SHOALING CHARACTERISTICS OF
THE GULF INTRACOASTAL WATERWAY IN TEXAS

by

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ABSTRACT

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Maintenance dredging records were used to compute average shoaling rates in 5000-foot reaches for the entire Texas Gulf Intracoastal Waterway. Environmental data pertinent to the waterway were gathered from published and unpublished sources. Computed shoaling rates and selected environmental features were plotted on Composite Factors Maps.

Similar reaches were grouped and examined using analysis of variance techniques to determine the effect of selected environmental factors on shoaling rates. A model was also developed to predict shoaling rate in a reach with known environmental factors.

The average shoaling rate over the entire waterway was found to be 10.5 inches per year. Shoaling in open bay areas was found to be an average of 3 inches per year greater than in land-cut areas. The combination of dredged material mounds, or fetch greater than 5 miles, with water depths less than 6 feet (surrounding bay depth) increased average shoaling rates 5 inches per year. The placement of dredged material in mounds on the windward side of the waterway increased the average shoaling rate of open bay areas by 7 inches per year. In bay areas with long fetches and depths less than three feet, it was found that windward placement of dredged material was actually advantageous.

Hurricanes did not appear to have a drastic impact on shoaling rates; however, localized effects were noted in several areas.

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INTRODUCTION

Waterway Description

The Gulf Intracoastal Waterway in Texas is a shallow draft navigation channel, which extends from Port Arthur to Brownsville. The Texas portion of the waterway is 125 feet wide, 12 feet deep and 380 miles long.

The waterway passes through the low-lying areas adjacent to the Texas Gulf Coast. It passes through both land-cut and open bay areas. Land-cut areas, normally dry at low tide, are typically marsh, mud flats, or pastures. An idealized section of waterway through a land-cut area is shown in Figure 1. The depth and general character of the bay varies from the extremely shallow, saline water of Laguna Madre to the fairly deep, medium salinity waters of Galveston Bay. An excellent cartographic and narrative description of the geology, climate and general environments of the coast is presented in the Environmental Geologic Atlas of the Texas Coastal Zone series (12).

Economic Importance of the Waterway

Phillips (22) has estimated that 75% of the total goods transported out of Texas each year are carried on inland waterways. He has also assessed the waterway's direct economic contribution to Texas as $1.8 billion per year. The recreational value of the waterway

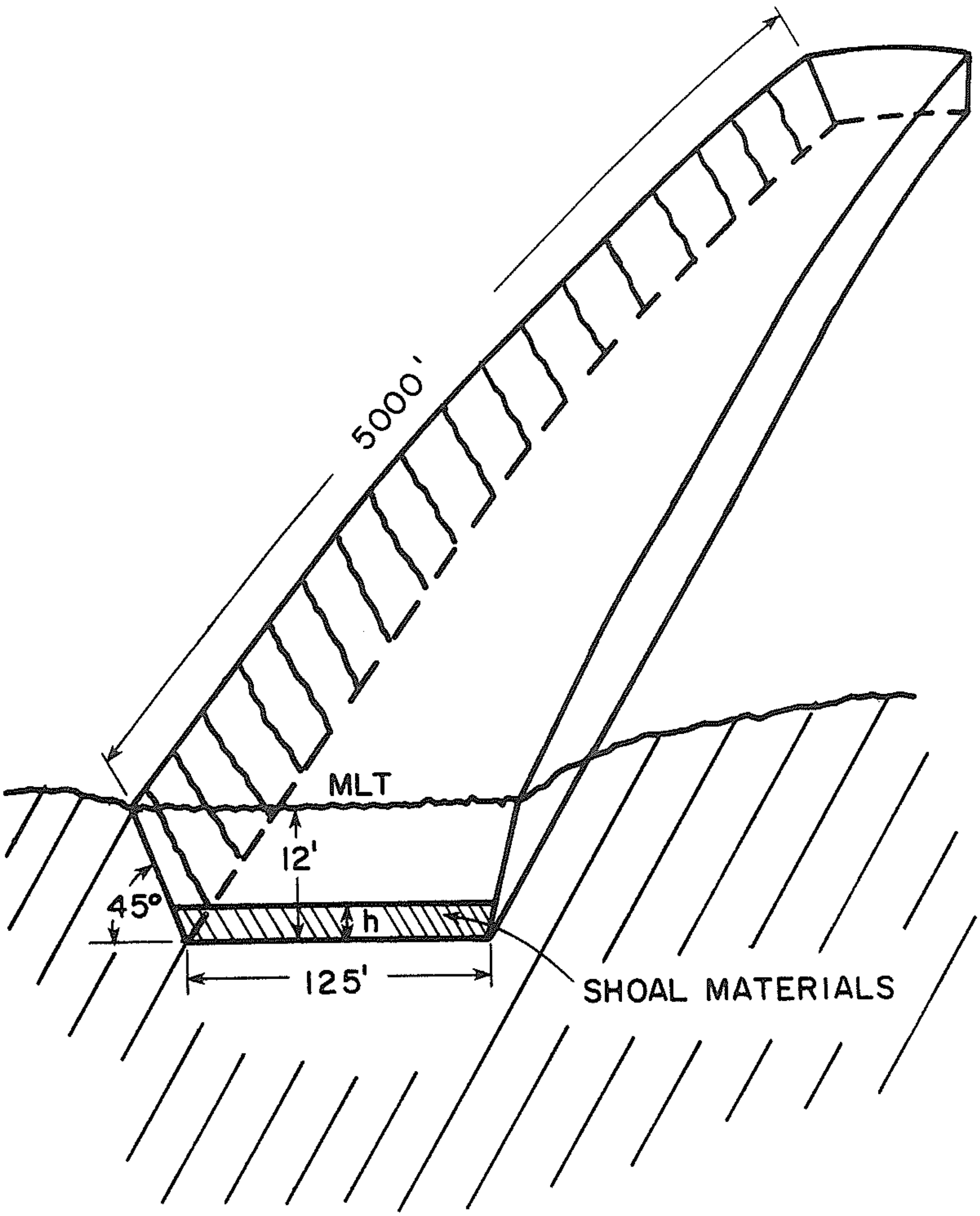

Fig. 1 Typical Land-Cut Section of the Gulf Intracoastal Waterway

alone is considerable. Simply stated, the Gulf Intracoastal Waterway is one of the state's most valuable resources.

Waterway Shoaling

Description. The natural forces of wind, waves, currents, and rain continually work to fill the waterway with sediment. This sediment is termed shoal material since it reduces waterway depth (Fig. 1). About 8 million cubic yards per year is removed from the Texas section of the waterway (20). This represents an average accumulation of about 10 inches per year over the 380 miles of main channel in Texas. At $0.40 per cubic yard for maintenance dredging (4) this amounts to an annual expenditure of over $3 million.

Consequences. Shoaling reduces the goods-carrying capacity of the waterway. Barges operate at reduced efficiency when depth restrictions force them to carry less than full loads. Tug fuel consumption is also increased as depth below the keel is reduced. Siltation of the waterway could also limit its value to boats seeking protected passage along the coast.

Before the waterway was completed there was little circulation in Laguna Madre. The result was hypersaline water which discouraged plant life and was thought to be a factor in several fish kills which occurred there (10). Allowing the waterway to shoal could cause a gradual return to this situation.

Control. The waterway is dredged continually to control the shoaling described above. This dredging has created much controversy.

Studies concerning least damaging dredging techniques (21) as well as dredged material disposal practices (6) also reflect this concern.

On the other hand, dredging is expensive. Until recently the method of disposal of dredged material was mainly an economic decision. Frequently, the method of disposal which is most appealing from an environmental standpoint is the worst economic alternative. The cost of various disposal techniques varies considerably. For example, Cable (6) has stated that open water disposal in the Chesapeake Delaware canal was 50% cheaper than the next least expensive alternative. In many cases, the most environmentally acceptable disposal solution would be to barge or pipe dredged materials long distances from the dredging site. The economic factor will probably continue to be important as long as the cost of dredging and disposal remain high. Any solution of the problems associated with waterway maintenance will be a delicate balance between economic and environmental considerations.

One obvious alternative which has been noted (4) is to reduce maintenance dredging by reducing shoaling. This would require three basic things: (1) knowledge of the rate of shoaling in particular areas, (2) knowledge of the factors which caused this shoaling, (3) the ability and resources to control those factors.

This research addresses only the first two objectives.

OBJECTIVES OF STUDY

The objectives of this research were: (1) to determine shoaling rates along the entire length of the Gulf Intracoastal Waterway in Texas, and (2) to correlate these rates with several characteristics of the local environment. The effect of wind and dredged material mounds on observed shoaling rates was of special interest.

LITERATURE REVIEW

Few field studies have been directly concerned with shoaling of the waterway. The studies which do address waterway shoaling have been primarily concerned with the erosion of dredged material mounds or the effect of dredging on the environment. A recent study (3) in Galveston Bay noted that 63% of the material deposited on a designated mound was gone after 22 weeks. There was also evidence that some of this material returned to fill the waterway again.

Cronin (8) noted that material deposited in 15 feet of water in Chesapeake Bay spread out to cover an area five times as large as the designated spoil area to a minimum depth of one foot. He also noted that 12% of the material originally deposited was gone after 150 days.

Saila and Pratt (26) attempted to relate movement of dredged material to current direction and velocity at the bottom. They indicated that accurate knowledge of bottom current patterns was needed to accurately predict material movement.

Hellier and Kornicker (14) did a field study in Redfish Bay near Aransas Pass, Texas. They used colored gravel to indicate the accumulation of dredged material. The authors noted increased accumulation of material on the leeward side of dredged material mounds.

Boyd (4) gave an extensive review of Corps of Engineer dredged material disposal research, and dredging practices in general. He discussed sources of shoal material, disposal alternatives and some of the practical problems associated with channel maintenance.

The U.S. Army Corps of Engineers Draft Environmental Statement

(10) describes the disposal areas adjacent to the waterway. It also includes summary information about the physical and biological environment. Proposed and existing disposal sites are discussed. The report also describes the factors involved in dredged material disposal site selection.

Einstein and Krone (11) indicated that broad shallow bays stirred by wind are probably prime sources of shoal material. In a study using radioactive tracer in San Francisco Bay, they found that the direction of sediment movement was not necessarily in the direction of wave movement. They postulated that sediment was placed in suspension by waves, then carried by existing currents. Similarly, Smith (29) noted that stirring action by the wind may be augmented by return flow opposite to the wind direction at the bottom.

Several authors have suggested that hurricanes may be a significant force shaping the Texas coast (5). The importance of the prevailing southeast wind in transporting sand (12), and in generating wave-induced bottom turbulence (27) has also been noted by most authors who deal with the Texas coast.

Herbich (22) computed shoaling rates in several broad reaches of the Gulf Intracoastal Waterway. He points to bank erosion, hurricanes, and wind-blown sand as shoaling mechanisms in certain problem areas of the Waterway.

Basco (2) has given an exhaustive review of the literature dealing with the erosion of subaqueous disposal areas. The work also contains a summary of the theoretical mechanisms involved in sediment transport.

A thorough discussion of math models available for the prediction of the movement of suspended sediment is given by Johnson (15). He points out that most models available today are water quality models which are not acceptable for predicting suspended sediment movement.

Storm (30) modified a water quality model to assess the impact of maintenance dredging. The model was primarily designed to predict the short-term movement of materials suspended during dredging operations.

Physical models have been used extensively to study navigation channel shoaling. Rhodes and Boland (24) used the physical model of Matagorda Bay to find optimum spoil mound orientation and location. Simmons (28) used the physical model of Galveston Bay to investigate a similar problem. In fact, a physical hydraulic model exists for most major ports. Physical models are most useful in comparing specific alternatives in a given area. They do not provide quantitative estimates of shoal accumulation. The Gulf Intracoastal Waterway has not been modeled. To do so would be a complex and enormously expensive task.

The numerous and controversial theories of sediment transport had little direct application in this study. The qualitative description of shoaling described by Ippen (16) was used in this study to explain characteristics of observed shoaling.

HISTORICAL DREDGING RECORDS

Problems in Determination of Shoaling Rates

Accurately measuring accumulation of material in the waterway, in even a small area, presents many technical problems (3). To conduct a scientific field study to find out the rate of sediment accumulation in the entire waterway would be a monumental task. For this reason, maintenance dredging records were investigated as a source of field data.

The Corps of Engineers has maintained dredging records (20) over the whole waterway which specify the amount of material removed during routine maintenance dredging. These records date back to original excavation of the waterway. Although not compiled under classical scientific control, the records are fairly extensive and complete. They were edited and verified by Corps of Engineer employees familiar with dredging policies and procedures.

The following basic approach was used to determine shoaling rates. First, it was assumed that a given section of waterway was dredged to the same depth each time that maintenance was performed. Thus, the amount of material which was removed during each dredging occurrence was the amount of sediment which had entered that section since it was dredged last. Dividing by the time between initial and final dredging, a rate of filling was computed. This rate was termed the shoaling rate.

Description of Dredging Records

Dredging may be classified according to the type of work which is performed. New work designates dredging of areas which have not been previously dredged. Maintenance dredging is simply re-dredging a channel which has been filled by sediment. A typical maintenance dredging sequence might be like this. From experience, or perhaps the report of a local representative, the corps decides when a given section of waterway needs to be dredged. A dredge contract is let specifying the depth to which the channel is to be dredged. In most cases, the channel is dredged to design depth plus an additional two feet, which is designated advanced maintenance. In addition, the contractor is usually allowed another foot of leeway since the dredge cannot operate exactly at the required depth. As soon as practicable after completion of the work, the section is surveyed to determine the amount of material actually removed from the waterway. The contractor is paid according to this amount.

Computation of Shoaling Rates

Sections of waterway which have been dredged are described in the contracts, and in the dredging records, using the Corps of Engineers stationing system. This system measures distances in thousands of feet. There are four separate stationing systems used for four geographic sections of the waterway. For example, a typical report from the Corps of Engineers Fort Point Area Office (see Appendix II for location) might indicate that 60,000 yd^3 was dredged from station

237+000 to station 242+000. This simply means that the waterway was dredged from station 237,000 feet to 242,000 feet, a distance of 5,000 feet. For continuity and clarity, these station numbers were converted to waterway miles using the equations shown in Appendix III. This mileage system was used throughout this report. It was also superimposed over the waterway on the Composite Factors Maps.

The 60,000 cubic yards of material taken from this reach was distributed uniformly over the distance specified. (i.e. 60,000 $yd^3/5000$ ft = 12 yd^3/ft). Since most recent dredging contracts were let in 5000-foot reaches, the entire waterway was divided accordingly. This allowed maximum use of the accuracy in the data itself. To divide the waterway any finer than this would be misleading, since dredging amounts were reported in 5000-foot reaches. Conversely, to express the amounts dredged in reaches longer than this would unnecessarily broaden the data base. The waterway was, therefore, divided into 402 five-thousand-foot reaches. Amounts specified by the dredging records were placed into appropriate 5000-foot reaches. The endpoints of these reaches were converted to waterway miles and plotted along the bottom of the Composite Factors Maps. (i.e. reach 1 = mile 288.6 to mile 289.5).

The amount of material dredged from each reach was totaled and divided by the total time from the end of original channel dredging through the year the reach was last dredged. This was taken as the shoaling rate per year for that reach. This rate in cubic yards per year was also converted to feet accumulation of sediment per year.

This value was computed for each reach by assuming that the channel had a rectangular cross section 125 feet wide.

Summary of Assumptions Used to Compute Shoaling Rates

The following basic assumptions were made in computing shoaling rates from the maintenance dredging records.

1. For a given reach, the required depth specification remained constant from year to year.
2. Surveying errors were normally and independently distributed about zero.
3. The waterway had a 125-foot-wide rectangular cross section (to the depth of shoal accumulation).
4. The year of accomplishment of dredging was the year in which most of the dredging was done. For example, if dredging were conducted from October, 1948, until June, 1949, on a given contract; it was assumed that all dredging took place in 1949.
5. Shoaling occurred during the entire year in which original (new) work was completed and during the entire year that dredging was last reported. These two assumptions were made to simplify computations.

A short example illustrating the above explanation should clarify the procedure used.

Example 1.--Computation of Shoaling Rate in the Gulf Intracoastal Waterway from Maintenance Dredging Records.

Given: Amount dredged from Station 20+064 to Station 25+064 in the Corpus Christi to Mud Flats areas (Appendix II).

Find: Annual Rate of Shoaling.

	Year	Amount Dredged (yd^3)
	1942	New work completed.
	1945	60,000
	1948	80,000
	1951	40,000
Total	10 years	180,000 yd^3

1. Amount of shoal per year = $\frac{\text{Total amount dredged}}{\text{Number of Years}}$

$$= \frac{180{,}000\ (yd^3)}{10\quad (yrs)}$$

$$= 18{,}000\ (yd^3/yr)$$

2. Convert station numbers to waterway miles using equations from Appendix III Station 20+064 = 20,064 feet.

Waterway Mile = Station distance/5280 + 548.2 miles

$$= (20{,}064\ ft)\ X\ \frac{(1\ mile)}{(5280\ ft)} + 548.2\ miles$$

$$= 552.0\ miles$$

3. Repeat step 2 for end mile.

$$Mile = (25{,}064\ ft)\ X\ \frac{(1\ mile)}{(5280\ ft)} + 548.2\ mile$$

$$= 552.9\ miles$$

Thus an average of 18,000 yd^3/yr accumulates between mile 552.0 and mile 552.9.

4. Convert volume of shoal material per year into thickness of shoal layer as shown in Figure 1.

Assume: Rectangular waterway cross section 125 feet wide.

Volume/yr = (length) (shoal depth) (width)

$$(18{,}000\ yd^3/yr)\ X\ (27\ ft^3/yd^3) = (5000\ ft)\ X\ (h)\ X\ (125\ ft)$$

$$\text{shoal depth} = h = \frac{(18{,}000\ yd^3/yr) \times (27\ ft^3/yd^3)}{(5000\ ft) \times (125\ ft)}$$

$$h = 0.77\ ft/yr$$

Shoaling rates were computed in this manner for the entire length of the waterway using a digital computer. Length of record for particular reaches varied according to the year in which that section of the waterway was completed. Data was complete through 1974 for most reaches. A summary of the annual shoaling rate for each of the 402 reaches in Texas is given in Appendix IV and plotted under the appropriate mile on the Composite Factors Maps. Figure 2 shows the total amounts of material which have been removed from the entire waterway by year. Considerable variability from year to year is apparent.

Accuracy of Computed Shoaling Rates

The records used to compute shoaling rates were, in some cases, approximate values determined by Corps personnel many years after dredging was actually done. The accuracy of many of the earlier entries can only be surmised. Obviously, the longer period of record available, the better chance that the computed rate represents the actual shoaling rate. Most sections of the waterway had been dredged at least 3 times. However, a few reaches had been dredged only once or twice. The number of times that a given reach was dredged is plotted above the bar graph on the Composite Factors Maps, and is included in Appendix IV.

