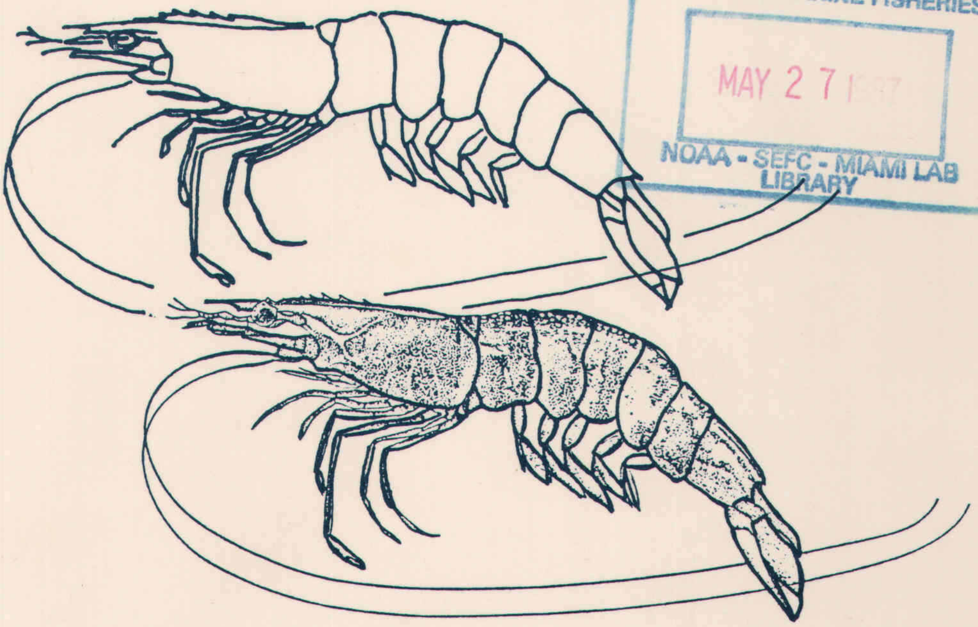
NOAA Technical Memorandum
NMFS-SEFC-189

Freshwater Inflow Needs of the Matagorda Bay System with Focus on Penaeid Shrimp



U. S. DEPARTMENT OF COMMERCE
National Oceanic and
Atmospheric Administration
National Marine Fisheries Service
Southeast Fisheries Center
Galveston Laboratory
Galveston, Texas 77550

MARCH 1987

NOAA Technical Memorandum
NMFC-SEFC- 189

Freshwater Inflow Needs of the Matagorda Bay System with Focus on Penaeid Shrimp

By

Allan J. Mueller
U. S. Fish and Wildlife Service
And
Geoffrey A. Matthews
National Marine Fisheries Service

U. S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
Anthony J. Calio, Administrator

National Marine Fisheries Service
William E. Evans, Assistant Administrator for Fisheries

MARCH 1987

FRESHWATER INFLOW NEEDS OF THE MATAGORDA BAY SYSTEM WITH FOCUS ON PENAEID SHRIMP

by

Allan J. Mueller
U.S. Fish and Wildlife Service
17629 El Camino Real, #211
Houston, TX 77058

and

Geoffrey A. Matthews
National Marine Fisheries Service
4700 Avenue U
Galveston, TX 77551-5997

March 1987

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

PREFACE

The health and abundance of fish and wildlife resources in Texas are closely tied to the management and distribution of freshwater. Human freshwater demands are constantly increasing and there are many programs to more tightly control the distribution of water through reservoirs, canals and aqueducts. The most comprehensive of these programs is the Texas Water Plan, which was recently updated by the Texas Department of Water Resources (1984a). Natural resource agencies have not previously conducted a similar comprehensive examination of the impacts of water development on fish and wildlife resources.

Such an examination is a massive task that cannot be completed easily or quickly. The United States Fish and Wildlife Service, the National Marine Fisheries Service and the Texas Parks and Wildlife Department have jointly begun such an effort. Initially, three separable fish and wildlife-water development issues have been identified: on site terrestial and wetland impacts of reservoir construction, modifications of instream flows and modifications of freshwater inflows to the bays and estuaries. This report addresses the freshwater inflow issue for one of the major estuaries in Texas.

Texas has seven major estuarine systems, all of which depend on freshwater inflow to maintain their character and health. The Matagorda Bay system was chosen for this study for several reasons. First, this bay has valuable commercial fisheries and sports interests boosting the state's and nation's economy. Second, its major tributaries are being blocked by reservoir construction, Palmetto Bend Reservoir on the Navidad River being the most recent. There is a proposal to extend this reservoir to also block the Lavaca River. Several new reservoirs are being planned on the Colorado River. Third, the Colorado River is to be diverted to flow directly into Matagorda Bay. Fourth, there was a considerable data base for our analyses. River flow and fisheries data from 1960 thru 1982 were used in this study.

This report has two objectives. The first is to estimate the amount and scheduling of freshwater inflows required to maintain fishery productivity in Matagorda Bay. Although the shrimp fishery, upon which we focus, is but one of the valuable fisheries in this bay, it is a major one for which data have been collected over many years. To estimate the levels of river flows required, we principally used correlation and regression analyses of commercial shrimp catches and of Texas Parks and Wildlife Department (TPWD) samples versus gaged river flows. The second objective is to evaluate recommendations of the Texas Department of Water Resources (TDWR) in view of our results, thus giving two independent estimates of freshwater needs for Matagorda Bay.

Matagorda Bay is a shallow estuary on the central Texas coast. Evapotranspiration is higher than rainfall, consequently there is a net annual precipitation deficit of about 6 inches (Woodruff 1975). Three rivers and several creeks contribute freshwater inflow to the system. The Colorado River is the largest, but much of its flow empties directly into the Gulf of Mexico. Its maximum annual flow was 3,812,800 acre-feet (ac-ft), its minimum was 344,000 ac-ft, and its mean was 1,720,600 ac-ft from 1960 through 1982. The Lavaca River and Navidad River join about five miles before the Lavaca River enters the bay, and their maximum annual combined flow was 2,023,900 ac-ft, minimum was 133,900 ac-ft, and their mean was 795,900 ac-ft. In May 1980, Palmetto Bend Dam on the lower Navidad River was closed, forming Lake Texana. Since it is very close to the bay, its impacts on freshwater inflow are significant, especially since there are no "pass-through" requirements in its management. It reduces inflow by 92,000 ac-ft annually and sediment input to the Lavaca delta by 49% (U.S. Bureau of Reclamation 1974).

Floods are also important to estuaries. They inundate bordering marshes, initially flushing out nutrients into the bay, and subsequently depositing sediments and additional nutrients back into the marshes. Receding flood waters also draw accumulated detritus out of marshes and into the bay. Thus, by flushing nutrients and detritus into the bay, floods promote the phytoplankton and detritus based food webs that support economically important species. Through the deposition of sediments and nutrients, floods help build marshes, which are excellent habitats for juvenile fish, crabs and shrimp. For the Lavaca delta, minimum daily river flows of 9,000 cubic feet per second (cfs) should flood its marshes (TDWR 1980), and for the postdiversion Colorado delta, minimum daily river flows of 10,000 cfs should flood its marshes. Sediment transport for building both areas' marshes is accomplished mainly by floods with flow-rates over 30,000 cfs. The small floods normally occur during the spring and fall each year, but the large floods occur only once every two or three years either in the spring or in the fall.

There is a thriving commercial fishery for white (Penaeus setiferus) and brown shrimp (P. aztecus) in Matagorda Bay. Between 1977 and 1982 the average annual white shrimp catch increased to 1.5 million pounds of tails, an increase of 50% over the 1960-1975 average catch. Between 1979 and 1982 the average annual brown shrimp catch increased to 1.1 million pounds of tails, an increase of nearly 350% over the 1960-1978 average catch. These increased catches were due to a doubling of fishing effort for white shrimp, and a tripling of effort for brown shrimp. The value of the 1980-1984 mean annual landings by the bay commercial fleet in Matagorda Bay was $4.8 million for brown shrimp and $5.9 million for white shrimp, and it has been estimated that for every dollar in shrimp landings at least $3.08 are stimulated in the total economic output in the region (Jones et al. 1974).

Additionally, the multi-million dollar annual shrimp harv st from th Gulf of Mexico off Texas is dependent on the health of Texas estuaries, because the large shrimp caught offshore have spent their youth feeding and growing in these estuaries. Since 1960, the brown shrimp harvest in statistical subarea 19 (SS-19), an area directly offshore from Matagorda Bay, has averaged 10.5 million pounds of tails per year, and the white shrimp harvest has averaged 2.2 million.

R sults

To maintain the 2.6 million pound annual shrimp harvest, we recommend an annual gaged inflow of 850,000 ac-ft from the Lavaca-Navidad River and 1,782,000 ac-ft from the Colorado River (Table i). For the months of January, February, May, July, August, November and December, which showed no significant correlations between their flows and shrimp harvests, we recommend the monthly mean flows (1960-1982) from each river be used to maintain the habitat for shrimp production. Significant ($p<0.10$) correlations were found between March, April, June, September and October river flows and shrimp harvests; these months we term "Critical Flow Months." Spring and fall flows exert the most predictive influences on shrimp harvests and require slightly above average flows.

Our analyses suggest that flows higher than the historical average could result in even higher shrimp productions. The recommended flows to achieve maximum shrimp production are at or near the historical highs for March, April, June and October for the Lavaca-Navidad River, and for April and October for the Colorado River. It would not be necessary, nor would we recommend, that all these high flows occur in the same year to obtain an increased shrimp harvest. In fact, it is unlikely that this could occur no matter how upstream reservoirs are operated.

Superimposed on the total monthly flow requirements are floods. Based on historical flooding patterns, for the Lavaca River we recommend four annual floods with a minimum average daily flow of 9,000 cfs, and one flood every two or three years with a minimum average daily flow of 35,000 cfs (Table ii). For the post-diversion Colorado River we recommend four annual floods of 10,000 cfs each, and an annual large flood of 33,000 cfs. River flow volumes required by floods are included in our monthly flows recommended for each river.

Table i. Recommended river flow volumes by month, including a comparison with flows recommended by the Texas Department of Water Resources (1984a). Alternatives listed by TDWR are: IV = Biotic Species Viability, I = Subsistence, II = Maintenance of Fisheries Harvest, III = Shellfish Harvest Enhancement. Values are thousands of acre-feet.

LAVACA - NAVIDAD RIVERS

Alternatives:	IV	I	II		III	
	TDWR	TDWR	TDWR	This Study	TDWR	This Study
January	9	22	22	63	22	90
February	9	27	27	59	27	99
March	6	17	17	50	17	172
April	18	26	68	62	115	382
May	16	116	116	127	167	127
June	9	32	98	156	116	849
July	6	16	18	30	16	30
August	7	10	35	22	10	22
September	17	14	97	116	24	160
October	13	18	78	78	18	237
November	7	18	18	44	18	60
December	10	18	18	43	18	43
	126	343	612	850	568	*

COLORADO RIVER

Alternatives:	IV	I	II		III	
	TDWR	TDWR	TDWR	This Study	TDWR	This Study
January	10	88	88	148	88	179
February	10	99	99	160	91	196
March	23	76	76	130	76	197
April	100	101	133	143	101	355
May	116	140	188	264	140	264
June	82	105	160	248	105	334
July	33	53	53	110	162	130
August	45	49	49	50	110	50
September	146	148	148	130	148	234
October	94	92	92	119	92	438
November	9	80	388	156	384	156
December	13	82	322	124	325	124
	681	1113	1798	1782	1830	*

*We do not recommend all these high flows in the same year. These are presented to show the potential of increased flows in an individual month.

Table ii. Flooding recommendations.

Minimum Average Daily Flows (cfs)	Frequency	Timing[1]
	Lavaca River	
9,000	2/yr	Mar-June
9,000	1/yr	Sept-Oct
9,000	1/yr	Nov-Feb
35,000	1/2-3 yrs	Apr-June, Sept or Oct
	Colorado River	
10,000	2/yr	Mar-June
10,000	1/yr	Sept-Oct
10,000	1/yr	Nov-Feb
33,000	1/yr	Apr-June or Sept

[1]Emphasis was placed on recommending floods during the Critical Flow Months - see text.

The Texas Department of Water Resources (1980) made a detailed study of the freshwater needs of the Matagorda Bay System. They proposed flow schedules for three alternative management policies:

Alternative I - Subsistence

Alternative II - Maintenance of Fisheries Harvest

Alternative III - Shellfish Harvest Enhancement

Later, Alternative IV - Biotic Species Viability, was added (Texas Department of Water Resources 1984a).

Our flow recommendation to maintain the mean historical commercial shrimp harvest is similar to TDWR's Alternative II. However, our objective was to find the flow regime that would support the mean shrimp catch and TDWR's objective was to find the minimal flow that would maintain the average commercial finfish and shellfish harvest. Our total annual recommended flow is 222,000 ac-ft greater (9%) than TDWR's (Table i).

To minimize flows, TDWR concentrated 75% (458,000 ac-ft) of the Lavaca-Navidad River annual flow in April, May, June, September and October. Except for the exchange of May for March, these are the months we identified as Critical Flow Months. We also recognize that May is often a high inflow month. So we agree with their approach that if flow is to be minimized, flows should be maintained or elevated during the Critical Flow Months to reduce the impact on the commercial fishery. Our total flow recommendation for the Lavaca River was larger, in part, because the average flows used by TDWR are different from ours. Their period of record, 1941-76, has an average annual discharge of 614,000 ac-ft. The 1960-82 period we use has an average annual Lavaca River discharge of 790,000 ac-ft. Our period corresponds to the span of reliable shrimp harvest records, whereas TDWR's flow period includes many years not used in their harvest data analysis.

Our flow recommendations for the Colorado River are very similar to TDWR's in terms of the annual total, but the monthly distribution of flows is very different. Our recommendation retains a pattern similar to the Lavaca-Navidad River, with 51% of the flow in April, May, June, September and October. TDWR puts only 40% of the flow in those months, but puts 39% of the annual flow in November and December. Their Estuarine Linear Programming Model projected that these flows were necessary to achieve average harvests of oysters and blue crabs. TDWR did not present details of their Estuarine Lin ar Programming Mod 1, so we were not able to evaluate its structure. However, for the 1960-1982 period, TDWR's recommended November flow exceeded gaged November flows for 20 of the 23 years. Their recommended December flow exceeded December flows in 22 of the 23 years. Thus, these flows seen inappropriately high. We found no significant relationship for December flows.

TDWR's Alternative III is entitled Shellfish Harvest Enhancement. On the surface this would seem to be equivalent to our flows for maximum shrimp production. However, TDWR constrained their model from exceeding historical (1941-76) average flows. This prevented them from exploring the full potential of high flows. On the Lavaca-Navidad River they increased spring flows at the expense of fall flows. Operating within their constraints, we agree with this change, because we also feel that spring flows are more important than fall flows. For the Colorado River, TDWR decreased spring flows, increased summer flows and retained their extremely high November and December flows. The summer flows were increased because TDWR's salinity model indicated a need for reduced salinities in the east arm of Matagorda Bay in July and August to enhance shellfish habitat conditions. The salinity model was not displayed for examination, but this is a potentially critical time for juvenile shrimp, and summer salinity conditions were an aspect that we were not able to thoroughly investigate. Oyster habitat considerations would also dictate higher summer flows. With regard to the reduction in spring flows, our data show that reduction, not enhancement, would occur in shrimp harvests. We certainly recommend maintaining or enhancing spring flows.

For the Lavaca-Navidad River, TDWR recommends two "small" spring floods and one small fall flood. We make these same recommendations with the addition of another small flood for the November to February period.

TDWR made no provisions for "large" floods on either the Lavaca-Navidad River or the Colorado River. Large floods flush areas not normally exposed to tidal inundation, and bring a new source of nutrients and detritus to bear on the ecosystem. After diversion of the Colorado River into Matagorda Bay, flooding will be essential to achieve the predicted ben fits to the fishery.

TDWR's flow recommendations for Alternative I on both the Lavaca-Navidad and Colorado Rivers are much less than our recommendations for maintaining the mean shrimp harvest. A permanent reduction to Alternative I flow levels would likely result in a great reduction of the commercial shrimp fishery in Matagorda Bay. Salinity levels would be consistently higher, nutrient input greatly reduced and no opportunity provided for large floods. Even small floods would occur at a much reduced frequency. This would likely cause a steady decline in the vigor of the delta marshes and could easily cause their eventual conversion to open water because of salinity stress and sediment starvation. Without adequate nutrient input and with the loss of marsh nursery areas, shellfish and finfish productivity could easily fall below levels that allow a profitable commercial harvest.

Alternative IV, Biotic Species Viability, is designed to meet only the monthly salinity viability limits of estuarine-dependent organisms (TDWR 1984a). We were unable to determine if the recommended flows for each month are appropriate, however, with the possible exception of April, the Alternative IV flows for the Lavaca-Navidad River are so extremely low that even a single month at those levels would severely stress the estuarine ecosystem and almost certainly would reduce the white shrimp harvest.

The Colorado River Alternative IV recommended flows are adequate for the purposes of this alternative in some months, but clearly inadequate in others. The recommended flows for April, June, August, September and October could be satisfactory; however, the 1960-82 flows have never been as low as the Alternative IV recommendations for January, February, November and December, and were lower than the March recommendation only twice in twenty-three years.

Current reservoir proposals on the Lavaca and Colorado Rivers have the potential to greatly reduce freshwater inflows to Matagorda Bay. These reductions, if great enough, would adversely effect the productivity of both the estuarine system and the adjacent Gulf of Mexico. The biological, economic and social impacts of the reduction of freshwater inflows make wise water management decisions critical to continued diversity and prosperity along the Texas coast.

ACKNOWLEDGEMENTS

The authors thank the many people who contributed to this study. The following gave advice and assistance that improved our perspective and the end product for which we are grateful:

H. Dale Hall (U.S. Fish and Wildlife Service - Houston, TX)
Edward F. Klima (National Marine Fisheries Service - Galveston, TX)
B. D. King, III (USFWS - Houston, TX)
Joan A. Browder (NMFS - Miami, FL)
Frank J. Patella (NMFS - Galveston, TX)
Dennis B. Koi (NMFS - Galveston, TX)
Paul Fore (USFWS - Albuquerque, NM)
Donald Moore (NMFS - Galveston, TX)
K. Neal Baxter (NMFS- Galveston, TX)
James Matis (Texas A&M University, College Station, TX)
Ric Ruebsamen (NMFS - Baton Rouge, LA)
David Frederick (USFWS - Houston, TX)
Norman Sears (EPA - Dallas, TX)
William Sheffield (Texas Governor's Office - Austin, TX)
Brandt Mannchen (Sierra Club - Houston, TX)
Daniel Patlan (NMFS - Galveston, TX)

A special thanks to Mary Watzin for allowing us prepublication use of the "Texas Barrier Island Region Characterization - Narrative Report."

