TEXAS
WATER
DEVELOPMENT
BOARD

REPORT 43

A NEW CONCEPT
WATER FOR PRESERVATION OF BAYS AND ESTUARIES

APRIL 1967

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A NEW CONCEPT--
WATER FOR PRESERVATION
OF BAYS AND ESTUARIES

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FOREWORD

During the preparation of the preliminary Texas Water Plan, the Water Development Board had a number of studies prepared by The University of Texas, Texas A & M University, and Texas Technological College. Other investigations were prepared by the staff, or under contract with various consultants. A number of these reports have been published heretofore by the Board.

Water requirements and the means for preservation of the bays and estuaries received detailed attention during the preparation of the preliminary Plan. This attention resulted from: (1) the important role the bays and estuaries play in the total economic life of Texas; and (2) the statuatory reference to consideration of the bays and estuaries in comprehensive planning.

Article 8280-9, V.A.C.S., Section 3b, states in part: "Consideration shall also be given in the plan to the effect of upstream development upon the bays, estuaries, and arms of the Gulf of Mexico and to the effect upon navigation."

Publication of this report is a continuation of the Board's policy of providing the widest possible distribution of information concerning the preliminary Plan.

Texas Water Development Board

Joe G. Moore, Jr.

Joe G. Moore, Jr.
Executive Director

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INTRODUCTION

In evolving a Texas Water Plan, and while exploring the impact of ever-increasing return flows on the bay systems, the Texas Water Development Board correctly recognized the implications of possible serious damage to the estuaries and fishery by major but inevitable modifications in the river flows.

This is an exploration, from the coastal engineering and tidal hydraulics standpoint, to evolve some new concepts that would permit both reasonable maximum river development and preservation – plus enhancement – of the Texas Coastal bays and estuaries.

It is found that this is a mixed-water problem and cannot be reasonably solved as a simple fresh water demand. The basic concept evolved is that increased and improved distribution of gulf water inflow into the estuaries may be a good substitute for apparent large fresh water needs. Hydraulic structures for controlled fresh water releases into some designated prime spawning and nursery areas may then be expected to provide maximum benefits to the fishery with minimum fresh water. See Fig. 1, Basic Concept of Estuary Water Needs, following last page.

Reduction in, and responsible control of, excessive pollution and spoiling is considered to be a prime requisite in maintenance and preservation of the recreation and fishery aspects of these bays and estuaries. Brought to specific attention is the delicate balance of the life of the commercial oyster in San Antonio and Matagorda Bays.

DEFINITIONS

Some of the terms used in this concept for preservation and enhancement of the bays and estuaries need to be clearly defined.

ESTUARY

A true estuary is defined as a passage where the tide meets the river current, and especially an arm of the sea at the lower end of a river. Along the Texas Coast, the estuaries of interest consist of large bodies of brackish water (except hypersaline Laguna Madre) separated from the Gulf of Mexico by a chain of barrier islands. They are separated, or combined, herein as – Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, Upper Laguna Madre with Baffin Bay, and Lower Laguna Madre.

WATER

Water for estuaries has a rather broad meaning. It consists of a mixture of gulf water and fresh water. Sources of fresh water are: runoff from land, creeks, and rivers; rainfall directly on the bay surface less the evaporation loss from this surface; and effluents or return flow from the various domestic, industrial, and agricultural uses around the bay. Gulf water flows in and out of the bays and estuaries thru the limited inlets across the barrier islands. Knowledge of the intricate mixing of these waters of different density (measured by salinity in parts per thousand) is of the utmost importance in any study of these bays. Fresh water needs cannot be properly determined without consideration of the needs for gulf water, as determined by special operation studies peculiar to bays and estuaries.

FISHERY

Here fishery means a place for catching fish or taking other sea products and includes the habitat where fish can spawn and be carried thru the nursery period. All the fish of interest are known as euryhaline – that is, they have a tolerance for a rather wide range of salinity.

POLLUTION

For the present purposes, pollution is defined more from the standpoint of the fishery than from the viewpoint of the usual water uses by man. From this standpoint pollution controls may be broadly defined by five major categories: (1) salinity control; (2) silt and clarity control; (3) provision of a minimum amount of dissolved oxygen;

(4) bacteria control; and (5) control of nutrients where some are necessary, but too much or too little are undesired by the fishery. The concept discussed herein covers only the first two categories – with the understanding that municipal, industrial, and agricultural return flows will either be treated so as to be satisfactory for the fishery, or be prevented from entering the bays and estuaries.

VALUE OF ESTUARIES

The only known attempt to make a complete evaluation of the Texas Coastal Bays and Estuaries is limited to a report by the Bureau of Business Research, University of Texas, entitled "Marine Resources of the Corpus Christi Area."[1] The estimated annual value of Corpus Christi and Aransas Bays for 1958 was $370 per bay surface acre. This is the sum of all averages of all tangible and imputed surface acre values associated with all present activities related to the bays. These activities included: recreation and sport fishing at $151; commercial fishing at $15; minerals at $130; cooling water at $10; transportation at $63; and effluent disposal at $1.00 value per bay surface acre per year.

For want of complete coverage of the bays, and as an exercise, if this value is applied to 1.3 million acres of coastal bays, the total annual value would be $483 million. Now applying one of the basic formulas of mathematics of finance, when computed as an annuity of $483 million per year at 5.0 percent for 50 years, the present worth is $8.8 billion ($6,780 per acre).

This matter of water for preservation and enhancement of the estuaries applies to the activities of recreation, including sport fishing, and commercial fishing – valued at $166.25 per acre per year in the Corpus Christi area. If this value (45% of total) is applied like the total, the annual value of the bays would be computed at $216 million with a present worth of $4.0 billion ($3,200 per acre) for recreation and fishery.

The commercial fishing is valued at less than 10 per cent of the combined recreation and fishery; that is, $14.64 per acre per year. Then computed as above, annual value of commercial fishing is $19 million with a present worth of $347 million ($267 per acre).

In any event, a complete inventory and evaluation is needed and is certain to show that the preservation and enhancement of the bays and estuaries for recreation and fishery are of tremendous value to the State. Further, it is believed that it will be found that the State can hardly afford not to preserve this valuable heritage.

THE VARIABLE ENVIRONMENT

The environment of these estuaries, with respect to the fishery, is highly variable and subject to many extremes. Baffin Bay and Upper Laguna Madre is too salty while Galveston Bay usually has too much fresh water, and Sabine Lake is overwhelmed by fresh water. In places, they have been choked from needed gulf water. At other places, they are being choked with pollution and silt. It is a harsh climate, with salinities ranging from 1 to 80 ppt (parts per thousand) including wide ranges in monthly and annual values. Also involved are variable density or stratified flows and salinity gradients. All of this – plus the impact of changing fresh water flow, added pollution loads, threat of further choking of Gulf water inflow by hurricane protection works, and rapidly increasing pressure for recreation – really makes for some highly disturbed estuaries.

AREA OF GREATEST VARIABILITY

There is a significant climatic map in "Hydrology"[2] which is a map of the United States showing percentage of years that annual rainfall has been less than demands for evaporation and transpiration from the land surface. The frequency study was based on measured difference between rainfall and runoff. The critical areas and area of greatest variability with respect to droughts lie between the lines of 80 per cent and 20 per cent frequency, located between Corpus Christi Bay and Sabine Lake. This means, on the average expectancy, at the 20 per cent line there will be 8 years of excess rainfall followed by a 2 year "drought;" and at the 80 per cent line there will be 2 years of excess rainfall followed by an 8 year "drought."

Galveston Bay is in the humid region between the 30-40 per cent lines. Matagorda Bay is in the moist subhumid region between the 60-70 per cent lines. San Antonio Bay is in the moist subhumid region between the 70-80 per cent lines. Aransas Bay and Corpus Christi Bay are in the dry subhumid region near the 80 per cent line. Baffin Bay and the Upper and Lower Laguna Madre are in the semi-arid region between the 80-90 per cent lines.

SALINITY VARIATIONS

Average salinity of the oceans is approximately 35 ppt (parts per thousand), but varies generally between 33 ppt and 37 ppt. See pages 50, 66 and 123 of "The Oceans."[3] Gordon Gunter[4] reported in 1941 and 1942 (high average rainfall period) the salinity range was 26.7 ppt to 36.7 ppt in the Gulf of Mexico from 2 to 5 miles offshore from Aransas Pass. Other very limited reports range from 25.3 to 37.7; hence, for operation studies, salinity of the Gulf water inflow is needed.

Whitten, Rosene, and Hedgepeth[5] report an annual mean surface salinity in Galveston Bay at Galveston of 23.7 ppt in the period 1922-1944. From 1961 to 1964 (generally low average conditions) salinities ranged from 4 to 33.5 ppt throughout the bay system.

Weiser and Armstrong[6] reported the salinity of Matagorda Bay varies from nearly zero near the mouths of streams to 25 to 32 ppt near Pass Cavallo. The data was secured in 1959, with rainfall at near normal.