An average error of about 1% was introduced in the annual shoaling rate by assuming a rectangular, rather than trapezoidal

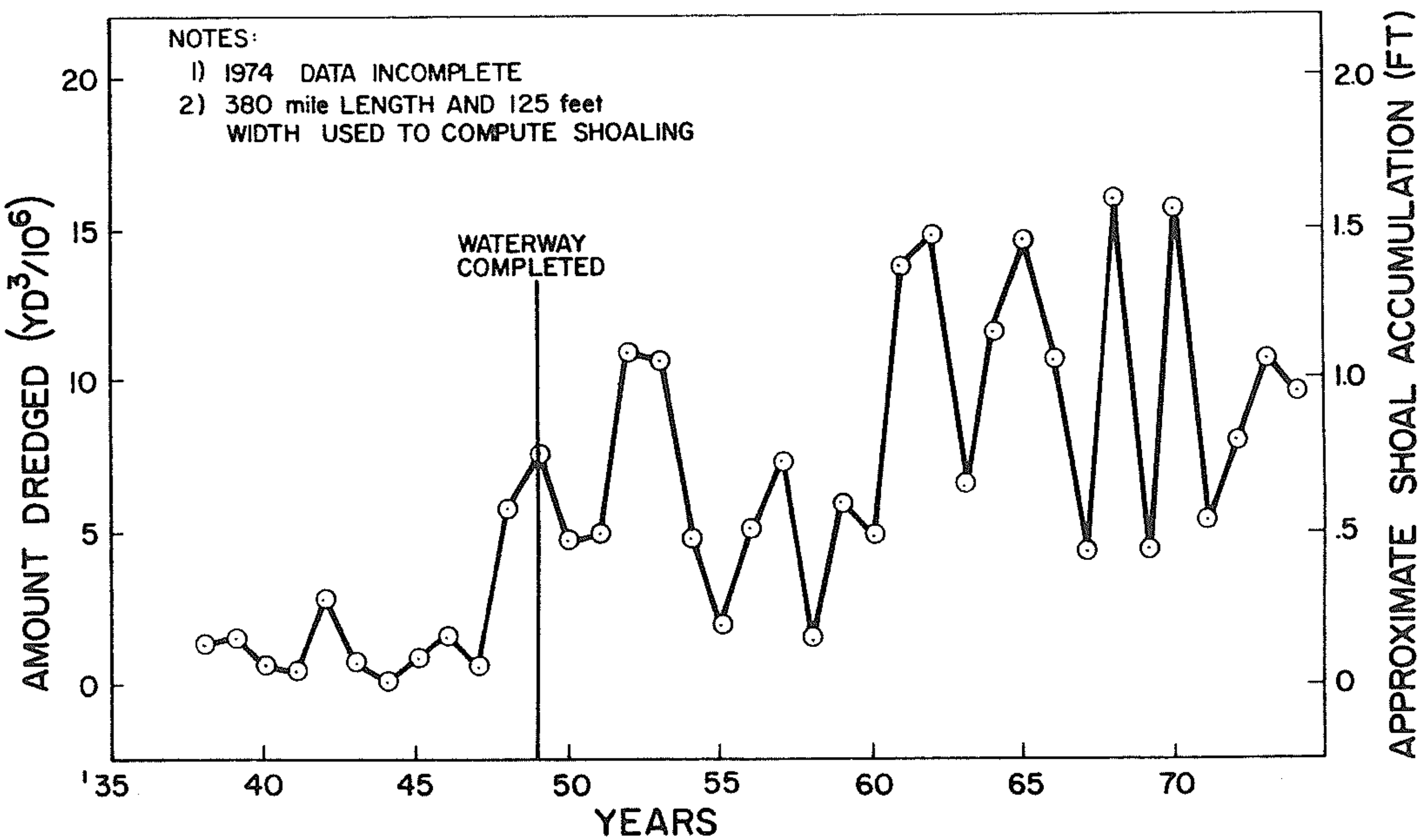

Fig. 2 Total Material Removed From the Waterway by Maintenance Dredging

waterway cross section. This error increases slightly in reaches with higher than average shoaling rates. The error results in reported shoaling rates slightly higher than true rates.

For waterway reaches having 30 or more years of record, a maximum error of almost 7% could be introduced due to the assumption (no. 5, p. 15) concerning shoaling during beginning and ending years.

THE PHYSICAL ENVIRONMENT

Sediment Sources

Sediment may enter the waterway from five generalized sources as shown in Figure 3. These sources are expanded in Table 1. The list is not intended to be exhaustive; however, it should show the wide variety of mechanisms which could produce shoal material.

Sediment Distribution in the Waterway

To find out what type of sediment constitutes actual shoal material, samples were taken from the bottom of the waterway (19) in January, 1975. A grain size analysis using a visual accumulation tube was performed on all sediment which was larger than .074 mm (19). The results were plotted against waterway mileage in Figure 4. The mean sand grain size was .173 mm, a fine sand. High clay content was found in areas near river mouths. This was especially obvious near the Brazos and San Bernard Rivers from mile 395 to mile 440. Most of the material sampled was fine sand. Original data is given in Appendix V.

Wind Data

Wind data (31) was analyzed to determine whether or not a prevailing wind direction could be specified. Information in Table 2 was tabulated from the wind roses shown in Appendix VI. Since there are eight directions represented on the diagrams, it was reasoned

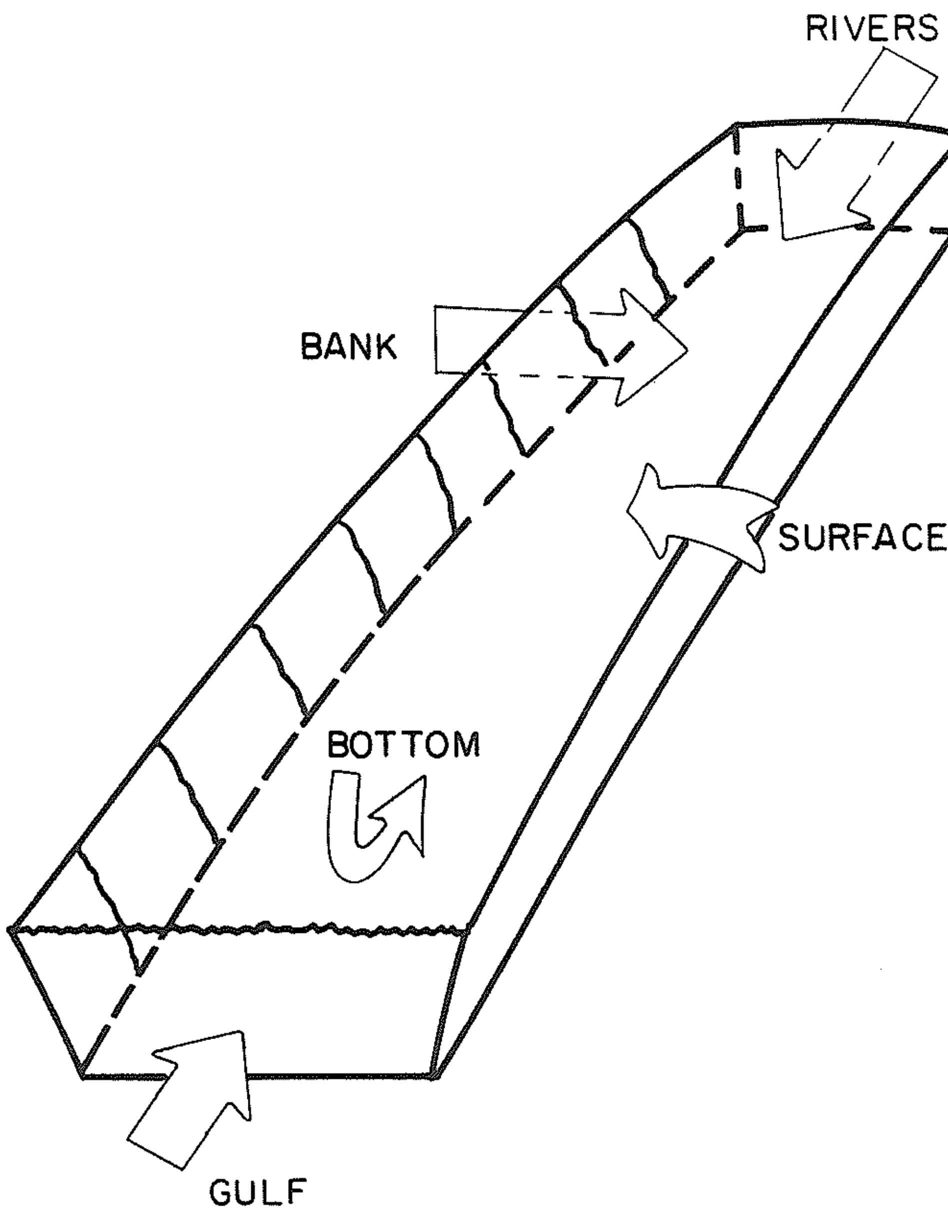

Fig. 3 Generalized Sediment Sources

TABLE 1.-- Explanation of Sediment Sources

Source	Mechanism or Cause
Bottom	Wind and ship-generated waves. Wind and wave-generated currents. Ocean swell. Tidal currents. Propeller-generated currents. Shrimp trawlers. Dredging operations. Spoil mound erosion.
Bank	Wind and ship-generated waves. Wind and wave-generated currents. Ocean swell. Tidal currents. Industrial or municipal outfalls.
Surface	Upland runoff. Wind-blown sand. Spoil-mound erosion.
River	Suspended and bedload material.
Gulf	Littoral drift. Hurricane washovers.

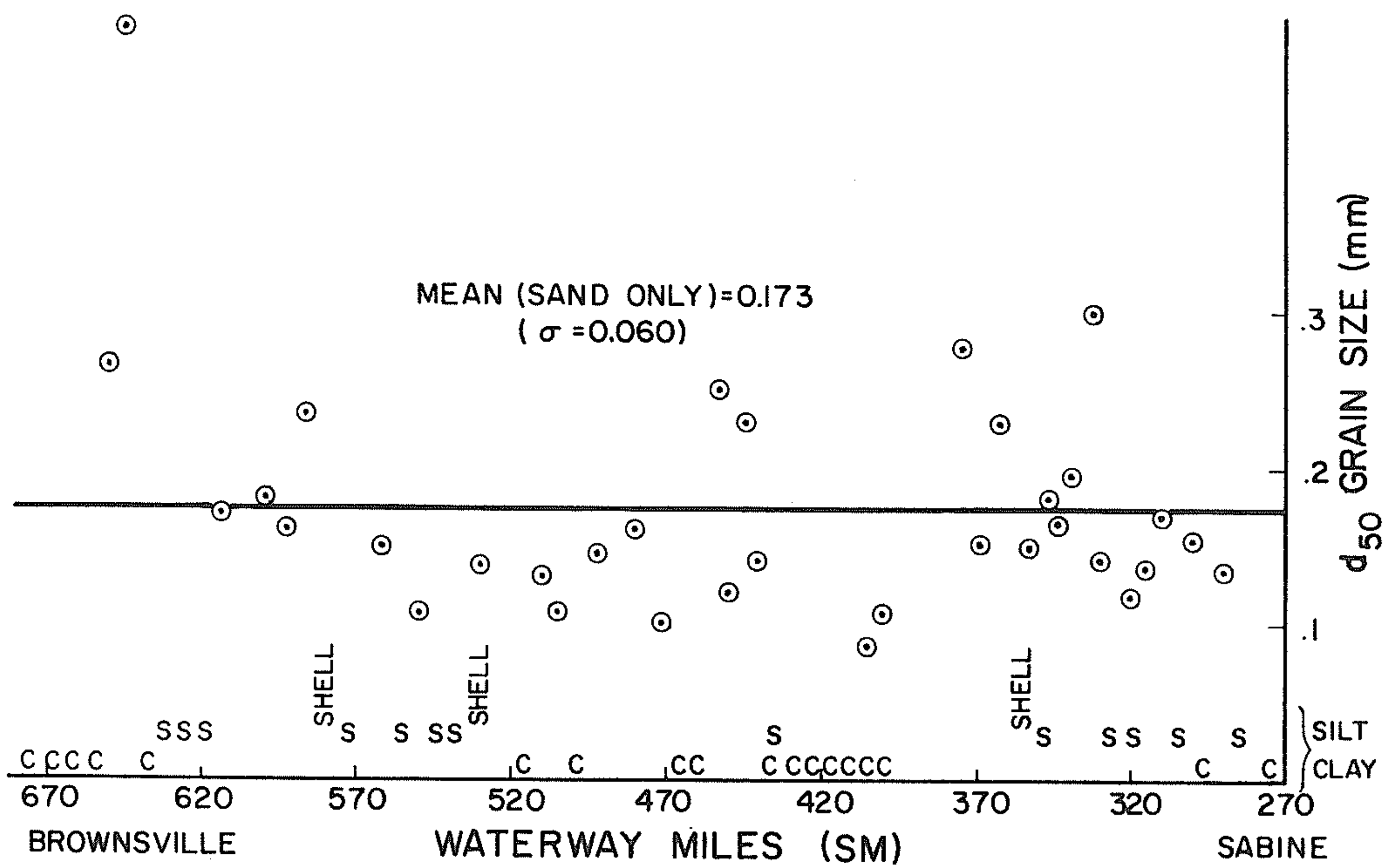

Fig. 4 Sediment Analysis of Material Sampled from the Waterway

TABLE 2.-- Predominance of Combined North and Southeast Winds

Percent of Time Wind was From N or SE

Month	Galveston Area	Corpus Christi Area
Jan.	38	44
Feb.	34	40
Mar.	38	44
Apr.	43	50
May	41	48
Jun.	38	48
Jul.	29	44
Aug.	27	35
Sept.	30	40
Oct.	31	42
Nov.	38	49
Dec.	37	45
Total	424	519
Avg.	35.3	43.3

Overall Average = (35.3 + 43.3)/2 = 39%

Conclusion: The wind blows from the north or southeast a total of 39% of the time on the Texas Coast.

Data Source: U.S. Naval Weather Service (31).

that the wind should blow equally from all directions if in fact there was not a dominant wind direction. In other words, the wind should blow 12.5% of the time from each direction. Analysis and averaging of data over the coast showed that the wind was from the southeast 27% of the time. The southeast winds were then removed from the total. This left, 100%-27%=73% of the time or 266 days for the other seven directions. Using reasoning similar to that above, the wind should blow 10.4% of the time from each of the remaining seven directions. It was found that the North wind blew 11.9% of the remaining time.

Although not clearly dominant from a direction standpoint alone, the unusually high velocities associated with north winds were considered adequate reason to include that direction as dominant also. A procedure which took the product of wind frequency and velocity as a criteria for determining direction was used by Fisher (12) to obtain similar results.

Carrying the analysis one step further, the north and southeast winds in the Galveston and Corpus Christi areas were combined as shown in Table 2. The combination of north and southeast wind occurred an average of 39% of the time.

Rusnak (27), Fisk (13), Fisher (12), and others have pointed to the significance of the southeast wind as the primary physical force on the Texas Coast. Brown (5) has indicated that polar fronts and resulting north winds are also important in shaping the coast.

Summarizing, the north and southeast winds were shown to be dominant. These wind directions were plotted on the Composite Factors Maps when they crossed the waterway with fetches greater than one mile.

Tide Data

Astronomical tides are not generally considered significant along the Texas coast, except near ocean passes (12). The diurnal tidal component is predominant, averaging one foot in height (range).

To get a better understanding of tides and tidal currents in the waterway, several tide gauges were selected which were within or adjacent to the waterway. Average tidal heights were determined from U.S. Geological Survey records (33) for several locations. Average monthly extremes and overall extremes were also computed. A summary of results is shown in Table 3 and Figure 5.

Computations were made to get a rough idea of the magnitude of tidal currents possible with these tidal heights. Tides from the Sabine area were used for the computation. A one-dimensional model was used (16). Assuming that a tide of 1.1 foot is impressed at the mouth of an infinitely long canal of uniform cross section, maximum velocities of one foot per second resulted at the canal mouth. A current of four feet per second resulted when a monthly extreme tidal height of 3.7 feet was used. It should be noted that these currents are extremely rough estimates because of the simple model which was assumed. However, they do indicate that fairly significant currents might occur during tides with amplitudes on the order of the monthly extremes.

Current Data

Detailed current measurements for the entire waterway are not available. A summary of measurements taken as a result of several

TABLE 3.--Observed Tidal Ranges[a]

Location	USGS Gauge No	GIWW Mile	Yrs Avdg.	Av (ft)	Av Extremes (ft)	Extremes (ft)
Sabine	S-2	284.5	71-73	1.1	3.7	5.3
Galveston	---	357.3	-----	1.25[b]	---	---
Port O'Connor	L-13	476	70-71	0.8	2.4	4.8
Aransas Bay	---	514	71-74	1.0	2.5	4.2
Corpus Christi	N-6	540	71-74	0.5	2.5	4.5
Port Isabel	P-7	666.5	70-70 (7 mos)	1.1	2.3	3.1

Source:
(a USGS (33)
(b Masch and Epsey (21)

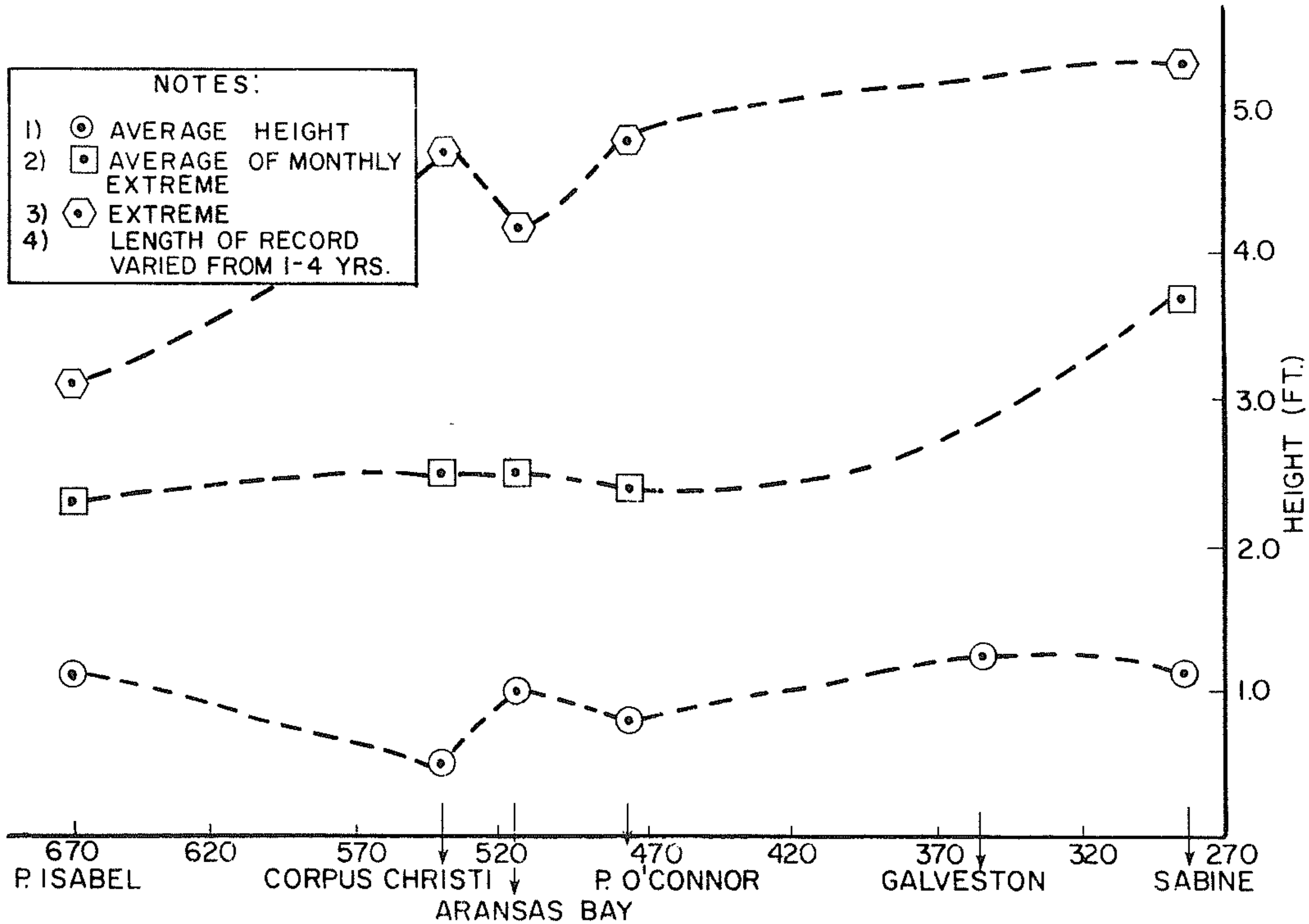

Fig. 5 Tidal Observations

localized studies is given in Table 4. Generalized current patterns for all major Texas bays are summarized in the "Report on Gulf Coast Deep Water Port Facilities Texas, Louisiana, Mississippi, Alabama, and Florida." (25) Fisher has observed that currents are more a function of winds than astronomical tides (12). Wind, combined with the shallow depths and the gentle slope of Texas Bays has a strong effect on bay circulation (25).

