TEXAS WATER DEVELOPMENT BOARD

REPORT 38

ADDITIONAL TECHNICAL PAPERS ON SELECTED ASPECTS OF THE PRELIMINARY TEXAS WATER PLAN

Four Technical Papers
Presented at the February 6-9, 1967
ASCE Environmental Engineering Conference

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FOREWORD

The Texas Water Development Board has, in compliance with the requirements of the Water Resources Administration Act, prepared a preliminary Texas Water Plan and held 27 public hearings in river basins throughout the State on its preliminary Plan. In addition, the Board held three public meetings to assure the widest possible distribution of information concerning the Plan. At each of these hearings, the Board presented its preliminary Plan for development of the river basin in which the hearing was held, outlined proposed diversions that were a part of the Plan, and invited the views, comments, criticisms, and suggestions of those interested in water development.

The Water Resources Administration Act, directing the preparation of the Texas Water Plan and the hearings, requires that "thereafter in preparing its Plan the Board shall give consideration to the effect such Plan will have on the present and future development, economy, general welfare, and water requirements of the areas of such river basin" or "of the areas affected."

On September 21, 1966 the Board released a statement relative to the preliminary Plan and outlined a program of work to examine in as much detail as is logical and feasible each of the many valid suggestions, criticisms, and proposals for Plan modification or alternatives to the proposed Plan.

The Board's policy of providing the widest possible distribution of information concerning the preliminary Plan has been continued, with publication in September, 1966 of Report 31. That report contained three technical papers on selected aspects of the preliminary Plan. Four technical papers on additional selected aspects of the preliminary Texas Water Plan were presented at the February 6-9, 1967 National Environmental Engineering Conference sponsored by the American Society of Civil Engineers.

Three of the papers were prepared by personnel of the Board's staff. The fourth, "Tidal Inlets for Preservation of Estuaries" by Mason G. Lockwood and H. P. Carothers, contains the results of investigations made by the firm of Lockwood, Andrews and Newnam, Inc., Consulting Engineers, under contract with the Board.

These four papers describe information relative to the preliminary Plan and do not reflect possible modifications to the Plan which may result from the program of work outlined by the Board in its September 21, 1966 statement.

Texas Water Development Board

Joe G. Moore, Jr.

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Executive Director

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THE ROLE OF GROUND WATER IN THE TEXAS WATER PLAN

Introduction

The Texas Water Plan is a flexible proposal for the protection, conservation, development, redistribution, and administration of water resources to meet water needs throughout the State to the year 2020 and beyond. The Plan is geared to the optimum utilization of the State's water resources to meet projected needs for water for all purposes. Surface water, underground water, return flows, low quality water, and desalted brackish water were included in the studies of the total available supply.

Preparation of the Texas Water Plan was accelerated in August 1964 following receipt of a letter from Governor John Connally requesting it and providing emergency funds for the program.

The Texas Legislature had adopted a Water Planning Act in 1957. In December 1958 the State agency (then the Board of Water Engineers) produced a report describing in some detail the status of availability of various data and information, and outlining the programs necessary to provide the foundation data for preparation of a Texas Water Plan. Ground-water investigations proposed included reconnaissance studies for each river basin, followed by detailed studies of most areas of the State, and continuing programs of monitoring areas and maintaining data on a current basis after detailed studies had been made. The reconnaissance program for the entire State was completed in August 1963. Detailed studies on an individual county or groups of counties were available for 25 percent of the State on September 1, 1965. These sources, plus a tremendous additional volume of data for the High Plains and other areas formed the basis for the ground-water evaluations made in preparing the Texas Water Plan.

The preliminary draft of the Plan was completed in May 1966. It was prepared in two parts: (1) a preliminary State planning report, now in draft form, proposing the overall distribution of the water of the State; and (2) detailed preliminary plans for each of the river and coastal basins in the State which summarize information of the State Plan relating to each basin. Twenty-seven public hearings were held during the summer months of 1966 to present the preliminary Plan and to receive testimony regarding these plans.

From information presented in the basin hearings, additional studies of alternatives and possible modifications to the preliminary Plan are being made now by the Water Development Board.

After completion of these studies and possible modifications, the Plan must then be tentatively adopted by the Texas Water Development Board and referred to the Texas Water Rights Commission for a hearing to determine that water rights are adequately protected and that the Plan takes into account modes and procedures for the equitable adjustment of water rights affected by the Plan. When the Water Rights Commission determines that the Plan meets these objectives, and certifies same to the Texas Water Development Board, the Board may then finally adopt the Plan.

Following adoption of the Plan by the Water Development Board, it will then be printed in final form for presentation to the Governor and to the Legislature, and for distribution to the people of Texas. While the Texas Water Plan does not require formal adoption by the Texas Legislature, it may contain recommendations for statutory changes to secure implementation of some units in the years ahead. On its completion and adoption by the Board, the Plan will be a flexible guide to the development of the State's water resources into the next century. Its flexibility will only be possible by a continuing program of evaluation of changes.

This plan differs from the many other plans which now line your bookshelves in that for the first time the entire State was examined in the light of water availability and requirements projected into the next century. It is different because it proposes the means to implement the Plan's components. And, it is different because for the first time ground water has been given extensive attention and is being relied upon to supply a large segment of the future water needs.

The primary reason for including ground water is its history of past use and the economics of using ground water. In the past ground water has been--and presently is--relied on to supply the larger share of the State's water requirements. More than 1,000 municipalities in the State depend on ground water for their public supply. And, as long as the supply is adequate, many of them will remain on ground water in the future because it is far less expensive than the surface-water supplies they could obtain. The quantity of ground water pumped for municipal, industrial, and irrigation purposes in 1960 was 12,170,000 acre-feet, as compared with 3,340,000 acre-feet of surface water. It is only reasonable to assume that ground water will continue to be an important segment of the overall supply.

Under Texas Law, unappropriated waters of rivers or natural streams belong to the State. The use of this water is obtained through Certified Filings and Permits which fall under the jurisdiction of the Texas Water Rights Commission. However, in the case of ground water there is a different situation. Ground water belongs to the individual owning the land under which it occurs. And, the law specifically excludes ground water from management as public waters. Even though ground water is excluded from State management, it is necessary that ground water be depended upon to meet a part of the future water requirements.

Development of the Plan

The development of the Plan began with projections of water requirements which were prepared on the basis of many complex factors of future growth and change. The Plan's flexibility will provide for a continuing assessment of these changes so that development keeps pace with actual needs.

Estimates of future population and water requirements for municipalities and industries were developed by the Texas Water Development Board in cooperation with the Bureau of Business Research of The University of Texas, and from information provided through a detailed industrial use questionnaire completed by industries throughout the State. Future agricultural water requirements were prepared by the Texas Water Development Board, based on a study by Texas A & M University of the irrigation potential throughout the State. Water needs for secondary recovery by the petroleum industry were based on reports from consultants, and on estimates by Mid-Continent Oil and Gas Association.

Figure 1 shows the population projections and the resulting municipal and industrial water requirements. There were approximately 9.6 million people in Texas in 1960. The population projections show that there will be approximately 18.0 million in the State by 1990 and approximately 30.5 million by the year 2020. The resulting municipal and industrial water requirements are projected to increase from the 2.6 million acre-feet used in 1960 to 6.5 million acre-feet in 1990 and to 12.1 million acre-feet by the year 2020.

In preparing the Plan, a tentative allocation was made of the water requirements between ground and surface water, considering sources of existing supply, quality, availability, cost, dependability, and other factors. The availability and location of ground-water supplies were studied with respect to the present use and future needs. Surface-water supplies were then considered to determine the most economical source available for meeting the remaining future water requirements. Figure 2 and the following table show the municipal, industrial, irrigation, and mining water requirements for Texas in 1960 and the projected requirements for the years 1990 and 2020. Figure 2 and the table show how these requirements were met in 1960 and how they will probably be met in the years 1990 and 2020.

MUNICIPAL, INDUSTRIAL, IRRIGATION AND MINING
WATER REQUIREMENTS FOR TEXAS*

Requirement	Ground water	Surface water	Total
	1960		
Municipal and industrial....	1,500,000	1,100,000	2,600,000
Irrigation..................	10,300,000	2,200,000	12,500,000
Mining......................	370,000	40,000	410,000
Total.....................	12,170,000	3,340,000	15,510,000
	1990		
Municipal and industrial....	1,800,000	4,700,000	6,500,000
Irrigation..................	5,200,000	5,600,000	10,800,000
Mining......................	370,000	40,000	410,000
Total.....................	7,370,000	10,340,000	17,710,000
	2020		
Municipal and industrial....	2,300,000	9,800,000	12,100,000
Irrigation..................	3,000,000	6,400,000	9,400,000
Mining......................	50,000	10,000	60,000
Total.....................	5,350,000	16,210,000	21,560,000

*These requirements do not include additional out-of-state quantities essential to meet future irrigation water requirements.

FIGURE I

POPULATION PROJECTIONS AND
MUNICIPAL AND INDUSTRIAL WATER REQUIREMENTS

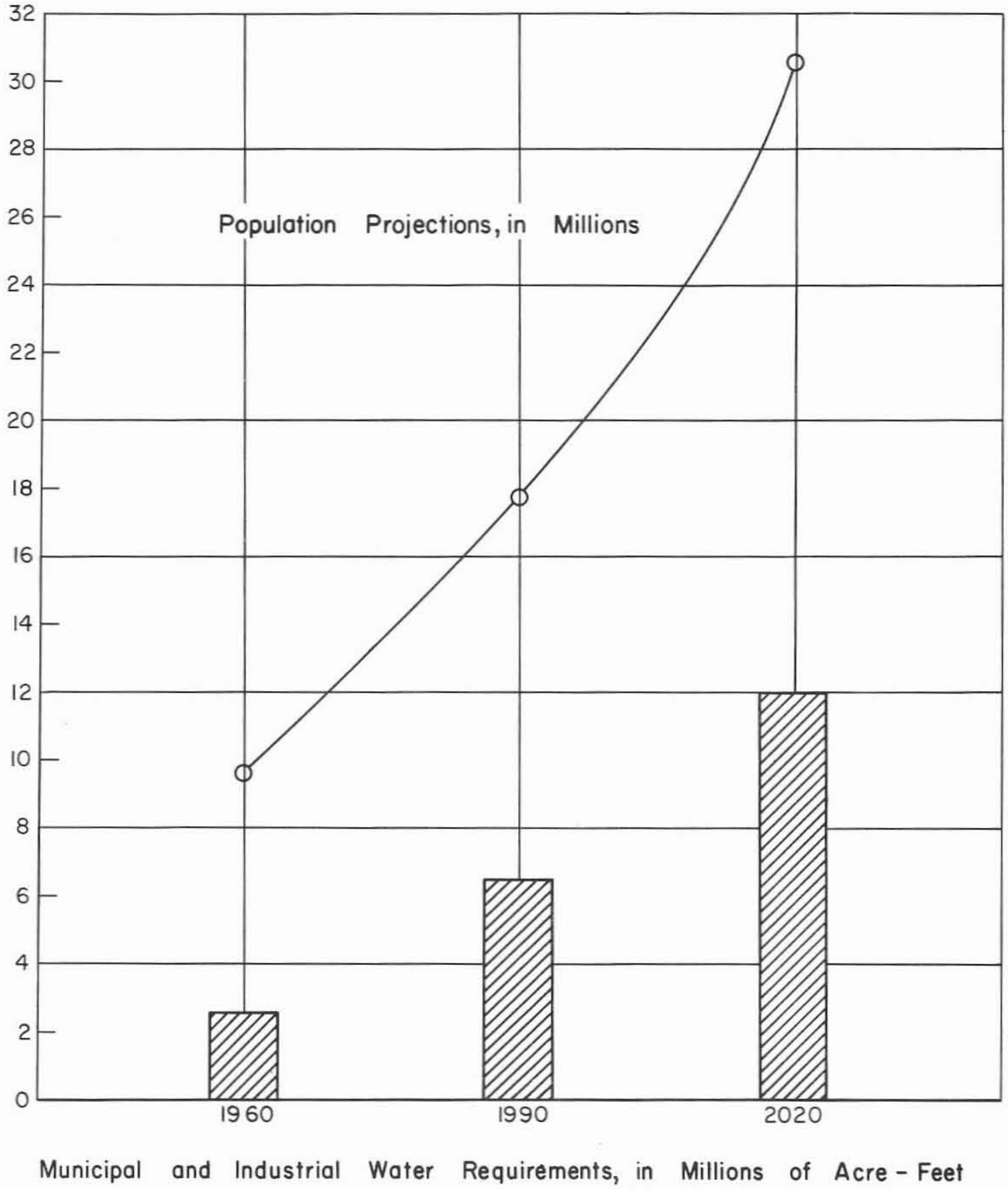
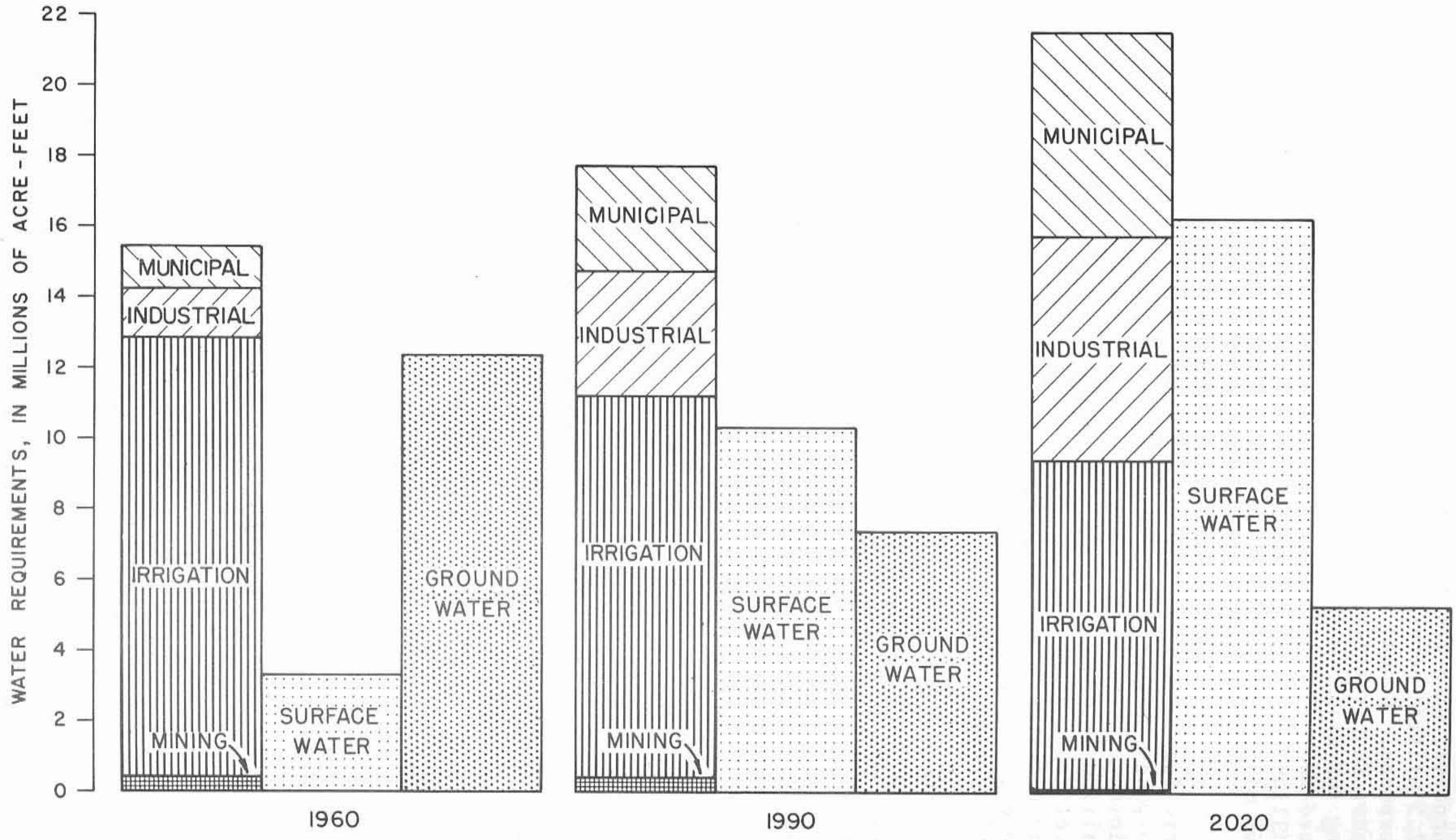


FIGURE 2

MUNICIPAL, INDUSTRIAL, IRRIGATION, AND MINING WATER REQUIREMENTS FOR TEXAS



In 1960 approximately 15.5 million acre-feet of water was used for all purposes, with 2.6 million acre-feet for municipal and industrial requirements, 12.5 million acre-feet for irrigation, and 0.4 million acre-feet for mining purposes. Ground water provided approximately 12.2 million acre-feet of these water requirements, compared to 3.3 million acre-feet for surface water. Breaking the ground water down into the various requirements we find that 1.5 million acre-feet of ground water was used for municipal and industrial purposes, 10.3 million acre-feet was used for irrigation, and 0.4 million acre-feet was used for mining purposes.

The projected water requirements for the year 1990 amount to 17.7 million acre-feet of water, with 6.5 acre-feet being used for municipal and industrial purposes, 10.8 million acre-feet for irrigation, and 0.4 million acre-feet for mining. It is anticipated that ground water will supply approximately 7.4 million acre-feet of these requirements, as compared with 10.3 million acre-feet from surface-water sources. A breakdown of the various requirements shows ground water supplying 1.8 million acre-feet for municipal and industrial purposes, 5.2 million acre-feet for irrigation, and 0.4 million acre-feet for mining requirements.

By the year 2020, the projected requirements amount to 21.6 million acre-feet of water, with 12.1 million acre-feet being used for municipal and industrial purposes, 9.4 million acre-feet for irrigation purposes, and 0.1 million acre-feet for mining purposes. By the year 2020, ground water will be supplying only 5.4 million acre-feet of these requirements, as compared to 16.2 million acre-feet supplied by surface water. Of this 5.4 million acre-feet of ground water, 2.3 million acre-feet will be used for municipal and industrial purposes, 3.0 million acre-feet will be used for irrigation, and only about 50,000 acre-feet will be used for mining purposes.

The reduction in the use of ground water from 12.2 million acre-feet in 1960 to 5.4 million acre-feet by the year 2020 is primarily because of the large quantities of water now being pumped from the Ogallala Formation for irrigation on the High Plains. The water from the Ogallala is being pumped from storage and will not be available by the year 2020. Four and four-tenths million acre-feet of the 4.8 million acre-feet of reduction in ground-water pumpage between 1960 and 1990 is due to Ogallala depletion. One and seven-tenths million acre-feet of the 2 million acre-feet of ground-water pumpage reduction between 1990 and 2020 is also due to Ogallala depletion. The mining requirements will also be reduced, because most of the water is being used for water flood or secondary recovery operations, and it is anticipated that by the year 2020 most of the secondary recovery operations will have been completed. Contrary to the diminished irrigation and mining requirements, it is expected that the ground water will furnish 2.3 million acre-feet of municipal and industrial water requirements by the year 2020 as compared to the 1.5 million acre-feet supplied in 1960.

Ground-Water Availability

Approximately 5 million acre-feet of water is available annually from the major and minor aquifers of the State. Unfortunately ground water, like surface water, is poorly distributed in Texas, most of it occurring in the eastern part of the State. In addition, approximately 365 million acre-feet of water is available from storage in aquifers which receive little or no recharge.

These are generally in the western part of the State and are developed primarily for irrigation purposes. The water in storage will be available to meet requirements until such time as the water levels become too deep for economical pumpage of this water or until the aquifer has been depleted.

Major Aquifers

Figure 3 shows the major aquifers in the State. Our definition of a major aquifer is one that yields large quantities of water in large areas of the State.

Ogallala Aquifer

The Ogallala Formation is composed of interconnected sands and gravels mixed with clay, silt, and caliche, forming a large unconfined ground-water reservoir. The formation ranges in thickness from 0 to about 900 feet, with generally less than 300 feet of saturation. The thickest part of the aquifer occurs in the northern part of the High Plains, with lesser amounts of saturation and heavier development in the southern part. Well yields range from less than 100 gallons per minute to more than 2,000 gallons per minute with the average being about 500 gallons per minute.

Approximately 280 million acre-feet of water in the Ogallala is considered economically recoverable from storage. The rate of replenishment to the Ogallala is very small compared to the present withdrawal. Approximately one-third of the available water occurs in the "breaks," land which is not considered suitable for irrigation. This water coupled with surface water from Lake Meredith is adequate to supply the projected municipal and industrial needs of the High Plains to the year 2020. The decrease in available water will occur in the irrigation areas where in 1960 a total of 7.6 million acre-feet of water was used for irrigation, and it is projected that for the year 2020 only 1.5 million acre-feet will be available.

Alluvium Aquifer

The Alluvium aquifer as shown on Figure 3 actually consists of five different areas completely separated but yet hydrologically similar. Collectively they are shown under a single heading, but will be discussed separately.

Alluvium (Seymour Formation)

Remnants of the Seymour Formation and other alluvial sediments in 13 areas of the Red and Brazos River basins have sufficient thickness to constitute an aquifer. They are presently being used for irrigation and some public supplies. The thickness of the deposits ranges from a few feet to as much as 360 feet of sand, gravel, silt, and clay, with the saturated part of the formation generally being less than 100 feet thick. The yields of large-capacity wells range from less than a 100 gallons per minute to as high as 1,300 gallons per minute, with the average being about 300 gallons per minute.

Recharge to the alluvium is by direct infiltration of precipitation. It is estimated that approximately 100,000 acre-feet is available annually from the 13 areas. In some of the areas, the 1960 pumpage exceeded the average annual recharge, and thus water is being pumped from storage. It will be necessary that the amount of pumpage in these areas be reduced in the future. All of the water available annually from recharge will be used by the year 2020, mostly for irrigation.

Cenozoic Alluvium and Bolson (El Paso)

Cenozoic alluvium and bolson deposits are located in El Paso County and southwestern Hudspeth County and consist of unconsolidated sand, gravel, clay, and caliche. The deposits range in thickness from a few feet to more than 5,000 feet but contain fresh water only to a maximum depth of 1,400 feet in the area immediately east of the Franklin Mountains. The yields of large-capacity wells generally are between 1,000 and 1,500 gallons per minute.

There is estimated to be approximately 50,000 acre-feet of water available annually from recharge to the aquifer. In addition, large quantities of fresh water are stored in the aquifer, and it is estimated that 4 million acre-feet of the stored water can be economically recovered. By using a combination of the small surface-water supply available to El Paso, recharge to the aquifer, and the recoverable water in storage, the municipal and industrial requirements of the area can be met until about the year 2010. Between the years 2010 and 2020, an additional 2.3 million acre-feet (cumulative total) of water will be needed to meet the municipal and industrial requirements of the El Paso area.

Meeting these future requirements will involve use of the current sources of water and one or more of the following:

(1) Extend the time of use of better quality ground water in storage by initiating a program of blending inferior quality ground water with the present source.

(2) Separately, or in conjuction with item 1, add a series of saline-water-conversion plants to stabilize the withdrawals of better quality ground water.

