase shift, ϕ , inherent in exponential filters, is given by

$$\phi = \tan^{-1}(2\pi\lambda/T).$$

Graphs of both $R(T)$ and ϕ are presented in Appendix A and show that with a time constant of 56 seconds high frequency variations are nearly completely removed by the filter, while tidal period and longer variations are essentially unaffected.

The Hovenga Instrumentation gages provide data in analog form. The chart paper moves at a speed of 12.9 mm ($\frac{1}{2}$ inch) per hour. A water level variation of one meter corresponds to 15.78 cm on the chart. The chart paper is scaled in feet, with 50 divisions per foot. Water levels were read to the nearest 0.01 foot with an accuracy of better than ± 0.01 foot.

No datum plane was established for the temporary gages. Water levels were read relative to an arbitrary zero value. During the data analysis, a datum plane of one foot below mean sea level was approximated by arithmetically equating the mean of the water levels recorded along the west shore of the study

site with the mean recorded at the Corps of Engineers gage. This assumes that there was no permanent slope in the surface during the two field studies.

Wind data collected at the Coast Guard Station at Port Aransas were obtained through the National Weather Service in Corpus Christi. The anemometer is positioned approximately 20 meters above the ground and approximately 22 meters above sea level. The anemometer is located approximately 1300 meters from the coast. Windspeeds were recorded in knots at three hourly intervals; wind directions are recorded as the nearest sixteenth point of the compass. The distance from the Coast Guard Station to the study site is approximately 30 kilometers. Wind data collected between 15 January and 15 February, 1975, were obtained to correspond with the second field exercise, in which the effects of frontal passages were of particular interest.

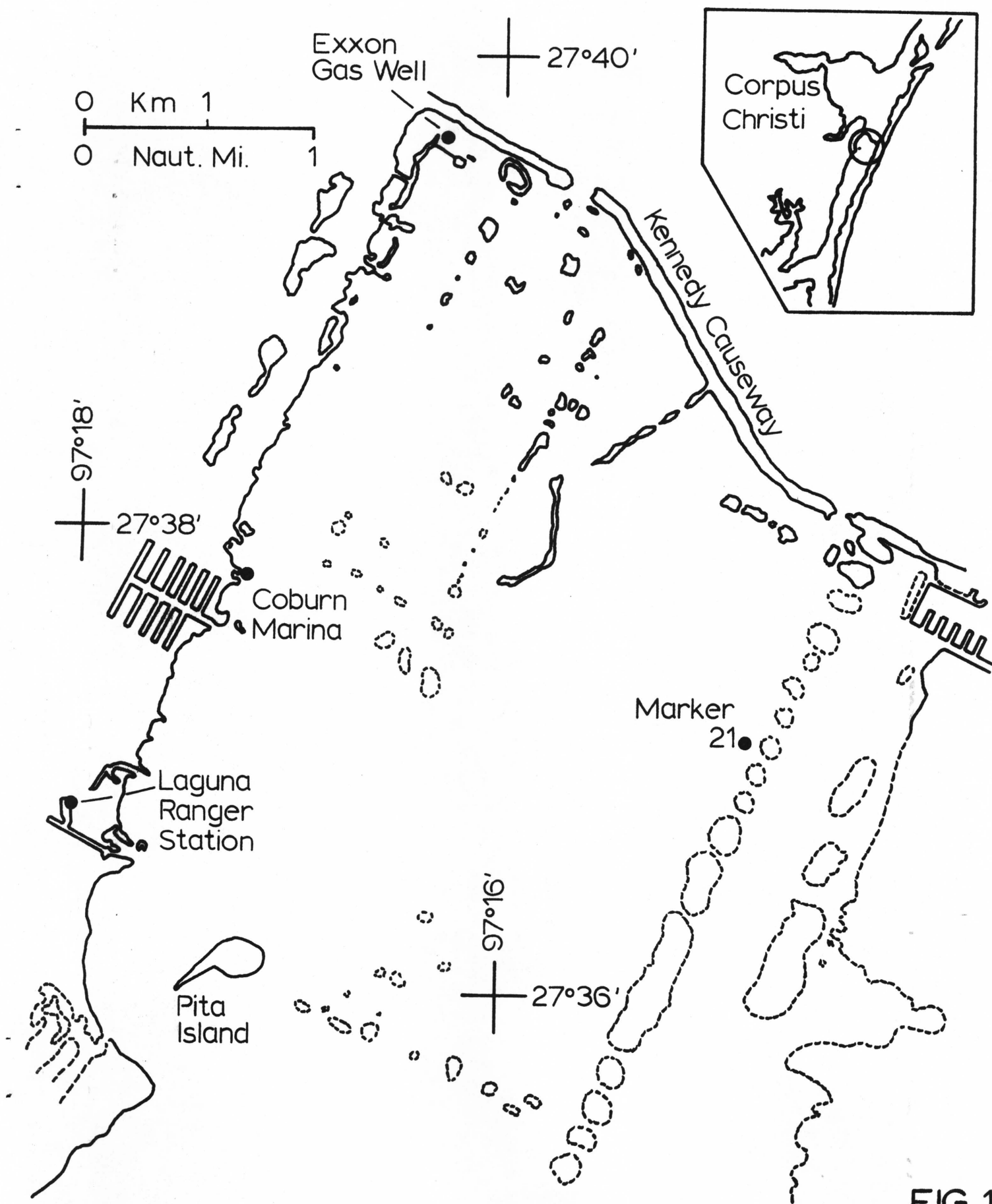


FIG.1

Methods of Analysis

Most of the analytical techniques used in this study to characterize water level variations in Upper Laguna Madre fall under the general heading of time series analysis. Spectral analysis, in three forms, was used on the two long time series from the South Jetty of the Aransas Channel at Port Aransas and at Marker 21 of the Intracoastal Waterway in Laguna Madre to investigate the movement of tidal and long period water level variations from the Gulf, through Corpus Christi Bay to the study site. Energy density, coherence and phase spectra were computed, using a computer program developed by Fee (1969). The linear trend is removed as a first step in the computation. Thus, annual or longer period variations in sea level (Marmer 1954) should be largely eliminated. The 5% and 95% confidence limits were computed for the energy density spectra, using the expression χ^2/v , where v is the number of degrees of freedom, given approximately by

$$v = \frac{2N - m/2}{m}$$

(see Panofsky and Brier 1963). Here N is the total number of data points, and m is the maximum time lag in the computation. Once v has been determined, the values of χ^2/v are easily calculated to obtain the critical 5% and 95% limits which must be exceeded to identify a statistically significant presence or absence of water level variations at a given period.

In a similar manner, the 95% confidence level was computed for the coherence spectrum, relating water level variations in Upper Laguna Madre with those occurring at the coast at Port Aransas.

Twenty-nine day segments of water level data from Port Aransas, Marker 21 and the three temporary monitoring sites along the west shore of the study site were used to compute the harmonic constants of the principal tidal constituents. A harmonic analysis program (Dennis and Long 1971) was obtained from the National Ocean Survey for this purpose.