Salinity Data

Salinity varies tremendously along the length of the waterway. Laguna Madre is characterized by hypersaline water. Salinity varies drastically depending on rainfall, evaporation, and tidal height. Normal range could be from 5 ppt to 60 ppt in northern Laguna Madre. As one moves north along the coast, salinity generally decreases in both amount and variability. The Galveston and Matagorda Bay systems generally have salinities from 35 ppt to 15 ppt (10). Constant mixing of the shallow waterway by wind, and low fresh water inflow in most areas has resulted in very small salinity changes with depth. This pattern is frequently upset temporarily by heavy rains. However, the usual profile is reestablished rapidly (12). Exceptions to this general rule frequently occur near rivers where a vertical salinity gradient is usually present.

Active Shorelines

There are 1100 miles of bay shorelines on the Texas coast (12). Much of this shoreline is undergoing various rates of erosion or

TABLE 4.-Summary of Current Velocities near the Waterway

Mileage	Source/Method	Velocity (ft/s) Av.	Dir.	Max.	Dir.
355-356	Bassi & Basco (3) Field Study Current drogues, aerial photos of dye patches	1.1 0.8	NE NE	1.1 0.8	NE NE
Galveston Bay (all)	Fisher et al. (12)	1.0			
401-401	TWDB (22) Report near Brazos (estimated from Figure 7).	1.0 0.5	DS[a] US[b]	2.3	DS
351-351	Simmons (28) - physical model of Galveston Bay entrance			1.4 1.0	Flood Ebb
350-350	In Houston ship channel (entrance) (28)	4.2	Flood	4.2 2.5	Flood Ebb
456-457	TWDB (18) near Palacios (estimated from Figure (9,24). Math model.	0.2	W	0.2	E

a) DS = Downstream, near surface

b) US = Upstream, near bottom

deposition. Brown (5) estimates that 37% of this shoreline is eroding. He also states that principal erosion occurs during hurricanes, polar fronts, and tropical storms. Erosional or depositional shorelines (12), which could indicate availability of sediment, are plotted on the Composite Factors Maps.

Hurricanes

Henry and McCormack (15) compiled a list of hurricanes and tropical storms which have affected the Texas coast from 1871-1973. Carr (7) and Brown (5) have also listed hurricanes, storm tracks and other related data. Table 5 is a compilation of data gathered from these references. It indicates the approximate location where each hurricane crossed the waterway. Hurricane landfalls are also shown on the Composite Factors Maps. Only hurricanes which occurred after waterway completion were plotted.

Summary of Waterway Characteristics

A summary of the physical environment described above is given in Table 6.

TABLE 5.--Hurricane Landfalls

Date	Approximate Landfall (Waterway Mileage)	Name	Remarks
8/7/40	285		
9/23/41	434		
8/29/42	336		
9/21/42	456		
7/27/43	456		
8/27/45	338		
10/3/49	428		
6/25/54	670		
6/27/57	260	Audrey	
7/25/59	377	Debra	
9/11/61	473	Carla	Most severe hurricane on record.
8/17/63	324	Cindy	
9/20/67	669	Beaulah	
8/3/70	536		
9/10/71	570	Fern	Traveled along coast for great distance.

TABLE 6.--Summary of Environmental Data

Factor	Description	Plotted on Maps
Sediment	Fine sand except near rivers.	No
Wind	Dominant north and southeast.	Yes
Currents	Less than 1 kt except near ocean passes or during high winds.	No
Tides	Range less than 1 ft except near passes and during high winds.	No
Salinity	Great seasonal and geographic variation, but fairly constant with depth. Fluctuations with large rainfall.	No
Active Shore	Erosional or depositional shorelines.	Yes
Hurricanes	Landfall. Significant in causing erosion and shaping of shorelines. Move large amounts of sediment rapidly.	Yes

SYNTHESIS OF ENVIRONMENTAL DATA WITH SHOALING RATES

Composite Factors Maps

The basic approach in combining shoaling rates with general environmental factors was to consider the entire waterway as one body of water. A series of Composite Factors Maps was developed to display computed shoaling rates and observed environmental factors simultaneously. These maps allowed a large number of factors present in a given reach to be noted and linked intuitively to the computed shoaling rate for that area. They preserved the broad nature of the research while allowing full use of the accuracy of data available. Although this research was concerned with gross physical forces along the entire waterway, the maps should also be useful as preliminary information for studies in specific areas.

Basic geographic features on the maps were taken from the Bureau of Economic Geology Maps (12). Environmental factors which were thought to influence shoaling were then plotted on the maps. Shoaling rates, computed for 5000-foot reaches, were plotted below corresponding sections of the waterway.

Statistical Procedures

Two separate statistical procedures were followed. First, an analysis of variance was done to determine which of the chosen factors could be isolated as "significant" environmental factors. This was done by grouping reaches according to environmental factors present.

The variance of shoaling rate for each grouping was compared to the variance of the shoaling rate of all other groupings using an F-test.

Second, a prediction (regression) equation was developed to predict the shoaling rate in a reach with known environmental factors. A linear regression model, incorporating the same factors used in the analysis of variance was employed.

Two basic assumptions were necessary in formulating the statistical models. First, the error between the predicted value of shoal and the actual value was assumed to be distributed normally, with mean zero. Second, the observations of the dependent variable (shoaling rate per year) were assumed to be independent. In most cases adjacent reaches were dredged sequentially and, therefore, probably not completely independent. Similarly, adjacent reaches are more likely to have identical environmental factors present. In other words, the shoaling rate in one reach was somewhat related to the rate in adjacent reaches in many cases.

Determination of Significant Physical Factors

An analysis of variance procedure (1) was followed to determine significant factors in the shoaling process. Each 5000-foot reach of the waterway was classified according to the environmental factors present in that reach. Factors were chosen on the basis of 1) intuitive insight from study of the Composite Factors Maps, 2) possible physical explanation for observed shoaling, 3) basic assumptions about the nature of the waterway, 4) ease of including the factor in the model.

A basic factor which was considered was whether a reach was in "open bay (OB)" or "land-cut (LC)" area. Open bay was defined as an area in which the banks of the waterway were covered by bay water at low tide. Land-cut areas were those reaches where the banks were not normally under water at low tide.

In open bay areas the average depth of water within about two miles of a reach was specified as less than three 3 feet (D3), between 3 feet and 6 feet (D36), between 6 feet and 12 feet (D612), or greater than 12 feet. The presence of unconfined dredged disposal mounds adjacent to a reach in open bay was designated by "S". A fetch of 5 miles or greater aligned with either north or southeast wind direction and ending at the waterway, was symbolized by "F". The five-mile fetch was chosen for two reasons: 1)some preliminary investigations had revealed that initiation of sediment motion probably occurred if the prevailing southeast wind blew over a fetch of this length, and 2) fetches of this length or greater were common along the waterway. If both fetch and dredged material mounds were present, another classification was made. The location of the dredged material mound either windward (WS) or leeward of the channel was specified. The windward factor is shown diagramatically in Figure 6. Reaches within one mile of active shorelines, as defined by Fisher (12), were labeled "SL". Reaches within 5 miles of a Gulf Inlet were designated "GI".

In land-cut areas, the presence of a river (R) within 5 miles of a reach, or the presence of a small sediment source (CR) like a creek was noted. The criteria of 5 miles from rivers was chosen because study of Composite Factors Maps (Map 2) indicated this distance as an approxi-

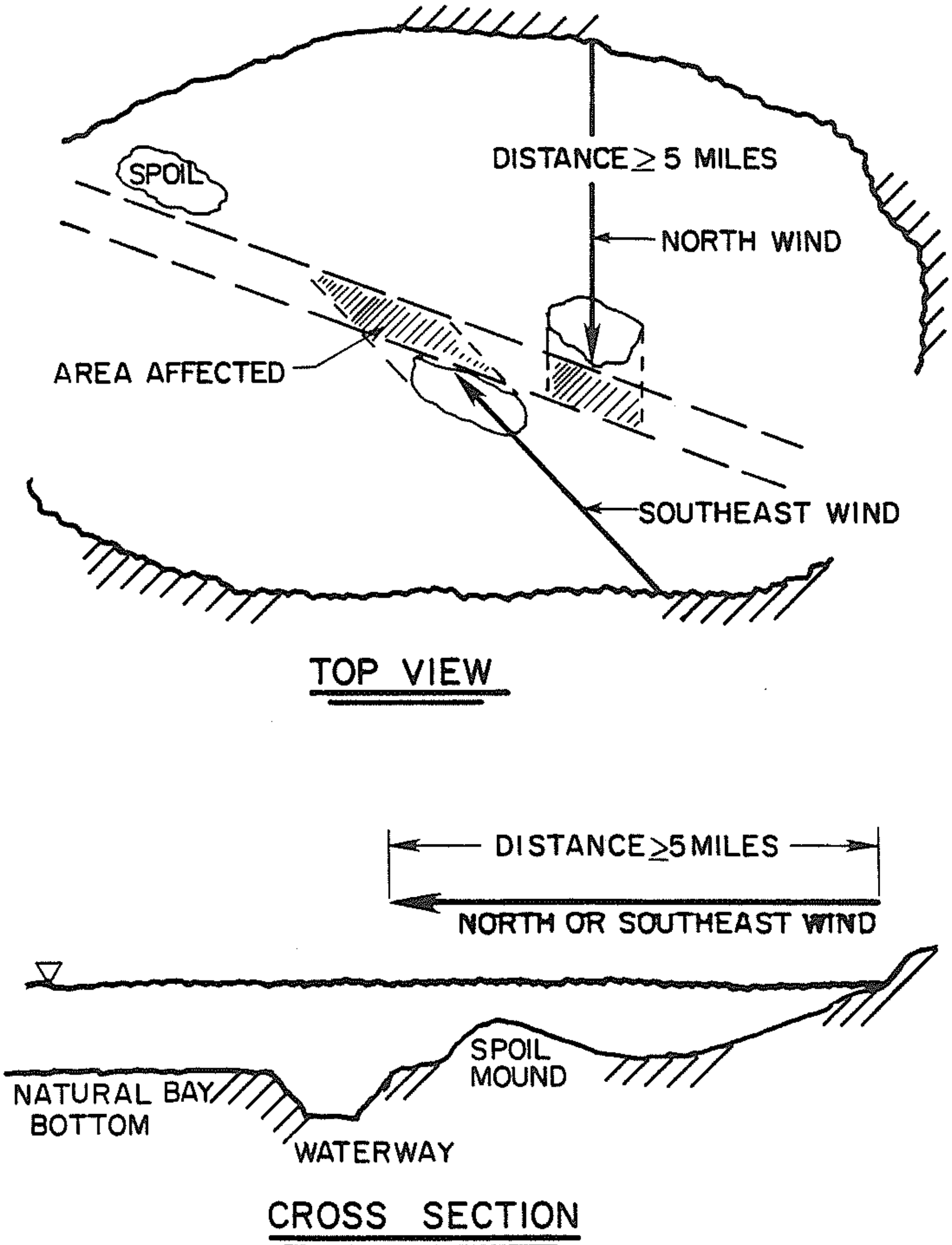

Fig. 6 Definition of Fetch and Windward Spoil

mate limit of river effect.

These environmental factors are summarized in Table 7. The number of miles of waterway in which that factor exists is also shown. Those factors plotted on the Composite Factors Maps were noted.

The mean shoaling rate for the entire waterway, grouped according to these factors, is shown in Figure 7. The number of 5000-foot reaches in which each factor was present is also specified.

An analysis of variance was then done to determine whether the observed difference between shoaling rate with a particular factor present, and the rate with that factor absent was a true effect or simply a consequence of data variability.

For example, land-cut reaches containing factor "R" were compared to land-cut reaches not containing "R". The ratio of the respective estimates of variance in shoaling rates was then calculated. This ratio would have the same distribution as an F random variable if the two categories were equivalent. If not equivalent the ratio would be greater than an appropriate F value. A difference in the two categories as indicated by this test was taken as evidence that the factor tested was significant in explaining shoaling. Due to unequal occurrence of environmental factors a regression within the analysis of variance was necessary. Each environmental factor was tested at the 0.05 level of significance. Loosely interpreted, this means that there would be a 5% chance that a positive indication of significance would be incorrect. A computerized solution routine (1) was used for computations. It should be noted that just because a factor was

TABLE 7.--Explanation of Environmental Factors used in Reach Classification

Symbol	Explanation	Miles	% Bay or (Land Cut)	Plotted CFM
OB	Open Bay Areas.	193.0	100.0	Y
D3	Depth in vicinity less than 3 feet.	88.0	45.5	N
D36	Depth greater than or equal 3 feet and less than 6 feet.	57.8	30.0	N
D612	Depth greater than or equal 6 feet and less than 12 feet.	9.5	5.0	N
----	Depth greater than 12 feet.	38.0	19.5	N
S	Unconfined dredged material adjacent to reach	152.5	79.0	Y
F	Fetch of dominant N or SE wind greater than 5 miles.	102.3	53.0	Y
SL	Erosional or depositional shoreline within 1 mile.	44.5	23.0	Y
GI	Gulf entrance within 5 miles.	25.6	13.0	Y
WS	Spoil mound on windward side of waterway (Figure 6).	60.0	31.0	Y
LC	Land-cut areas.	187.5	(100.0)	Y
R	River crosses waterway within 5 miles.	25.6	(13.6)	Y
CR	Small stream crossing waterway	72.0	(38.0)	Y

a) Composite Factors Maps

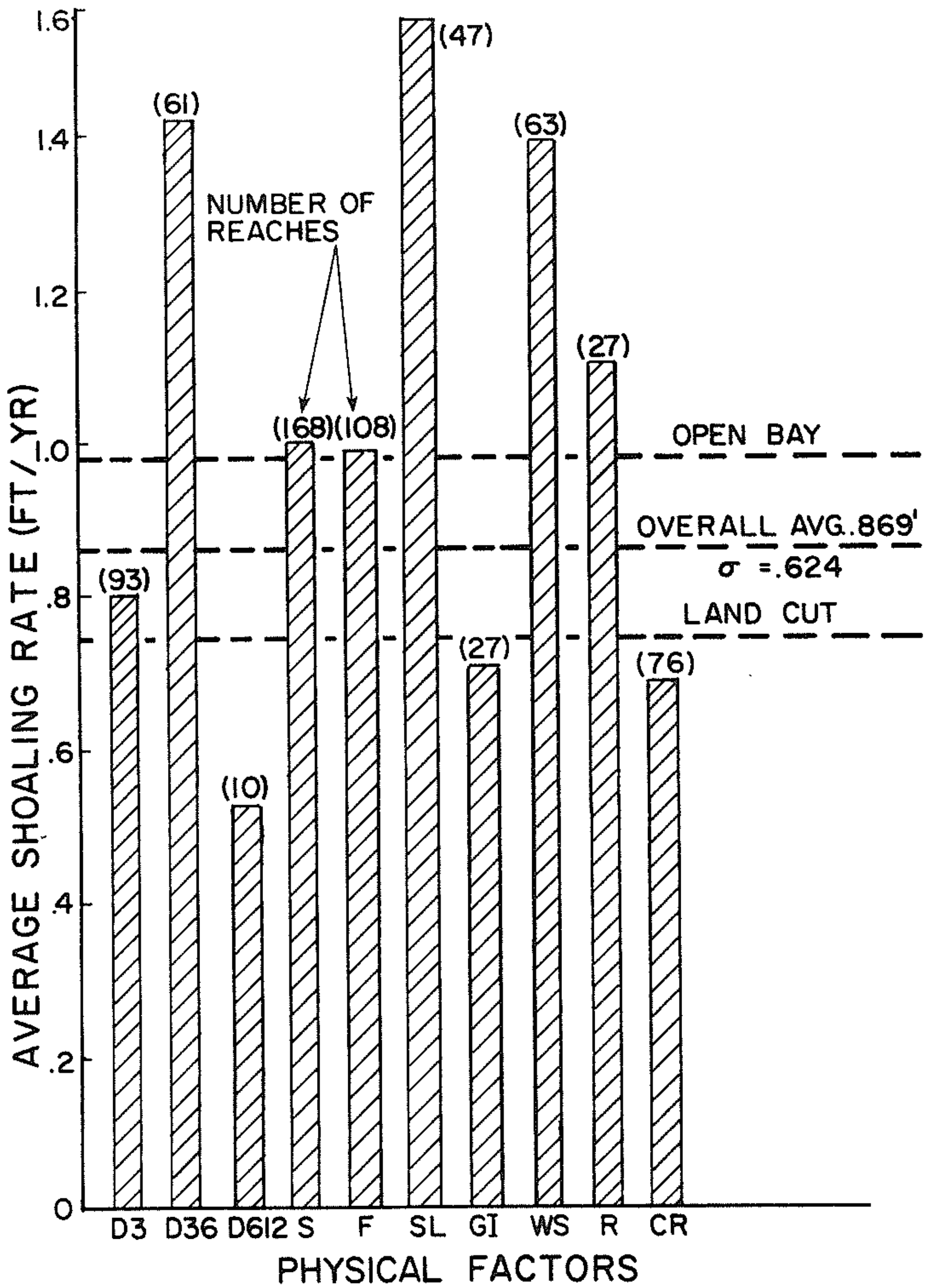

Fig. 7 Computed Shoaling Rates versus Physical Factors

termed "not significant", does not mean that the factor doesn't affect shoaling. It does mean that either data variability or model deficiencies account for the difference observed with or without the factor.

Results. Factors and interactions which were significant at the 0.05 level were land cut, river, spoil plus depth of 3 feet, spoil plus depth of 3 feet to 6 feet, fetch plus depth of 3 feet, fetch plus depth of 3 feet to 6 feet, and windward spoil. The analysis of variance table and associated F values are given in Table 8.

Discussion. Land-cut areas were readily differentiated from open bay areas in the analysis. Therefore, the shoaling difference between land cut and open bay areas in Figure 7 is the result of a true effect.

As was expected the factor"R" (river) had significant effect on the observed shoaling rate. Only the presence or absence of a factor was considered in this analysis. As stated above there appeared to be a definite relationship between distance from the river and shoaling rate (Brazos River on Map 3). An analysis of covariance would be required to include this relationship.

Neither "S", "F", "D3", or "D36" had a strong effect alone. However, the interaction of these factors was significant, as shown by Table 8. The placement of dredged material or the presence of fetch in open bay areas with depths of less than 6 feet had a significant effect on the shoaling rate. In other words, dredged material presence or fetch in bay depths less than 6 feet were significant. These factors were not significant in depths greater than 6 feet.