(3) Provide for more than 12,200 acre-feet per year of Rio Grande water for municipal and industrial use, by conversion of additional water from irrigation use as irrigated lands become urban lands, and blend this water with the better quality ground water.

(4) Develop a long-distance transmission facility to obtain water from one of the following sources:

A. Obtain ground water from the Edwards-Trinity (Plateau) aquifer in southern Terrell and Val Verde Counties. The development of this source would require extensive exploration to locate an adequate supply. Also, the development of this source would result in a decreased flow in the lower part of the Rio Grande.

B. Diversion of surface water from Amistad Reservoir to El Paso with replacement of an equivalent quantity of water to the lower Rio Grande Valley area from the State Water Project.

C. Importation of water from out-of-State sources.

Cenozoic Alluvium and Bolson (Salt Basin)

The alluvial and bolson deposits of the Salt Basin extend from Dell City on the Texas-New Mexico border in Hudspeth County southward to Presidio County. The deposits consist of unconsolidated sand, gravel, clay, and caliche, with the thickness ranging from 0 at the edge of the basin to as much as 1,600 feet. The large-capacity wells producing from this aquifer yield from 250 to 2,500 gallons per minute.

The amount of water received by the aquifer each year through recharge is not known. Based on the thickness of the fresh water-bearing part of the bolson that underlies the Wildhorse Draw and Lobo Flats area, there is estimated to be at least 400,000 acre-feet of water available from storage. Most of this water is used for irrigation and it will be depleted before the year 2020.

Cenozoic Alluvium (Pecos Valley)

The alluvial deposits of the Pecos River Valley consist of unconsolidated to partly consolidated sand, silt, gravel, boulders, clay, gypsum, and caliche. The thickness of the alluvium is from 100 to 300 feet in most of the area. However, there are two troughs where the thickness generally ranges from 600 to 1,500 feet. The yields of the large-capacity wells range from 200 to 2,500 gallons per minute with the average being about 1,000 gallons per minute. The quality of the water from the aquifer ranges from 200 parts per million dissolved solids to as much as 13,000 parts per million. However, most of the water that is used ranges from 1,000 to 4,000 parts per million dissolved solids, and it is generally used for irrigation purposes.

There is estimated to be approximately 70,000 acre-feet of water received as recharge each year, and this quantity is available on a perennial basis. Most of this water is being discharged from the underlying Edwards-Trinity (Plateau) aquifer. In addition, there is estimated to be 60 million acre-feet of water which can be economically recovered from storage.

There seems to be sufficient water in the aquifer to meet the needs of the area, but quality deterioration will limit its use in some areas. As the water levels decline in some of the heavily pumped irrigation areas, poor quality water from the Pecos River is being drawn into the aquifer. Although there is an adequate supply of water in the alluvium to meet the municipal and industrial needs, it may be necessary for some cities to extend their well fields for some distance from the town or go to a desalting process to obtain their drinking water.

Brazos River Alluvium

The Brazos River Alluvium aquifer extends in a narrow strip 1 to 7 miles wide along the Brazos River from McLennan County southward to Fort Bend County. The saturated thickness ranges from about 4 feet in McLennan County to as much as 85 feet in Washington County. The yields of wells range as high as 1,350 gallons per minute with the average for large-capacity wells being about 500 gallons per minute.

Approximately 50,000 acre-feet of water is available annually from the Brazos River alluvium from McLennan to Washington County. The water is used primarily for irrigation and is sufficient to meet the present and future needs of the area. South of Burleson County the availability has been included with that of the Gulf Coast aquifer because the two aquifers are hydrologically connected.

Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) aquifer covers a large area of the Rio Grande and Colorado River basins. The aquifer is composed of water-bearing sands and limestones of the Washita, Fredericksburg, and Trinity Groups. The upper part of the aquifer is made up of Georgetown, Edwards, and Comanche Peak Formations which are limestones, and the lower part of the aquifer is made up of sands of the Trinity Group. The thickness of the aquifer ranges up to 1,000 feet, and the sand thickness is generally less than 100 feet. The water in the aquifer generally occurs under water-table conditions in fractures and solution cavities in the limestone and in the underlying Trinity sands. The yields of wells completed in the aquifer range from a few gallons per minute to as much as 3,000 gallons per minute.

There is estimated to be approximately 650,000 acre-feet of water which could be intercepted and developed annually from the aquifer. In addition to the water available annually from recharge, approximately 12 million acre-feet of water is available for development from storage in the aquifer north of the Middle Concho River. However, most of the available recharge water occurs in an area of little need. Also, any large-scale development of ground water would result in a reduction of the base flow of the streams draining the Plateau, thus reducing the surface-water supply. The water available in the aquifer in the Nueces and Guadalupe River basins is not included in the availability figure inasmuch as this water is later utilized downstream either as surface flow or as recharge to the Edwards (Balcones Fault Zone) aquifer.

Edwards (Balcones Fault Zone) Aquifer

The Edwards (Balcones Fault Zone) aquifer extends across five river basins from Brackettville on the west to southern Bell County on the northeast. The ground-water movement in the aquifer is unaffected by the river basin boundaries between the Nueces, San Antonio, and Guadlupe River basins. In the Colorado River basin, most of the water discharged in the basin is also recharged within the same basin. In the Brazos River basin, the water discharged at Salado Springs is also recharged within the boundaries of the river basin.

The following discussion is limited only to that part of the Edwards (Balcones Fault Zone) aquifer in the Nueces, San Antonio, and Guadalupe River basins, where the heaviest demands placed on the aquifer are at San Antonio. The primary source of recharge to the aquifer is in the Nueces River basin from seepage from streams that cross the aquifer outcrop. In the Balcones fault zone the water in the aquifer moves eastward and northeastward, roughly parallel to the main system of faults, and is discharged by pumpage in all three river basins and from spring flows primarily in the San Antonio and Guadalupe River basins.

Based on the amount of recharge to and discharge from the aquifer during the period 1934 through 1959, it is estimated that the perennial yield of the aquifer is on the order of 500,000 acre-feet per year. The storage capacity of the reservoir is unknown below the lowest elevation to which the water level has been drawn. There is a possibility that poor quality water in the Edwards limestone south and southeast of the aquifer might be drawn into the reservoir if the water levels are lowered significantly below their lowest level. Because of these factors, it is believed that pumpage from the aquifer should be limited to about 400,000 acre-feet per year until more can be learned concerning the storage capacity of the reservoir at lower levels and the possibility of movement of poor quality water into the good water zone.

Most of the available yield of the aquifer probably could be obtained by pumping from almost any locality within the reservoir boundary. However, the ground water to be used in each river basin was estimated in the following table, which shows the 1960 use and the projected 1990 and 2020 use of the available ground water from the Edwards (Balcones Fault Zone) aquifer:

River basin	Available (acre-feet)	Ground-water use (acre-feet)		
		1960	1990	2020
Nueces	90,000	37,100	84,600	90,000
San Antonio	260,000	147,200	255,800	260,000
Guadalupe	50,000	13,250	27,200	42,000
Total	400,000	197,550	367,600	392,000

An annual pumpage of 400,000 acre-feet within the three river basins would stop the flow from Comal and San Marcos Springs part of the time. Based on the period of record (1934-59), it is estimated that these two springs would not flow at all 2 years out of 26 years. There would be flow throughout the year during only about half of the remaining 24 years and intermittent flow the other 12 years. If some springflow is to be maintained at all times, pumpage from the aquifer would have to be held to 300,000 acre-feet annually. This amount of pumpage would provide a minimum springflow during critical years and excessive springflow, as much as 300,000 acre-feet, during the wet years.

To obtain maximum benefits from the aquifer in the Nueces and San Antonio River basins, and also to maintain springflows at Comal and San Marcos, it would be necessary to make conjunctive use of surface water and ground water. The springflow from Comal Springs can be effectively controlled by pumpage in the San Antonio area as demonstrated in 1956. But even in 1956, when Comal Springs were dry for several months, 71,000 acre-feet of water was discharged as springflow: 24,000 acre-feet from Comal and 47,000 acre-feet from San Marcos Springs.

If springflows are to be maintained year round and maximum use is to be made of the ground water, pumpage throughout the aquifer would have to be controlled. Springflows would have to be picked up below the springs and returned to the west to offset the reduced pumpage during the critical years, or some of the excess flow from the San Marcos Springs could be intercepted by wells located between New Braunfels and San Marcos and returned to the west.

A possible alternate method would be to study the possibility of maintaining Comal Springs flow during the critical years by injection wells. This would allow pumpage in the San Antonio area to remain at a higher and more constant level than would be otherwise possible. Flow from the San Marcos Springs can be controlled more effectively by San Antonio pumpage if it is not necessary to maintain water levels high enough to allow Comal Springs to flow at all times. This method would eliminate the need for additional wells between New Braunfels and San Marcos and a pump-back system, and it would require no pump-back from Comal Springs and very little from San Marcos Springs.

Conjunctive use of ground-water pumpage and surface water will be necessary if the springflows are to be maintained and if the 400,000 acre-feet of water is to be utilized annually from the aquifer.

Additional water could be made available from the aquifer in the Nueces River basin for irrigation and in the San Antonio River basin for municipal and industrial requirements if it were possible to vary the quantity of surface water imported into the area. More ground water could be pumped annually and the springflows maintained if it were possible to deliver larger quantities of surface water to the San Antonio area during the summer months. As much as 600,000 acre-feet could be pumped from the aquifer during the wet years provided that larger quantities of surface water could be brought in during the dry years to make up for the necessary reduction in ground-water pumpage. This, of course, would require strict control and management of both the ground and surface water in the area.

Trinity Group Aquifer

The Trinity Group aquifer covers the central part of the Brazos River basin, the upper part of the Trinity River basin and the lower part of the Red River basin. The aquifer is made up of sands of the Paluxy and Travis Peak Formations ranging in thickness from less than 200 feet to as much as 1,200 feet. The well yields of the large-capacity wells average between 300 and 400 gallons per minute, with some wells yielding up to 2,000 gallons per minute.

Approximately 70,000 acre-feet of water is available from the aquifer annually, and it is expected that most of this available water will be utilized by the year 2020. The aquifer has been overdeveloped in the Dallas-Fort Worth area, but additional water is available in the area north of Dallas and Tarrant Counties.

Carrizo-Wilcox Aquifer

The Carrizo-Wilcox aquifer extends from the Rio Grande on the west to the Arkansas and Louisiana border on the east and consists of alternating beds of sand and shale.

Approximately 580,000 acre-feet of water is available annually from the Carrizo-Wilcox aquifer. Of this amount, approximately 285,000 acre-feet is in the Sulphur, Cypress, Sabine, Neches, and Trinity River basins. In this area, the aquifer ranges in thickness from a few feet up to 2,200 feet with about 50 percent of the total thickness consisting of sand. Well yields range from less than 100 gallons per minute to 1,200 gallons per minute. It is expected that only about 70,000 of the 285,000 acre-feet available will be utilized by the year 2020.

Approximately 230,000 acre-feet of the available water occurs in the Brazos, Colorado, Guadalupe, and San Antonio River basins, where the thickness of the aquifer ranges up to 2,200 feet. Well yields range from less than 100 gallons per minute to 3,000 gallons per minute. In this area, it is projected that only 65,000 acre-feet of the available 230,000 will be used, mostly because the demand is not there.

There is estimated to be 65,000 acre-feet of water available annually from the aquifer in the Nueces River basin. The thickness of the aquifer in this area is from 800 to 3,000 feet, downdip from the outcrop. The well yields range from less than 100 gallons per minute to 1,200 gallons per minute. In 1960, approximately 385,000 acre-feet of water was pumped from the Carrizo-Wilcox aquifer in the Nueces River basin, primarily for irrigation purposes. Most of this water is being pumped from storage and will not be available at this rate on a continual basis. It will be necessary long before the year 2020 to reduce the pumpage back to the 65,000 acre-feet perennial yield of the aquifer.

Gulf Coast Aquifer

The Gulf Coast aquifer consists of interbedded sand and clay of the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont Formations. There is estimated to be 2.4 million acre-feet of water available annually from the Gulf Coast aquifer, and of this amount, approximately 2.2 million acre-feet of excellent quality water occurs east of the Guadalupe River basin.

In the eastern part of the aquifer usable quality water occurs to a maximum depth of 3,000 feet below the land surface with the maximum net sand thickness being about 1,500 feet. Yields of large-capacity wells go as high as 4,500 gallons per minute, with the average being about 1,600 gallons per minute. All but 390,000 acre-feet of the 2.2 million acre-feet available will be utilized by the year 2020. Most of the 390,000 acre-feet of surplus ground water occurs east of Houston.

Approximately 200,000 acre-feet of water is available annually from the Guadalupe River basin south. The maximum depth of the aquifer below the land surface is 1,800 feet with the maximum net sand thickness being about 800 feet. The average yield of large-capacity wells is 500 gallons per minute, with some yielding as high as 3,000 gallons per minute. The quality of water in the southern part of the aquifer is much poorer than that to the northeast, with the dissolved solids ranging from about 1,000 to 1,500 parts per million. In much of the area, fresh water is overlain by saline water. All but about 65,000 acre-feet of the 200,000 acre-feet of available water will be utilized by the year 2020. The 65,000 acre-feet does not occur in the areas of requirement.

Minor Aquifers

Not as much information is available on the minor aquifers of the State, and in some cases, not enough information is available to make an estimate of the amount of water available or to know the exact areal extent of the aquifer. Our definition of a minor aquifer is one that yields large quantities of water in small areas or relatively small quantities of water in large areas of the State. Although they do not contain the quantities of water found in the major aquifers, they are sometimes capable of supplying requirements in areas where no other supply is available and thus are of major local importance. Figure 4 shows the location of the minor aquifers in Texas.

Edwards-Trinity (High Plains) Aquifer

The Edwards-Trinity (High Plains) aquifer occurs in the subsurface under the Ogallala Formation in parts of the Brazos and Colorado River basins. It consists of a thin sand overlain by shale and limestone, with water occurring in the limestone only on the western edge of the aquifer. The amount of water available from the aquifer is not known; however, the recharge would be small and from the Ogallala aquifer. Water that could be pumped from storage in the Edwards-Trinity (High Plains) aquifer probably is not more than 2 million acre-feet.

Santa Rosa Aquifer

Water in the Santa Rosa aquifer is contained in interbedded lenses of sand, hard sandstone, gravel, and shale. The aquifer contains usable quality water in two different areas, one on the Texas-New Mexico border in the Rio Grande and Colorado River basins, and the other in Mitchell, Nolan, and Scurry Counties to the east.

In the eastern part of the aquifer, the thickness ranges from 0 to approximately 400 feet, with wells yielding up to 1,150 gallons per minute and averaging about 250 gallons per minute. The water generally contains less than 1,000 parts per million dissolved solids. There is estimated to be 35,000 acre-feet of water available annually in the eastern part of the aquifer, with the water being used primarily for irrigation in Mitchell, Nolan, and Scurry Counties.

In the western area, the aquifer is about 300 feet thick and well yields generally average less than 300 gallons per minute. The dissolved solids contained in the water range from 100 to 4,000 parts per million, with most of the water containing more than 1,000 parts per million. The amount of water available in the western part of the aquifer is unknown.

Bone Spring-Victorio Peak Aquifer

The Bone Spring-Victorio Peak aquifer, located in the northeast corner of Hudspeth County, is not shown on Figure 4. Water occurs in fractures and solution cavities in the limestone which is about 1,300 feet thick. Well yields range from 150 gallons per minute to 2,200 gallons per minute. The aquifer contains generally poor quality water (1,000 to 8,000 parts per million dissolved solids), which is good only for irrigation use. Dell City is considering the possibility of desalting the water for their municipal supply.

It is estimated that there is 50,000 acre-feet of water annually available as recharge to the aquifer. The present pumpage of about 100,000 acre-feet for irrigation purposes exceeds the annual recharge, and it will be necessary to reduce the pumpage to equal that of the recharge long before the year 2020.

Blaine Aquifer

The boundaries of the Blaine aquifer are not known, but water from the aquifer is being used in the Red River basin in Collingsworth, Childress, Hardeman, Cottle, and King Counties. The aquifer consists of up to 250 feet of anhydrite, gypsum, shale, and dolomite. Wells yield up to 1,500 gallons per minute and average about 400 gallons per minute. The water is of very poor quality, and normally would not be considered in the total availability except that it is currently being used for irrigation and it is assumed that it will continue to be used in the future. The dissolved solids range from 2,000 to 5,000 parts per million, with sulfates ranging from 1,000 to 2,000 parts per million.

It is estimated that about 40,000 acre-feet of water is available annually from this aquifer.

Hickory Aquifer

The Hickory aquifer, located in the Colorado River basin, has a maximum thickness of 400 feet of sand and shale with the sand making up approximately 50 to 75 percent of the total thickness. Well yields generally are between 200 and 500 gallons per minute with some as high as 1,500 gallons per minute.

Approximately 45,000 acre-feet of water is available annually from this aquifer. It is projected that 20,000 acre-feet will be used for irrigation, municipal, and industrial purposes by the year 2020, with a surplus of 25,000 acre-feet.

Ellenburger-San Saba Aquifer

The Ellenburger-San Saba aquifer, located in the Colorado River basin, consists of limestone and dolomite of the Ellenburger Group and San Saba Formation, and has a thickness of more than 1,000 feet. The average yield of high-capacity wells is 500 gallons per minute with some yielding as high as 1,000 gallons per minute.

There is 25,000 acre-feet of water available annually from this aquifer with only a small amount presently being used, mostly for municipal and industrial purposes. Approximately 10,000 acre-feet will be utilized by the year 2020 for municipal and industrial requirements and some irrigation, leaving a surplus of 15,000 acre-feet of water.

Woodbine Aquifer

The Woodbine aquifer extends from just north of Waco in the Brazos River basin to the Red River. It consists of interbedded sand and clay with the thicker sands occurring in the lower half of the formation. The aquifer is between 400 and 600 feet thick, and about 50 percent of the total thickness is sand. Yields of the large-capacity wells average about 150 gallons per minute with a few yielding as high as 700 gallons per minute. Many areas of the aquifer contain poor quality water with the dissolved solids ranging from less than 1,000 to more than 1,500 parts per million.

There is estimated to be 25,000 acre-feet of water available annually from the Woodbine aquifer. Presently about 10,000 acre-feet of water is being used from the aquifer, and it is estimated that by the year 2020 only about 5,000 acre-feet will be used because it occurs in an area where more and more municipalities and industries are turning to surface water.

Queen City Aquifer

The Queen City aquifer extends from the Nueces River basin on the southwest to the Arkansas-Louisiana border on the northeast. The aquifer consists of unconsolidated sand interbedded with clay and glauconite. The aquifer's thickness ranges from a few feet to 600 feet with the sand content varying from 25 to 75 percent of the total thickness. The well yields are generally small, less than 400 gallons per minute.

There is estimated to be 25,000 acre-feet of water available annually from this aquifer. Only small quantities of water are now being used from this aquifer because most users of ground water, where the Queen City is located, go to the underlying Carrizo-Wilcox aquifer for the more desirable quality water and larger well yields. It is estimated that only small quantities will be used in the future, as most of the available water occurs in an area of little need.

Sparta Aquifer

The Sparta aquifer occurs generally in the same area as the Queen City aquifer. It consists of unconsolidated sand interbedded with shale. The aquifer has a thickness of up to 300 feet with approximately 60 to 70 percent of the total thickness being sand. The more massive sand beds are near the base of the formation. The average yield of high-capacity wells is between 400 and 500 gallons per minute with some wells yielding as high as 1,200 gallons per minute.

Approximately 95,000 acre-feet of water is available annually from the Sparta aquifer. Only small quantities of water are now being used, and are expected to be used in the future. Most of the available water occurs in an area of little need.

Interrelationship of Ground-Water and Surface-Water Development

An overall objective of the Texas Water Plan is the proper management, conservation, and optimum utilization of the total water resources of the State. Although ground water has received more recognition and has been used more in this Plan to meet the future water requirements than ever before, ground water still has not been used to its fullest extent. The requirements met by ground water were based on current and anticipated trends of ground-water use rather than total availability. It could not be done otherwise under the existing ground-water law, because the State cannot effectively exercise any degree of conservation or control over water-use practices involving ground water.

The interrelationship of ground- and surface-water development has been recognized in preparing the Texas Water Plan. In many cases, pumpage from an aquifer will reduce the available surface-water supply. This will happen more and more in the future as aquifers are developed to their fullest extent. Therefore, it is necessary to consider these effects and to obtain the most beneficial use of the water whether it be ground or surface water. Before ground water can be developed to its fullest value to meet its share of the State's future water requirements, extensive studies will be required to provide the details necessary to refine the estimates of available ground water which can be depended on in the future and to determine the effects of ground-water development on surface-water supplies. This Plan, in its implementation, contains sufficient flexibility to properly adjust to changes in the legal and economic considerations and to those considerations based on additional information that is being and will be obtained on ground water and its interrelationship with the surface-water supplies.

IRRIGATION UNDER THE TEXAS WATER PLAN

By Mrs. Jean O. Williams[a] and Paul T. Gillett[b]

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IRRIGATION UNDER THE TEXAS WATER PLAN

Introduction

Texas found itself in a unique situation in 1957. It had become--historically almost overnight--a diversified urban industrial and mechanized agricultural society where two decades earlier it had only begun to stir from a predominantly rural culture.

Water planning had been discussed in those intervening years, but suddenly, in the middle 1950's, the State was shaken by one of the major droughts of the century followed by floods which devastated urban areas and farmlands alike.

The political power structure of the State moved swiftly to begin a process of water-resource planning, a process accelerated at the direction of Governor John Connally in 1964, which culminated in development of the present preliminary Texas Water Plan.

The keys to resource planning are an analytical evaluation of the environment toward which planning is to be directed, and the allocation of the available--or obtainable--resource among competing demands to create that environment. We have advanced technologically so that physical infeasibility is rarely the primary constraint on desirable development, certainly in water-resource development. Thus, when less than optimal development is planned, the constraints of tradition, local or individual greed and pride, or lack of vision have generally intervened.

Texas is geographically outsized; its physical, cultural, and economic environment is diverse. This imposed on Texas water planners an obligation to work toward a balanced program of water availability to all parts of the State to meet a broad range of uses.

There is general acceptance of the need to meet municipal and domestic needs for water of good quality. There is only moderate controversy over the demands of industry for water to meet present and projected needs. The reasonable requirements of water supply dedicated to maintenance of water quality, recreational purposes, fish and wildlife, are accepted generally. But for a variety of reasons, there is not a widespread understanding of the importance to the State's economy of supplying a present--and potentially tremendous--irrigated agricultural development to the fullest possible extent.

This reluctance in some quarters to commit a major resource to irrigation has many roots--the bad taste left by some early Federal practices directed toward management of an agricultural production capability which was revolutionized prior to World War II; rebellion, conscious or unconscious, against the lack of personal opportunity in traditional family farming; differential tax evaluations on capital investments in rural and urban development appearing in some cases to pit city and rural dwellers against one another.

Whatever the cause in an individual instance, the decision reached in the Texas Water Plan to meet the needs of present irrigation, to provide for expanded irrigation where possible, and to undertake studies of possible water sources to meet the potential for irrigation development in the State has not been universally popular.

This decision was not taken lightly. It was based on careful economic and agricultural studies of the valid potential for future development of the entire economy. More importantly, it was based on an appraisal of the role Texas must play in meeting the food and fiber needs of the nation and of a hungry world.