Within Laguna Madre, and for both the late summer and winter field studies, water level data from trios of stations were used to compute the surface gradient vectors of the free surface of the study site, which was approximated by a plane. Temporal variations in the magnitude and direction of the surface slope will reflect the effect of net transport within the study site in response to meteorological forces. The hourly surface gradients were then plotted in head-to-tail fashion, forming a progressive vector diagram. This more qualitative presentation of variations in the surface tilt of the bay is directly related to tidal motions and meteorological forcing, as surface windstress transports water from the windward to the leeward shores of Laguna Madre.

Surface gradient vectors were then decomposed into components parallel and perpendicular to the axis of Upper Laguna Madre. The allignment of the Intracoastal Waterway through the study site, 025° - 205° , was taken to represent the axis of Upper Laguna Madre. The components of each computed hourly surface gradient were entered on a corresponding grid pattern composed of blocks 0.05 cm/km on a side. The number of vector end points falling within each block was then converted to a percent, and contours were drawn, forming a vector frequency diagram. The pattern presented

by the frequency isopleths indicates the relative importance of a steady wind as opposed to periodic or transient aperiodic forces in influencing the surface gradient of the bay.

Water level data obtained within the study site and at Port Aransas were filtered, using the "D₃₉" filter described by Groves (1955) to remove tidal periodicities. This filter is of the form

$$Y(t) = \sum_{i=-n}^n w_i y(t-i), \text{ where } -w_1 = w_1.$$

The sum of the filter weights, w_i , equals unity. Filters of this type do not produce a phase shift in the smoothing process.

The variance of the data was computed at all locations, both before and after the numerical filtering. The ratio of the variances of the filtered to the unfiltered data is a measure of the local importance of tidal period motions. This ratio may also vary seasonally, as the effects of winter frontal passages are recorded at the study site.

The variations in water levels at the study site may be equated with volume changes and thus net flushing, given the surface area of the study site. The surface area was therefore determined using a compensating polar planimeter. For this purpose, the southern boundary of the study site was arbitrarily taken to be 27°36'N, which passes through Pita Island.

Recorded wind velocities, \vec{V} , were converted to windstress vectors, $\vec{\tau}$, using the expression

$$\vec{\tau} = \rho C_D \vec{V}^2,$$

where ρ is the air density and C_D is the drag coefficient. For this study, both ρ and C_D were assumed constant, with values of

1.23 kgm/m³ and 0.0013, respectively. Windstress vectors were then plotted in head-to-tail fashion to produce a progressive vector diagram.

Results

The spectral analysis of the 148.5 day records from the Corps of Engineers tide gages at Port Aransas and at Marker 21 along the Intracoastal Waterway provide a good overview of how tidal and longer period water level variations move from the coast to the study site. The energy density spectrum from Port Aransas is shown in Figure 2. Only energy levels at periods of five hours and longer have been plotted. Frequency resolution for both spectra is 0.001 hour^{-1} .

Dominating the spectrum of Port Aransas water level variations are well defined energy peaks at periods of greater than 50 hours and at periods of 23-26 hours, 12-12.5 hours and 8.2-8.5 hours. The very long period energy levels are largely in response to meteorological forces, including variations in the onshore component of the pressure gradient, and the onshore component of the surface windstress. No pressure gradient or surface wind data were obtained for this time interval.

The rise in energy levels at periods between approximately 23 and 26 hours is due to the diurnal period tides. Smith (1974) has shown that the K_1 and O_1 tidal constituents, with periods of 23.93 and 25.82 hours, respectively, are the principal diurnal tidal constituents at Port Aransas, with amplitudes of just under 12 cm (0.4 foot).

The spectral peaks computed at periods between approximately 12 and 12.5 hours are due to the semi-diurnal tidal constituents, i.e., the S_2 and M_2 partial tides, respectively, with periods of

12.00 and 12.42 hours and amplitudes of approximately 7.6 cm and 2.4 cm (Smith 1974).

A smaller and somewhat broader energy density peak is noted at periods slightly longer than eight hours. This may be due to the M_3 tidal constituent, with a period of 8.28 hours, however no information is available on the amplitude of the M_3 constituent in the northwestern Gulf of Mexico. In a theoretical study, Platzman (1972) has shown that free oscillations of the Gulf may occur at these periods, thus this spike may be of meteorological origin.

Another rise in energy levels is found at a period of just over six hours. This may be due to the MS_4 tidal constituent, with a period of 6.10 hours, but again no information is available. Because of the low amplitude nature of energy levels below five hours, and because they do not appear to move from the Gulf through Corpus Christi Bay and into the study site--a distance of 35 kilometers (19 nautical miles)--the spectra were not plotted at periods below 5 hours.

Figure 3 shows the spectrum computed from water level data collected at Marker 21, along the Intracoastal Waterway at the study site. The longest period energy levels are nearly identical with those found in the Port Aransas spectrum, however values quickly drop off to approximately half an order of magnitude below those computed from the Port Aransas data.

The O_1 and K_1 tidal constituent energy levels are still clearly separated, but the amplitude of the K_1 constituent is noticeably smaller than that of the O_1 constituent in Upper

Laguna Madre, whereas it had been slightly higher at the coast. This suggests a preferential filtering which is inversely proportional to the period of the constituent.

At the semi-diurnal periodicities, the M_2 constituent is still noticeable, though it has declined in amplitude by nearly 2.5 orders of magnitude from the energy levels computed from the South Jetty data. The S_2 and shorter period tidal constituents are missing altogether.

Figure 4 shows coherence squared values for water level variations measured at Marker 21 and the South Jetty between 30 January and 27 June, 1974. Highest values occur at periods longer than about $2\frac{1}{2}$ days, resulting from long period variations in pressure and/or windstress which drive water against or remove it from the coast, and eventually from the study site through Corpus Christi Bay. Occurring over such long periods, there is sufficient time for water to move into or out of Corpus Christi Bay and Upper Laguna Madre, maintaining a near equilibrium condition. This represents an effective flushing mechanism for the bays and lagoons of South Texas.

Coherence squared values drop off abruptly and remain low between periods of approximately 60 and 30 hours, then rise sharply at the diurnal tidal periodicities. Both the O_1 and K_1 tidal constituents can be identified in the spectrum by slightly higher coherence squared values.

The semi-diurnal motions are coherent at the M_2 period only, with a coherence squared value of over 0.65 at a period of 12.5 hours. The immediate decrease in coherence squared values

indicates that the S_2 constituent probably does not move from the Gulf into the study site.

Table 1 gives the phase lag of water level variations at diurnal and semi-diurnal periods recorded at Marker 21 at the study site relative to those recorded at the coast at Port Aransas. At roughly diurnal periods, between 23.3 and 27.0 hours, phase lags of between 122° and 132° are computed, corresponding to time lags of between 8.5 and 9.3 hours. With a distance from the coast to the study site of approximately 35 kilometers, this corresponds to a speed of propagation of approximately 4 km/hour. At semi-diurnal periods of between 12.3 and 12.7 hours, the phase lag lies between 204° and 206° , corresponding to a time lag of between 7.0 and 7.2 hours and a speed of propagation of approximately 5 km/hour.

