DEVELOPMENT REPORT

ON

FISH PASSES AND WATER 43/ INTERCHANGE

FOR

THE UPPER LAGUNA MADRE

AND

CORPUS CHRISTI BAY, COASTAL TEXAS

PREPARED FOR

GAME AND FISH COMMISSION

STATE OF TEXAS

CONSULTING · LOCKWOOD, ANDREWS & NEWNAM · ENGINEERS

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GRANT BUILDING
3230 REID DRIVE
CORPUS CHRISTI, TEXAS

March 18, 1959

Game and Fish Commission
State of Texas
Walton State Building
Austin 14, Texas

Gentlemen:

Pursuant to the contract of July 22, 1958, we submit this development report, together with all maps and supporting data complete, as contemplated by the contract. This submission, therefore, constitutes the results of our investigation of the feasibility of constructing passes through the barrier islands within the Study Area of the Upper Laguna Madre and Corpus Christi Bay Areas. It also furnishes our conclusions and recommendations as to the benefits such passes may represent to the fisheries from the standpoint of improved conditions of water interchange within those bodies of water.

To complete this study in the relative short time has proved quite more demanding -- both for our staff and yours -- than anyone anticipated. Without the complete cooperation of many interested persons, agencies, and firms, it would have been impossible to have completed this elaborate study in the time indicated.

Our work on this project has been under the full-time direction of Mr. H. P. Carothers of our firm. He largely conceived the techniques for processing, obtaining and presenting the great mass of data; some of these are quite original and may prove of substantial collateral value to the Game and Fish Commission and others in the future planning of coastal developments.

We trust the information developed and assembled herein will adequately fulfill its intended purpose of furnishing a basis for a sound decision on the part of the Commission toward the construction of coastal improvements, which have been requested urgently by so many of the citizens of the State of Texas.

Respectfully submitted,

Lockwood, Andrews & Newnam

By Homer C Innis

Homer C. Innis, Head
Corpus Christi Office

HCI:nc

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SYNOPSIS

It has long been recognized that there is a need for a fish pass or passes and water interchange improvements that would benefit the fisheries in the Upper Laguna Madre and Corpus Christi Bay areas of the Texas Coast. This is a large complex area in which conditions have been changed in the last few years by the dredging of the Intracoastal Waterway, lateral channels and man-made restrictions such as the landfill section of Padre Island Causeway. High salinities exist at frequent intervals in the entire Laguna Madre area and there is no direct connection to the Gulf for the fish.

On July 22, 1958, the Texas Game & Fish Commission authorized the field investigations, studies, and report submitted herewith for the purpose of determining the existing topographical, geological and tidal conditions in and adjacent to this area, analysing possible construction projects that would improve these conditions and recommending the specific projects that should be constructed to accomplish the desired objectives. Full utilization was made of the previous work accomplished by us and others in the area, by the assistance and advice of the field representatives of the Commission, and others interested in the area.

Field surveys were made, sufficient to define the bay and lagoon bottoms, define critical or more restricted sections between basins, beach profiles, profiles of the several passes considered, and to establish datum for tide gages. Tide gages were installed and operated, samples of sand and shell at several locations in the study area were taken, tested and analysed because of their importance to the problem. Inspection trips by boat and car were made with marine biologists and geologists. Many technical papers and publications pertinent to the problem were studied, particularly in connection with the investigation of data collected by other agencies in the area.

From a study of the information and data obtained, several technical formulas were developed or modified for tidal hydraulics and water interchange computations. These are listed and explained in the technical section of the report, because, in addition to their use in this study, it was felt that they will be very valuable to the Commission and others in connection with any further development of this area of the State, and for use in the future design and development of fish passes and water interchange for the improvement of coastal fisheries.

A more economical type of protection has been developed, for the Gulf end of any fish passes that are constructed in the area, which should be sufficient to prevent migration of the mouth of the pass. It is not designed for major hurricanes and will not necessarily prevent some maintenance dredging from time to time.

A thorough study was made of possible fish passes, and connecting channels or other interchange improvements, that might be constructed in the area. Analyses were made of the size, locations, relative construction costs and benefits to be obtained from each one as well as from various combinations.

From an analysis of these studies, definite recommendations have been made and submitted herein covering the two fish passes and minor spoil removal that will provide the vitally needed openings for passage of fish to the Gulf and also provide the necessary water interchange to reduce maximum salinities and in other ways benefit the fisheries in the area. The recommended improvements can be separated into two projects, which can be constructed separately, but both should be constructed eventually to accomplish the designed intention:

(1) The Corpus Christi Fish Pass (10 ft. deep, 250 ft. bottom width and 10,000 ft. long), estimated to cost about 1.3 million dollars is designed primarily as a fish pass, but by acting in cooperation with the second proposed fish pass, will serve to materially improve the salinity in Bird Island Basin.

(2) The Boggy Slough Fish Pass (25 ft. deep, 330 ft. bottom width and 15,000 ft. long - located opposite Baffin Bay) will serve as a fish pass and also as the main Gulf water interchange between Corpus Christi Bay and the south end of Murdock Basin.

This should serve to control the maximum salinity in this area down to almost the desired maximum. A construction of this pass together with minor channel construction and spoil bank removal as recommended herein will cost about 3.1 million dollars.

The construction costs required are large, but the benefits should be far reaching and of inestimable value to this very large segment of the Texas Coast. The depth and width of the pass, in each case, is designed to produce the velocities and quantities of water movement required to keep maintenance dredging to a minimum and to produce the designed amount of water interchange.

The Game and Fish Commission has made a major step forward towards the improvement of Texas coastal fisheries by first authorizing a thorough collection of data, studies and preliminary designs for this large area before authorizing any construction. This will permit, as funds become available, the orderly and proper development of the recommended construction projects with a knowledge of the probable results that will be achieved. In addition, the design procedures established, and the formulas developed, for the design of these passes will be very valuable in connection with the planning of any similar or related improvements along the Texas Gulf Coast.

PURPOSE AND SCOPE

The simple purpose of this "Development Report on Fish Passes and Water Interchange for The Upper Laguna Madre and Corpus Christi Bay, Coastal, Texas", is: (1) to investigate the Upper Laguna Madre and adjacent Corpus Christi Bay areas of the Texas Gulf Coast; and (2) report to the Game and Fish Commission the recommended fish pass or passes found to be feasible and desirable and the water interchange improvements found to be necessary to control the hypersaline conditions of the Upper Laguna Madre, and thus improve the fisheries in the area.

The complex and exhaustive investigation and the technical portions of this report, namely "Environment of the Upper Laguna Madre" and "Tidal Hydraulics" will appear, at first glance, to greatly exceed the requirements for such a simple purpose.

The scope of the investigation was, however, necessary to the solution of the problem, and the technical portion of the report is submitted to the Commission as a valuable addition to its technical library for use in connection with any development in the area, and for use in future design and development of fish passes and water interchange for improvement of the Coastal fisheries.

This scope of the work included:

(1) Survey work to define the bay and lagoon bottoms, restricted sections between basins, beach profiles, location and profile of several passes considered, and to establish datums for tide gages.

(2) Accumulation of many maps from which the base maps for the Plates A through C, historic maps for Figures 1 through 3 and current charts for Figure 7 were developed.

(3) Numerous inspection trips, by boat and car, with marine biologist and geologist as needed to become acquainted with the waters, watershed and general geology of the area.

(4) Operation and analyses of several tide gages for establishing tidal differentials.

(5) Sampling, testing and analyses of the sand and shell in typical beach profiles spaced throughout the limits of the study area.

(6) Review of many technical papers and publications pertinent to the investigation and solution, as partly indicated by the 19 technical references included with the report.

(7) Development or modification of several technical formulas for the tidal hydraulics and water interchange computations.

(8) Development of more economical protective works for the Gulf end of fish passes.

Using the data thus accumulated, studies were made of the (1) location, (2) size, (3) effect, and (4) approximate relative cost of the many possible alternate fish passes and water interchange improvements that could be constructed in the subject area. Based on a study and consideration of all factors involved, recommendations are presented herein covering location, size, general features and cost estimates of the two fish passes and accompanying minor water interchange improvements that appear feasible and desirable to accomplish the desired objectives.

ENVIRONMENT OF UPPER LAGUNA MADRE

Geography

The geographic environment of the Upper Laguna Madre, including location of the study area and its topography, is illustrated on Plates A through E. See Table of Contents for Illustrations. The base maps for these plates were reproduced from the latest maps of the U. S. Geological Survey and the U. S. Coast and Geodetic Survey. Much additional information has been secured and superposed on these base maps.

Location. The location of the study area, including the southeast portion of Corpus Christi Bay, extends in a southerly direction along the Texas Coast from Corpus Christi, Texas, through the Upper Laguna Madre (including the Baffin Bay System) to the southern portion of the Landcut. This Landcut, located just south of Latitude 27° North, is the wide area of sand and mud flats in Kenedy County that divides the Upper and Lower Laguna Madre. See Plate A, "Environment of Upper Laguna Madre".

Basin Areas and Volumes. For calculation of water interchange and other purposes, the Upper Laguna Madre was divided into basins at restricted sections. These basins from north to south are: Bulkhead Flats, from Corpus Christi Bay to the Padre Island Causeway; Bird Island Basin; Green Hill Basin; Boggy Slough Basin, opposite Baffin Bay; Murdock Basin; and The Hole Basin, in the north part of the

Landcut area. See Plates B, C and D. Although some use was made of available soundings, the generalized bottom contours of the Basins are based largely upon sections and soundings made in connection with this study. The contours of the sand and mud flats in the Landcut area on Plate D are from the Humble Oil and Refining Company.

The topography of the Baffin Bay System is shown on Plate E. The surface areas and volumes of the various basins, as computed from these plates, are tabulated in Table I, "Basin Areas, Volumes and Depths". See Table of Contents for Tables and Graphs.

Sand Flats. The sand and mud flats are one of the outstanding features of the area. These result mostly from the invasion of wind blown sand across Padre Island from the Gulf beaches. Exclusive of the Bulkhead Flats and the Landcut, they cover about 35 000 acres, or about 31 per cent of the Upper Laguna Madre.

Climate

Climatic Region. The Upper Laguna Madre, Baffin Bay System and the entire watershed (or drainage area contributing fresh water inflow) are located in a semi-arid region. The division line between this semi-arid region and the dry sub-humid is located across Corpus Christi Bay as shown on Plate A.

In such climatic regions evaporation exceeds rainfall, stream flow is intermittent, and the gravity water table (except near the coast) drops considerably below general ground elevation, except for short periods after excessive rainfall.

The climate is mild, except for several penetrating "northers" each winter. The area is well south of the average zero frost penetration line as well as the average 1 inch snowfall line. Freezing weather is rare, with average date of first killing frost about December 15 to 25 and the last killing frost about January 30.

Rainfall. The average annual rainfall over the drainage area is 22.7 inches. Over the water surface of the Upper Laguna and Baffin Bay System, average annual rainfall is estimated at 25.2 inches. Most of the runoff producing rainfall occurs about the months of May and September.

Evaporation. The annual gross evaporation from the water surface areas is estimated at 60.4 inches with a net annual evaporation loss (gross evaporation less rainfall) of 35.2 inches. The gross monthly evaporation varies almost uniformly as a percentage of the gross annual evaporation, from about 4.6 per cent in January to about 13.2 per cent in August.

Wind. The prevailing and predominant wind direction is from the southeast, as illustrated by the wind rose and the predominant runway orientations shown on Plate A, "Environment of the Upper Laguna Madre".

Historical

Here, historical refers to the most significant changes in the study area as reflected by comparisons between the available maps from the year 1867 to date. Only two good shore line maps are available for most of the Upper Laguna Madre; namely, 1881-2 and 1952. However, maps or partial maps have been secured for the Corpus Christi Pass area for the years 1867, 1881-2, 1934, 1938, and 1952. Accurate maps of the water depths have never been made.

Matching of the horizontal and vertical controls of the old and new maps is difficult and requires considerable judgement, which replaces accuracy. This must be kept in mind when making any interpretation of the possible changes indicated by the various maps.

This comparative study of the historical maps is illustrated by: Figure 1, "Historic Map-Bird Island Basin and Bulkhead Flats"; Figure 2, "Historic Map-Murdock, Boggy Slough and Green Hill Basins"; and Figure 3, "Historic Map-Corpus Christi Pass". The most significant changes are indicated by notes and arrows on these Figures. The notes are identified by rectangular border lines. Other notes were simply copied from the maps.

Changes in Shore Lines and Water Depths. On Figure 1, it is indicated generally that the beach line is probably advancing gulfward, except the reverse is indicated near the various locations of Corpus Christi Pass. Alternate local advances and retreats of the beach line are to be expected near the various locations of the pass as it was alternately open and closed. On Figure 2, there is an indication of a definite trend for the beach line to be advancing gulfward at an average rate of about 0.6 feet per year. This rate must not be taken literally, but it is believed that, historically, the beach line is generally advancing slowly gulfward. For this study, it is desired to determine, simply, whether the beach line is advancing or retreating with respect to the Gulf of Mexico.

Comparison of the older and latest recorded water depths in Corpus Christi Bay indicate siltation at the rate of about 2.4 feet per century. It appears reasonable to assume that the average siltation rate over the deeper parts of the bay is probably at least half that amount.

The location of the approximate minus one contour in 1881-2, shown on Figure 1, through the Bulkhead Flats and for about 40 000 feet in Bird Island Basin, is of particular significance. This large area inside the minus one contour has always been extremely shallow, historically speaking. In 1881-2, the Bulkhead Flats were indicated as "Sand flats seldom having more than six inches of water". This natural flat seriously restricts for about nine miles any tidal interchange between Corpus Christi Bay and the Upper Laguna Madre. The subsequent obstruction and siltation of most of this area since 1882 by spoil banks, land fill, and related siltation is insignificant; that is, hydraulically speaking and from the standpoint of efficient tidal water interchange between Corpus Christi Bay and the entire Upper Laguna Madre and the Baffin Bay System.

However, for the relatively narrow but deeper water between the minus one contour and the mainland, the subsequent placement of the landfill between Flour Bluff Point and Demit Island, the land fill part f the Padre Island Causeway (about 6000 feet next to mainland) and spoil banks have definitely reduced the tidal interchange. Fortunately, this loss has just about been regained by the placement of the Intracoastal Waterway through the Bulkhead Flats.

This may best be explained by two illustrations. First, for similar condition of water slope and channel roughness, the velocity of flow varies as the two-thirds power of the hydraulic radius. In an infinitely wide flat-bottom channel, the hydraulic radius is equal to the depth of water. From a hydraulic radius of 1 to 2. 9 the velocity is doubled. From a radius of 2. 9 to 8, the velocity is again doubled. From 8 to 22. 6 for the hydraulic radius, the velocity is again doubled. Or, from a water depth of 1 foot to a depth of 22. 6 feet in a very wide channel, the velocity is increased 8 times, where the water slope and channel roughness remain the same.

Second, although the landfill of the Padre Island Causeway blocked 16 500 square feet of effective shallow opening, the 7 100 square feet at the deeper Intracoastal Waterway and Humble Channel Bridge more than replaces the obstructed waterway area in capacity for water interchange.

On Figure 2, it is noted that the estimated siltation rate in Baffin Bay is 1. 0 to 1. 5 feet per century. It may be inferred from the historic maps that the bay has silted at least one foot in 70 years, or 1. 4 feet per century. The Soil Conservation Service has estimated for part of the drainage area an average delivery of sediment of 0. 13 ac. ft. per sq. mi. per year. From Drainage Areas A and B (see Figure 4) this computes to cause siltation in the deeper portions of Baffin Bay at rates of 1 to 1.75 ft. per century, depending on the unit weight of sediment. A rate of 1.0 to 1.5 feet per century appears reasonable.

Historically, Murdock Basin appears to be relatively stable. In fact, the minus one contour is shown as retreating toward the middle ground from 1881-2 to 1959. Where the 1881-2 map had the notation of "about eight feet of water", the 1959 contours (see Plate C) indicate 8 to 9 feet. Of course, the extent of the deeper water might have been reduced considerably, but sufficient comparative data is not available. However, the continuous spoil bank along the east side of the Intra-coastal Waterway has now almost completely cut off most of Murdock Basin from the Upper Laguna Madre.

The minus one contour has retreated in Boggy Slough Basin, but has advanced, at a rate of up to 108 feet per year, into Green Hill Basin. The most extensive recent advance of the Padre Island shore line into the Upper Laguna Madre is into Green Hill Basin and near the restricted section between this basin and Bird Island Basin.

From geological investigations in the Lower Laguna Madre, Lohse has estimated that the sand and mud flats (until they reach an elevation high enough to incur wind erosion) in the Upper Laguna Madre probably build up at general average rates of about 0.8 to 2.1 feet per century, and the deeper parts of the basins silt up at various rates of about 0.3 to 0.8 feet per century.

Geologically speaking, the Upper Laguna Madre is considered to be a dying lagoon. However; historically speaking, and insofar as the contemporary fishermen are concerned, there is lots of life remaining in the old lagoon. It does need a shot of effective water interchange to prevent excessive salinities.

Corpus Christi Pass. The historic Corpus Christi Pass, which is now closed, had a rather hectic, intermittent, shifting life. See Figure 3, "Historic Map-Corpus Christi Pass". In 1881-2 the pass was about 33 000 feet long with a maximum depth of 17 feet, reduced from 19.5 in 1869. Based on the assumption of a hydraulic radius of 15 and a coefficient of roughness at 0.025, and using the tidal hydraulics developed by this study; it is computed that the median velocity in 1882 was 1.2 ft. per sec. where a median velocity of 1.7 ft. per sec. was needed to maintain the pass. This estimate, or hindcast, indicates that the pass was too long for the conditions and was destined to sand up as it did.