TABLE 8.--Analysis of Variance Table for Environmental Factors Affecting Shoaling Rate

Source	DF[a]	Sum of Squares	Mean Square
Regression	19	82.853	4.361
Error	382	148.607	0.389
Corrected Total	401	231.460	

Standard Deviation = 0.624

Mean = 0.869 ft/yr

Source	DF	Partial SS	F-Value[b]
*LC	1	6.690	17.196
*R	1	3.892	10.004
S	1	0.452	1.162
F	1	0.138	0.355
SL	1	0.088	0.226
D3	1	0.411	1.056
D36	1	0.754	1.938
D612	1	0.015	0.039
GI	1	0.010	0.026
S+F	1	0.005	0.013
SL+D3	1	0.070	0.180
SL+D36	1	0.019	0.049
SL+D612	1	0.398	1.024
*S+D3	1	12.698	32.641
*S+D36	1	7.300	18.765
CR	1	0.005	0.012
*F+D3	1	9.249	23.776
*F+D36	1	8.184	21.037
*WS	1	7.384	18.982

* Exceed the critical value (3.92) for F with 1and 382 degrees of freedom at the 0.05 level of significance.

a) Degrees of Freedom

b) F = (partial SS/DF)/(error SS/DF)

The "windward spoil" category was found to be significant also. It was interesting to note that the interaction of "fetch plus spoil" without regard to spoil location, was not significant.

None of the other factors or interactions were significant.

Prediction of Shoaling Rates

A regression technique was used to predict the amount of shoaling in a reach with known environmental factors. The regression was actually a special case of a normal regression since the independent variables (environmental factors) did not take on a full range of values. Instead, only presence or absence of the factor was specified. The regression model was modified further to account for special factors "WS", "R", and "CR" which were defined only when certain basic factors were present. An additional variable was introduced to adapt the model for this. The linear model and appropriate coefficients are given in Table 9.

Another regression model was developed using only those 7 factors which were determined to be significant in the analysis of variance. It was rejected due to significant lack of fit. To provide the most accurate prediction possible, all 19 factors and interactions shown in Table 8 were used in the final prediction.

Discussion. Using the final regression model, the quantitative effect of the 7 significant factors was investigated. The predicted effect of each factor is shown in Table 10. These values represent the shoaling rate to be expected when the specified factor, and no

TABLE 9.-- Regression Model and Coefficients for Predicting Shoaling Rate

The Model: Shoaling Rate in ft per year = $1.465+\Sigma D_i K_i$. See note [a]

Basic Environmental Factors	i	Ki	Interactions	i	Ki	Special Factors	i	Ki
LS	1	-0.388	S*F	9	0.013	R	17	0.215
S	2	-0.131	SL*D3	10	0.058	CR	18	0.005
F	3	-0.071	SL*D36	11	-0.031	WS	19	0.299
SL	4	-0.105	SL*D612	12	-0.213			
D3	5	-0.155	S*D3	13	-0.831			
D36	6	-0.213	S*D36	14	-0.655			
D612	7	0.418	F*D3	15	0.678			
GI	8	0.013	F*D36	16	0.659			

a) D is a dummy variable and its value is determined according to the appropriate ruls listed below:

1. In the 8 basic environmental factors (i=1 to 8);
   - If the environmental factor is present: $D_i=+1$
   - If the environmental factor is absent: $D_i=-1$
2. In the 8 interaction terms (i=9 to 16):
   - If both factors are present or absent: $D_i=+1$
   - If only one factor is present: $D_i=-1$
3. In the 3 special factors (i=17 to 19):
   - If the environmental factor is present: $D_i=+1$
   - If the environmental factor is absent: $D_i=-1$
   - If the environmental factor is not defined: $D_i=0$

b) Special factors were defined only when the following basic factors were present.

1. R or CR--LC must be present.
2. WS--S and F must be present.

TABLE 10.--Predicted Shoaling Rate for Significant Environmental Factors

Factor	Predicted Shoaling Rate in ft per yr [a]	Observed Rate	Number of Observations	Remarks
LC	0.779	0.690	95	
R	1.209	1.120	27	R is measured only in LC areas
S*D3	1.015	0.575	19	
S*D36	1.467	1.446	7	
F*D3	1.525	0.788	3	
F*D36	1.197	---	0	
WS*D3	1.236	0.839	14	WS is measured only when S and F are present
WS*D36	1.612	1.744	18	

Average Shoaling Rate of Entire Waterway = 0.869 ft/yr

a) Predictions and observations are for a 5000-foot reach where the factor specified is the only environmental factor present.

others, are present. This was done to clarify the magnitude of effect of each significant factor. To obtain a prediction of expected shoaling rate in a given area, all environmental factors in that reach must be considered.

Observations About Shoaling Characteristics

After careful consideration of environmental and statistical data, the author proposed the following explanations for observed shoaling rates.

Land-cut areas typically experience 3 inches per year less shoaling than open bay areas. The absence of water to serve as a transporting mechanism for shoal material is believed to account for this difference. The fact that water does not completely cover the channel and surrounding areas is believed to be a major factor in the observed difference. This lack of water removes a major transporting agent for shoal material. Therefore, sediment sources are limited and shoaling is diminished. Should a land-cut area become temporarily flooded, an increase in shoaling rate could be expected.

Increased shoaling rates in reaches near river mouths were expected. Flooding, tributary streams and direct deposition from the main stream all contribute to this increase.

The placement of dredged material alongside the waterway in open bays increases the shoaling rate more in depths between 3 feet to 6 feet, than in depths less than 3 feet. A difference of over 5 inches per year was predicted by the statistical model for these two categories. Spoil mounds in depths of 3 feet to 6 feet are thought to contribute more to waterway shoaling for two primary reasons. First, the mound of material is more completely submerged than in shallower depths. In depths less than 3 feet most of the mound is emergent; only a small area is exposed to bay water. Thus more erodible material is exposed in deeper water. Second, the movement of water normal to the waterway is probably greater for the deeper bay areas than in the shallower bay areas. Sediment transport is directly related to circulation. In fact the mounds are thought to inhibit circulation to a greater extent in shallower water.

The pattern noted above is accentuated even more when the dredged material is located on the windward side of the channel. In both depth categories an additional increase of about 2 inches per year was noted when windward spoil was present. The strongest single effect occurs when windward spoil is placed in depths of 3 feet to 6 feet. A shoaling rate of almost 9 inches per year more than the waterway average was predicted by the model. This indicates that large amounts of material are continually eroded from these mounds and transported in the direction of prevailing wind.

The effect of fetch on increasing the shoaling rate was greatest in depths less than 3 feet. The prediction indicated that this factor would result in an increase of 8 inches per year over the waterway average. This is roughly 16,000 yd^3 per year increase in a 5000-foot reach. This increase in the effect of fetch in shallow depths is reasonable. Shallower depths allow waves to disturb bottom sediments. Consequently, medium velocity winds which blow most frequently, have a greater effect here than in deeper depths.

It was especially interesting to note that "fetch plus depth of 3 feet" experienced more shoaling than "fetch plus windward spoil plus depth of 3 feet." Perhaps in shallow water, with long fetches, the mound actually acts as a sediment barrier for the waterway.

Before leaving this discussion, the reader should note that 75% of the bay areas adjacent to the waterway are less than 6 feet deep. Almost 20% are greater than 12 feet deep. Only about 5% are between 6 and 12 feet deep. Shoaling in depths greater than 12 feet is minimal. So it was reasonable to expect that depths less than 6 feet were important since the bulk of shoaling occurred there.

Explanation of Shoaling in Selected Reaches

The predictive model using all 19 factors, does not accurately predict shoaling in several areas. In these areas it is expected that the assumptions made in formulating the model were weak. Unfortunately, in many of these areas shoaling rates are significantly higher than expected, thus of particular interest. A brief description of several of the areas follows. Several possible explanations for model inaccuracy are advanced.

A prediction of 1.0 ft/yr was made near the entrance to Galveston Bay at mile 348. The observed rate was 2.3 ft/yr. The reach is a semi-protected area out of the main stream of tidal flow through Bolivar Pass. This area of low current velocity probably makes an ideal sediment trap for material traversing the pass during tidal exchange.

Mile 400.4 near the Brazos River experienced a shoaling rate of about 4 ft/yr. The predicted rate was 1.1 ft/yr. As seen from the maps, this reach receives the brunt of sediment from the River. In the predictive model, reaches within 5 miles of a river were assumed to receive equal amounts of sediment from the river. A casual view of the map for this area shows that, in fact, sediment is at a peak at mile 400.4 and drops off quickly in both directions. The uniform distribution of sediment near rivers assumed in the model was inaccurate.

Mile 430.6 is a land-cut area near East Matagorda Bay which experienced about 1.8 feet per year of shoal material. A rate of 0.7 ft/yr was predicted for this reach. Surrounding reaches also received surprisingly large amounts of sediments for land cuts. These areas are frequently innundated by high water. Re-working of dredged material mounds, banks and general scour of surrounding land probably occurs. As hypothesized above, increased shoaling can be expected to occur in reaches covered with water.

Extremely high shoaling rates of almost five feet per year were noted from mile 454.3 to 457.0 near the area where the waterway enters Matagorda Bay. Predictions for these areas averaged about 2 ft/yr less than observed values. The average currents in this area are westward at less than 0.2 ft/sec along the bay shoreline. This net transport is almost perpendicular to the waterway. It was also noted from computer-generated velocity plots (32) that under certain flow conditions currents converge in this area, resulting in consistently low velocities. Sediment carried in from the nearby Gulf Inlet, as well as the sediment carried along the bay shoreline are probably trapped here.

Average shoaling rates of about 2.7 ft/yr were noted in San Antonio Bay from mile 492 through mile 500. Predictions indicated that only 1.6 ft/yr should have accumulated. Dredged material mounds are located on both sides of the channel. Prevailing winds from both the north and southeast have fetches greater than 5 miles and cross the waterway at large angles. This, combined with the fact that San Antonio Bay is about 4-6 feet deep throughout , produced the perfect situation for high shoaling rates. In the model, no allowance was made for dredged material located on both sides of the channel. If the effect of windward spoil was doubled to account for spoil on both sides of the channel, the prediction would have been 2.33 feet. This bay is especially interesting since the amount of fresh water inflow as well as exposure to tidal influence is low. The major factors involved in shoaling are wind, spoil, depth, and fetch. A detailed study of this area, using computed shoaling rates as field data, should provide excellent insight into the mechanism of erosion and deposition of bay bottom and spoil mound sediments.

The current pattern in Baffin Bay is quite complex. Both north and southeast winds produce currents which flow out of Baffin Bay and across the large dredged material island at the lower end of the bay. Currents converge on an area close to the Intracoastal Waterway (25). It is felt this convergent area is responsible for the 1.6

ft/yr rate near mile 580 in Baffin Bay. A rate of 0.5 ft/yr was predicted.

Mile 596 to 604 are land-cut areas at the southern limit of Baffin Bay. These areas experienced shoaling of almost 2 ft/yr. The predicted rate was about 0.7 ft/yr. This area is subjected to innundation during high water and wind-blown sand, from large unvegetated sand dunes in the area. These two factors could have significantly increased the shoaling rate here. Numerous channels have also been cut from the waterway to the section of Laguna Madre known as "the hole". These passages encourage circulation and exchange of water between "the hole" and the waterway. During strong north winds, current velocities are increased through these channels and innundation of much of this area occurs. Dredged material mounds along the east side of the channel probably erode significantly under these circumstances.

In southern Laguna Madre from mile 657 to 660 an average rate of 2.7 ft/yr was noted. A rate of 0.4 ft/yr was predicted. Although little is known about current velocities and patterns in this area, it has been found that currents in the waterway, which are opposite in direction to surface currents do exist under some conditions (9). It is hypothesized that prevailing currents from both the north and south (depending on wind direction) cross the waterway here. The nature of sediment (clay) taken from this reach indicates that flocculation was probably a factor in deposition.

An area of no dredging was noted near the Port Isabel channel from mile 663 to 665. The predicted rate for this area was 1.0 ft/yr.

The area is near Brazos Santiago pass and is possibly the point where flow departs the waterway during peak tidal flow. This increased tidal current activity is thought to prevent sediment from accumulating in the area.

Each of the areas listed above could be the subject of an entire research effort. The factors considered in this research and the intuitive explanations proposed above are intended as a first step toward detailed research.

The Effect of Hurricanes on Shoaling

Hurricanes were considered separately from other environmental data. Hurricanes, unlike other factors, occur as isolated incidents. A hurricane, unlike other environmental factors which are continuous, affects shoaling in a particular year. Since shoaling rates were computed as an average over a long period of time, they could not be used confidently to determine the effect of a hurricane in a particular year. The following procedure was devised to try and surmount this difficulty. All hurricanes were assumed to be identical in all respects and to affect areas up to 50 miles from the eye of the hurricane. Hurricanes which struck the coast between 1940 and 1973 were considered. It was postulated that the additional shoal material caused by a hurricane would be reflected in increased dredged volume during subsequent dredging. Dredging incidents were recorded only by year, as explained earlier. It was assumed that dredging done in the same year as a hurricane occurred after the hurricane. This assumption was made after examining a number of specific cases. Then, dredged material for each reach of the waterway was classified as material which was dredged after a hurricane (hurricane material), and material which was not dredged after a hurricane. Multiple hurricanes during a period between dredging were treated as one hurricane. For each reach, the amounts dredged during hurricane years were subtracted from the amounts dredged during non-hurricane years. Example 2 illustrates this procedure.

Example 2.--Computation of Shoal Material Caused by Hurricanes in a Hypothetical Reach

Refer to Figure 8.

Compute amount dredged after hurricane impact within 50 miles:

Amount (yd^3)	Years
20,000	6
30,000	6
40,000	8
90,000	20

Amount per year during hurricane periods = 90,000/20
= 4,500 yd^3/yr

Compute amount dredged during non-hurricane years:

Amount (yd^3)	Years
50,000	5
40,000	6
25,000	3
115,000	14

Amount per year during non-hurricane periods = 115,000/14
= 8,214 yd^3/yr

Difference = Hurricane rate-non hurricane rate
= 4,500-8,214 = -3,714 yd^3/yr

Differences were computed for each 5000-foot reach of the waterway. Using a test for paired observations for the difference between means of two normal populations (23), the following hypothesis was tested at the 0.05 level of significance. Hypothesis: the rate of shoaling during hurricane years is equal to the rate during non-hurricane years. It was found that there was insufficient evidence to reject the hypothesis. Therefore, shoaling increase due to hurricanes could not be proven. Calculations are shown in Appendix VII. It was also noted that the shoaling rates after hurricanes were greater than the non-hurricane rates in only 82 reaches. In 219 reaches the non-hurricane rates were actually greater. There was insufficient data for comparison in 101 reaches. Of the 82 reaches affected by hurricanes, 57 were open bay and 25 were land-cut areas.

It was found that the amounts dredged from year to year in a given reach varied greatly. In many cases the effect of a hurricane became indistinguishable. To illustrate this point, the effect of hurricane Carla on four separate reaches was examined. Figure 9 shows the four reaches which were considered. The computed shoaling rates were plotted against years. The date of impact of hurricane Carla is indicated. The only reach which clearly indicated the effect of Carla was at mile 425.0. A drastic increase in dredging was noted immediately after Carla. This reach is a land-cut area along a bay shoreline. Other reaches, for example, mile 460 showed no apparent effect of Carla even though the hurricane passed much closer. It was interesting to note that another land-cut reach (mile 434.4)

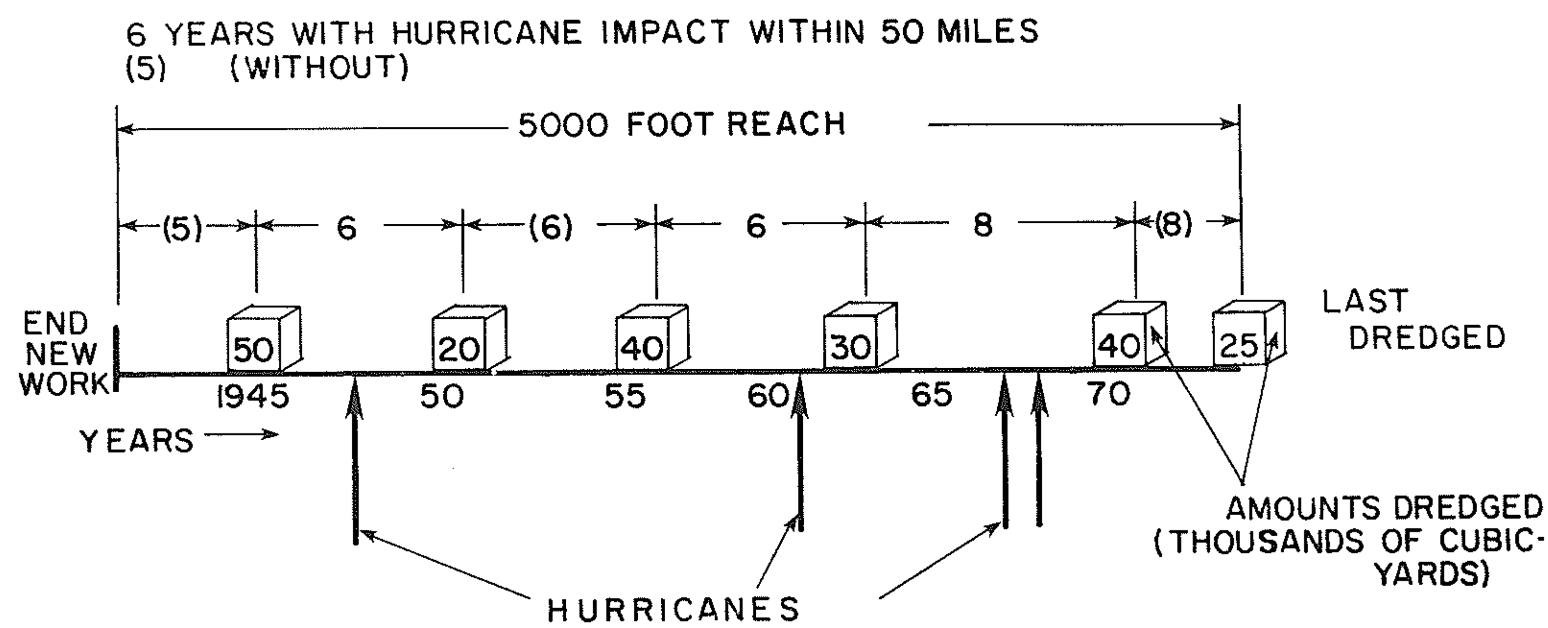

Fig. 8 Computation of Hurricane versus Non-Hurricane Shoal Material

only about 10 miles from the reach where Carla had a strong effect, showed no evidence of increased shoaling. Obviously, a major factor here is the considerable year-to-year variation of dredging in a particular reach. The hurricane effect was also masked in another way due to averaging of dredged volumes. For example, assume that a hurricane caused an additional foot of shoaling in a reach in a given year. Then since shoaling rates were computed from one dredging incident to the next by dividing total amounts by total years elapsed, the apparent amount of increase caused by the hurricane would be divided by the total years elapsed. Thus for four years between dredging incidents an increase in only 0.25 feet would be seen in shoaling rate. This small amount is easily lost when compared to the fairly large variation of dredging amounts that normally occur from year to year.

Hurricanes undoubtedly do have an effect on some sections of the waterway. However, the location of these particular areas could not be determined from the data available.