The harmonic constants for the principal tidal constituents computed from the six time series collected as part of the two field studies are given in Table 2. The diurnal K_1 and O_1 constituents are the largest, but all computed amplitudes are less than 0.1 foot (3 cm). Most phase angles are consistent with the idea of the tidal crest moving into Laguna Madre from Corpus Christi Bay, however the phase angles of such low amplitude waves cannot be considered statistically valid.

The numerical filtering of the long time series from Port Aransas and Upper Laguna Madre provide some interesting quantitative results regarding the extent to which tidal period water level variations dominate the data collected at these two locations. The results are shown in Table 3. The total variance computed from

Table 1. Phase lags of diurnal and semi-diurnal period water level variations at Marker 21, relative to those at Port Aransas.
30 January to 27 June, 1974.

<u>Period (hours)</u>	<u>Phase Lag at Marker 21 (degrees)</u>	<u>Corresponding Time Lag (hours)</u>
27.0	124	9.3
26.3	125	9.1
25.6	125	8.8
25.0	122	8.5
24.4	125	8.5
23.8	130	8.6
23.3	132	8.5
12.7	204	7.2
12.5	205	7.2
12.3	206	7.0

Table 2. Harmonic Constants of the Principal Tidal Constituents.
Amplitudes, η , in feet; local phase angles, κ , in degrees.

A. Summer Field Study, 29 days starting 0000 CST, 20 August, 1974.

		K(1)	O(1)	P(1)	M(2)	S(2)
1. Coburn Marine	κ	78.9	54.6	78.9	273.4	203.7
Starts 0000, 20 Aug.	η	0.06	0.05	0.02	0.01	0.00
2. Laguna Ranger Station	κ	111.5	65.0	111.5	310.2	182.9
Starts 2300, 26 Aug.	η	0.09	0.08	0.03	0.00	0.01
3. Marker 21	κ	48.8	51.4	48.8	273.2	287.2
	η	0.09	0.07	0.03	0.02	0.01

B. Winter Field Study, 29 days starting 0000 CST, 16 January, 1975.

		K(1)	O(1)	P(1)	M(2)	S(2)
1. Exxon Gas Well	κ	43.1	31.7	43.1	256.6	41.7
Starts 0000, 16 Jan.	η	0.07	0.08	0.02	0.01	0.01
2. Laguna Ranger Station	κ	54.9	53.9	54.9	268.1	60.0
Starts 0000, 16 Jan.	η	0.05	0.06	0.02	0.01	0.01
3. Marker 21	κ	64.5	52.3	64.5	267.2	294.5
	η	0.07	0.09	0.02	0.01	0.00

Table 3. Variances of Filtered and Unfiltered Water Level Data.

A. Summer Field Study, 0000 CST, 20 August to 2300, 18 September, 1974.

	<u>Unfiltered</u>	<u>Filtered</u>	<u>Filtered/Unfiltered</u>
1. Coburn Marina	0.027 ft ²	0.021 ft ²	0.769
2. Laguna Ranger Station	0.082 ft ²	0.075 ft ²	0.914
3. Marker 21	0.084 ft ²	0.074 ft ²	0.875

B. Winter Field Study, 0000 CST, 15 January to 2300 CST, 17 February, 1975.

	<u>Unfiltered</u>	<u>Filtered</u>	<u>Filtered/Unfiltered</u>
1. Exxon Gas Well	0.031 ft ²	0.021 ft ²	0.698
2. Laguna Ranger Station	0.036 ft ²	0.027 ft ²	0.755
3. Marker 21	0.040 ft ²	0.030 ft ²	0.769

the 155 day record obtained at the South Jetty in Port Aransas was 384.6 cm^2 (0.414 foot^2). The corresponding filtered variance, with tidal period variations removed, was 185.8 cm^2 (0.200 foot^2), or about 48% of the unfiltered variance value. This suggests that water level variations recorded at the coast are approximately equally distributed between tidal and non-tidal motions.

The 148.5 day record from Marker 21 had an associated variance of 162.6 cm^2 (0.175 foot^2) before being filtered, and 149.6 cm^2 (0.161 foot^2) when tidal period variations had been removed. Thus, at the study site, approximately 92% of the recorded water level variations were not of tidal origin. This is consistent with the concentration of energy density in the long-period part of the spectrum (Fig. 3).

The results from the numerical filtering of the data collected during the two field studies are shown in the second half of Table 3. Of particular interest is the fact that there is no significant difference between the results of the two field studies--the variability of water levels in the study site does not appear to increase appreciably during the winter months, when frontal passages reverse the direction and increase the magnitude of the windstress vector. Throughout the year, tidal motions account for between 10% and 30% of the total water level variability in Upper Laguna Madre. To the extent that a trend is apparent, there seems to be a greater variation of water levels during the summer field study.

Another technique for quantitizing the magnitude of tidal motions involves the relationship between the amplitude of a sine wave, η , and the associated variance:

$$\text{variance} = \frac{1}{2} (\eta)^2$$

(Panofsky and Brier 1963). The total variance associated with tidal motions may then be obtained by summing the variances computed from the amplitudes of the individual tidal constituents. The results of these summations for the six time series obtained in the two field studies are shown in Table 4. Corresponding to the total tidal variance is a single constituent, hypothetical tide, the amplitude of which is also given in Table 4. In view of the dominance of diurnal tidal constituents in Upper Laguna Madre, there is some justification for thinking of the real tide in terms of its hypothetical counterpart.

The results are fairly consistent, both in space and time, indicating that maximum tidal amplitudes characteristic of Upper Laguna Madre are on the order of 3-4 cm. This does not include the fortnightly or longer period tidal constituents, however these are generally of smaller amplitude than the principal diurnal and semi-diurnal constituents.

Water level data from the winter field study were used to compute surface gradient vectors--the hour-by-hour variations in the surface tilt in the study site. The results, shown in Figures 5 and 6, provide information relating to several aspects of the short-period motions within the study site.

Figure 5 shows the progressive vector diagram, formed by plotting surface gradient vectors in head-to-tail fashion over the 29 day sampling period. The positive x-axis parallels the Intra-coastal Waterway along a bearing of 025° . By convention, positive gradients point in the direction in which water levels decrease.

Table 4. Tidal Variances and Effective Amplitudes in Upper Laguna Madre.

	<u>Total Variance</u>	<u>Effective Amplitude</u>
A. Summer Field Study		
1. Coburn Marina	3.25 cm ² (0.0035 ft ²)	2.55 cm (0.08 ft)
2. Laguna Ranger Station	7.27 cm ² (0.0078 ft ²)	3.81 cm (0.13 ft)
3. Intracoastal Waterway, Marker 21	6.85 cm ² (0.0074 ft ²)	3.70 cm (0.12 ft)
B. Winter Field Study		
1. Exxon Gas Well	6.38 cm ² (0.0069 ft ²)	3.57 cm (0.12 ft)
2. Laguna Ranger Station	3.31 cm ² (0.0036 ft ²)	2.57 cm (0.08 ft)
3. Intracoastal Waterway, Marker 21	6.26 cm ² (0.0067 ft ²)	3.54 cm (0.12 ft)

The pattern is characterized by a southerly-directed slope on the order of 2.5 cm/km during the first eight days of the study. The progressive vectors make an anticyclonic loop, then drift slowly off to the northeast through February 2. Northerly directed slopes were computed for the last part of the study, with gradients increasing during the final two days.