The maps indicate some retreat in the shoreline near the various locations of the pass. The shape and off-set of the gulf end of the pass in 1881-2 is now generally interpreted to be indicative of predominant littoral transport southward. On the other hand, the shape of Newport Pass and Corpus Christi Pass in 1934 indicate a practical balance in the northward and southward littoral transport. The 1934 branch, which was slightly open about half way between Newport Pass and the 1934 Corpus Christi Pass, may indicate predominant littoral transport northward but this shape might also be attributed to the irregular, reversed flow in this temporary branch.

It is believed that the weight of evidence indicates a long-time predominant littoral transport southward, but the northward littoral transport is often strong and approximately equal to the southward littoral transport. The longshore direction of the littoral transport shifts from day to day and season to season, depending largely on the direction of wave attack.

Since 1881-2 the pass has shifted or relocated its gulf outlet toward the north in desperate attempts to reduce its length and thus meet the tidal hydraulic requirements for balance in silting and erosion, but failed to develop sufficient median velocity and now it is closed.

Padre Island Causeway. Construction of the Padre Island Causeway was completed in 1950. The landfill sections of the causeway were started at the mainland or Flour Bluff end on April 13, 1949 and were completed at the Padre Island end on September 30, 1949. See Plate B.

Three bridges were placed in the landfill, one at the Humble Channel and one at the Intracoastal Waterway. Sections of these bridges are shown on Figure 12, "Restricted Sections". The third bridge was placed in the sand and mud flats between the Intracoastal Waterway and Padre Island. This bridge was and is of no practical value, from the standpoint of normal tidal interchange.

Intracoastal Waterway. The Intracoastal Waterway, constructed by Corps of Engineers, U. S. Army, between Corpus Christi Bay and through the Upper and Lower Laguna Madre to Port Isabel was completed on June 14, 1949, when northward and southward working dredges met in the landcut.

In October 1946, the dredge working from Corpus Christi Bay had cut through the Bulkhead Flats and was near Pita Island. In May 1947, the dredge was between North and South Bird Islands. The dredge was cutting between Green Hill and Boggy Slough Basins in January 1948, and in April 1948, was well into Murdock Basin.

The Intracoastal Waterway through the Bulkhead Flats has approximately replaced the naturally effective water interchange capacity cut off by the landfill portions of the Padre Island Causeway. Although the cutting through the Landcut has probably eliminated the extreme salinity readings above 85 ppt near the Landcut (by internal redistribution of low volume - high salinity waters), a weighted-statistical analysis made with this study fails to disclose any appreciable improvement or deterioration in the general or overall salinity conditions of the combined Upper Laguna Madre and Baffin Bay System attributable to the combined effects of the causeway and waterway.

...GY

Dr. E. Alan Lohse, Consulting Geologist, Corpus Christi, Texas, past president of Gulf Coast Association of Geological Societies, was employed to prepare a detailed report on a geological investigation of the study area. Most of the geology of the basins included herein has been extracted from that report.

The basins of the Upper Laguna Madre, as defined for this study, and with the exception of the Baffin Bay system, consist of basins set apart by natural constrictions within the lagoon. These basins result from distinct modifications of the normal lagoonal basin, brought about by the influx and deposition of reworked eolian and fluvial clastic sediments.

Separation of the lagoon into the Upper and Lower (northern and southern) Laguna Madre took place during the last few centuries with deposition of a large sand and clay transverse bar across the lagoon in central Kenedy County. This is the Landcut (source of name is the long cut of Intracoastal Waterway through exposed sand and mud flats) area shown on Plate D, "The Hole Basin". From unpublished plates furnished by Dr. H. N. Fisk, Humble Oil & Refining Company, the final closure at mean water level occurred near Mesquite Rincon sometime between the years 1804 and 1836. The exhaustive investigations by Humble of the sand flats in the Landcut area well substantiates an average rate of aggradation (vertical build up) of about 1/3 inch per year (2. 75 feet per century).

Geological Resume of Basins. The restrictions dividing the basins are probably the result of, and largely due to, wind setup of the water surface, with resulting wind driven currents and the consequent development of seiches upon sudden release or reversal of the wind stress. The seiche is a harmonic oscillation (rocking back and forth) about a stationary nodal line or lines. Either the nodal lines are drawn to restrictions or maximum desposition of bay sediments takes place along the nodal lines.

The Hole Basin is a remnant possibly maintained at the present by wind setup from northers which drive lagoonal waters southward. Although these waters deposit appreciable quantities of clay minerals, they inhibit the advance of dune sands. The retreat of the approximate minus one foot contour between the years 1882 and 1959 in the south portion of Murdock Basin is probably the result of wind setup from northers. See Figure 2, "Historic Map".

In the area of The Hole, Murdock and Boggy Slough Basins, the sand and mud flats adjacent to Padre Island occupy slightly more than 50 per cent of the lagoonal basin proper. These flats consist primarily of sand blown northwestward into the lagoon, with secondary amounts of clays derived from the Baffin Bay System. These sediments are deposited in a harmonic system of bars and spits.

The importance of the Little Shell area (See Plate C near Union Beach Profile and opposite Boggy Slough Basin) in feeding eolian sand into the lagoon is substantiated by field observations by Lohse and by analogy with Big Shell. Big Shell and Little Shell are primary and secondary nodal points, respectively, of the Coastal-drifting process acting along the Texas Gulf beaches.

The areas of accumulation of sand and shell detritus are shifted in short-term seasonal fluctuations and long-term annual fluctuations. Any variation in the relative effectiveness of the northward and southward littoral transport will move the nodal points correspondingly. See general area of shifting nodal points indicated on Plate A, "Environment of Upper Laguna Madre". This occurs to some extent each season, but occurs to a large extent in yearly variations. Field observations by Lohse indicate that during the winter of 1957-58, "Little Shell" received more detritus than during any time since at least 1950.

The Green Hill Basin shows, at present, the most rapid invasion of the shoreline of Padre Island in the form of shifting transverse sand dunes. The present rate is so rapid that there are cliffs (12 to 18 inches) of loose sand where it is dropping off into the lagoonal waters.

This locally rapid advance (between the years 1882 and 1952) is reflected on Figure 2, "Historic Map-Murdock, Boggy Slough and Green Hill Basins". Also, local measurements at one spot indicates a rate of advance of about 140 feet per year between the years 1952 and 1959. This was during one of the most severe drought periods known in the last 500 years.

The division of the normal lagoon, between Boggy Slough Basin and the Bulkhead Flats, into Green Hill Basin and Bird Island Basin appears to be rapid at present. This process is possibly aided and abetted by spoil banks located generally where the basin flow crosses the Intra-coastal Waterway in the vicinity of the restricted section shown on Plate

C. The developing division or restriction is suggested by the turning under and reversal of wind driven currents near Marker 75 as reported by Simmons[11] and reproduced on Graph 2.

The Bird Island Basin shows distinct changes from two factors: (1) siltation along the eastern portion, between the continuous spoil banks and Padre Island, and (2) increasing shoaling northward toward the Causeway. The spoils segment this basin into two separate parts, depriving the eastern portion of any effective energy. This is reflected in the increased width of the sand and mud flats adjacent to the island.

Spoils extending across the basin from Pita Island are especially detrimental to basin maintenance. These spoils impede the wave action and flow of waters from both the north and southeast winds. They divide the northern quarter of the basin into a separate segment, and, together with the Padre Island Causeway, probably increase the natural siltation rate.

The area of The Bulkhead Flats is geologically identical to the flats at the north end of Espiritu Santo Bay, immediately south of Pass Cavallo, Texas. Sediments are derived principally from Corpus Christi Bay and consist of both silt and mud deposited by natural action of wind waves and currents of the bay. The separation of this area from the Bird Island Basin by the Padre Island Causeway localizes and concentrates the deposition of bay sediments that would otherwise be distributed more uniformly southward.

The Causeway only amplifies this process, however. The Bulkhead Flats are a typical physiographic feature created where the competency and capacity of sediment-laden waters are reduced through velocity decrease.

Analyses of Sand Dune Migration. Analyses of the general trend of migration of sand dunes, particularly longitudinal dunes, provides a good indicator of the predominant direction of wind movements.

The direction of this trend may be taken as a logical alignment of a fish pass located in this semi-arid region in order to minimize the invasion of the pass by the shifting sands, as well as to enhance the water interchange through the pass.

From "Principles of Geology"[9], measurements of wind speed in dune areas indicate that sand motion begins when the average velocity reaches about 11 miles per hour. Above this approximate wind velocity, the wind stress should provide some assistance to water interchange through the pass, if orientation of the pass is coincident with the predominant wind movement. Also, longitudinal dunes form typically where wind is of constant direction and where topographic gaps, even wind-made ones, channel the sand.

The trend of such longitudinal dunes are shown by the hatch line arrows on Plate C. The trend varies from N42° W to N50° W with a modal trend of N46° W.

Sand banners, which are angular modifications of the simple longitudinal dune, are illustrated on Plate D, "The Hole Basin". The modal trend of the bisecting angle of the sand banners is N55° W, with angle of divergence of about 24° and trend of the north leg at N43° W.

Price[10] has reported on the banner complex (sand banners) in Kenedy County, with trends of the bisecting angle from N45° W to N55° W.

The modal trend of the longitudinal dunes is considered to be the more reliable index for the purpose, particularly since it is practically the same as the location (S45° E) of the predominate runway at Corpus Christi, which runway location is based on a detailed analysis of the available wind data.

Hence, it is concluded that the preferred orientation of any fish passes within the limits of the study area should be due northwest-southeast (S45° E). If variation of this preferred orientation is required by local conditions, it should be limited to somewhere between S40° E and S55° E.

The dune forms on Padre Island do not lend themselves to such forthright analysis due to complexity. It is presumed that the island dunes must be subject to frequent modification by storm and hurricane tides, hence, they have been omitted from these analyses.

<u>Geology of Drainage Area</u>. The surface geology of the watershed contributing fresh water inflow into the Upper Laguna Madre and Baffin Bay System consists principally of Sand Dunes, Beaumont Clay and Lissie Sand of Recent and Quaternary Age and of Goliad Sand of the Pliocene Epoch. There are insignificant areas of outcrops of Oakville Sandstone and Catahoula Tuff of Miocene Epoch in the upper portion.

See Figure 4, "Geology and Drainage Area".

The Beaumont Clay consists of impervious, nearly flat, gently tilted, clay and clay-loam prairie, with slight mounds and depressions. The area between Kingsville and Corpus Christi is extensively cultivated. Surface runoff is slow and subject to high evaporation losses.

The Lissie Sand forms a nearly featureless, gently sloping plain with broad, shallow stream valleys. The sandy-loam soils are only moderately pervious. The area is generally cleared pasture or covered with mesquite, chaparral and cactus.

The Goliad Sand consists of pervious sands with some sandy clay and caliche. The area is deeply dissected, used mostly for pasture, with scattering growth of mesquite and cactus. There is thick chaparral where the soil is thin.

Surface drainage from the southern portion of the watershed (Drainage Area C) from Hebbronville, Falfurrias, and Sarita has been effectively intercepted by invasion of eolian Sand Dunes. The sand is chiefly light-colored quartzose sand windborn inland from Padre Island. The sand dunes reach about elevations 15 to 35 feet on Padre Island and up to elevation 75 inland. There is no surface runoff from this Area C into the Laguna or Baffin Bay, except during extremely heavy rainfall. Generally, there is seepage flow through pervious sand over underlying impervious sand-clay. The area is characterized by many active-longitudinal sand dunes.

This sand sheet, in modified form, extends northward from about Falfurrias to Alice where it restricts, but does not intercept, the surface runoff from Drainage Area B. The sand dunes are generally weathered to conical shape and are stabilized by vegetation.

Hence, for the total watershed of 4 686 square miles, about 1 335 square miles are non-contributory to surface runoff due to active sand dunes, and about 1 575 square miles are somewhat restricted by the northern extension of the less active sand sheet. From this geology of the watershed located in a semi-arid region, comparatively very low surface runoff is to be expected.

Hydrology

The science of hydrology is applied to this study for the specific purpose of estimating the fresh water inflow and evaporation from the water surface, for use in determination of their effects on salinity in the Basins and related effects on tidal interchange.

Rainfall-Runoff Relations. There are no stream gaging records for the creeks that flow into the Baffin Bay System, hence, runoff or fresh water inflow must be estimated from the available rainfall records.

The relations of rainfall to measured runoff for three watersheds on the Mission, San Antonio and Frio Rivers in the general vicinity have been determined and the results are plotted in the upper left portion of Figure 5, "Relations of Rainfall, Runoff and Evaporation".

The Mission River watershed is located at the division line between semi-arid and dry sub-humid regions, with most of the area above

Refugio (643 sq. mi.) located on outcrops of Lissie and Goliad Sand. The geology and terrain are similar to that of the study area, except for the absence of drifting sand dunes.

The sub-watershed of the San Antonio River between Falls City and Goliad (1 847 square miles) is located in the dry sub-humid region, on outcrops of Goliad Sand, Lagarto Clay, Oakville Sandstone and Catahoula Tuff. This sub-watershed has similar geology but a higher proportion of rolling and hilly terrain than the study area.

The watershed of the Frio River near Derby (3 493 square miles) is located in the semi-arid region, same as the study area. The geology of the upper portion, above the Balcones Fault Zone, is completely dissimilar because of limestone formations. However, the U. S. Geological Survey reports that part to most of the headwaters flow enters limestone in the fault zone. A considerable portion of the area below the fault zone is outcrops of Carrizo and Queen City Sands, similar to the Goliad Sand. Hence, this watershed is considered most similar to a considerable portion of the study area, both being in the same climatic region, similar sandy formations and with the Balcones Fault intercepting runoff somewhat similar to the sand sheet over the southern portion of the study area.

From these comparisons, the annual runoff from Drainage Area A (See Figure 4) has been estimated from Curve A (See Figure 5) derived from the Mission and San Antonio. The runoff from Drainage Area B has been estimated from Curve B derived from Frio. Runoff from

Drainage Area C, once in 18 years, has been estimated as 50 per cent of Curve B. Runoff from Drainage Area D, once in 18 years, has been estimated as 50 per cent of Curve A.

An approximation for assumed uniform annual seepage inflow from Area E (narrow strip around the Laguna) has been made from seepage computations using a coefficient of permeability of 0. 01115 feet per minute for sand with effective size of 0. 15 mm and porosity of 34 per cent. After study of the topographic maps and trial computations, the calculations were simplified by using seepage hydraulic gradients of 5 feet per mile through 7. 5 feet of sand for 60 per cent of the shoreline, and gradient of 20 feet per mile for the remaining 40 per cent.

These annual estimates of runoff are considered reasonable except for the years 1953 and 1955, when excessive monthly rainfall occurred. To estimate runoff for these two years, the "Monthly Rainfall-Runoff Relations", shown on the lower-right portion of Figure 5, was developed from the Mission River Watershed.

It required at least 3 and sometimes 5 inches of monthly rainfall to produce any appreciable runoff. In using this curve in a semi-arid region, it should be considered that the monthly runoff may often be zero when the monthly rainfall is less than about 3 or 4 inches.

The average rainfall over the watershed for August 1953, was 11. 5 inches, slightly over half of the annual rainfall.

From the monthly rainfall, runoff relations shown on Figure 5, "Relations of Rainfall, Runoff and Evaporation", it is estimated that there was 2.65 inches of runoff from Area A and half that amount from Area B (Figure 4). The average rainfall over the watershed in September 1953 was 3.5 inches, which after such heavy August rain is estimated to yield 0.45 inches from Area A and half that amount from Area B.

The average rainfall over the watershed in September 1955, was 11.7 inches, again a little more than half the total annual rainfall. Similar use of the monthly rainfall-runoff curve indicates runoff of 2.8 inches from Area A and half that amount from Area B.

Fresh Water Inflow. The results of these estimates in inches are tabulated in Table II, "Rainfall - Runoff Upper Laguna Madre". The conversions of runoff in inches to acre feet of fresh water inflow into the system for the years 1940 to 1957 are tabulated in Table III, "Fresh Water Inflow - Acre Feet".

From an average annual rainfall of 22.7 inches over the watershed, the average annual fresh water inflow is estimated at 137 500 acre feet or about 0.55 inches of runoff from the total area of watershed. Thus, on the average, only about 2.4 per cent of the rainfall on the watershed appears as runoff and seepage inflow into the Baffin Bay System and the Upper Laguna Madre. The annual inflow varies from about 22 500 to 469 000 acre feet. The capacity of the complete system (between the Landcut and the Padre Island Causeway, including the Hole Basin and Baffin Bay System) is estimated at 431 000 acre feet. The average annual fresh water inflow of 137 500 acre feet is about 32 percent of the capacity.

Evaporation. The annual evaporation from the water surface in the Upper Laguna and Baffin Bay has been estimated as follows: average the B. P. I. pan evaporation from 1940 to 1957 at Beeville and Weslaco,[1] after applying an annual coefficient of 0.97 to convert from annual pan to gross reservoir evaporation; average the annual rainfall at Corpus Christi and Sarita, and deduct the annual rainfall from gross evaporation to determine net evaporation loss from the water surface in inches.

The net evaporation loss in inches converted to feet times a surface area of 165 000 acres (including sand flats) gives the annual net evaporation loss in acre feet. The results of these calculations are tabulated in Table IV, "Annual Net Evaporation Loss from Upper Laguna Madre and Baffin Bay System".

The average annual evaporation loss from 165 000 acres is estimated at 485 000 acre feet. This is greater than the total capacity of the system by about 1.1 times. If the evaporation should be estimated from the average of the low water surface area of 125 000 acres and area including sand flats of 165 000 acres, the average annual net evaporation loss would be estimated at 427 000 acre feet from 145 000 acres and be equal to 99 per cent of the capacity of the system.

The monthly reservoir evaporation is estimated to vary from the pan evaporation by coefficients ranging from 0.76 in April to 1.17 in November. After application of these monthly coefficients it is found that the monthly evaporation is consistently a percentage of the annual varying from about 4.5 per cent in January to about 13.5 per cent in

August. This monthly variation is illustrated in the upper right portion of Figure 5, "Relations of Rainfall, Runoff and Evaporation".