For Aransas Bay, including Copano Bay, Collier and Hedgepeth[7] reported an average salinity of 20 to 23 ppt, ranging from 1 to 36.8 ppt. This average appears to represent somewhat above average climatic conditions (above average rainfall-runoff-evaporation relations).

The maximum salinities in Corpus Christi Bay are due to both the hypersaline waters of the Upper Laguna Madre and reduced river flow. Salinities up to 58 ppt in the underflow from the Laguna to the Bay were measured by D. W. Hood.[8] Recently, salinities in Nueces Bay ranged up to 55 ppt.

Salinity of Baffin Bay and Upper Laguna Madre usually ranges greater than 45 ppt and goes up to 80 ppt according to Simmons[9] and Breuer.[10]

The average annual salinities increase generally from east to west. In each bay there is a wide annual variation from the wettest to driest year. For each range of annual climatic condition (rainfall, runoff, and evaporation relations) there are variable salinity gradients from Gulf inlets to far reaches of the estuary. These horizontal salinity gradients vary from month to month and often superposed are vertical salinity gradients causing density or stratified flows in the bays and channels. Hence, any fish in these estuaries must be euryhaline (tolerance for wide range of salinity) and their natural ability to adjust to wide ranges of salinity is often greatly underrated.

FLOODS AND TIDES

Infrequently, these estuaries are subjected to rather extreme floods from rainfall runoff and from hurricane tides. Insofar as the fishery are concerned, these infrequent floods and tides do much harm and provide little, if any, benefit. Even the local 10 to 13 feet hurricane tides of "Carla," September, 1961, provided amazingly little flushing action in Trinity Bay (Galveston Bay System). This is shown by the minor effects on monthly mean salinity measured February, 1961 to April, 1962 and reported in "Results of the Trinity Bay Study."[11] The upper portion increased from 2 to 3 ppt, while the remainder of the bay decreased from about 5 to 2 ppt.

The basic Gulf water inflow-outflow and mixing depends mostly on the "normal" day-in, day-out Gulf tides, which are rather small and decrease somewhat going from east to west along the coast. This Gulf water inflow is as necessary as fresh water runoff. It must also be protected for the preservation of the estuaries.

RAINFALL-RUNOFF-EVAPORATION RELATIONS

The first approximation (this is admittedly not well validated, and which may or may not be considerably in error with respect to evaporation from the bay water surface) of the wide variability of present or natural rainfall-runoff-evaporation relations within these bays and estuaries are listed in Table I, following page.

TABLE 1

ANNUAL RAINFALL – RUNOFF – EVAPORATION RELATIONS (Q_r OR Q_e)

(MILLION ACRE FEET PER YEAR)

ANNUAL CLIMATIC CONDITIONS	GALVESTON BAY	E. MATAGORDA BAY (without Colorado River)	MATAGORDA BAY (without Colorado River)	MATAGORDA BAY (with Colorado River)	SAN ANTONIO BAY	ARANSAS BAY	SAN ANTONIO & ARANSAS BAYS	CORPUS CHRISTI BAY	BAFFIN BAY & UPPER LAGUNA MADRE
Wettest (1941)	+19.7	+0.86	+2.74	+8.89	+3.30	+1.00	+4.30	+1.37	+0.38
High Average (1940-46)	+14.9	+0.48	+1.65	+4.42	+2.03	+0.35	+2.38	+0.64	–0.15
Average Annual	+ 9.7	+0.27	+0.77	+2.75	+1.15	+0.01	+1.16	+0.33	–0.35
Low Average (1950-56)	+ 3.2	+0.06	–0.09	+0.69	+0.23	–0.27	–0.04	–0.14	–0.55
Driest (1956)	+ 1.2	–0.08	–0.86	–0.29	–0.18	–0.50	–0.68	–0.50	–0.85

NOTES: The figures are sum of rainfall on bay surface plus runoff into the bay minus gross evaporation from bay surface

+ means rainfall plus runoff exceeds evaporation

– means evaporation exceeds rainfall plus runoff

In Galveston Bay, rainfall and runoff always exceeds evaporation, even in the driest year when there is still an excess of 1.2 million acre feet per year.

Prior to 1925, the Colorado River flowed directly into the east arm of Matagorda Bay. Sometime between 1925 and 1930 nature and man combined to divert most of this river flow direct into the Gulf. Some flow presently escapes into the bay through the Intracoastal Waterway and some by flood overflow. The amount and distribution of this fresh water flow into the bay is not known. Hence, the rainfall-runoff-evaporation relations are listed both without and with the Colorado River flow. The true conditions lie somewhere between these limits.

The first prerequisite for Matagorda Bay is to make accurate accounting of present runoff and evaporation. Even with all the Colorado River flow, it appears that this bay is naturally due to become more salty than the nearshore Gulf waters during the driest year, because there is a deficiency of 0.29 million acre feet per year to prevent evaporation from exceeding rainfall plus runoff during driest years.

San Antonio Bay now has an ample supply of fresh water except for the driest year, when there is an indicated deficiency of 0.18 million acre feet per year.

It will be noted that Aransas Bay is near "balance" around average annual climatic condition with deficiency below average and excess above average.

Corpus Christi Bay has an indicated deficiency of 0.14 and 0.5 million acre feet per year for the low average and driest climatic condition. In this analysis, natural runoff before construction of Lake Corpus Christi was used. But the major trouble with this bay is the extremely high salinity inflow from the Upper Laguna Madre. Under this condition, it certainly can ill afford any reduction in the original natural fresh water supply.

Baffin Bay and Upper Laguna Madre are always deficient, with the exception of the wettest year.

SILTATION AND CLARITY

The main sources of siltation are river floods, shore erosion, sand transport at inlets and hydraulic dredging. Any reduction in river silt loads, due to river development, will be good for the bay fishery. Convenient dumping of hydraulic spoil in the bays with subsequent "recirculation" back into channels by waves and currents and out again by maintenance dredging has for many years been causing serious damage by "mudding up" the clarity of the bays. Indiscriminate spoil disposal has caused loss of valuable habitat, and there are innumerable cases of seriously blocking or changing bay water circulation and water interchange. It looks as though this trend is increasing, instead of being placed under more responsible control. Most channels cut in the bays benefit the fishery by improved circulation of both water and recreation boats. But the only control over placement of dredge spoils is in the interest of commercial navigation – not in the interest of preservation and enhancement of the bay fishery.

Wave-suspended and current-transported silt from shell dredging and shell washing operations (along with floods and high salinities) have killed live oyster reefs – leaving them without legal protection. The dredging operations for commerce are necessary, vital, and valuable – but surely the indiscriminate abuse of the fishery can be reduced. Shell dredging may not be compatible with the overall economy, unless it can be and is actually done without serious damage to the ecology of the bay fishery. Correction of these abuses would help these estuaries withstand the impact of inevitable changes in fresh water runoff and increased, but polluted, return flow.

A significant advance in the science of tidal hydraulics was recently made (May 1965) with publication of Report No. 3 of the Committee on Tidal Hydraulics, C. of E., U.S. Army, entitled: "Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena." Chapter VII, by Johnson and Marcroft, is entitled "Dredging and Disposal Practices in Estuaries." Therein, the basic consideration is to locate spoil areas so that dredged material does not find its way back into the navigation channel to contribute to excessive volumes of maintenance dredging. Of particular interest is the statement that the dredged material must be transported to a place where it will do no harm – neither to channel nor to valuable beds of the fishery. The proper dredging and disposal practices to do this are described in detail. The same basic principles and practices should also be applied to any permitted shell dredging operations, including washing and spoil disposal.

Much of the spoil consists of silt and clay that is flocculated by the saline estuary waters. For study of the silting problems and design of proper desilting basins, the "apparent gradation," or settling rate, or equivalent sedimentation diameter of the silt and clay particles should be determined by hydrometer analyses without use of deflocculating agent and with use of saline bay water for dilution instead of the usual fresh water.

It is suggested that hydraulic spoiling from channel and shell dredging could be designed to improve -- instead of spoil – the bays and estuaries. For instance, selection of sand and shell spoil could be used to improve the fishery – if properly planned and placed. Other spoil could be used to build up low areas subject to hurricane tides. The spoil that cannot be used to advantage should be dredged by proper equipment (see "Dredging and Disposal Practices in Estuaries") and be disposed of where it will not be detrimental to the fishery.

Incidently, the hopper dredge is now used extensively in lower Galveston Bay and spoil disposal in the nearby Gulf. However, disposal is not far from the end of the jetties and sometimes the countercurrents west of the south jetty return some of the suspended silt to spoil Galveston East Beach and South Jetty fishing.