Tidal period variations in the direction of the slope are not well defined and become apparent only when the gradient vector roughly parallels the y-axis. This is consistent with the idea of tidal crests of small amplitude moving into the study site from Corpus Christi Bay, then through Upper Laguna Madre to the south.

The vector frequency diagram presents an interesting, tri-modal pattern, with concentrations of surface gradient vectors lying roughly along the axis of the Intracoastal Waterway. Characteristic slopes seem to be either approximately ± 3 cm/km or about 0.5 cm/km. The two concentrations of gradient vectors at plus or minus 3 cm/km correspond with the long period reversal of progressive vectors and probably represent a slow draining and refilling of Upper Laguna Madre waters under the influence of surface windstress and surface pressure gradients.

Coastal winds were monitored at the Coast Guard Station at Port Aransas (see Fig. 1) between 15 January and 15 February, corresponding to the winter field study. During this time interval, two well defined frontal passages occurred. Sharp discontinuities are seen in the progressive vector diagram (Fig. 8) on 20 January and 6 February. The resultant windstress

vector is directed along a heading of 185° , however the pattern is a result of several periods of northwesterly and southeasterly winds, following and preceeding the frontal passages. Strongest winds occurred on the 19th and 20th of January, and on the 6th, 7th and 9th of February. Periods of nearly calm conditions were recorded on 15, 21 and 25 January and on 8 and 13 February. With the Intracoastal Waterway alligned in a direction of 025° - 205° , the net effect of windstress over this time interval would be to force water from Corpus Christi Bay through the study site and into Baffin Bay. The observed alternation of northwesterly and southeasterly winds, however, while directed nearly perpendicular to the axis of Upper Laguna Madre, could have the effect of transporting water back and forth through the study site between Corpus Christi Bay and Baffin Bay. Synoptic field surveys would be required to confirm this, perhaps using salinity as a tracer.

Figure Captions

- Figure 1. The study site in Upper Laguna Madre, South Texas.
- Figure 2. Energy density spectrum using South Jetty, Port Aransas water level data, 30 January - 27 June, 1974.
Computed with 500 lags. Energy density values not plotted at periods below five hours.
- Figure 3. Energy density spectrum using Marker 21, Upper Laguna Madre water level data, 30 January - 27 June, 1974.
Computed with 500 lags. Energy density values not plotted at periods below five hours.
- Figure 4. Coherence-squared spectrum for South Jetty and Marker 21 water level data, 30 January - 27 June, 1974.
Computed with 500 lags. Coherence-squared values not plotted at periods below five hours.
- Figure 5. Progressive vector diagram of surface gradients computed from hourly water level data collected during the winter field exercise, 15 January - 14 February, 1975. Calendar dates point to 0000 CST.
- Figure 6. Vector frequency diagram of surface gradients computed from hourly water level data collected during the winter field exercise, 16 January - 13 February, 1975. Axes in cm/km.
- Figure 7. Progressive vector diagram of surface windstress vectors computed from three-hourly wind data recorded at Port Aransas during the winter field exercise, 14 January - 15 February, 1975. Calendar dates point to 1800 CST.