Fresh Water Inflow - Evaporation Relations. The annual differences and cumulative quantities in acre feet for estimated fresh water inflow and net evaporation losses from 1940 to 1957 are tabulated in Table V, "Annual Fresh Water Inflow - Evaporation Relations".

The average annual net evaporation loss less the average annual runoff or fresh water inflow is estimated at a net annual loss of about 347 500 acre feet. This annual water loss amounts to approximately 81 per cent of the total capacity of the system in the study area.

The annual and cumulative relations of fresh water inflow and evaporation are also illustrated on Figure 5. There is one year in 18 years that runoff exceeds evaporation, by 380 000 acre feet. The maximum annual evaporation less runoff is estimated at 861 000 acre feet, or about twice the capacity of the entire system. If evaporation is computed from the average surface area instead of all the sand flats, this maximum annual net loss still amounts to about 1.7 times the capacity.

The average annual difference between net evaporation loss and runoff amounts to a net average inflow of 480 cubic feet per second in excess of outflow which must come through the openings in the Padre Island Causeway and the Landcut to replace the evaporation loss. The estimated monthly net inflow over outflow of salt water ranges from 264 to 758 cfs. This maximum monthly rate amounts to 1 520 acre feet per day or about 0. 13 inch per day for the average surface area.

For the year of maximum net evaporation loss over runoff, an average inflow of salt water of about 1 190 cfs is required to replace evaporation. The monthly variation ranges from 655 to 1 880 cfs or a maximum of about 0. 31 inch per day over the average surface area.

Following is a summary tabulation of the various general relations between the rainfall, freshwater inflow and evaporation for the Upper Laguna Madre and Baffin Bay System:

SUMMARY OF THE
RAINFALL - FRESH WATER INFLOW -
EVAPORATION RELATIONS

Item	Unit	Minimum Annual	Maximum Annual	Average Annual
Rainfall on Watershed	Inches	13. 6	39. 5	22. 7
Runoff	Inches	0. 1	1. 9	0. 55
Rainfall on Water Surface	Inches	15. 5	41. 7	25. 2
Gross Evaporation - Water Surface	Inches	48. 1	82. 4	60. 4
Net Evaporation - Water Surface	Inches	6. 4	64. 2	35. 2
TOTAL RUNOFF	Ac. Ft.	22 500	469 000	137 500
*TOTAL NET EVAPORATION	Ac. Ft.	89 000	884 000	485 000
EVAPORATION LESS RUNOFF	Ac. Ft.	-380 000	861 500	347 500

*From Water Surface and Sand Flats Area of 165 000 acres.

Oceanography

The branches of the science of oceanography related to waves, currents and hurricanes are applied in this study for the specific purpose of making a qualitative analysis of the littoral transport within the limits of the study area. Admittedly, insofar as is known, these branches of the science (including extensive work by the Beach Erosion Board) have not yet been developed to a degree to permit good quantitative estimates of the littoral transport.

Littoral drift is the sand and shell material that is moved along the shoreline. Littoral transport is the longshore movement of sand and shell, largely by wave action. This movement of material causes passes to migrate, lengthen, and sand-up and for jettied navigation passes is the major cause of the usually necessary maintenance dredging.

Wave Energy. The best available data on normal wave distribution near the study area is the wave rose near Corpus Christi, shown on Plate A, "Environment of the Upper Laguna Madre". This rose, entitled, "Annual Rose of Wave Heights for 27°38.7'N - 97°03.5'W, March 1945 - December 1952" was reproduced from a report, dated April 1954, by A. H. Glenn and Associates to the Gulf Oil Corporation. Glenn, who is well known for reliable forecasts of waves in the Gulf, computed this wave rose by hindcast from wind observations made at the Corpus Christi Naval Air Station.

In calculating the annual resultant wave energy from this Corpus Christi wave rose, a correlation between wave height and wave period was developed from Table B-2, page B-14 of the Beach Erosion Board Technical Memorandum No. 85.[2]

This relationship was used with the wave energy or total wave work equation 14, page 18, of the Beach Erosion Board TM No. 42,[3] for calculation of the instantaneous wave energy as a function of wave height. Values of the variables in the energy equation were taken from Table D-1, Appendix D, of the Beach Erosion Board Technical Report No. 4[4].

With the various directions and heights of waves converted to wave energy, an annual resultant deep water wave energy vector was computed. For estimates of littoral transport this wave energy must be refracted into shallow water and the longshore component of wave energy determined.

The next step may be considered as an over-simplification in computations, but probably justified for a qualitative, not quantitative, analysis. In this step an imaginary solitary wave height with energy equal to the resultant deep water wave energy was determined.

This imaginary wave of 4.3 feet height (considerably greater than average wave height) could then be refracted into shallow water by use of the Refraction Template, Figure 17, page 32 of "Shore Protection Planning and Design".[4]

The results of this refraction of annual resultant wave energy into shallow water at the new Corpus Christi Pass and Yarborough Pass are illustrated on Figure 6, "Wave Energy and Littoral Transport". The longshore component, northward in both cases, is considerably stronger at Yarborough than Corpus Christi.

A similar process was then applied to separate grouping of waves northward and southward of normals to the shore lines at these two points. These are also shown on Figure 6.

Littoral Transport by Wave Energy. The longshore components of northward and southward wave energy were then converted to littoral transport by extrapolation and use of a graph showing "Relationship of Littoral Drift to Wave Energy", page 20, and Formula 16, page 21, of "A Study of Sand Movement at South Lake Worth Inlet, Florida."[3]

This gives at Yarborough an indicated annual northward littoral transport of 242 000 cubic yards at six foot depth and 96 000 cubic yards southward at six foot depth.

At Corpus Christi, the estimated annual northward littoral transport is indicated at 142 000 cubic yards at six foot depth and 112 000 cubic yards southward at six foot depth.

Subject to modification by hurricane waves and Gulf currents, it appears that normal wave action shifts the littoral transport almost equally northward and southward at Corpus Christi, but there is a definite net annual trend northward at Yarborough. There should be a greater amount of littoral transport to contend with at Yarborough than at Corpus Christi.

It may be mentioned that at depths greater than 6 feet the computed transport rapidly increases to the order of 1/2 million cubic yards annually, but extrapolation is so far beyond the experimental data, the figures can only serve to warn of increasing interception of drift with larger passes or longer jetties.

<u>Gulf Currents</u>. The data available on Gulf currents has been assembled for evaluation of possible effects of these currents on the littoral transport. The monthly pattern, strength and steadiness of the Gulf currents, as secured from the "Atlas of Pilot Charts",[5] are illustrated on Figure 7, "Gulf Currents".

Except for the December current of 2.03 feet per second, the currents as reported simply do not have the strength for appreciable transport of sand of median size of 0.15 mm found along the beach. This is generally verified by the lack of sand (clayey silt and silty clay) reported on the Gulf bottom out from the study area and beyond the bottom effects of waves (about the -60 foot bottom contour).

Another presentation of monthly currents, as developed from "Monthly Current Charts",[6] is shown on Plate A, "Environment of the Upper Laguna Madre". Again, the indicated currents are too weak for appreciable transport of sand.

Bullard (1942)[7] has called to attention the following quote from the U. S. Coast Pilot, 1936, page 42-43:

> "In about latitude 27° North, where the trend of the coast changes from southwest to southeast, a counter current is formed which attains a considerable velocity of rotation and has been called the whirlpool of the Gulf. Drift in the waters southeastward frequently go ashore abreast of this whirlpool".

The velocity and location of this whirlpool, or counter current, have not been defined. The approximate location might be suggested, as indicated by light dash lines on Figure 7.

Until these currents are definitely located and measured within the sand zone, it is surmised that for the study area where passes are being considered the major force for littoral transport must be the wave energy. It is likely that these Gulf currents reduce somewhat the northward shift of littoral transport, with corresponding increase in the southward shift - with respect to that computed from wave energy.

Bullard (1942)[7] has also traced a distinctive Rio Grande marker (heavy mineral basaltic hornblende and pyroxene) in the beach sands from the Rio Grande to about Latitude 27° North, where there is a sudden and drastic reduction in this marker. This is coincident with the gap in live sand dunes opposite the Hole Basin as well as the suggested counter current of the "Whirlpool of the Gulf".

There is a definite and rather rapid reduction in the northward longshore component of wave energy north of Latitude 27° as the coast line bends to the northeast. The concurrence of this rapid reduction in transporting power; with the quick reduction of the basaltic hornblende marker; the existence of the Hole Basin opposite the gap in the shifting sand dunes on Padre Island; and the counter currents of the suggested location of the whirlpool may well mark the northward limit of consistent predominant littoral transport northward from the Rio Grande Delta, and near the beginning of shifting nodal points in this transport.

Hurricanes. Although the Commission has indicated, definitely, that it is desired to omit expensive hurricane protection in fish pass design, consideration must be given in this study to the probable effects of hurricanes on the littoral transport as well as on pass construction.

The paths of record hurricanes, as shown on the Pilot Charts[5], and the maximum hurricane tides reported by the Beach Erosion Board are illustrated on Figure 8, "Hurricanes".

From "Hurricane Wave Statistics for the Gulf of Mexico"[8], the general direction and normal variation of the highest deep water waves to be anticipated from hurricanes off Brownsville are indicated graphically on Figure 6. This indicates, qualitatively, a strong southward longshore component of hurricane wave energy at Corpus Christi, but a slight northward component at Yarborough.

Inclusion of particularly high energy waves from the less frequent-more severe hurricanes indicates, generally, that the zone destined to ultimately receive the greater concentration of drift from the higher energy hurricane waves is from the Landcut to Green Hill Basin. This includes: all of the wide sand flats through the area of the Landcut; the Hole Basin; Murdock Basin; Boggy Slough Basin; and Green Hill Basin.

In consideration of the normal wave energy, Gulf currents, and higher energy hurricane waves; it is concluded that, for practical application in fish pass design, the shoreline of the Upper Laguna Madre is in a zone of shifting nodal points for predominant littoral transport (littoral transport alternating northward and southward). The predominant littoral transport is southwestward to the vicinity of the northerly end, and the predominant littoral transport is northward to the vicinity of the southern end. This trend is illustrated on Plate A, "Environment of Upper Laguna Madre".

The normal wave energy has the main effects on this transport. Over long periods of time, high energy hurricane waves may sometimes cause a predominant southward transport at Corpus Christi. The Gulf currents appear to have the least effect on the littoral transport.

Marine Biology

The development of fish passes and water interchange is for the improvement of the marine fisheries. The most vital connecting links and interrelationship between tidal hydraulics, water interchange and marine biology are grouped under this heading.

Salinities. Simmons[11] has provided a most valuable design criteria for use in the tidal hydraulic and water interchange analyses by indicating (verbally) that a maximum salinity of 45 parts per thousand (ppt) instead of about 80 ppt (maximum tested in the Upper Laguna Madre since completion of the Intracoastal Waterway) would be desirable in the Upper Laguna Madre. This design limit is reasonably substantiated by his referenced report on the Upper Laguna Madre.

The maximum, minimum and mean salinities measured in the years 1952 through 1955 by Simmons has been reproduced from his study and included for convenience of reference as Graph 3.

A more extensive simultaneous coverage of the area, including the land cut, was made by Humble Oil & Refining Company on August 13,

1948. The tests for chloride have been converted to salinity (ppt) and are shown on Graph 1.

Breuer[12] has published a summary of salinity tests in the Baffin Bay System from September 1951 to March 1953. Also, photostatic copies of all the detailed tests have been furnished by Breuer for use in this study.

Collier and Hedgpeth[13] have published the results of salinity tests in Upper Laguna Madre and Baffin Bay from July 1946 to October 1948. These are plotted on page 165 of the reference. Copies of the tests made during the same period in the Lower Laguna Madre have been made available by the Marine Laboratory at Rockport.

<u>Salinity Drops.</u> One particularly noticeable characteristic of the salinities is the often abrupt drop in the fall within one or two months. Collier and Hedgpeth[13] concluded in 1950 that runoff or fresh water inflow was inconsequential, usually, and that only the fall tides could produce these observed effects. On the other hand, Simmons[11] concluded in 1957 that salinity was in direct ratio to local rainfall, particularly torrential rainfall in September and October, and that the mixing of the spring and fall high tides was negligible and the tidal prism receded virtually intact.

In order to reconcile these differences of opinion, but more specifically to develop techniques and confidence in making forecasts of salinity and water interchange from possible improvements, the changes in salinities were estimated by use of the rainfall, runoff, evaporation and tidal hydraulic relations. These estimates were then compared with the recorded salinities.

The results of the estimates of the reduced salinities (salinity drops) for the falls of 1946, 1948, 1952, 1953 and 1955 are tabulated below:

Hindcast of *Salinity Drops

Year & Month	Average Salinity Tested Before Drop	Average Salinity Tested After Drop	Estimate of Reduced Salinities by Use of inflow, Evaporation & Tidal Relations	Per Cent of Drop Accounted For by Runoff
1946, Sept. -Oct.	62. 6	49	50. 5	89%
1948, Aug. -Sept.	70	59	61	82%
1952, Aug. -Sept.	65. 5	58. 8	58	86%
1953, Aug. -Sept.	75	32	38	86%
1955, Sept. -Oct.	60	35	33	108%

*Salinity expressed in parts per thousand (ppt)

For 1946, it was estimated from the monthly rainfall over the watershed that 80 per cent of the annual runoff occurred in September - October. Computation of the reduction due from fresh water inflow accounts for 89 per cent of the salinity drop.

For 1948, monthly rainfall distribution indicated about 85 per cent of annual runoff probably occurred in September and accounts for 82 per cent of the actual drop in salinity.

In 1952, the distribution of the salinity drops was very irregular, as shown on Graph 4, "Drop in Salinities Aug. -Sept. 1952". The maximum drops are in Alazon Bay and near the causeway. For this

In 1954 there was no particular September-October drop in the salinities when the fall tides were reported to cause the drops, but the rapidly rising salinity did level out during the fall of the year (See Graph 3). That year the mean salinity tested in the Upper Laguna Madre increased from 30 to 55 ppt. It is calculated, from the fresh water inflow-evaporation, that the mean salinity would have increased to about 70 ppt if there had been no tidal interchange during the year.

From page 147 of "The Oceans",[14] the following formula has been utilized to estimate the tidal interchange required to prevent the increase of salinity from 55, as tested, to 70 as estimated due from evaporation:

$$Ti = D \frac{Su}{Su - Si}$$

Ti = Total amount of inflow in given time
D = Gross Evaporation less rainfall on water surface less fresh water inflow

Si = Average Salinity of inflow

Su = Average Salinity of outflow

This formula applies to stationary conditions; hence, it is assumed that the salinity at end of the year is stable and that average salinity of inflow from Corpus Christi Bay is 26 ppt.

$$\text{So: } Ti = 680\,000 \times \frac{55}{55-26} = 1\,290\,000 \text{ Ac. Ft.}$$

This amount of annual inflow, equal to 1 785 cfs or 0. 34 inches per day over 125 000 acres, must be mixed throughout the Laguna Madre waters in order to limit the build up of salinities. This important requirement for mechanical mixing of the waters is not included in the formula; however, the amount appears reasonable for the 11 000 sq. ft. of opening at the Padre Island Causeway. Humble measured a mean tidal prism of 0.14 feet or 1.7 inches at Point of Rocks. The relation of mixed inflow (0.34 inches) to the mean tidal prism (1.7 inches) suggests a 20 per cent efficiency in tidal interchange and mixing.

It is concluded, from these hindcasts of salinity drops and of tidal interchange in 1954, that the appreciable and relatively sudden drops in salinity often noted in the fall are largely due to fresh water inflow and, also, that the salinity records indicated that the definitely restricted tidal interchange (including the fall tides) has a low efficiency in mixing and controlling salinities in Bird Island Basin and extremely low efficiency in the remainder of the basins. In other words, these computations support the relevant conclusions of Simmons[11].

Weighted Salinities. The term weighted salinities is applied to adjusted mean values of salinity based on the relative capacity or volume of the basin where the various tests were made. Some typical test runs have been converted to weighted salinities in order to evaluate the possible combined affects on salinity and water interchanges by the Intracoastal Waterway and the Padre Island Causeway.

Before the causeway construction, and up to the time of progress of the dredging on the waterway from Corpus Christi Bay to Murdock Basin, Collier and Hedgpeth[13] reported there was no perceptible effect on salinity relationships. This was before the causeway was constructed and prior to penetration of the land cut by the waterway.

Simmons[11] in 1957 reported:

> "Salinity prior to the dredging of the Intracoastal Canal reached 113.9 ppt. The highest salinity recorded after completion of this project was 79.0 ppt." - - - "The region particularly modified was that portion near Baffin Bay. The upper areas, however, were often less saline prior to dredging of the canal and to building of the earthfill causeway" - - - "When the highly saline water reached either the causeway or the landcut, it piled up; and literally bounced back against the fresher water" - - - "The causeway may have been responsible for more rapid than normal siltation and sedimentation".

The causeway was completed in 1950, with fill sections started April 13, 1949 on mainland and completed to Padre Island on September 30, 1949. The waterway was connected through the Landcut on June 14, 1949.

The highest salinity of 113.9 mentioned was tested in Murdock Basin (not in the Baffin Bay System) on August 12, 1948. The extremely high salinities originate from the Landcut area and the Hole Basin (See Graph 1) where evaporation is extremely high with relation to volume of water to dilute the salts.

The mean weighted salinity for Baffin Bay and Upper Laguna Madre on August 12, 1948, including Murdock Basin, was computed as 79.3 ppt. The mean weighted salinity of the Upper Laguna Madre in August, 1953 (when the maximum subsequent salinity was recorded) was computed as 75.8 ppt. This might indicate a slight improvement, but no salinity tests were made in August, 1953 in the Baffin Bay System or in Murdock and Boggy Slough Basin. In fact, the weighted salinity for the Upper Laguna Madre, exclusive of Murdock Basin, on August 12, 1948 was

72 in comparison with the weighted salinity of 75.8 in August, 1953.