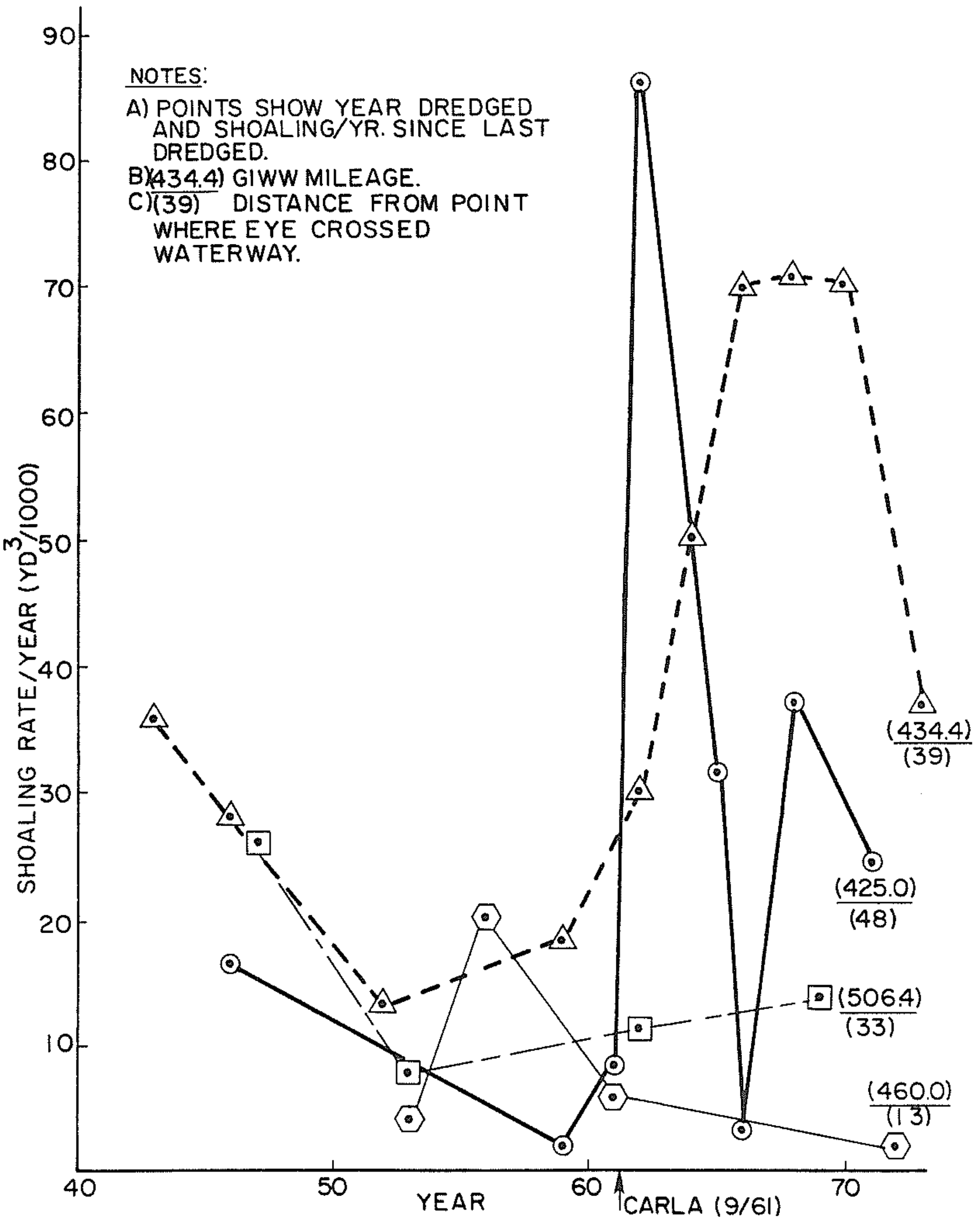

Fig. 9 The Effect of Hurricane Carla on Shoaling Rate in Four Selected Reaches of the Waterway

CONCLUSIONS AND RECOMMENDATIONS

Maintenance dredging records were found to be a usable source of field data for computing shoaling rates. Records from the Gulf Intracoastal Waterway were used to compute rates in 5000-foot reaches for the entire length of the main channel in Texas. The average rate for the waterway was found to be 10.5 in./yr.

On the basis of the statistical procedures performed, five physical factors examined were found to significantly affect shoaling. These factors were: 1) land cut, 2) river crossings, 3) dredged material mounds in bay areas with depths less than 6 feet, 4) fetch of 5 miles or greater aligned with prevailing wind direction, in depths less than 6 feet, 5) windward placement of dredged material mounds in bay areas less than 6 feet deep.

The rate in land-cut areas averaged 3 in./yr less than the rate in open bay areas. The lack of water above bank level was concluded to be the primary reason for this decrease.

An average increase of 4 in./yr over the waterway average was noted for reaches within 5 miles of major river crossings. A peak shoaling rate of almost 4 ft/yr adjacent to the crossing was observed. This rate dropped sharply with increased distance from the river.

The interaction of open-bay dredged material mounds, or wind fetch greater than five miles, in depths less than 6 feet increased the shoaling rate significantly. The effect of dredged material mounds was largest in depths of 3 feet to 6 feet, where shoaling rates of 7 in./yr above the waterway average were predicted. In bay areas less than 3 feet deep an average increase of less than 2 in/yr over waterway average was noted. This was thought to be a result of the increased mound area exposed to water in the deeper areas.

In contrast, the effect of fetch was greatest in depths less than 3 feet. An increase of almost 8 in./yr above the overall average was predicted. A rate of 14.5 in./ yr, 4 in./yr over waterway average, was found in depths of 3 feet to 6 feet. This result is compatible with sediment transport theories which predict greater disturbance of bottom sediment in shallower depths.

In depths from 3 feet to 6 feet, windward placement of dredged material increased the shoaling rate 9 in./yr over the waterway average. The effect was less in depths less than 3 feet, increasing the average rate by only 4.5 in./yr. This indicates that windward placement of dredged material was actually advantageous in bay areas with a long fetch over very shallow water. The mounds were thought to act as a barrier to sediment inflow from the broad, open-bay areas.

The statistical model did not fully account for shoaling rates in several areas. These areas should be given careful attention when deciding on locations for future study. To accurately explain shoaling mechanisms, a deterministic relationship between winds, fetch and depth must be obtained. Average wind, fetch, and depth for several areas combined with shoaling rates computed here could be used to obtain such a relationship. The broad, flat area of San Antonio Bay is recommended as the ideal location for such a study. The effects of wind, fetch, and dredged material mounds are the only apparent physical factors active there.

A hypothesis-testing technique was used to determine whether or not hurricanes have an effect on the shoaling rate. From the data available, no significant difference could be determined in the shoaling rates before and after hurricanes.

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APPENDIX II--GIWW Sections Normally Dredged Under a Single Contract

Source: Galveston District Office, U.S. Army Corps of Engineers

Area	Station Number (ft)		Channel Miles (Statute)	
	From	To	From	To
Port Arthur Area Office Port Arthur to High Island	0+00	1620+00	288.6	319.3
Fort Point Area Office High Island to Port Bolivar	1620+00	3203+00	319.3	349.3
Port Bolivar to Galveston Causeway	3203+00	13+318	349.3	357.2
Galveston Causeway to Bastrop Bayou	13+318	145+000	357.2	382.2
Bastrop Bayou to Freeport Harbor	145+000	213+350	382.2	395.1
Freeport Harbor to Cedar Lakes	213+350	269+000	395.1	405.6
Cedar Lakes to Colorado River	269+000	452+000	405.6	441.0
Colorado River to Matagorda Bay	452+000	566+400	441.0	461.4
Corpus Christi Area Office Matagorda Bay to San Antonio Bay	566+400	427+400	461.4	492.3

Area	Station Number (ft) From		Station Number (ft) To	Channel Miles (Statute) From	Channel Miles (Statute) To
San Antonio Bay to Aransas Bay	729+400		866+000	492.3	518.1
Aransas Bay to Corpus Christi Bay	866+000	**	2+000	518.1	550.0
Corpus Christi Bay to Mud Flats	2+000		298+856	550.0	614.0
Brownsville Area Office					
Mud Flats to Port Isabel	298+856	***	8+000	614.0	669.1

*Equation - Station 3582 + 86.45 = Station 9+350.45
**Equation - Station 1021 + 744.65 = Station 0+000
***Equation - Station 311+000 from Corpus Christi = Station 327+739 from Brownsville

APPENDIX III--Conversion of Corps of Engineers Stationing System to Waterway Miles

Equation	Range of Application (Waterway Miles)
Mile = Station number (ft)/5280 (ft)+ 288.6 (miles)	288.6 - 356.5
Mile = Station number (ft) -9,350 (ft)/5280 ft +356.8 (miles)	356.6 - 548.2
Mile = Station number (ft)/5280 (ft) +548.2 (miles)	548.3 - 607.1
Mile (starting mile) = 669.2 (mile) - (ending) Station number (ft)/5280 (ft)	607.2 - 669.2

APPENDIX IV--Summary of the Shoaling Rate for Each Reach of the Waterway

SUMMARY OF SHOALING FOR EACH MILE
FROM 288.6 TO 668.6 FROM YEAR 33 THRU 74

MILE*	REA	TOT YD3	TOT/YR	SHOAL FT/YR	NO. DRED	END NEW WORK	END MAINT
288.6	1	77917.	3895.83	0.168	1	33	52
289.5	2	84924.	2071.32	0.089	2	33	73
290.5	3	112915.	2754.03	0.119	3	33	73
291.4	4	142846.	3484.06	0.151	3	33	73
292.4	5	140909.	3436.80	0.148	3	33	73
293.3	6	133618.	3258.96	0.141	3	33	73
294.3	7	136712.	3334.44	0.144	3	33	73
295.2	8	140056.	3416.00	0.148	3	33	73
296.2	9	157374.	3838.39	0.166	3	33	73
297.1	10	315810.	7702.69	0.333	3	33	73
298.1	11	334760.	8164.88	0.353	3	33	73
299.0	12	348751.	8506.11	0.367	3	33	73
300.0	13	282221.	6883.44	0.297	3	33	73
300.9	14	283515.	6914.99	0.299	3	33	73
301.9	15	267984.	6536.20	0.282	3	33	73
302.8	16	275941.	6730.27	0.291	3	33	73
303.7	17	275494.	6719.36	0.290	3	33	73
304.7	18	273648.	6674.34	0.288	3	33	73
305.6	19	275863.	6728.37	0.291	3	33	73
306.6	20	278989.	6804.60	0.294	3	33	73
307.5	21	291986.	7121.61	0.308	3	33	73
308.5	22	338584.	8258.13	0.357	3	33	73
309.4	23	337888.	8241.16	0.356	3	33	73
310.4	24	351626.	8576.25	0.370	3	33	73
311.3	25	362266.	8835.76	0.382	3	33	73
312.3	26	362253.	8835.43	0.382	3	33	73
313.2	27	356734.	8700.84	0.376	3	33	73
314.2	28	345729.	8432.41	0.364	3	33	73
315.1	29	312025.	7610.35	0.329	3	33	73
316.1	30	306056.	7464.79	0.322	3	33	73
317.0	31	280077.	6831.13	0.295	3	33	73
318.0	32	280106.	6831.85	0.295	3	33	73
318.9	33	562823.	13400.55	0.579	9	33	74
319.8	34	777951.	18522.64	0.800	8	33	74
320.8	35	633027.	15072.08	0.651	9	33	74
321.7	36	540895.	13192.56	0.570	6	33	73
322.7	37	546808.	13336.78	0.576	6	33	73
323.6	38	583305.	13888.22	0.600	9	33	74
324.6	39	838617.	19967.07	0.863	12	33	74
325.5	40	1176394.	28009.38	1.210	10	33	74
326.5	41	1004219.	23909.98	1.033	11	33	74
327.4	42	1181098.	28121.38	1.215	12	33	74
328.4	43	1653592.	39371.23	1.701	12	33	74
329.3	44	1427525.	33988.69	1.468	13	33	74
330.3	45	820314.	20007.65	0.864	10	33	73
331.2	46	772286.	18836.24	0.814	10	33	73
332.2	47	606336.	14788.68	0.639	9	33	73
333.1	48	602503.	14695.18	0.635	9	33	73
334.0	49	496912.	12422.79	0.537	9	33	72
335.0	50	483619.	12090.47	0.522	8	33	72
335.9	51	532595.	13314.87	0.575	8	33	72
336.9	52	532676.	13316.90	0.575	8	33	72
337.8	53	557002.	13925.04	0.602	10	33	72
338.8	54	720229.	18005.72	0.778	9	33	72
339.7	55	625104.	15627.60	0.675	10	33	72

340.7	56	539409.	13485.21	0.583	9	33	72
341.6	57	608185.	16004.86	0.691	9	33	70
342.6	58	757828.	18043.53	0.779	10	33	74
343.5	59	1078050.	25667.86	1.109	12	33	74
344.5	60	773266.	18411.09	0.795	12	33	74
345.4	61	1184542.	28203.38	1.218	13	33	74
346.4	62	1255282.	29887.66	1.291	10	33	74
347.3	63	901275.	21458.94	0.927	12	33	74
348.2	64	2230742.	53112.90	2.294	11	33	74
349.2	65	124762.	2970.52	0.128	6	33	74
350.1	66	331256.	8079.41	0.349	6	33	73
351.1	67	933998.	46699.88	2.017	8	54	73
352.0	68	772794.	38639.70	1.669	8	54	73
353.0	69	882831.	44141.56	1.907	7	54	73
353.9	70	869772.	43488.59	1.879	6	54	73
354.9	71	770789.	38539.46	1.665	6	54	73
355.8	72	578914.	28945.70	1.250	6	54	73
356.8	73	211414.	7047.13	0.304	3	34	63
357.7	74	305911.	9270.04	0.400	4	34	66
358.7	75	484586.	14684.43	0.634	5	34	66
359.6	76	200183.	6066.13	0.262	3	34	66
360.6	77	211775.	5723.66	0.247	7	34	70
361.5	78	1212533.	32771.16	1.416	9	34	70
362.5	79	1045799.	28264.82	1.221	10	34	70
363.4	80	849613.	22962.51	0.992	7	34	70
364.4	81	875406.	23659.61	1.022	7	34	70
365.3	82	604057.	16325.85	0.705	6	34	70
366.3	83	563335.	15225.27	0.658	5	34	70
367.2	84	515661.	13936.78	0.602	6	34	70
368.2	85	472426.	12768.27	0.552	5	34	70
369.1	86	482693.	13045.76	0.564	5	34	70
370.1	87	492096.	13299.88	0.575	5	34	70
371.0	88	332437.	10723.78	0.463	5	40	70
371.9	89	368712.	11893.94	0.514	4	40	70
372.9	90	538792.	17380.38	0.751	5	40	70
373.8	91	609886.	19673.75	0.850	7	40	70
374.8	92	1153604.	37213.03	1.608	7	40	70
375.7	93	1116964.	36031.09	1.557	7	40	70
376.7	94	1034624.	33374.95	1.442	7	40	70
377.6	95	732092.	23615.86	1.020	9	40	70
378.6	96	489837.	16890.92	0.730	4	40	68
379.5	97	450653.	15539.75	0.571	4	40	68
380.5	98	437220.	15076.56	0.651	4	40	68
381.4	99	488483.	16844.24	0.728	4	40	68
382.4	100	298031.	10276.94	0.444	4	40	68
383.3	101	99335.	3425.35	0.148	3	40	68
384.3	102	16492.	568.70	0.025	1	40	68
385.2	103	8683.	299.40	0.013	1	40	68
386.2	104	33834.	1163.42	0.050	1	40	68
387.1	105	26010.	896.88	0.039	1	40	68
388.0	106	22203.	765.62	0.033	1	40	68
389.0	107	4163.	143.55	0.006	1	40	68
389.9	108	0.	0.00	0.000	0	40	74
390.9	109	0.	0.00	0.000	0	40	74
391.8	110	0.	0.00	0.000	0	40	74
392.8	111	0.	0.00	0.000	0	40	74
393.7	112	0.	0.00	0.000	0	40	74
394.7	113	52058.	1679.28	0.073	3	40	70
395.6	114	334891.	11547.96	0.499	4	42	70
396.6	115	482313.	16631.48	0.718	6	42	70

397.5	116	574144.	19798.05	0.855	7	42	70
398.5	117	865169.	29833.41	1.239	11	42	70
399.4	118	1121134.	38659.79	1.670	12	42	70
400.4	119	2673094.	92175.63	3.982	18	42	70
401.3	120	1003032.	34587.30	1.494	13	42	70
402.2	121	807734.	27852.91	1.203	10	42	70
403.2	122	860916.	29686.74	1.282	10	42	70
404.1	123	1014408.	34979.59	1.511	11	42	70
405.1	124	743973.	25654.24	1.108	12	42	70
406.0	125	122221.	5313.95	0.230	1	42	64
407.0	126	179621.	7809.61	0.337	2	42	64
407.9	127	74417.	2480.56	0.107	5	42	71
408.9	128	444887.	14829.55	0.641	7	42	71
409.8	129	438768.	14625.59	0.632	7	42	71
410.8	130	344819.	11493.97	0.497	6	42	71
411.7	131	255375.	8512.49	0.368	4	42	71
412.7	132	61072.	2544.66	0.110	1	42	65
413.6	133	62716.	2613.18	0.113	1	42	65
414.6	134	64274.	2678.06	0.116	1	42	65
415.5	135	64496.	2687.33	0.116	1	42	65
416.4	136	70672.	2944.67	0.127	2	42	65
417.4	137	127162.	3973.82	0.172	4	42	73
418.3	138	333320.	10416.26	0.450	6	42	73
419.3	139	334354.	10448.57	0.451	6	42	73
420.2	140	382153.	12738.45	0.550	5	42	71
421.2	141	332009.	11066.96	0.478	6	42	71
422.1	142	391193.	13039.76	0.563	6	42	71
423.1	143	224505.	7741.54	0.334	4	42	70
424.0	144	279515.	9317.15	0.403	7	42	71
425.0	145	435740.	14524.66	0.627	7	42	71
425.9	146	561591.	18719.71	0.809	10	42	71
426.9	147	802453.	25076.64	1.083	12	42	73
427.8	148	871262.	27226.93	1.176	10	42	73
428.8	149	791869.	24745.90	1.069	8	42	73
429.7	150	873676.	27302.37	1.179	12	42	73
430.6	151	1317023.	41157.13	1.778	14	42	72
431.6	152	1091377.	34105.53	1.473	14	42	73
432.5	153	778085.	24315.15	1.050	12	42	73
433.5	154	836245.	26132.65	1.129	12	42	73
434.4	155	1088077.	34002.41	1.469	10	42	73
435.4	156	1003286.	31352.67	1.354	10	42	73
436.3	157	765414.	23919.18	1.033	10	42	73
437.3	158	736811.	23025.34	0.995	10	42	73
438.2	159	830743.	25960.71	1.122	11	42	73
439.2	160	849947.	26560.86	1.147	11	42	73
440.1	161	900123.	28128.84	1.215	17	42	73
441.1	162	1605662.	48656.42	2.102	18	42	74
442.0	163	929769.	28174.80	1.217	10	42	74
443.0	164	879096.	26639.28	1.151	10	42	74
443.9	165	682553.	20686.45	0.894	11	42	74
444.9	166	593661.	17989.73	0.777	10	42	74
445.8	167	825618.	26632.83	1.151	10	42	72
446.7	168	818642.	26407.79	1.141	10	42	72
447.7	169	771392.	24883.62	1.075	10	42	72
448.6	170	793316.	24039.87	1.039	10	42	74
449.6	171	1137934.	34482.85	1.490	15	42	74
450.5	172	1717267.	52038.39	2.248	15	42	74
451.5	173	1174051.	35577.30	1.537	14	42	74
452.4	174	1033031.	31303.98	1.352	11	42	74
453.4	175	1229377.	37253.85	1.609	14	42	74