EXISTING INLETS

Galveston and Matagorda Bays have naturally developed near full potential of Gulf water inflow-outflow. The inlets are Bolivar and San Luis Passes (for Galveston Bay) and Pass Cavallo plus the Matagorda Channel (for Matagorda Bay). The rest of the Bays are seriously choked from the standpoint of receiving needed Gulf water. Note that Aransas Pass alone must supply part of San Antonio Bay, plus all of Aransas, Corpus Christi, and Baffin Bays and Upper Laguna Madre.

Rollover Pass (at east end of East Galveston Bay) is artificially choked and provides insignificant water inflow. The original cut at Rollover Pass was made without securing necessary basic data to permit application of proper tidal hydraulics and coastal engineering, and with inadequate right of way. It was too short in length and immediately showed excessive erosion. The eroding pass was providing Gulf water inflow at a rate of about 3.0 million acre feet per year. With this inflow, the horizontal salinity gradient was reversed and conditions were as quoted below from "Biologic and Hydrographic Adjustment in a Disturbed Gulf Coast Estuary:"[12]

> "Rollover Pass was faunistically rich. Fishing pressure was considerable, with dozens of fishermen present daily. When the water was clear, speckled trout were frequently caught, especially underneath the highway bridge. Sand trout, croaker, spadefish, drum, redfish, pigfish, silver perch, pinfish, big-eyed herring (ladyfish), catfish, shark, ray, eel, and small pompano were taken regularly. Blue crab were commonly caught, particularly along the bayward sides of the Pass."

Unfortunately, and without proper water interchange studies, the pass was then excessively choked in order to control erosion.

Brown Cedar Cut (at east end of East Matagorda Bay) was naturally closed in 1964, after operating for many years at low hydraulic efficiency. This was caused by slow filling of the narrow end of the bay by sand intercepted from the beach sands shifting along the Gulf shore. The flow had been divided into several winding, shallow streams – a condition which makes for extremely low hydraulic efficiency in both the inflow and outflow. Local fishermen have been making desperate but futile attempts (without benefit of proper investigation and design) to reopen this cut at its completely "sanded" and abandoned location.

The Matagorda Bay Channel (deep water ship channel now under construction) is a large artificial inlet. It has been found to be a too-short, high-velocity pass imbalanced toward excessive erosion.

Cedar Bayou is an intermittent small pass, with inadequate water interchange, between Mesquite Bay and the Gulf. It is too long, stretched to near its "elastic limit," and imbalanced toward siltation. It was improved by dredging and reopened in 1959. Fortunately, Hurricane "Carla" provided some needed "maintenance" flushing in 1961, but it is now (Jan., 1966) nearly closed again, and is similar to the 1952 mapping. Its operation and behavior has been almost precisely as forecast mathematically back in 1959. A balanced design could have been achieved by relocation, shortening, and providing stabilization works – but this was not done because of right-of-way difficulties and lack of funds.

Brazos Santiago Pass provides sufficient water interchange for the southern part of Lower Laguna Madre. It is suspected that the Port Mansfield Channel provides inadequate Gulf water inflow into the northern part of Lower Laguna Madre – but this area is particularly in need of a complete study. This Mansfield channel is a man-made, small-size. too-long, low-velocity inlet imbalanced toward excessive siltation.

First approximation of annual Gulf water inflow through Bolivar and San Luis Passes into Galveston Bay amounts to 71.0 million acre feet. Cavallo Pass with the new Mata-Channel is tentatively rated at 35.8 million acre feet per year to Matagorda Bay. Inflow from Cavallo Pass to Espiritu Santo Bay is unknown. Aransas Pass supplies something like 25.1 million acre feet to the system of San Antonio, Aransas, Corpus Christi, and Baffin Bays, and the Upper Laguna Madre.

These total to say 132 million acre feet per year of Gulf water inflow. It appears that on the average approximately 4 parts of Gulf water inflow-outflow is required to mix one part of brackish estuary water. This is called 25 per cent efficiency in mechanical mixing, and probably varies from 10 to 40 per cent. At 25 per cent, this means that the "effective" Gulf water interchange amounts to 33 million acre feet per year.

POLLUTION AND FLUSHING

For the purpose of this concept of water for preservation of the estuaries, the areas classified by the Texas State Department of Health as insanitary and closed to the harvesting of shellfish and areas conditionally approved for such harvesting are considered as polluted bay areas (1965). It is evident that even runoff floods and hurricane tides cannot satisfactorily flush out this pollution. Certainly, man cannot expect to transport enough fresh water to flush it out.

Further, the efficiency of mixing between Gulf water inflow and fresh water runoff (including polluted return flow) is low – even when the full potential tidal interchange is developed. In this mixed estuary environment, most sanitary engineers overestimate the capacity of the bay to assimilate pollution. For instance, the following is quoted from

"Pollutant Distribution in Tidal Estuaries:"[13]

> "To date, attempts to solve the diffusion equation for estuarine application have not been successful.--- Sanitary engineers have long employed the 'tidal prism' calculation, which assumes that the volume of water which enters and leaves a basin with the rise and fall of the tide is available to dilute the increment of pollution added to it during each tidal cycle. Ketchum points out that this assumption could only lead to correct estimates if the water in the basin were completely mixed and if none of the water which escaped during the ebb returned on the following flood tide. Since these conditions are not met generally, the tidal prism concept gives an exaggerated estimate of the rate of flushing."

The best available formulation for evaluation of the tidal flushing process in bays and estuaries is described in "Dispersion and Flushing of Pollutants" by D. W. Pritchart.[14] For a period of time when local fresh water inflow is relatively small with respect to the Gulf water inflow, the following formulas may be used to: (1) find the efficiency of mixing between tidal and bay waters; (2) exchange coefficient related to tidal flushing; and (3) time interval required for flushing a given fraction of bay water.

<u>Formulas for Tidal Flushing</u>

$$K_t = \frac{Q_i E}{V_b} = \frac{\Delta S_o}{S_i - S_o} \quad \cdots\cdots\cdots\cdots (1)$$

$$E = \frac{(\Delta S_o) V_b}{Q_i (S_i - S_o)} \quad \cdots\cdots\cdots\cdots (2)$$

$$t_f = \frac{V_b}{Q_i E} \log_e \left(\frac{1}{1-f}\right) \quad \cdots\cdots\cdots\cdots (3)$$

where:

K_t = exchange coefficient related to tidal flushing, the fractional rate of renewal per unit time, equal to the volume of new water brought into bay in each unit of time divided by the total volume of the bay.

Q_i = total quantity of inflow thru the inlet (Gulf to bay) in a given time, acre feet.

E = efficiency of mixing Gulf and bay water, or the portion of the tidal inflow that is new water and well mixed with the bay water before returning as outflow (expressed as percentage ÷ 100).

V_b = volume of bay at mean sea level, acre feet.

ΔS_o = change in mean salinity within bay after given increment of time, ppt

S_i = mean salinity of inflow from Gulf to bay, ppt, during same time interval.

S_o = mean salinity within the bay at initial time t, in ppt.

t_f = time interval required for flushing to renew or exchange a given fraction (f) of bay water.

$\log_e$ = natural or Napierian logarithm, log to the base e (2.718).

f = fraction of bay water flushed out or exchanged.

The rate of flushing, renewal, or exchange of the water in the bay is an exponential process. Theoretically, an infinite time is required to renew or flush out <u>all</u> of the water in the bay. A concept of the effects of this exponential process on the tidal flushing may be realized from the following listing:

The Exponential Flushing Process

Fraction of Bay Water Flushed f	Value of $\log_e (\frac{1}{1-f})$
0.5	0.693
0.75	1.386
0.90	2.3
0.95	3.0
0.99	4.6

The implication of this exponential flushing process is, for instance, that it will require 2 to 3 times as long to flush out 90 to 95 per cent of the bay water than would normally be expected with a linear flushing process.

Whenever the evaporation from bay surface exceeds rainfall and runoff, the term $(S_i - S_o)$ is changed to $(S_o - S_i)$ in these formulas.

The appalling example of estuary pollution is the Houston Ship Channel. No doubt, under low runoff conditions, it has stratified flow and suffers from a severe case of eutrophication (extreme loss of oxygen from the lower stratum). With flushing runoff, including septic, low-dissolved-oxygen sewage from Houston's old combined storm and sanitary sewers, the result is often a major fish kill.

It is known that these major fish kills usually occur right after ample flushing action from rainfall runoff. By making several reasonable assumptions with respect to density differences in the probable stratified flow, and by application of hydraulic equations including the necessary gravitational adjustment – it is computed that flushing fresh water flows of about 3,000 cfs to 10,000 cfs are required to start and then nearly complete flushing out this lower stratum of low-oxygen, stagnant, polluted water that is probably the basic cause of the major fish kills. This range of flushing fresh water flow is at the rates of 2.2 to 7.2 million acre feet per year.

All this means – flushing that may well be applied to polluted fresh water streams will have little or no chance of being beneficial in fighting pollution in the coastal bays and estuaries.