Thanks also to Eugene Hinds and John Goar of the Bureau of Reclamation, Amarillo, TX, who provided us with monthly freshwater releases from Lake Texana through Palmetto Bend Dam.

Special thanks are extended to Dr. Sammy M. Ray of Texas A&M University at Galveston for his contributed appendix (E) on oysters and their freshwater requirements, and to Zoula Zein-Eldin (NMFS Galveston, TX) for the appendix (F) on environmental effects on shrimp and shrimp populations.

Special thanks also to our typists, especially Beatrice Richardson, who survived the 20+ drafts.

Texas has seven major estuarin systems (Fig. 1), all of which are greatly influ nced by the amount and timing of freshwater inflow. This study is restricted to the Matagorda Bay System (Fig. 2), because there are several imminent water development proposals that could modify the freshwater inflows of that bay. The objective of this report is to make an estimate of the amount and scheduling of freshwater inflows required to maintain and enhance fishery productivity in the Matagorda Bay System. Although the shrimp fishery is not the only valuable fishery in the Matagorda Bay System, it is a major one for which data have been collected over many years, and it is the primary focus of this report.

The general method used was statistical analysis of commercial catches and of Texas Parks and Wildlife Department (TPWD) sampling data to identify statistically significant relationships between biological data and flow data from which levels of river flow required to maintain or enhance the shrimp fishery can be calculated. Detailed methods are described in later sections of this report.

Water Planning in Texas

Water supplies in Texas vary from abundant in the east to almost nonexistent in the west. It has long been recognized that freshwater distribution and abundance has a tremendous influence on the economic prosperity of a region. In response to this reality, the state of Texas has formulated a series of long range water management plans. The "Texas Basins Project", prepared by the U.S. Bureau of Reclamation in 1965, was the first long range comprehensive plan and it remains at the core of the state's water development plans today. Through a series of reservoirs and aqueducts, water would be moved from the water-rich east Texas watersheds to the water-poor Corpus Christi and lower Rio Grande valley areas. This idea was later incorporated into the Texas Water Plan (Texas Water Development Board 1968) and expanded to include water transfer to the west for irrigation of the Texas and New Mexico high plains, and water import from the Mississippi River. This plan was updated in 1977 and most recently in 1984 by the Texas Department of Water Resources (TDWR 1977,

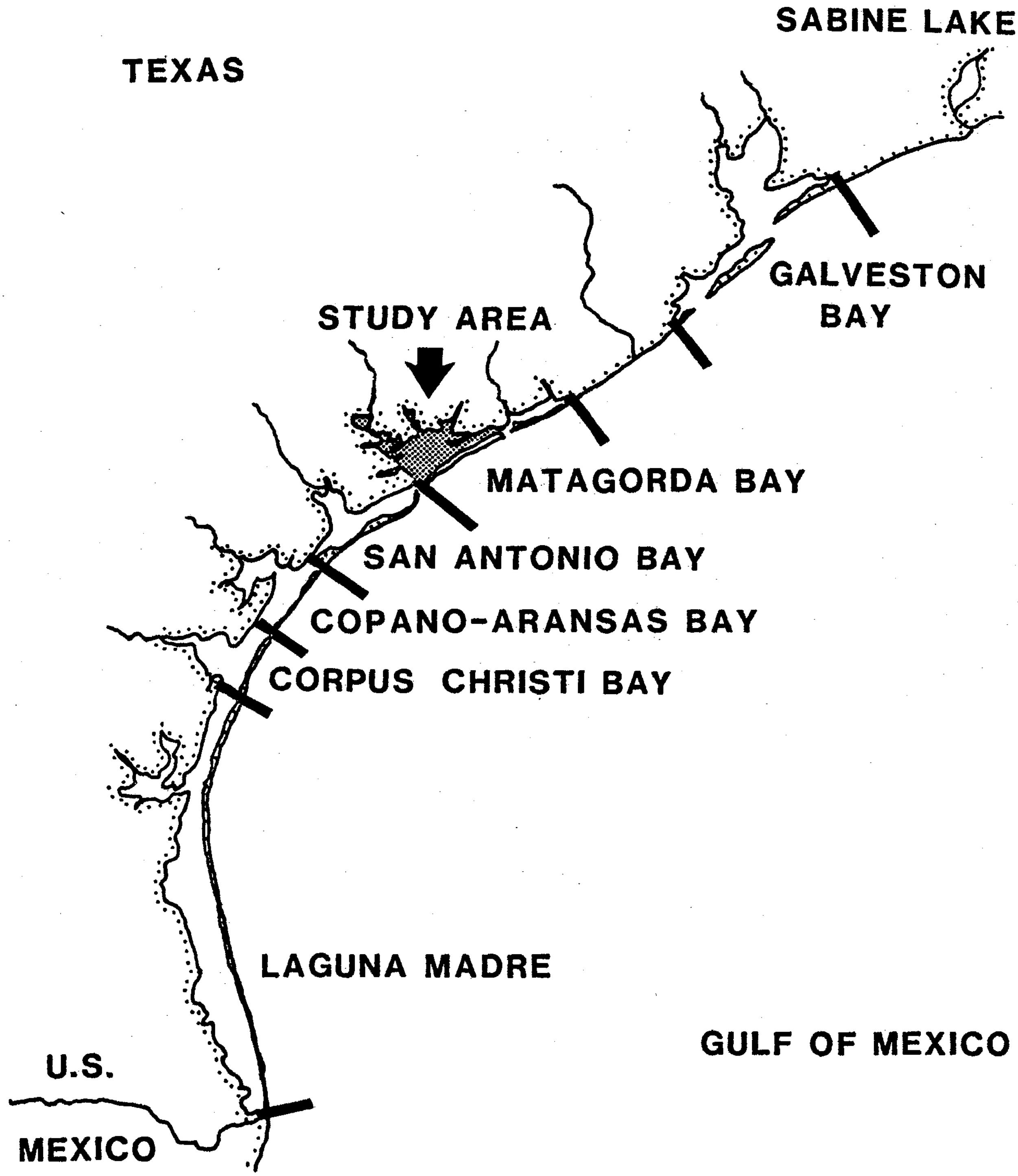


Figure 1. Texas bay and estuarine systems.

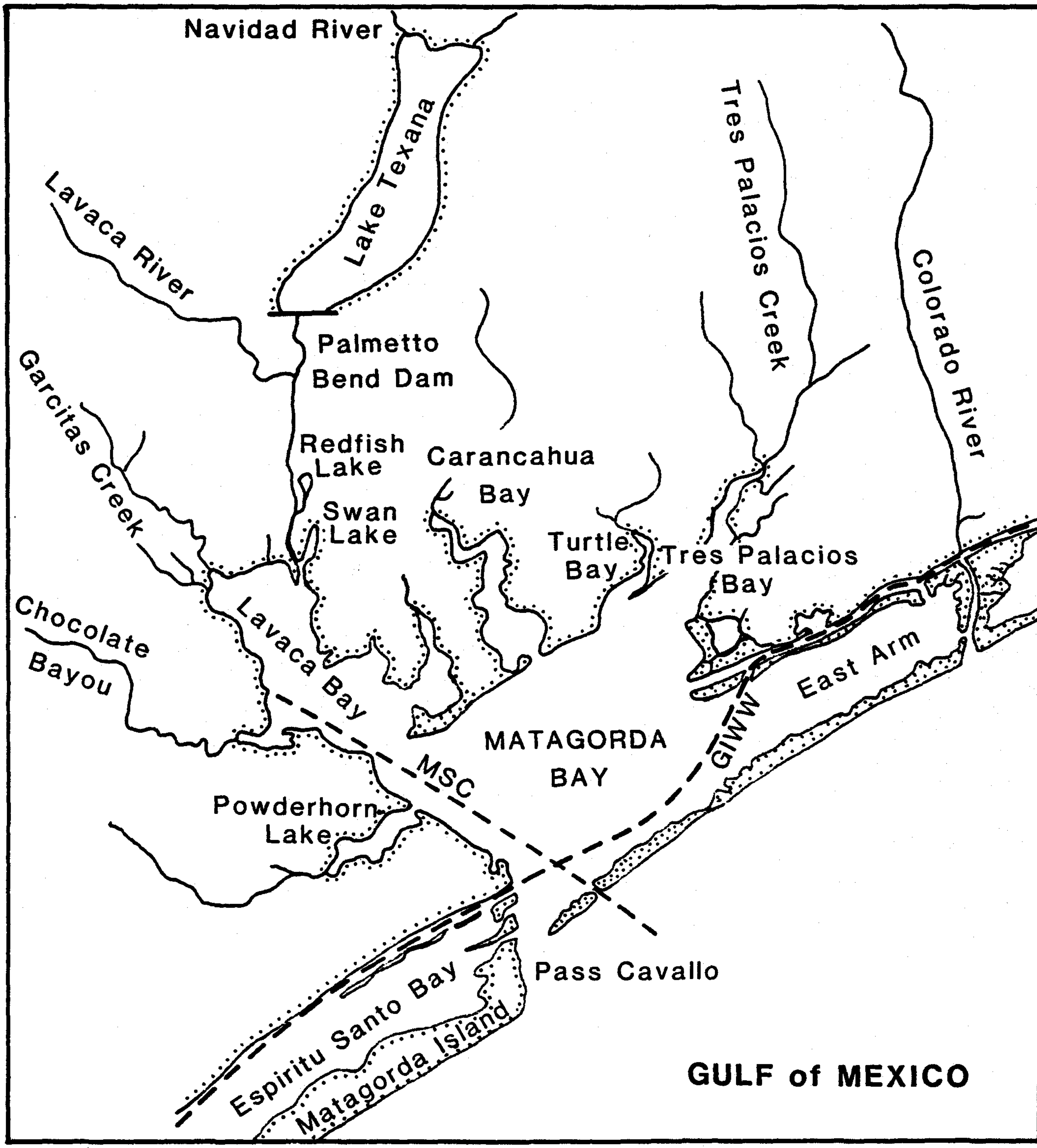


Figure 2. The Matagorda Bay System and its tributaries.

1984a). Interbasin water transfer from wet to dry areas remains a key element of the plan, but the proposal to import water from the Mississippi River has been temporarily inactivated.

Previous Freshwater Inflow Studies in the Study Area

The impacts of the Texas Water Plan on estuarine resources were examined on a broad scale by Chapman (1966, 1971). Hildebrand and Gunter (1952) and Gunter and Hildebrand (1954) examined the relationship between statewide rainfall (roughly equivalent to freshwater inflow) and statewide white shrimp (Penaeus setiferus) commercial harvest. They found significant ($p < .05$) correlations between the harvest and the total rainfall of the same year and between harvest and the rainfall of the two previous years. While these studies illustrate the importance of freshwater to estuarine productivity, they are of little value in determining the freshwater needs of an individual bay.

Gilmore et al. (1976) investigated the effects of freshwater inflow on plankton, benthos and nekton in Lavaca Bay, a secondary bay of the Matagorda Bay System. Nutrient levels in the bay were positively correlated with freshwater inflow. Phytoplankton standing crops were highest as bay salinities began to stabilize after high inflows from the Lavaca River. No significant correlations were found between zooplankton or benthos standing crops and freshwater inflow. Nekton responded more to water temperature than to freshwater inflows.

The Texas Department of Water Resources (1980) has conducted detailed studies of the freshwater inflow needs of Matagorda Bay and the other Texas estuaries. We have closely examined their data and techniques. A detailed discussion of their results and a comparison with our results are provided in a later section.

Espey, Huston and Associates (1979, 1982) examined various physical, chemical and biological characteristics of Matagorda Bay in an effort to determine freshwater inflow needs. Much of their baseline data was used in the preparation of this report.

Description of the Matagorda Bay System

The Matagorda Bay System is a shallow estuary located on the central Texas coast. It includes the major secondary bays: Carançahua, Tres

Palacios, East Matagorda (east of the Colorado River) and Lavaca (Fig. 2); however, the portion of East Matagorda Bay that is east of the Colorado River is excluded from this study. The area west of the river is referred to as the east arm of Matagorda Bay. The study area covers about 382 mi^2 (Diener 1975) with approximately 54 mi^2 of salt and brackish marsh in the system. Lavaca and Matagorda Bays contain over 14 mi^2 of oyster reefs and many clumps of oysters too small to map and measure occur in Keller, Cox, Chocolate and other small tertiary bays in the system (Longley and Wright in preparation).

In the Matagorda Bay System the small secondary and tertiary bays typically have depths of less than 5 ft (Fig. 3). The average depth of Lavaca Bay is about 6.6 ft. A large portion of the center of Matagorda Bay is 12 ft deep. A few areas, including the ship channel through Matagorda Peninsula, are deeper because of scouring by tidal exchange with the Gulf or due to dredging. The most eastern portion of Matagorda Bay is a shoal with depths of less than 5 ft (Longley and Wright in preparation).

The sediment in the small bays is largely sandy mud or muddy sand with mud in some of the deepest portions. Sediments are sandier near the mouth of the Lavaca River and Garcitas Creek in Lavaca Bay. Sediments in the remainder of Lavaca Bay and nearly all of Matagorda Bay are muds.

Three rivers and several creeks contribute freshwater inflow to the Matagorda Bay System (Fig. 2). The largest river is the Colorado River, with a contributory drainage basin of about 29,000 mi^2 (TDWR 1980). Major tributaries to the Colorado River include the Concho River, Pecan Bayou, the San Saba River, the Llano River and the Pedernales River. Flow from the Colorado River enters the estuary thru the Gulf Intracoastal Waterway (GIWW), Culver Cut and Tiger Island Cut, but a large percentage of the flow empties directly into the Gulf of Mexico. The Lavaca and the Navidad Rivers join about five miles before the Lavaca River enters Lavaca Bay. They drain a basin of about 2,310 mi^2 of coastal plains.

Local runoff enters the bay system from two coastal drainage basins. Runoff from about 890 mi^2 of the Lavaca-Guadalupe Coastal Basin enters the bay system via Garcitas Creek, Coleto Creek, Placedo Creek and

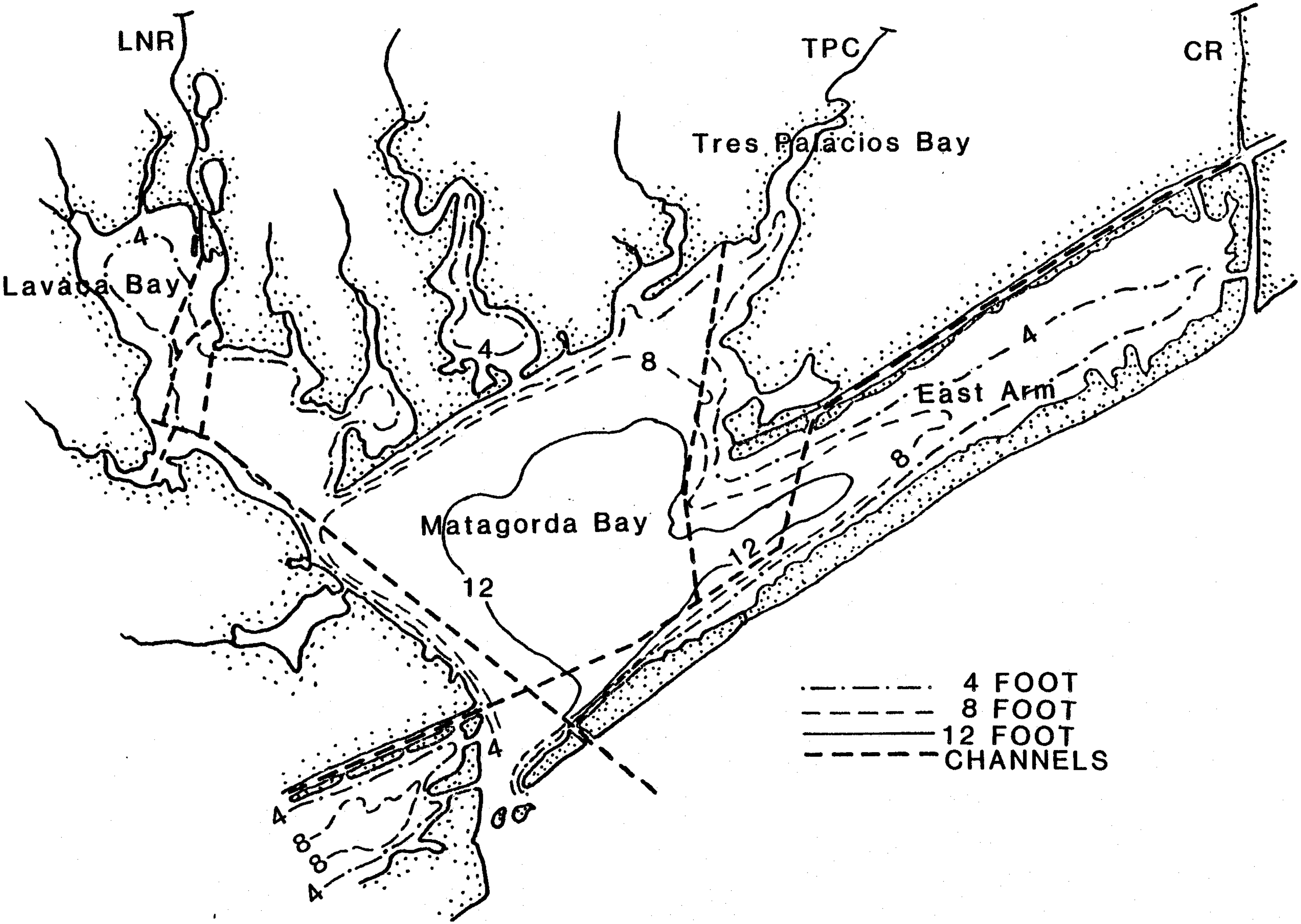


Figure 3. General bathymetry and channelization of the Matagorda Bay System (from Longley and Wright in preparation). CR= Colorado River, LNR= Lavaca-Navidad River, TPC= Tres Palacios Creek.

Chocolate Bayou. Runoff from about 940 mi^2 of the Colorado-Lavaca Coastal Basin enters the bay system via Cox Creek, Keller Creek, Carancahua Creek, Turtle Creek and Tres Palacios Creek (TDWR 1980).

Under average wind, freshwater inflow and tidal influence conditions, the general pattern of water movement is from the inflow areas toward the passes (McGowen et al. 1976a, 1976b). The Texas Department of Water Resources (1981) simulated steady-state flows using a hydrologic model of the bay system based on monthly inflow and weather patterns determined over a 35-year period. Results from the model indicate long-term net flows rather than actual currents. Patterns of circulation are very complicated and display large variations from month to month. Central areas in Matagorda Bay showed complex gyres, and the flux of water through Pass Cavallo was particularly strong.