Planning studies were directed to establishing the level of agricultural production in Texas, competing with production in other areas, required to meet the need for these commodities in the growing economy of the United States (Table 1). In projecting this production level, it was assumed that the export of agricultural commodities would be maintained at the existing proportion of foreign demand.

Two myths of farming and agriculture have been almost superimposed on one another in this country. One, the earlier, was of the stalwart family farmer--meeting his own needs, and needing the aid of no one. The other was the myth of the fat opportunist, collecting subsidies without productive effort, while magically uneconomic surpluses grew and were wasted. Neither image is totally untrue, but neither is wholly valid.

Family farming producing solely for on-farm consumption is no longer economic. Of greater significance from the national viewpoint, and that of the world, uneconomic surpluses no longer exist on a substantial scale.

There has been continuing discussion about crop surpluses. Why produce more and more crops through irrigation, when some are generally in apparent surplus? First, it is economically advantageous to produce irrigated crops on a smaller number of acres than is possible without irrigation. In Texas irrigated acreage has increased since 1958 by more than 150,000 acres per year while dryland crop production has been terminated on several million acres. This has not been the result of a differential stimulation in the form of subsidy between irrigated and nonirrigated agriculture, but rather of the economics of comparative advantage. Irrigators have simply been able to produce at a higher level with less expensive labor and other production inputs at a lower overall cost per unit than have nonirrigated crop producers.

Second, through mechanization, elimination of use of work animals, and reduction of farm labor, acreage has been released to produce non-feed crops and commodities which have been periodically in surplus. Future food and fiber requirements must be met largely from further technological advancement because early increments of increased production resulting from changes in technology have probably been utilized.

Export trade in agricultural commodities has become an important feature of the national agricultural production picture. The increase in world population will create critical demands on the combined world food and fiber production capabilities, both in the gross quantitative sense, and as the newer nations develop more sophisticated needs for a wider range of agricultural commodities.

Table 1.--Projected Requirements For Texas Production Of Major Farm Products[1]

Commodity	Unit	1980	2000	2020
Livestock Products:[2]		(Millions)	(Millions)	(Millions)
Beef and Veal	lbs	4,676	6,471	8,805
Lamb and Mutton	lbs	188	250	330
Pork	lbs	289	358	433
Chickens	lbs	745	996	1,317
Turkeys	lbs	205	299	426
Milk	lbs	3,309	4,243	5,370
Eggs	no.	2,875	4,254	5,727
Crops, Non-Feed:		(Thousands)	(Thousands)	(Thousands)
Wheat	bu	78,608	109,114	149,403
Cotton	bale	4,784	6,356	8,465
Rice (Rough)	cwt	22,770	27,725	34,123
Peanuts	lb	292,005	456,909	692,403
Other Oil Crops	bu	13,886	26,232	44,206
Sugar Beets	tons	1,203	2,836	5,547
Potatoes	cwt	5,447	8,556	13,001
Sweetpotatoes	cwt	1,347	2,043	3,021
Vegetables	cwt	70,008	106,124	156,879
Grapefruit	tons	981	1,465	2,144
Other Citrus	tons	449	821	1,374
Fruits, Non-Citrus	tons	30	52	84
Tree Nuts	lbs	39,488	58,587	85,092
Crops, Feed:[3]		(Thousands)	(Thousands)	(Thousands)
Corn for Grain	bu	8,916	14,572	21,475
Oats	bu	1,773	2,700	3,984
Barley	bu	1,764	1,932	2,467
Sorghum for Grain	bu	85,168	89,900	94,631

1/ Including exports, assumed to be approximately the existing proportions of world demands.
2/ Live weight requirements.
3/ Requirements only for human foods and exports.

The world cannot attain peace and prosperity with half of its peoples and countries underfed while the other half applies artificial restraints to hold food production below its capabilities. The United States is a producer nation with ample capacity to export food and fiber at a level which could be a major factor in meeting world needs. Agricultural export is used currently primarily as a tool to rebuild economies throughout the world. Ultimately, however, exportation of agricultural commodities must be recognized as a valuable sector of our own economy.

In planning development of its water resources, as a part of environmental planning, Texas must compete for its share of the national production of agricultural products required to meet world demand.

Planning in Texas was based on the concept that the costs of development of water supplies proposed in the Texas Water Plan--both capital costs and annual operating costs--will be met by the beneficiaries of these developments. At the same time, it must be recognized that these costs, when calculated for massive movements of water on a regional or interstate scale, may be beyond the payment capacity of individual irrigators.

Federal participation in planning, financing, and construction will be needed for major systems of diversion of water to meet predominantly agricultural needs. The criteria which will guide this participation are written into Federal law, and will play a large part in determining the basis for repayment of costs allocated to agricultural water supply.

When studies of these costs, and of the return to irrigators of a full available water supply, are completed, the people in the major irrigation areas of the semiarid southern and western regions of Texas, the citizens of the rest of the State, and the leadership of the Nation, are going to be faced with some very hard political and legal decisions. These decisions will range from the need for changes in local governmental structures and taxing authority to an examination of the impact of irrigation on the economy of the State and the Nation as a whole. The answers to these questions must be made through a rational process of considered judgment, for which the planning studies must provide necessary facts for decision.

Texas--An Agricultural State

Twenty-three river basins and coastal basins have been designated (Figure 1) officially as a basis for developing the Texas Water Plan. These have been subdivided, for water-planning purposes, into 57 separate units or river-basin zones. Each has basic physical characteristics that influence opportunities for economic development. Crop production and large agriculturally oriented segments of the municipal and industrial development form the basis for the present economy of many of the 57 zones. The economy of some zones will remain agriculturally oriented because the resources of these areas place them in an excellent competitive position to remain prime agricultural producing areas. Few or no future alternative opportunities will exist, in several zones, to supplant economic dependence on agriculture.

Many of these zones are major producing areas contributing greatly to Texas' second ranking among States in value of all crops produced (about $1\frac{1}{2}$ billion annually) and first ranking for several important commodities, including cotton, grain sorghum, and rice. Agricultural production values and the agribusiness associated therewith are second only to those of the petroleum and natural gas industries in total value to the State of Texas and amount to some $8½ billion annually. The overall economy of Texas seems destined to remain agriculturally based for years to come.

A large proportion of the State's agricultural values stems from and is associated with field crop production, and over half of these values now comes from irrigated lands. In many climatically unfavorable years, the proportion from irrigated lands is even greater--two-thirds or more. Trends are strongly towards proportionately higher amounts from irrigation with sharply reduced numbers of producers operating fewer but larger farm businesses and utilizing highly sophisticated production methods, including irrigation. Producing areas and production techniques are being carefully selected to minimize the ever-increasing cost of labor as an input. By the time Texas' population exceeds 30 million, projected to occur about the year 2020, it is estimated that some 85 percent will be urban dwellers, so the prospects are great that farm labor will be in even shorter supply. To predict that by the turn of the century three-fourths of our crop production will come from irrigated lands should not stagger imaginations. A proportion of this magnitude is only a conservative continuation of trends from our present one-half to two-thirds level.

Of Texas' 143 million acres of farmland, nonirrigated cropland totals between 28 and 29 million acres, and irrigated cropland, including a small acreage of improved, tame pastures, 7.7 million acres. So over half of the value of Texas' agricultural crop production is coming from the irrigated one-fifth of all cropland acreage.

Burgeoning Texas Irrigation

Let's briefly look at how irrigation farming has grown in Texas (Figure 2). Only about 400,000 acres were irrigated in 1909. In the next 30 years (by 1939) irrigation had reached approximately 1.1 million acres. In the next 25 years (by 1964) it had mushroomed to 7.7 million acres. Expansion in irrigation was gradual until the 40's but has zoomed since then, largely as a result of rapid development of irrigation on the High Plains, supplied by ground water from the Ogallala sands.

Some Observations Concerning Irrigated Agriculture

Over 80 percent of Texas irrigation is supplied with ground water. Irrigators using ground water bear the entire cost of their irrigation operations and enjoy no special inducements of subsidy not equally received by dryland-crop producers. It is interesting to note that the shifting of the center of Texas cotton production to the High Plains was not a phenomenon induced by the large-scale development of irrigation there. On the contrary, Texas cotton production shifted to this area, first, as a dryland crop because of the obvious production advantages it held over other dryland producing areas. Irrigation development came later, replacing dryland farming because of advantages of irrigation over dryfarming on the High Plains. This growth of an irrigation economy of major impact, based completely on producer-borne costs of irrigation, has come about solely because it has been economically advantageous to irrigate the crops grown there. With irrigation, the High Plains is now a cotton center of world-wide importance. It supports the world's greatest concentration of cotton ginning and processing.

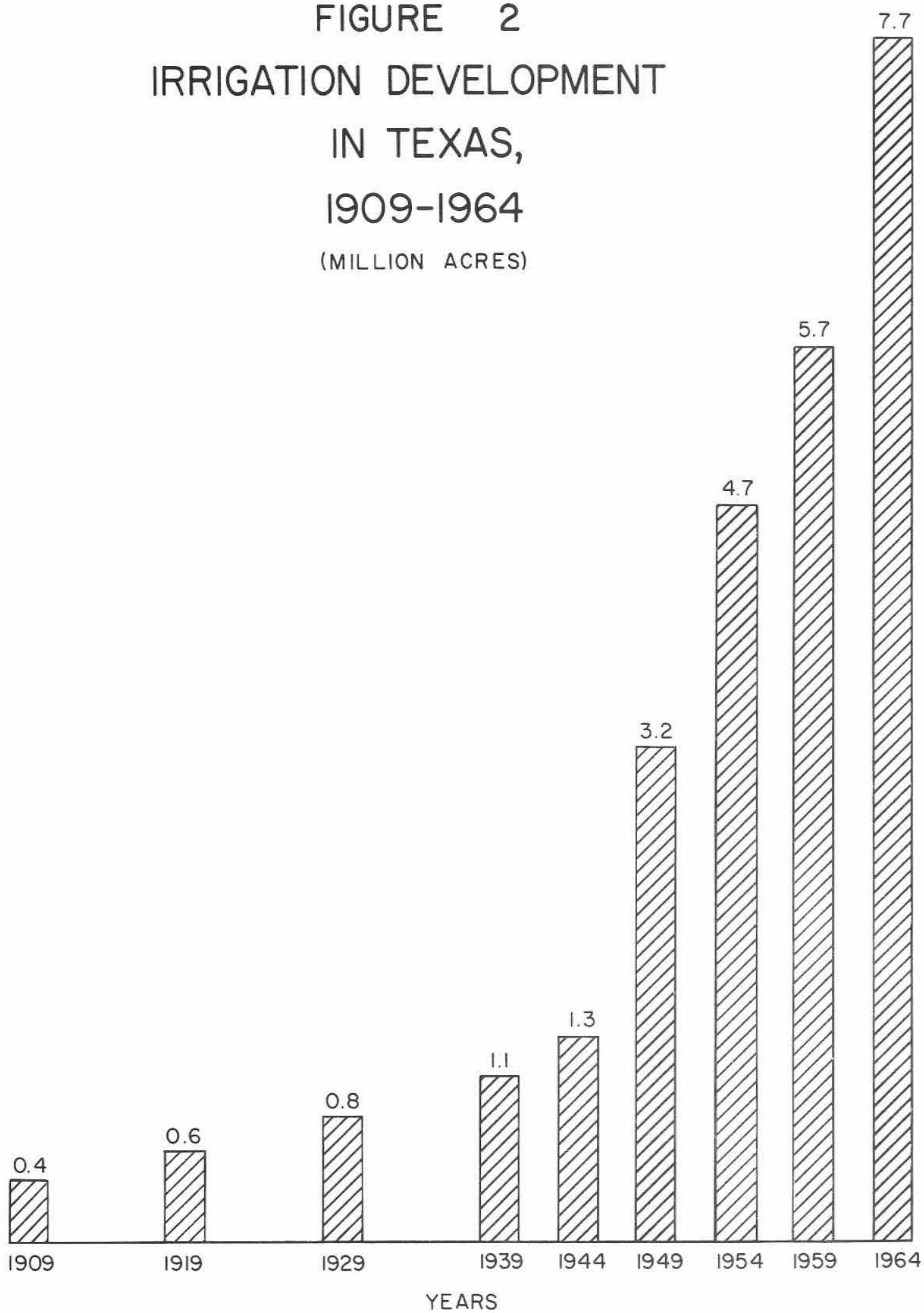

FIGURE 2
IRRIGATION DEVELOPMENT IN TEXAS,
1909-1964
(MILLION ACRES)

Capital investments in all kinds of farming are very high and going higher. A multirow cotton picker costs in the neighborhood of $20,000. Investment of from $75,000 to $150,000 in a commercial field crop enterprise is common and probably conservative as an average. Investments in speciality-crop enterprises and in the larger, most productive farms will far exceed this range. Such investments are attractive and can earn adequate return only if high production values can be attained and maintained. This, in turn, demands higher investment in the input costs of crop production and very careful, well-informed management that includes eliminating the fluctuations in production and threats of production failure from controllable causes. Under irrigation, drouth and moisture inadequacies become controllable; under dryland conditions, weather vagaries continue to be the most important uncontrollable factor in production fluctuations and crop failure. Even in areas blessed with copious and generally well-distributed rainfall, such as in the lower Mississippi Valley, commercial cotton and soybean producers are protecting extremely high investments by turning to irrigation to eliminate the weather hazard and permit the use of intensified input measures. Irrigation permits investments in costly seed and plant selections, higher planting rates, increased fertilizer application, multirow equipment, and highly mechanized field and harvest operations. By the turn of the century irrigation will provide protection of costly investments for most commercial operations. Areas without the water to support the needed irrigation can be expected to contribute less and less to the economy.

The consuming public is also a big factor making it a certainty that most future crops will be grown on irrigated land. Even now the food-buying public demands quality, year-round supply, taste, appearance and nutritional characteristics of the commodity that can be obtained and uniformly assured, crop after crop, only under irrigation. This is especially evident in the fruit and vegetable category, both fresh and processed, but commodity production specialists are also examining closely the most likely future consumer demands in the other food categories and even in the category of natural fibers. Controlled moisture supply, in both time and amount, is becoming identified as an important factor in attaining the kind of fiber products that consumers demand for durability, strength, and other characteristics. These consumer demands dictate what the producer must supply if he expects to get us to use his products. Crop production of tomorrow--of the years up to and beyond the year 2000--must turn largely to irrigation because you and I will demand it by requiring products that can be produced only that way. We are likely to become more and more choosy, not less so.

Ultimately, the water, land, and other resources of Texas are of significance only to the extent they are useful and are put to work to support the people of our State. The farming, agribusiness, and food and allied products industries of Texas sustain a larger part of our population by far than any other sector of our economy. This dependence will grow, even though the number of people engaged directly in farming is decreasing.

Land resource inventories in Texas have established that there is, in fact, an area of about 89 million acres of land that is considered to be physically suitable for cultivation. This is, in a way, misleading, however, since there is by no means this much good land that can actually be considered as available for crop production. A large proportion will be unavailable because of various constraints, such as ownership and tenure. Some areas are isolated geographically, are within pasture, range, or forest areas unlikely to be developed, or are in types of cover that will present too costly conversion requirements or will have more value managed in noncrop use.

Areas totalling several million acres in central and east Texas have now been returned to pasture, forest, or recreation-area use. These areas are unlikely ever again to be used for crop production. An area of only about 40 million acres of land physically suited for cultivation is now in cropland use, and of the remaining 49 million acre area now in pasture, range, and forest use only a relatively small portion is likely to be converted to cropland use. Most of the acreage that will be converted is likely to have good productive soils with smooth topography and be suitable for irrigation. Such areas are, for the most part, concentrated in the major irrigation areas of the State.

Irrigation Potentials In Texas

Texas has some advantages that will permit capturing a greater portion of future markets if the proper environment, including water for irrigation, is created and maintained. Statewide irrigation inventories conducted cooperatively by the Texas Water Development Board (actually its predecessor agency), the State Soil and Water Conservation Board, and U.S. Soil Conservation Service personnel in Texas in 1958 and 1964 revealed that Texas has 37 million acres of land that would respond favorably to irrigation development. Information obtained in these inventories has been compiled in Texas Water Development Board Bulletin 6515. Most of Texas' irrigable land lies in or adjacent to areas where there are significant amounts of irrigation already. In these areas the production know-how, the agribusiness, and the marketing, processing, transportation, and merchandizing requirements are already in operation. These areas are composed of good, productive soils, with level to nearly level topography and good drainage. Many are blocked well for efficient management of irrigation systems. The expanse of such lands on the High Plains is unsurpassed anywhere, and many other large areas exist in the Lower Rio Grande Valley, in other inland parts of the Rio Grande Plain land-resource area, the Trans-Pecos, and along the Gulf Coast. Texas climate favors a wide variety of crops, from the wheat, corn, and other crops of the cooler parts of the country to semitropical fruits and vegetables, and rice along the humid Gulf Coast. The Lower Rio Grande Valley is the southernmost major agricultural area of the United States and as such has unique semitropical advantages, including adaptability of citrus crops, that Texas needs to develop optimally. Kept in tip-top productivity, this border area can be a show-window, so to speak, to reflect the high levels of agricultural development that the United States can attain. Climatic characteristics of the semiarid inland Trans-Pecos and Rio Grande sections place these areas in excellent competitive position for growing the melons, long-staple and special varieties of cotton, vegetables, and other crops grown best under such conditions.

Analysis of Texas Irrigation Needs

All of these considerations have been analyzed in the process of developing the irrigation sector of the Texas Water Plan. The Texas Water Development Board was given tremendously big assists in these analyses by a number of special studies. Texas A & M University carried out a study of agricultural resources related to water development in Texas. The A & M studies were conducted by A & M staff economists, engineers, and soil and plant scientists who were thoroughly familiar with Texas resources for agricultural production and with the other factors affecting the production of each of the commodities, both in Texas and in other producing areas of the Nation. They analyzed production potentials in every land-resource area throughout Texas, commodity by commodity, projected the needed production of each, and the irrigated and non-irrigated acreages expected to be required to attain these amounts at projected yields for each. Irrigation was assumed for only those combinations of crops, producing areas, soils, and other conditions which these experts considered could be more economically irrigated than dry-farmed.

Special economic investigations by economists of Texas Technological College, as well as by Texas Water Development Board economists, examined irrigation cropping on the High Plains and in each of the other major irrigation areas of Texas to determine not only the primary values of irrigation to the irrigators but also the secondary and tertiary impacts of irrigation agriculture on the economy of the various communities, the State, and Nation. These studies were also fashioned to provide basic data to analyze ability or irrigators to absorb water cost and other costs and capital investments in irrigation farming. A study of High Plains water, 1970-2020, and the future potential for High Plains irrigation development was made by a special High Plains group called the "2020 Water Study Committee for the High Plains of Texas." Studies of playa lakes, and an inventory of the uses being made of effluents were also carried out by members of the staff of Texas Technological College.

These studies have pointed up that of the 37 million acres of land in Texas considered physically irrigable, the irrigation of about 16.8 million acres will be needed by the year 2020 and be feasible to develop if water is no more limited for irrigation use, physically or costwise, than it is presently. In other words, the production from this much irrigated land will be needed, and Texas land resources include at least this much acreage that will respond excellently to irrigation and hold comparative advantage over or be competitive with dry-farmed production from the same land, and both dry-farmed and irrigated production in other producing areas, assuming irrigation costs no higher than now in proportion to total production input costs.

Further analyses have indicated that an area of nearly 13 million acres of the 16.8 million acres of irrigation that will be needed by the year 2020 is located where it could be effectively and practically developed for irrigation. It would be supplied either with (1) ground water or surface water expected to be available for irrigation from local sources, within or immediately adjacent to the use areas of the river basins and coastal basins of the State; (2) from surface water, over and above anticipated in-basin needs 50 years hence, that could be developed by impoundments in Texas and transmitted to use areas elsewhere in Texas, outside the basins of origin: or (3) from out-of-State surface-water sources from which water could be imported to use areas in Texas. The remaining acreages of irrigable land do not have adequate local sources of either ground water or surface water, are poorly located, or are otherwise unsatisfactory for project-type development that would be required to make transmission of irrigation water from out-of-basin or out-of-State sources practicable and feasible.

Where Irrigation Is Planned

As could be expected, the bulk of this potentially developable 13 million acres of needed irrigation is located in arid and semiarid West Texas, including the High Plains, North-Central Texas (west of the 99th meridian), and the Trans-Pecos and Rio Grande areas above Amistad Reservoir (Figure 3). Areas of about 9.8 million acres are in West Texas--High Plains, 8.57 million; North-Central Texas, 0.76 million; and Trans-Pecos, 0.48 million. Developable areas in the rest of the State total about 3 million acres, with most of it concentrated in the Gulf Coast rice-producing area (0.67 million acres); the Rio Grande Valley, between Amistad and Falcon Reservoirs (0.14 million); the Lower Rio Grande Valley (0.82 million); the Coastal Bend (0.54 million); the Winter Garden and adjoining areas of the Rio Grande land-resource areas below the Balcones Escarpment to the east of the Winter Garden (0.37 million); and other areas, mostly in Central and East Texas, including the Brazos River bottoms (approximately 0.5 million).

How Irrigation Needs Will Have To Be Met

In-basin supplies of ground water and developable in-basin surface water can supply all potential irrigation water needs for the miscellaneous areas in Central and East Texas and the Gulf Coast rice area. Export needs for that basic world food, rice, the major irrigated crop in this area, is a matter for considerable conjecture at this time, and therefore future needs for Texas rice production and irrigation water needs to produce it are also a real question mark.

Existing supplies of Rio Grande water from Falcon Reservoir are sufficient for full irrigation of only about 650,000 arces in the Lower Rio Grande Valley. Therefore, enough surface water to irrigate an additional 174,000 acres will be required to fulfill the estimated 2020 Valley needs of 824,000 acres. This is estimated to require the transmission of approximately 385,000 acre-feet of water annually to central delivery points in the Valley.

About 500,000 acres of the potential 540,000-acre 2020 needs for the Coastal Bend will require transmission of surface water from out-of-basin sources since ground water in this area is not satisfactory and there is practically no surface water available from the minor coastal watersheds. This will require the transmission of about 880,000 acre-feet of water annually to central delivery points in both the upper and lower Coastal Bend areas.

Ground water, now supplying most of the irrigation needs of the Winter Garden and vicinity, is expected to become decreasingly available. There is only very limited opportunity to develop local in-basin surface-water supply for irrigation. The transmission of enough water into this area to supply about 196,000 acres, coupled with estimated sustainable ground-water use and limited potential local surface-water development, will be required to reach the estimated 2020 needs, only a slight increase over the present level of irrigation in this area. It is estimated that this would require the delivery to a central delivery point of about 421,000 acre-feet of water annually. If any or all of this were to be diverted from the Rio Grande, below Amistad--a concept now receiving study--adjudication of Rio Grande water rights would be a prerequisite, and delivery of replacement water to Lower Rio Grande Valley users who would be affected by the diversion will also be required.

There is a potential need by 2020 of developing an additional 76,000 acres of irrigation in the reach of the Rio Grande between Amistad and Falcon Reservoirs, but to do so will require transmission of water to Lower Rio Grande Valley users to replace water that would not be available to them if users in the Amistad-to-Falcon area, upstream, were to divert water for additional acreage. The amount of water that would have to be replaced will depend upon adjudication of water rights in this reach. For planning purposes, thus far, the replacement amount has been assumed to be about 190,000 acre-feet annually.