In other words, the Texas Coastal Bays and Estuaries can no longer be considered as substitutes for proper and adequate treatment plants. It is the concept herein, with respect to water for preservation of the bays and estuaries, that municipalities, industry, and agriculture do not have the inherent right to pollute these waters – no more than they do for fresh water streams. Instead of holding pollution at present levels in these estuaries, it must be greatly reduced. If not, man must be prepared to "write off" the bays for recreation and fishery and turn them over entirely to serve industry and commerce, and to act as "holding ponds" for polluted waters.

OPERATION STUDIES

Operation studies must be made on the bay and estuary systems, just as operation studies are made before any conception is reached concerning fresh water reservoirs. But formulation is different, with more complexities, and peculiar to the estuary. Finally, system operation analyses will be needed, including runoff from regulated watershed, Gulf inflow, and water exchange between bays.

WATER BALANCE AND SALINITY

Conceptual operation studies have been made to indicate the probable range of average annual salinity of outflow from the estuaries with increased Gulf inflow through new or improved inlets operating under present runoff conditions. The Gulf inlets are balanced by tidal hydraulics for efficient mixing; and average salinity is a weighted salinity based on segmented volumes of the bay. These are hypothetical studies, based on many assumptions; and they were made hurriedly to help form a logical concept. Numbers are used to present a picture of the resultant concept and to illustrate how to find the correct answers. These numbers, therefore, cannot be used literally to arrive at any final solutions.

The basic, steady-state, mixed-water and salinity balance equations are:

For Rainfall & Runoff Exceeding Evaporation:

$$Q_i = \frac{Q_r S_o}{E(S_i - S_o)} \qquad \text{.................} \quad (4)$$

And For Evaporation Exceeding Rainfall & Runoff:

$$Q_i = \frac{Q_e S_o}{E(S_o - S_i)} \qquad \text{.................} \quad (5)$$

Where:

Q_i = total quantity of inflow through the inlet (Gulf to bay) in a given time, acre feet.

Q_r = net quantity, in acre feet, of rainfall on bay surface plus runoff into bay less gross evaporation from bay water surface.

S_o = weighted average salinity (ppt, or parts per thousand) of outflow from bay to Gulf.

E = efficiency of mixing Gulf and bay water, or the portion of the tidal inflow that is new water and well mixed with the bay water before returning as outflow (expressed as percentage ÷ 100).

S_i = average salinity of Gulf inflow through inlet into the estuary, ppt.

Q_e = net quantity, in acre feet, of evaporation from bay surface minus rainfall on bay surface minus runoff into bay.

For Baffin Bay salinity of Gulf inflow is assumed as equal to average sea water at 35 ppt. From Galveston Bay to Corpus Christi, based on extremely meager data and under present conditions of river flow into Gulf, the following range in average salinities of Gulf inflow have been assumed:

Average Salinity of Gulf Inflow

Annual Climatic Condition	S_i (ppt)
Wettest (1941)	27
High Average (1940-46)	29
Average Annual	31
Low Average (1950-56)	32.5
Driest (1956)	34

Results of these conceptual operation studies are listed in Table 2, following page; which is ready for comparison of salinities under present and future runoff conditions and to compute fresh water needs. It should be remembered that a steady-state formula does not reflect the wide seasonal variations nor salinity gradients toward lower salinities in upper reaches of runoff sources, nor hypersalinities in upper reaches when evaporation exceeds rainfall plus runoff. Based upon reasonably good spacing of inlets, the efficiency (E) of mixing was assumed as 25 per cent.

The general increase in salinities, going from east to west, will be noted. Galveston Bay salinities are always less than the nearshore Gulf. East Matagorda Bay may be able to operate wholly from its local coastal watershed – but the actual runoff to this portion of bay must be carefully determined. Matagorda Bay is compared with and without the Colorado River. This indicates that with all the Colorado River flow Matagorda Bay should have been good for oysters except for the driest year.

San Antonio Bay now has a good fresh water supply. Aransas Bay has definitely limited fresh water supply, but it does get some fresh water through limited connections with San Antonio Bay. Also, it is suspected that the present runoff used herein for Aransas Bay may be overestimated.

This particular operation study of Corpus Christi Bay is far from indicating its present condition. It will be noted that it is assumed that Corpus Christi and Boggy Slough Passes and Demit Island Channel are in place. Further, in this case the natural runoff of Nueces River before construction of Lake Corpus Christi was used to evaluate present effects as well as future river development.

TABLE 2

CONCEPTUAL AVG ANNUAL SALINITY (PPT) OF OUTFLOW FROM ESTUARIES WITH PRESENT RUNOFF AND WITH GULF INFLOW INCREASED BY INLETS BALANCED FOR EFFICIENT MIXING

ANNUAL CLIMATIC CONDITIONS	GALVESTON BAY (Enlarge Rollover)	E. MATAGORDA BAY (Brown Cedar Cut & without Colorado River)	MATAGORDA BAY (without Colorado River)	MATAGORDA BAY (with Colorado River)	SAN ANTONIO BAY (Panther Point & Cedar Bayou)	ARANSAS BAY (Mud Island Pass)	SAN ANTONIO & ARANSAS BAYS (Panther Point, Cedar Bayou & Mud Island Passes)	CORPUS CHRISTI BAY (with Corpus Christi & Boggy Slough Passes & Demit Island Channel)	BAFFIN BAY & UPPER LAGUNA MADRE (with Corpus Christi & Boggy Slough Passes & Demit Island Channel	SALINITY GULF INFLOW S_i (ppt)
Wettest (1941)	13	12	21	15	16	22	17	20	32	27
High Average (1940-46)	16	17	24	20	20	27	22	25	37	29
Average Annual	20	22	28	24	25	31	27	29	39	31
Low Average (1950-56)	28	30	33	30	31	35	34	34	41	32.5
Driest (1956)	32	39	38	35	35	39	38	39	45	34

. . . . (1)

. . . . (2) HYPERSALINE
EXCEEDS 35 ppt

The range of salinities from 32 to 45 ppt in Baffin Bay and Upper Laguna Madre is computed with the assumption that Boggy Slough and Corpus Christi Passes and Demit Island Channel are in operation; and has reduced maximum salinity from 80 ppt to 45 ppt.

There is insufficient data available to even attempt to make a conceptual study of the Lower Laguna Madre. It is, however, suspected that Mansfield Channel needs to be enlarged for proper salinity control in the Lower Laguna Madre.

SALINITY AND EURYHALINE FISH

Hofstetter[15] reports the optimum range of salinity for oysters is between 15 and 30 ppt. That is, insofar as possible, the salinity gradients over prime oyster reefs should be maintained between these limits.

Simmons and Breuer[16] reports the optimum range of salinity for redfish (channel bass) is between 20 and 45 ppt; that is, in the drier climate this is where they are most often found.

In the drier climate, satisfactory range of salinity for speckled trout (sea trout) and redfish for spawning, nursery and catching is between 10 and 45 ppt. This same range also produces shrimp.

Simmons and Breuer[16] also report that the black drum (large source of commercial meat fish) particularly like hypersalinities in excess of 45 ppt. The normal feeding habits of black drum are considered detrimental to the grass beds and consequently detrimental to sea trout, small redfish, and juvenile shrimp which use these areas as spawning and nursery grounds. The black drum can adapt quickly to wide ranges in salinity. Hence, there appears to be no need to cater to the excessive hypersaline (+45 ppt) taste of the black drum.

It appears that between the adaptabilities of the three shrimps (brown, white, and pink) satisfactory shrimp production can be maintained within the approximate ranges of 5 or 10 to 40 or 45 ppt, considered along the entire Texas Coast. The lower salinity ranges are particularly desired for shrimp and other fish food production in selected, shallow, protected areas used as spawning and nursery grounds.

In "Crabs of Texas,"[17] it is reported that the most important blue crab can adapt itself to many different environments, and is found on all parts of the Texas Coast. Although it is more prominent in bays and around the mouths of rivers, the blue crab prospers in the Gulf as well as in brackish flats and areas of almost fresh water. The blue crabs are especially numerous in the many salt flats and shallow estuarine areas along the coast.

SALINITY CONTROL

In order to make the first step in development of a concept including salinity control over these highly variable estuaries, it is convenient, but admittedly over-simplified, to take as a postulate – provide salinity control with reasonable limits for the oyster, shrimps, speckled trout, and redfish, and then the blue crab, black drum, menhaden, and other euryhaline fish can take care of themselves.

To keep within reasonable limits, it is then convenient from the standpoint of climatic regions to take as the second postulate – keep the bays in humid climate good for oysters with maximum salinity of 30 ppt (Galveston Bay); limit hypersalinities to a maximum of 40 or 45 ppt in semi-arid and dry subhumid climate (Baffin Bay, Upper and Lower Laguna Madre, Corpus Christi Bay and Aransas Bay). Then in moist subhumid climate (Matagorda Bay and San Antonio Bay) the question remains as to whether or not these estuaries will be kept good, or restored, for oysters.