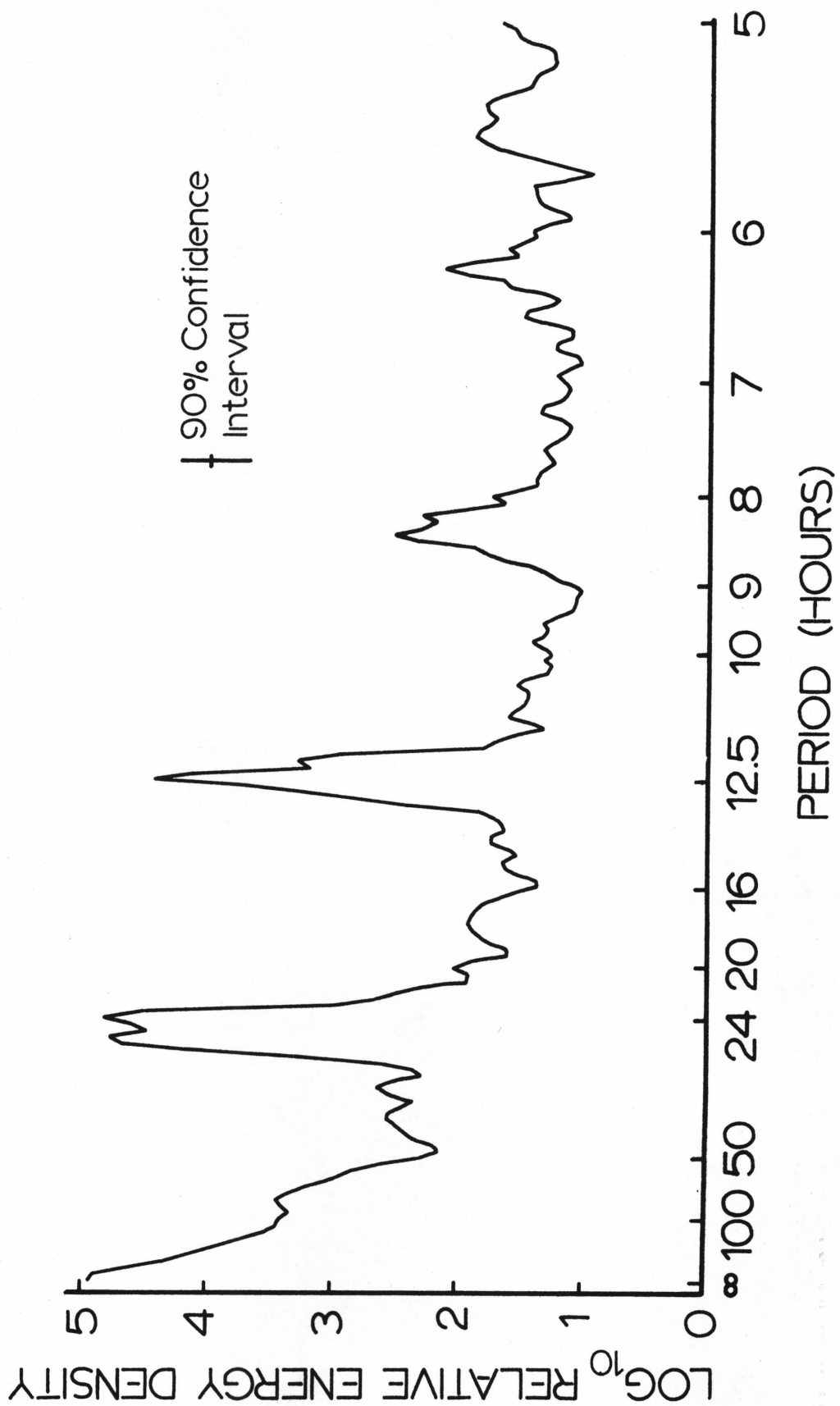


FIG. 2

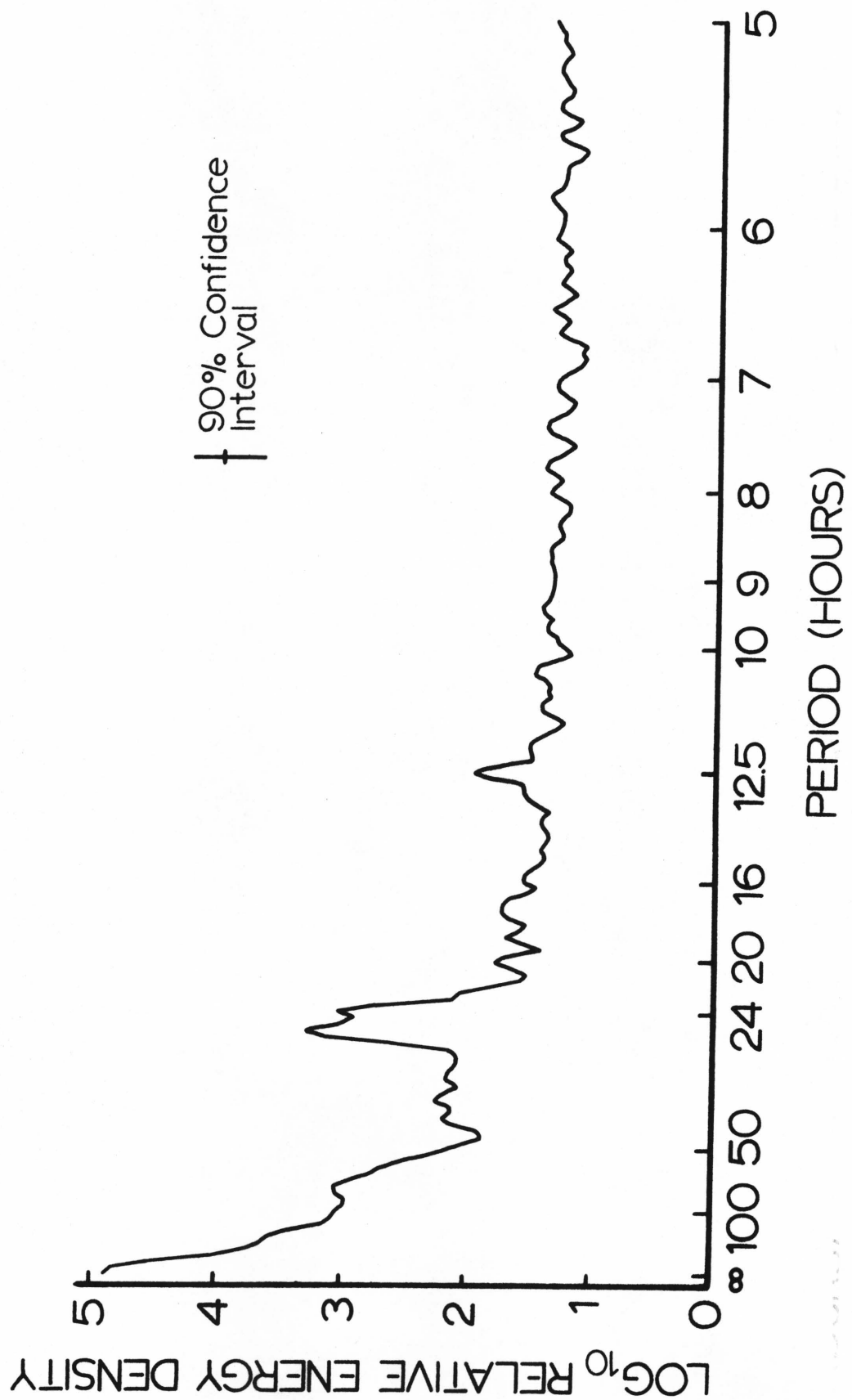


FIG. 3

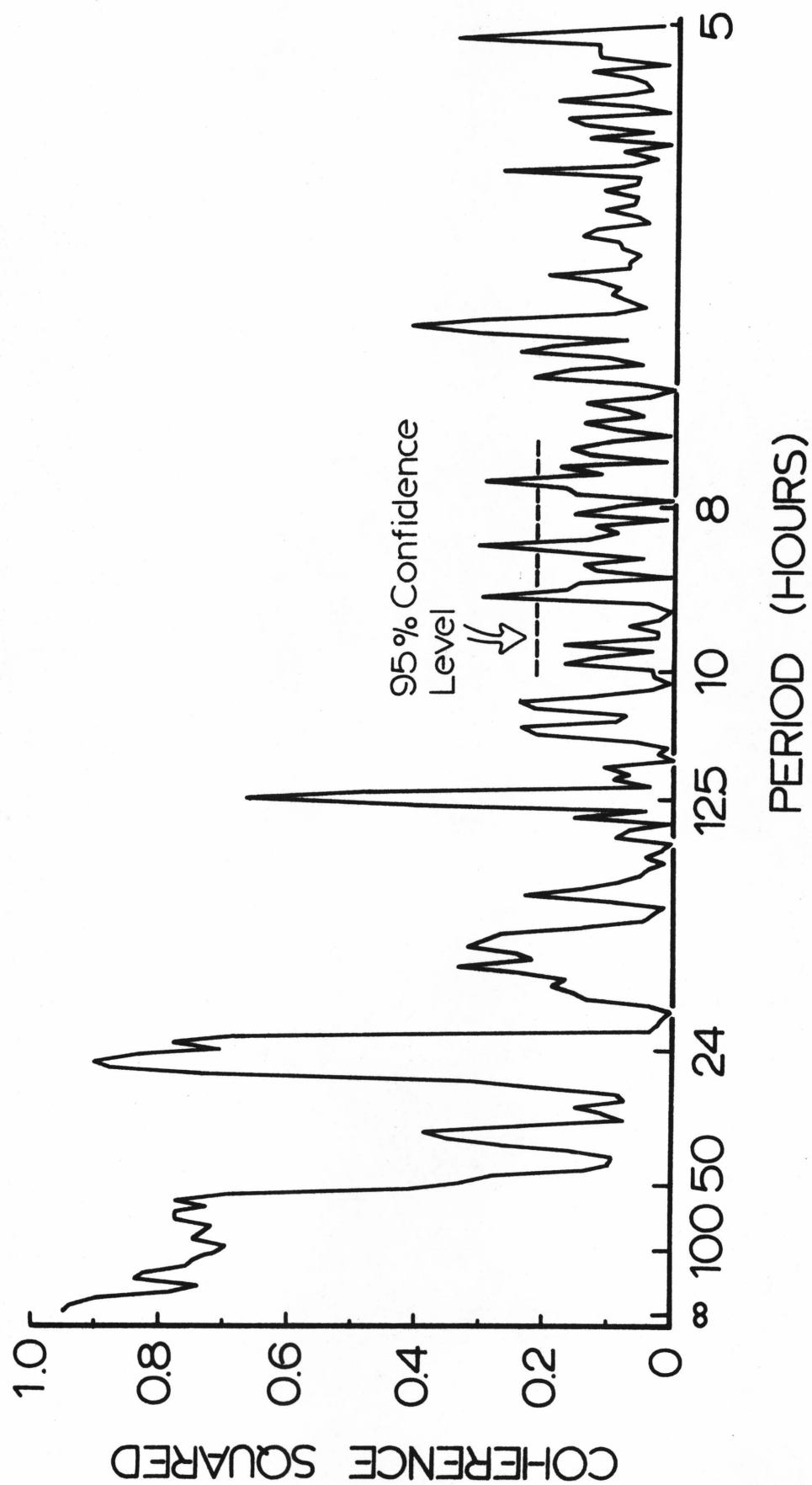