Bay shorelines are affected by wave action and the nearshore circulation patterns. McGowen and Brewton (1975) found that almost all of the bay shorelines in the Matagorda Bay System were eroding, except for a few that were accreting at deltas and near passes.

The yearly average temperature in the Matagorda Bay System is 70.5°F; the average summer high temperature is 83.5°F, and the average winter low temperature is 45.5°F. Mean rainfall in the system is 40 inches (Williams et al. 1976). The greatest portion of yearly rainfall occurs in September (17% at Port Lavaca and 15% at Bay City) with June, October and August following in descending order. March has the lowest average rainfall (Bomar 1983). Evapotranspiration is higher than rainfall in all months except January, February, September and December (Espey, Huston and Associates 1979c); consequently there is a net annual precipitation deficit of about 6 inches (Woodruff 1975).

Salinities in the Matagorda Bay System are variable (Fig. 4). Because of the shallow depths in the system, vertical stratification is generally absent or limited to the deeper areas during calm weather. However, horizontal salinity gradients frequently exist, with seawater salinities at the tidal exchange passes and near zero salinities at the river mouths (Ward and Armstrong 1980).

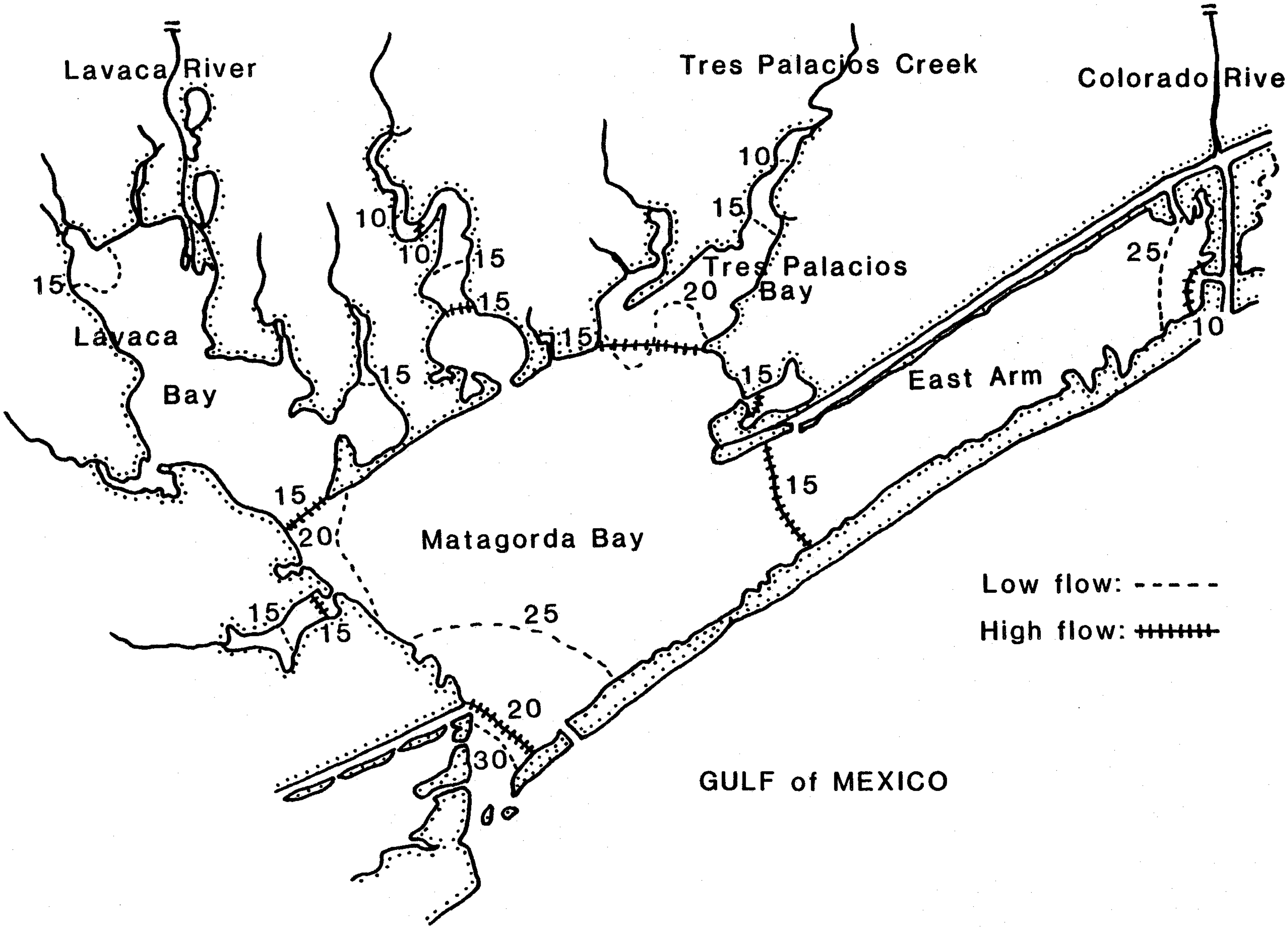


Figure 4. General salinity distribution in the Matagorda Bay System
(from McGowen et al. 1976a and 1976b).

The production of oil and gas is an important sector in the area's economy. Recreation and tourism also contribute to the economy, although they are not nearly as important as oil and gas production. Hunting and sportfishing are an important part of the recreation and tourism sector. In 1978 nearly 2,000 deer were harvested by sportsmen (Liebow et al. 1980) and the expenditures by sport fishermen were nearly $6 million (TDWR 1980) in this area. The direct value to the fisherman of the various commercial fisheries catches in the basin was more than $23 million in 1976 (TDWR 1980). This was a significant value, and the indirect and induced benefits contributed even more to the economy. Jones et al. (1974) estimated that $1.00 of output by the shrimp industry had a total economic output impact on the Texas economy of $3.08.

Perturbations

The Matagorda Bay System is very dynamic and has been subjected to a series of increasingly frequent natural and man-made perturbations. The lower Colorado River has flowed in its present channel for only a few hundred years (Bouma and Bryant 1967). Previously it flowed in the channel of what is now Caney Creek. After moving to its present channel, an enormous log jam formed, which blocked sediment transport to the bay. In 1929 the log jam was broken by a combination of dredging, dynamiting and flooding. The trapped sediment was released and the present delta rapidly began to form. Dredging to relieve upstream flooding channelized the delta formation and opened the channel through Matagorda Peninsula, allowing the Colorado River to discharge directly into the Gulf of Mexico (Sheffield and Walton 1981). By 1941, approximately 11.1 mi^2 of Matagorda Bay was covered by the delta (McGowen and Brewton 1975) and East Matagorda Bay was separated from the remainder of the estuary. In addition, there was a reduction in the amount of both freshwater and sediment entering Matagorda Bay. Delta growth is now restricted to a small area around Tiger Island Cut and an even smaller area at Culver Cut (Coastal Environments Inc. 1980).

A series of upstream reservoirs (primarily the Highland Lakes) and increased diversions have greatly reduced the discharge at the mouth of the Colorado River. The average annual discharge (1899–1936) of the Colorado River at Austin prior to regulation by upstream reservoirs was 1,964,000 ac-ft, but following regulation it fell to 1,499,000 ac-ft (1937–1977). Current average discharge records (period after regulation began) indicate that below Austin the discharge builds to 2,179,000 ac-ft at the Columbus gage, but falls off to 1,795,000 ac-ft at the Bay City gage due to diversions, primarily for irrigation (U.S. Geological Survey 1978).

The Lavaca-Navidad drainage has also been affected by reservoir construction. In May 1980, Palmetto Bend Dam on the lower Navidad River was closed, forming Lake Texana. This reservoir covers 28.9 mi^2 at conservation stage. Since it is very close to the bay, its impacts on freshwater inflow are significant, potentially reducing inflow by 92,000 ac-ft. annually and reducing sediment input to the Lavaca delta by 49% (U.S. Bureau of Reclamation 1974).

Man-made navigation channels are another important perturbation in the system (Fig. 3), with 115 mi of channels in Matagorda Bay. Almost 9,000 ac. of bay bottom and associated lands have been disturbed by dredging and spoil placement. The annual average maintenance spoil volume is about five million yd^3. The annual spoil load for each mile of channel is high, 43,535 yd^3 per mile (Espey, Huston and Associates 1976). The Matagorda Ship Channel to Port Lavaca and Point Comfort is about 36 ft deep and 300 ft wide. There is also a channel to Palacios of about the same dimensions and a shallower channel up the Lavaca River. The GIWW, which crosses the breadth of Matagorda Bay, is maintained to a depth of 12 ft. In addition to the direct disturbance, the dredging of the GIWW has created a hydrologic barrier between the bay and over 11,000 ac of formerly supporting wetlands (Sheffield and Walton 1981).

Matagorda Bay's connections to the Gulf of Mexico have frequently changed. Pass Cavallo, the natural pass separating Matagorda Peninsula and Matagorda Island, appears to be shoaling because of destabilization by the creation of the Matagorda Ship Channel in 1963 and the resulting tidal-prism capture (Ward 1982). Tiger Island Cut was dredged near the mouth of the Colorado River after the d lta had crossed the bay. Ther are also several washover areas on Matagorda Peninsula that are open for varying periods following storms. Green's Bayou is the most important of these, but it has been closed since at least 1971 (Ward and Armstrong 1980).

Matagorda Bay is periodically struck by hurricanes and other tropical storms. Henry and McCormack (1975 as cited in Espey Huston and Associates 1979c) found that the probabilities of Matagorda Bay being affected by tropical storms are higher than for any other 50-mile segment of the Texas coast. In addition to causing extensive damage to humans and their property, these storms can cause great changes to the natural system. Erosion, flooding, resuspension and redistributiuon of sediments and a sudden influx of freshwater are some of the estuarine impacts. The last major hurricane to landfall in Matagorda Bay was Carla in 1961. A minimal hurricane (Fern) landed at Palacios in 1971.

Although all of the streams that drain into the Matagorda Bay System are fishable and swimmable (TDWR 1984b), water pollution is a problem in some parts of the bay. The tidal portion of the Colorado River has moderate public health problems as the result of high bacterial levels from point-source discharges and agricultural runoff. In addition, the Colorado River channel between the GIWW and the Gulf receives poorly treated sewage from vacation homes on the banks and has been closed to oyster fishing by the Texas Department of Health (1983). About 20% of Lavaca Bay and 10% of Matagorda Bay are also closed to oyster harvesting. Mercury pollution has been a significant problem in Lavaca and Cox Bays (TDWR 1984b).

Other changes have occurred or are currently taking place in the system. The major land use changes have been the conversion of grasslands to cropland and the development of a few urban areas (Liebow et al. 1980). The Houston Lighting and Power Company (no date) reported that areas of forest along the Colorado River had been treated with the plant hormones 2,4-D and 2,4,5-T over a period of several years. The hormones, which selectively kill woody plants, have been used in a program of land clearing to increase the amount of range in the basin.

The South Texas Project—a nuclear generating plant—is currently under construction 6.2 mi north of the GIWW just to the west of the Colorado River. A cooling pond, which occupies 10.9 mi^2 has substantially increased the total area of lake and reservoir habitat in the area. The South Texas Project will be a net consumer of water from the Colorado River with the predicted removal of 36,500 to 54,100 ac-ft of water each year and the return about 16,200 ac-ft (Houston Lighting and Power Company 1978).

Also currently under construction is the navigation portion of the Mouth of Colorado River project. Stone jetties and a sediment-trap basin have been built adjacent to the entrance channel to prevent shoaling. The existing channel is to be dredged to 15 x 200 ft at the entrance and 12 x 100 ft upstream to Matagorda. Tiger Island Cut will be filled with dredged spoil. A second phase of this project, not yet under construction, will divert the entire Colorado River flow into Matagorda Bay. The construction of only the navigation feature would decrease freshwater inflow to Matagorda Bay, causing an increase of salinity, loss of salinity gradient and the reduction of sediment and nutrient input.

The net result of these many and on-going changes is that Matagorda Bay is continually under the stress of readjusting to new conditions and as such is likely not to be at peak productivity (U.S. Fish and Wildlife Service 1979). Our analysis in this study is based largely on past biological responses of the system to changes in freshwater inflow. These past responses are used as a "baseline" against which future management options are evaluated. However, because of the constant perturbations in the system, this "baseline" was constantly changing. No matter how sophisticated the analytical techniques used, past system responses (productivity) can only be a rough estimate of future management effects. The past system cannot be duplicated and at any one time the system was either still responding to the latest change or was operating at a productivity level less than that possible. Any analysis that strives only to sustain the productivity of the recent past is ignoring all of the de facto negative impacts and missing an opportunity to improve the existing conditions. Under these circumstances (i.e. no reliable baseline) general principles of estuarine functioning and examples from other bays must be used to make up for the shortcomings of the data.

Further perturbations to the Matagorda Bay System are planned. The most recent Texas Water Plan (TDWR 1984a) discusses seven new reservoirs in the Colorado River basin. The U.S. Bureau of Reclamation is studying a potential reservoir on the Colorado River near Columbus. The details of this reservoir have not been resolved, but it could greatly change freshwater inflow amounts and patterns. Further upstream, Stacy Reservoir is also planned for construction on the Colorado River. Upper Pecan Bayou, San Saba, Mason and Pedernales reservoirs are planned for construction on tributary streams, if the surface-water supply need develops. The Baylor Creek Reservoir in Fayette County is planned to serve as a cooling lake for stream-electric power generation. Even without any additional reservoirs being built, flows in the Colorado River are predicted to decrease by 18% by the year 2030 (Espey, Huston and Association 1979f).

At this time only one additional reservoir is proposed in the Lavaca River basin. The Stage II Palmetto Bend Reservoir on the Lavaca River is a congressionally authorized project that would have a firm annual yield of 35,000 ac-ft and further reduce freshwater inflow to Matagorda Bay.

Surface-water use in the coastal basins surrounding Matagorda Bay is predicted to increase (Espey, Huston and Associates 1979f). This would have a small impact on the bay system by itself, but may be important when other freshwater inflows also become curtailed.

MATERIALS AND METHODS

River Flow Data

Gaged river flow data were obtained from publications by the Texas Department of Water Resources in cooperation with the U.S. Geological Survey. Monthly flow volumes in acre-feet (ac-ft) and flow rates in cubic feet per second (cfs) were obtained for the Lavaca, Navidad and Colorado Rivers from 1960 through 1982. Similar data were obtained for Tres Palacios Creek flows from 1971 through 1980. Gaged flow records are also available for Garcitas Creek and Placedo Creek, but the period of record is too short to be useful. The monthly volumes of water released each month from Lake Texana since flow curtailment was initiated in May 1980 were provided by the Bureau of Reclamation (pers. commun. Mr. John Goar and Mr. Eugene Hinds). These data are provided in Appendix A.

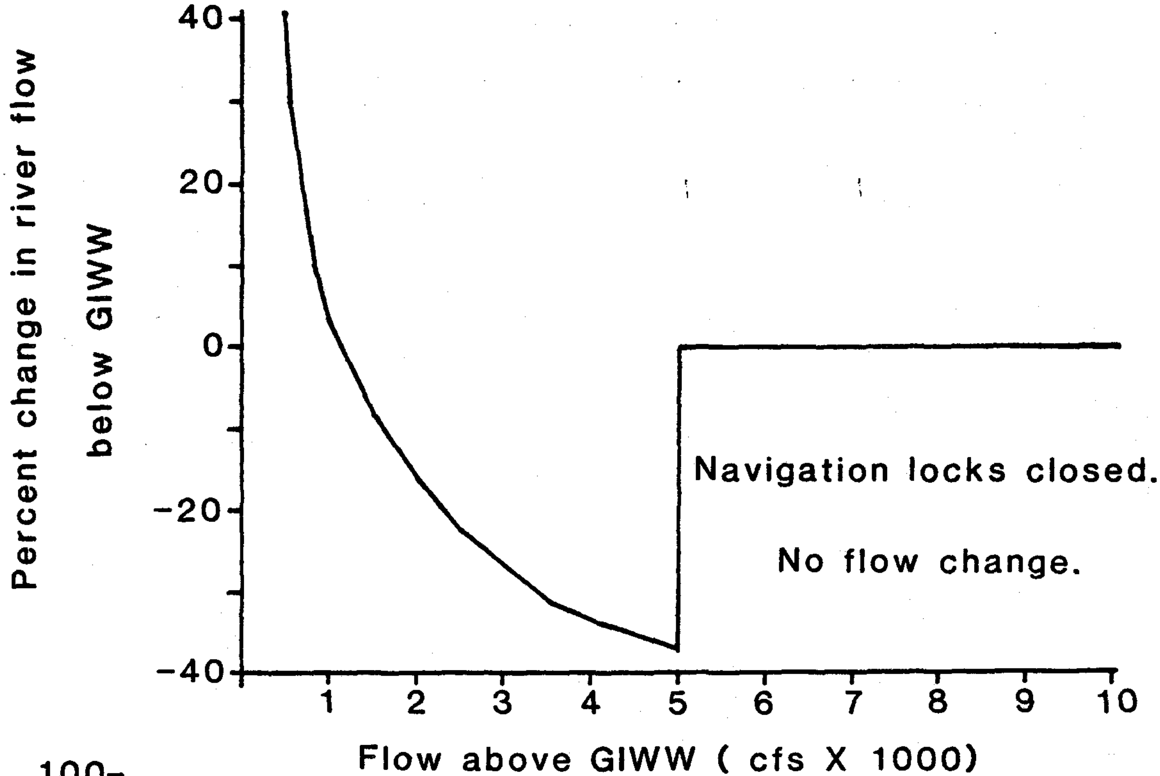
Flow adjustment for the Colorado River

The Colorado River empties into Matagorda Bay and into the Gulf of Mexico. The flows calculated to enter Matagorda Bay were based on gaged flows recorded near Bay City subjected to adjustment procedures based on Figures 5-26 and 5-27 of LP-106 (TDWR 1980), see our Figure 5. The graphs were simplified on each end of the flow scale: 1) for flows less than 1,300 cfs, 90% of the flow was projected to enter the bay, and 2) for flows greater than 5,000 cfs, 65% of the flow was projected to enter the bay. At intermediate flows the percentage projected to enter the bay was calculated based on two regressions, the first estimated the amount flowing into the GIWW and the second estimated the amount flowing into the bay thru Tiger Island Cut (TIC). Although the graphs show curvilinear relationships, we again simplified them to linear ones, sacrificing little as noted by high r^2's.