From September 1951, to March 1953, when salinity tests were being made both in Baffin Bay and the Upper Laguna Madre, the maximum salinity recorded in Baffin Bay was 75 ppt, while the maximum in Upper Laguna Madre was 69 ppt. (but plotted on Graph 3 at about 63). The probabilities are that the maximum salinity in the Baffin Bay System was up to the usual 85, or more, when the maximum test of 79 was made in the Upper Laguna Madre.

For most of the time that the "often less saline" conditions were found in Bird Island Basin near the causeway,but before its construction, the runoff of the Nueces was over twice the normal and should have materially reduced salinities in Corpus Christi Bay. The salinities in this area, however reached 77 in August 1948 (before causeway) and 76.4 in August 1953 (after causeway).

From 1946 to 1948, all salinities above 89 and up to the quoted maximum of 113.9 were measured in Murdock Basin. Since 1949, when the waterway was completed through the Landcut, the maximum salinity reported was 63.8 but no measurements were made in this basin when the highest salinities were tested north of Murdock Basin.

It would, however, require only little water movement and interchange through and next to the Landcut to mix the low volume extremely high salinities in Murdock Basin with the adjacent high volume water.

It is believed that the dredging of the Intracoastal Waterway through the Landcut has practically eliminated these local, extremely high salinities near the Landcut. However, the statistical analyses by weighted salinities and other comparisons of available data do not reflect any other significant improvement nor decline in overall salinity and water interchange conditions from the combined affects of the Intracoastal Waterway and the Padre Island Causeway.

TIDAL HYDRAULICS

The development and modification of the science of tidal hydraulics for application to fish pass design is the most essential ingredient of this report.

Tides

For determination of the characteristics and differentials of the tides, five recording tide gages and two staff gages were set and operated in December, 1958 and January 1959. Representative data from five tide gages, operated by the Humble Oil and Refining Company in 1947, 1948 and 1949, provided valuable supplementary tidal data. See Plates B, C and D for location of these tide gages.

Recording tide gages, Hall Pier, Flat, Red, Baffin and Yarborough were located for determination of tidal differentials at various possible sites for passes. Staff gages North and South were located at the mainland end of the Padre Island Causeway to measure head loss due to the landfill portions of the causeway.

The Humble tide gages Flour Bluff, Point of Rocks, Riviera Beach, Coyote and Topo were located at the Bulkhead Flats, Baffin Bay, and just north and south of the Landcut.

Astronomical. Astronomical tides are caused by the combined effects of the moon and sun. The maximum north and south declination of the moon, called tropic tides, have the greatest effect on Texas Coastal tides. When the moon is near the equator, called equatorial tides, the declination of the moon has the minimum effect on Texas Coastal tides. See Figure 9, "Typical Tides and Currents".

The moon phases indicate when the gravity of the moon and sun are working together or in opposition. The maximum tidal force is with new and full moon. The minimum tidal force is with the first and third quarter.

The distance of the moon from the earth also has its effect on the tides. At perigee, closest to earth, the pull of gravity is greatest and at apogee, greatest distance from earth, this force is at a minimum.

By consideration of these relative maximum and minimum tidal producing forces, it has been possible to utilize the vast amount of Humble tidal data, and permit design of the fish passes from only one lunar month of tidal readings at the pass location.

Sampling of the Humble data for two or three day periods at times of various combinations of the tidal forces reveal, by hourly frequency analyses, that a combination of three maximums result in median tidal differentials about 152 per cent of long time median. A combination of three minimums shows median tidal differentials about 33 per cent of normal median. Weighted sampling of various combinations resulted in a median differential of 0.42, which is in agreement with the median differentials of about 0.42 computed from the full lunar month of tides sampled in December, 1958 and January, 1959.

Meteorological. Meteorological tides result from wind stresses and changing barometric pressures. With the sudden release or change of stress, seiches may form, which is essentially rocking back and forth of the water. The effect of wind set up is well illustrated by the relation of wind and tide level on the Humble Coyote and Topo gages. See "Wind Set Up at Landcut" on Figure 9.

These gages are on the north and south sides of the Landcut. After one to three days of steady, fresh to strong wind down the length of the lagoon, the amount of set up about equals predicted set up using the formula on page 52 of "Shore Protection Planning and Design."[4]

This formula indicates that wind set up increases with decreasing depth. Over the very flat slopes of the sand flats, the water literally crawls up the slope. This is well illustrated on Plate D, "The Hole Basin", showing areas covered by water due to wind set up from both strong north and southeast winds. This wind and tide data is also from the Humble Oil and Refining Company.

The sampling of tides for computing the tidal differentials were so made as to include, properly, the wind set up. Examination of the recording gage records indicate that in the shallow Upper Lagura Madre the seiches are simply too small in magnitude to have any significant effect on the tidal differentials.

<u>Differentials</u>. Hourly frequency analyses of the tidal differentials between the Gulf and Corpus Christi Bay, Boggy Slough Basin, and Murdock Basin have been made for a lunar month, about 29 days. Also, similar analyses have been made between Corpus Christi Bay and Bird Island Basin and for the head loss on the mainland end of the Padre

Island Causeway. The results are shown on Graphs 5 through 9 which are plots on probability by logarithmic charts.

For comparison, the median (50% of time) and 15 per cent of time tide differentials are stated value or greater are tabulated as follows:

Tide Differentials

Tide Gages	Median or 50% Value Feet	15% Value Feet
Bob Hall - Flat	0.44	0.94
Bob Hall - Baffin	0.42	0.95
Bob Hall - Yarborough	0.43	0.92
Flat - Red	0.24	0.46
Staff North - Staff South	0.14	0.27
Cedar Bayou - Winter	0.42	0.85
Cedar Bayou - Summer	0.37	0.75

The similar tide differentials from Gulf of Mexico to Mesquite Bay computed for winter and summer at Cedar Bayou are also listed for comparison. The summer values at Cedar Bayou were slightly less than the winter values, as expected due to northers. However, two of the winter values, at Upper Laguna Madre, are greater than the winter value at Cedar Bayou. In any event, the median value of the tidal differentials appears to be reasonably well established at about 0.42 feet. It is believed that this highly significant figure would not vary much even with hourly analyses of a full year of gage readings.

From the tidal differentials computed between Flat-Red, See Graph 8, and Staff North-Staff South, see Graph 9, the hydraulic head for tidal interchange across the Bulkhead flats, next to the mainland, is reduced about 42 per cent by that land fill section of the Padre Island Causeway.

Velocity Analyses

The basic design intent in sizing the pass is simply to develop a balance between the median energy of the tidal flow and the silting and erosion characteristics of the sand and shell in the littoral drift. The value of median energy or tidal differential is exceeded half the time, and half the time the recorded value is less than median. The sand and shell material has been sampled, tested and analyzed as follows:

Beach Profiles. Six beach profiles were taken, about evenly spaced within the limits of the study area where passes were to be considered. The location of these profiles are shown on Plates B and C. The sections are located near, and except in one case named after, triangulation stations shown on the base map. The plotted profiles and location of sand and shell samples are shown on Figure 10, "Beach Profiles".

Sand Analyses. The results of the gradation tests and analyses of the size and gradation of the sand and shell material are illustrated on Figure 11, "Sand Analyses".

The material at sections Crane, Hall Pier, Quail and Midwest (from Corpus Christi Bay to the northern portion of Green Hill Basin) is practically all fine sand. The median diameter at Crane and Hall Pier is above 0.15 mm, slightly increasing to the south with 0.16 mm at Quail and 0.165 mm at Midwest. The 84% and 16% size varies from about 0.11 mm to 0.21 mm, about the limits of fine sand. The 84% and 16% size is the diameter that 84% or 16% of the material is greater than.

The Coefficient of Sorting varies from about 1.17 to 1.25, indicating a well sorted beach sand. Skewness varies from 0.99 to 1.01, indicating the point of maximum sorting coincides with the median diameter. Well sorted means all the sand is about the same size. A skewness of less than one indicates an excess of coarse material, and greater than one indicates an excess of fine material - with respect to median.

The Union and Thunder sections show a drastic change to about 52% shell and 48% sand. Union is in the "Little Shell" area and Thunder is between "Little Shell" and "Big Shell". The median size at Union and Thunder are about the same, average of 0.38 mm with variation from 0.365 mm to 0.395 mm. The median size at these sections opposite Boggy Slough and Murdock Basins is about 2.5 times the median size of fine beach sand to the north. This increase in median size is highly significant in the velocity analyses and fish pass design.

The sand and shell is graded (considerable variation in sizes) instead of being well sorted as at the other sections. Union, with a skewness greater than 1, shows sorting on the fine side of the median. The mean diameter (average of 84% and 16% sizes) is considerably greater than the median diameter, 0.62 to 0.92 mm, instead of about 0.38 mm.

In order to determine whether to use the mean or median in the velocity analyses, further study was made of the hydraulic characteristics of the shell. The apparent specific gravity of various samples and sizes of the shell ranges from 2.7 to 2.86. To correct for the shape and specific gravity of the shell, measurement was made under the supervision of our engineers at the Commission's Marine Laboratory in Rockport, Texas of the fall velocity of various sieve fractions of shell in a large plastic cylinder. This fall velocity was converted to equivalent "sedimentation diameter" by use of the "Chart of Sedimentation Diameter versus Fall Velocity in Water" on page 781 of "Engineering Hydraulics"[15] by Rouse.

This materially reduces the hydraulic effective size of the shell graded by sieves above 0.5 mm, as shown on Figure 11 and noted as "an adjustment to equivalent sedimentation diameter". For the average of Thunder and Union and with this adjustment the mean diameter is 0.42 mm as compared with a median diameter of 0.38 mm. Hence, a diameter of 0.40 mm was used in this velocity formula to determine the desired median velocity for a pass in the shell area.

Design Velocities. The design velocities have been computed by Formula 15-5, page 398 of Fair & Geyer[16]. This formula for velocity is:

$$V = \frac{1.486}{n} r^{1/6} (1.65 k \frac{d}{304.8})^{1/2}$$

where:

V	=	Channel velocity in ft/sec for condition of entrainment function
n	=	Roughness coefficient
r	=	Hydraulic radius (area ÷ wetted perimeter)
k	=	Entrainment function
d	=	Diameter of particles - mm (or equivalent sedimentation diameter)

The entrainment function, k, was secured from the graph, "Analysis by Shields of the Entrainment Function" on page 790 of "Engineering Hydraulics"[15].

An n value of 0.025 and k values of 0.4 and 0.6 have been used for saltation (beginning of bed load movement) and for suspension, respectively. These two values of k give the upper and lower limits of median vecolicty desired in the pass.

At the present state of knowledge, it is considered that the best balance in design is to provide a pass of such size and length that the median velocity due to the tidal differentials, is equal to the computed velocity of saltation (beginning of bed load movement) for the material encountered in the beach or littoral drift at the site.

The significance of the various factors involved in these velocity analyses is illustrated in the following tabulation showing the relations between hydraulic radius (the hydraulic measure of depth of water in the pass), and design velocities for the fine sand (median diameter of 0.15 mm) and sand-shell (median diameter of 0.4 mm):

Relations of Hydraulic Radius
Design Velocity and Beach Material

Hydraulic Radius	Design Velocity - Ft. per Sec. Fine Sand Md = 0.15 mm	Sand and Shell Md - 0.4 mm
3	1.3	2.1
5	1.4	2.3
10	1.6	2.6
15	1.7	2.7
20	1.8	2.9
25	1.8	3.0

Water Interchange

It is evident, from the extremely high salinities, that the Upper Laguna Madre and the Baffin Bay System are literally starved for tidal water interchange with the Gulf. This is also true, to a lesser degree, for the entire system of connected bays and lagoons from Pass Cavallo to the Landcut, which are served by only one connection with the Gulf of Mexico, that is, Aransas Pass.

Tidal Flow Through Passes. The first approximation of degree of deficiency in Gulf tidal interchange and subsequent mechanical mixing may be computed by application of the following simple formula:

$$A = 0.185\,S$$

where:

A = Cross-sectional area of pass in square feet
S = Surface area of connected bays in acres

This formula indicates a general relation for this section of Coastal Texas of the size pass to the size of connected bays for reasonable potential development of tidal interchange. The formula has been developed: first, from "Stability of Coastal Inlets"[19] where the ratio of the area of gulf passes in square feet to the tidal prism in acre feet is 0.44; and second, by the tidal hydraulics developed in this study that indicates the reasonable potential for tidal prism in feet of depth is about equal to the median tidal differential, or 0.42 feet. The 0.44 times 0.42 gives the factor 0.185 used in this formula.

For the first approximation of the potential Gulf tidal interchange and subsequent interbasin mixing, it has been assumed that an ideal arrangement and size for Gulf passes, between Pass Cavallo and the Landcut would be as follows:

Hypothetical Location and
Size of Gulf Passes -
Between Pass Cavallo and Landcut

Assumed Pass Name	Main Bay System	Surface Area Acres S	Size of Pass in Square Feet A (A=0.185S)
Boggy Slough	Baffin	125,000	23,100
Corpus Christi	Corpus Christi	126,000	23,300
Mud Island	Aransas	127,000	23,500
Cedar Bayou	Mesquite	8,650	1,600
Panther Point	San Antonio	120,000	22,200
		Total Passes - Sq.Ft.	93,700
		Less Aransas Pass	44,000
		Deficiency - Sq.Ft.	49,700

Of course, with the millions of dollars invested in navigation and jetties at Aransas Pass, it must be considered as fixed. The size of Aransas Pass, 44,000 square feet between jetties, is only 2,800 sq.ft. deficient for potential development of water interchange of the adjacent Corpus Christi and Aransas Bay Systems, exclusive of the remaining systems.

The navigation branch of Aransas Pass has a size of about 20,800 square feet, indicating a deficiency of about 2,500 square feet for potential development of the Corpus Christi Bay System only. Hence, it appears that a Corpus Christi Fish Pass should have a size of at least 2,500 to 2,800 square feet to make up the apparent deficiency in water interchange for the Corpus Christi Bay System.

There then remains a deficiency of 23,100 square feet of pass, or passes, for potential development of Gulf water interchange into the Baffin Bay and Upper Laguna Madre System. This deficiency is now carried as a 100 per cent overburden on the Corpus Christi Bay System.

Basin Interchange. After introduction of the Gulf tidal water interchange through the pass there remains the distribution of the tidal prism by interbasin flow, usually through restricted sections. The profiles of the restricted sections between the various basins are shown on Figure 12, "Restricted Sections". The computed cross-sectional areas in square feet of these sections are also shown on this figure.

Usually, the velocities of flow through these restricted sections must be limited to about 0.5 to 1.0 foot per second, depending upon hydraulic radius and the small amount of hydraulic head remaining available after induction of flow through the pass.

Salinity Currents. Salinity currents, or density currents in the form of stratified flow or gravity underflows, must occur in the Upper Laguna Madre as a result of the horizontal and vertical gradients in salinity, which is a direct measure of density differences.

In "A Hydrographic and Chemical Survey of Corpus Christi Bay and Connecting Water Bodies"[17], it is reported on Page 20 that heavier salt water was moving from the Upper Laguna Madre into Corpus Christi Bay along the bottom at a velocity of 1.07 feet per second while the surface current was almost zero.

Simmons[11], Breuer[12], and Collier and Hedgpeth[13], have reported salinity tests which show wide ranges and variations in the horizontal and vertical salinity gradients in the Upper Laguna Madre and Baffin Bay. Salinity gradients simply indicates slope of the difference in unit weight of water in either direction.

From "Thermal Density Underflow Diversion, Kingston Steam Plant" and "Submerged Sluice Control of Stratified Flow",[18] the following modification of the normal Manning hydraulic equation has been developed to evaluate the probable effects of salinity currents on the present and future distribution of salinities and on water interchange:

$$V = \left(\frac{d_b - d_t}{d_b}\right)^{1/2} \frac{1.486}{n} r^{2/3} S^{1/2}$$

where:

V	=	Velocity of salinity current in feet per second
d_t	=	Density at top
d_b	=	Density at bottom
n	=	Roughness coefficient
r	=	Hydraulic radius, and here taken as depth of water in feet ÷ 4, in order to include the interface between the stratified flows in the length of wetted perimeter (normal r = area divided by wetted perimeter).
S	=	Slope of the density gradient in feet per foot determined from difference in horizontal density, or

$$S = \frac{D - \dfrac{D\,d_2}{d_1}}{L}$$

where:

D	=	Depth of water in feet
d_1	=	Average upstream density
d_2	=	Average downstream density
L	=	Length of reach in feet

Various vertical salinity gradients were often measured at 0.5 to 3 ppt from top to bottom, and sometimes differentials of 6 to 14 ppt. Horizontal salinity gradients of 10 ppt in 5 to 10 miles were often measured during times of most rapid changes in salinity.

Application of this formula to various probable combinations of vertical and horizontal salinity gradients over long distances indicate salinity currents of about 0.003 ft. per sec. to 0.04 ft. per sec. This is very slow but does suggest that over periods of 4.5 to 6 months these salinity currents in a wide bay probably play an important part in providing slow but sure mechanical mixing, and in controlling of horizontal salinity gradients.

For instance, for a wide shallow basin with a vertical salinity gradient of 2.5 ppt and a horizontal salinity gradient of about 10 ppt in 7.5 miles, the flow from salinity currents is computed to be about 30 per cent of the normal inflow required to replace evaporation losses. In other words, here about 30 per cent of the interchange or mechanical mixing might be attributed to salinity currents.

This means that if it is desired to take advantage of salinity currents, new water interchange must be introduced near Baffin Bay instead of the extremely long distance through the Bulkhead Flats.