454.3	176	1953633.	59201.00	2.557	15	42	74
455.3	177	2805149.	93504.94	4.039	15	45	74
456.2	178	3359788.		4.838	15	45	74
457.2	179	3116008.		4.487	15	45	74
458.1	180	1912057.	63735.23	2.753	15	45	74
459.1	181	979270.	32642.35	1.410	9	45	74
460.0	182	151496.	5410.56	0.234	4	45	72
460.9	183	37682.	4186.90	0.181	1	45	53
461.9	184	37682.	4186.90	0.181	1	45	53
462.8	185	37682.	4186.90	0.181	1	45	53
463.8	186	37682.	4186.90	0.181	1	45	53
464.7	187	37682.	4186.90	0.181	1	45	53
465.7	188	37682.	4186.90	0.181	1	45	53
466.6	189	37682.	4186.90	0.181	1	45	53
467.6	190	37682.	4186.90	0.181	1	45	53
468.5	191	37682.	4186.90	0.181	1	45	53
469.5	192	37682.	4186.90	0.181	1	45	53
470.4	193	62151.	2219.68	0.096	2	45	72
471.4	194	102102.	3646.50	0.158	2	45	72
472.3	195	37682.	4186.90	0.181	1	45	53
473.3	196	802096.	26736.54	1.155	8	45	74
474.2	197	391712.	13057.06	0.564	3	45	74
475.1	198	342687.	11422.90	0.493	3	45	74
476.1	199	358025.	11934.16	0.516	4	45	74
477.0	200	378298.	12609.94	0.545	4	45	74
478.0	201	363574.	12119.12	0.524	4	45	74
478.9	202	348953.	11631.75	0.502	3	45	74
479.9	203	285032.	9501.05	0.410	3	45	74
480.8	204	196266.	6542.21	0.283	4	45	74
481.8	205	165318.	5510.61	0.238	3	45	74
482.7	206	167880.	5596.01	0.242	3	45	74
483.7	207	173091.	5769.68	0.249	3	45	74
484.6	208	191447.	6381.57	0.276	5	45	74
485.6	209	380719.	12690.62	0.548	4	45	74
486.5	210	369828.	12327.58	0.533	4	45	74
487.5	211	356986.	11899.52	0.514	4	45	74
488.4	212	237666.	7922.20	0.342	4	45	74
489.3	213	215913.	7197.09	0.311	3	45	74
490.3	214	262449.	8748.29	0.378	3	45	74
491.2	215	374131.	12471.04	0.539	7	45	74
492.2	216	1487921.	51307.62	2.216	11	45	73
493.1	217	1810183.	62420.10	2.697	10	45	73
494.1	218	1828916.	63066.07	2.724	10	45	73
495.0	219	1835806.	63303.65	2.735	10	45	73
496.0	220	1858862.	64098.69	2.769	10	45	73
496.9	221	1863323.	64252.52	2.776	10	45	73
497.9	222	1870570.	64502.41	2.787	10	45	73
498.8	223	1702040.	58691.03	2.535	9	45	73
499.8	224	1709048.	58932.69	2.546	9	45	73
500.7	225	1770589.	61054.79	2.639	9	45	73
501.7	226	1105448.	36848.27	1.592	13	45	74
502.6	227	1090763.	36358.77	1.571	7	45	74
503.6	228	1070496.	35683.20	1.542	7	45	74
504.5	229	643739.	21457.95	0.927	7	45	74
505.4	230	303408.	12136.33	0.524	5	45	69
506.4	231	322950.	12918.01	0.558	4	45	69
507.3	232	274787.	10991.48	0.475	4	45	69
508.3	233	46146.	5127.34	0.222	1	45	53
509.2	234	52145.	2896.92	0.125	2	45	62
510.2	235	163844.	9102.44	0.393	2	45	62

511.1	236	186193.	6649.74	0.287	4	45	72
512.1	237	1422238.	47407.93	2.048	10	45	74
513.0	238	1877256.	62575.20	2.703	10	45	74
514.0	239	1844313.	61477.10	2.656	11	45	74
514.9	240	1098817.	36627.23	1.582	9	45	74
515.9	241	877811.	31350.41	1.354	6	45	72
516.8	242	1074364.	38370.14	1.658	6	45	72
517.8	243	1288425.	46015.18	1.988	7	45	72
518.7	244	972868.	34745.29	1.501	9	45	72
519.6	245	914125.	32647.33	1.410	7	45	72
520.6	246	901168.	32184.58	1.390	7	45	72
521.5	247	867571.	30984.66	1.339	6	45	72
522.5	248	582169.	20791.76	0.898	5	45	72
523.4	249	377709.	13489.60	0.583	5	45	72
524.4	250	358954.	12819.78	0.554	4	45	72
525.3	251	247825.	8850.91	0.382	5	45	72
526.3	252	286871.	11952.97	0.516	4	45	68
527.2	253	275155.	14481.85	0.626	3	45	63
528.2	254	46841.	11710.19	0.506	2	60	63
529.1	255	46841.	11710.19	0.506	1	60	63
530.1	256	44454.	11113.54	0.480	1	60	63
531.0	257	220739.	73579.63	3.179	1	60	62
532.0	258	76562.	25520.64	1.102	1	60	62
532.9	259	209295.	13953.01	0.603	2	60	74
533.8	260	89669.	5977.90	0.258	2	60	74
534.8	261	84042.	5602.82	0.242	1	60	74
535.7	262	74157.	4943.77	0.214	1	60	74
536.7	263	123254.	8216.92	0.355	2	60	74
537.6	264	113793.	7586.23	0.328	2	60	74
533.6	265	58020.	11604.09	0.501	1	60	64
539.5	266	140113.	9340.83	0.404	4	60	74
540.5	267	0.	0.00	0.000	0	47	74
541.4	268	0.	0.00	0.000	0	47	74
542.4	269	0.	0.00	0.000	0	47	74
543.3	270	0.	0.00	0.000	0	47	74
544.3	271	0.	0.00	0.000	0	47	74
545.2	272	0.	0.00	0.000	0	47	74
546.2	273	0.	0.00	0.000	0	47	74
547.1	274	0.	0.00	0.000	0	47	74
548.2	275	286218.	13009.89	0.562	5	47	68
549.1	276	545724.	24805.63	1.072	6	47	69
550.1	277	79573.	3616.95	0.156	3	47	68
551.0	278	0.	0.00	0.000	0	47	74
552.0	279	0.	0.00	0.000	0	47	74
552.9	280	0.	0.00	0.000	0	47	74
553.9	281	69403.	4337.71	0.187	1	47	62
554.8	282	104711.	6544.44	0.283	1	47	62
555.8	283	104711.	6544.44	0.283	1	47	62
556.7	284	115980.	5799.02	0.251	3	47	66
557.7	285	198670.	9933.52	0.429	2	47	66
558.6	286	218655.	7809.09	0.337	3	47	74
559.6	287	213608.	7628.87	0.330	4	47	74
560.5	288	117786.	5889.27	0.254	2	47	66
561.5	289	108582.	6786.38	0.293	1	47	62
562.4	290	109975.	7331.67	0.317	1	48	62
563.3	291	110786.	7385.70	0.319	1	48	62
564.3	292	197466.	13164.38	0.569	5	48	62
565.2	293	569706.	21100.21	0.912	6	48	74
566.2	294	589989.	21851.43	0.944	7	48	74
567.1	295	678189.	25118.09	1.085	7	48	74

568.1	296	903513.	33463.44	1.446	10	48	74
569.0	297	1219803.	45177.89	1.952	10	48	74
570.0	298	1077426.	39904.66	1.724	8	48	74
570.9	299	861523.	31908.26	1.378	8	48	74
571.9	300	499822.	18511.93	0.800	6	48	74
572.8	301	465417.	17237.65	0.745	7	48	74
573.8	302	648699.	24025.89	1.038	7	48	74
574.7	303	746127.	27634.33	1.194	9	48	74
575.7	304	723367.	26791.36	1.157	7	48	74
576.6	305	543820.	23644.33	1.021	6	48	70
577.6	306	817693.	32707.72	1.413	9	48	72
578.5	307	996965.	39878.62	1.723	9	48	72
579.4	308	1021445.	42560.21	1.839	9	49	72
580.4	309	881284.	36720.15	1.586	12	49	72
581.3	310	673807.	25915.64	1.120	9	49	74
582.3	311	953344.	36667.09	1.584	10	49	74
583.2	312	777382.	32390.90	1.399	8	49	72
584.2	313	626346.	24090.22	1.041	8	49	74
585.1	314	636018.	24462.21	1.057	6	49	74
586.1	315	644182.	24776.23	1.070	6	49	74
587.0	316	917539.	35289.97	1.525	11	49	74
588.0	317	1011808.	38915.70	1.681	9	49	74
588.9	318	537291.	22387.13	0.967	8	49	72
589.9	319	446428.	22321.39	0.964	5	49	68
590.8	320	427658.	21382.89	0.924	5	49	68
591.8	321	413308.	24312.25	1.050	5	49	65
592.7	322	371381.	21845.93	0.944	5	49	65
593.6	323	354861.	20874.17	0.902	3	49	65
594.6	324	389137.	19456.83	0.841	4	49	68
595.5	325	634461.	31723.05	1.370	6	49	68
596.5	326	827498.	41374.91	1.787	5	49	68
597.4	327	947509.	47375.47	2.047	5	49	68
598.4	328	977225.	48861.27	2.111	5	49	68
599.3	329	792180.	39609.01	1.711	5	49	68
600.3	330	860634.	43031.69	1.859	6	49	68
601.2	331	1041094.	52054.68	2.249	7	49	68
602.2	332	983940.	49196.99	2.125	7	49	68
603.1	333	835192.	41759.58	1.804	5	49	68
604.1	334	818411.	40920.53	1.768	4	49	68
605.0	335	532463.	26623.15	1.150	5	49	68
606.0	336	604004.	30200.18	1.305	5	49	68
607.1	337	607785.	30389.27	1.313	4	49	69
608.0	338	292282.	14614.09	0.631	4	49	69
609.0	339	282544.	14127.21	0.610	4	49	68
609.9	340	216047.	10802.35	0.467	4	49	68
610.9	341	153367.	8071.97	0.349	5	49	67
611.8	342	491385.	23399.27	1.011	6	49	67
612.8	343	981302.	39252.09	1.696	10	49	73
613.7	344	1119462.	44778.48	1.934	14	49	73
614.7	345	1064063.	42562.52	1.839	9	49	73
615.6	346	962707.	41856.82	1.808	9	49	71
616.6	347	680651.	29593.54	1.278	8	49	71
617.5	348	489214.	23295.91	1.006	6	49	69
618.5	349	346117.	15048.57	0.650	4	49	71
619.4	350	419297.	18230.32	0.788	4	49	71
620.4	351	504310.	21926.53	0.947	4	49	71
621.3	352	476964.	20737.54	0.896	8	49	71
622.2	353	439208.	19964.00	0.862	4	49	70
623.2	354	441453.	20066.06	0.867	4	49	70
624.1	355	374540.	17024.53	0.735	6	49	70

625.1	356	380646.	15225.86	0.658	4	49	73
626.0	357	643697.	25747.88	1.112	6	49	73
627.0	358	698175.	27926.99	1.206	8	49	73
627.9	359	534771.	23250.93	1.004	5	49	71
628.9	360	320596.	13938.94	0.602	5	49	71
629.8	361	388427.	15537.08	0.671	5	49	73
630.8	362	889209.	34200.35	1.477	6	49	74
631.7	363	874578.	33637.60	1.453	4	49	74
632.7	364	108343.	4710.56	0.203	2	49	71
633.6	365	265042.	11043.43	0.477	6	49	72
634.6	366	419322.	17471.76	0.755	4	49	72
635.5	367	412196.	17174.83	0.742	4	49	72
636.4	368	237319.	9888.27	0.427	4	49	72
637.4	369	219774.	9555.39	0.413	3	49	71
638.3	370	181857.	7906.82	0.342	3	49	71
639.3	371	134304.	5839.30	0.252	3	49	71
640.2	372	65404.	3847.29	0.166	1	49	65
641.2	373	5317.	312.77	0.014	1	49	65
642.1	374	0.	0.00	0.000	0	49	74
643.1	375	34902.	34901.97	1.508	1	49	49
644.0	376	296262.	11394.68	0.492	9	49	74
645.0	377	597305.	22973.27	0.992	10	49	74
645.9	378	209467.	9974.63	0.431	3	49	69
646.9	379	197450.	9872.51	0.426	2	49	68
647.8	380	203472.	7825.84	0.338	3	49	74
648.8	381	248237.	9547.56	0.412	3	49	74
649.7	382	175774.	6760.55	0.292	3	49	74
650.6	383	121097.	4657.56	0.201	2	49	74
651.6	384	154215.	5317.75	0.230	2	46	74
652.5	385	153053.	5277.69	0.228	2	46	74
653.5	386	156923.	5411.13	0.234	2	46	74
654.4	387	192148.	6625.80	0.286	4	46	74
655.4	388	397491.	14721.88	0.636	6	46	72
656.3	389	1050424.	36221.52	1.565	13	46	74
657.3	390	1887220.	65076.55	2.811	14	46	74
658.2	391	1771793.	61096.31	2.639	13	46	74
659.2	392	1534919.	52928.24	2.286	14	46	74
660.1	393	1136889.	39203.07	1.694	13	46	74
661.1	394	645799.	22263.91	0.962	7	46	74
662.0	395	200610.	6917.59	0.299	4	46	74
663.0	396	0.	0.00	0.000	0	46	74
663.9	397	0.	0.00	0.000	0	46	74
664.9	398	79727.	4196.17	0.181	4	46	64
665.8	399	684179.	36009.44	1.556	5	46	64
666.7	400	135251.	7118.47	0.308	6	46	64
667.7	401	250300.	27366.66	1.204	3	46	54
668.6	402	362852.	21344.22	0.922	4	46	62

* Explanation of column headings:

MILE--Waterway mileage, Corps of Engineers Mileage System
REA--Reach,waterway divided into 402, 5000 foot reaches
TOT YD3--Amount of material dredged from reach since new work was completed
TOT/YR--Average amount (yd^3/yr) dredged per year from the reach
SHOAL--Average accumulation of material per year (ft/yr)
NO DRED--Number of times particular reach was dredged
END NEW WORK--The year in which new work was completed
END MAINT--The year in which maintenance dredging was last accomplished

APPENDIX V--Sediment Data From the Intracoastal Waterway

Source: Y. C. Liou (19)

Mileage	Depth (ft)	Grain Size (b,c,d) d50 (mm)	S.D.
265.4	28	.225	2.10
274.2	10	clay	gray
278.0	20		
285.0	35	silt	
290.0	14	.135	2.16
296.6	13	clay	
301.2	15	.160	206
305.4	15	silt	
309.4	15	.175	2.69
315.0	12	.135	2.00
319.0	10	.120	2.23
320.5	15	silt	
326.5	8	silt	
329.8	11	.140	1.70
332.3	12	.300	2.32
337.7	11	.195	2.12
342.5	12	.165	.175
346.2	12	.180	2.10
350.2	15	clay	gray
353.4	12	.150	1.45
358.2	12	shell	
362.4	14	.230	1.74
	13	.150	1.93
374.0	13	.298	2.55
379.9	9	.300	2.20
388.0	11	clay	(red)
382.4	10	clay	(red)
398.4	13	clay	
399.9	14	.105	2.65
400.8	14	clay	
402.0	14	clay	(red)
404.4	12	clay	(red)
405.0	12	.085	1.45
406.0	11	clay	(red)
411.5	10	clay	(red)
417.8	12	clay	(red)
421.5	11	clay	(red)
428.4	11	clay	gray
434.8	10	silt	
437.3	9	clay	(red)
440.7	11	.140	2.11
441.5	11	clay	
442.5	12	.230	2.50
447.0	12	.120	2.85
453.5	12	0.250	2.35
460.5	12	clay	gray

Mileage	Depth (ft)	Grain Size (b,c,d) d50 (mm)	S.D.
466.2	13	clay	
471.2	12	.100	2.10
479.0	13	.162	1.44
485.2	12	.270	2.05
492.0	13	.145	2.351
498.4	12	clay	gray
505.2	12	.106	1.35
510.2	12	.130	1.33
519.5	11	clay	
524.2	6	shell	
530.1	11	.138	1.99
536.3	12	silt	
542.0	11	silt	
548.8	12	.108	1.50
555.6	11	silt	
561.8	13	.150	2.18
568.2	11	.190	1.66
574.6	10	silt	
580.8	11	shell	
587.0	11	.234	1.56
593.0	11	.160	1.43
598.9	12	.180	1.68
605.0	9	.270	2.01
612.9	11	.170	1.73
619.1	12	silt	
625.0	12	silt	
631.4	12	silt	
668.3	11	clay	gray
644.1	12	.500	1.25
650.8	12	.265	1.81
656.9	11	clay	(gray)
663.1	10	clay	(gray)
668.9	15	clay	(gray)
675.2	32	clay	(gray)
682.1	32	clay	(gray)

a) Depth is measured by echo sounding.

b) Grain Sizes were analyzed using a visual accumulation tube.
(Range 0.0625 - 1.0 mm)
Soil samples were taken from the channel bottom.

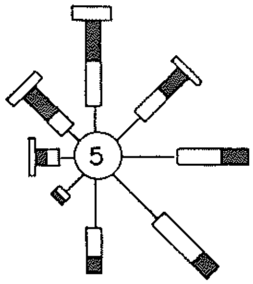
c) Standard deviation $= \frac{1}{2}\left(\frac{d84}{d50} + \frac{d50}{d10}\right)$

d) Silt: Grain Size d50 = 0.074 to 0.005 mm.
Clay: Grain Size d50 <0.005 mm.