Flow into GIWW = -6.11 + 0.1 Flow above GIWW $r^2 = .90$

Flow into TIC = 90.15 - 0.005 Flow below GIWW $r^2 = .99$

Although this method of calculating the freshwater flow into the bay from the Colorado River is imprecise, we think it provides reasonable estimates. Other important factors that control the amount of freshwater



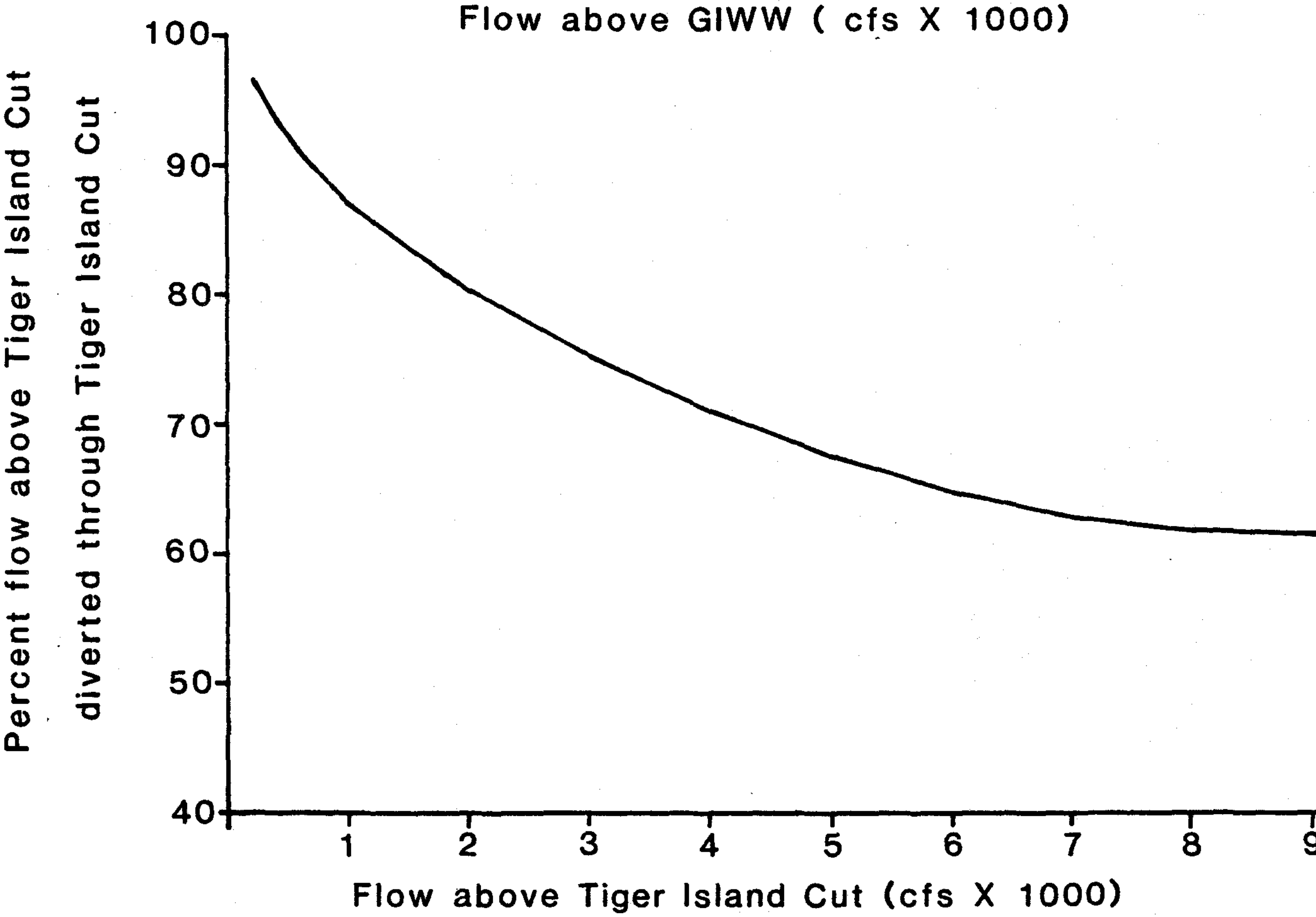


Figure 5. Bases for adjustment of gaged Colorado River flows to obtain the amount entering the Matagorda Bay System. Upper graph is from Fig. 5-26 and lower is from Fig. 5-27 of LP-106 (TDWR 1980).

entering the bay that have been ignored because of the lack of reliable data are tidal stage and the amount of shoaling at the mouth of the Colorado River (Espey, Huston and Associates 1979d). Consequently, our estimates of the historical freshwater inflows to Matagorda Bay from the Colorado River, while based on the best available data, probably do not reflect actual inflows in all cases.

Weather Data

Temperature and rainfall data were extracted from weather records. Five stations' data were evaluated for maxima, minima and means for temperature and rainfall; these stations were Point Comfort, Port Lavaca No. 2, Port O'Connor, Palacios FAA Airport and Matagorda No. 2. Monthly data from January 1960 thru December 1982 published in Climatic Data, Texas were examined (U.S. Department of Commerce, 1960-1982). Summary statistics of the temperature and rainfall data are presented in Appendix B.

Commercial Shrimp Fishery Data

Catch and effort data for the shrimp, crab, oyster and finfish fisheries in the Matagorda Bay System were obtained from the TPWD and National Marine Fisheries Service (NMFS) cooperative publications entitled "Texas Landings" (U.S. Department of Commerce and Texas Parks and Wildlife Department, 1961-1984). Catch and effort data for the Texas offshore shrimp fishery were obtained from NMFS publications entitled "Gulf Coast Shrimp Data" (U.S. Department of Commerce, 1961-1984). Shrimp landings used herein are in pounds of shrimp tails, and are presented in Appendix C. Shrimping effort is given in number of trips made and in number of "days" fished - a day being a block of 24 hours of fishing time.

Texas Parks and Wildlife Department Shrimp Samples

Harvest independent shrimp abundance and size data for the Matagorda Bay System were obtained from samples collected by TPWD from 1963 through 1980 (Matthews et al. 1984). TPWD recorded abundance and size of white, brown and pink shrimp caught in trawl and barseine samples at selected sites in most areas of the bay system (Fig. 6). Because several differ nt sized trawls were dragged for varying lengths of time, we converted all catches to mathematically standardized values. Thus, relative abundances were put in the equivalents of numbers of shrimp caught by a 25-ft trawl dragged for 15 minutes. Shrimp lengths were measured in millimeters from tip of rostrum to tip of telson. Water temperature and salinity measurements were also recorded with each sample.

Occasionally sample sites were changed or discontinued, gear type was chang d or personnel expertise changed. This led to situations where standardization procedures could not adequately adjust catches to maintain uniformity thru the years. This occurred in Lavaca Bay trawl samples and this data had to be discarded, which reduced our ability to use TPWD harvest independent data in river flow requirement tests.

Correlation and Regression Analyses

Analyses of the fisheries and river flow data to identify relationships between them were accomplished on the NMFS computer network. Available in this system are a Burroughs 7800 computer housed in Seattle, WA, and a Tektronix 4051 microcomputer housed in Galveston, TX. Regression analyses and data plotting were accomplished using the BMDP statistical software programs P1R, P2R and P6D, and the Tektronix package for multiple and polynomial regressions. Biological and ecological harvest-independent data were sorted and compiled with FORTRAN programs, also operating on the Burroughs 7800.

Our analysis of the freshwater inflow required to maintain or enhance the shrimp fishery involved the correlation and regression of various flows with commercial harvest data and with TPWD sampling data. Our analysis of the commercial harvest data for each of the two major shrimp species used the following steps:

1. Correlation of annual flow of each major river (Lavaca-Navidad and Colorado) versus annual catches.
2. Correlation of seasonal flows of each major river versus annual catches.

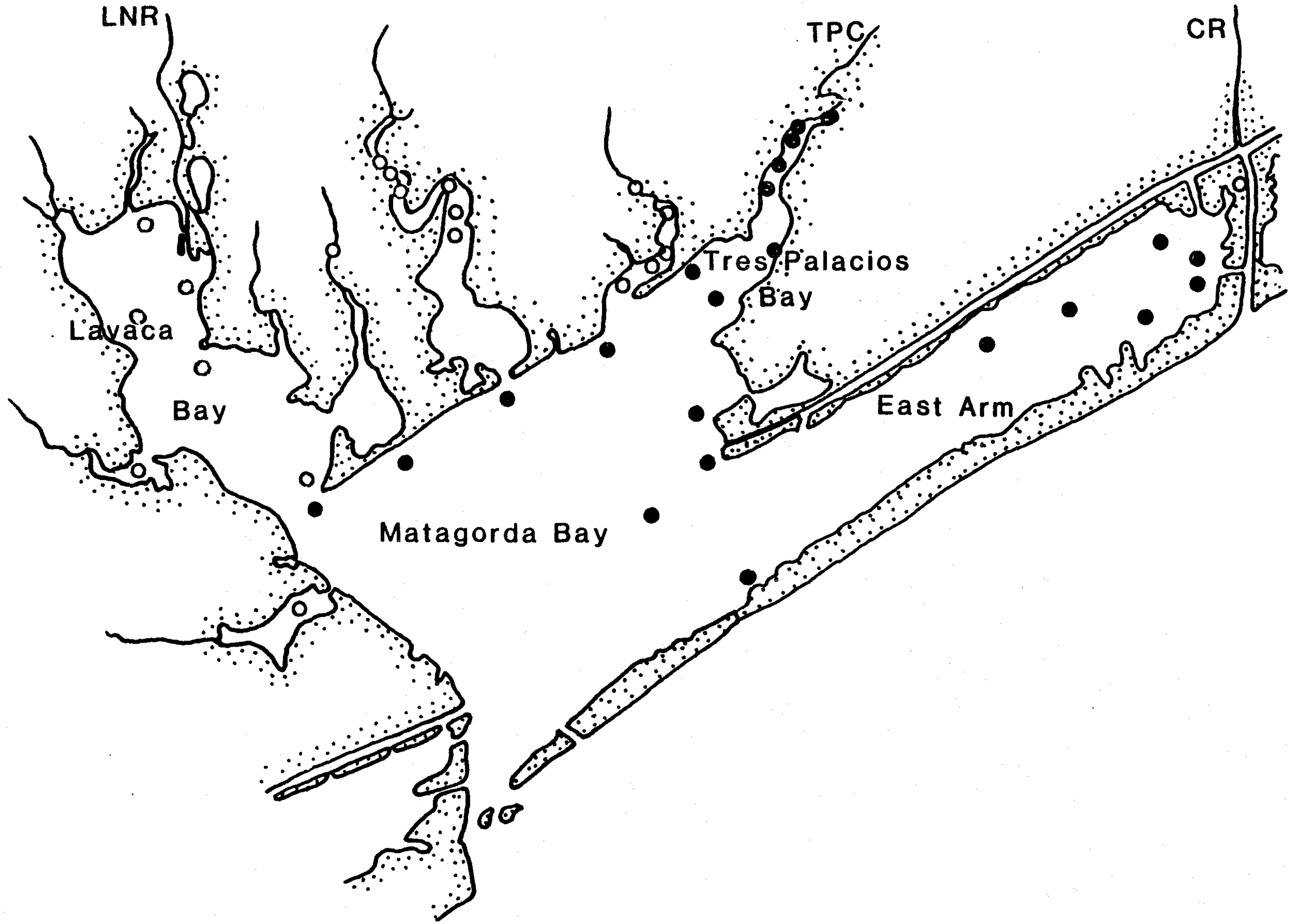


Figure 6. Texas Parks and Wildlife Department shrimp sampling sites, 1963-80. Sites used in this report are indicated by a solid circle. CR= Colorado River, LNR= Lavaca-Navidad River, TPC= Tres Palacios Creek.

3. Correlation of monthly flows of each major river versus annual catches.
4. Regression of monthly flows of each major river and of their combined flows versus residual catches.
5. Derivation of several sets of monthly flows from the regression analyses (or from mean flows for 1960-1982 in cases where there was no statistically significant regression relationship).
6. Derivation of required number, scheduling and size of floods.
7. Reduction of several sets of monthly flow volumes from #5 and the flooding requirements from #6 to one flow value for each month.

Residual catch is that portion of the annual catch that occurred during and after the flow month under analysis. For example, January flows were regressed against the total annual catch, but February flows were regressed only against the February thru December catch. This prevents February flows from trying to explain the January catch. Since there was little if any harvest in December, December flows of the previous year were regressed against annual harvests for the current year.

Both linear and quadratic regression equations were tested. Since these two regression types were our principle tools in determining inflow values, greater precision was sought here than it was for the correlations. These relationships were used to find two sets of flows: those needed to maintain the mean shrimp harvest, and those calculated to produce a maximum harvest.

The curve for the September Lavaca River flows (Fig. 7) illustrates two characteristics of some of the quadratic regressions. The mean residual white shrimp catch for September (1961-76) is 684,438 lbs. Entering the y-axis at that point gives two flow values on the x-axis, 15,000 and 310,000 ac-ft. Using only this curve, there is ambiguity as to which value is required to maintain the historical mean shrimp harvest. However, this curve does provide a good method of determining the flow needed for maximum harvest. In this case, and others, the relationship between flow and harvest holds until flow surpasses a certain level, a threshold. It app ars that very high flows in September depress the white shrimp catch for the remainder of the year. This allows us to select the peak of the curve as the optimum flow, above which increased flows have a negative effect on

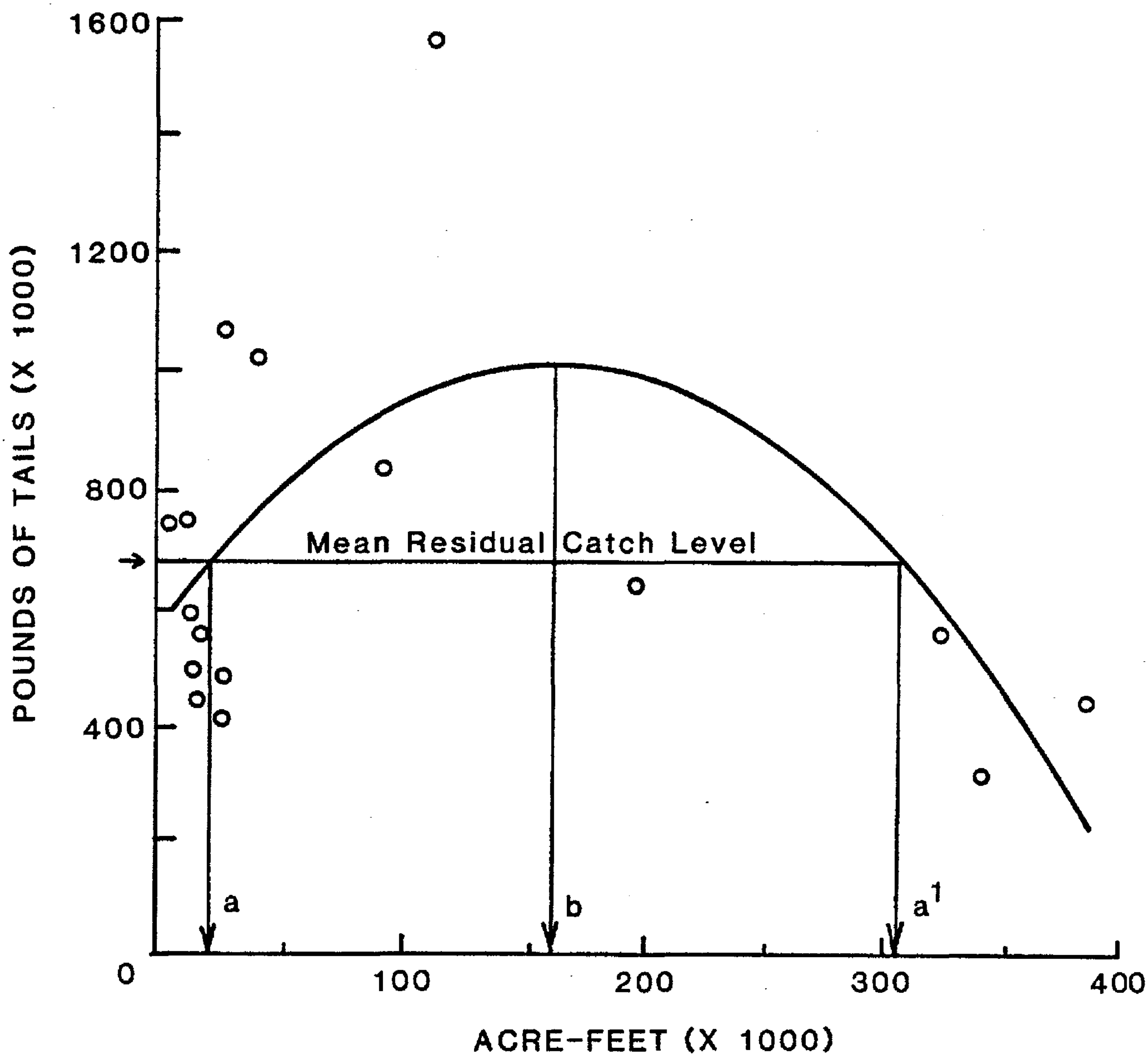


Figure 7. The curve representing the quadratic regression between September flows of the Lavaca-Navidad River (X) and the residual commercial white shrimp catches (Y) in the Matagorda May system, 1961-76. Intersecting lines represent the graphical method of determining the flows needed for maintenance of the mean residual catch (lines a & a^1) and for maximization of the catch (line b).

harvest. We refer to this procedur as "thresholding" and view it as a powerful tool.

We used procedures which emphasiz values derived from significant equations and the use of thresholding to reduce a list of several possible flow values to the one best set of values. These procedures are listed in Table 1. Where the analysis has not provided reliable guidance in flow requirements, we have selected the mean historical flow for that month. Without significant relationships, mean flows are the best available recommendation, since they have at least provided conditions suitable for the mean harvest over the period of record.

Analyses using TPWD samples were limited. The fragmented data base allowed only the use of Tres Palacios Bay, the east arm of Matagorda Bay and th main body of Matagorda Bay samples (Fig. 6), and only for brown shrimp at that. Monthly residual catches were calculated for 1971-1980 trawl samples from Tres Palacios Bay using the standardized catch values, and were regressed with monthly Tres Palacios Creek flows. Residual brown shrimp bar-seine catches, 1971-80, from Tres Palacios Bay were also regressed with monthly Tres Palacios Creek flows. Standardized April and May brown shrimp trawl catches from the east arm of Matagorda Bay, 1966-77, were regressed with monthly adjusted Colorado River flows. Standardized April and May brown shrimp trawl catches from the main body of Matagorda Bay, 1963-80, were regressed with monthly Lavaca-Navidad River flows and with adjusted Colorado River flows.

Table 1. Procedures for flow selections using the linear and quadratic regression equations.

Step

1. If both equations are significant ($p<0.10$) and select the same flow value, use that value.

2. If both equations are significant and the quadratic equation selects two values for the mean harvest level, use the mean harvest flow value selected by the linear equation.

3. For the remaining cases where both equations are significant but select different flow values, use the average of the two values.

4. If the linear equation is significant and the quadratic equation is not, use the flow values selected by the linear equation.

5. If the quadratic equation is significant and the linear equation is not, use the flow values selected by the quadratic equation, except in cases where the quadratic equation selects two flow values for the mean harvest level.