FIG.4

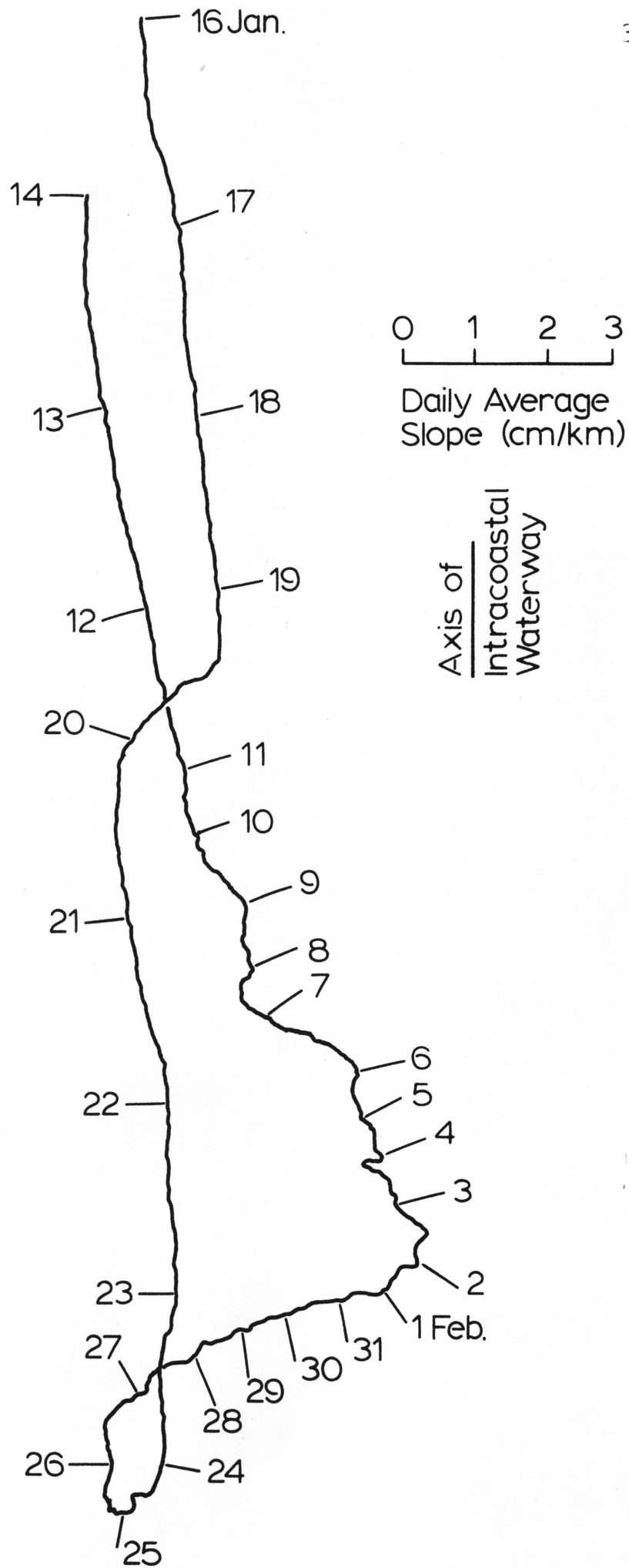
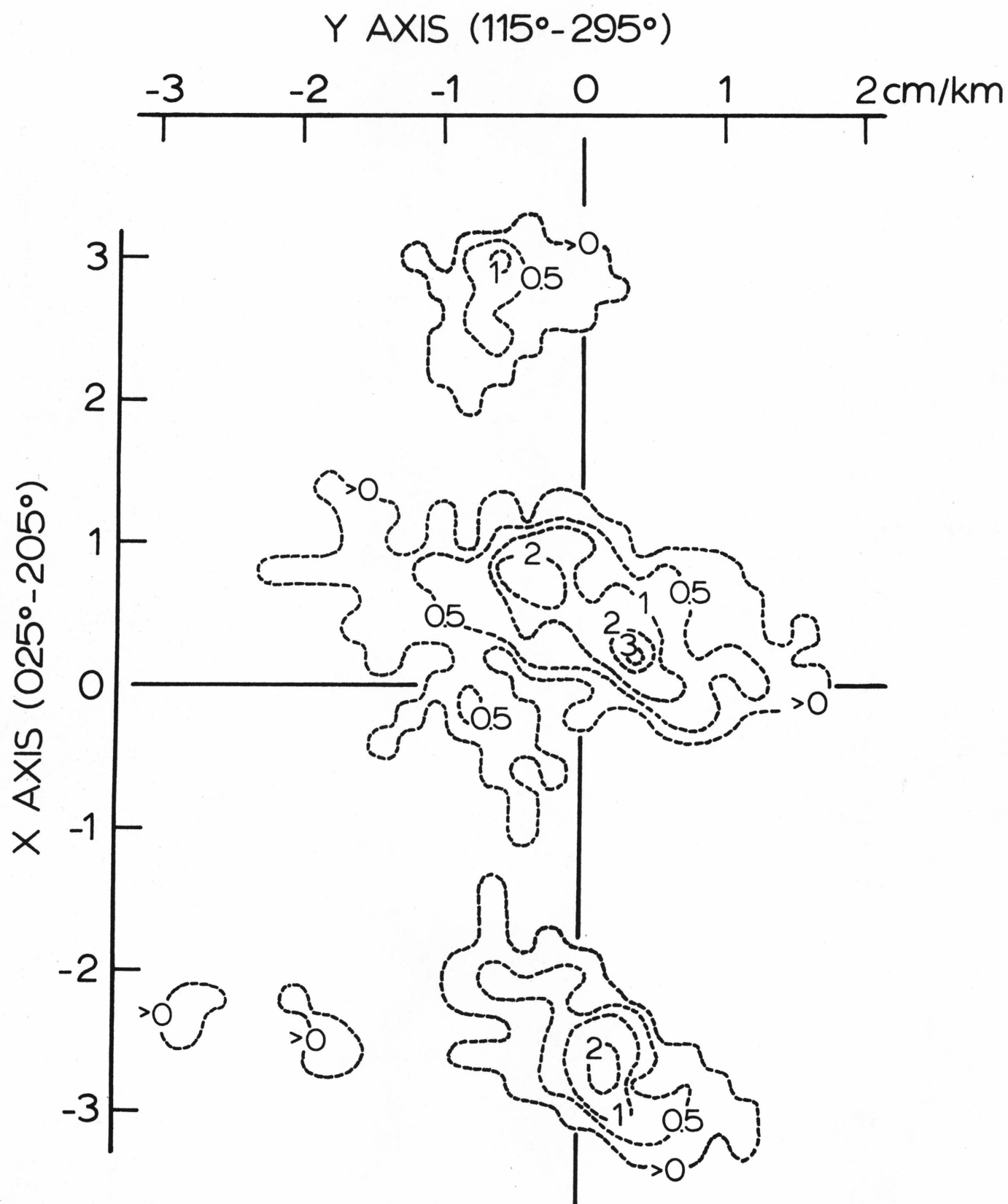
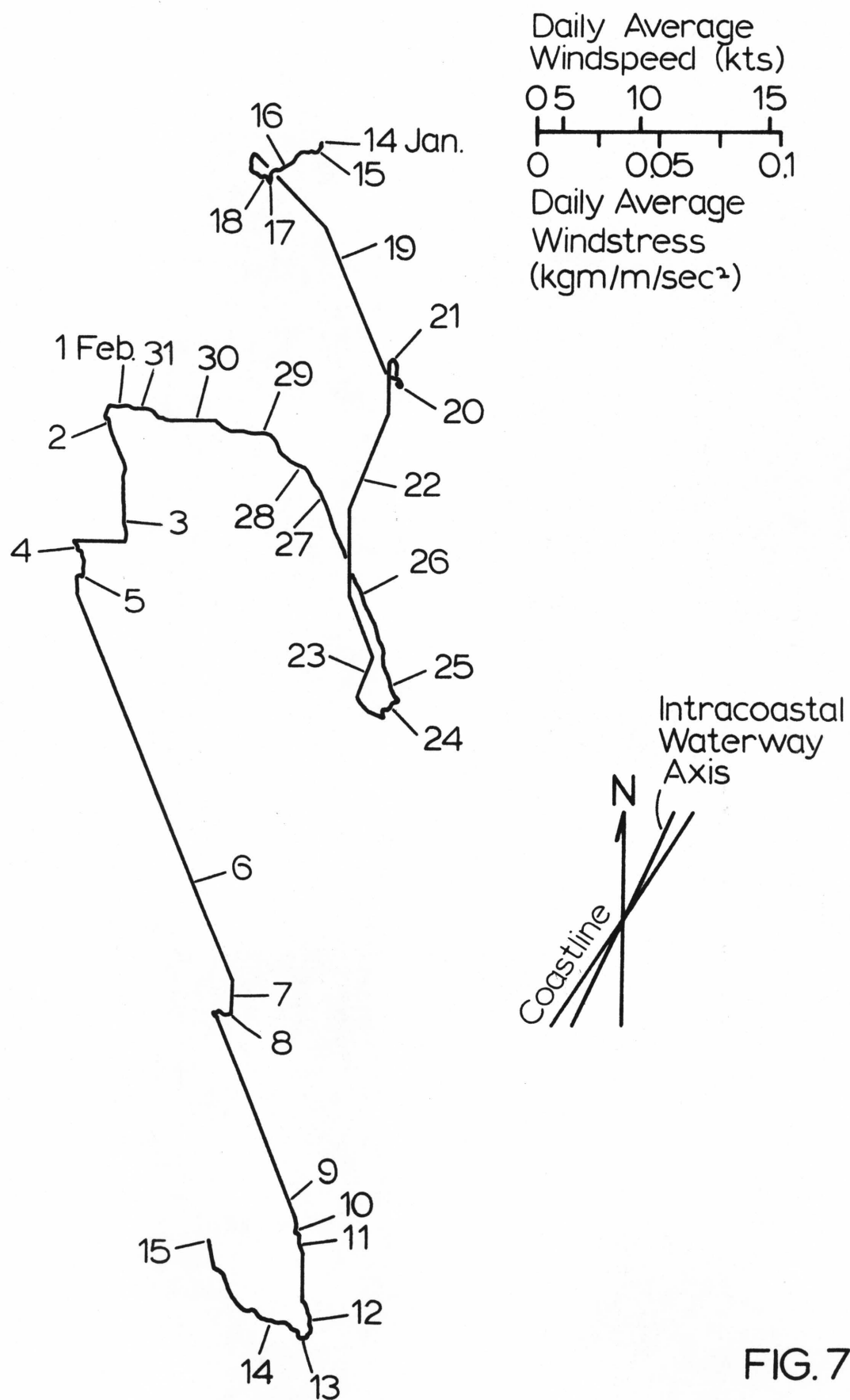