Ground water is being seriously depleted in Trans-Pecos areas. By 2020, ground water is expected to be able to supply, coupled with a small amount of surface water in the Pecos Valley and Rio Grande water in the El Paso Valley, only about 120,000 acres. Rio Grande flows available by treaty with Mexico and interstate compact with Colorado and New Mexico for U.S. irrigators in the El Paso Valley, ground water, and return flows from El Paso and environs are expected to maintain about the present irrigated acreage (65,000) in this area. In order to reach the estimated Trans-Pecos 2020 need, it will be necessary to transmit enough water to irrigate around 350,000 acres. It is estimated that this will require the transmission to a central delivery point of about 1.2 million acre-feet annually.

Local North-Central Texas ground-water and surface-water supplies are expected to be sufficient to sustain, by 2020, about 170,000 acres of irrigation. In order to reach the estimated 2020 needs it will be necessary to transmit to North-Central Texas areas enough water to irrigate about 590,000 acres. This is estimated to require delivery of nearly 1.3 million acre-feet annually to central delivery points.

Ground water, essentially the only local supply for High Plains irrigation, is being depleted. By 2020, it is expected that ground water will be supplying only about 2.19 million acres of irrigation, compared to the present 5.07 million and an expected peak of nearly 6 million acres by the 1980's. In order to reach the estimated 2020 need of 8.57 million acres it will be necessary to transmit to the High Plains enough water to supply about 6.38 million acres. This is estimated to require delivery to central delivery points of about 12.7 million acre-feet annually.

Referenced to the potentially developable 13 million acres of irrigation needed by 2020, the local supplies of ground water and surface water to serve them, and the additional estimated quantities of water that would need to be transmitted to central distribution points, are summarized in Table 2. A meaningful plan for Texas irrigation development cannot stop with merely using local available supplies of ground water and surface water. The prospect is for a net loss of ground-water support for over 3.5 million acres of over 6.3 million now being irrigated with ground water, and only limited opportunity to increase irrigation through development of acreage that can be served with locally available (in-basin) supplies of surface water--1.8 million acres compared to about 1.4 million now. The only way to use a substantial portion of the resources with which Texas is blessed for keeping agricultural production and agribusiness a healthy, vigorous segment of our economy was to include in the Texas Water Plan objectives the development and movement of large quantities of irrigation water to use areas outside the basins of origin. In fact, attaining this segment of the irrigation development plan is an important, if not the key segment, to successful overall water development in Texas.

TABLE 2.--DEVELOPABLE TEXAS IRRIGATION TO MEET ESTIMATED 2020 NEEDS

Irrigation area	Acreage, by source of water (1,000 acres)			
	Ground water	Locally available Surface water	Out-of-basin and out-of-State import	All sources
High Plains	2,191	--	6,375	8,566
North-Central Texas	108	60	590	758
Trans-Pecos and El Paso Valley	34	91	352	477
Rio Grande from Amistad to Falcon	5	59	76	140
Lower Rio Grande Valley	--	650	174	824
Coastal Bend	29	8	500	537
Winter Garden and Vicinity	112	62	196	370
Gulf Coast above Coastal Bend	221	449	--	670[1]
All other	105	393	--	498
State of Texas	2,805	1,772	8,263	12,840[2]
Estimated Water Required (1,000 acre-feet)				
State of Texas	2,994	4,468	17,063	24,525

[1] Rice production in this area may require a total of a million acres or more; ground water and locally available surface water can supply this additional acreage with existing systems and rights.
[2] Approximately 13.3 million acres, with additional rice (footnote 1).

The Continuing Irrigation Planning Task

It is obvious that the delivery of 17 million acre-feet of water annually to central distribution points for project-type irrigation development will involve not only optimal in-State surface-water impoundment but also planning and arranging for huge imports from out-of-State sources. Studies of both types are in progress and undoubtedly will need to continue for some time. It is likely that economically feasible means of providing water from out-of-basin and out-of-State sources to some areas of potential need for irrigation may not materialize for some time; supplying some needs may have to be indefinitely deferred because of excessive cost that will not be acceptable to prospective users. Economically feasible means, on the other hand, may be found to supply irrigation water for some areas of irrigation needs at early dates. Irrigation water shortages are critical in some areas such as the Lower Rio Grande Valley, the Trans-Pecos, parts of the Southern High Plains, and North-Central Texas right now. Irrigation needs will become acute soon in some areas while other area needs may not be critical for several decades. It is essential, therefore, that developments found to be feasible to fulfill emerging needs be carefully phased to meet critical situations at whatever locations and times they become manifest. This means attaining development of specific plan elements at early stages that will serve best the emerging needs whenever and wherever they occur. They must fit as many alternative concepts, plans, and systems of water impoundment, movement, and use as possible, flexibly and interchangeably. The irrigation planning process has to be a continuing one, but it must keep clearly in view the long-term objective, concluded from our planning studies, to attain and maintain between 13 and 14 million acres of irrigation. Determination and phasing of specific required elements or projects, over the years, will be dependent on unfolding needs and finding economically feasible means to fulfill them. The irrigation sector of the Texas Water Plan has been thus conceived.

WATER QUALITY ASPECTS OF THE TEXAS WATER PLAN

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WATER QUALITY ASPECTS OF THE TEXAS WATER PLAN

Introduction

The Texas Water Development Board completed in preliminary form in May 1966 its Texas Water Plan. Twenty-seven public hearings and three public meetings were held during the summer of 1966 to receive comments, suggestions, and criticisms on the preliminary Plan. Since that time the Board has been engaged in a number of studies to evaluate alternatives suggested at the public hearings. The Plan was and is considered to be a preliminary Plan.

Water requirements for all purposes were projected by decades to the year 2020, and means of meeting these requirements proposed. Sources of water for these various requirements included surface water, ground water, return flows, and the Gulf of Mexico.

Fifty-two additional major reservoirs were proposed in the Plan, plus the modification of seven existing reservoirs and two salt-water barriers. Fourteen of these reservoirs and conveyance facilities would be included in a proposed State Water Project to convey excess water from Northeast Texas to Central and Southwest Texas. As used in this paper, "Texas Water Plan" refers to all existing and proposed facilities, and "State Water Project" to the reservoirs and conveyance facilities included in the major interbasin transfer system.

Water-Quality Management

A basic part of the Texas Water Plan and any plan involving water-resource development is water-quality management. Essentially, water-quality management envisions a system for providing the right water quality at the right place. It embodies a set of procedures for keeping each segment of a surface-water resource in the continuous dynamic balance necessary to meet the requirements of each significant present and future use. Land-use management, waste treatment and disposal practices, sources of natural pollution and their abatement, operation of existing and proposed reservoirs, the need for State participation in local or regional systems designed to improve waste-discharge practices, and carefully designed programs of stream management are all part of the overall water-quality management problem.

On considering water quality in the Water Plan, two basic assumptions were made: (1) all discharges of municipal and industrial wastes will be treated and controlled so as to protect the public health and to prevent aesthetically objectionable conditions; and (2) pollution of water resources due to oil-field brines will be completely abated over time. Some basic concepts were also necessarily developed which apply within the framework of a program for planning the development of water resources.

In developing water-quality considerations for water resources to be used for domestic needs, the controlling factor must be the protection of the health and welfare of humans using the resource. The planning agency must also consider the water-quality requirements for all beneficial purposes set out by law in Texas; and water-oriented recreation, enhancement of fish and wildlife or mitigation of losses, and the cultural and aesthetic enjoyment of society.

All quality objectives, and measures adopted to achieve these objectives, must be realistic to provide effective machinery of enforcement. Thus, standards for a given stream must be based on the total uses of the water in the stream.

The critical significance of water-quality management stems from the well-known expanding demand for water against an essentially fixed supply. Therefore, the re-use of water must be accepted as a necessary part of our water-resource picture if we are to realize the full benefit from this resource. As a consequence, it is essential that the very highest standards of treatment of municipal and industrial effluents are maintained.

A final concept, essential to water-quality management, is that very close coordination must be maintained between the water-planning agency and the water pollution control agency. This insures the translation of water-quality objectives into effective water-quality control.

Water-Quality Criteria

Included in the process of developing water-quality concepts was the formulation of proposed water-quality criteria. In developing the criteria, the staff of the Development Board met with personnel of the State Department of Health, Parks and Wildlife Department, and with consultants to discuss fully all aspects of the subject. In addition to agreeing upon some general planning concepts and principles to be observed in considering water-quality aspects of the Plan, the group also developed criteria for consideration when dealing with fish and aquatic life, municipal water use, industrial water use, irrigation water use, reservoirs (to maintain recreation and sports fishing), and municipal, industrial, and irrigation uses of ground water (Appendix A).

Present Stream Quality

To achieve the objectives as laid out, it was necessary to determine the present stream quality in order to evaluate the effects of the planned program of development upon each river basin. Included in the determination of present stream quality was a determination of the present water uses in each basin, an evaluation of the quality and quantity of all waste discharges presently reaching the stream, and a projection for future effects.

National Engineering Company prepared, under contract with the Water Development Board, a compilation and evaluation of existing water-quality data for available sources. Their report, titled "Surface Water Quality in Texas," indicated definite areas of water-quality impairment by organic and inorganic contaminants. Areas reflecting water-quality degradation from organic contaminants included portions of the Trinity, San Jacinto, San Antonio, and Rio Grande basins. Inorganic contaminants were reflected in parts of all basins, with the possible exception of the Sulphur, Cypress, and Sabine basins.

The information presented by National Engineering Company, together with information from the U.S. Geological Survey, State Department of Health, and from the files of the Development Board were compiled and evaluated for each river basin. In addition, projected return flows and the effect of these flows on future water quality were determined for each river basin. Unfortunately, increases in population and industry will not only increase the demand for water, but will also increase the volume of return flows to Texas streams.

Waste Treatment

A report titled "Return Flows in Texas--Quality and Quantity of Municipal and Industrial Wastewater Streams," prepared for the Board by Dan M. Wells and Earnest F. Gloyna of the Center for Research in Water Resources, The University of Texas, estimated the projected return flows from municipal and industrial complexes throughout the State. The report indicated the present municipal and industrial waste-water releases to be 0.8 and 1.3 million acre-feet per year, respectively. Projected total waste-water releases were expected to reach 2.0 and 5.9 million acre-feet per year by 1980 and 2020. The report also estimated that by 1970 advanced waste-water treatment would be required in some areas.

Present levels of treatment will be inadequate for projected future volumes from municipal and industrial waste-water treatment plants. In this regard, a centralization of urban sewage systems probably offers more promise than any other general development in pollution control. A report, "Preliminary Report on Waste Collection, Treatment and Disposal in Certain Urban Areas in Texas," prepared for the Water Development Board by Forrest and Cotton in conjunction with Freese, Nichols and Endress and Lockwood, Andrews and Newnam, Inc., provided information to estimate capital costs for the facilities required to serve 21 major metropolitan areas of the State. The estimates indicated that the costs will reach almost one billion dollars by 1990. The report emphasized, however, that the regional approach: allows more effective planning for a large area; allows flexibility in serving communities involved; promotes economy of construction by providing one or more large plants as compared to a multiplicity of small plants; increases efficiency of operation; promotes economy of operation; provides economy in maintenance procedures; enhances industrial growth; and relieves individual cities of direct day-to-day responsibility of sewage treatment. Still to be worked out in each instance is the proper agency to operate such a regional treatment facility. Most important, however, is the fact that centralized treatment facilities promise to offer significant reduction in the pollutional load on many of our streams.

Another influence for the necessity for improved waste treatment is the fact that we cannot depend upon using much of a stream's assimilative capacity for the dilution of municipal and industrial waste. Increasingly, this assimilative capacity will be required to accommodate that pollution from land use which is beyond practical control.

Bays and Estuaries

Increased return flows and major modifications in the flow of the rivers could greatly affect the quality of water in the bay systems. Recognizing the present unsatisfactory conditions of the bays and estuaries, their increasing value, and possible further deterioration of the water quality due to increased return flows, the Development Board authorized and financed studies of the impact of return flows on the Texas bay systems and possible structural, hydraulic, and operating modifications of the system.

A report titled, "Return Flows--Impact on Texas Bay Systems," prepared for the Board by Bryant-Curington, Inc., indicated the results of a study designed to collect available data and to describe the general ecology of the bays, develop a mode of waste-water estimation, and project return flows to each bay system; and within the availability of the data prepared estimates on both the physical exchange and biological degradation which may occur as the diluted waste waters are transported into and through the bays. Attention was also directed to the fresh-water inflows necessary for each of the major bays and estuaries to preserve the existing fish and wildlife resources and the fresh-water inflows necessary to prevent the development of nuisance conditions under present and anticipated conditions. The report estimated that by 1980 about 1 million acre-feet of dilution water may be required for Galveston Bay to maintain the present level of dissolved oxygen, and about 3 million acre-feet to maintain relative phosphate levels. By 2020 the requirements for the bay may be as high as 3 million acre-feet and 12 million acre-feet, respectively. A report, titled "Water for Preservation of Bays and Estuaries," prepared for the Board by Lockwood, Andrews and Newnam, Inc., forecasted that 2.45 million acre-feet of fresh-water inflow would be needed in the six bays and estuaries to maintain them for recreation and fish spawning. The bays and estuaries studies were: Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, and Baffin Bay and Upper Laguna Madre. The estimate of necessary fresh-water inflow was based on the concept of making maximum use of Gulf water to minimize the fresh-water needs. Determinations of fresh-water needs were based upon maintaining estuary salinity levels in an optimum range for aquatic species. Also, "fresh water" could include return flows properly treated to meet peculiar requirements of the estuary. The study included consideration of possible structural, hydraulic, and operating modifications of the bay systems to improve circulation between the Gulf of Mexico and the bays.

In addition to the previous studies, the Texas Water Pollution Control Board is initiating a comprehensive study of the Galveston Bay System. The study, which will be conducted cooperatively by State, local, and Federal government entities, will hope to determine the optimum quality of water necessary to maintain the bay as a spawning and nursery ground for fish, and as a recreational area. Currently, a work plan has been completed to organize, schedule, and coordinate the work required for the comprehensive study.

Reservoirs and Conveyance Facilities

Water-quality conditions become a particular concern in a plan for progressive development of water resources through the impoundment of water in reservoirs, and its movement through conveyance facilities. Proposed transfers from Cypress Creek basin include the movement of water from Marshall Reservoir (through Lake O' the Pines) and Titus County and Franklin County Reservoirs to

Naples Reservoir in the Sulphur River basin. Total dissolved-solids concentrations in the Cypress basin reservoirs will probably range from 80 to 150 ppm (parts per million), and the mixed water transferred to Naples will contain about 100 ppm.

The use of water from the Red River basin involves the proposed diversion of 140,000 acre-feet per year from Lake Texoma to the Trinity River via White Rock Creek for augmentation of flow of a section of the upper Trinity; the diversion of 617,000 acre-feet from the lower Red River into Pecan Bayou Reservoir; and the pumpage of this water, plus the local yield of Pecan Bayou, to Naples Reservoir for subsequent transfer to the Trinity River basin.

The concentration of total dissolved solids in Lake Texoma for the past 10 years has averaged about 1,000 ppm, and in the lower Red River the average has been about 800 ppm. If the salinity-control measures proposed by the U.S. Army Corps of Engineers are carried out, they may reduce the average total dissolved-solids concentration in Lake Texoma and at the Pecan Bayou diversion site to about 800 and 600 ppm, respectively. Even with improvement, the mineral quality of the water of Red River will be poor in comparison with most other water involved in the proposed State Water Project. However, selective pumping from the lower Red River during periods of flow in excess of base flow will provide a better quality water than that shown for the average.

Water-resource developments in the Sulphur River basin will include Cooper, Sulphur Bluff, Naples, and Texarkana Reservoirs, with Naples Reservoir receiving water transferred from the Red and Cypress basins, and Cooper Reservoir serving as the terminal for transmission to the Trinity River basin. The reservoirs of the Sulphur River basin will impound water containing from 100 to 175 ppm total dissolved solids. The average for the basin, exclusive of imports, will be about 150 ppm.

When the system is completely operational, the water available for transfer from Cooper Reservoir to Lavon Reservoir in the Trinity River basin will contain from 190 to 250 ppm total dissolved solids. Any reduction in the percentage of water derived from Red River will reduce correspondingly the total dissolved solids in Cooper Reservoir.

Lavon Reservoir on East Fork Trinity River will receive water transferred to the Trinity basin from the Red-Sulphur-Cypress reservoir system. The natural yield of Lavon is similar in quality to the water which will be imported.

Under 2020 conditions of the State Water Project, 449,100 acre-feet will be pumped annually from Lavon for use in the Dallas area, 110,000 acre-feet to West Fork Trinity River below Fort Worth for augmentation of flow, and 330,000 acre-feet released in White Rock Creek for augmentation of flow in the Trinity River below Dallas. The remaining water transferred from Cooper Reservoir will be released from the Lavon Terminal through Forney Reservoir into East Fork Trinity River and thence will flow to the main stem of the Trinity River for subsequent transfer to the Brazos. This transferred water into the Trinity River will be the only means to effectively improve and maintain the quality of water below the Fort Worth-Dallas metropolitan complex.

At the Trinity River transfer point, above Tennessee Colony Reservoir, the flow of the Trinity will consist principally of the transferred water, and return flows from the Dallas-Fort Worth area. These return flows are expected to amount to 782,100 acre-feet per year and to contain from 450 to 500 ppm dissolved solids. Runoff from the uncontrolled drainage area of the Trinity River basin will not significantly affect the average quality of the water at this site, and the water available for transfer in the State Water Project out of the Trinity will probably contain from 270 to 330 ppm total dissolved solids.

To the water diverted from the Trinity River will be added the yield of Richland Creek and Tehuacana Creek Reservoirs, with slight resultant dilution. Thus, the water added to the Brazos River below Waco will probably average from 270 to 325 ppm total dissolved solids.

The quality of water in the lower Brazos River, as measured at Richmond, varies widely, due partly to variations in flow, but depending also on the proportion of the water which originates in the salt-contributing upper Brazos drainage area. During three representative years the discharges and weighted averages of total dissolved solids were as follows:

1959 - 3,200,000 acre-feet, 323 ppm

1962 - 3,260,000 acre-feet, 551 ppm

1963 - 1,998,000 acre-feet, 513 ppm

Proposed salinity-control measures in the upper Brazos might have reduced these concentrations to 260, 485, and 410 ppm, respectively.

Under the operation of Brazos River basin reservoirs contained in the Texas Water Plan, quality in the lower Brazos will be altered by the additional use of good-quality water from Bosque and Little Rivers and by return flows from municipalities. As the result of these changes and the proposed addition of State Water Project interbasin transfers, the following ranges of total dissolved solids may be expected at the Brazos-to-Colorado transfer terminal near Hempstead:

With 1959 flows - 270 to 330 ppm

With 1962 flows - 375 to 435 ppm

With 1963 flows - 320 to 380 ppm

The water being transferred into the Colorado River basin will flow for a short distance down the river and thus will mix with the water in the stream, which will include return flows from the area below Austin. Natural runoff in the Colorado contains from 250 to 350 ppm total dissolved solids, and the return flows in the Colorado River basin will contain 450 to 550 ppm. The net result will be only a slight change in the quality of the water transferred from the Brazos, and the water available for use in the lower Colorado River basin and for transfer to the Lavaca basin will contain from 275 to 430 ppm total dissolved solids.

Water will be transferred from the Colorado River to a tributary of the Navidad River and thence to Palmetto Bend Reservoir. The yield of the Lavaca River basin is low in total dissolved solids content (200 to 300 ppm) and will dilute slightly the Project water. On transfer from Palmetto Bend to Confluence Reservoir the water will probably contain 270 to 425 ppm total dissolved solids.

Confluence Reservoir, at the mouths of the Guadalupe and San Antonio Rivers, will serve as regulating storage for the Project. In addition to the imported water, the reservoir will receive much of the yield of Cuero and Goliad Reservoirs. Little change in quality will occur as a result of the mixing, and the combined storage in Confluence Reservoir will average between 280 and 430 ppm total dissolved solids. As no other large volumes of water will be added to the transfer system, little additional change will occur in the quality of the water before its delivery to users in the Coastal Bend and Rio Grande Valley areas.

Saline-Water Conversion

Another water-quality aspect of the Plan is the utilization of the State's saline-water resources. Economic studies have been conducted to determine the potential contribution of saline-water conversion to future water supplies of the State. That study included evaluation of all the cities in the State whose 1960 population was over 1,000. Of 586 communities evaluated, 37 were determined to be possible candidates for saline-water conversion.

The criteria used in the evaluation of the communities were: population and economic base; rainfall (cities with an average annual rainfall in excess of 40 inches were eliminated, except Galveston and Texas City); water supply; water quality; alternate sources; and supplies of brackish water. Costs of conversion were based upon the electrodialysis method at interior locations and the multistage flash distillation process at coastal locations.

Problems that must be given proper consideration when dealing with saline-water conversion are the methods and costs of disposal of the effluent from the conversion process. Careful study must be given to the proper disposal of the effluent so that other resources are not destroyed in the process of developing a water supply. Methods for disposal that have been evaluated in this study include: subsurface injection, lined surface pits, discharge into surface watercourses, re-use, and mixing with municipal return flows.

The total cost of conversion including disposal of brine effluent was compared with the costs of obtaining water by conventional means. The detailed analysis of the 37 cities identified 11 cities which could benefit from future use of desalted water. Nine of the 26 cities tentatively eliminated in the economic evaluation are located in the Rio Grande Valley. These nine present a special case for further study because of: (a) their close geographic proximity, (b) the possibility of providing economical municipal water supplies through provision of one or more large desalting plants instead of many smaller ones, and (c) the similarity of water problems in the area.

Cost comparisons made in this study were on the basis of the present "state of the art." All costs were based on actual plant construction and operating experience. The study did not attempt to forecast the timing and extent of future cost improvements in desalting methods. However, for those 26 study cities which did not qualify as prospective users of desalting, calculations were made assuring reductions in the capital costs of the desalting plant and in the operating costs. These recalculations were made for cost improvement increments of 5 percent from the base calculation to an assumed upper limit of 40-percent cost improvement. Two of the 26 cities had indicated favorable cost comparisons with conventional supplies when desalting costs were reduced from 25 to 30 percent, and one additional city when desalting costs were reduced from 35 to 40 percent.

The cost of desalted water as calculated for the Texas cities would prohibit its use as agricultural water. The least expensive desalted water calculated in the study was 30 cents per thousand gallons. Translated to a dollars per acre-foot basis, this water would cost about $98.00. In the Lower Rio Grande Valley where the demand for water is great, the least expensive desalted water calculated for any city was 32.1 cents per thousand gallons. This cost of $105.00 per acre-foot compares with water for irrigation currently costing between $10 and $15 per acre-foot.

Natural Pollution

A final aspect of water quality which received consideration in the Plan is natural pollution in streams in the western part of the State. Large volumes of surface water, and some ground water are being polluted by salt from salt-water springs and seep areas in the four largest river basins of Texas. Pollution from natural sources is extremely severe in the Pecos River of the Rio Grande basin, the Colorado River basin, the Brazos River basin, and the Red River basin.