6. Use thresholding, where possible, for the determination of the maximum harvest flow value, if the r^2 of the quadratic equation is at least 0.10 and the linear equation is not significant.

7. For any flow values that remain undetermined, use the mean historical flow for the period of analysis.

River Flow Patterns

Annual Volumes. Annual gaged flow volumes for the tributaries varied considerably between 1960 and 1982 (Table 2). The minimum annual flow for the Colorado River was 344,000 ac-ft in 1964. The maximum was 3,812,800 ac-ft in 1961, and the 23-year mean was 1,720,600 ac-ft. The Navidad River and the Lavaca River had minimum annual flows of 93,600 ac-ft and 40,300 ac-ft, respectively, in 1963, and they had maximum annual flows of 1,280,000 ac-ft and 743,900 ac-ft, respectively, in 1973. Their mean annual flows were 501,500 ac-ft and 294,400 ac-ft, respectively.

Trends and Cycles. Monthly river flows from 1960 thru 1982 for the Colorado River and for the Lavaca-Navidad River fluctuated widely (Figs. 8 and 9, and Table 3) and contributed to keeping the Matagorda Bay System a dynamic area, especially with regards to salinity. During these 23 years, monthly river flows often appear to erupt from a base flow whose rise and fall is not on an annual cycle, and often has periods of increase and decrease which extend two years or more. The base flow appears to be climatically directed as indicated by the nearly identical timing of changes in the base flows of both rivers.

The annual cycles in river flows for the Colorado and the Lavaca-Navidad are remarkably similar based on 23-year monthly averages, though the Colorado flows are greater (Table 2). Highest average monthly flows are in May and June and are about 175,000 ac-ft and 125,000 ac-ft for the Colorado and Lavaca-Navidad Rivers, respectively. Lowest average monthly flows are in March, July and August for the Lavaca-Navidad River, when they fall to about 25,000 ac-ft. The lowest for the Colorado River is also in August, when the mean flow falls to about 40,000 ac-ft. September mean flow is high for the Lavaca-Navidad reaching about 110,000 ac-ft. High mean monthly flows have greater variances than low mean monthly flows, and the seasonal cycles are much less regular than the succinct description given above.

Floods

Flooding is part of the natural hydrologic cycle of any stream. Floods are important events that shape channels and inundate the floodplain

Table 2. Gaged annual river flows (thousands of ac-ft) for the major tributaries of the Matagorda Bay System.

Year	Lavaca River	Navidad River	Colorado River
1960	471.8	787.1	3,187.0
1961	471.8	845.4	3,812.8 Max.
1962	96.4	138.5	670.5
1963	40.3 Min.	93.6 Min.	397.7
1964	54.0	118.4	344.0 Min.
1965	319.8	449.9	1,882.4
1966	135.4	329.4	1,090.8
1967	185.0	331.0	477.6
1968	333.3	742.9	3,604.3
1969	329.8	517.6	1,683.9
1970	200.1	438.1	2,383.7
1971	200.3	294.5	978.1
1972	304.2	461.1	765.3
1973	743.9 Max.	1,280.0 Max.	2,639.5
1974	341.7	707.4	1,049.1
1975	253.1	422.2	3,023.2
1976	358.2	470.2	1,874.8
1977	203.9	326.1	2,240.4
1978	244.4	400.3	665.0
1979	545.2	770.7	2,157.4
1980	121.4	134.4*	726.7
1981	466.1	981.2*	2,727.4
1982	352.0	493.9*	1,192.7
Mean:	294.4	501.5	1,720.6
# years:	23	23	23
sd:	169.1	297.5	1,078.0

*Palmetto Bend Reservoir in operation.

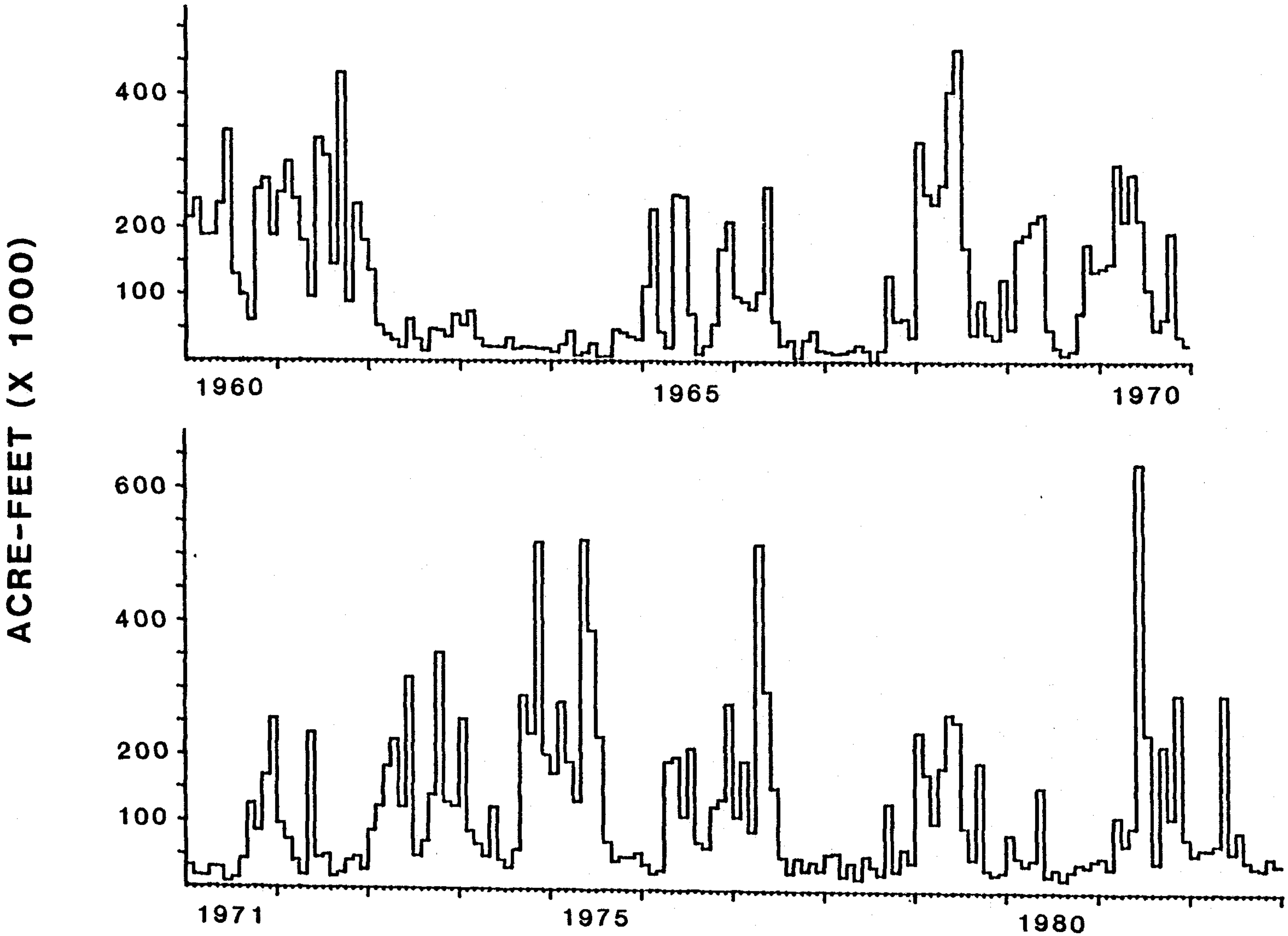


Figure 8. Monthly flows of the Colorado River gaged near Bay City, 1960-82.

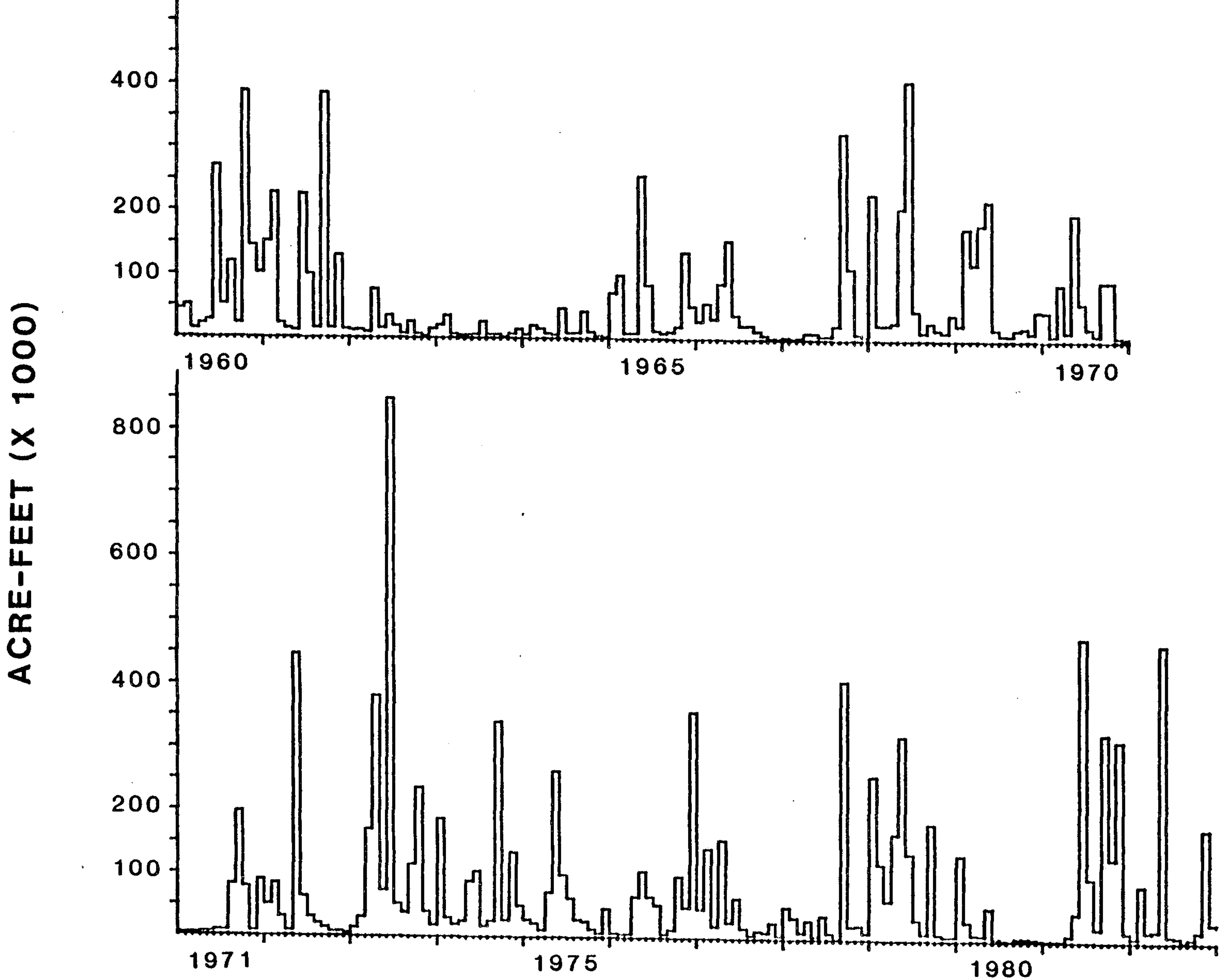


Figure 9. Combined monthly flows for the Lavaca River gaged near Edna and the Navidad River gaged near Ganado, 1960-82. Flows from the Palmetto Bend Reservoir are included beginning in September 1980.

Table 3. River flow statistics for monthly flow volumes for major tributari s to the Matagorda Bay System. Values are in thousands of acre-feet.

Months	Colorado River (1960-82)				Navidad River (1960-79)[a]				Lavaca River (1960-82)			
	Mean	SD[b]	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
January	148	126	16	506	42	52	2	168	21	26	2	96
February	160	137	14	460	38	43	1	165	21	22	1	64
March	130	121	16	453	21	29	1	106	12	15	2	65
April	166	183	7	798	40	56	2	228	26	36	2	154
May	264	215	14	808	72	75	2	256	55	61	2	199
June	248	274	9	986	85	132	4	552	46	67	<1	298
July	110	117	1	472	21	15	6	65	9	10	<1	35
August	50	40	7	177	16	18	1	80	6	11	<1	40
September	130	155	6	664	78	92	4	263	38	53	<1	169
October	112	124	22	548	32	45	1	165	24	50	<1	223
November	156	187	19	801	24	33	1	95	20	28	<1	104
December	124	116	18	431	27	47	1	210	16	30	<1	148
Totals:	1,798				496				294			

[a]Used only the years prior to 1980, 1980 is when Palmetto Bend Reservoir began operations.

[b]SD = standard deviation.

thereby flushing out detritus and nutrients, providing important temporary aquatic habitat and influencing riparian vegetative communities.

The role of floods in estuaries is equally complex. They provide a sudden influx of freshwater that lowers salinity and temporarily alters the plankton community (Gilmore et al. 1976, Matthews 1981). Floods also affect temperature and current patterns, but with regard to delta marshes floods have three primary functions: 1) to provide sediments that initially build the marsh and later maintain its elevation; 2) provide the medium for nutrient import and export to and from the marsh; and 3) provide the medium for import and export of detritus to and from the marsh.

Matagorda Bay has two major deltas, the Lavaca and the Colorado. The Lavaca delta is flooded regularly and is discussed in detail below. The Colorado River, however, is channelized and leveed (mostly unintentionally through dredge spoil deposition) to such an extent that river flooding of the delta marshes almost never occurs (TDWR 1978, 1980). The Corps of Engineers (1977) claims that flows of 50,000 cfs will flood the delta, but field observations by Goldstein (1978) refute this. In any case, flows of that size are infrequent, once every six years between 1960 and 1983, with three occurring in June and one in September. However, these marshes are flooded by tidal action (TDWR 1980, Goldstein 1978) which also serves for nutrient and detrital exchange.

The proposed diversion of the Colorado River into Matagorda Bay (Corps of Engineers 1981) will result in extensive delta growth (Coastal Environments Inc. 1980) by allowing the river to interact regularly with the bay. Of course, delta growth depends on a regular supply of sediment, which, in turn, depends on an unobstructed river and adequate flows. Upstream damming of the Colorado River has already reduced the historical sediment supply (Coastal Environments Inc. 1980, Espey, Huston and Associates 1979a). Further damming could reduce the supply even more, but for the purposes of the following discussion, we will assume that this will not occur. Since this assumption assures a continuing supply of sediment at present levels, we will address the flood requirements of the delta marshes that would be formed by the diversion of the Colorado River into Matagorda Bay.

Sediment and Floods. Sediment supply is not continuous, but is largely the result of discrete flood events. In many basins 90% of the sediment is moved during floods r curring at least once every five years (Wolman and Miller 1960). In g neral, floods of moderate magnitude and moderate frequency transport most of the sediment carried by rivers (Wolman and Miller 1960, Leopold et al. 1964, Dury 1969, Schumm 1974). In humid environments the moderate-magnitude moderate-frequency floods are roughly equivalent to the mean of the maximum annual flows (Leopold et al. 1964). This is about 33,000 cfs for both the Lavaca-Navidad River and the Colorado River (Table 4).

These flows should carry adequate sediment to allow delta growth, if the sediment is not trapped in reservoirs. This condition may already be violated for the Lavaca delta, which has historically been a prograding formation (McGowen et al. 1976a). Palmetto Bend Dam on the lower Navidad River is predicted to stop 49% of the sediment supply to the Lavaca delta (U.S. Bureau of Reclamation 1974). Thus reducing the sediment load from about 65,000 to 32,000 yd^3/yr (Espey, Huston and Associates 1979b).

The previously discussed moderate magnitude floods have frequencies of 2.4 years for the Lavaca-Navidad River (Table 5) and 1.3 years for the Colorado River (Table 6). Smaller, more frequent floods may not carry enough sediment to permit delta growth, but they could be important in the maintenance of existing Lavaca delta marshes and predicted (post-diversion) Colorado delta marshes. Any flood large enough to cover the marsh would serve this purpose. For the Lavaca delta, the Texas Department of Water Resources (1980) estimated that, at a normal tide, flows of 9,000 cfs would flood the marsh (Table 7).

The post-diversion Colorado delta does not exist yet, but based on the predicted growth pattern of the delta and the predicted discharge-stage relationship, 10,000 cfs should flood the delta marshes. This flow still carries a substantial sediment load of approximately 10,000 tons per day (Coastal Environment Inc. 1980). The frequency of events with this magnitude of flow is 0.25 years (Table 8).

Livingston (1981) found that the detritus content of a flood varied seasonally. This is also the likely pattern with sediment. In English salt marshes, Ranwell (1964) found the greatest sediment accretion in the fall. Because of fall plowing and the lack of cover crops on farm fields, we would predict that winter and early spring floods would have the highest sediment content in our study area, but we have no evidence to support this.

Table 4. Annual maximum gaged discharge rates in cubic feet per second.

Water Year	Colorado River	Lavaca-Navidad River
1960	84,100	
1961	66,400	46,800
1962	21,000	18,060
1963	8,580	8,390
1964	7,800	7,380
1965	27,000	23,000
1966	15,200	14,400
1967	19,000	49,100
1968	49,500	43,500
1969	24,200	23,400
1970	21,900	14,020
1971	19,400	23,600
1972	24,600	31,200
1973	60,800	129,200
1974	38,400	55,800
1975	48,900	23,800
1976	19,900	10,710
1977	50,300	21,570
1978	19,700	48,300
1979	40,400	32,000
1980	14,300	26,840*
1981	42,100	45,350
1982	46,400	33,800
1983	22,600	
Means:	33,020	33,192

*Palmetto Dam initially closed May 22, 1980.

Table 5. Lavaca-Navidad River flow events equal to or greater than 33,192 cfs. A flow event is defined as an average daily gaged flow of at least 33,192 cfs separated from similar flows by at least two consecutive days with average daily gaged flows of less than 4,000 cfs.

Calendar Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1960	—	—	—	—	—	—	—	—	—a	x			1
1961									x				1
1962													
1963													
1964													
1965													
1966													
1967									x				1
1968						x							1
1969													
1970													
1971													
1972													
1973				x		x							2
1974									x				1
1975													
1976													
1977													
1978									x				1
1979													
1980													
1981									x				1
1982										—	—	—	
Totals:				1		2			5	1			9

22 yrs avg/yr = 0.4 or one flood every 2.4 years; median = 0/yr.

a——— = no data.

Table 6. Colorado River flow events equal to or greater than 33,020 cfs. A flow event is defined as an average daily gaged flow of at least 33,020 cfs separated from similar flows by at least two consecutive days with average daily gaged flows of less than 8,000 cfs.