For the extremely long channel of the Intracoastal Waterways through the Landcut, about 125,000 feet, or 23.7 miles, where horizontal salinity gradients of 20 ppt have been often measured, salinity currents might account for about 1 to 5 per cent of the flow, as compared with normal flow from wind set up differentials of 0.3 to 1.5 feet.

However, for short reaches of channels and high salinity gradients flowing into a large bay or gulf, the salinity currents may reach critical velocities which might be approximately computed by the following normal critical velocity formula in which the acceleration of gravity is reduced by the term $\frac{d_b - d_t}{d_b}$

$$Vcr = \left(\frac{2}{3} g \frac{d_b - d_t}{d_b} H\right)^{1/2}$$

where:

Vcr	=	Critical velocity of the salinity current in feet per second
g	=	Acceleration of gravity, 32.2
d_t	=	Density at top
d_b	=	Density at bottom
H	=	Depth of density flow upstream from point critical flow can develop, here taken as one-half the water depth.

When the bottom current of 1.07 ft. per sec. with top velocity of zero was measured in October, 1952, between Upper Laguna Madre and Corpus Christi Bay,[17] the vertical salinity gradient was about 10 ppt. Computation of critical salinity current flow by the above formula with vertical gradient of 10 ppt yields a velocity of 1.06 ft. per sec. Here, it appears that the measurement was made at a time when the salinity current was at critical velocity.

Calculations of salinity currents between the extreme conditions of critical velocity and pure density gradients, may be made by application of backwater curves on the interface of the stratified flow. An approximation of the interface gradient may be on the order of about 0.2 of the depth divided by the length of reach.

<u>Salinity Control.</u> Under the heading of "Salinity Drops", it was mentioned that the formula, from page 147 of "The Oceans"[14], did not

include the important requirement for mechanical mixing in estimating tidal interchange for given stable conditions. Therefore, in order to apply the formula to the subject study, it has been modified as follows:

$$Ti = \frac{D \dfrac{Su}{Su-Si}}{E}$$

where:

E	=	Efficiency of Mechanical Mixing in per cent
Ti	=	Total amount of inflow in given time
D	=	Gross evaporation less rainfall on water surface less fresh water inflow
Si	=	Average salinity of inflow
Su	=	Average salinity of outflow

Efficiency of mechanical mixing here means that portion of the tidal inflow that is well mixed with the Lagoon waters before returning as outflow.

From the various computations using the formulas developed herein for salinity currents, and by application of this modified formula to the reported salinities as weighted and estimates of probable inflow at the time; a probable range of the factor E or efficiency of mechanical mixing, for the study area has been estimated.

The value of E, efficiency of mechanical mixing, is tentatively estimated for application to this particular project at 20 per cent for stable salinity of 40 ppt and increasing at the rate of 0.5 per cent per 1.0 ppt increase on desired stable salinity condition up to a value of 40 per cent at a salinity of 80 ppt. This sliding scale is considered to be due to increasing effects of salinity currents as a factor in mechanical mixing as the salinity gradients increase.

IMPROVEMENTS CONSIDERED

Passes and Water Interchange Considered

An illustration of the various possible locations for passes that were considered and the general extent of restricted sections between basins, that were studied for possible water interchange improvements, is shown on Figure 13, "Passes and Water Interchange Considered".

Corpus Christi Fish Pass. The "New Corpus Christi Fish Pass" is the best location found, within the limits of the study area, for a pass. This pass, hereafter named "Corpus Christi Fish Pass", is recommended for construction at an estimated cost of 1.3 million dollars. It is proposed as a fish pass near a center of dense population and to provide that portion of Gulf of Mexico water interchange that will be needed, in connection with another pass, to flow through Corpus Christi Bay into the Upper Laguna Madre for desired salinity control. It will, however, have no practical beneficial effects on salinity of the Upper Laguna Madre until a large Gulf water interchange pass is opened directly between the Gulf of Mexico and the Upper Laguna Madre.

Old Corpus Christi Fish Pass. It was found that the expanse of very shallow water along the location of the "Old Corpus Christi Fish Pass" is a snare and delusion in its appearance as possibly offering a good site for a pass. The water is too shallow to be of any significant hydraulic value. The alignment does not meet the criteria for orientation of the pass. The greater length required a considerably larger and more costly pass in comparison with the proposed pass. This location is not recommended.

Green Hill Fish Pass. In view of the relatively large pass evidently required for direct water interchange, between the Gulf of Mexico and the entire Upper Laguna Madre including the Baffin Bay System, an attempt was made to develop a nominal size pass at "Green Hill Fish Pass". This pass was tentatively designed to operate with "Corpus Christi Fish Pass" for improvement of Bird Island and Green Hill Basins, to the exclusion of the remaining basins and Baffin Bay. This scheme was: overwhelmed with excessive salinity due to inadequate gulf water interchange in dry years; fighting a desperate battle with a sea of shifting sand dunes; requiring high cost, inefficient water interchange improvements between Corpus Christi Bay and Bird Island Basin; and was finally sunk by an estimated cost of about 3.2 million dollars - too high a cost in view of its questionable factors.

Boggy Slough and Murdock Fish Passes. "Boggy Slough Fish Pass" was finally selected as the best and most economical pass for Upper Laguna Madre and Baffin Bay, but it necessarily must be large enough to provide the minimum requirements for gulf water interchange. This pass is estimated at about 3.1 million dollars in comparison with approximately 3.33 million dollars for an equivalent "Murdock Fish Pass". Although Murdock Pass is shorter, almost five million cubic yards of dredging would be required to develop proper water interchange out of the restricted Murdock Basin into the remainder of the basins. With the proposed "Boggy Slough Fish Pass", the restricted sections between basins are, generally, just barely sufficient to permit the large, but still relatively limited water interchange. This "Boggy Slough Fish Pass" is recommended primarily as a Gulf water interchange pass, designed to develop only about one-half of the potential interchange and limit salinities to about 50 ppt instead of the desired 45 ppt (present salinities reach as high as 85 ppt). This limit on salinities is indicated with certain reservations hereinafter stated.

Yarborough Fish Pass. This pass was abandoned for consideration in comparison with "Murdock Fish Pass", because of poor location with respect to invading shallow sands, greater length and its improper orientation.

With the two passes as proposed, it was found that no further improvements for water interchange through restricted sections should be necessary, except for minor spoil removal to improve circulation within Murdock Basin.

PROPOSED IMPROVEMENTS

General Features

The descriptive elements of the two proposed fish passes as located and shown on Plates B and C, are tabulated as follows:

Proposed Fish Passes

Description	Corpus Christi Fish Pass	Boggy Slough Fish Pass
Length - feet	10 000	15 000
Area - square feet	3 000	10 750
Depth - feet	10	25
Bottom width - feet	250	330
Top width - feet	350	530
Width - depth ratio	35	21
Side slopes	5:1	4:1
Median discharge - cfs	4 860	31 200
Median tidal prism - ft	0. 04	0. 21
Water interchange - million ac. ft. /yr.	1. 8	13
Salinity Control	-	50
Stabilization Works - feet	1 200	1 300
Gulf Section - feet	450	800
Land Section - feet	750	500
Estimated Cost - million dollars	1. 3	3. 1

The sizes of the passes are proportioned, particularly depth, with the design intention of inducing natural operation with a minimum of maintenance. The ideal fish pass operation is considered to be as follows:

(1) The beach material, which is moved by wave action is, during inflow through the pass, dropped largely at or near the Gulf outlet with a minimum amount of material carried through the pass to build bars near the bay inlet and lengthen the pass;

(2) During outflow, the material deposited near the Gulf outlet is carried back out to the Gulf because, as the Gulf bar builds up, the outflow velocity is increased and the velocity required to move the material is decreased. This is inconsistent with the requirements for navigation passes, where depth across the bar must be maintained.

The area (cross section in square feet) of the passes is proportioned to satisfy the minimum requirements of the Upper Laguna Madre and Baffin Bay Systems with urgently needed Gulf water interchange in order to reduce the extremely high salinities to tolerable levels. It is estimated that, during high evaporation-low fresh water inflow years, and with both passes (but mainly with Boggy Slough), the salinities may be reduced from present maximums (weighted by basins) of about 85 ppt to about 50 ppt. Higher salinities must be expected in The Hole Basin, in shallow waters on and density flows off the Landcut, and the upper shallow reaches of the Baffin Bay System. During normal years, it is computed that the weighted salinities may be reduced to less than 45 ppt.

Stabilization Works, see Figure 14, are proposed at the Gulf outlets to: (1) provide training walls and wave breakers where the wave energy in the surf must be converted to channel flow; (2) prevent migration of the Gulf outlet, which may tend to move either southward or northward depending on direction of wave attack from day to day and season to season; (3) control the reach of the pass that operates as an alternating siltation and erosion basin with inflow and outflow of the tidal waters; and (4) control the design depth of the pass during times of infrequent, higher tidal differentials.

The usual granite riprap jetties, of similar length and with hurricane protection included in the design, would cost about 1.5 million dollars for the Corpus Christi Pass, and some more at Boggy Slough. Such "jetties" have been converted to "Stabilization Works", estimated to cost about 0.5 million dollars, by three major modifications and developments. These are: (1) omission in the design of protection against hurricane waves and forces; (2) development of special sections of prestressed concrete bulkhead panels and cross wave breakers, used in conjunction with a nominal amount of riprap; and (3) combining the use of local, lower cost and low-quality rock to support the higher cost cap rocks of granite.

The local rock in mind is a coquina limestone (shells bound largely with calcium carbonate) usually in fairly thin layers and only a very small portion of the various rocks and reefs consist of the possibly usable stone under the granite riprap. Extensive core boring explorations and tests of the rocks would have to be made to substantiate the present belief that this local stone may be so used. If it cannot, precast concrete blocks or other materials would have to be considered at slightly higher costs.

Corpus Christi Fish Pass. The preliminary design and general layout of the proposed "Corpus Christi Fish Pass", with its Stabilization Works, are illustrated on Figure 14.

There are a scattering of live sand dunes in the immediate vicinity of the proposed location. However, with the orientation of the pass aligned with the predominate sand drift and with a nominal amount of dune stabilization, the amount or rates of dune invasion should not be serious. Also, when the rate of sand invasion is not too fast, the velocities for about 25 per cent of the time in the pass are computed to be able to hold in suspension the sand blown into the pass by the wind and sweep it out of the pass.

A bridge over the pass at the County Road to Port Aransas is estimated on the basis of a two-lane concrete bridge on concrete piling and 455 feet long, with end bents protected. The elevation of bridge over the pass is estimated at about 12 feet, to compensate for waves coming through the pass at about the time the remaining lower but protected sections of road would be inundated by tide. A center, removable section of lightweight concrete or steel that may be removed by barge, is included in the estimate to allow possible passage of maintenance dredge.

Such a bridge would provide considerable improvement over existing conditions; hence, the possiblities of securing partial to complete financing of the bridge by the County might well be investigated by the Commission.

A portion of the spoil from the dredging will be used to form a dune barrier between the land ends of the Stabilization Works, across the flats, to adjacent natural dune barriers.

The question may arise as to whether this pass might be detrimental to desired flow through the navigation channel at Aransas Pass. Even without the flow from Corpus Christi Bay to Upper Laguna Madre, the branch of Aransas Pass to the Corpus Christi Bay System is approximately computed to be 2 500 square feet deficient of the area needed for potential development of median tidal prism. The area of the proposed Corpus Christi Fish Pass is only 3 000 square feet, or about 14 per cent of the Corpus Christi Bay branch and only approximately 7 per cent of the area of Aransas Pass between the jetties.

In addition, this Fish Pass is sized just to handle the natural interchange flow between Corpus Christi Bay to Bird Island Basin. Further, Boggy Slough Fish Pass should relieve Aransas Pass of a considerable burden of excess inflow over outflow due to high evaporation losses and could, conceivably, result in a slight improvement of flow conditions at Aransas Pass.

In any event, the calculations indicate no ill effects to navigation. Also, to allay any fears that Corpus Christi Fish Pass may increase in size and rob Aransas Pass of desired flow, there is a sill included in the Stabilization Works. This sill, however, is otherwise justified.

Boggy Slough Fish Pass. The general location and layout of this pass is indicated on Plate C. The preliminary design features of this pass and its stabilization works are similar to, but larger than, the preliminary plans shown on Figure 14 for the "Proposed Corpus Christi Fish Pass."

This pass might better be called a large Gulf water interchange pass than just a fish pass. But frankly, the pass as proposed has been relocated, redesigned and modified several times toward the end of developing the smallest pass that could be dared to be offered as showing reasonable possibilities of satisfactory tidal operation and meeting the water interchange requirements.

There is the natural question: "How can a pass in this area be expected to even approach satisfactory operation in view of the ill-fated Yarborough Fish Pass?" This question can best be answered by the following tabulation of a few of the deficiencies of the latter as computed by the formulas (since developed and used on the proposed Boggy Slough Fish Pass).

Deficiencies of the
Old Yarborough Fish Pass

Description of Comparative Item	Proposed Boggy Slough Fish Pass (1)	Old Yarborough Fish Pass (2)	Ratio of Proposed Boggy Slough to Yarborough
Median Velocity - ft/sec	2.9	1.0	2.9
Depth - feet	25	5	5
Area - Sq. Ft.	10 750	450	24
Median Flow - cfs	31 200	450	70

The large deficiency in median velocity indicates that the pass was destined to close very rapidly, as it did. A flow 70 times greater than that estimated to have been supplied for a few days by the Old Yarborough Fish Pass is now computed to be about the minimum requirements for water interchange with the proposed Boggy Slough Fish Pass.

Fortunately, by using the extreme easterly variation considered allowable in orientation, S55° E, from the preferred of S45° E, the deeper part of Boggy Slough Basin is connected with the Gulf without being dangerously close to present shifting sand dunes.

The preliminary design includes considerable excavation in the shallow edge of the basin to make a much needed reduction in the effective hydraulic length of the pass, from 16 500 to 15 000 feet. There are two, branching, underwater channels from the basin end of the pass, connecting with the Intracoastal Waterway. These are designed, primarily, to intercept the bottom, denser, salinity currents and transport these waters of higher salinity to the Gulf. The secondary function of these branches is to insure proper distribution of inflow and outflow of the tidal water interchange.

It is contemplated, in the preliminary estimate of cost, that at least a one-way bridge will be required to cross the proposed pass. A single lane concrete bridge, with provision for possible future widening to two lanes, and with a lightweight, precast, removable span for passage of maintenance dredge is provided. This span may be removed by barge after placing the barge under the bridge and jacking up the removable span.

A sill is also provided near the Gulf outlet of this pass, for the same reasons as outlined for the Corpus Christi Fish Pass.

Proposed Water Interchange Improvements

There are several restricted sections between basins that are computed to be barely sufficient to permit proper interbasin-water-interchange with the proposed development, so no further improvements between basins are recommended.

However, circulation of water within Murdock Basin is very restricted by the continuous spoil bank of the Intracoastal Waterway, hence, it is proposed to remove two sections of spoil bank as shown on Plate C.

The Hole Basin remains as a very shallow, almost completely isolated remnant of a forme r basin. While the various other basins were being tested for salinities, at various intervals in the past, there appears to be no record of salinity tests in The Hole.

Also, the interest of the Commission and its marine biologist in possible further development in this remnant is not known at present. Hence, it is suggested that further consideration of The Hole Basin be deferred to the future. After completion of the Boggy Slough Fish Pass, and some operation time to allow development of stable salinity conditions, the marine biologist might then test this basin and report to the Commission as to any needs for improvement in water interchange.

Summary of Cost Estimates

Following is a summary of the preliminary cost estimates for the proposed "Corpus Christi Fish Pass", "Boggy Slough Fish Pass", and removal of spoil banks in Murdock Basin. The estimated cost of the removal of spoil banks, about $73 000, is included in the estimate for Boggy Slough Fish Pass.

Estimate Summary

Item	Corpus Christi Fish Pass	Boggy Slough Fish Pass
Dredging	$ 432 000	$ 1 852 900
Stabilization Works	520 125	660 090
Bridge	120 575	91 425
Dune Stabilization	10 675	-
	$ 1 083 375	$ 2 604 415
Plus Contingencies & Engineering	216 675	520 883
Total Estimated Cost	$ 1 300 050	$ 3 125 298

The following sheet shows the detail breakdown of the preliminary quantities and cost estimate.

PRELIMINARY ESTIMATE OF PROPOSED CORPUS CHRISTI FISH PASS 10' x 250' PASS

Item	Description	Quantity	Unit	Unit Price	Amount
1	Dredging	1 600 000	cy	$ 0.27	$ 432 000
2	Granite Riprap	6 600	cy	23.00	151 800
3	Local Coquina Limestone Riprap	5 000	cy	12.00	60 000
4	Prestressed Concrete Bulk-head & Wave Breakers	2 490	lf	110.00	273 900
5	Sill - Steel Sheet Piling	405	lf	85.00	34 425
6*	Bridge	455	lf	265.00	120 575
7	Dune Barrier Stabilization	42 700	sy	0.25	10 675
					$1 083 375
	Plus Contingencies & Engr.				216 675
	Total Estimated Cost				$1 300 050

PRELIMINARY ESTIMATE OF PROPOSED BOGGY SLOUGH FISH PASS 25' x 330' PASS

Item	Description	Quantity	Unit	Unit Price	Amount
1	Dredging				
	a) Pass Channel	6 878 200	cy	$ 0.20	$1 375 640
	b) Bay Mouth	1 496 800	cy	0.20	299 360
	c) Spoil Removal - (Murdock Basin)	364 800	cy	0.20	72 960
	d) Interchange Channels (150 x 14)	524 700	cy	0.20	104 940
2	Granite Riprap	9 800	cy	23.00	225 400
3	Local Coquina Limestone Riprap	7 500	cy	12.00	90 000
4	Prestressed Concrete Bulkhead & Wave Breakers (500' Inland-800' Gulfward)	2 690	lf	110.00	295 900
5	Sill-Steel Sheet Piling	574	lf	85.00	48 790
6	Bridge-One lane with provision for widening to two lanes (18-20' spans, 1-35' span)	575	lf	159.00	91 425
					$2 604 415
	Plus Contingencies & Engr.				520 883
	Total Estimated Cost				$3 125 298

*May be financed by other agencies

NOTE: Right-of-way costs are not included

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and brief summary of recommendations are enumerated below for convenience in review of this rather exhaustive development report.