ESTUARY WATER NEEDS

In this concept, water needs of the bays are expressed in terms of the broad definition and meaning of mixed water for estuaries. Minimum fresh water needs are expressed as herein needed from the various rivers (or some alternate source) that are planned for development. Full advantage is taken of the runoff from coastal watersheds and in maximum use of Gulf water to minimize these fresh water needs. This "fresh water" may, of course, include return flows properly treated to meet the peculiar requirements of the estuary. Certain gulf inlets, restoration of bay water circulation, and special hydraulic structures for control of water distribution are needed to fulfill this concept of estuary water needs.

GALVESTON BAY

Galveston Bay now has a considerable excess of fresh water, and surely too much pollution and spoiling. It appears that its natural ability to assimilate some reasonable amounts of pollutants has been impaired by spoil banks and dikes blocking major and effective circulation patterns. Certainly, excessive abuse by hydraulic spoiling can hardly be expected to help the estuary to receive the ever-increasing reductions in clarity from return flows. In this humid climate, there is now need for some increases in salinity – not decreases in salinity from added fresh water.

It appears that low average climatic conditions (with respect to present rainfall-runoff-evaporation relations) are optimum for this estuary. This concept envisions that Galveston Bay may reasonably be preserved good for oysters, except possibly only tolerable for the driest year – but always on the annual "wet" side of water balance.

It should be remembered that live oyster reefs are an important part of the ecology of the estuary, being prime sport fishing areas as well as places to harvest oysters. Also, when the bay is good for oysters it is also good for finfish, shrimp, and crabs.

With ultimate development of the Trinity and San Jacinto Rivers, there is due to be little or no runoff during low average and driest climatic conditions, but still ample floods and spills during average and wetter years to provide fresh water to the bay. Reduction in silt load should be beneficial. There is, also, substantial runoff from local watersheds other than the Trinity and San Jacinto Rivers.

Tentative operation studies for ultimate development indicate that Galveston Bay will have no specific fresh water needs during average annual and wetter years. But to meet these conceptual conditions during low average and driest climatic conditions, the fresh water needs amount to the order of 1.0 to 1.5 million acre feet per year, in addition to the local runoff and developed river spills. Return flows are estimated to be somewhat greater than this, and can be used if it is found economically feasible to treat them properly for acceptable assimilation by the bay and estuary.

For future conditions, the average salinity of Gulf inflow and amounts of local runoff, plus river spills, plus 1.5 million acre feet in low average and driest years, are assumed as follows:

Annual Climatic Condition	Assumed Average Salinity Gulf Inflow S_i (ppt)	Assumed Future Fresh Water Million Acre Feet
Wettest (1941)	28	13.3
High Average (1940-46)	30	9.3
Average Annual	32	5.0
Low Average (1950-56)	33.5	2.2
Driest (1956)	35	1.74

The comparative salinity conditions for present and future, under these concepts, are listed below:

Galveston Bay Salinities

Annual Climatic Conditions	Avg. Annual Salinity of Outflow, ppt	
	Present	Future
Wettest (1941)	13	16
High Average (1940-46)	16	20
Average Annual	20	25
Low Average (1950-56)	28	30
Driest (1956)	32	33

For comparison, the future salinities for wettest, high average, and average climatic conditions are computed without any return flow – indicating that only during low average and driest climatic conditions is there any specific fresh water needs, including properly treated return flows.

Galveston Bay naturally has somewhere near its full potential of Gulf water interchange, but East Galveston Bay needs improved circulation and increase in salinity in the upper reaches through Rollover Pass. It is believed that proper investigations and water interchange analyses will show something like 2.0 to 4.0 million acre feet of inflow per year. For illustration, 3.5 million acre feet per year is shown. The enlarged pass is not expected to make a very material change in total inflow to the overall Galveston Bay System – but it will improve circulation and efficiency of mixing, and increase salinity in the east half of East Galveston Bay.

As a starter for possible investigation of this enlarged Rollover Pass, the first approximation indicates: length 7000 ft.; bottom width 350-500 ft.; depth 7 or 8 ft.; and with 1 on 5 side slopes. Balanced length will need to be "created," probably by designed spoil banks. Interior end around the Intracoastal waterway may have to be designed as a sand catchment basin for dredged "sand bypassing" up to 80,000 cu. yd. per year of littoral sand to the downdrift (west side) beach. It may be found desirable to relocate the Intracoastal Waterway from the bay end of this pass. If so, no spoil disposal should be permitted across East Galveston Bay. Additional right-of-way will be needed.

The major obstructions to natural water circulation within Galveston Bay will probably be found to be Atkinson Island (old ship channel spoil bank just below Morgan Point) and the Texas City Dike. Restoration of some of this natural circulation to help assimilation of polluted bay waters should be given careful study and serious consideration. Any openings for circulation across the Texas City Dike will have to be by bridge, in order to retain this now valuable recreation facility. It is understood that both the Texas City Dike and Atkinson Island were constructed to minimize the return flow of hydraulic spoils conveniently placed along side the navigation channels.

As a suggestion, to help prevent fish kills where the polluted Houston Ship Channel flows into Galveston Bay, the old combined sewers in the central area should be completely separated; and consideration may well be given to the possibilities of mixing stratified flows and restoration of dissolved oxygen by air injection across the bottom of channel. Such mixing has been accomplished by air bubbles, as reported for instance in "Pneumatic Barrier Against Salt Water Intrusion."[18]

MATAGORDA BAY

With respect to the oyster in Matagorda Bay, the following is quoted from "Return Flows – Impact on Texas Bay Systems."[19]

> "There are six extensive oyster reefs in Matagorda Bay, and none of them is harvested extensively. The Matagorda area was, in years past, one of the centers of oyster production on the Texas coast. In the past two decades, the production from this area has declined to the point of insignificance. Only one major reef, Middle Ground Reef, is of commercial value. However, it has been closed to oystering since September, 1961, when Hurricane Carla destroyed the sewage treatment plant at Palacios and the State Health Department closed the area in which the reef is located. The other reefs in the Matagorda area are not worked extensively because of poor quality of oysters or shallow waters."

This long-term decline and fall of the commercial oyster in Matagorda Bay might be hindcast (from Table 1, Annual Rainfall-Runoff-Evaporation Relations and Table 2, Annual Salinity of Outflow from Estuaries) as being due to the diversion of most of the Colorado River flow from the bay to the Gulf. The annual water balance changed, for low average climatic condition, from plus 0.69 million acre feet with Colorado River to a minus 0.09 million acre feet without the river. For the driest year, an annual deficiency of minus 0.29 million acre feet was increased to minus 0.86 million acre feet. With the river, salinity for the low average climatic condition was at the upper optimum of 30 ppt for oysters. Without the river, salinities appear to be running a little too high for the oyster.

In order to consider restoration of the oyster, it is first forecast that average annual salinity of Gulf inflow in the future will be 28, 30, 32, 33.5 and 35 ppt, ranging from the wettest to driest climatic conditions. For future average and wetter years there is substantial runoff from local watersheds other than the developed rivers. Data on future spills from Colorado and Lavaca are not available. Then operation studies indicate that fresh water releases from the Colorado and Lavaca Rivers as listed below would need to range from 0.6 to 1.5 million acre feet per year to restore salinity conditions optimum for the oyster – except for the driest year.

Matagorda Bay – To Restore Oyster

Annual Climatic Condition	Annual River Releases – Million Acre Feet	Assumed Local Runoff – Million Acre Feet	Average Annual Salinity Outflow ppt
Wettest	0.6	0.85	23
High Average	0.6	0.64	27
Average	0.6	0.47	29
Low Average	1.5	0.17	30
Driest	1.5	0.02	32

On the other hand, to preserve the shrimp and crab and possibly improve the finfish, it appears that Matagorda Bay might operate quite well from its own coastal watershed during climatic conditions wetter than average – but river releases of the order of 0.3 million acre feet per year may be needed with conditions at and below average to maintain spawning and nursery grounds and certainly to limit salinities below 40 ppt, as

Matagorda Bay – Preserve Shrimp and Crab & Improve Fin-Fish

Annual Climatic Condition	Annual River Releases – Million Acre Feet	Assumed Local Runoff – Million Acre Feet	Average Annual Salinity Outflow ppt
Wettest	0	0.85	25
High Average	0	0.64	28
Average	0.3	0.47	30
Low Average	0.3	0.17	34
Driest	0.3	0.02	39

There appears to be no reasonable chance in the future to get enough (additional 1.2 million acre feet annually for low average condition) fresh water to restore the oyster in Matagorda Bay. Hence, the annual fresh water needs for Matagorda Bay in this concept are listed as 0.15 million acre feet from the Colorado River and 0.15 million acre feet from the Lavaca, or 0.3 from other sources. Then the so-called average "runoff" in the future would amount to 0.77 million acre feet annually (0.3 + 0.47).