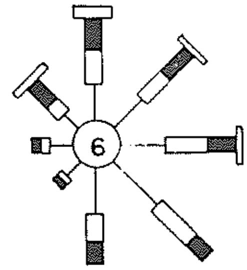
APPENDIX VI--Wind Data

Source: U.S. Naval Weather Service (31)

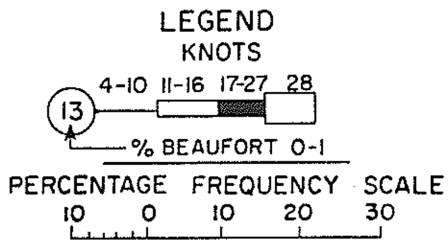
GALVESTON

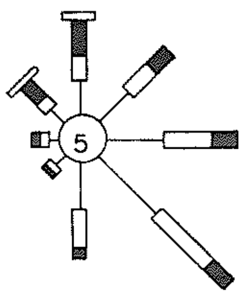


JANUARY

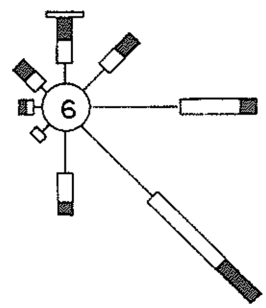


FEBRUARY

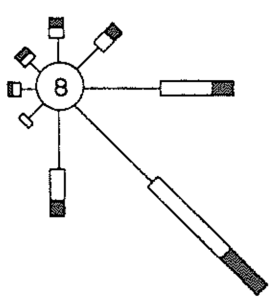




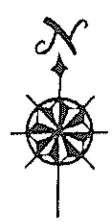
MARCH

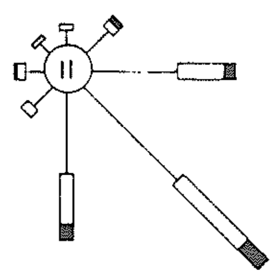


APRIL



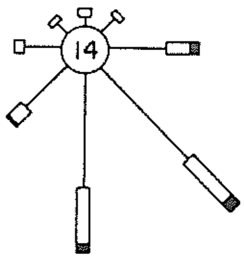
MAY



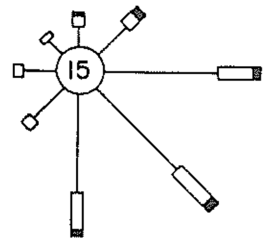


JUNE

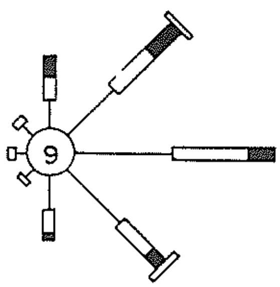
GALVESTON



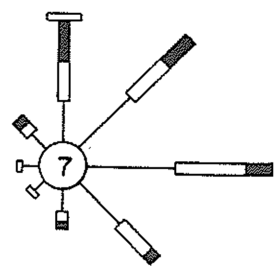
JULY



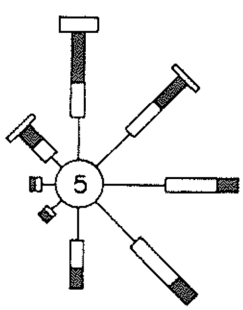
AUGUST



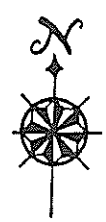
SEPTEMBER

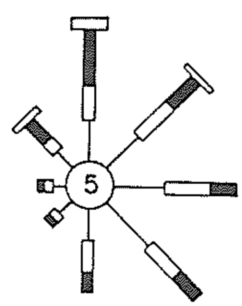


OCTOBER



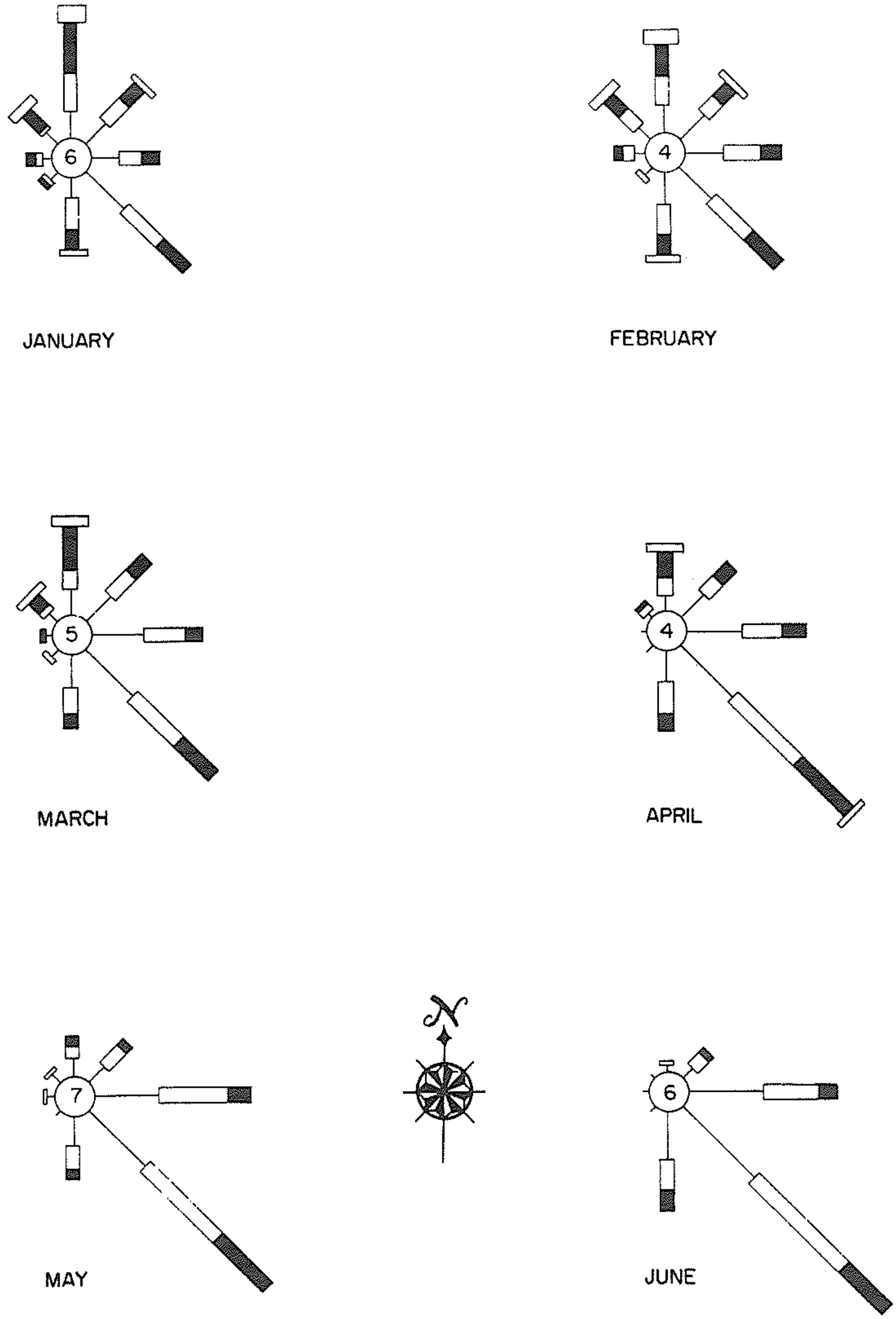
NOVEMBER



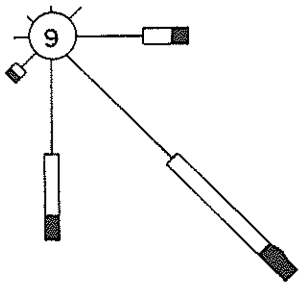


DECEMBER

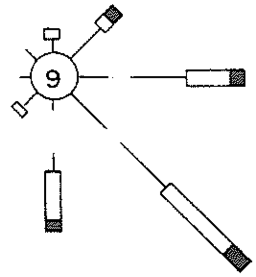
CORPUS CHRISTI



CORPUS CHRISTI



JULY



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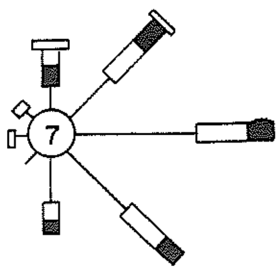

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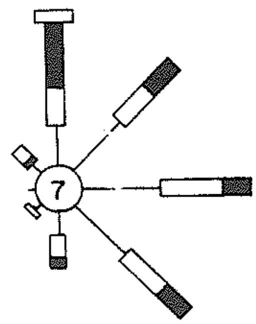

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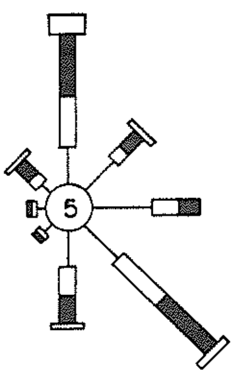

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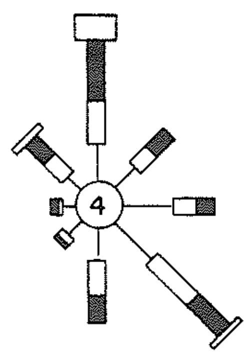


DECEMBER

APPENDIX VII--Test for the Effect of Hurricanes on Shoaling Rate

A t-test for paired observations of the difference between means of two normal populations with equal variance (23) was used. "D" was calculated for each reach of the waterway for which there was data. The procedure follows.

Hypothesis: Difference between shoaling rates (D) is equal to zero at the 95 percent confidence level.

y_h = shoaling rate during hurricane periods

y_{nh}= shoaling rate during non-hurricane periods

$D = Y_{nh} - Y_h$

$\overline{D} = D/N$

N = Number of observations (pairs of data)

S^2_D = variance of sample = $(\Sigma D^2 - (\Sigma D)^2/N)/(N-1)$

$S^2_{\overline{D}} = S^2_D/N$

$N = 301$

$D = 93,788 \text{ yd}^3$

$\overline{D} = -93,788/301 = 311.58 \text{ yd}^3$

$\Sigma D^2 = 1.3966 \text{ X } 10^{11}$

$(\Sigma D^2 = 8.7963 \text{ X } 10^9$

$S^2_D = 4.639 \text{ X } 10^8$

$S^2_{\overline{D}} = 1.546 \text{ X } 10^6$

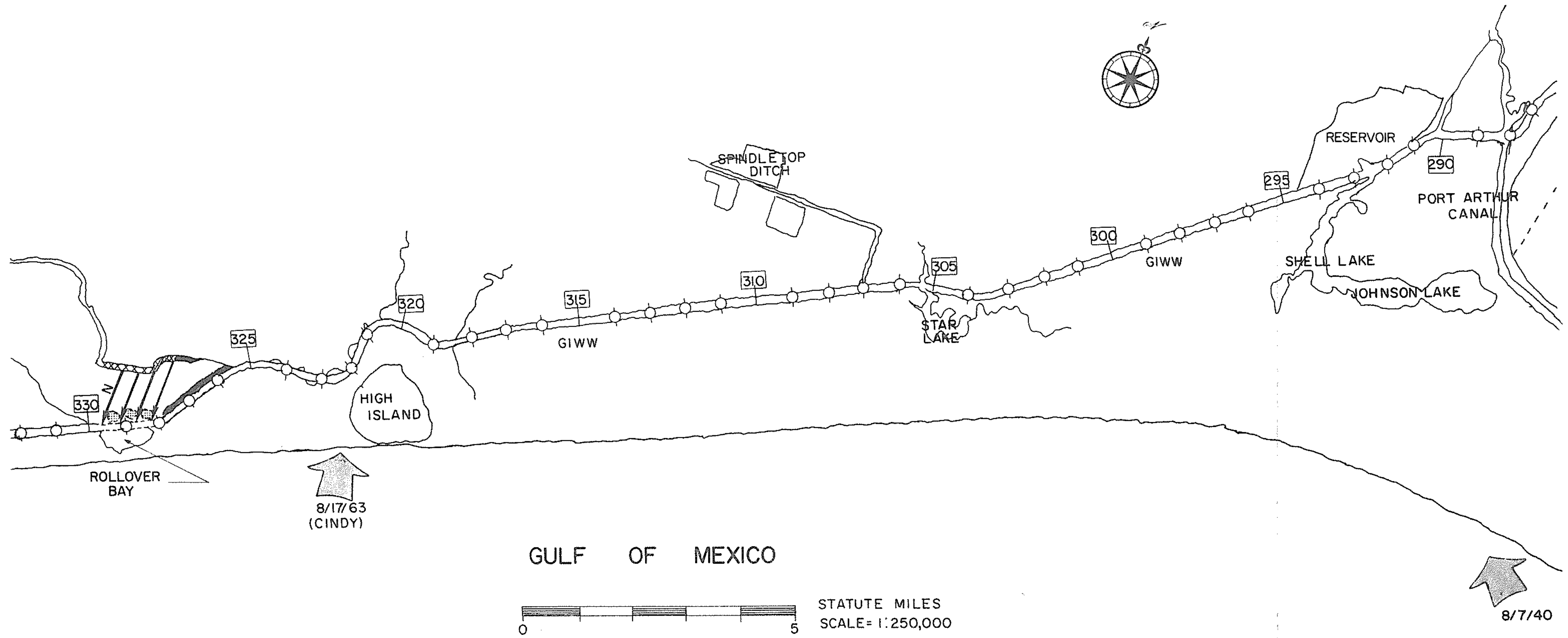
$S_{\overline{D}} = 1.243 \text{ X } 10^3$

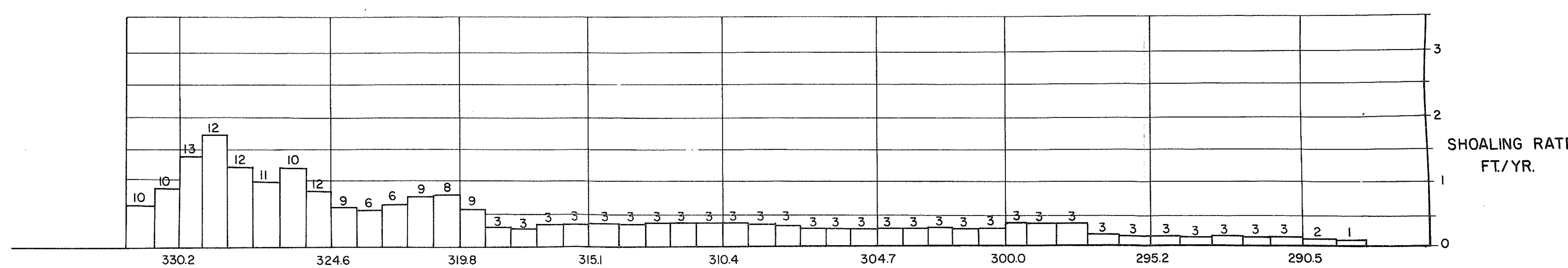
Test statistic: $t = \bar{D}/S_{\bar{D}} = -311.58/(1.243 \times 10^3) = -.250$

Rule: If the absolute value of the test statistic is greater than a t random variable with 300 degrees of freedom at the 0.05 level of significance (1.968), reject the hypothesis.

Decision: Since the absolute value of the test statistic is less than the critical value, the hypothesis cannot be rejected. Therefore, conclude that hurricanes do not have an effect on shoaling rate.

APPENDIX VIII--Composite Factors Maps





EXPLANATION

- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIRECT.
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- XX NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

NOTES

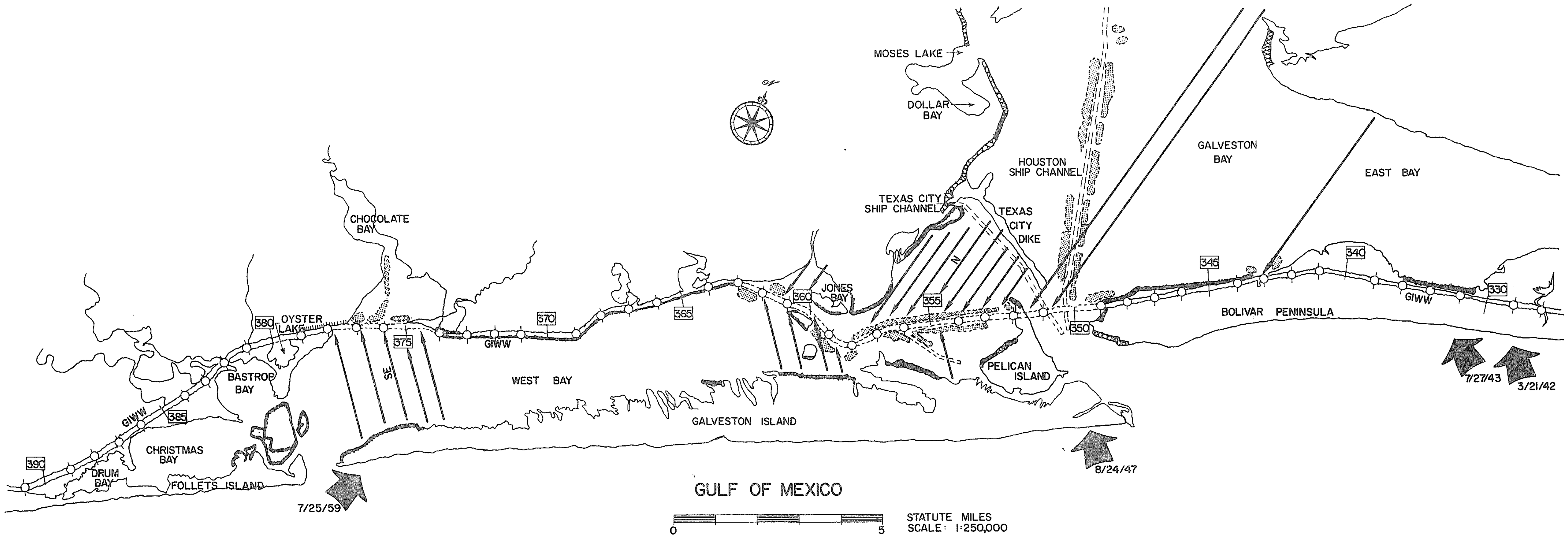
1) EROSIONAL AND DEPOSITIONAL SHORELINES WERE TAKEN FROM BUREAU OF ECONOMIC GEOLOGY MAPS.
2) MILE MARKERS REFER TO CORPS OF ENGINEERS WATERWAY MILEAGE SYSTEM.
3) SHOALING RATES WERE BASED ON MAINTENCE DREDGING RECORDS (CORPS OF ENGINEERS).

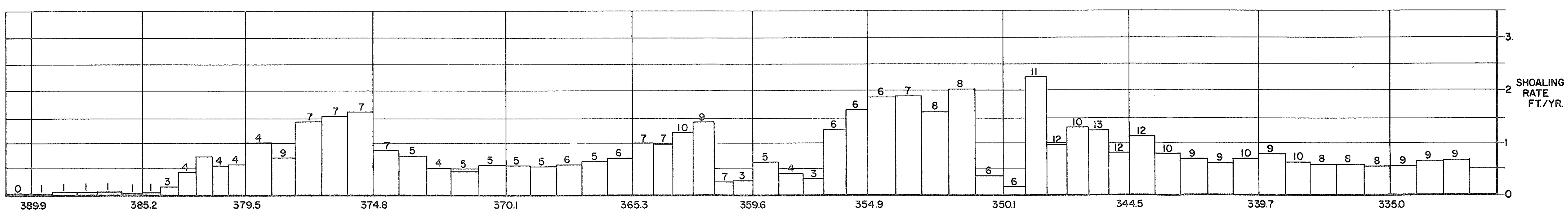
GULF INTRACOASTAL WATERWAY

MILE 288.6 TO 332.2

PORT ARTHUR — HIGH ISLAND AREA

COMPOSITE FACTORS MAP# 1





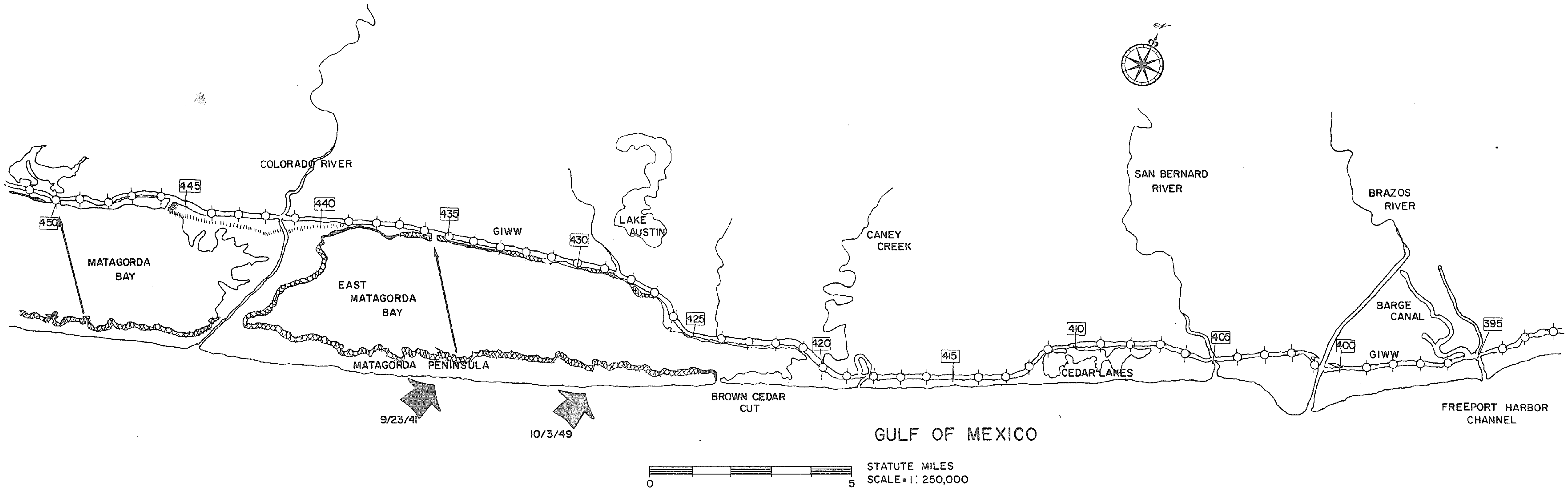
EXPLANATION

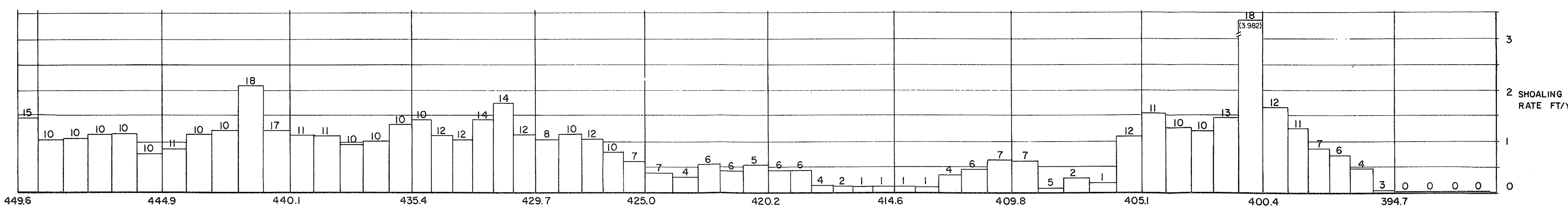
- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIRECTION
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- XX NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