1. The Upper Laguna Madre and the connected Baffin Bay System, located south of Corpus Christi along Coastal Texas (see Plate A), is in a semi-arid region, and has limited fresh water inflow, which is greatly exceeded in quantity by the evaporation from the water surface.

2. The entire system has no direct connection with the Gulf of Mexico, and only very restricted connection with Corpus Christi Bay to the north and by the Intracoastal Waterway through the Landcut to the Lower Laguna Madre.

3. Excess evaporation and restricted water interchange result in extreme salinities up to about 85 parts per thousand, which it is desired to reduce to about 45 parts per thousand for the benefit of the fisheries.

4. It is found that the study area is the "home" of littoral drift. That is, wave action moves the beach and nearshore sands from both the northeast and the south to accumulate in the area. Here, it both builds the beach gulfward and is blown by the prevailing southeast winds across Padre Island into the Lagoon to cause extensive development of sand and mud flats. With this invasion of sand, the Lagoon has developed restricted sections, separating it into several connected basins.

5. The deposition of sand into the Lagoon is, however, relatively slow and it is found that many years of life undoubtedly remain in the old Lagoon.

6. There has been considerable speculation as to whether the construction of the Padre Island Causeway, mostly of landfill sections, has seriously and further restricted water interchange. Also, it has been hoped that construction of the Intracoastal Waterway would greatly relieve the high salinity conditions. Careful check of the salinity and flow conditions, both before and after the completion of these projects, reveal no appreciable significant changes, except for some redistribution of extremely high salinity-low volume waters by the canal through the Landcut. The added restrictions of the landfilled sections of the causeway and spoil banks have approximately offset the added benefits of the Intracoastal Canal.

7. Wind set-up of the water surface in the shallow lagoon causes well over half the variation in water levels, with the true tidal changes merely reflecting about three day averages of mean daily Gulf level, due to the very restricted connections at the north and south ends.

8. It is found, however, that salinity currents, or density flows, must assist the wind driven currents and restricted tidal flow in slowly mixing the inflow with the highly saline waters. Formulas are developed to evaluate, approximately, the effects of these salinity currents.

9. With each cycle of inflow and outflow of the Gulf waters, only a portion of the volume of inflow is thoroughly mixed with Lagoon waters

to control salinities. This efficiency is estimated for the Lagoon, and formula modified for estimating inflow and outflow required for desired salinity control.

10. Analyses of the hourly tidal differentials reveal a highly significant figure of about 0.42 feet for median differentials in level between the Gulf of Mexico and Lagoon or Bays. Half the time the median is greater, and half the time the median is less than measured differencies in water level. This figure is an important tool in design of the passes. It is also considered to indicate the potential development of median tidal prism (rise and fall of bay water level from tidal inflow and outflow - not wind set-up). A formula is developed to use this figure for first approximate estimate of size of pass.

11. From the size of the sand and shell along the beach, its erosion and silting characteristics are estimated. The pass is then sized to balance the forces of velocity of flow in the pass, as nearly as possible, to the forces causing erosion or allowing siltation. It is the design intent to develop passes, as nearly as possible by use of the tools supplied by present knowledge, to operate naturally under average conditions.

12. Many possible passes have been studied (see Figure 13) and systematically eliminated or developed, which resulted in the recommendation of the construction of two passes within the limits of the study area.

13. Proposed Corpus Christi Fish Pass (located in southeast corner of Corpus Christi Bay, see Plate B), is designed primarily as a fish pass, but in addition is designed to supply about 14 per cent of the total water interchange, in operation with the proposed Boggy Slough Fish Pass. Alone, this Corpus Christi pass will afford no appreciable improvement to salinities in Laguna Madre, but in conjunction with Boggy Slough Pass, it contributes important salinity control to Bird Island Basin.

14. The Boggy Slough Fish Pass (located opposite Baffin Bay, see Plate C), is proposed, primarily, as the main gulf water interchange pass and is computed to be the minimum size pass to: first, meet tidal hydraulic design criteria; and second; control salinities to approximate maximums of about 50 ppt (except probably greater near Landcut and in upper shallows of Baffin Bay). The combined passes develop only about one-half the estimated potential tidal prism for the Upper Laguna Madre and Baffin Bay System. The construction cost of the project would have to be materially increased in order to achieve the desired maximum of 45 ppt.

15. Except for some minor spoil bank removal required in Murdock Basin, for circulation in that basin, and with the various basins presently branching three directions from the inflow at Boggy Slough, the restricted sections between basins are found by the computations, sometimes just barely, to allow sufficient basin-water interchange for the proposed 50 per cent development of potential tidal prism.

16. Fortunately, the usual vast expanse of shifting sand dunes pose no serious, immediate threat to the two locations as finally selected.

17. Bridges, with lightweight, removable center sections, are estimated at each pass. The one at Corpus Christi pass is two-way and consideration might be given to financing of this bridge by others. The bridge at Boggy Slough is one-way, but may readily be expanded to two-way in the future.

18. Stabilization Works for the Gulf outlets of the passes (see Figure 14) is provided at about one-third the cost of usual granite jetties by: (1) omission of hurricane protection; (2) use of prestressed concrete bulkhead panels and wavebreakers, specifically designed for use with minimum quantities of granite riprap; and (3) possible use of local rock to support the more exposed cap rocks of granite.

19. The recommended Corpus Christi Fish Pass is estimated to cost about 1. 3 million dollars, including contingencies and engineering, and the bridge that might be financed (entirely or partly) by others, but exclusive of right-of-way costs.

20. The recommended Boggy Slough Fish Pass (a large water interchange pass) is estimated to cost about 3. 1 million dollars, including contingencies and engineering and the minor spoil removal for circulation in Murdock Basin, but exclusive of right-of-way costs.

21. Priority of construction is deferred completely to the choice of the Commission with these comments: (1) Corpus Christi Fish Pass, alone, will be a good fish pass but provide no significant relief

to high salinities in the Upper Laguna Madre and Baffin Bay System; (2) Boggy Slough Fish Pass, alone, is computed to be a little deficient in water interchange but is estimated to supply sufficient to solve the basic problem of hypersalinity; and (3) the operation of both passes in conjunction are computed to complete the water interchange and circulation up to the designed level of control between Corpus Christi Bay and the south part of Murdock Basin.

22. Inasmuch as the two fish pass projects recommended herein are based upon actual field data and design calculations and are believed to be the minimum required for the designed results, it is recommended that each of the two separate projects be constructed essentially as recommended herein, or not be constructed at all. Either one of the projects could, however, be constructed without the other, although both should eventually be constructed inasmuch as they supplement each other in improving the Bird Island Basin area.

23. This development report culminates a seven year search for an acceptable design procedure for construction and operation of fish passes along Coastal Texas. There remains, as yet unaccomplished, the construction of a fish pass designed in accordance with criteria and formula developed herein. From such a pass, after thorough scientific check of its behavior, must come the inevitable adjustments of the design procedure and criteria.

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TABLES & GRAPHS

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FOR

TABLES AND GRAPHS

TABLE I

BASIN AREAS, VOLUMES AND DEPTHS

Bay or Basin	Area at Low Water Sq.Mi.	Area at Low Water Acres	Total Area Incl. Sand Flats Sq.Mi.	Total Area Incl. Sand Flats Acres	Vol. 1000 A/F	Max. Depth Feet	Avg. Depth Feet
1) Nueces			30.4	19 456	46.0	6.0	2.3
2) Corpus Christi			150.0	96 000	993.0	15.5	10.4
3) Redfish			16.8	10 752	16.0	5.0	1.4
TOTAL			197.2	126 208	1 055.0		
4) Penascal Basin	17.9	11 489	18.5	11 869	63.9	8.0	5.6
5) Baffin Basin	32.1	20 554	32.2	20 571	115.8	8.0	5.6
6) Alazan Basin	20.6	13 180	29.3	18 737	34.3	6.0	2.6
7) Cayo Del Infier-nillo	1.2	738	3.9	2 512	0.37	1.0	0.5
8) Cayo Del Grullo	10.9	6 972	15.8	10 105	17.11	6.0	2.5
9) Laguna Salado	4.5	2 861	5.1	3 284	6.25	6.0	2.2
TOTAL BAFFIN BAY SYSTEM	87.2	55 794	104.8	67 078	237.73		
TOTAL BAFFIN BAY SYSTEM LESS PENASCAL BASIN	69.3	44 305	86.3	55 209	173.83		
10) Bulkhead Flats	8.3	5 314	17.5	11 214	7.54	7.0	1.4
11) Bird Island Basin	47.2	30 241	55.0	35 214	72.71	6.0	2.4
12) Green Hill Basin	12.5	7 993	14.6	9 315	31.72	7.0	4.0
13) Boggy Slough Bsn.	12.3	7 853	18.9	12 077	33.21	10.0	4.2
14) Murdock Basin	15.6	10 024	23.8	15 207	43.9	9.0	4.4
15) Hole Basin	21.0	13 477	41.3	26 450	11.4	1.6	0.9
TOTAL UPPER LAGUNA MADRE	116.9	74 902	171.1	109 477	200.48		
TOTAL UPPER LAGUNA MADRE LESS BULKHEAD FLATS	108.6	69 588	153.6	98 263	192.94		
TOTAL BAFFIN BAY & LAGUNA MADRE LESS BULKHEAD FLATS		125 382	258.3	165 341	430.67		

TABLE II

RAINFALL - RUNOFF UPPER LAGUNA MADRE

Year	(1) Weighted Average Rainfall Inches	(2) Runoff Drainage A Inches	(3) Runoff Drainage B Inches	(4) Runoff Drainage C Inches	(5) Runoff Drainage D Inches	(6) Seepage Inflow E Inches
1940	22.93	0.57	0.32	0	0	0.13
1941	39.48	3.32	1.30	0.65	1.66	0.13
1942	25.52	0.88	0.41	0	0	0.13
1943	26.19	0.97	0.44	0	0	0.13
1944	22.44	0.50	0.31	0	0	0.13
1945	17.43	0.19	0.19	0	0	0.13
1946	26.19	0.97	0.44	0	0	0.13
1947	25.83	0.92	0.42	0	0	0.13
1948	21.75	0.43	0.29	0	0	0.13
1949	25.83	0.92	0.42	0	0	0.13
1950	13.63	0.12	0.12	0	0	0.13
1951	24.72	0.78	0.39	0	0	0.13
1952	14.52	0.13	0.13	0	0	0.13
*1953	21.27	3.10	1.55	0	0	0.13
1954	18.39	0.20	0.20	0	0	0.13
*1955	21.69	2.80	1.40	0	0	0.13
1956	15.46	0.15	0.15	0	0	0.13
1957	25.36	0.86	0.41	0	0	0.13

Avg. Annual 22.70

(1) Weighting of Rainfall Stations = Alice - 1, Kingsville - 1, Falfurrias - 1, Sarita - 1, Hebbronville - 2, and Corpus Christi - 0.5
(2) From Curve A of Rainfall - Runoff Relations
(3) From Curve B of Rainfall - Runoff Relations
(4) 50 Percent Curve B with Extreme Rainfall
(5) 50 Percent Curve A with Extreme Rainfall
(6) Estimated at 1052 Ac. Ft. per year by seepage computations.

* Extremely Heavy Monthly Rainfall

TABLE III

FRESH WATER INFLOW - ACRE FEET

Year	Area A	Area B	Area C	Area D	Area E	Total Acre Feet
1940	53 984	26 885	0	0	1 052	81 921
41	314 431	109 222	38 659	6 059	1 052	469 423
42	83 343	34 447	0	0	1 052	118 842
43	91 867	36 967	0	0	1 052	129 886
44	47 354	26 045	0	0	1 052	74 451
45	17 995	15 963	0	0	1 052	35 010
46	91 867	36 967	0	0	1 052	129 886
47	87 131	35 287	0	0	1 052	123 470
48	40 724	24 365	0	0	1 052	66 141
49	87 131	35 287	0	0	1 052	123 470
1950	11 365	10 082	0	0	1 052	22 499
51	73 873	32 766	0	0	1 052	107 691
52	12 312	10 922	0	0	1 052	24 286
53	293 000	129 000	0	0	1 052	423 052
54	18 942	16 803	0	0	1 052	36 797
55	265 000	117 000	0	0	1 052	383 052
56	14 206	12 602	0	0	1 052	27 860
1957	81 449	34 447	0	0	1 052	116 948
Total						2 494 685

Avg. Annual - 137 500 Ac. Ft. or 0.55 Inches of Runoff

Drainage Areas:

A - 1 136 500 Acres
B - 1 008 200 Acres
C - 713 700 Acres
D - 43 800 Acres
E - 97 100 Acres

Total 2 999 300 Acres

TABLE IV

ANNUAL NET EVAPORATION LOSS
FROM UPPER LAGUNA MADRE AND BAFFIN BAY SYSTEM

(1) Year	(2) Rainfall Corpus Christi Inches	(3) Rainfall Sarita Inches	(4) Average Rainfall Corpus Christi & Sarita Inches	(5) Gross Evaporation Average Beeville & Weslaco	(6) Net Evaporation Loss Col(5)-(4) Inches	** (7) Evaporation From Water Surface Acre Feet
1940	25.15	22.21	23.68	54.90	31.22	430 149
41	42.13	41.23	41.68	48.14	6.46	89 006
42	33.67	24.07	28.87	49.16	20.29	279 556
43	26.87	31.58	29.23	57.36	28.13	387 575
44	26.45	20.90	23.68	53.42	29.74	409 758
45	30.14	22.20	26.17	57.10	30.93	426 154
46	34.09	27.44	30.77	53.91	23.14	318 823
47	31.86	28.62	30.24	53.16	22.92	315 792
48	22.43	-	*21.49	57.11	35.62	490 772
49	30.28	-	*29.34	53.23	23.89	329 156
1950	15.48	-	15.48	62.99	47.51	654 593
51	26.91	23.00	24.96	59.36	34.40	473 963
52	21.31	13.20	17.26	59.18	41.92	577 574
53	24.14	22.82	23.48	59.32	35.84	493 804
54	16.02	19.19	17.61	69.68	52.07	717 420
55	21.87	25.68	23.78	80.46	56.68	780 937
56	21.73	14.72	18.23	82.40	64.17	884 134
1957	28.00	26.55	27.28	76.10	48.82	672 642
Avg. Annual			25.18	60.39	35.21	485 100