The chemical quality situation in the Red River basin was intensively investigated by the United States Public Health Service under a federally financed project titled "The Arkansas-Red River Basin Water Quality Conservation Project." The Public Health Service, in conducting the early phases of this investigation, had as its objectives: (1) to locate and define the significant natural and man-made sources of salt pollution, (2) to determine the effects of these sources on the quality of water in the receiving streams, (3) to propose possible methods and procedures for reduction of these highly mineralized discharges, (4) to estimate the results of reduction of these discharges on stream quality, and (5) to determine the benefits of water-quality improvement to present and future municipal, industrial, and agricultural water users. At the conclusion of the Public Health Service study, suggestions were made to the Corps of Engineers to determine the feasibility of elimination of the brine problem by: (1) subsurface disposal, (2) permanent storage retention of concentrated brines in the source area, (3) elimination of fresh recharge water to the brine generation areas, (4) imposition of back pressure on brine springs to suppress flows, (5) transportation of concentrated brine to non-damaging sites, and (6) utilization of salt.

The Corps of Engineers followed up the initial study by preparing a report on the problem, the main purpose of which was to describe the hydraulics of the river system, to design a structure for controlling the salt water to keep it out of the main river course and to report on the results of experimental projects such as the ring dike at Estelline Springs, near Estelline, Texas. The report, "Arkansas-Red River Basins, Water Quality Control Study, Texas-Oklahoma-Kansas, Part I," proposed construction of the Wichita River Project, Texas, for control of natural chloride pollution in the Wichita River basin. The project includes three low-flow dams, one each on the North, Middle, and South Forks of the Wichita River; two brine reservoirs, one on Canal Creek and another on a small tributary of the North Fork; and pumping plants and pipelines to transmit the brine from low-flow sites to the brine reservoirs. Based on the fact that a continuing reduction in chlorides will result through leaching and with continuing proper disposal methods, it does not appear unreasonable to anticipate an 85 percent reduction in man-made chloride by the year 1975. Projects in the Part I report were authorized by the Congress in 1966.

A second report by the Corps, titled, "Arkansas-Red River Basins, Water Quality Control Study, Texas-Oklahoma-Kansas, Part II," proposed a Red River Project which would consist of four brine reservoirs and four brine collection systems and pumping systems which would supplement the Wichita River Project. This report will be submitted to the Congress in 1967.

After a thorough review of these proposed natural pollution control projects, they were included as an important phase of the Texas Water Plan.

Investigative activities in the Brazos River basin have been conducted on Federal, State, and local levels. Some of the agencies involved in investigative activities in the basin are the Brazos River Authority, Texas A & M University, the Texas Water Development Board, and the U.S. Geological Survey. The Corps of Engineers has a multiple-purpose investigation of the Brazos River basin in progress which includes study of remedial measures for natural pollution in the upper Brazos.

Investigations sponsored by the Colorado River Municipal Water District revealed that there was a considerable amount of highly mineralized water in the Colorado River above the Robert Lee Reservoir site. Much, if not most, of the salt water is oil-field brine from the oil fields of the area. Since the natural brine occurs with the oil-field brine in the river, both are being dealt with under the same program. This salt water alleviation program consists of a plan for catching the low flow of the river and then selling the salt water to companies that will use it for water flooding in various oil fields in the area. This particular approach to dispose of saline water is somewhat different from means of salt-water control being used elsewhere in the State.

Investigations to determine the source and extent of salt water which affects the Red Bluff Reservoir have been made by the U.S. Geological Survey and Pecos River Commission. The investigation revealed that the principal source of salt water was saline ground-water discharges into the Pecos River at Malaga Bend, New Mexico, near the state boundary. The brine-yielding geological formation was studied in sufficient detail to show that by pumping brine from the formation, the water level in the formation could be controlled in such a way that the brine would not enter the river.

The Congress authorized the Bureau of Reclamation to construct the Malaga Bend Experimental Salinity Alleviation Project in 1958. The facilities for collecting and disposing of the salt water at Malaga Bend have been constructed, and the project is being evaluated during its operation. Disposal of the salt water is into a large natural depression where the water will be evaporated leaving the precipitated salt. Operation and maintenance of the pumpage and disposal system is being carried on by the Red Bluff Water Power Control District.

A necessary phase of action by the Water Development Board as a part of the Texas Water Plan includes continued and expanded research into the hydrologic systems contributing to the natural pollution load of these river basins and into local ground-water supplies. This will include a continued analysis of projects currently under study. After a complete evaluation of projects now in operation, recommendations can be made for future studies and useful information provided for design and construction of salinity-control projects in the Red and Brazos basins.

A Coordinated Effort

While the Development Board, in determining the water uses for the planned projects, sets the general guidelines for water quality necessary for these uses, the Water Pollution Control Board has the responsibility for actually setting stream standards and, through its permitting procedure, controlling the volume and quality of effluent discharges into streams.

For each of the river basins the Pollution Board prepared a draft of water-quality criteria based on information available for the period 1957-1965. The criteria were submitted to the participants at each of the 27 basin hearings on the preliminary Texas Water Plan which were held jointly with the Development Board, and comments solicited. After comments have been received, a review will be made of all information available and the draft material will be revised, where necessary. The Water Pollution Control Board is giving consideration to holding a few additional regional hearings for the purpose of allowing the people of these regions to submit additional comments on the revised material. Upon completion of the review of such comments as may be received, the Water Pollution Control Board will adopt the revised criteria as standards for the specific streams and submit them to the Federal Water Pollution Control Administration for approval. These guidelines will then govern the issuance of permits by the Pollution Board.

In any attempt for water-quality management, water quantity and water quality are inseparable; thus, administrative functions involving water development, water rights, and water-pollution control must be carefully evaluated. Any plan for water development which includes proposed impoundments, movement of water through conveyance facilities, and return flows, crosses these administrative lines and emphasizes the necessity for those agencies involved to closely correlate their activities.

APPENDIX A

PROPOSED WATER QUALITY CRITERIA FOR FORMULATION OF TEXAS WATER PLAN

1. General Planning Concepts and Principles

A. Wherever feasible within reasonable economic cost limits, municipal surface supplies shall be obtained from sources lying upstream from major discharges of treated municipal sewage and industrial wastes. There will be, however, no absolute prohibition against the establishment and use of adequately designed and operated sewerage systems in such watersheds.

B. In evaluating the assimilative capacity of a stream reach, particularly reservoirs, and of the coastal bays and estuaries, allowance shall be made for the pollutants added by uncontrollable runoff from urban-industrial areas and from agricultural areas.

C. All reservoirs, except water system regulating reservoirs, will be utilizable for sportfishing and recreation.

D. Within reasonable technological and economic limits, no stream quality conditions shall be permitted which would be inimical to fish and aquatic life.

E. Low flow augmentation for assimilation and transport of treated municipal sewage and industrial wastes will be considered as a permanent solution only in event no other procedure is found to be feasible for maintenance of specified criteria. It may be considered as an interim aid where it is found to be economically desirable and can be accomplished without detriment to other requirements.

F. Dilution of naturally poor quality water will be considered where this would not result in waste of water.

G. All feasible means will be used to control and dispose of sources of naturally poor quality water such as saline springs.

H. In-stream treatment, such as aeration, will be considered as a possible supplemental method of maintaining stream and reservoir water quality.

I. Sufficient fresh water inflows to maintain salinity gradients in the areas of the major coastal bays and estuaries necessary for fish spawning and nursery purposes will be maintained to the extent that adequate water of suitable quality can be made available at an economically justified cost. The amounts of these inflows cannot be determined pending completion of detailed studies of the biology and hydraulics of the bays and estuaries.

J. The bays and estuaries and other coastal waters will be maintained in a condition favorable to aquatic resources, sportfishing, commercial fishing, and recreation.

2. Assumptions.

A. All discharges of municipal sewage and industrial wastes will be so treated and controlled as to protect the public health, and to prevent nuisance and aesthetically objectionable conditions.

B. Pollution due to oil field brines will be completely abated over time.

3. Stream and reservoir criteria are related to the type of use to be made of the water and are applicable to all reservoirs and stream reaches above and below reservoirs, the waters of which are to be controlled and developed for beneficial use under the Texas Water Plan, and to bays and estuaries, and other coastal waters insofar as the criteria are applicable to fishery and recreational use.

A. Fish and Aquatic Life Environment

1) Where preservation and enhancement of fish and aquatic resources, and other forms of water associated wildlife resources, are a primary consideration.

a) Wherever not limited by natural phenomena, DO concentration shall not be less than 5 mg/1 at the low point of the diurnal cycle.

b) Concentrations of toxic materials shall not be sufficient to damage fish and aquatic resources and wildlife or to change the overall ecology to an extent detrimental to these forms of life.

c) No controllable bottom deposits.

d) pH - between 6.5 and 8.5

2) Where fish and aquatic resources, and other forms of water associated wildlife resources, are to be maintained but enhancement of those resources is not a principle consideration.

a) DO concentration shall not be less than 2.5 mg/1 at low point of diurnal cycle at any time or place, as measured at mid-depth of the stream or at 3 feet in depth whichever is the lesser. This criterion will apply in those cases where treated municipal sewage and industrial waste effluents comprise 50% or more of the streamflow during low flow months.

b) Concentrations of toxic materials in effluents shall not exceed the 48 hour $\frac{TLm}{10}$, and long term or chronic toxicity effects will be negligible.

c) pH - between 6.0 and 9.0

B. Municipal Use (Raw water surface supply)

1) USPHS Drinking Water Standards, 1962, recommended limits, insofar as those constituents which cannot be removed by conventional water treatment processes are concerned, except SO_4 which shall not exceed 75 mg/1 if economically feasible to attain.

a) Where water having greater concentrations of mineral substances from uncontrollable sources up to a TDS concentration of 1000 mg/1 has been successfully used, and it is not economically feasible to improve the stream quality through dilution, greater concentrations will be permitted. Sulphates shall not exceed 250 mg/l insofar as is feasible.

C. Industrial Use (General use)

1) Water satisfactory for municipal supplies will generally be satisfactory for industrial fresh water supplies, and USPHS Drinking Water Standards, 1962, recommended limits, and as further qualified above for municipal use, as regards mineral constituents will prevail. Where a large industrial use requiring high quality fresh water exists or is anticipated, chloride concentrations should not exceed 100 mg/l. Where water is required of a superior quality to that normally available from a surface supply, it shall be assumed that the industry will provide additional water treatment.

D. Irrigation Use

1) Use criteria are based on irrigation water classification system developed by University of California at Davis and United States Salinity Laboratory at Riverside. Criteria for Class I irrigation water to be met wherever economically feasible.

Class I - Excellent to good, or suitable for most plants under most conditions.

Category	Quality
% Sodium $\left(\frac{Na \times 100}{Na + Ca + Mg + K \text{ as Meq/l}}\right)$	30-60%
Boron	general 0.5 Mg/l; tolerant plants 1.5 Mg/l
Chloride (Cl)	195 Mg/l
Sulphate (SO_4)	480 Mg/l
Spec. Conductivity Micro mho/Cm^2 @ 25°C	1000
Total Dissolved Solids	700 Mg/l

Category	Quality

Class II - Good to injurious, harmful to some plants under certain conditions of soil, climate, practices.

% Sodium $\left(\frac{Na \times 100}{Na + Ca + Mg + K \text{ as } Meq/l}\right)$	30-75%
Boron	.5 - 2.0
Chloride (Cl)	570 Mg/l
Sulphate (SO_4)	960 Mg/l
Spec. Conductivity Micro mho/Cm^2 @ 25°C	3000
Total Dissolved Solids	2100 Mg/l

Class III - Injurious to unsatisfactory, unsuitable under most conditions.

% Sodium $\left(\frac{Na \times 100}{Na + Ca + Mg + K \text{ as } Meq/l}\right)$	>70%
Boron	>2.0 Mg/l
Chloride (Cl)	>570 Mg/l
Sulphate (SO_4)	>960 Mg/l
Spec. Conductivity Micro mho/Cm^2 @ 25°C	>3000
Total Dissolved Solids	>2100 Mg/l

E. Additional criteria for reservoirs - to maintain recreation and sport-fishing.

1) It is assumed that concentrations of nutrients, i.e. total C total N and P will be maintained at such levels as not to stimulate undesirable aquatic growths.

4. Ground Water Criteria

A. Municipal use

1) USPHS Drinking Water Standards, 1962, recommended limits, insofar as those constituents which cannot be removed by conventional water treatment processes are concerned, except SO_4 which shall not exceed 75 mg/l if economically feasible to attain.

a) Where water having greater concentrations of mineral substances from uncontrollable sources up to a TDS concentration of 1000 mg/l has been successfully used, greater concentrations will be permitted. Sulphates shall not exceed 250 mg/l insofar as is feasible.

B. Industrial Use (Raw water surface supply)

1) Water satisfactory for municipal supplies will generally be satisfactory for industrial fresh water supplies, and USPHS Drinking Water Standards, 1962, recommended limits, and as further qualified above for municipal use, as regards mineral constituents will prevail. Where a large industrial use requiring high quality fresh water exists or is anticipated, chloride concentrations should not exceed 100 mg/l. Where water of a superior quality to that normally available from a present supply, it shall be assumed that the industry will provide additional water treatment.

C. Irrigation Use

1) Use criteria are based on irrigation water classification system developed by University of California at Davis and United States Salinity Laboratory at Riverside. Criteria for Class I irrigation water to be met wherever economically feasible. Class I - Excellent to good, or suitable for most plants under most conditions.

Category	Quality
% Sodium $\left(\frac{Na \times 100}{Na + Ca\ Mg + K \text{ as Meq/l}}\right)$	30-60%
Boron	general 0.5 Mg/l; tolerant plants 1.5 Mg/l
Chloride (Cl)	195 Mg/l
Sulphate (SO_4)	480 Mg/l
Spec. Conductivity Micro mho/Cm^2 @ 25°C	1000
Total Dissolved Solids	700 Mg/l

Class II - Good to injurious, harmful to some plants under certain conditions of soil, climate, practices.

% Sodium $\left(\frac{Na \times 100}{Na + Ca + Mg + K \text{ as Meq/l}}\right)$	30-75%
Boron	.5 - 2.0

Category	Quality
Chloride (Cl)	570 Mg/1
Sulphate (SO_4)	960 Mg/1
Spec. Conductivity Micro mho/Cm^2 @ 25°C	3000
Total Dissolved Solids	2100 Mg/1

Class III - Injurious to unsatisfactory, unsuitable under most conditions.

% Sodium $\left(\frac{Na \times 100}{Na + Ca + Mg + K \text{ as Meg/1}}\right)$	>70%
Boron	>2.0 Mg/1
Chloride (Cl)	>570 Mg/1
Sulphate (SO4)	>960 Mg/1
Spec. Conductivity Micro mho/Cm^2 @ 25°C	>3000
Total Dissolved Solids	>2100 Mg/1

TIDAL INLETS FOR PRESERVATION OF ESTUARIES

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TIDAL INLETS FOR PRESERVATION OF ESTUARIES

Synopsis

A basic proposition of the Texas Water Plan is to preserve and enhance bay and estuary environments. The Plan proposes to use Gulf waters as much as possible, thereby minimizing needs for reservoir fresh water releases. Reviewed from the standpoint of coastal engineering and tidal hydraulics are the complex problems involved in the design and building of balanced tidal inlets to allow free inflow of adequate Gulf water. Environmental controls include use of inlets both to increase and decrease salinity, aid circulation and mixing of the waters, and provide sufficient tidal flushing to help the estuary assimilate treated return flows. Concepts of typical inlet design, including the sediment transport aspects, water and salinity balance, and tidal flushing process, are presented.

Introduction

For at least three decades there has been a definite, progressively increasing need for more tidal inlets through the barrier islands of the Texas Coast, for the improvement of the coastal fisheries. Some of the bays are too salty while others have too much fresh water. Fresh water inflows historically into the bays have wide seasonal variations, ranging from severe droughts to major floods. In places these estuaries are being choked with pollution and spoil from dredging operations. All of this--plus the diminishing fresh water flow, increasing pollution loads, the threat of further choking of Gulf water inflow by hurricane protection works, and the rapidly rising demand for recreation--produces some wildly disturbed estuaries.

In creating a Texas Water Plan during the last two years, and while exploring the problem of increasing return flows on the bay systems, the Texas Water Development Board wisely recognized the implications of possible serious damage to the estuaries and fishery by major but inevitable modifications in the river flows. This emphasized the imperative need for an entirely new concept, in terms of coastal engineering and tidal hydraulics, one that would permit optimum river development and at the same time preserve and enhance the Texas coastal bays and estuaries. This has been done.

The new concept is that increased and improved distribution of Gulf water inflow into the estuaries will be a quite satisfactory substitute for large quantities of fresh water. The exchange would be accomplished by using tidal inlets long needed for the migration of fish.

This paper is a review of the complex problems involved in the design and use of tidal inlets for environmental controls to save Texas coastal bays and estuaries, including maximum use of Gulf water to minimize future fresh water requirements. Co-author Carothers provided the technical basis for the paper.

Value of Estuaries

Preservation and enhancement of the Texas coastal bays and estuaries is one of the objectives of the Texas Water Plan. Pending a complete inventory and evaluation, some indication of the astonishing order of magnitude of the value of these estuaries for recreation, sport and commercial fishing alone is suggested by an expansion of the annual value of \$166 per bay surface acre estimated for 1958 in the Corpus Christi area. This value included \$151 for recreation and sport fishing and \$15 for commercial fishing. The study from which these values were taken was made by Bureau of Business Research and Institute of Marine Science.[1] It is the only known attempt to make a complete evaluation of Texas bays.

If these values, perhaps now obsolete and understated, were applied to the 1.5 million surface acres of Texas bays and estuaries, the value would be on the order of \$249 million annually. Then, if the "present value" formula for annuity is applied at 5 percent for 50 years, the bays of the Texas Coast have a present value of \$4.55 billion ($1.5 \times 10^6 \times \$166 \times 18.25 = \$4.55$ billion) for recreation and fishery. Recreation and sport fishing contribute most to this value, which amounts to \$3,200 per surface acre.

Another imprecise approach at evaluation of the bays may be derived from the expenditures for salt-water fishing in 1960. The U.S. Department of Commerce[2] reported that \$109 million was spent for 6.2 million man-days of salt-water fishing activity. This amounts to \$17.50 per man-day. The Texas Water Development Board has a projection of 13.5 million man-days of salt-water fishing per year by the year 2020.

From these data, it is projected that expenditures will amount to \$20 per man-day for 7.0 million man-days (\$140 million) in the year 1970; and \$30 per man-day for the 13.5 million man-days (\$405 million) of salt-water fishing activity in 2020. Then, computed in 5-year increments by discount factors (5%-50 yr), the Texas salt-water sport-fishing activity has a present value of about \$4.0 billion.

Although this includes offshore salt-water sport fishing, the marine scientist and biologist indicate the nearshore Gulf fishery is largely dependent on the coastal bays. These exercises clearly establish the necessity to save these aspects of the bays and estuaries.

The Variable Environment

Geographically, Texas coastal bays and estuaries lie athwart the critical area of water balance variation, which extends north-south through the central

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[1] "Marine Resources of the Corpus Christi Area," The University of Texas, Research Monograph No. 20, 1960.

[2] "Texas Hunting and Fishing Survey," 1960, U.S. Department of Commerce, Bureau of the Census.

United States. Figure 1 is a map showing the percentage of years that annual precipitation has been less than evaporation and transpiration. The area of greatest variability with respect to droughts is between the 80 and 20 percent frequency lines.

Locations of the coastal bays, rivers, and existing tidal inlets are shown on Figure 2, Texas Bays and Estuaries. Figure 3 shows that the climate varies from humid, moist subhumid, dry subhumid, to semiarid, with average annual rainfall, from west to east, ranging from 25 to 52 inches.

Fresh water balance in an estuary consists of: rainfall on bay surface together with runoff from land and return flow (used water), less gross evaporation from the bay surface. When fresh water balance is negative, evaporation exceeds rainfall and runoff, a condition requiring enough Gulf water inflow with efficient mixing to prevent intolerable hypersalinities--that is, salinities in excess of 45 ppt (parts per thousand).

Average annual fresh water balances of the major bay systems, under present natural riverflow conditions, are shown in Plan in Figure 4, Coastal Water Balance. The balance varies from minus 350,000 acre-feet per year in Baffin Bay to plus 9.7 million acre-feet per year in Galveston Bay. Also shown in Figure 4 is the estimated annual Gulf water tidal inflow. This amounts to 25.1 million acre-feet through Aransas Pass to supply four bay systems--Baffin, Corpus Christi, Aransas, and San Antonio Bays. Tidal inflows to Matagorda and Galveston Bays are computed at 35.8 and 71.0 million acre-feet per year, respectively. Because of limited available data, Lower Laguna Madre was not included in this study.

Extreme variations in annual fresh water balance from Baffin Bay to Galveston Bay, under wettest, average, and driest climatic conditions, are shown graphically in Figure 5.

Baffin Bay and Upper Laguna Madre are always deficient or negative in fresh water balance, with the exception of the wettest year. This "dead" or "stagnant" estuary in semiarid climate has no direct tidal inflow, resulting in intolerable hypersalinity. Its remaining limited "lifeline" source of Gulf water is the Intracoastal Waterway.

Corpus Christi Bay (dry subhumid) is already suffering from the effects of river development, and this is not reflected in the natural fresh water balance shown. But the major trouble with this bay is the highly saline inflow as a density current or stratified flow from the Upper Laguna Madre. Under this condition, the bay can scarcely afford any reduction even in the original natural fresh water supply.

Aransas Bay (dry subhumid) is balanced around the average annual climatic condition, with fresh water deficiency below average and excess above average.

San Antonio Bay, in moist subhumid climate, now has an ample supply of fresh water except for the driest year. This is the first bay, going eastward toward wetter climate, that is good for the commercial oyster fishery.

Prior to 1925, the Colorado River flowed into the east arm of Matagorda Bay (moist subhumid climate). Sometime between 1925 and 1930, nature and man combined to divert most of this riverflow directly into the Gulf of Mexico, thus cutting off part of the east arm of the bay. The drastic reduction in fresh water balance to this estuary is shown by arrows on Figure 5. Incidentally, the decline of the commercial oyster fishery in Matagorda Bay in the last two decades may be due to this diversion.

In Galveston Bay (humid climate), 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.

Salinity Variations are shown in Figure 6. The average salinity of sea water is 35 ppt (parts per thousand). The salinity of nearshore Gulf of Mexico varies from about 25 to 37.7 ppt. Average annual salinities decrease west to east from about 55 ppt in Baffin Bay to about 20 ppt in Galveston Bay. The extreme hypersalinity amounts to about 80 ppt in Baffin Bay, although extreme flooding occasionally reduces salinities to 1 ppt or less near rivers.

In each bay there is a great annual variation from the wettest to the driest year. For each range of annual climatic condition (rainfall, runoff, and evaporation relations) there are variable salinity gradients from tidal 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 currents or stratified flows in the bays and channels. Although the fish in these estuaries have considerable tolerance for wide ranges of salinity, intolerable salinities, either too salty or too fresh, do occur. The most intolerable are the hypersalinities in excess of 45 ppt in Baffin Bay and Upper Laguna Madre during dry years.