GULF INTRACOASTAL WATERWAY

MILE 332.2 TO 391.8
GALVESTON BAY AREA

COMPOSITE FACTORS MAP # 2





EXPLANATION

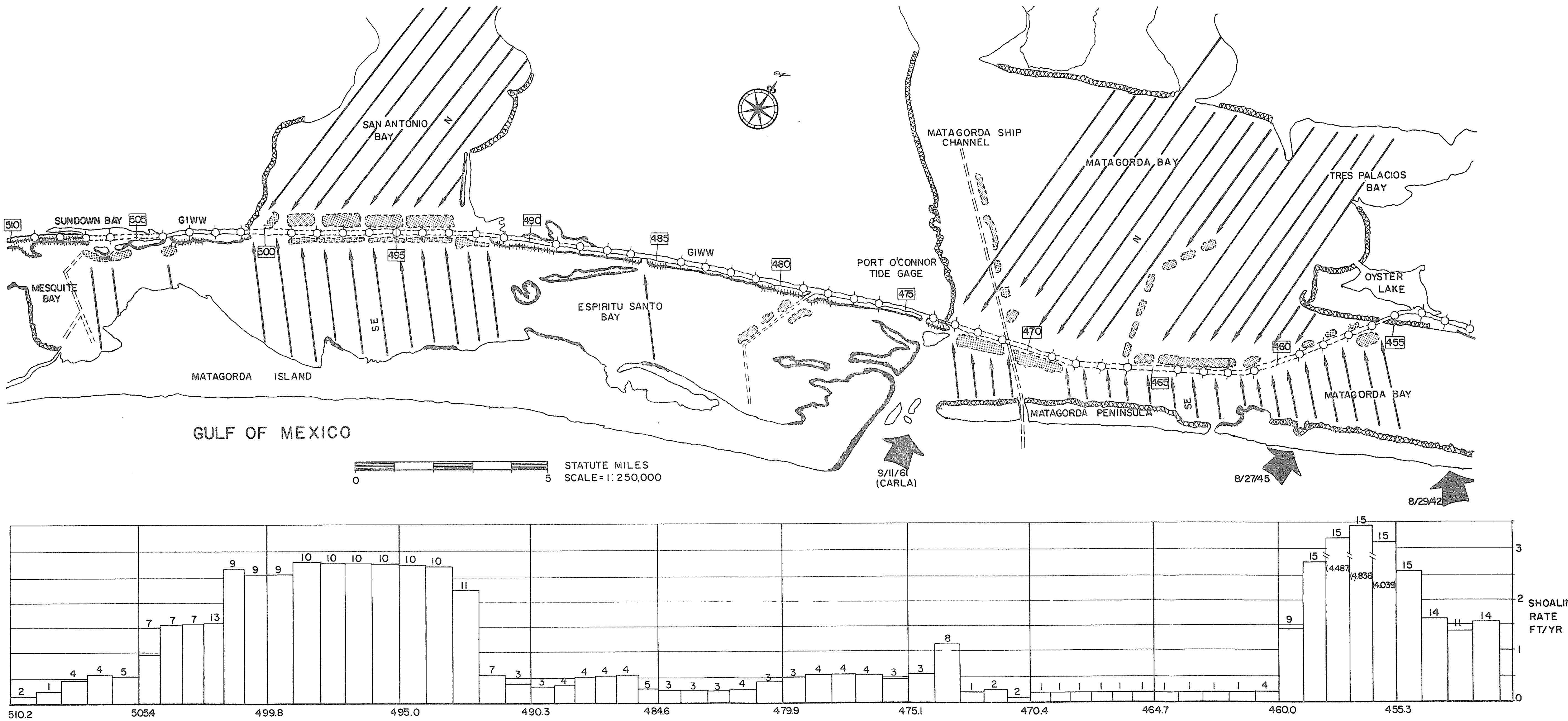
- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIR.
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

GULF INTRACOASTAL WATERWAY

MILE 391.8 TO 452.4

BRAZOS RIVER – MATAGORDA BAY AREA

COMPOSITE FACTORS MAP # 3



EXPLANATION

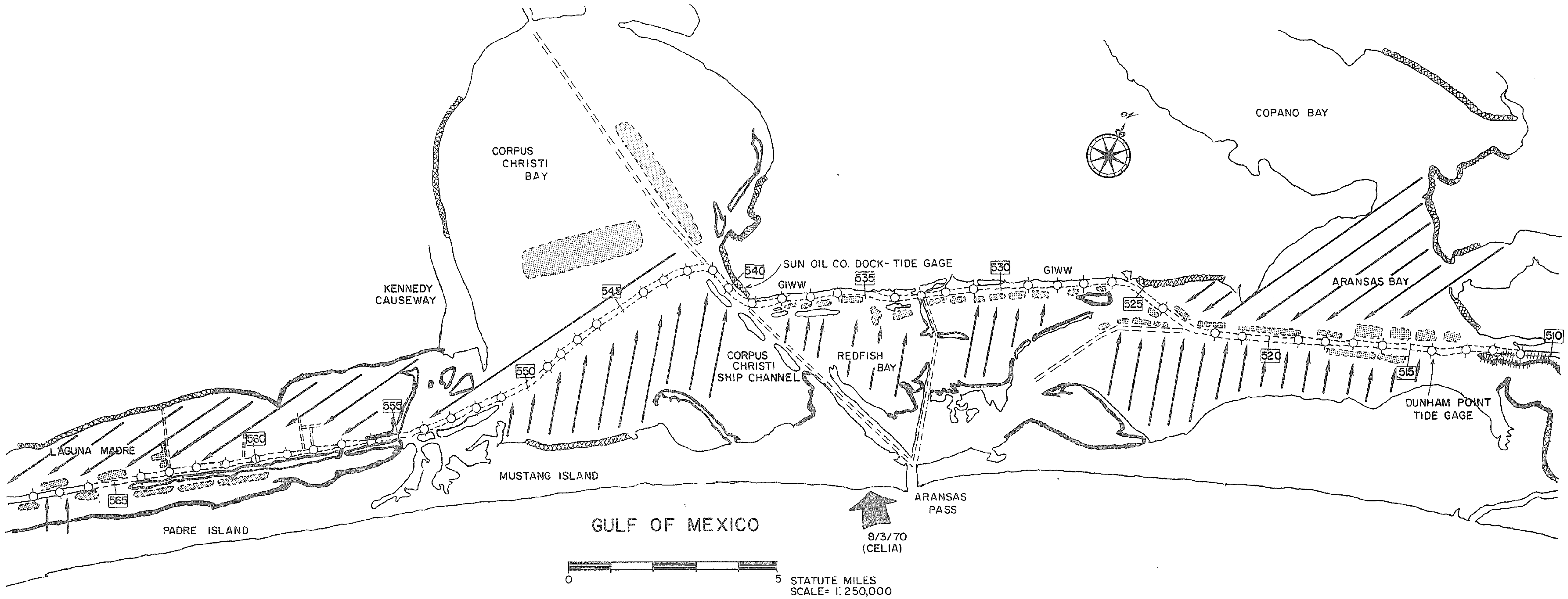
LAND CUT	PREDOMINANT WIND DIRECT.
OPEN BAY	SUBAQUEOUS SPOIL MOUNDS
WATERWAY MILE MARKERS	HURRICANE LANDFALL
DEPOSITIONAL SHORELINE	NUMBER OF TIMES DREDGED
EROSIONAL SHORELINE	SHOALING RATE IN 5000 FT. REACH
DIKED DISPOSAL AREA	

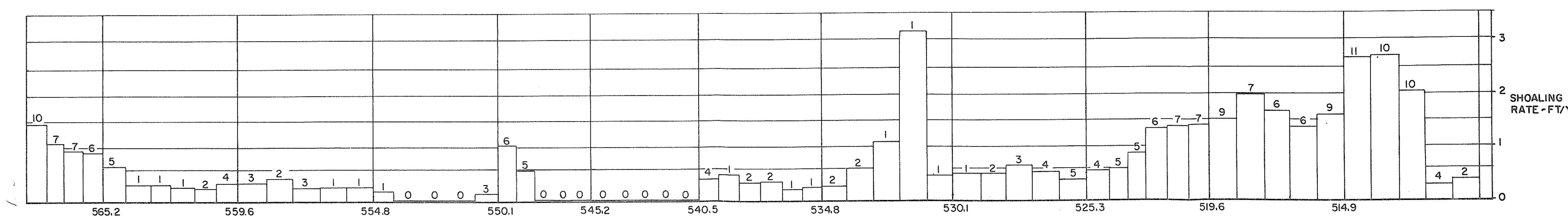
GULF INTRACOASTAL WATERWAY

MILE 452.4 TO 510.2

MATAGORDA—SAN ANTONIO BAY AREA

COMPOSITE FACTORS MAP # 4





EXPLANATION

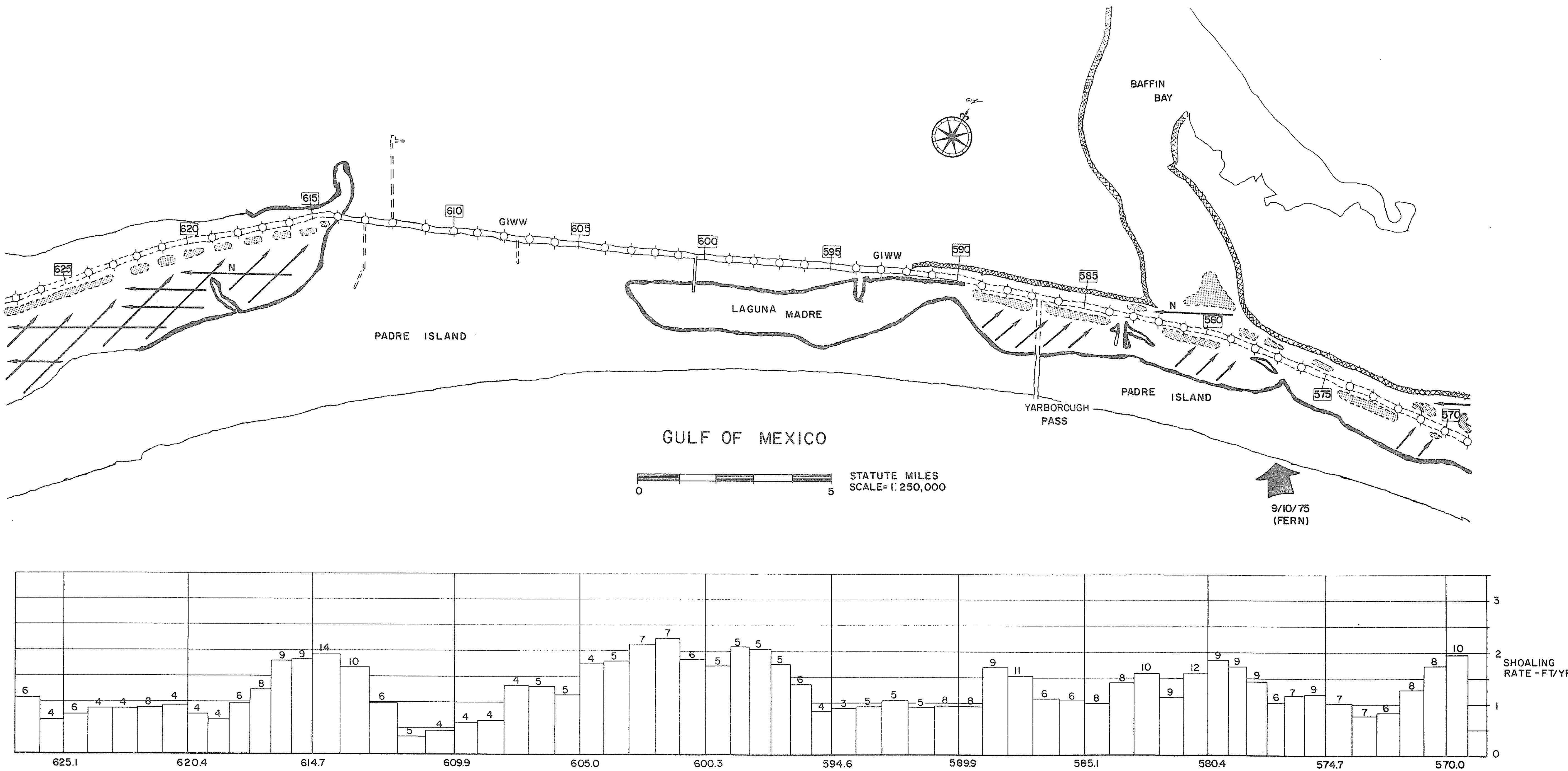
- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIRECT.
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

GULF INTRACOASTAL WATERWAY

MILE 510.2 TO 568.1

ARANSAS BAY– CORPUS CHRISTI AREA

COMPOSITE FACTORS MAP#5



EXPLANATION

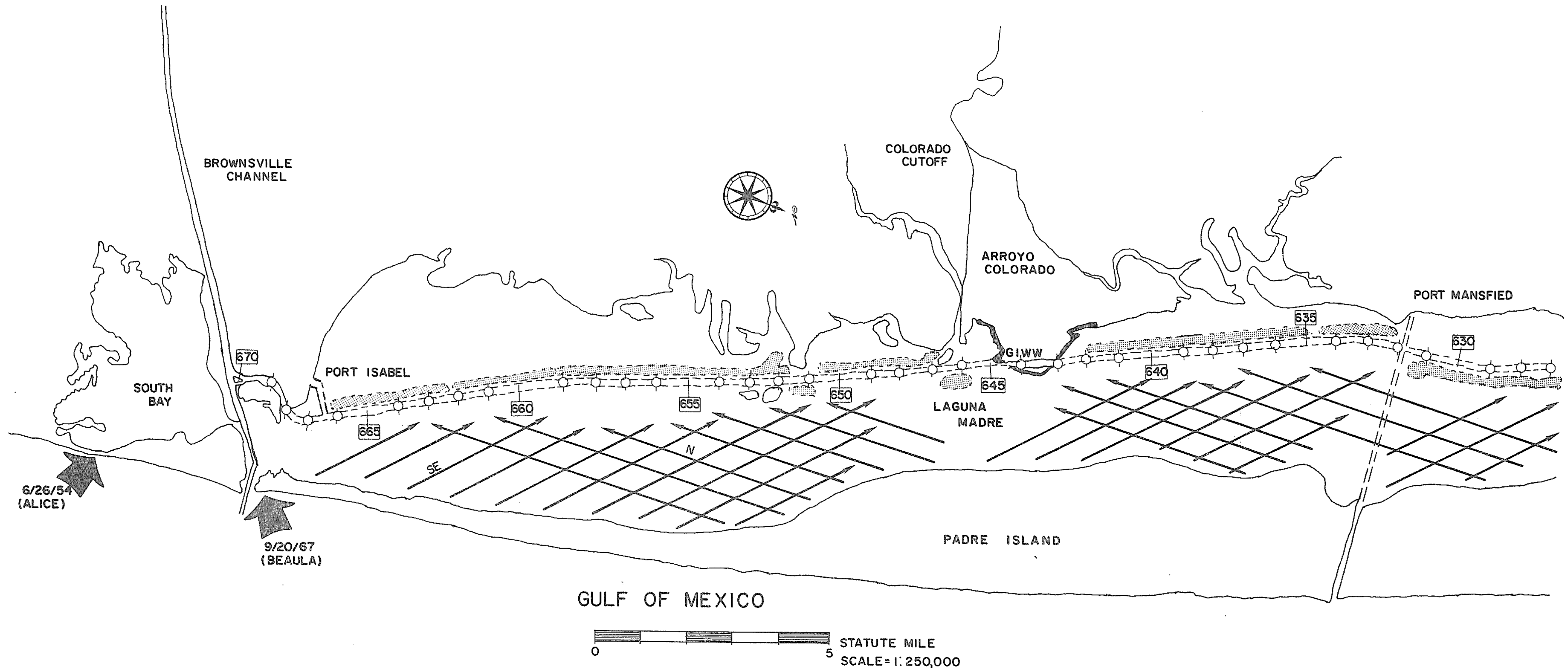
- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIRECT.
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

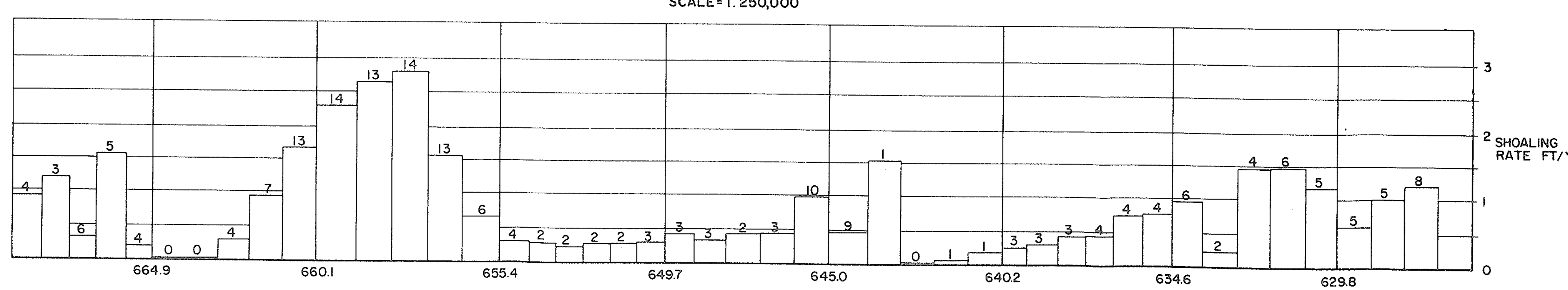
GULF INTRACOASTAL WATERWAY

MILE 568.1 TO 627.0

NORTHERN LAGUNA MADRE AREA

COMPOSITE FACTORS MAP # 6





EXPLANATION

- LAND CUT
- OPEN BAY
- WATERWAY MILE MARKERS
- DEPOSITIONAL SHORELINE
- EROSIONAL SHORELINE
- DIKED DISPOSAL AREA
- PREDOMINANT WIND DIRECT.
- SUBAQUEOUS SPOIL MOUNDS
- HURRICANE LANDFALL
- NUMBER OF TIMES DREDGED
- SHOALING RATE IN 5000 FT. REACH

GULF INTRACOASTAL WATERWAY

MILE <u>627.0</u> TO <u>669.5</u>
SOUTHERN LAGUNA MADRE AREA

COMPOSITE FACTORS MAP #7