Calendar Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1959	—	—	—	—	—	—	—	—	—[a]				
1960						x					x		2
1961						x	x		x				3
1962													
1963													
1964													
1965													
1966													
1967													
1968	x					x							2
1969													
1970													
1971													
1972													
1973				x		x							2
1974									x		x		2
1975					x								1
1976													
1977				x									1
1978													
1979						x							1
1980													
1981						x			x		x		3
1982					x								1
1983										—	—	—	
Totals:	1			2	2	6	1		3		3		18

24 yrs avg/yr = 0.8, or one flood every 1.3 years; median = 1/yr.

[a]—— = no data.

Table 7. Lavaca-Navidad River flow events equal to or greater than 9,000 cfs. A flow event is defined as an average daily gaged flow of at least 9,000 cfs separated from similar flows by at least two consecutive days with average daily gaged flows of less than 4,000 cfs.

Calendar Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1960	—	—	—	—	—	—	—	—	—[a]	2	1		3
1961	2	2				1	1		1				8
1962				1									1
1963													0
1964													0
1965	1	1			2	1					1		6
1966				1	1								2
1967									1	1			2
1968	1				1	1							3
1969		1	1	1	1								4
1970					1				1	1			3
1971								1	1			1	3
1972		1			1								2
1973			1	1	1	2				1			6
1974	2				1	1			1		1		6
1975					2								2
1976										1		2	3
1977		1		1		1							3
1978									1				1
1979	2	1	1	1	2	1			1				9
1980	1				1								2
1981						1			1		1		3
1982					3					—	—	—	3
Totals:	9	7	3	6	17	9	1	1	8	6	5	3	75

22 yrs avg/yr = 3.4 or one flood every 0.3 years; medium = 3/yr.

[a]—— = no data.

Table 8. Colorado River flow events equal to or greater than 10,000 cfs. A flow event is d fined as an average daily gaged flow of at least 10,000 cfs separated from similar flows by at least two consecutive days with average daily gaged flows of less than 8,000 cfs.

Calendar Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1959	—	—	—	—	—	—	—	—	—[a]	1	1		2
1960						1				1	2	1	5
1961	2	2				1	1		1		1		8
1962													0
1963													0
1964													0
1965	1	1			3	1					1	1	8
1966					1								1
1967									1				1
1968	1			1	2	2						1	7
1969		1	1	1	1								4
1970			2		1					2			5
1971									1			1	2
1972					1								1
1973			1	1		1			1	1			5
1974	2				1				2		2		7
1975		2			2	1							5
1976				1	1	1					1	2	6
1977		1		1	1								3
1978									1				1
1979	3	1	1	2	3	1			1				12
1980	1				1								2
1981						1	1		1		1		4
1982					2								2
1983		1	1		1				1	—	—	—	4
Totals:	10	9	6	7	21	10	2	0	10	5	9	6	95

24 yrs avg/yr = 4.0 or one flood every 0.25 years; median = 3.5/yr.

[a]—— = no data.

Nutrients and Floods. High river flows inundate delta marshes and have the potential to export larg amounts of accumulated detritus and nutrients. Since the Colorado delta in its present configuration is almost never flooded by river flows, this discussion will primarily concern the Lavaca delta.

The preceived role of marshes in the nutrient cycles of estuaries is currently under revision. Previous studies of particulate organic detrital transport disagree on both the net directional movement and the percentage of overall vascular plant productivity involved in this movement. Estimates range from near 50% net export to net imports of particulate organic detritus. Nadeau (1972), Moore (1974), Heinle and Flemmer (1976), Shisler and Jobbins (1977 a,b) and Woodwell et al. (1977) all reported net imports or at least no significant exports of suspended particulate organic detritus. Schelske and Odum (1962), Teal (1962), Odum and de la Cruz (1967), Heald (1969), Day et al. (1973), Nixon et al. (1976) and Moore (1974) reported net exports. The characteristics of each marsh system cause it to function differently, which undoubtedly accounts for much of the variation in results. In general, there is a tendency for coastal wetlands to import nutrients at the beginning of and during the growing season and to export nutrients in the fall and winter (Odum et al. 1984). In a one year study, Espey, Huston and Associates (1977) estimated that 62% of the annual Lavaca delta marsh production occurred in the spring and summer, while 69% of the annual loss of detritus occurred in the summer and fall.

Marshes may serve as holding areas for materials discharged by rivers, importing material during high river discharge periods and exporting material when that discharge is small (Blum 1969). Thus, marshes could act as a control mechanism by removing materials from the water when the concentration of these materials is high and exporting materials when conc ntrations are low. The marshes, then, dampen oscillations in the concentration of suspended materials in nearby bodies of water. This would t nd to produce a more even release of material to adjacent waters. Even if some marshes export little of their own production as suspended particulate matter, they could be important in the regulation of the overall export of material from estuaries (Hackney 1978).

This concept is somewhat contrary to the classic idea that floods flush large amounts of nutrients and detritus from delta marshes. Studies of the Lavaca delta by Armstrong et al. (1975) and Dawson and Armstrong (1975) present a model of continuous export of nutrients from the marsh with a greatly increased rate during flooding when it follows a period of marsh drying. Gilmore et al. (1976) found a correlation between the Lavaca River discharge and bay nutrient levels. They felt the release of nutrients by marsh flooding contributed to this relationship. Espey, Huston and Associates (1979b) found little net movement of nutrients from the Lavaca delta marshes except during high flows, when there was a large export.

Both of these concepts, the marsh as a storer/regulator of nutrients and the quick release of nutrients by floods, could be functioning together. However, for the Lavaca delta the predominate operation appears to be the rapid release of nutrients during floods. The period of high nutrient release rates may last for one or two days, and is followed by a period when release rates decline rapidly (TDWR 1981). Dawson and Armstrong (1975) found that high release lasted about one week for ammonia-nitrogen, 12 to 24 hrs for nitrite-nitrogen and nitrate-nitrogen, 12 to 48 hrs for organic-nitrogen, 24 hrs for phosphorus and 12 to 24 hrs for carbon. Based on these release rates we have used floods of a single day duration as our standard.

The importance of marsh derived nutrients to the overall nutrient budget and productivity of an estuary is another important consideration. As proposed by Espey, Huston and Associates (1982), the nutrient budget for Matagorda Bay (Table 9) indicates that marshes provide less than 10% of the major nutrients and only a small portion of that is provided by flood inundation. These small percentages are not because of a lack of marsh productivity nor a lack of detrital export, but reflect the small amount of marsh in Matagorda Bay relative to the large amount of freshwater inflow.

There is more nutrient export from tidal action than from the less frequent river flooding. However, not all parts of the Lavaca delta are subject to regular tidal inundation. The areas around Redfish Lake and upstream of the confluence of the Lavaca and Navidad Rivers are flooded mainly by high river flows (TDWR 1980). These flows provide the bay with both allochthonous materials from upland and floodplain sources and marsh production from areas not regularly flooded by tides. Espey, Huston and Associates (1977) estimated an annual plant biomass export of at least

Table 9. An estimate of nutrient inputs into the Matagorda Bay System (from Espey, Huston and Associates 1982).

Source	Total Organic Carbon (10^3 lbs yr^{-1})	(%)	Total Nitrogen (10^3 lbs yr^{-1})	(%)	Total Phosphorus (10^3 lbs yr^{-1})	(%)
Freshwater Inflows	167,029	92.8	7,903	82.8	2,886	84.9
Marshes						
Tidal Exchange	11,797	6.6	118	1.2	236	6.9
Flood Inundation	103	0.2	75	0.8	86	2.5
Tidal Exchange	2	<0.1	2	<0.1	0.4	<0.1
Precipitation	-		1,125	11.8	82	2.4
Waste Discharges	840	0.5	327	3.4	109	3.2
Totals	179,969		9,550		3,399.4	

7,572.56 tons from the Redfish Lake area. The primary mechanism for export of this material to the estuary is large floods. Based on elevation cross sections and stage-discharge curves provided by the Bureau of Reclamation (pers. comm. William H. Karsell), a flow of approximately 36,000 cfs would flood the Redfish Lake area with enough water to facilitate detrital and nutrient export. Floods of this size occur approximately once every 2.8 years, in the months of April, June and September.

These large floods, which expose the bay to non-tidal detrital and nutrient sources, were related to commercial brown and white shrimp harvests. Early floods (April and June) could influence the current year's catch, but because of food chain delays and the fact that most of the year's catch has already past by September, late floods would have a greater influence on the next year's catch. We postulated that when an early flood occurred, that year's harvest should be larger than both the previous and following year's, and when there was a late flood, the next year's catch would be larger than the current year's. This pattern was followed in six of seven cases for white shrimp and in five of seven cases for brown shrimp (Fig. 10). So while the nutrient budget indicates that river flooding of marshes provides less than 3% of the total Matagorda Bay nutrients, there still appears to be a relationship to productivity for floods large enough to provide the bay with a pulse of detritus and nutrients from sources not regularly available.

Shrimp.

Life History. The life histories of brown (*Penaeus aztecus*) and white shrimp (*P. setiferus*) are well documented and have been reviewed by Cook and Lindner (1970) and Lindner and Cook (1970). Their general life cycles begin in the Gulf of Mexico where mature shrimp spawn. The eggs hatch within a few days of being released, and the larvae pass thru several naupliar, protozoeal and mysis substages before becoming postlarvae (PL). This development requires two to four weeks depending upon the water temperature and food availability. The PL's, now 10 to 13 mm long, make their way into the bays and estuaries where they find an abundance of food and protective habitat (Minello and Zimmerman 1983, Zimmerman and Minello 1984, Zimmerman et al. 1984). PL's soon become juveniles and growth continues at a rapid pace for the next two to three months. When the juveniles are 70 to 90 mm long, they begin their migration back to the Gulf to perpetuate

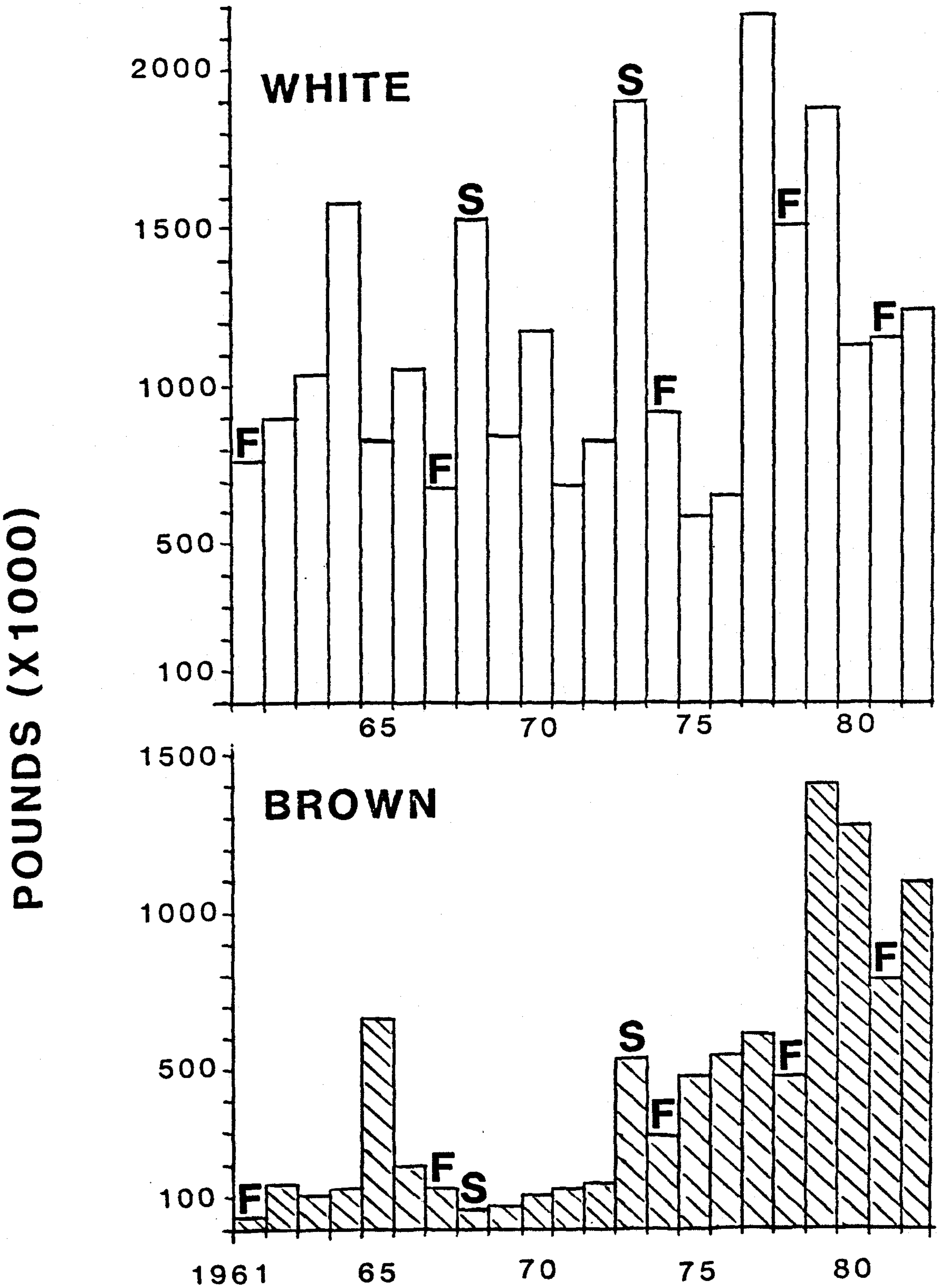


Figure 10. Occurrences of major floods (>36,000 cfs) on the Lavaca-Navidad River as they relate to annual white and brown shrimp commercial catches in the Matagorda Bay System. "S" indicates a major flood in April or June of that year, and "F" indicates a September major flood. Major floods on the Lavaca-Navidad River occur only in those three months.

the cycle.

The brown shrimp PL's begin entering the bays along the Texas coast earlier than the white PL's. There are usually two waves of brown shrimp PL's that enter each year. The main influx usually begins in February and continues thru April (Baxter and Renfro 1967, Berry and Baxter 1969, King 1971). These shrimp enter the brackish waters of secondary bays and marshes and grow rapidly through the spring. TPWD sampling provides specific evidence supporting this early arrival of the new-year-class juvenile brown shrimp in the Matagorda Bay System (Appendix C). These small shrimp were caught in trawl and bar-seine samples in the very early spring. Bar-seine samples collected in Tres Palacios Bay show that 25-40 mm juveniles became very abundant in April and May. Trawl samples collected in Tres Palacios, Turtle, Carancahua and Lavaca bays, all secondary bays of the Matagorda Bay system, show these areas were excellent habitats for the growing juvenile brown shrimp. The shrimps' mean lengths increased from about 40 mm in April to about 75 mm in July. They also became particularly abundant in the trawl samples during May and June which coincides with the time of their migration back towards the Gulf. At this time they become the target of the bay commercial fishermen.

A second, smaller wave of brown shrimp PL's usually enters the bay in the fall (Baxter and Renfro 1967, King 1971) and contributes to late fall and winter catches of brown shrimp. This minor wave appeared as an increase in abundance of small brown shrimp in bar-seine samples collected in Tres Palacios Bay beginning in September and extending into December. Commercial statistics do not accurately measure this fall stock of brown shrimp, because of the preponderance of white shrimp in the catches in the last four months of the year.

The annual white shrimp postlarvae influx usually begins at the passes in May and continues thru the summer (Baxter and Renfro 1967, Espey, Huston and Associates 1979e, King 1971). Small juveniles became evident in the Tres Palacios Bay barseine samples in June. These small white shrimp follow the same cycle as the brown shrimp, moving into the low salinity secondary bays and marshes where they grow rapidly in the abundance of food and cover. Trawl samples in the secondary bays also show the arrival of the new-year-class white shrimp by increases in abundances and decreases in mean lengths. From March thru May, a small population of large, overwintering, white shrimp were found in TPWD bay samples. These shrimp ranged in length from 90 to 140 mm, and they added support to the bait and bay commercial shrimp fisheries at this time of year.

The new-year-class of white shrimp begins migrating back thru the bays towards the Gulf in August. Emigration by white shrimp is not the rapid process it appears to be for brown shrimp. New-year-class white shrimp stocks build substantially in secondary bays in July, and in Matagorda Bay proper in August, where the stocks remain substantial thru November. This period also corresponds to the time when greatest commercial shrimp catches are being made. Because white shrimp remain in the primary bays longer than the brown shrimp, they are more available to the repeated fishing efforts of the bait, commercial and sport shrimpers. Consequently, white shrimp provide the larger portion of the annual bay commercial harvest.

These seasonal differences in the two species make it logical to treat the two separately with regard to the effects of changing river flows. Each species' relationship with river inflow will contribute to our understanding of the inflow's importance in maintaining the commercial fishery in the Matagorda Bay System, and to that of the offshore shrimp fishery in adjacent waters of the Gulf of Mexico.

Bay Shrimp Fishery. The thriving commercial shrimp fishery in the Matagorda Bay System is based on brown and white shrimp populations which are renewed each year (U.S. Department of Commerce and Texas Parks Wildlife Department 1961-1984). The mean annual catch for brown and white shrimp combined is about 1.6 million pounds of tails (Table 10). Catches increased substantially beginning in 1977 when shrimping effort also increased (Figs. 11 and 12). After this increase in effort, catch per unit effort declined slightly for white shrimp, and increased slightly for brown shrimp (Fig. 13). Such may be an indication that the white shrimp fishery could be approaching its maximum sustainable yield under present fishing regulations, environmental conditions and fishing pressure.

Although the bay commercial fishery extends from May thru December, it seems appropriate to describe the two portions of the annual fishery separately since they are based largely on the two shrimp species. These two species occupy several bay habitats that are the same, but are able to

Table 10. Shrimp catch statistics for the Matagorda Bay System, 1960-82.