*Corpus Christi less 1/2 Avg. Difference

Average Annual Rainfall Corpus = 26.22
Average Annual Rainfall Sarita = 24.34

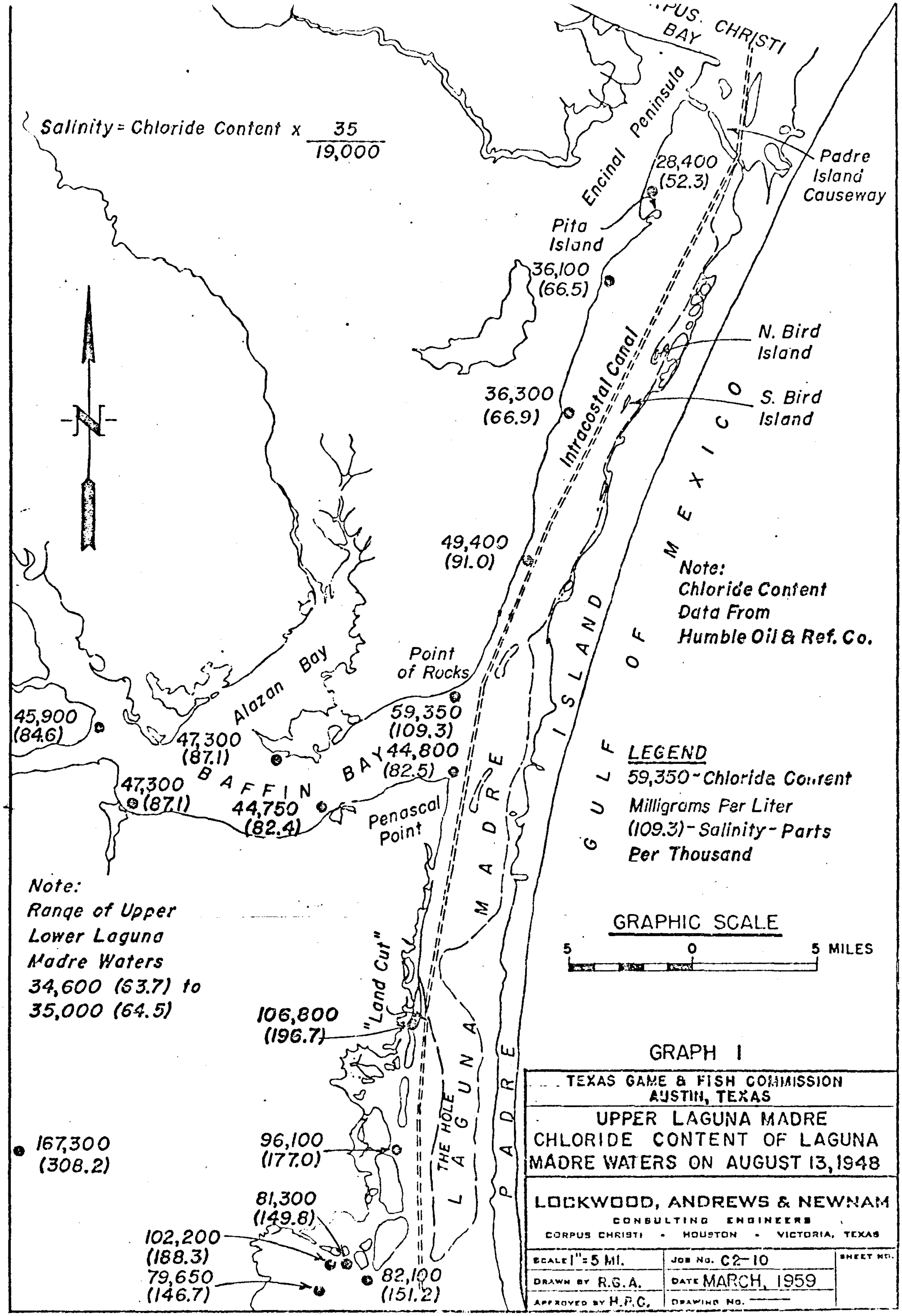
Difference 1.88 x 0.5 = 0.94

** For Water Surface Area of 165 341 Acres.

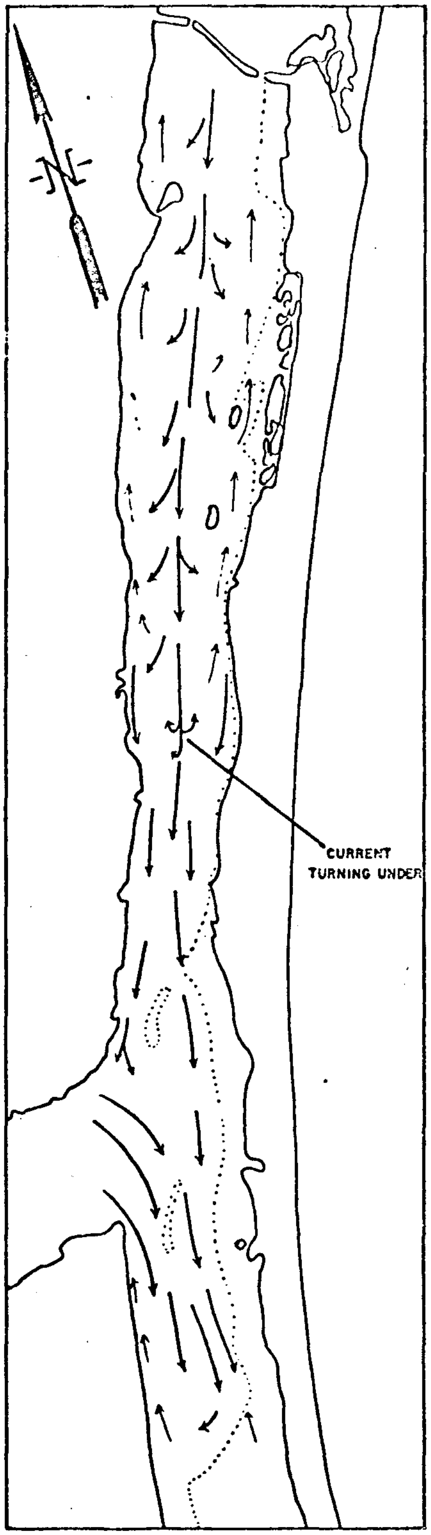
TABLE V

ANNUAL FRESH WATER INFLOW - EVAPORATION RELATIONS

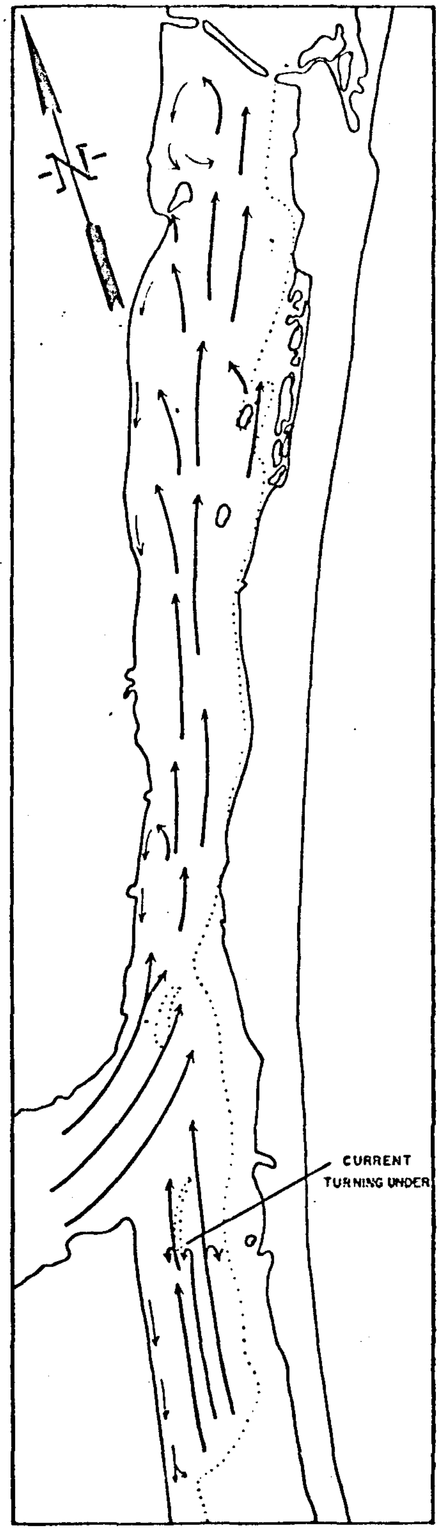
Year	Annual Fresh Water Inflow Ac. Ft.	Annual Net Evaporation Loss Ac. Ft.	Annual Diff. + Inflow - Evap. Ac. Ft.	Cumulative Fresh Water Inflow Ac. Ft.	Cumulative Evaporation Loss Ac. Ft.
1940	81 921	430 149	-348 228	81 921	430 149
41	469 423	89 006	+380 417	551 344	519 155
42	118 842	279 556	-160 714	670 186	798 711
43	129 886	387 575	-257 689	800 072	1 186 286
44	74 451	409 758	-335 307	874 523	1 596 044
45	35 010	426 154	-391 144	909 533	2 022 198
46	129 886	318 823	-188 937	1 039 419	2 341 021
47	123 470	315 792	-192 322	1 162 889	2 656 813
48	66 141	490 772	-424 631	1 229 030	3 147 585
49	123 470	329 156	-205 686	1 352 500	3 476 741
1950	22 499	654 593	-632 094	1 374 999	4 131 334
51	107 691	473 963	-366 272	1 482 690	4 605 297
52	24 286	577 574	-553 288	1 506 976	5 182 871
53	423 052	493 804	- 70 752	1 930 028	5 676 675
54	36 797	717 420	-680 623	1 966 825	6 394 095
55	383 052	780 937	-397 885	2 349 877	7 175 032
56	27 860	884 134	-856 274	2 377 737	8 059 166
1957	116 948	672 642	-555 694	2 494 685	8 731 808



CORPUS CHRISTI BAY
Salinity = Chloride Content x 35/19,000
Encinal Peninsula
Padre Island Causeway
28,400 (52.3)
Pita Island
36,100 (66.5)
N. Bird Island
S. Bird Island
36,300 (66.9)
Intracostal Canal
GULF OF MEXICO
49,400 (91.0)
Note: Chloride Content Data From Humble Oil & Ref. Co.
Point of Rocks
Alazan Bay
45,900 (84.6)
47,300 (87.1)
59,350 (109.3)
44,800 (82.5)
BAFFIN BAY
47,300 (87.1)
44,750 (82.4)
Penascal Point
PADRE ISLAND
LAGUNA MADRE
LEGEND
59,350 - Chloride Content Milligrams Per Liter
(109.3) - Salinity - Parts Per Thousand
Note: Range of Upper Lower Laguna Madre Waters 34,600 (63.7) to 35,000 (64.5)
GRAPHIC SCALE
5 0 5 MILES
"Land Cut"
106,800 (196.7)
GRAPH I
THE HOLE
TEXAS GAME & FISH COMMISSION
AUSTIN, TEXAS
UPPER LAGUNA MADRE
CHLORIDE CONTENT OF LAGUNA MADRE WATERS ON AUGUST 13, 1948
167,300 (308.2)
96,100 (177.0)
81,300 (149.8)
LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS
102,200 (188.3)
79,650 (146.7)
82,100 (151.2)
SCALE 1" = 5 MI.
JOB NO. C2-10
SHEET NO.
DRAWN BY R.G.A.
DATE MARCH, 1959
APPROVED BY H.P.C.
DRAWING NO.



Currents flowing during north winds.



Currents flowing during south winds.

Reproduced from "An Ecological Study of the Upper Laguna Madre of Texas" by Ernest G. Simmons, Marine Biologist, Texas Game and Fish Commission.

GRAPH 2

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS

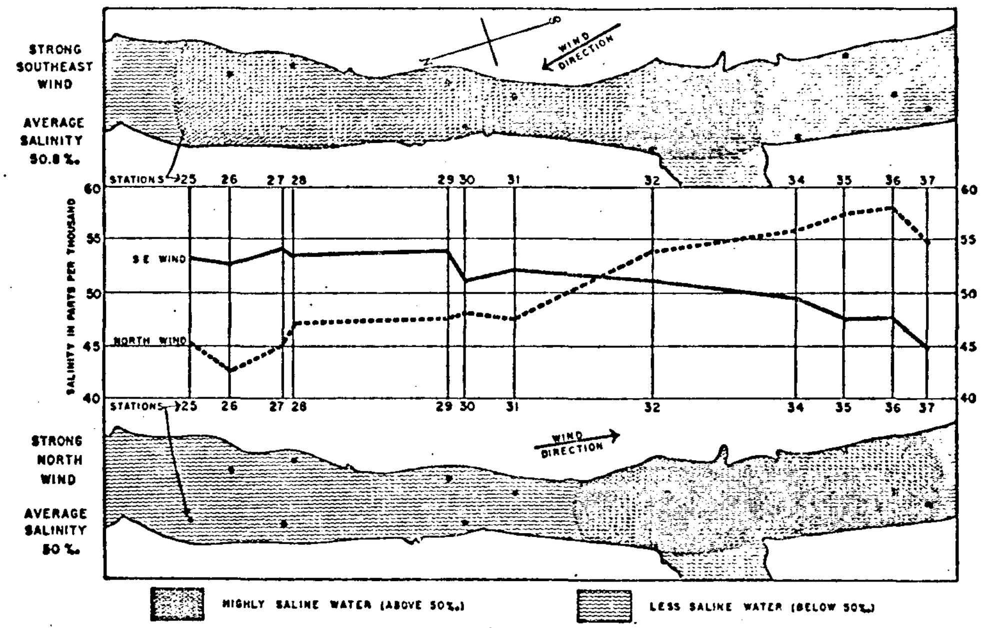
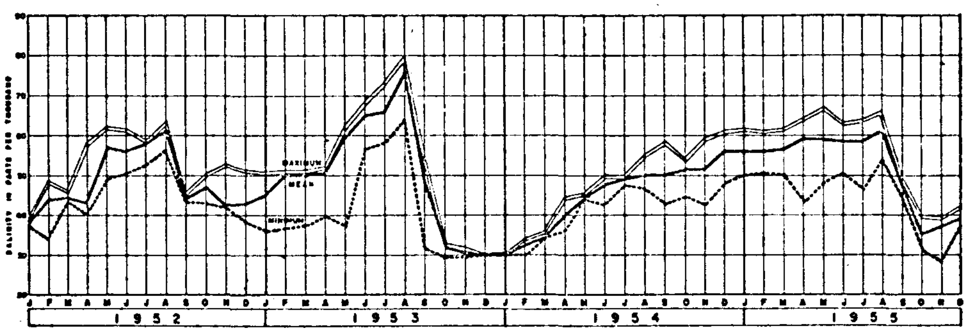


Diagram showing movement of salinity block with prevailing wind tide, and corresponding graph showing salinities at each station during southeast and north winds.

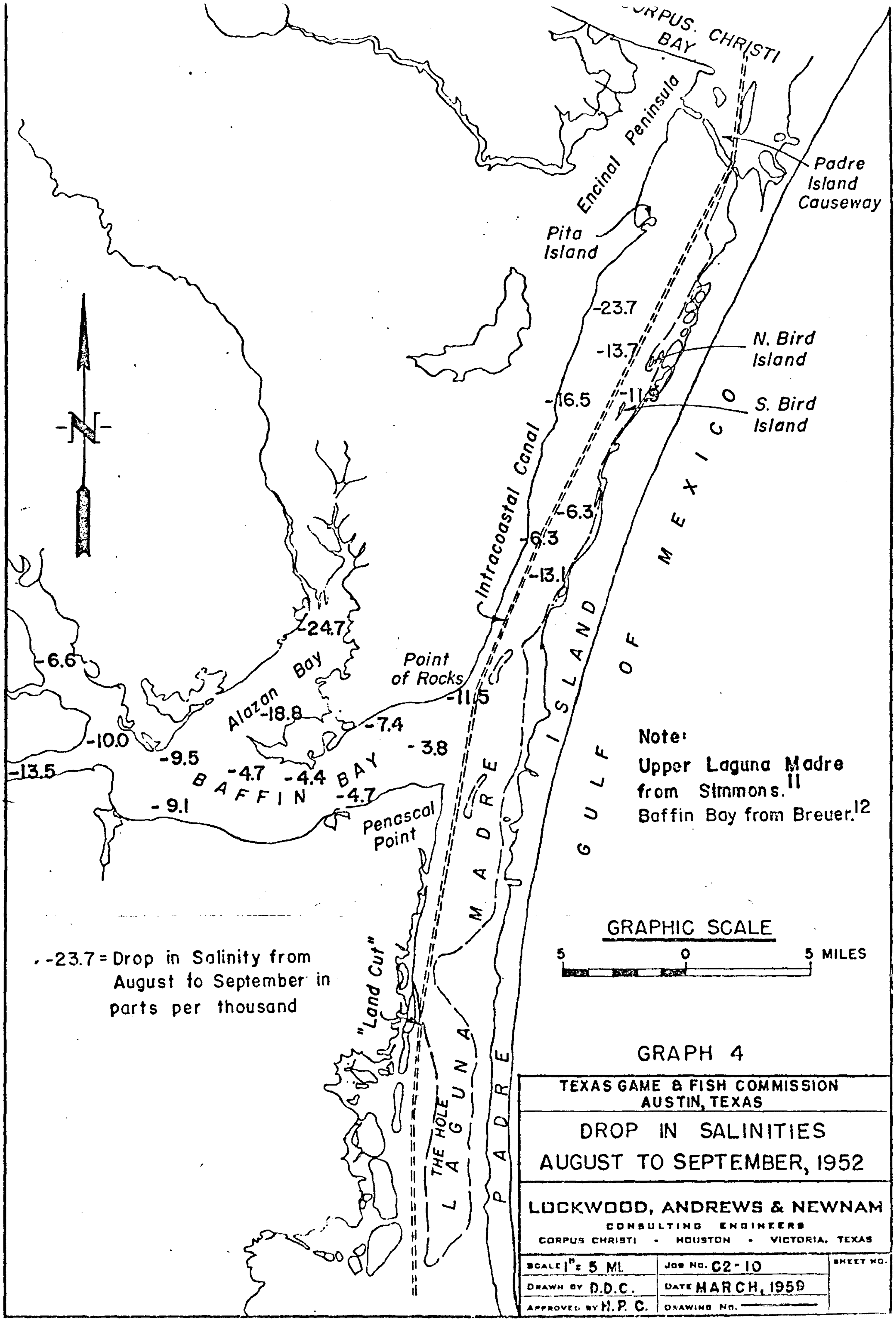


Maximum, minimum, and mean salinity by month for twelve stations in the upper Laguna Madre.

Reproduced from "An Ecological Study of the Upper Laguna Madre of Texas" by Ernest G. Simmons, Marine Biologist, Texas Game and Fish Commission.