FIG. 5





Discussion

The results of the first year's tidal and circulation study indicate that the circulation of Upper Laguna Madre is made up of three components. There is a steady outflow of water from the study site of $926,666 \text{ m}^3/\text{day}$ into the Central Power and Light generating station. This outflow corresponds to a lowering of 3.76 cm/day in the water level of the defined study site. This figure should be interpreted with caution, however, as the southern boundary of the study site is open-ended and was arbitrarily selected.

This steady lowering of water levels near Pita Island is, for the most part, balanced by an inflow through the Kennedy Causeway, since nowhere near $926,666 \text{ m}^3/\text{day}$ ($10.7 \text{ m}^3/\text{sec}$) enters through the three small rivers that empty into Baffin Bay. These provide the primary source of fresh water into Laguna Madre north of the Land Cut, and much of this inflow may be lost through evaporation before reaching the study site.

Hahl and Ratzlaff (1972) have constructed cross-sections of the three channels cut through the Kennedy Causeway. The primary channel, the Intracoastal Waterway between Upper Laguna Madre and Corpus Christi Bay, has a cross-sectional area of approximately 800 m^2 . Thus, for $926,666 \text{ m}^3/\text{day}$ to enter through this cut, a hypothetical steady inflow of 1.35 cm/sec would be required. The total cross-sectional area of the three channels is approximately $1,390 \text{ m}^2$, to which would correspond an inflow of 0.77 cm/sec . It is unlikely, however, that a uniform inflow is found at all three entrance channels.

Hall and Ratzlaff conducted short volume transport surveys, which included sampling at the Intracoastal Waterway cut through the Causeway. The flow through this channel was found to be over three times greater than that through either of the other two cuts in the Causeway.

A second form of circulation, also involving flow through the Kennedy Causeway, is that associated with the tidal variations in water level recorded throughout the study site. Unpublished water level data from near the junction of Upper Laguna Madre and Baffin Bay suggest that tidal motions well south of the study site are virtually absent. It is logical to assume that the net inflow required to support the computed tidal amplitudes must occur through the Kennedy Causeway. Indeed, the high coherence values at diurnal and semi-diurnal periodicities, and the computed phase angles indicate that tidal motions can be traced back through Corpus Christi Bay to the Gulf tides occurring at Port Aransas.

Within the study site, these tidal currents oscillate back and forth, utilizing the navigational channels as paths of least resistance. Surface windstress and dense beds of seagrasses, primarily shoal grass (*Halodule wrightii*) and widgeon grass (*Ruppia maritima*), combine to greatly retard the free movement of the waters of Upper Laguna Madre.