Indiscriminate hydraulic spoil disposal in these estuaries has caused the loss of valuable habitat. There are many cases in which spoil blocks or changes bay water circulation and water interchange. This trend appears to be increasing. The disposal of spoil in all these bays should be more responsibly controlled.

Pollution of some sections of the Texas bays and estuaries has reached appalling proportions. It cannot be effectively abated by either fresh water or tidal flushing. No longer can the estuaries be considered cost-free substitutes for adequate waste treatment. Neither municipalities nor industry nor agriculture have any inherent right to pollute these waters. Pollution in these estuaries must be eliminated. If it is not, Texas must be prepared to "write off" the bays for recreation and fishery and thereafter consider them tools for industry and commerce, and as "holding ponds" for polluted waters from all sources.

Imbalanced Tidal Inlets

In stable tidal inlets there is a balance between the scouring action of the tidal currents, tending to keep the channels open, and the longshore transport of beach sand, tending to close them. Inlets migrate in the direction of the dominant longshore transport, unless the channels are stabilized naturally by headlands or artificially by jetties. Dominent direction along Texas Coast is from both east and south to accumulate beach sand near Baffin Bay. This collection of sand is the major source of windborne sands forming the Recent South Texas Sand Dune area.

Reason dictates that a scientific use must be made of balanced tidal inlets along the Texas Coast. Cuts through the barrier islands for fish passes and navigation channels generally constitute misuse of inlets because they were not balanced. These include Mansfield, Yarborough, Corpus Christi, Cedar Bayou, Matagorda Ship Channel, Brown Cedar Cut, and Rollover Pass, all situated as shown on Figure 7, Imbalanced Inlets. Some discussion of these is in order.

Mansfield Pass, probably too long for its size, lost its original jetties in 1957 when they sank into soft, recent muds and the pass rapidly sanded up at the Gulf end. This indicates imbalance toward siltation. Since then new jetties have been built.

Attempts to open Yarborough Pass started in 1941. This extremely small pass had no capacity to transport sediment (with tractive force of 0.033 psf and only one-third of that needed--see empirical correlations with tractive force in the Appendix) and was due to be closed rapidly by the littoral transport, which is exactly what happened. In fact, it was reported that during one attempt the dredge was so overwhelmed by littoral transport that it had to dredge its way back out into the bay.

Attempts to reopen Corpus Christi Pass were started in 1939. After several attempts, this pass was abandoned. Later analysis shows that the pass had migrated to excessive lengths and was imbalanced to definite and fairly rapid siltation.

Cedar Bayou is an intermittent small pass, with inadequate water interchange, between Mesquite Bay and the Gulf. It is too long, stretched nearly to 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 in January 1966 it was further lengthened by migration and nearly closed again. Its operation and behavior has been as predicted mathematically 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. The maintenance dredging provided a little less than half enough tractive force or 0.045 psf; the pass is approaching natural closure with tractive force at about 0.035 psf, or only one-third of that needed for a balanced tidal inlet.

The Matagorda Bay Channel (new deep water ship channel) is a large artificial inlet. It has been found to be too short, a high-velocity pass imbalanced toward excessive erosion. Indicated tractive force appears to be over twice that desired for a balanced tidal inlet. Regardless of that, such high-velocity inlets are strongly attractive to fish and fishermen.

Brown Cedar Cut (at east end of East Matagorda Bay) was naturally closed in 1964, after operating for many years at low tidal 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.

Rollover Pass (at east end of East Galveston Bay) is artificially choked and provides insignificant water inflow. The original high-velocity opening at Rollover Pass was made in 1955 without securing necessary basic data to permit application of proper tidal hydraulics and coastal engineering, without making water interchange studies, and with inadequate right-of-way. It was too short in length and immediately showed excessive erosion. The tractive force at 95 percent tidal differential (at tropic or diurnal tide and equivalent to spring tide) amounted to 0.44 psf, or about 4 times too high for a stable, balanced tidal inlet. 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 in the bay was reversed and conditions were reported by marine science as "faunistically" rich; and reported by sports fishing as "fantastic." Unfortunately, the pass was then choked in desperation as an immediate erosion control measure.

The construction of a tidal inlet with proper balanced design based on adequate basic data has never been undertaken, at least along the Texas Coast. It is understandable that many Texans, including some of the technical and scientific community, are under the impression that balanced tidal inlets cannot be designed and built. The future planning, to use Gulf water to minimize fresh water needs, may well profit by observation of these many examples of the past imbalanced tidal inlets. As reflected in the Appendix, scientific formulae and technique are available to attain dynamic balance in the design of these inlets.

Use of Balanced Inlets

The basic concept of the proper use of balanced tidal inlets along the Texas Coast to save the recreation and fishery, and to minimize future fresh water needs of bays and estuaries is illustrated by Figure 8. Only the first approximation sizing for balance of the sediment transport aspects, water balance, salinity controls, and tidal flushing, have been made. The estimated annual Gulf water inflows through the new inlets are shown in millions of acre-feet.

Boggy Slough Pass should be a large Gulf water interchange inlet (1) to reduce hypersalinity in Baffin Bay and Upper Laguna Madre to tolerable amounts and (2) to relieve Corpus Christi Bay of this burdensome appendage. This inlet would transform Baffin Bay from a "dead" to a "live" estuary. Clearly, in such a condition it would be a valuable asset to the Padre Island National Seashore.

As mentioned in the Appendix, the efficiency of mixing between Gulf and estuary waters is greatly decreased where tidal inlets are spaced over 25 to 30 miles apart. With the appendage of Upper Laguna Madre and Baffin Bay replacing its high evaporation losses with tidal water from Corpus Christi Bay--returning stagnant, highly saline water--the rate of tidal flushing in Corpus Christi Bay is now very slow. The fresh water flow from Nueces River during drought years has already been cut off from the estuary by Lake Corpus Christi.

Therefore, Corpus Christi Bay is seriously threatened with undue and intolerable hypersalinity, as well as more pollution than it can assimilate--even from fairly well treated return flow. Corpus Christi Pass, in conjunction with Boggy Slough Pass, is thus proposed to provide efficient water interchange, salinity control, and good tidal flushing--as well as to create an ideal location for recreation fishing along and near the pass. It would be considerably shorter than the old abandoned Corpus Christi Pass.

The nearly complete closing (by uncontrolled hydraulic spoiling and land filling) of the Upper Laguna Madre's limited natural life line of flow from Corpus Christi Bay is used here as the horrible example of man's indiscriminate destruction of the fishery habitat. Since 1936, spoil banks from oil-field channels and small boat channels, and landfill roads for oil field and the Padre Island Causeway have been increasingly obstructing the natural flow. About 4,200 acres of prime spawning and nursery grounds is being lost by resulting siltation. At \$166 per bay surface acre per year (from the Corpus Christi study mentioned under "Value of Estuaries"), the computed damages by present worth formula amounts to \$12.7 million (4,200 x \$166 x 18.25). This is the proposed location of Demit Island Channel, to restore natural flow and complete water circulation and salinity control between the Corpus Christi and Boggy Slough Inlets, and to replace some part of the destroyed spawning and nursery grounds.

A key part of the Texas Water Plan (1966) is to develop fully the Guadalupe and San Antonio Rivers, which flow into San Antonio Bay. Normal river development means reduction of flood flows and increase of low flows, and this should be good for any estuary. But full river development means practically no natural flow during low average and driest climatic conditions. Aransas Bay gets a substantial portion of its fresh water from San Antonio Bay. With present rather limited Gulf inflow together with such full river development, excessive hypersalinities may be expected in both these bays. Ample Gulf water inflow with efficient mixing will then be needed to minimize the fresh water needs of these estuaries. Mud Island Pass, Cedar Bayou Pass, and Panther Point Pass are proposed as efficiently operating tidal inlets to serve Aransas and San Antonio Bays.

Matagorda Bay now has about fully developed Gulf water interchange through Pass Cavallo and the nearby Matagorda Bay Channel (a deep water ship channel recently cut through Matagorda Peninsula), and no additional tidal inlets are 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 the natural closure of Brown Cedar Cut. This cut needs to be relocated opposite deeper water in the bay and designed to provide about 2.5 million acre-feet of Gulf inflow per year. The primary purpose of this relocated inlet is to replace a small natural inlet which, until 1964, was locally famed for its excellent sport fishing.

Galveston Bay naturally has somewhere near its full potential of Gulf water interchange, but East Galveston Bay needs improved circulation and increased salinity in the upper reaches through the now choked Rollover Pass. Proper investigations and water interchange analyses probably 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 much relative increase in total inflow to the overall Galveston Bay System--but it will improve circulation, efficiency of mixing, and tidal flushing, as well as increase salinity in the east half of East Galveston Bay. Balanced length will have to be "created," by designed spoil banks. The interior end around the Intracoastal Waterway may have to be designed as a sand catchment basin for dredged "by passing" of up to 80,000 cubic yards 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 first direct measure of the effects of these new tidal inlets on the estuary environment is the degree of salinity control achieved. The average annual salinities for the range of climatic conditions with present or natural river runoff are plotted in Figure 9, Salinity Control with New Inlets.

The maximum salinities of about 80 ppt in Baffin Bay and Upper Laguna Madre are reduced to 45 ppt, which is the upper design limit for salinity control in this estuary. The maximum salinities of nearly 60 ppt in Corpus Christi Bay (including Nueces Bay) are reduced to a more desirable upper limit of 40 ppt.

Aransas Bay alone now has a "negative" fresh water balance nearly half the time as shown on Figure 5. It will be easy to cause the salinities to spiral up into intolerable hypersalinity ranges with a reduction in below average annual runoff. The water and salinity balance equations (see Appendix) indicate the need for additional Gulf inflow to help prevent this. Mud Island Pass is proposed to supplement the divided and somewhat limited inflow from Aransas Pass.

The chief advantage of shortening Cedar Bayou is to reopen it as a balanced tidal inlet to save recreation fishing in Mesquite Bay, together with a relatively small contribution to salinity control. This is a small bay located between Aransas and San Antonio Bays. Water interchange between it and the large bays is somewhat restricted.

The proposed full development of the San Antonio and Guadalupe Rivers will cut off practically all fresh water flow from San Antonio Bay. With little return flow and its present limited Gulf water interchange, salinities will literally skyrocket to excessive hypersalinity. For that reason there will very likely be a massive man-made oyster kill in San Antonio Bay. Most of the developed water supply would have to be released to the bay to maintain salinities below 30 ppt for the commercial oyster fishery. But with a substantial increase in tidal inflow thru Panther Point Pass, salinities can be controlled below 40 ppt with nominal fresh water releases. This will actually enhance the highly valuable recreation fishery, but at the expense of the relatively low value commercial oyster.

If this concept is followed, it will open the way for legal exploitation of the sometimes "dead" shell reefs--which are still very valuable to the ecology of the fishery. Surely there is a way to provide the coastal fisheries the legal, technical, scientific, and engineering backing necessary to permit 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. If not, shell dredging may not be compatible with the overall economy.

Although not indicated on Figure 9, it is the design intent to limit salinities to 40 ppt in East Matagorda Bay, where the relocation of Brown Cedar Cut is proposed. It appears that with this relocated Brown Cedar Cut, East Matagorda Bay may well operate with its local runoff, without any controlled releases from the Colorado River.

Also, the salinity gradients in East Galveston Bay are not indicated in Figure 9, where it is proposed to enlarge Rollover Pass. Here, it is the design intent to reverse completely the horizontal salinity gradient and to increase salinities in the eastern half of this arm of Galveston Bay.

Typical design of a balanced tidal inlet is illustrated by Panther Point Pass at San Antonio Bay (see Figure 10). Tractive force at diurnal tide is about 0.1 psf. Median velocity is 1.8 fps with Shields entrainment function (a tractive force function) approaching 0.6 (between saltation and suspension of the median sand size). Velocity at diurnal tide is 3.4 fps. Annual tidal inflow is 6.3 million acre-feet.

Jetties, shaped for efficient inflow without contraction, extend out to a Gulf depth roughly two-thirds of the channel depth where the Gulf bar will function as a natural sand bypass for a large portion of the littoral drift. Stabilization works include jetties and section controls with sheet piling. Jetties can be used for "jetty" fishing. Spoil will be used to build protective dunes at inland end of jetties as well as to build up low ground along the pass for recreational use. The bridge will be built to clear hurricane waves, which will also permit small sport-fishing boats to use the pass to fish offshore. Ample right-of-way for public use must be secured.

This concept of typical tidal inlet design from first approximation has, however, a long way to go. There is much basic data to secure. From analysis of tidal differentials to final dynamic balance, several steps need to be computerized. Computer programs will greatly simplify the technical complexities of design, including programs for: (1) analysis of tidal differentials from tide-gage readings and forecast of changed tidal flow with a new pass; (2) detailed analyses of littoral transport rates in both directions alongshore and out to various Gulf water depths; (3) making trial balances to find proper length, depth, width, and integrated tidal inflow and outflow; (4) integration of the sediment transport with tidal inflow, outflow, and final dynamic balance using the highly variable Gulf bar acting as a natural sand by-passing mechanism with a minimum of sediment transport into the bay; and (5) analyses of the complex salinity controls and tidal flushing processes. Movable bed models of the inlet, including waves, are needed for final design check and to help locate and shape the jetties.

Fresh Water Needs

Initial estimates of large fresh water needs for estuaries would not permit reasonable river development in the Texas Water Plan. But from this expanded study of the possible uses of balanced tidal inlets, the concept has evolved that increased and improved distribution of Gulf water inflow into the estuaries will be a good substitute for such excessive fresh water requirements.

The concepts of minimum fresh water requirements are expressed in millions of acre-feet per year in Figure 11. These amounts are needed from the various rivers (or some alternate source) that are planned for development and do not reflect amounts of runoff available from coastal watersheds. It is contemplated that by designed and controlled releases as needed for prime spawning and nursery grounds, the actual fresh water needs will be found to be of the order indicated. This "fresh water" may, of course, include return flows properly treated to meet the peculiar requirements of the estuary.

For the bays and estuaries, annual fresh water needs from the developed rivers are roughly computed to total 2.45 million acre-feet while the annual Gulf water needs (through new tidal inlets) amount to 33.4 million acre-feet. It is thought that this will permit reasonable river development as well as save the most valuable fishery.

Generally, the indicated estuary fresh water needs are no more than the projected return flows; where they exceed such projections it may mean that other future fresh water requirements around the estuary have been underestimated. The 1.5 million acre-feet per year shown for Galveston Bay is designed to maintain oyster fishery and amounts to less than the projected return flow. It is quite an understatement to say that it will be a problem to treat the return flows so as to be satisfactory for the oyster and sport fishery in this estuary.

Complexity of the Problem

There are numbers of complicated problems involved in changing these ideas into reality. To solve them will require better communication and closer liaison between many divisions of the scientific and engineering community--coastal and hydraulic engineers, marine scientists and fishery biologists, geologists, sanitary engineers, hydrologists, hydrographers, cartographers, waterway engineers, and others. A good deal of money is needed merely to collect the necessary input data for the computer programs. On the subject of these long neglected bays and estuaries there is a dearth of scientific information, and this must be collected and put into usable form.

With seven tidal inlets in mind but not yet placed into final dynamic balance, surely the State can well afford to establish--one way or another--somewhere in Texas a first class coastal engineering and tidal hydraulics laboratory qualified and equipped to make tidal inlet model studies, as well as to assist in collecting scientific data and putting it into usable form. Such a lab might be expanded and developed into the needed communication center.

Equitable financing of this program of tidal inlets is complicated by the multiple uses, widespread benefits, and various responsibilities with respect to aspects of preservation, enhancement, and damages to the estuaries. The multiple uses of tidal inlets include: (1) they are excellent grounds for marine sport fishing; (2) fish move in and out of them to spawn and nurse in the shallow, protected areas of the bays; (3) they are used to control salinities--sometimes to reduce, sometimes to increase them; and (4) they provide the slow but necessary tidal flushing to move in new Gulf water, move out excess flood waters, and flush out a reasonable amount of pollution.

To a variable degree for individual tidal inlets--each has its unique design, function, and benefits--the widespread benefits include: (1) improvement of recreation and sport fishing, thereby inviting more tourists with resulting benefits to related commerce; (2) improvement of commercial fishery; (3) creation, preservation, or improvement of spawning and nursery grounds; (4) assistance in restoration or replacement of damage incurred from spoiling by navigation and shell dredging; (5) pollution control; and (6) reduction of the estuary fresh water needs to allow well planned, long termed development of rivers in the Texas Water Plan.

Responsibilities and interests vary from local, to State, to National. Agencies and people involved include Parks and Wildlife, sport fishing, commercial fishing, tourism, water development, pollution control, navigation, shell dredging, Padre Island National Seashore, wild fowl hunters, and many others. The benefits and responsibilities are so diverse and complex that financing will have to be based on some general, simplified formula of State and Federal participation.

Perhaps the really difficult problem is to convince the people that balanced tidal inlets can be built along the Texas Coast and serve these various purposes. The past record will be hard to overcome.

Conclusions

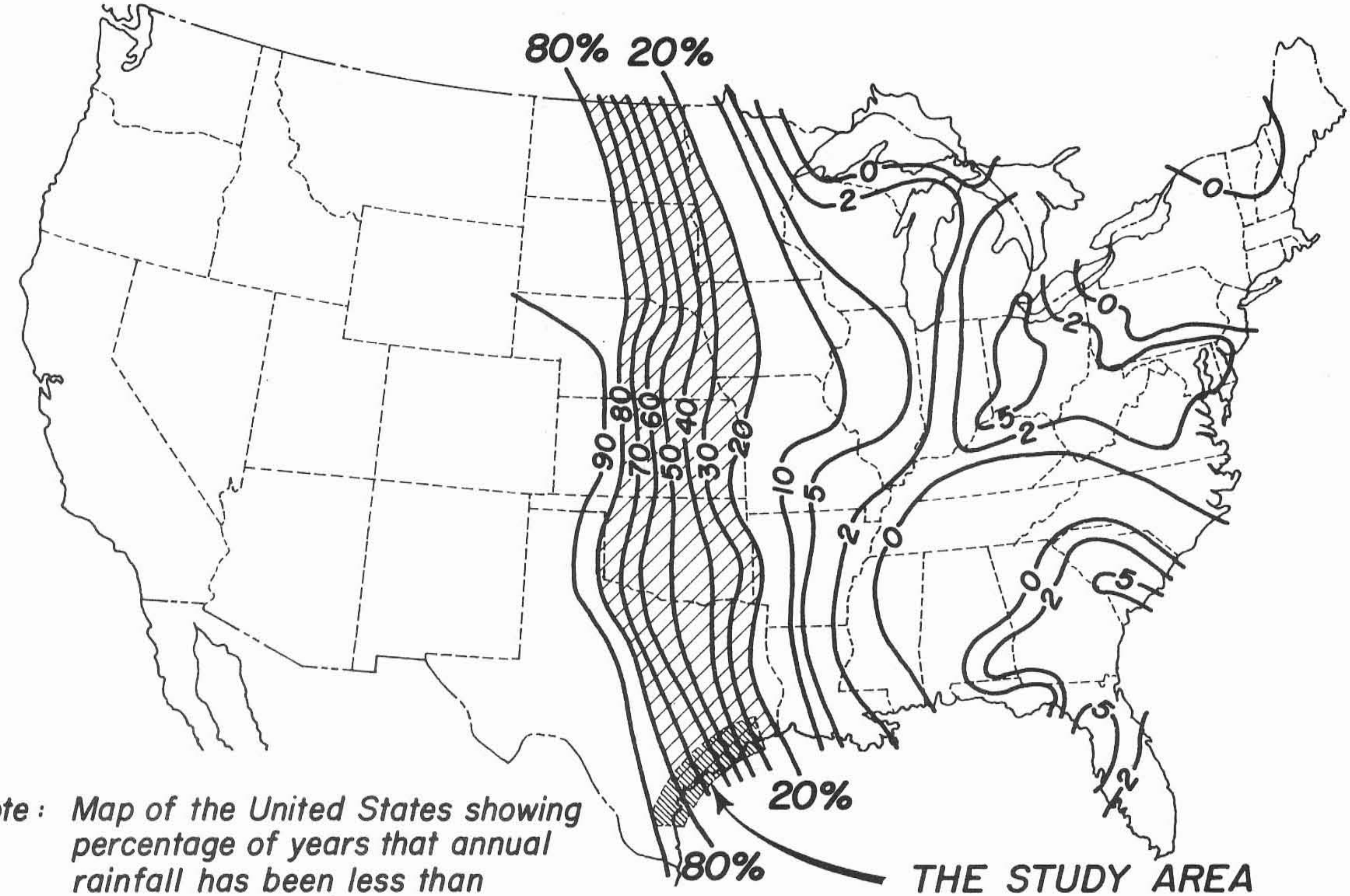
1. Balanced tidal inlets can and should be designed and built along the Texas Coast and used to preserve and enhance the recreation and fishery aspects of the bays and estuaries.

2. The same tidal inlets can also be used to minimize estuary fresh water needs, thus permitting reasonable river development in the Texas Water Plan.

3. The technical problems, while complex, can be simplified by systematic collection of scientific data for input to computer programs.

4. The State of Texas should establish a tidal hydraulics laboratory to make model studies on these tidal inlets. Such a lab may be expanded to assist in collection of information and to serve as the needed scientific communication center.

5. Reduction and responsible control of excessive pollution and spoil from dredging operations is a prime requisite in maintenance and preservation of the recreation and fishery interests of these bays and estuaries.



Note : Map of the United States showing percentage of years that annual rainfall has been less than evaporation and transpiration.