A. Annual Statistics.

	WHITE SHRIMP			BROWN SHRIMP		
YEAR	CATCH[1]	TRIPS	CATCH/TRIP[2]	CATCH[1]	TRIPS	CATCH/TRIP[2]
1960	1,254	4,056	309	2	1,005	2
1961	774	4,587	169	29	1,185	24
1962	912	6,194	147	138	3,154	44
1963	1,040	9,291	112	105	1,658	63
1964	1,582	7,642	207	124	2,810	44
1965	838	8,603	97	667	5,740	116
1966	1,067	10,987	97	198	3,287	60
1967	686	6,184	111	132	2,192	60
1968	1,545	5,060	305	51	528	97
1969	857	6,502	132	68	1,222	55
1970	1,184	5,957	199	108	1,343	81
1971	695	7,120	98	135	1,336	101
1972	840	6,596	127	148	2,153	69
1973	1,907	12,685	150	544	5,149	106
1974	921	11,244	82	292	5,217	56
1975	598	8,067	74	488	4,757	103
1976	667	8,641	77	551	3,734	148
1977	2,185	15,568	140	621	4,734	131
1978	1,524	13,385	114	480	7,353	65
1979	1,898	20,196	94	1,413	11,131	127
1980	1,136	16,315	70	1,281	15,252	84
1981	1,157	11,121	105	790	4,363	181
1982	1,252	15,112	83	1,106	10,719	104
Means:						
1961-76	1,007.1	7,835.0	136.5	-	-	-
1961-78	-	-	-	271.1	3,197.3	79.1
1960-82	1,153.0	9,613.6	134.7	411.8	4,348.8	83.5

B. Monthly Statistics

	WHITE SHRIMP				BROWN SHRIMP			
	1960-1982			1961-1976	1960-1982			1961-1978
Month	Min.[1]	Max.[1]	Mean[1]	Mean[1]	Min.[1]	Max.[1]	Mean[1]	Mean[1]
Jan	0	29.4	4.3	3.7	0	0	0	0
Feb	0	22.2	1.2	1.4	0	0	0	0
Mar	0	36.2	1.6	2.3	0	4.2	0.2	0
Apr	0	57.0	7.6	6.8	0	11.4	1.4	1.3
May	0	119.0	30.0	33.2	0	306.6	101.8	68.4
June	0	86.8	19.0	19.8	0	819.5	224.3	141.5
July	0	53.2	11.0	12.2	0	304.2	64.8	37.0
Aug	42.0	644.5	270.4	243.8	0	274.2	14.3	17.8
Sept	120.5	846.5	334.3	291.9	0	10.2	1.0	0.3
Oct	117.9	512.1	288.6	260.0	0	5.2	0.5	0.5
Nov	17.3	388.9	141.3	111.2	0	38.2	2.4	3.1
Dec	0	197.6	43.7	20.7	0	10.5	0.9	1.2

[1]Thousands of pounds of tails.
[2]Pounds of tails.

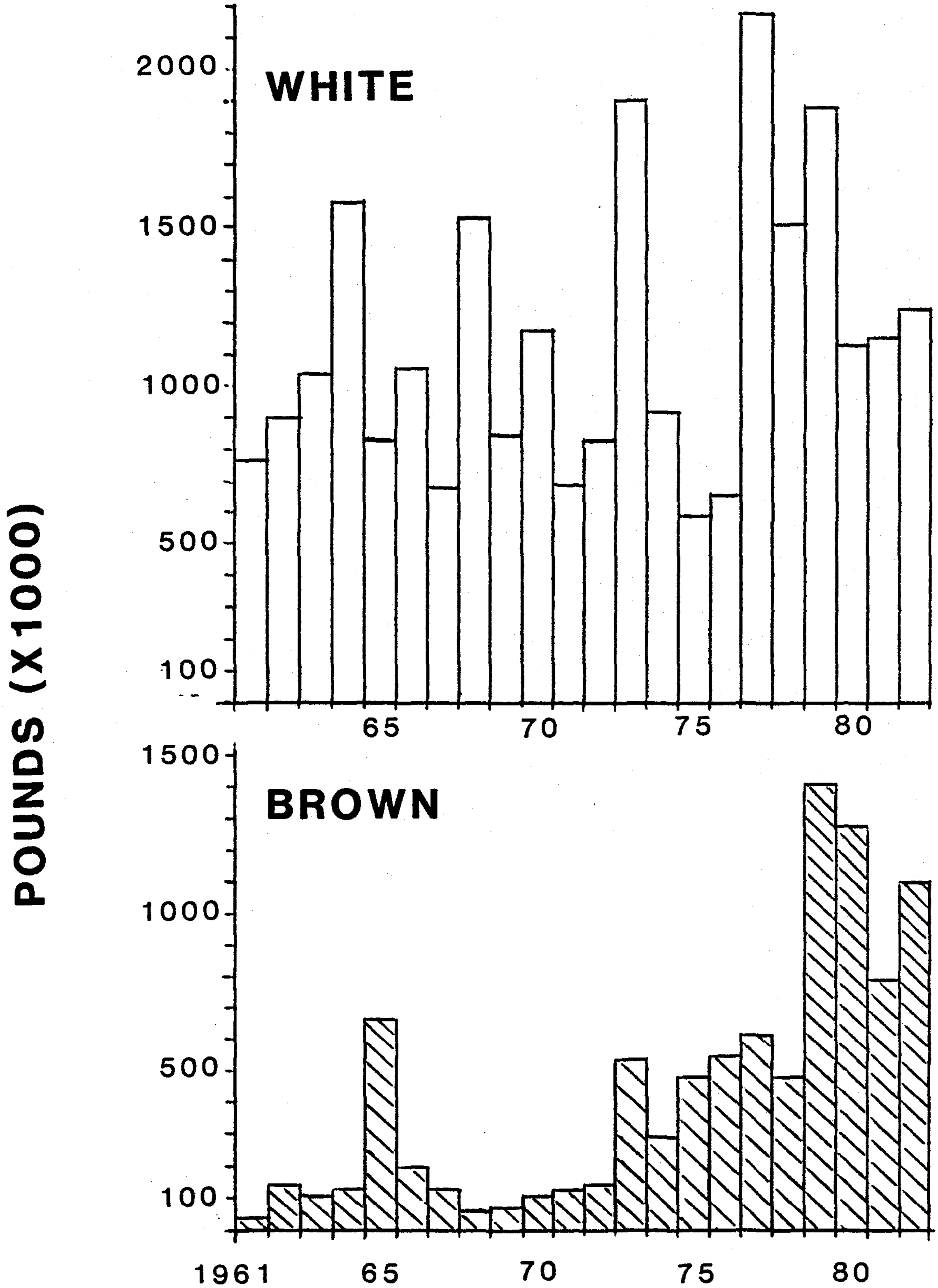


Figure 11. Annual commercial catches of white and brown shrimp in the Matagorda Bay System, 1961-82. Values are in pounds of shrimp tails.

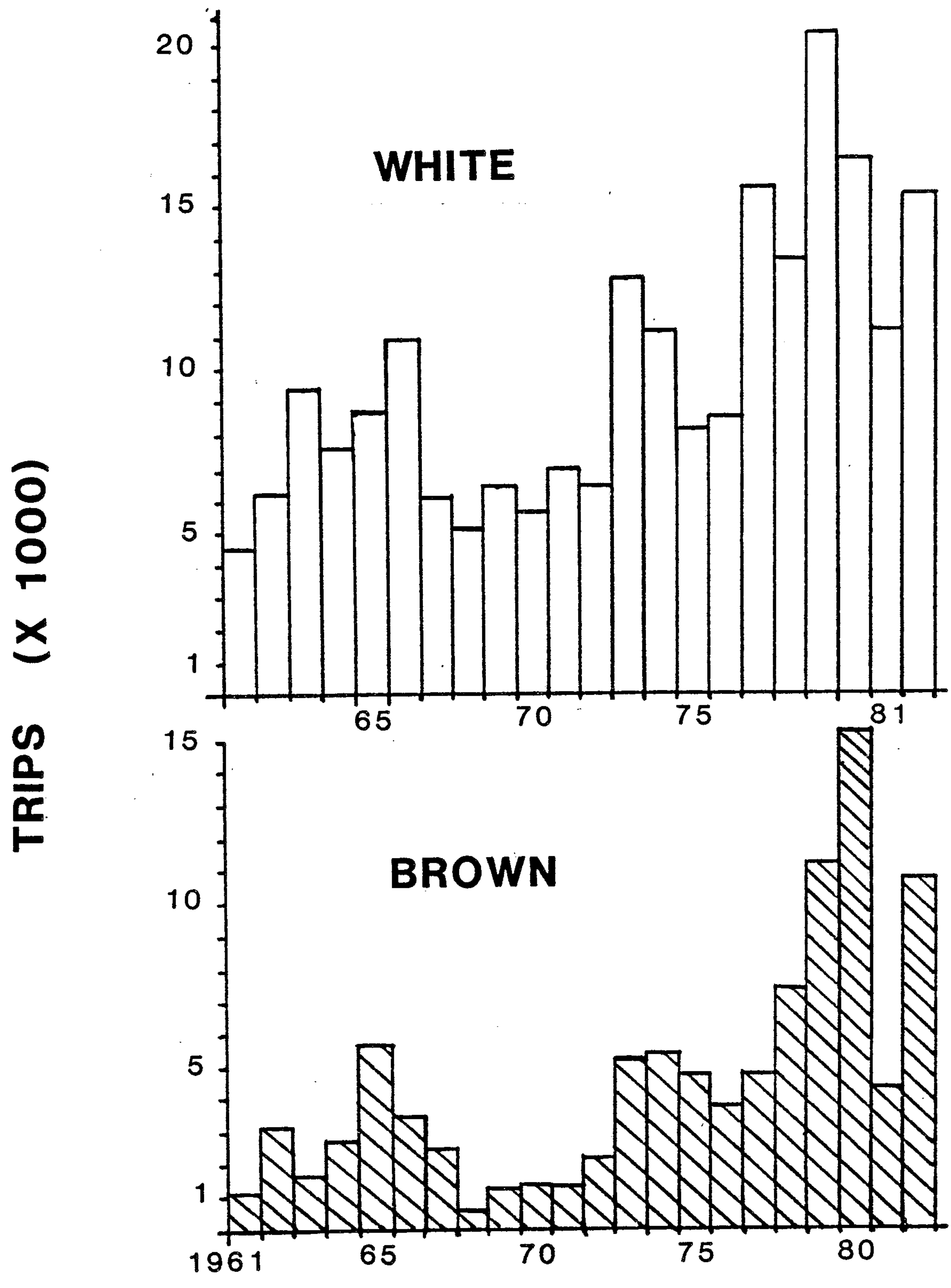


Figure 12. Annual effort directed at white and brown shrimp in the Matagorda Bay System commercial fishery, 1961-82.

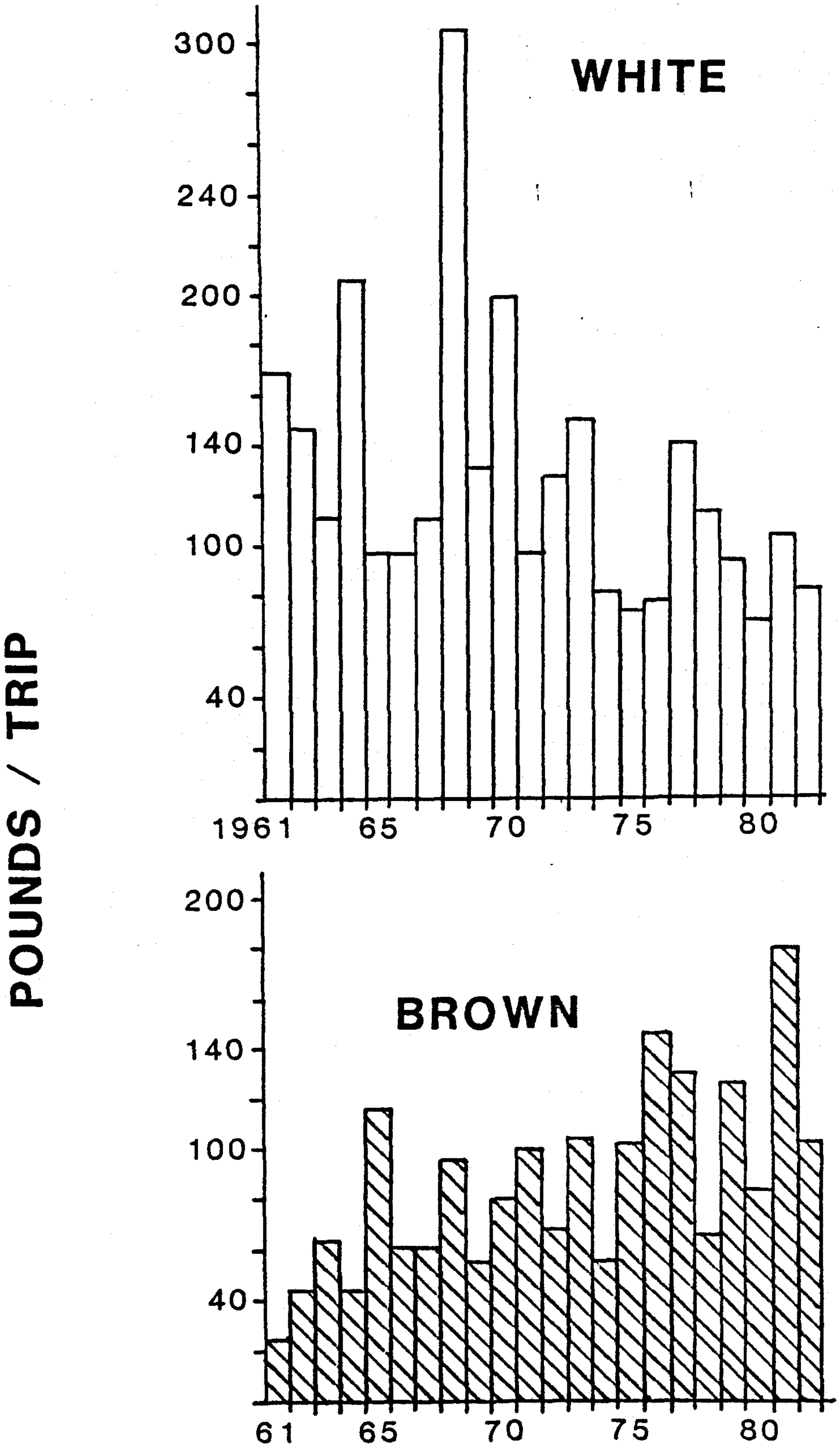


Figure 13. Catch per unit effort for the white and brown shrimp commercial fishery in the Matagorda Bay System, 1961-82.

partition the resource by occupying the habitat in different seasons. The first portion of the annual fishery begins in May and continues thru July (Fig. 14). About 94% of the annual brown shrimp catch is made during this period, which is also when the new-year-class juveniles and subadults are migrating back to the Gulf. Catches in June average about 57% of the annual brown shrimp catch in the bay; those in May and July average about 23% and 14%, respectively. Naturally these percentages vary from year to year. The second portion of the annual fishery begins in August and continues thru December. This five month period accounts for 93% of the annual white shrimp catch in the bay (Fig. 14). Catches in August, September and October account for 23%, 29% and 25% respectively.

The annual brown shrimp bay fishery increased nearly ten-fold from the early 1960's to the early 1980's. There appear to be three stages in the advancement of this fishery. The mean annual catch from 1961 thru 1972 (excluding 1965) was about 200,000 lbs from a mean annual effort of about 2,500 trips. For 1973 thru 1978, the mean annual catch increased to about 500,000 lbs from a mean annual effort of about 4,500 trips. The last stage was from 1979 thru 1982. The mean annual catch increased to about 1 million lbs from a mean annual effort of about 9,000 trips, thus, a doubling of catch for a doubling of effort. When annual catch was correlated with annual effort over the 22 year period, the relationship was strong ($r = 0.9$, $p<.01$). This indicates a growing fishery over our study period and consequently a probably inaccurate representation of the brown shrimp stock by the early annual catches. In an effort to select a period with a fairly uniform effort, we have restricted our analyses to the 1961 through 1978 catches.

There appear to be two stages of advancement in the white shrimp fishery during the study period. From 1961 thru 1976, annual catches fluctuated around a mean of about 1,000,000 lbs. Only catches in 1964, 1968 and 1973 were considerably greater, and only those of 1975 and 1976 were considerably lower. Effort fluctuated between 5,000 and 15,000 trips per year during these 17 years, but the catch to effort correlation was not significant ($r = 0.2$). This indicated the amount of effort had little influence on the size of the catch, and that environmental changes, such as changes in river flow, may have been operating here. The second stage was from 1977 thru 1982, and the mean annual catch increased to about 1.3 million lbs.

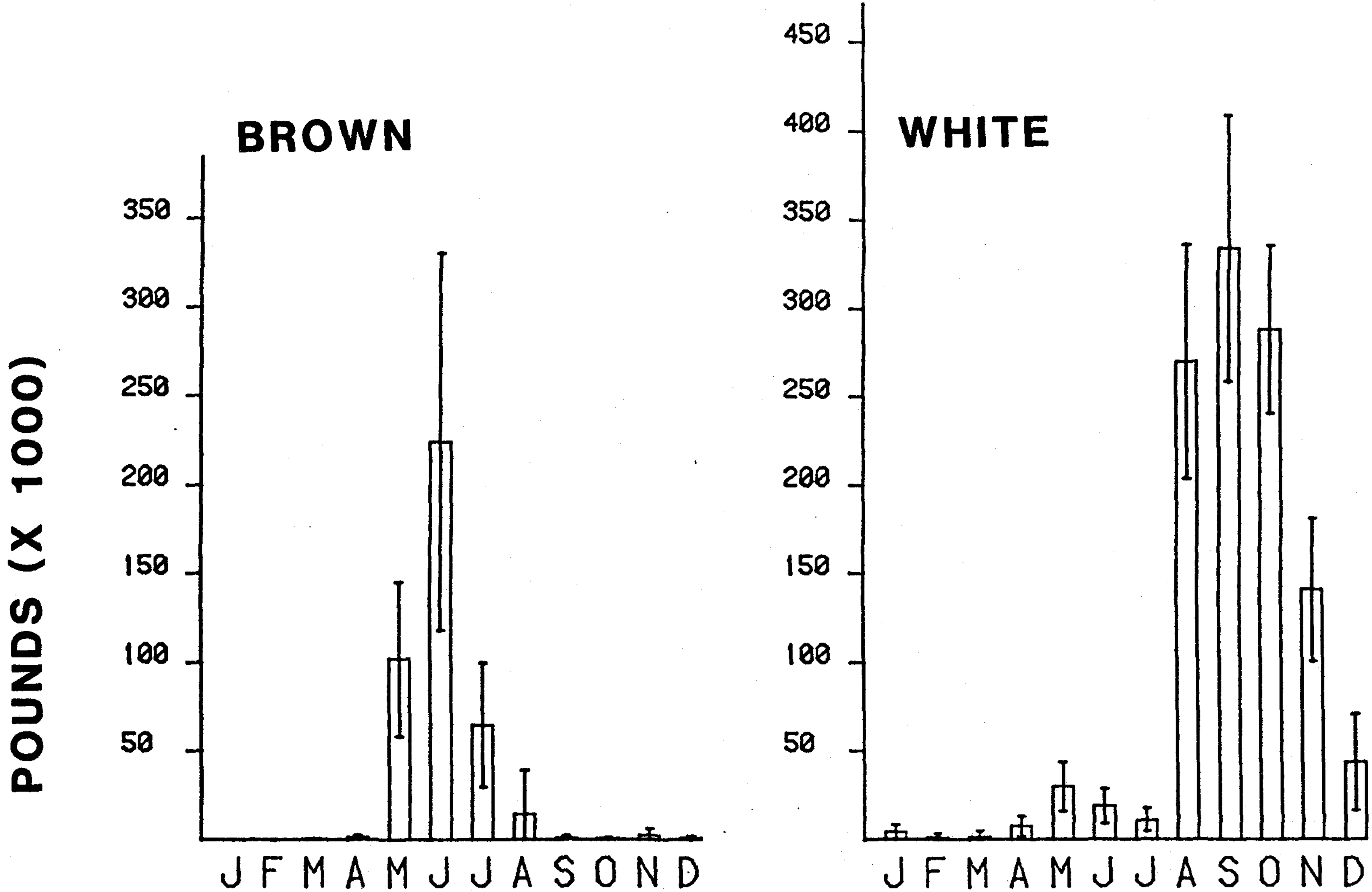


Figure 14. Means and 95% confidence limits for monthly commercial catches of brown and white shrimp in the Matagorda Bay System, 1961-82. Values are pounds of shrimp tails.