In order to secure maximum benefits to spawning and nursery with minimum fresh water, the circulation, salinity pattern and salinity gradients should be plotted and then consider controlled releases to Lavaca, Carancahua, and Tres Palacios Bays to provide controlled salinities when and as found needed.

East Matagorda Bay (the severed and forgotten arm) has been cut off from Matagorda Bay by the Colorado River delta across this arm of the bay. It is now cut off from direct Gulf connection by natural closure of Brown Cedar Cut. This cut needs to be relocated opposite deeper water in the bay and designed to provide say about 2.5 million acre feet of Gulf inflow per year. For first approximation it is sized: length 8,000 feet; bottom width 350 feet; depth 10 feet; and side slopes of 1 on 5. Stabilization works, depth and section controls, and designed use of spoil for length control are contemplated.

Very careful accounting of the rainfall – local runoff – evaporation relations for East Matagorda Bay is needed. In the meantime, it appears from Tables 1 and 2 that, with the relocated Brown Cedar Cut, East Matagorda Bay may well operate without any controlled releases from the Colorado River.

SAN ANTONIO BAY

San Antonio Bay, including Espirutu Santo, Ayres, Hynes, and Mesquite Bays is by all classifications strictly a median bay. It is intermediate in size and in unit production of the basic control fish – finfish, crab, oyster, and shrimp. It has neither good Gulf water interchange nor is it completely choked like the Upper Laguna Madre. Its distinctions are: (1) forecasts indicate a six-fold increase in man-days fishing activity (recreation) instead of two-fold increase for other bays; (2) it is located along the Aransas National Wildlife Refuge; (3) extreme municipal and industrial expansion is, at least, not yet forecast around this bay; and (4) it has no significant local runoff, depending almost entirely on San Antonio and Guadalupe Rivers for fresh water.

With the present and tentatively proposed full development of the San Antonio and Guadalupe River, practically all fresh water flow will be cut off from San Antonio Bay. Then, with little return flow and its present limited Gulf water interchange, salinities will literally skyrocket to excessive hypersalinity. It is then forecast that there will be a massive, man-made, oyster kill in San Antonio Bay.

To keep and improve this estuary for good oyster production, it is first assumed the salinities must be kept below 30 ppt. The minimum computed releases from the future developed San Antonio and Guadalupe Rivers that will probably be needed are compared below with the present runoff.

San Antonio Bay – For Oysters

Annual Climatic Condition	Present Annual Runoff Million Acre Feet	Future Annual Releases Million Acre Feet
Wettest (1941)	3.3	0.1
High Average (1940-46)	2.1	0.2
Average	1.4	0.5
Low Average (1950-56)	0.6	0.8
Driest (1956)	0.3	1.1

Whether this would work will also probably depend on the nature of spills (presently not known) from the future developed rivers. For good oyster production it is assumed that the salinity gradient should vary down toward the lower limit of 15 ppt at times, and it may be found that Panther Point Pass would not be desired with oyster culture.

On the other hand, if it is desired to prepare for the impact of six-fold increase in recreation and sport fishing, the production of trout and redfish and the fishery might well be improved for recreation by control of salinities between 20 to 40 ppt and by providing improved Gulf water interchange.

It is then assumed that Panther Point and Cedar Bayou Passes are installed and that with future over-all river development the salinity of the nearshore Gulf will tend to increase somewhat – say like 29, 31, 33, 35 and 37 ppt for the five climatic conditions from wettest to driest. Then with uniform releases (probably into Hynes Bay) for all years but amounting to only about 0.3 million acre feet per year, which is about the minimum present flow for the driest year, the computed salinity ranges are compared below with those listed in Table 2 for present runoff conditions.

San Antonio Bay – For Recreation

Annual Climatic Condition	Present Annual Runoff Million Ac Ft	Avg. Annual Salinity of Outflow, ppt with Present Runoff	Avg. Annual Salinity of Outflow, ppt Future – with 0.3 Million Ac Ft
Wettest (1941)	3.3	16	27
High Average (1940-46)	2.1	20	29
Average	1.4	25	32
Low Average (1950-56)	0.6	31	36
Driest (1956)	0.3	35	39

Now to weigh the problem of oyster versus recreation in San Antonio Bay, the following considerations are offered: (1) with the future desperate search for fresh water, it is the basic concept herein to consider making maximum use of Gulf water to minimize the fresh water needs of the estuaries; (2) the fresh water needs for recreation in this estuary appear to be about half that needed for the oyster; (3) it is forecast that man-days fishing (recreation) will increase six-fold in San Antonio Bay; and (4) evaluation cited herein does indicate that recreation, now or later, may be worth ten times commercial fishing.

From all this, it is then foreseen that at least in this estuary recreation will probably win out over the oyster; so the fresh water needs for San Antonio Bay from the combined San Antonio and Guadalupe Rivers is noted at 0.3 million acre feet per year.

If this concept is followed, it must be realized that sooner or later there will likely be considerable oyster mortality in San Antonio Bay. This will open the way for legal exploitation of the "dead" shell reefs – which are still very valuable to the fishery.

Surely, there must be a way to give the coastal fisheries the needed legal, technical, scientific and engineering backing to let there be reasonable production of excess shell and still leave the fishery in somewhat better condition – instead of the way it has been done in the past.

A balanced inlet, Panther Point Pass, to provide about 6.3 million acre feet per year of Gulf inflow to San Antonio Bay may be located across Matagorda Island about 2 miles west of Panther Point and connecting with the deeper water in San Antonio Bay. It is located about 3 miles west of the west boundary of the Matagorda Island gunnery range. This is a substantial sized pass, which by first approximation is indicated with dimensions of: length 14,000 feet; bottom width 500 feet; depth 17.5 feet; side slopes 1 on 5; and area of 10,000 square feet. Stabilization works and depth control sills at Gulf end are contemplated. A bridge over the pass will be needed and ample right-of-way (say at least one mile wide) should be secured for both construction and public use.

Mesquite Bay is naturally restricted for water interchange between San Antonio and Aransas Bays. Cedar Bayou may be balanced by shortening to about 11,000 feet length with Gulf inflow increased from nil to about 2.1 million acre feet per year. First approximation sizing indicates: bottom width 220 feet; depth 12 feet; side slopes 1 on 5; and area of 3,360 square feet. Stabilization works, control sills, and a bridge are contemplated; as well as ample right-of-way about one mile wide across Matagorda Island.

ARANSAS BAY

Aransas Bay with Copano Bay is poor for commercial oyster production but excellent for finfish and blue crab and good for shrimp. From p 154 of "Tidal Waters of Texas,"[7] it is apparent that only in years of above-normal precipitation does the salinity of Aransas Bay fall low enough to be considered an optimum oyster environment.

In 1963-64 with low average climatic conditions there was a serious oyster mortality. During this period the salinities at test platforms ranged from 28 to 42 ppt, while optimum upper limit for oysters is 30 ppt. The lower salinities were recorded after the higher salinities. It will be noted from Table 1 that for low average climatic condition evaporation exceeds rainfall plus runoff by 0.27 million acre feet per year. If Mud Island Pass, which would tend to moderate the highest salinities, had been installed it is likely that there would have been no material help for the oyster. It will be noted from Table 2 that with Mud Island Pass and present runoff conditions the average-weighted salinity of outflow for average annual climatic conditions is computed at 31 ppt. This agrees with the statement that only in years of above-normal rainfall does the salinity of Aransas Bay fall low enough to be considered an optimum oyster environment.

It does not appear reasonable to attempt to improve conditions for the oyster in Aransas Bay. But the reefs, with or without live oysters at all times, should be strictly preserved and protected for the ecology of the fishery.

It is then the concept to limit design salinity of Aransas Bay to 40 ppt. For the five climatic conditions, wettest to driest, it is assumed that average salinity of Gulf inflow will be – 29, 31, 33, 34.5 and 36 ppt. Operation studies indicate that fresh water needs from the Aransas and Mission Rivers amount to approximately 0.15 million acre feet per year; and the Gulf water needs are Mud Island Pass with 4.0 million acre feet of inflow per year. The present and future salinity conditions along with releases plus local runoff, compare as follows:

Aransas Bay Salinities

Annual Climatic Condition	Future 0.15 plus Local Runoff Million Acre Feet	Avg. Annual Salinity Outflow, ppt	
		Present with M.I. Pass	Future with M.I. Pass
Wettest	0.47	22	26
High Average	0.31	27	30
Average Annual	0.24	31	33
Low Average	0.19	35	36
Driest	0.154	39	40

Mud Island Pass is tentatively located S 30° E across St. Joseph Island and Blind Pass, at the junction of Mud Island, and connecting with the deeper water of Aransas Bay. For annual Gulf inflow of 4.0 million acre feet, first approximation formulas indicate size of pass as: length 9,000 feet; bottom 440 feet; depth 12 feet; and area 6,000 sq. ft. Stabilization works, control sills, and ample right-of-way at least one mile wide across St. Joseph Island is contemplated, which includes a short landing strip and a building.