FIG. I - CRITICAL AREA OF WATER BALANCE VARIATION

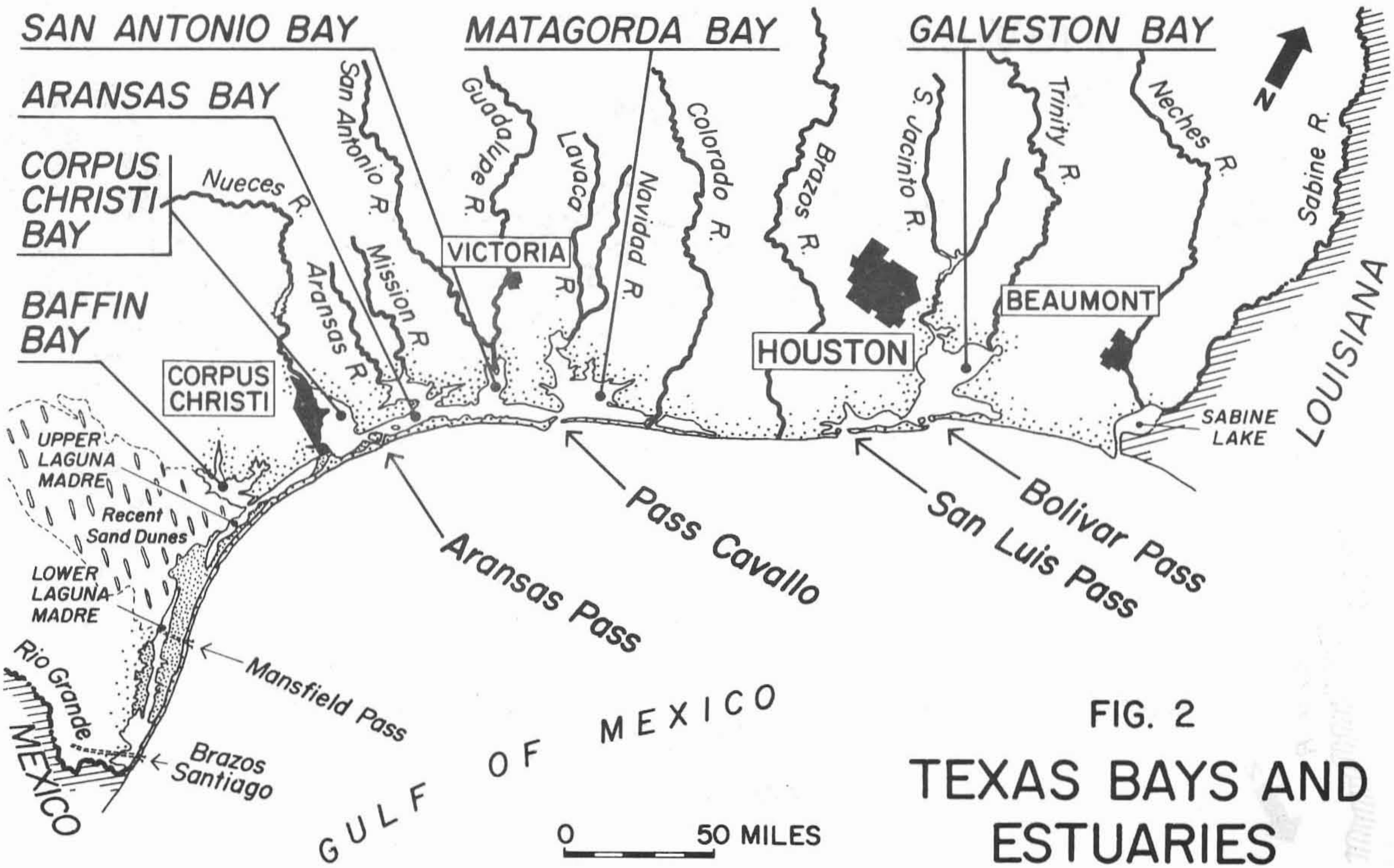


FIG. 2

TEXAS BAYS AND ESTUARIES

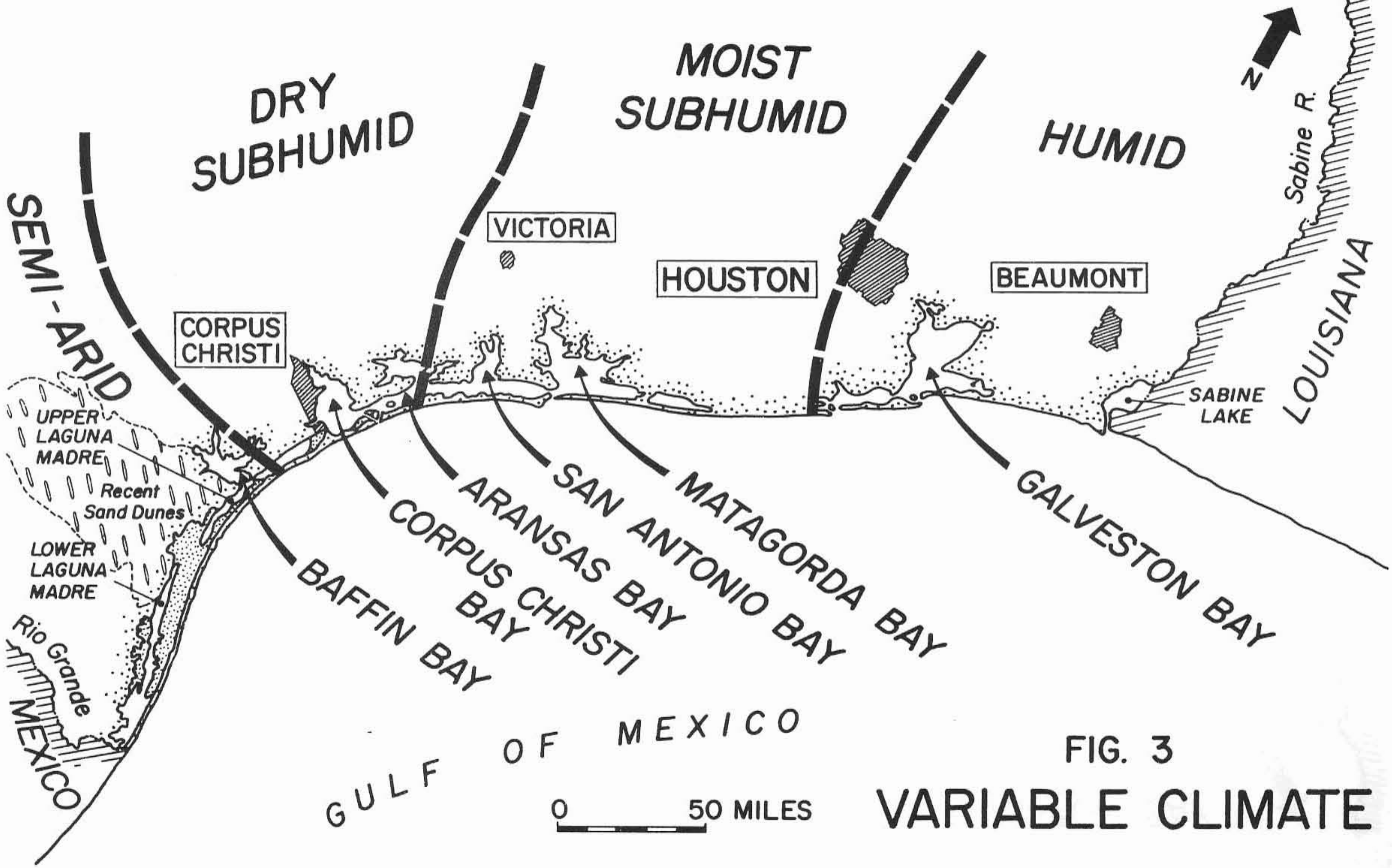


FIG. 3
VARIABLE CLIMATE

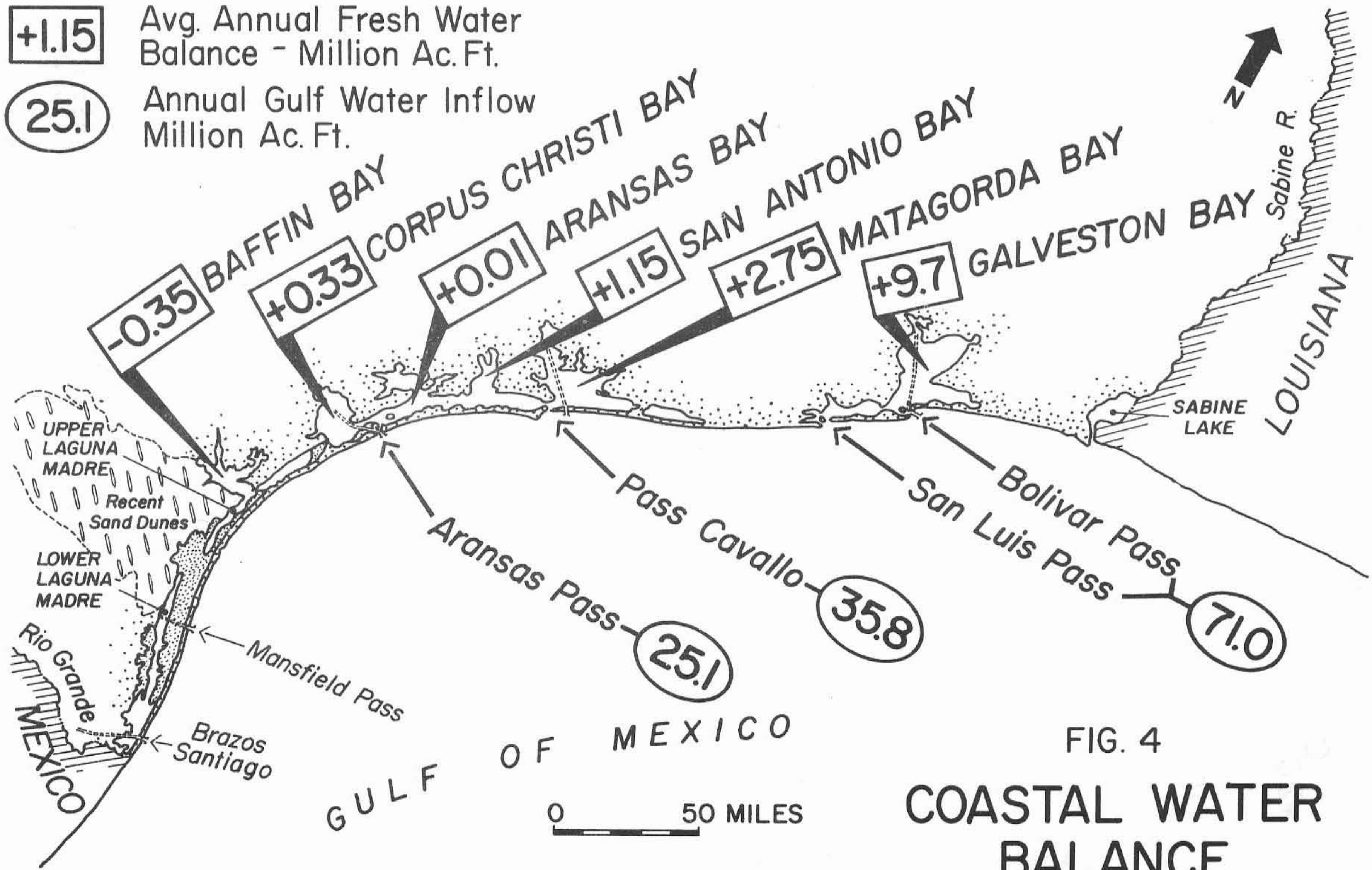


FIG. 4

COASTAL WATER BALANCE

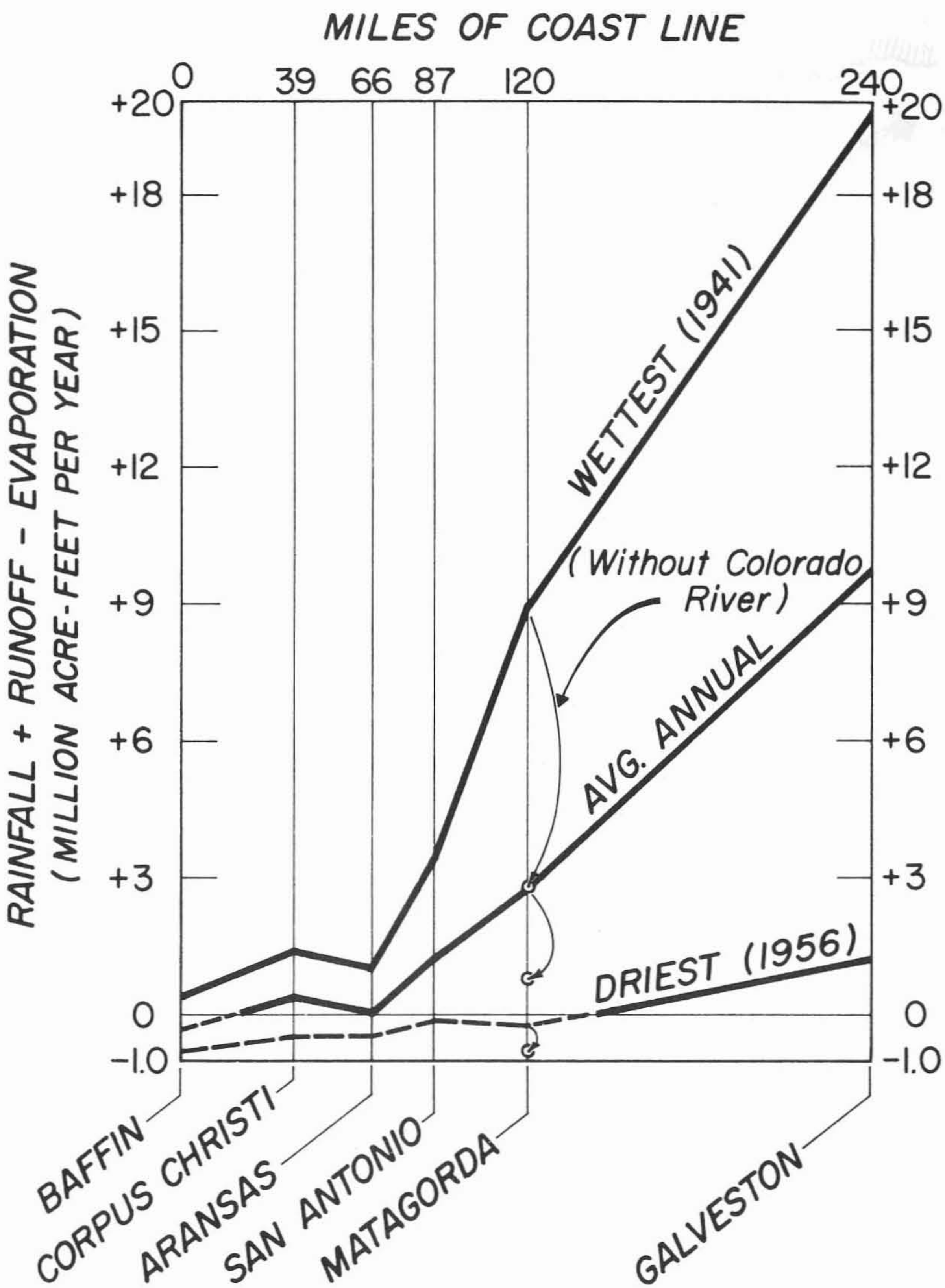


FIG. 5 - VARIATIONS IN ANNUAL FRESH WATER BALANCE

Salinity, ppt (parts per thousand)