Tidal amplitudes on the order of three centimeters (0.1 foot) in the study site, combined with a surface area of 24.64 km², indicate that volumes of approximately 750,000 m³ must oscillate through the three channels in the causeway to explain

water level variations observed in the study site alone. These volumes correspond to maximum current speeds of 0.3 cm/sec through the cuts, assuming the tides to be primarily diurnal. Current speeds through the navigation channels within Laguna Madre, being less restricted, are likely to be substantially less. Even at the Causeway, tidal currents would be too slow to be measured.

The third type of currents in Upper Laguna Madre are those in response to meteorological forces which produce both a long period net flushing of the study site and a local internal circulation. Long period variations in surface pressure gradients and surface windstress, including the effects of frontal passages, effect a net loss of water from all of Upper Laguna Madre, Corpus Christi Bay and the Texas Gulf coast. Exchanges of this type occur over periods of several days and longer, merging with the long period tides and semi-annual water level variations, noted by Marmer (1954) for all areas along the northern rim of the Gulf. While a slow process, this is an effective mechanism for flushing the bays, since longshore currents at the coast (Smith 1975) sweep away the water coming out of the bays, and the later return flow to the bays involves shelf water supplied from upstream regions.

The progressive vector diagram and vector frequency diagram are good indicators of the internal motions within the study site. The progressive vectors return approximately to the origin, and the vector frequency pattern is symmetrically distributed about the origin, however this is a necessary consequence of arithmetically equating the means of the three time series for

the two field studies. The assumption of no quasi-permanent slope in the free surface may be a poor one. Smith (1974) has shown that neighboring Corpus Christi Bay, under the influence of the same coastal winds, has surface slopes of characteristically 0.5 cm/km during the winter months at least. Nevertheless, the analysis of surface gradients computed from hourly water level observations is well suited for describing internal motions occurring over time intervals which are short with respect to the total 29 day time series.

Of particular interest is the fact that tidal period oscillations are all but negligible in the progressive vector pattern. Dominating the pattern is a single southward tilt in the free surface, followed after about a week of nearly flat surfaces by a tilt to the north. This corresponds rather poorly to the simultaneously recorded windstress vectors. Frontal passages are indicated for the study site on 18 January and 2 February. While slopes are consistent with water being removed from the study site following the 2 February frontal passage, surface slopes prior to and following the 18 January front suggest that water is being piled up against the Kennedy Causeway. One can tentatively conclude that long period volume transport is only poorly related to long period variations in surface gradients, and that the slow rise and fall in water levels occurs nearly simultaneously throughout the study site.

In situ observations of current speeds and directions demonstrated the expected pattern of surface layers being skimmed off toward the downwind shore under the influence of surface

windstress. Currents of generally less than 10 cm/sec were observed in the upper few centimeters of the water column in water on the order of 25 centimeters deep. A thick mat of seagrasses prevented the wind drift from penetrating very far into the water column.

No attempt has been made to superimpose arrows representing current vectors onto a base map of the study site. The dominance of the wind drift component of the total circulation, together with the highly variable nature of the winds especially in winter, make it unadvisable to attempt to depict the internal circulation of the study site with the currents measured during a particular *in situ* study. One may characterize the general circulation of Upper Laguna Madre in the most general terms, however the great temporal and spatial variability of current patterns makes it impossible to represent the circulation with a collection of arrows on a base map.

The 1974-75 field studies had as a secondary goal such a general characterization. The data collected over the past year, while primarily for the purpose of describing the tides and long period net flushing, can be used to infer something of the gross features of the circulation. The emphasis in the proposed 1975-76 continuation of the study will be less on the tides and more on the direct observation of water movements within all of Upper Laguna Madre.

The most remarkable feature of the tide in Upper Laguna Madre is the low amplitude of the individual constituents. None of the principal tidal constituents has an amplitude greater

than 3 cm (0.09 foot). While the amplitudes are geometrically additive, one must still think of tides in the study site as being on the order of a few centimeters. Price (1971) has stated that the range of the daily astronomical tide in northern Laguna Madre is 1.0 foot, but this appears to be about an order of magnitude too high.

The diurnal K_1 and O_1 constituents are largest with amplitudes generally between 0.05 and 0.09 foot. The two principal semi-diurnal constituents have computed amplitudes of 0.02 foot or less.

The computed phase angles are generally consistent with the idea that tidal crests enter the study site from Corpus Christi Bay and move through to the southwest. With such low amplitudes, however, the validity of the phase angles is questionable, as it is difficult to determine the crest of a very low amplitude sine wave.

Flushing rates may be approximated by first order computations based on water level variations observed in the defined study site. Tidal ranges on the order of 6 cm (0.2 foot) could conceivably flush the study site over a time interval of 8-9 days, taking 0.5 m as a representative depth, and assuming the water ebbing into Corpus Christi Bay continues on to the Gulf. Similarly, the calculated 3.6 cm drop in water levels due to the cooling water intake by the Central Power and Light station could remove a volume of water equal to that contained in the study site in as little as two weeks. It is apparent that the water quality of Upper Laguna Madre is directly related to that

of Corpus Christi Bay, due to the continual exchange of water between these two basins.

The numerical filtering to remove tidal period water level variations demonstrates clearly that the non-tidal forces are of major importance in flushing Upper Laguna Madre. If tidally-induced flushing can occur in as little as eight days, it appears that a volume of water equal to that contained in the study area could move through in as little as 2-3 days following a strong frontal passage. While less dependable, winter cold fronts seem to be the most efficient flushing mechanism in Upper Laguna Madre.

Recommendations for Future Research

In the course of the first year's Tide and Circulation Study, it became apparent that research should be continued in several areas, relating directly to the results presented in this report. Recommendations for expanding or continuing the first year's study are summarized below.

A. Research in Upper Laguna Madre should be spatially expanded to include the entire region between the Kennedy Causeway and the Land Cut. This is the logical unit of study, with restricted exchanges at either end which can be monitored for inflow and outflow.

B. Temperature and salinity distributions should be determined in several field studies to record internal flushing and circulation using natural tracers.

C. Field studies should be conducted to directly measure current speeds and directions in the Intracoastal Waterway and major lateral navigation channels, and at the northern and southern entrances to Upper Laguna Madre. The currents through the Land Cut may be determined implicitly by measuring the slope of the free surface along the channel.

D. The net volume change of all of Upper Laguna Madre should be related to surface winds as measured at the Ranger Station on Padre Island. The flushing and internal circulation of Upper Laguna Madre should show a higher correlation with local winds than with winds measured at Port Aransas.

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Appendix A

Response Characteristics of the Hovenga Instrumentation Tide Gage.

The electronics of the Hovenga Instrumentation Tide Gage provides for an exponential filtering of periodic water level variations between the mechanical sensor in the stilling well and the analog recorder. It is a characteristic of all exponential filters that a phase shift is put into the filtered analog of the input signal, and that the response of the filter to the amplitude of the input signal is a function of the periodicity.

Both the phase shift and the response of the tide gages are shown as a function of period in the following figures. It is apparent that at the short periods associated wind waves (1-3 seconds) the filtering of this unwanted component of the total signal is very nearly complete. At the semi-diurnal and diurnal tidal periods, and at longer periods, the response of the tide gages is very nearly unity, and the phase shift is negligible.