In "Abnormal Marine Ecosystems of Texas,"[20] it is reported that Copano Bay receives extensive bleedwaters (pollution from oil field brine wastes). Proper accounting of these saturated salt solutions should be included in the mixed-water balance and salinity equation and studies of salinity gradients. Part of the design intent is to produce lower salinities in Copano Bay with a minimum of fresh water releases into that Bay. It may be found that this oil field pollution should be stopped before precious fresh water is released to "freshen" the Copano Bay waters.

CORPUS CHRISTI BAY

Corpus Christi Bay is already suffering from the impact of Nueces River development. The Texas Coast for the last 3 or 4 years has been under low average climatic conditions. Water hoarding (holding water for future use that is not presently needed and thus not available as return flow) by Lake Corpus Christi appears to be the basic cause of extreme hypersalinity, measured at about 55 ppt, in Nueces Bay.

Corpus Christi Bay has practically no other source of runoff than the Nueces River. Annual average runoff has already been reduced from about 610,000 to 505,000 acre feet per year. With contemplated future developments there will be no river flow into Corpus Christi Bay in 13 out of 16 years. Present return flows amount to only about 35,000 acre feet per year, but five times this much (177,000 acre feet per year) is forecast for the year 2020. With the enormous burden of excess evaporation over rainfall and runoff – minus 1.38 million acre feet in the driest year from Corpus Christi and Baffin Bay and Upper Laguna Madre – Corpus Christi Bay is certainly in poor condition to assimilate this future pollutional load. In 1953, Donald W. Hood[8] concluded that this bay would be one of the easiest bays in the Texas Bay System to contaminate with non-metabolizable wastes or noxious materials.

It appears that Nueces and Corpus Christi Bays are seriously threatened with undue and intolerable hypersalinity, and more pollution than it can assimilate – even from fairly well treated return flow.

Under present conditions, Corpus Christi Bay needs more than all the natural runoff from the Nueces River. The first water need is ample Gulf water to relieve the extreme hypersalinity of the adjacent Upper Laguna Madre and Baffin Bay. This may be done by the Corpus Christi and Boggy Slough Passes and Demit Island Channel. See References 21 and 22 for reports on these passes and channel.

With this relief, it is then believed that proper investigations and operation studies will indicate that the fresh water needs of Corpus Christi Bay amounts to about 0.15 to 0.20 million acre feet per year. It is the intent of this concept to limit maximum salinities (weighted average) to around 40 ppt in Corpus Christi Bay and 45 ppt in Nueces Bay.

This estuary is not now a commercial oyster producer and this concept does not attempt to make it one. Nevertheless, any reefs that might develop oysters during wetter years certainly should be preserved as good for the ecology of the estuary.

The problem is complicated in Nueces Bay, where salinities are now up to 55 ppt. In "Abnormal Marine Ecosystems of Texas"[20] it is pointed out that cooling water is drawn from the ship channel and harbor and pumped into Nueces Bay at a rate of 155 million gallons per day. Nueces Bay salinity varied from 1 to 45 ppt during the period of study (1960-61-62), but salinities have recently gone up to 55 ppt. This circulation, possible increase in evaporation rates in the shallow Nueces Bay, points of return flow, the need for some "make-up" water, and control of releases for maximum benefits with minimum fresh water must be considered in the detailed investigation of this estuary. These studies should include determination of whether any openings in spoil banks are needed for circulation of mixed waters in Corpus Christi Bay.

With Corpus Christi and Boggy Slough Passes and Demit Island Channel in place and with natural runoff in Nueces River (before Lake Corpus Christi) the variations in salinity are listed in Table 2. This is compared below with future runoff conditions plus 0.18 million acre feet per year of treated return flow and releases, and with salinities of Gulf inflow ranging from 29 to 36 ppt from the wettest to driest years.

Corpus Christi Bay Salinities

Annual Climatic Conditions	Average Annual Salinity of Outflow, ppt Natural Runoff with Passes	 Future Runoff With Passes
Wettest	20	24
High Average	25	29
Average Annual	29	34
Low Average	34	36
Driest	39	40

The point is, this estuary needs the fresh water now – not in the year 2020.

BAFFIN BAY AND UPPER LAGUNA MADRE

Baffin Bay, particularly and partly the Upper Laguna Madre, may best be described as a turbid, dark brown, polluted, dead sea – instead of a live estuary. It is naturally polluted with excessive hypersalinity and aided and abetted by man to remain so. It is not a live estuary because normal Gulf tides do not reach a river current. The "tides" are mostly wind-induced tides that simply rock the polluted waters back and forth. This polluted water is "bled" off by stratified (density) flow into Corpus Christi Bay. Baffin Bay is the home of the rooting, salt-loving black drum – but even it is sometimes blinded by the extreme salinities. Extensive land areas are being blighted by wind transported salt from the flats of this dead sea.

The almost final closing of its limited natural life line of flow between Demit and Pita Islands (next to Corpus Christi Bay) is used herein as the horrible example of man's spoiling. This is the proposed location of Demit Island Channel.

The Baffin Bay System has no specific fresh water needs from the Texas Water Plan – but it does need a large inlet connection with Gulf water, so it may enter the family of live estuaries along the Texas Gulf Coast.

The problem has been studied, well investigated, and reported to the Texas Game and Fish Commission (now Texas Parks and Wildlife Department). See References 21 and 22. Solution to the problem consists of: (1) Boggy Slough Pass – 11.5 million acre feet annual Gulf inflow; (2) Corpus Christi Pass – 3.5 million acre feet annual Gulf inflow; and (3) Demit Island Channel – 2.2 million acre feet inflow from Corpus Christi Bay to Upper Laguna Madre.

It will be noted that Boggy Slough Pass is located opposite Baffin Bay and across the Padre Island National Seashore. If road access and a large State Park could be located on the shores of Baffin Bay near Boggy Slough Pass, it would certainly help the Texas Coast to take the impact of recreational demands as now projected.

SUMMARY OF WATER NEEDS

Under this concept of making maximum use of Gulf water to minimize the fresh water needs of the bays and estuaries, it is forecast that intensive investigations and studies will show the water needs to be on the order of:

Annual Water Needs – Million Acre Feet

Estuary	Local Runoff	Fresh Water	Gulf Water
Galveston Bay	5.0	1.5	3.5
East Matagorda Bay	0.3	0.0	2.5
Matagorda Bay	0.47	0.3	0.0
San Antonio Bay	0.0	0.3	8.4
Aransas Bay	0.09	0.15	4.0
Corpus Christi Bay	0.0	0.2	3.5
Baffin Bay System	0.0	0.0	11.5
Totals	5.86	2.45	33.4

It should be remembered that fresh water needs are expressed as either releases or treated return flow from the pertinent developed rivers and that local runoff is simply listed as average annual. Gulf water is listed as amount of inflow through the suggested inlets.

SUMMARY OF POSSIBLE INLETS AND STRUCTURAL MODIFICATIONS

Suggested herein for intensive investigation, study, and consideration for possible use in the preservation and enhancement of the bays and estuaries are the following gulf inlets, modifications in water circulation, and other hydraulic control structures:

1. Galveston Bay. Enlarge Rollover Pass at east end of East Galveston Bay to improve circulation and increase salinity. Restore some of the natural bay water circulation by openings in Atkinson Island and by bridges in the Texas City

Dike. Determine the location, time and rates of specific fresh water releases – if treated return flows do not supply fresh water needs.

2. Matagorda Bay. Relocate Brown Cedar Cut opposite deeper water near east end of East Matagorda Bay; and verify, or modify the tentative assumption that no specific fresh water releases will be needed for this arm of Matagorda Bay. Determine the location, time, rate, and distribution of specific fresh water releases – which will probably be to Lavaca, Carancahua and Tres Palacios Bays.
3. San Antonio Bay. If sufficient fresh water is not made available to maintain the commercial oyster in San Antonio Bay, then install Panther Point Pass. Shorten Cedar Bayou to provide a balanced Gulf inlet to Mesquite Bay. Determine the proper location (possibly Hynes Bay), time, rates, and distribution of specific fresh water releases.
4. Aransas Bay. Install Mud Island Pass; and determine location, time, rates, and distribution of the specific fresh water releases. These releases will probably be divided into Copano, Mission, and St. Charles Bays.
5. Corpus Christi Bay. Provide Corpus Christi Pass and Demit Island Channel as part of the program to control hypersalinities in this bay and adjacent to Laguna Madre. Determine distribution and rate of fresh water releases into Nueces Bay. Determine whether any openings in spoil banks are needed for proper and efficient circulation of mixed bay waters within Corpus Christi Bay.
6. Baffin Bay and Upper Laguna Madre. Construct Boggy Slough Pass, including intensive studies to locate somewhat extensive spoil removal to definitely provide and restore much needed bay water circulation.
7. Lower Laguna Madre. Make water balance and salinity control studies of the Lower Laguna Madre to determine whether Mansfield Channel needs enlargement.