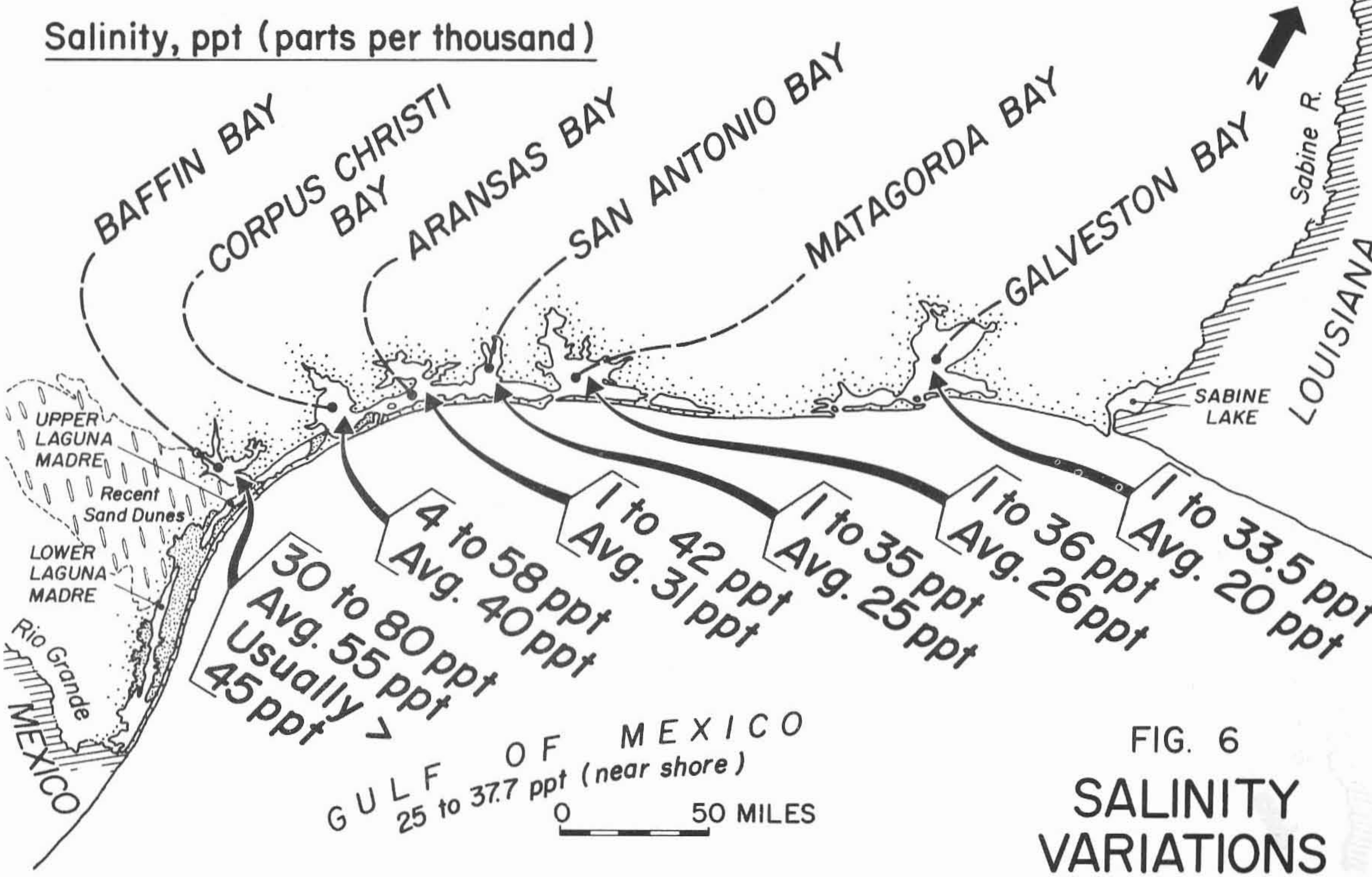


FIG. 6
SALINITY VARIATIONS

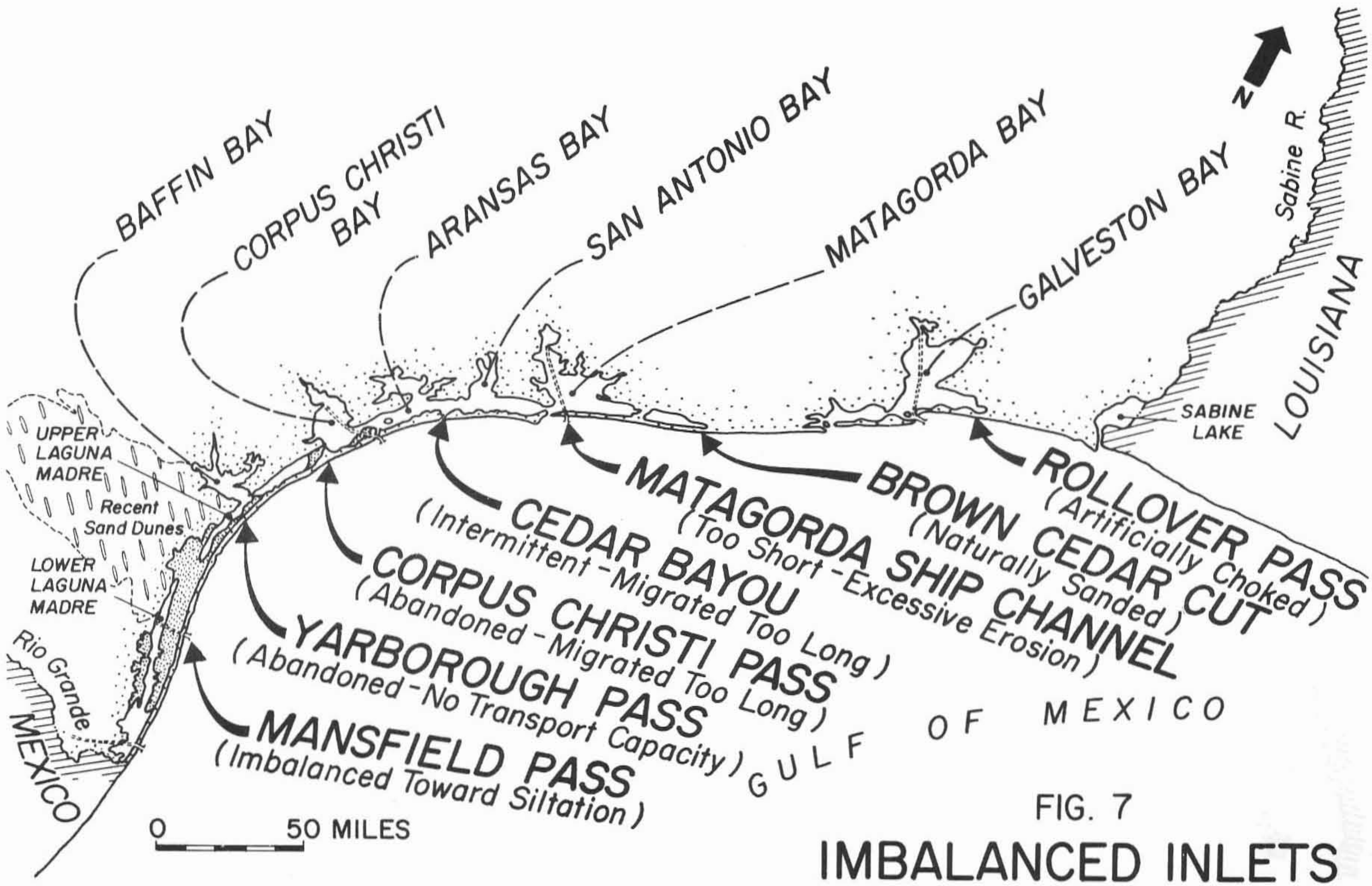


FIG. 7

IMBALANCED INLETS

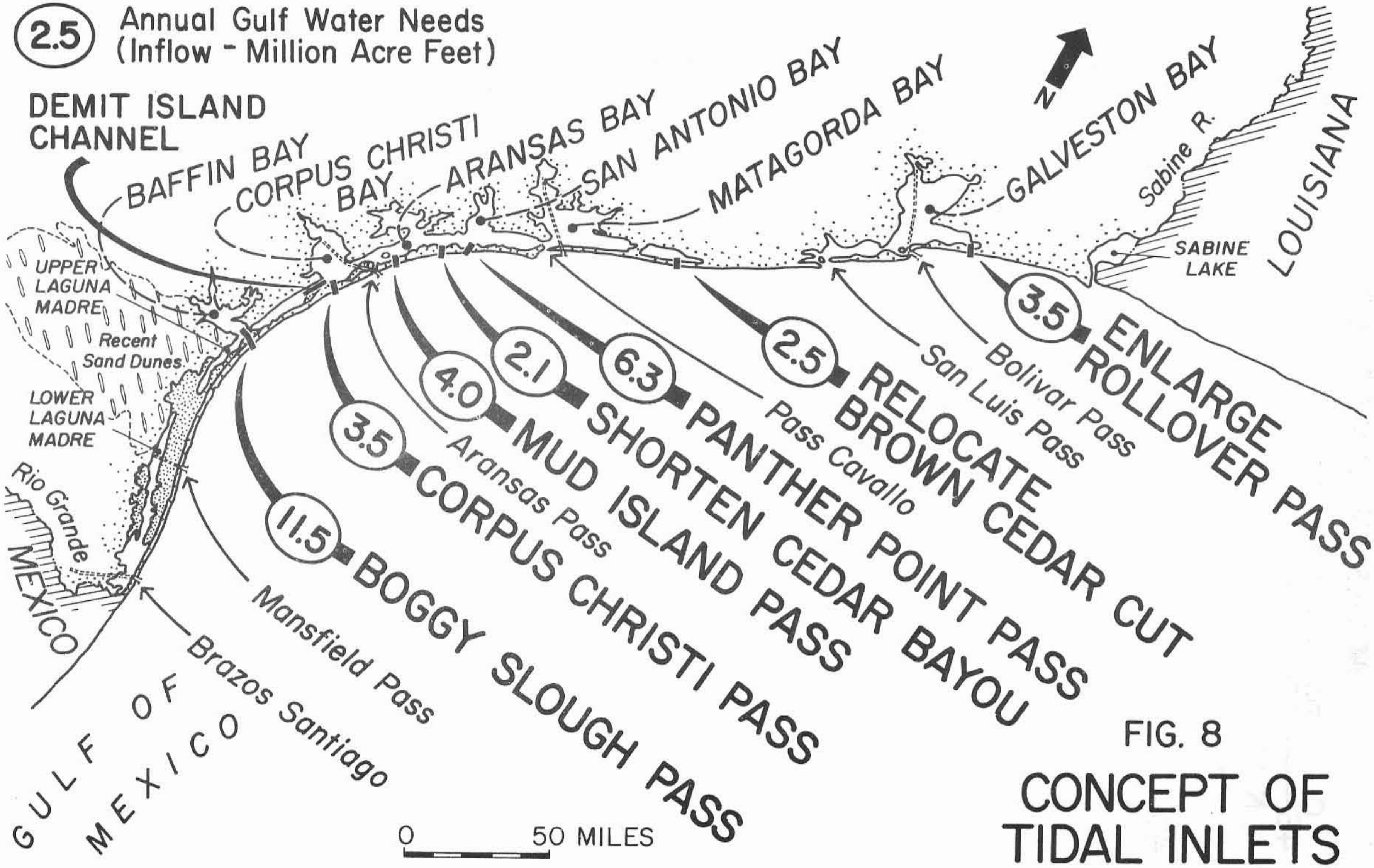


FIG. 8

CONCEPT OF TIDAL INLETS

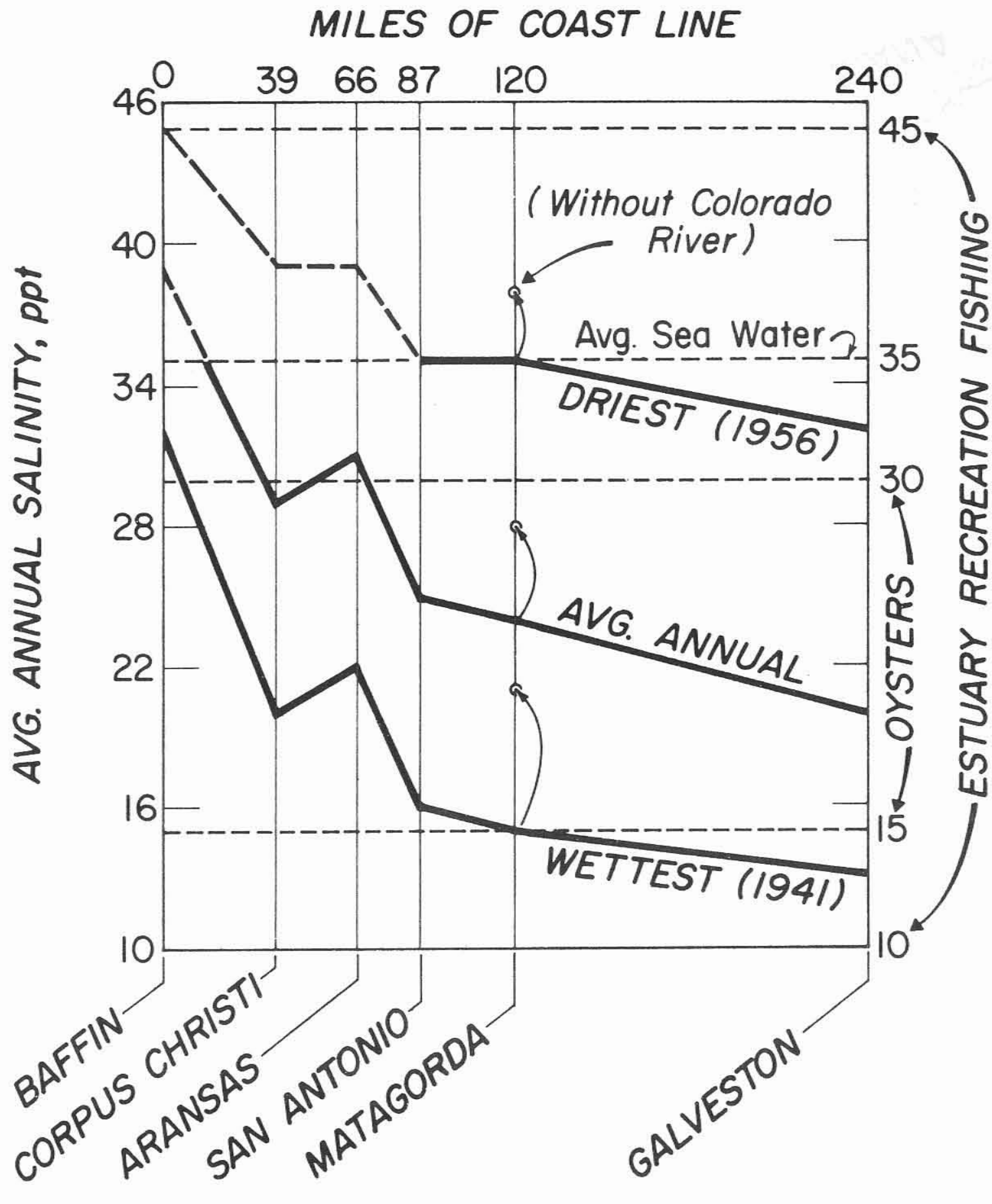


FIG. 9 - SALINITY CONTROL WITH NEW INLETS

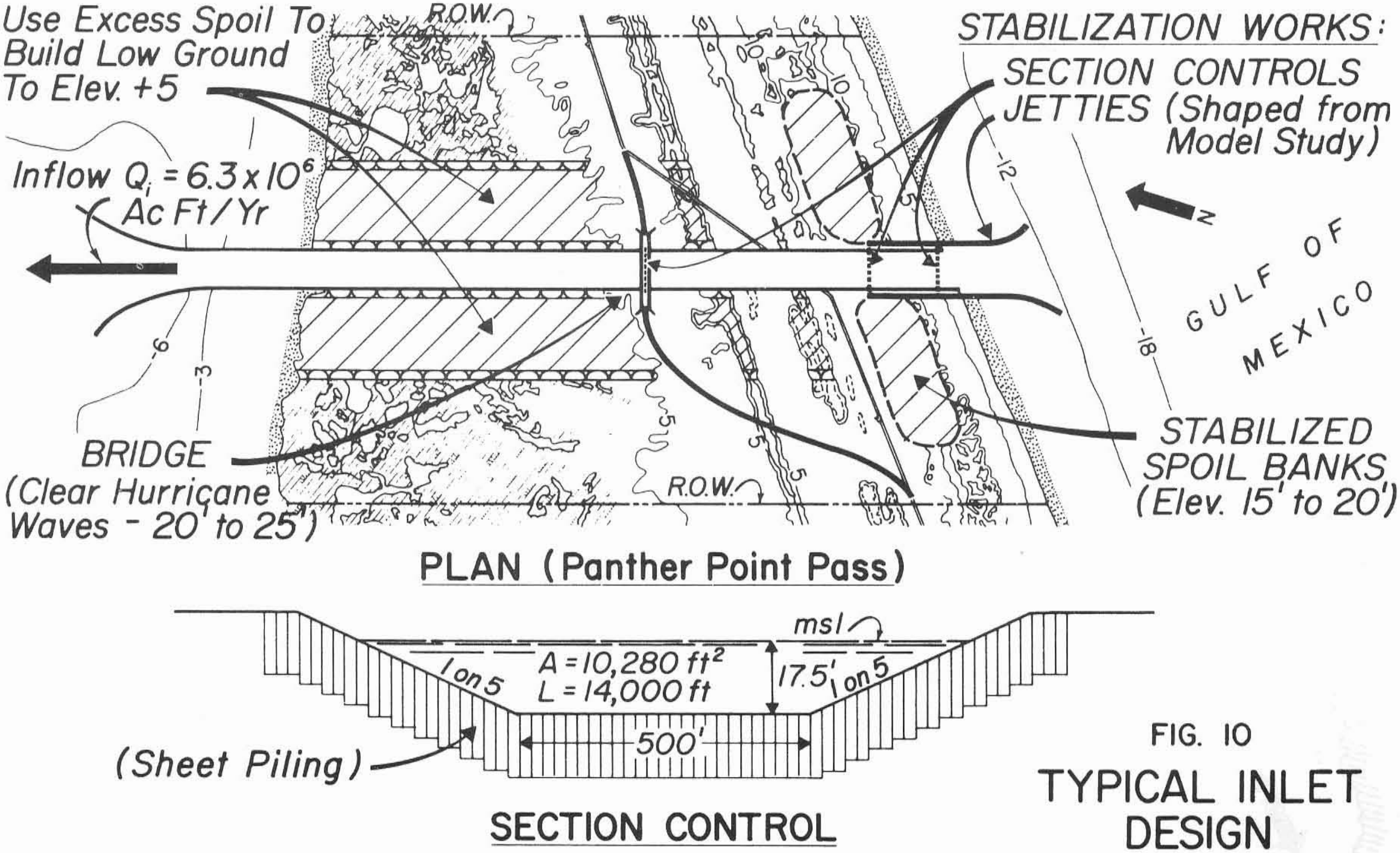


FIG. 10

TYPICAL INLET DESIGN

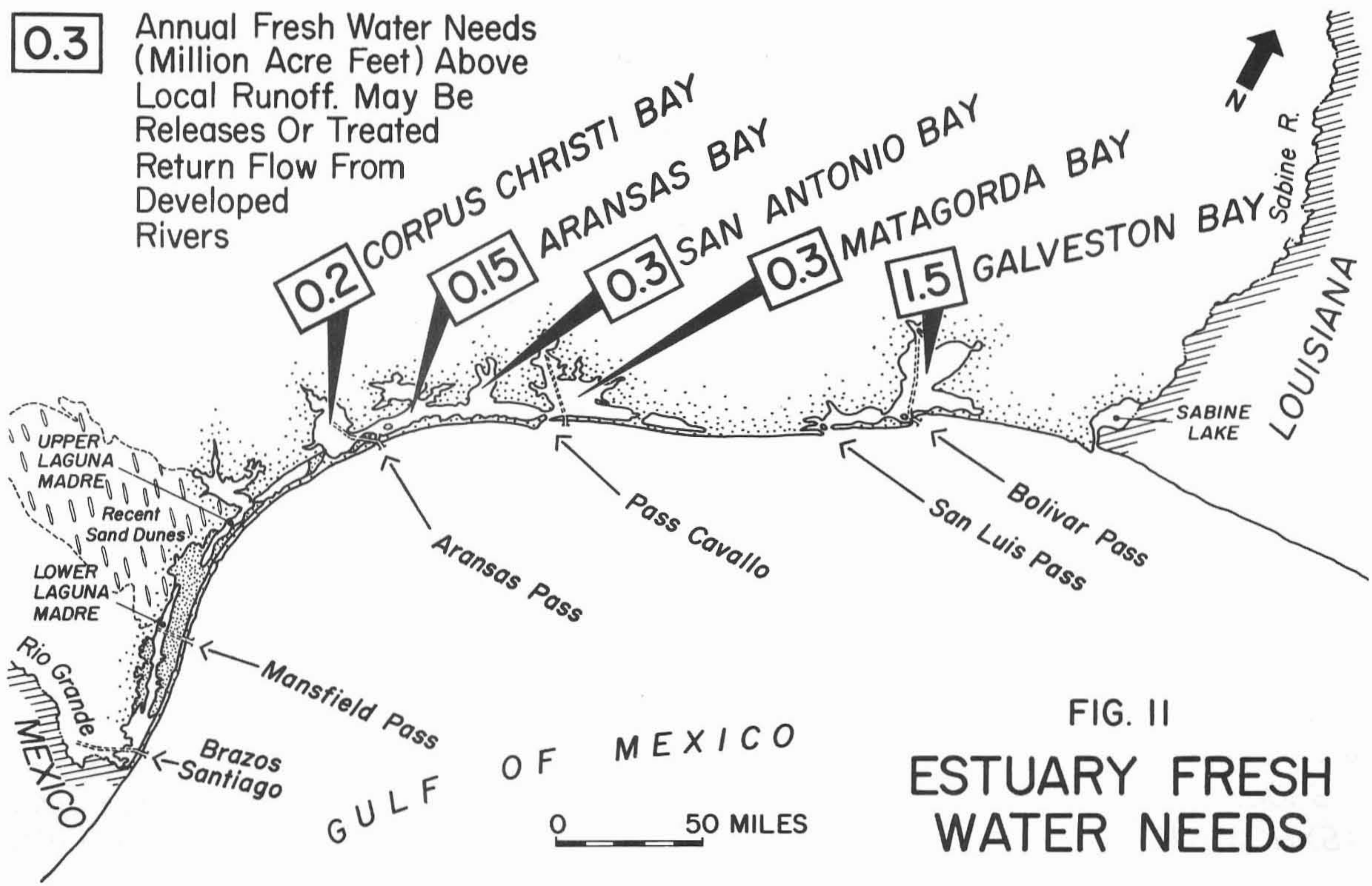


FIG. II

ESTUARY FRESH WATER NEEDS

APPENDIX A

THE SEDIMENT TRANSPORT ASPECT, WATER AND SALINITY BALANCE, AND TIDAL FLUSHING PROCESS IN DESIGN OF TIDAL INLETS

Tidal inlets thru the barrier reef, between the Gulf and bay, intercept littoral drift; that is, beach sand transported along shore by wind waves and current action. The basic tidal hydraulics consists of application of sediment transport formulas, described fully by Carothers and Innis in "Design of Inlets for Texas Coastal Fisheries," ASCE Transactions, Vol. 127, 1962, Part IV, p. 231.

The first trial balance is based on a median (50% total differential) velocity above which the sediment tansport capacity is rapidly increasing. This desired initial balanced velocity is computed by formula:

$$V_{50} = \frac{1.486}{n} R^{1/6} \left(1.65kd\right)^{1/2} \quad . . . . . (1)$$

in which V_{50} is velocity in feet per second for specified condition of Shields Entrainment Function; n is the Manning roughness coefficient, usually 0.02 to 0.03; R is hydraulic radius in feet (area divided by wetted perimeter); k is Shields Entrainment function with value of 0.4 to 0.6; and d is median diameter of sand in feet (with specific gravity of 2.65 and with d in mm divided by 304.8 = d in feet).

The sediment transport formula used in balanced design of Texas inlets may be conveniently reduced to:

$$Q_S = \frac{(3.06 \times 10^7)\ (RS)^{5/2}}{d_{mm}} \quad . . . . . (2)$$

in which Q_S is unit bulk volume rate of sediment transport, cu yd per day per ft width; R is hydraulic radius of inlet, ft; S is slope of energy gradient from tidal differentials; and d_{mm} is diameter of sediment particle in millimeters.

There is an empirical substantiation of the theoretical formulation and design of inlets by relations to tractive force (bottom shear stress) which is fundamental to sediment transport. Formula for tractive force is:

$$\tau = \gamma R S \quad . . . . . (3)$$

in which τ is tractive force, psf; γ is unit weight of water, pcf, or 64 lb for sea water; R is hydraulic radius of inlet, ft (area divided by wetted perimeter); and S is slope of energy gradient from tidal differentials, feet per foot.

The recommended limiting tractive forces for canals in "Design of Stable Channels," by E. W. Lane, ASCE Transactions, Vol. 120, 1955, p. 1234, are shown on Figure 1A. In "Stability of Coastal Inlets," by P. Bruun and F. Gerritsen, North-Holland Publishing Company, Amsterdam, 1960, the empirical correlations between tractive force and stable inlets, based on spring tide conditions, are reported and shown to be well above those for canals. The average values of tractive force of stable inlets for conditions of light, medium, and heavy littoral drift are shown in Figure 1A.

When an inlet is sized and dynamically balanced by these formulas in "Design of Inlets for Texas Coastal Fisheries," it is found that the tractive force computed at tropic tides (or differential at 95 to 98 percent of time equaled or less and equivalent to spring tides) is usually in the range of 0.093 to 0.108 pounds per square foot. These values are in the range of existing stable inlets with medium to heavy littoral drift, considered applicable to the Texas Coast. This range is plotted on Figure 1A to illustrate the significant substantiation of the theoretical design by the empirical correlations using the tractive force parameter.

Length and depth of inlet controls the hydraulic radius and energy slope (RS) and its unit sediment transport capacity. Then width of inlet is the variable control for quantity of inflow from Gulf to bay and total sediment transport capacity.

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

<u>For Rainfall & Runoff Exceeding Evaporation:</u>

$$Q_i = \frac{Q_r \, S_o}{E \, (S_i - S_o)} \quad \ldots\ldots (4)$$

<u>And For Evaporation Exceeding Rainfall & Runoff:</u>

$$Q_i = \frac{Q_e \, S_o}{E \, (S_o - S_i)} \quad \ldots\ldots (5)$$

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.

Location and spacing of tidal inlets are vital to the efficiency (E) of mixing Gulf and bay water for the desired salinity controls. This efficiency tends to decrease rapidly when inlets are spaced greater than about 25 to 30 miles apart. For instance, the San Antonio, Aransas, Corpus Christi and Baffin Bay complex with 120 miles of shoreline is served by one inlet, Aransas Pass; but at least four inlets are needed for efficient operation. Checks using these balance equations indicate that an efficiency of 25% may be considered as good tidal inlet operation.

Even with reasonably good treatment of return flow, balanced and efficient inlets are needed for the bays and estuaries to assimilate these return flows. For evaluation of the tidal flushing process, the following formulas are derived from "Dispersion and Flushing of Pollutants" by D. W. Pritchart, Chapter VIII of Report No. 3, "Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena," C. F. Wicker, Editor, Committee on Tidal Hydraulics, Corps of Engineers, U.S. Army, May 1965.

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>

$$K_t = \frac{Q_i E}{V_b} = \frac{\Delta S_o}{S_i - S_o} \qquad \text{. . . . . (6)}$$

$$E = \frac{(\Delta S_o) V_b}{Q_i (S_i - S_o)} \qquad \text{. . . . . (7)}$$

$$t_f = \frac{V_b}{Q_i E} \log_e \left(\frac{1}{1-f} \right) \qquad \text{. . . . . (8)}$$

where:

K_t = exchange coefficient related to tidal flushing, the fractional rate of renewal per unit time, equal to the volume of <u>new</u> 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 all 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 $\log_e\left(\frac{1}{1-f}\right)$
0.5	0.693
0.75	1.386
0.90	2.3
0.95	3.0
0.99	4.6
0.999	6.9

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 percent 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.

These formulas represent the major and basic aspects of balanced tidal inlet design. The inlet must be sized for dynamic balance in its sediment transport capacity to handle the intercepted littoral drift, without excessive erosion or siltation. Ample Gulf water inflow thru efficiently operating inlets is needed for proper balance in mixed water and salinity controls. Even with good future treatment of return flows, the bays and estuaries will need near maximum efficiency in the tidal flushing process to help them assimilate these return flows.

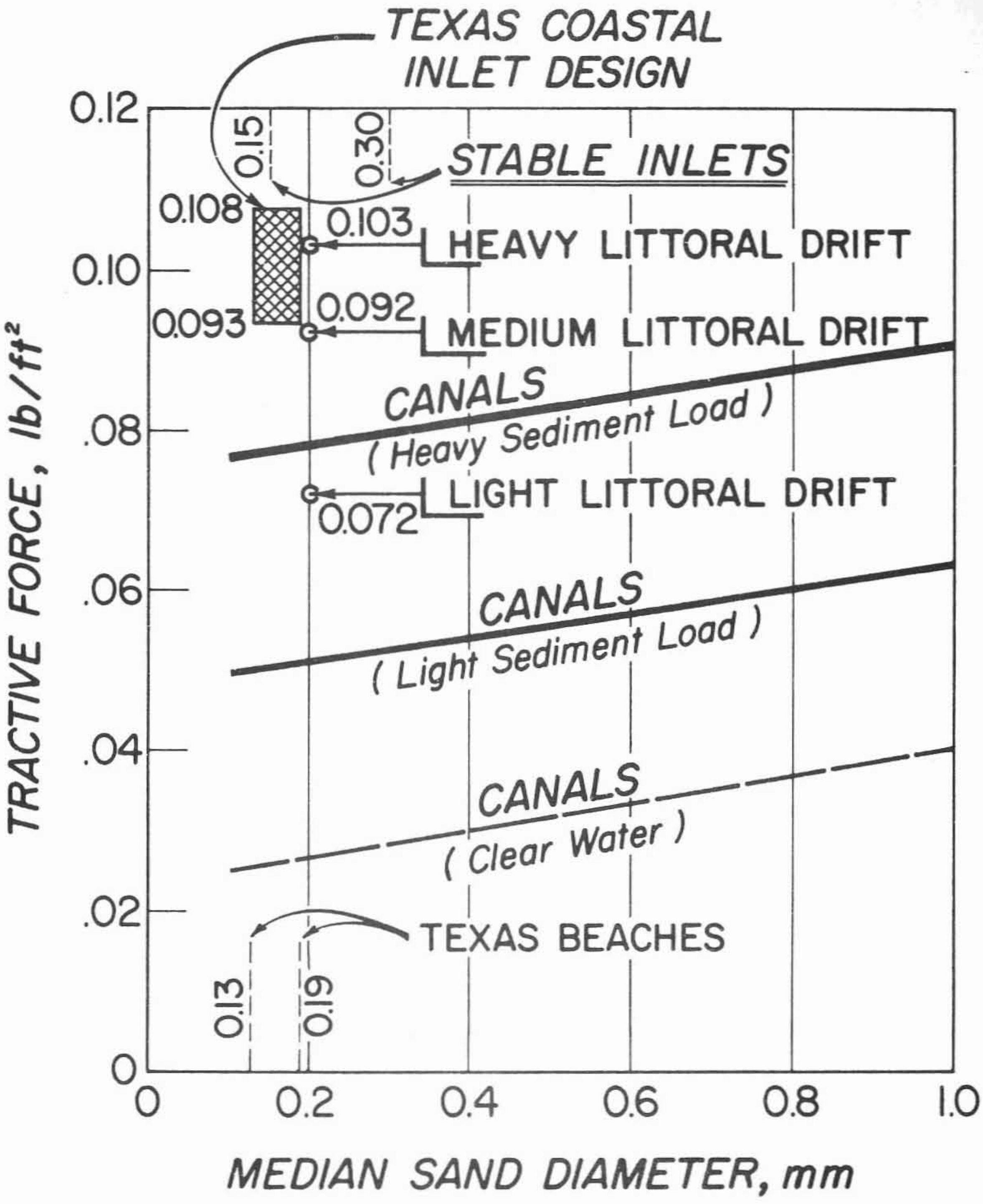


FIG. 1A - EMPIRICAL CORRELATIONS WITH TRACTIVE FORCE