GRAPH 3

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS



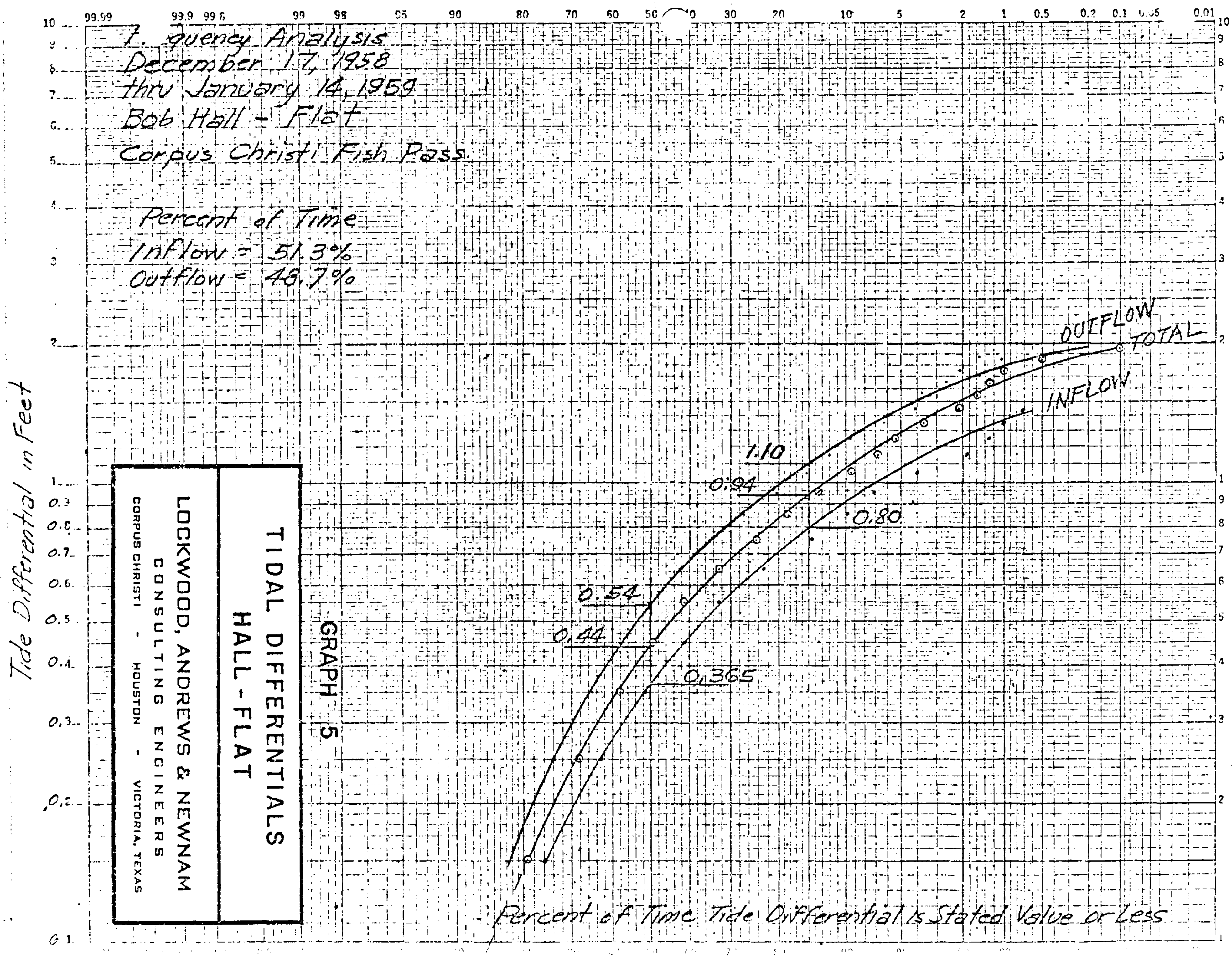
GRAPH 4

TEXAS GAME & FISH COMMISSION
AUSTIN, TEXAS

DROP IN SALINITIES
AUGUST TO SEPTEMBER, 1952

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI • HOUSTON • VICTORIA, TEXAS

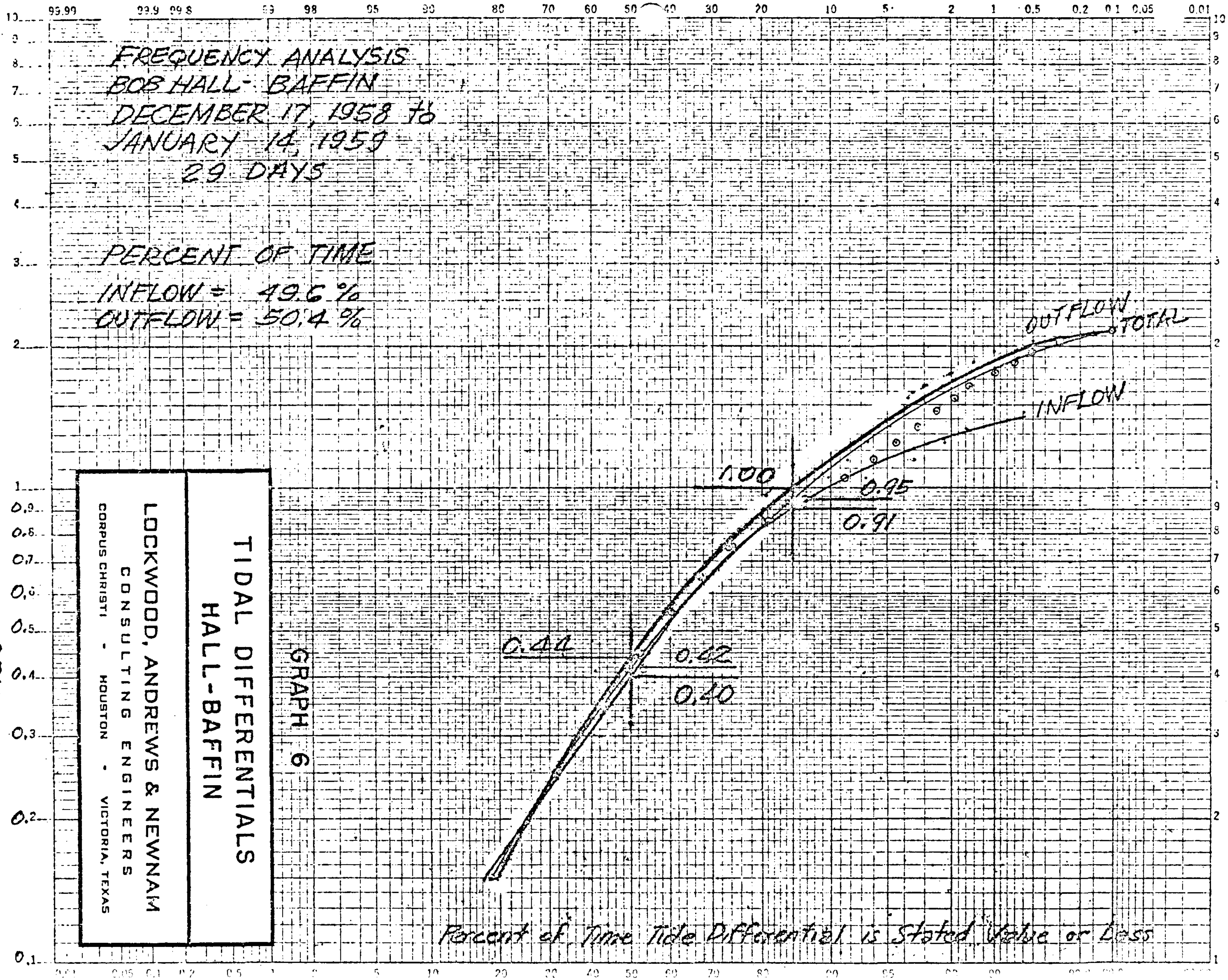
SCALE 1" = 5 MI.	JOB NO. C2-10	SHEET NO.
DRAWN BY D.D.C.	DATE MARCH, 1959	
APPROVED BY H.P.C.	DRAWING NO.	



GRAPH 5

TIDAL DIFFERENTIALS
HALL-FLAT

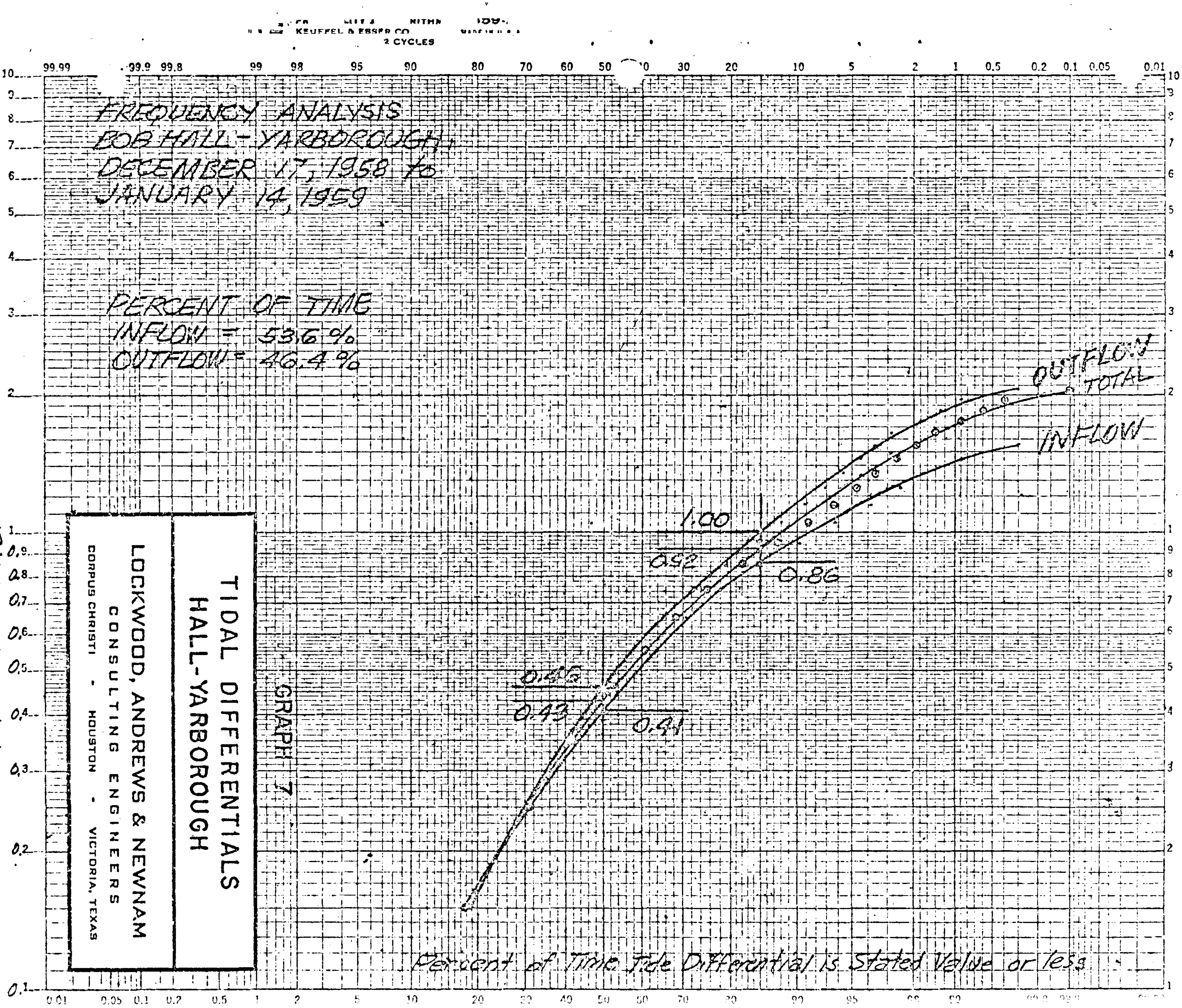
LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS



GRAPH 6

TIDAL DIFFERENTIALS
HALL-BAFFIN

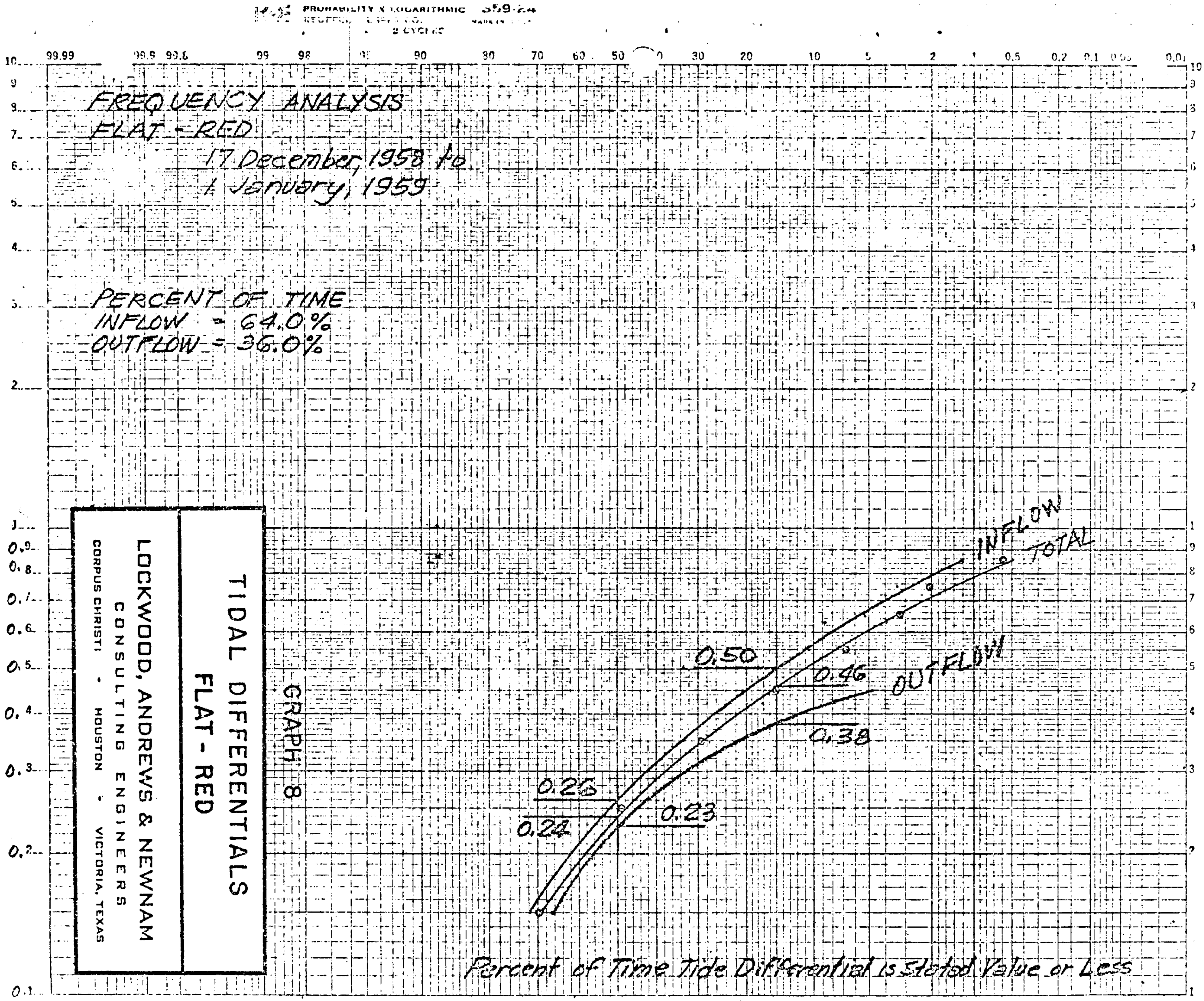
LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS



GRAPH 7

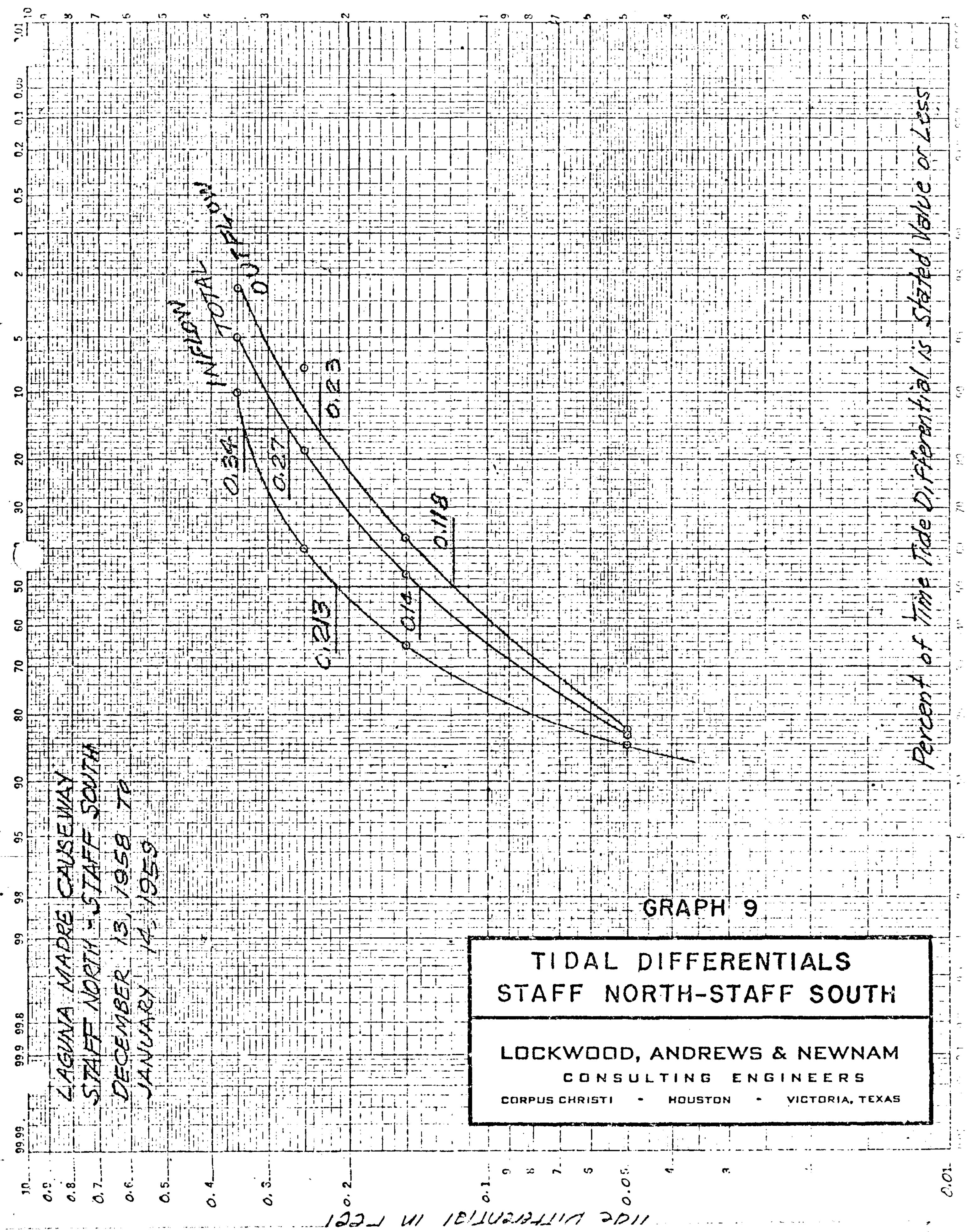
TIDAL DIFFERENTIALS
HALL-YARBOROUGH

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS



TIDAL DIFFERENTIALS
FLAT - RED

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
CORPUS CHRISTI - HOUSTON - VICTORIA, TEXAS



GRAPH 9

TIDAL DIFFERENTIALS
STAFF NORTH-STAFF SOUTH

LOCKWOOD, ANDREWS & NEWNAM
CONSULTING ENGINEERS
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ILLUSTRATIONS

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