Finally, in order just to start consideration of this concept, it is mentioned that the "order of magnitude" of cost of all these gulf inlets may be found to be somewhere around $30 million, more or less.

BASIC DATA NEEDS

In order to change the herein so-called "illustrative" numbers into literal numbers, a considerable amount of vital basic data must be secured and put into usable form.

COMMUNICATION AND LIAISON

The first need is for improved communication and close liaison between many divisions of the scientific and engineering community. The problems are many and complex. To solve them will require the cooperative work of – marine scientists, marine fishery biologists, coastal engineers, geologists, hydraulic engineers, sanitary engineers, hydrologists, hydrographers, cartographers, waterway engineers, and others.

ANALYSIS OF TIDAL DIFFERENTIALS

Many tidal readings have been taken along the coast, but very little has been put into usable form insofar as the problems at hand are concerned. For each bay, some additional tidal readings are needed. The scientific sampling, analysis, and plotting of tidal differentials to put this vital basic data into usable form is covered in Reference 21 and in "Design of Inlets for Texas Coastal Fisheries."[23]

SALINITY DISTRIBUTION AND GRADIENTS

Typical synoptic maps of horizontal salinity distribution, shown as isohalines, of the bay systems are needed – along with simultaneous measurements of all quantities used in the mixed-water balance and salinity operation studies. Typical profiles of salinity gradients, including vertical differentials, and study of stratified flow are needed.

TYPICAL CURRENTS AND CIRCULATION

Synoptic maps of the typical current directions, strength, and circulation patterns are needed. For instance this would include: with tropic and equatorial tidal inflow and outflow; with fresh northerly winds; and with fresh southerly winds.

RAINFALL-RUNOFF-EVAPORATION RELATIONS

The use of inland based evaporation stations to estimate gross evaporation from the surface of these large bays has been and should be seriously questioned. Complete weather stations properly located are needed to permit both direct measurement and theoretical computation of the evaporation from these bays located between the gulf and the inland evaporation stations, as well as rainfall on the bay surface.

Careful accounting of both present and future runoff into the various pertinent parts of these bays and estuaries is needed and must be properly segmented for the specific need of making operation studies of the bays – both separate and as part of the complete water system.

EFFICIENCY OF MIXING

Insofar as is presently known, the best way to determine the efficiency of mixing for the various estuaries is to carefully measure all quantities for a given time that go into the "mixed-water balance and salinity formulas" and simply solve for E (efficiency of mechanical mixing). It should be noted that difference in salinities of inflow and outflow should amount to 5 ppt, or more, when using this technique. At times, the formulas for tidal flushing may be used to determine the efficiency of tidal mixing.

HYDRAULIC MODELS – INLETS

The basic formulations for dynamic balance in design of Texas Coastal inlets to permit efficient gulf water interchange for salinity control and fish passage through the littoral barriers have been developed and published in "Design of Inlets."[23] The final conclusion in this technical paper is quoted:

> "To verify and refine the design, there is now a distinct need for the use of hydraulic models with movable bed to complete the design stage and then the construction of an inlet balanced in accordance with criteria and formulas developed herein."

CLASSIFICATION MAPS

One of the best ways to start communication on the problem of preservation and enhancement of the estuaries is to have prepared good and complete classification maps of the bays – from the specific viewpoint of the fishery. These maps should show important spawning and nursery grounds, and particularly all shell reefs – with or without commercial live oysters – that are of real value to the fishery.

PLANNING FOR ESTUARY PRESERVATION AND ENHANCEMENT

After fulfilling the basic data needs, it is this concept that complete planning for the mixed water needs for preservation and enhancement of the coastal bays and estuaries may well be along the following lines:

1. Maximize the use of gulf water to minimize the needs for fresh water.
2. Reduce pollution by treatment to some tolerable amount that may be assimilated by the bays; and at the same time restore or improve bay water circulation and improve efficiency and distribution of gulf water interchange to help the bays assimilate these return flows.
3. Get the maximum benefits out of minimum fresh water by designed and controlled releases to selected and valuable spawning and nursery areas.
4. There remains, as a major and basic water planning decision, the fate of the commercial oyster in San Antonio and Matagorda Bays.
5. When and where it is planned to preserve and enhance the bays and estuaries for recreation and fisheries – and considerable funds are expended to do this – then surely the planning should include curing the matter of hydraulic dredge spoiling by placing it under some responsible control, in order to protect the corrective and improvement investments, as well as this valuable heritage.
6. When and where the future inevitable reduction of fresh water flow to these bays and estuaries may be involved in oyster mortality, surely the planning can find reasonable ways and means to either save or replace these valuable reefs – and at the same time permit reasonable and valuable mining of shell that is of no use to the fishery.
7. There remains to be accomplished, at least along the Texas Coast, the construction of a Gulf inlet with proper balanced design based on adequate basic data. If gulf water is used to minimize fresh water needs, the planning may well profit by observation of the awful examples of the past imbalanced inlets.

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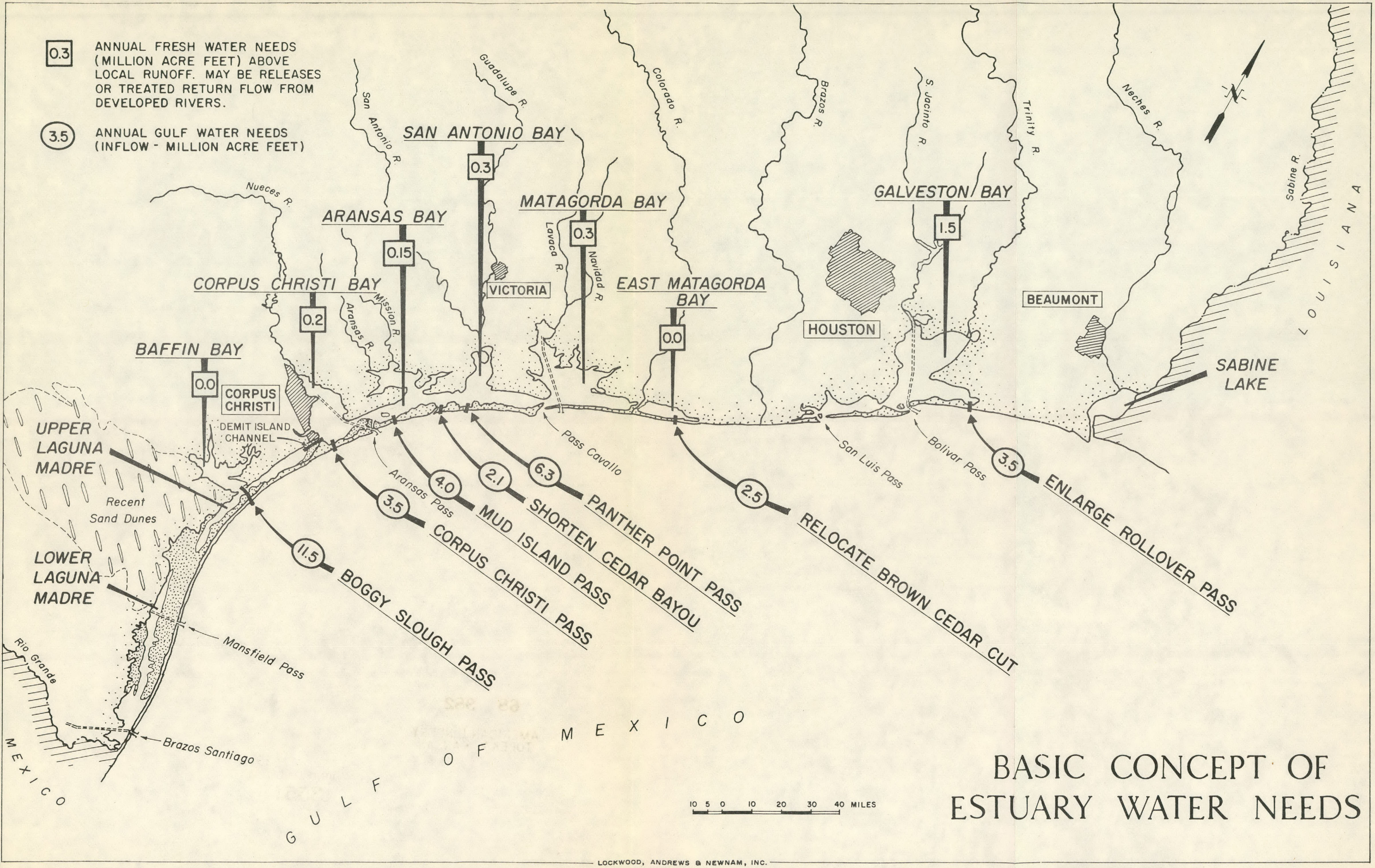

BASIC CONCEPT OF ESTUARY WATER NEEDS

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