Annual efforts were about double those in the first stage. Thus, an increase in mean annual catch of about 51% was achieved through an increased mean annual effort of 95%. Because this greatly increased effort in recent years distorts the catch data, we have concentrated our subsequent analyses using white shrimp data from the 1961-1976 period.

Gulf Shrimp Fishery. It is important to remember that the multi-million dollar annual shrimp fishery in the Gulf of Mexico off the Texas coast is dependent on the health of the estuaries. The large shrimp caught in the Gulf have spent their youth feeding and growing in the estuaries. Since the quantity, timing and quality of freshwater entering each estuary via its tributaries have significant effects on the estuarine environments which support stocks of growing young shrimp, these freshwater inflows also impact the offshore shrimp stocks. The Matagorda Bay System is the third largest bay system in Texas, and as such contributes significantly to the shrimp stocks that are exploited by all facets of the Texas shrimp fishery.

Tagging studies done in the bays and Gulf of Mexico off Texas and Louisiana have shown that about 75% of the shrimp tagged were recaptured within a radius of 30 miles from where they were released (Gazey et al. 1982a, 1982b, Hollaway and Sullivan 1982, Lyon and Boudreaux 1983). Using such a limit to migratory expansion one can readily see that a very substantial portion of the shrimp stock in statistical subarea 19 (SS-19) must come from Matagorda Bay, and a smaller contribution should be expected to originate in Galveston Bay and San Antonio Bay, based on the locations of San Luis Pass and Cedar Bayou with respect to SS-19 (Fig. 15). Statistical subareas are used for the convenience of summarizing fisheries statistics (Klima 1980).

Shrimp catches in SS-19 have composed a substantial portion of the offshore fishery in Texas (U.S. Department of Commerce, 1961-84). Since 1960, the brown shrimp harvest in SS-19 has averaged 10.5 million pounds of tails per year, and the white shrimp harvest has averaged 2.2 million. Although there has been some annual variation, these averages are the highest among the four subareas along Texas (Table 11). Combining the values of the SS-19 and Matagorda Bay shrimp fisheries for the last five

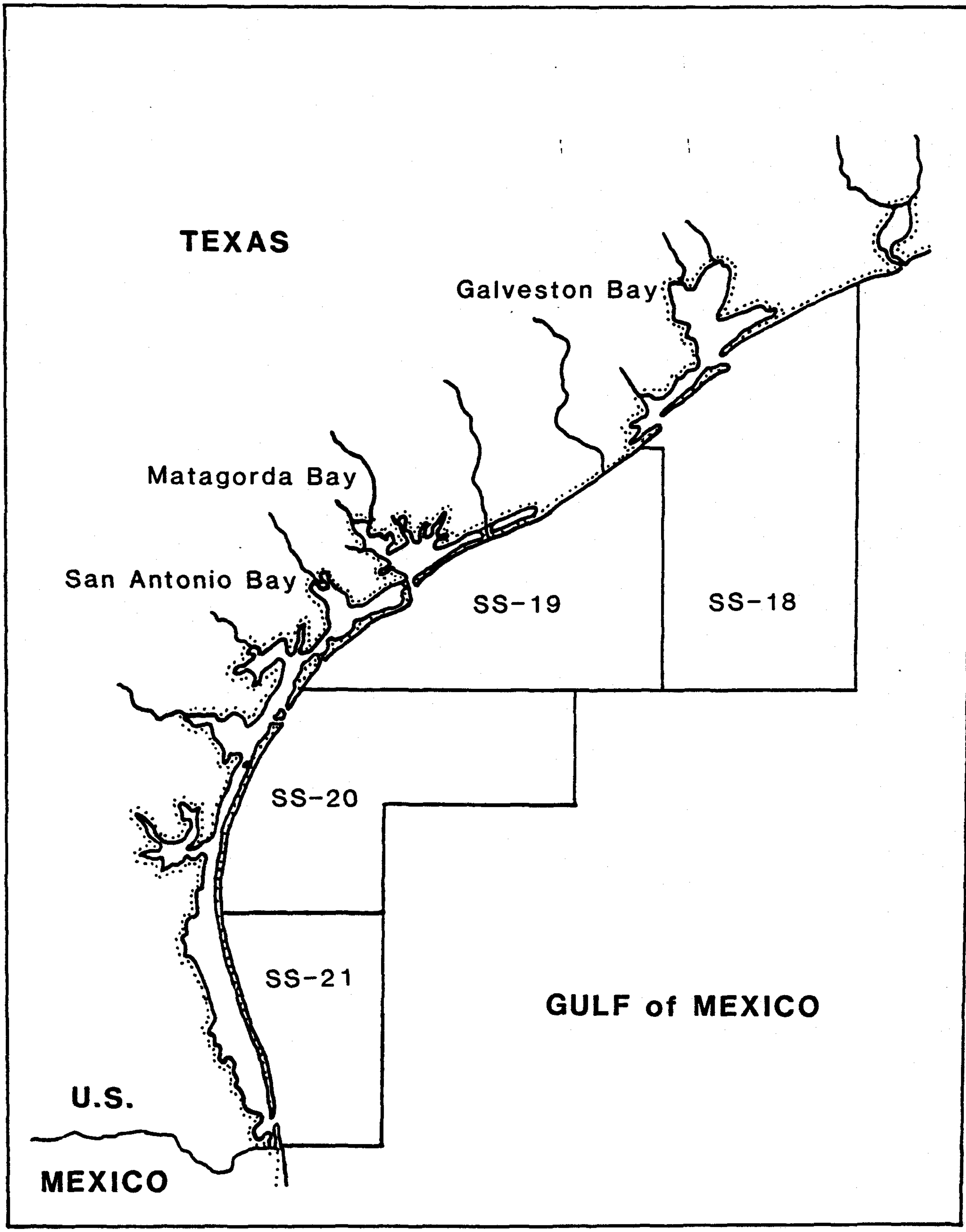


Figure 15. The Texas Gulf coast showing the boundaries of the four statistical subareas used for collecting shrimp fishery statistics.

Table 11. Shrimp landings from statistical subareas 18-21 and from the Matagorda Bay System. Landings are in millions of pounds of tails. See Figure 15 for locations of the statistical subareas.

	Brown Shrimp				White Shrimp				Matagorda Bay	
	18	19	20	21	18	19	20	21	Brown	White
1960	7.3	15.5	6.4	3.7	1.5	2.3	0.3	0.04	0.002	1.3
1961	2.5	5.4	4.6	2.8	0.9	2.3	0.7	0.1	0.03	0.8
1962	2.1	7.4	5.3	1.9	0.9	1.0	0.1	0.04	0.1	0.9
1963	3.5	13.1	4.1	3.5	1.3	1.6	0.1	0.01	0.1	1.0
1964	2.7	8.7	5.4	2.3	1.6	1.8	0.2	0.04	0.1	1.6
1965	4.1	14.1	4.2	3.5	1.2	1.7	0.1	0.02	0.7	0.8
1966	2.8	12.6	5.9	4.6	1.4	2.3	0.2	0.01	0.2	1.1
1967	10.9	19.1	8.7	9.5	1.3	1.4	0.4	0.1	0.1	0.7
1968	2.1	13.7	5.0	6.1	1.6	2.9	1.0	0.3	0.05	1.5
1969	2.3	9.8	5.0	6.5	2.2	3.3	0.7	0.3	0.07	0.9
1970	2.8	13.5	7.7	7.2	2.5	3.4	0.4	0.3	0.1	1.2
1971	7.2	14.6	6.2	4.3	2.5	2.3	0.2	0.2	0.1	0.7
1972	4.2	17.4	10.1	4.7	2.1	2.9	0.6	0.1	0.1	0.8
1973	1.9	5.8	8.5	7.0	2.6	3.3	1.0	0.3	0.5	1.9
1974	8.2	4.8	7.9	5.5	3.2	2.3	0.8	0.2	0.3	0.9
1975	4.0	6.7	7.8	6.2	2.1	1.6	0.4	0.08	0.5	0.6
1976	6.2	7.7	6.1	6.1	2.3	1.5	0.5	0.05	0.6	0.7
1977	8.1	10.0	7.2	7.2	2.0	2.3	0.5	0.2	0.6	2.2
1978	7.6	8.6	8.3	3.2	4.3	2.3	1.0	0.3	0.5	1.5
1979	2.9	5.2	5.1	5.5	1.8	1.6	0.6	0.2	1.4	1.9
1980	4.4	8.7	7.5	7.5	2.1	1.4	0.4	0.08	1.3	1.1
1981	7.0	16.0	9.4	7.6	3.1	1.8	0.4	0.1	0.8	1.2
1982	5.1	8.4	4.0	5.2	2.4	2.3	0.6	0.2	1.1	1.3
1983	2.9	5.9	4.9	4.2	2.8	2.4	0.4	0.1	2.0	2.3
Mean	4.7	10.5	6.5	5.2	2.1	2.2	0.5	0.1	0.5	1.2
sd	2.5	4.2	1.8	1.9	0.8	0.7	0.3	0.1	0.5	0.5

y ars, yields an average yearly value of about $53 million (Table 12). Although not all of this can be attributed to Matagorda Bay-reared shrimp, a very substantial portion can be. Also recall that the bait shrimp and sport fisheries within Matagorda Bay have not been included due to lack of data, and these have a significant dollar value that should at least be kept in mind.

It would be useful to show relationships between the Matagorda Bay shrimp harvests and those in SS-19 to solidify the links between the stocks. The best opportunity for finding such a relationship between the two brown shrimp stocks would be to compare the totaled inshore catches from May thru August with the totaled offshore catches from June thru September. These periods are when the new-year class shrimp become most available to bay and offshore fisheries, respectively (Table 13 and Fig. 14). No meaningful relationship was found between these data from 1960 thru 1978 (Fig. 16). This is probably due to the low shrimping effort applied to the Matagorda Bay brown shrimp stocks during these years. From 1979 thru 1982 (the current limit of our data) effort directed at brown shrimp in Matagorda Bay doubled over what it had been during the previous years. With this change an inverse relationship emerged such that whenever the catch in Matagorda Bay increased or decreased from what it was the previous year, the catch in SS-19 decreased or increased respectively from what it was the previous year. Increases and decreases in efforts do not explain the relationship (Appendix C). One possible explanation is that the fishing effort on brown shrimp in Matagorda Bay has reached the level where a large portion of the new-year class is being caught in the bay and thus pre-empted from incorporation into the offshore stock of SS-19. Another possible explanation is that there was some larger, perhaps environmental or economic, controlling factor. There is some evidence for this, since offshore catches in subareas 18, 19 and 20 all changed in the same direction from year to year from 1979 thru 1982.

White shrimp usually inhabit shallower waters in the Gulf of Mexico than do brown shrimp, and as such have a shorter migratory path from the bays to their offshore maturing and spawning grounds. Some white shrimp have been found to move back into the bay in the spring after spending the winter offshore (Gaidry 1974).

Table 12. Estimated dockside values for the commercial brown and white shrimp harvests in statistical subarea 19 and in the Matagorda Bay System (U.S. Department of Commerce, 1961-1984). The values of the bait shrimp and sport shrimp fisheries are not included. Values are in millions of dollars (not adjusted for inflation).

	Subarea 19		Matagorda Bay		
Year	Brown	White	Brown	White	Totals
1980	29.1	4.9	3.5	4.6	42.1
1981	46.6	7.4	2.3	3.7	60.0
1982	36.9	10.4	3.6	5.9	56.8
1983	26.1	10.0	9.4	7.8	53.3
1984	33.4	11.2	5.0	7.3	56.9
Means	34.4	8.8	4.8	5.9	53.8

Table 13. Monthly shrimp catch statistics for statistical subarea 19, 1960-82. Values are in thousands of pounds of tails.

A. Brown Shrimp

	Mean	SD	Min.	Max.
January	158	88	29	299
February	126	90	33	364
March	95	66	8	226
April	100	64	20	264
May	180	101	23	358
June	434	527	2*	2706
July	2392	1313	716	5451
August	2848	1338	1033	5230
September	1906	982	410	3966
October	1215	556	277	2449
November	782	416	184	1599
December	501	313	118	1181

B. White Shrimp

	Mean	SD	Min.	Max.
January	61	60	1	219
February	54	43	0	159
March	116	75	10	348
April	92	50	14	220
May	159	118	36	418
June	72	62	5	261
July	129	71	42	335
August	69	40	15	136
September	237	216	45	723
October	509	256	111	1128
November	481	168	199	868
December	180	109	20	510

*This was during the Texas Closure of 1981.

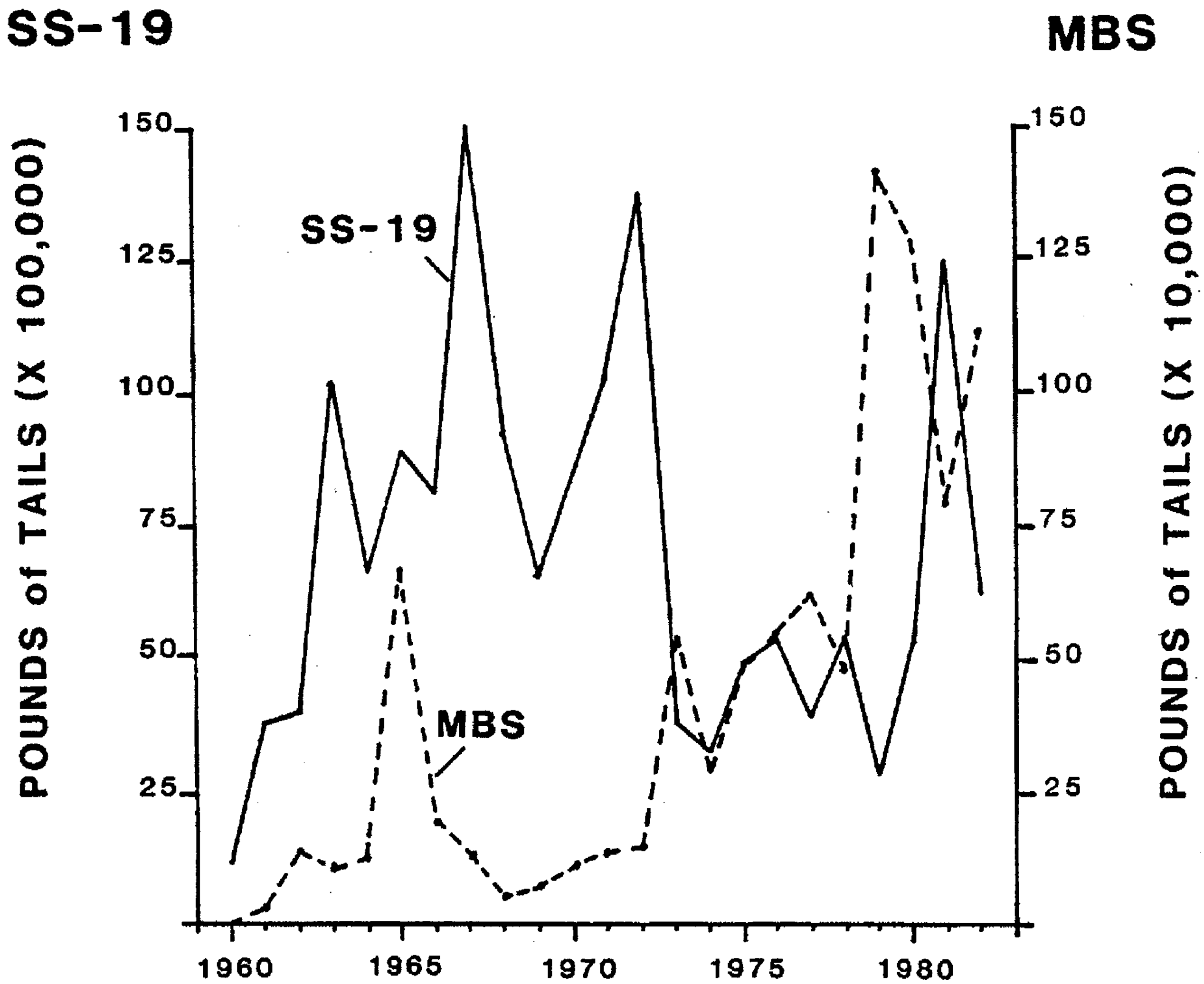


Figure 16. Seasonal and annual catches of brown shrimp in statistical subarea 19 (SS-19) and the Matagorda Bay System (MBS). The seasonal catches in SS-19 include June through September catches. The annual catches in the MBS include January through December catches.

Values are for shrimp tails.

With this, and the well established bay and offshore white shrimp fisheries, a direct relationship was found between the Matagorda Bay stocks and SS-19 stocks of white shrimp. New-year-class white shrimp enter the bay fishery usually in August and last thru December, after which most of the remaining survivors have migrated offshore. The new-year-class enters the offshore fishery usually in September (Table 13), which might be termed the start of the fishery-year. Thus the offshore fishery-year would run from September thru next August (Fig. 17). A correlation analysis using Spearman's rank correlation test yielded a significant correlation between the bay and offshore catches during the period for 1960-1976 when fishing effort was fairly uniform in Matagorda Bay, $r_s = 0.50$ ($p < 0.05$). This relationship supports the bay-to-offshore link in stocks.

Correlations of Bay Shrimp Catches with River Flows.

Correlation analysis was performed to determine the most promising ways to organize the data for regression analysis. Annual and monthly commercial catches were tested with annual, seasonal and monthly river flow volumes (acre-feet) from the Lavaca-Navidad River and the Colorado River separately, first to see if annual inflow — the most general case of inflows — could be used to explain annual shrimp harvests, and then to see if subsequent refinements in the time span for the inflows — to season and then to month —would be more useful in explaining annual harvests. Colorado River flows were adjusted downward to include only that portion which we estimated entered the bay. For white shrimp, annual river flows were the sums of the 12 monthly flows from the previous December thru the current November (Table 14). For brown shrimp, annual river flows were the sums of the 12 monthly flows from the previous August thru the current July. Seasonal river flows also differed by species. For white shrimp they were: winter = previous December-March, spring = April-June, summer = July and August, and fall = September-November. For brown shrimp they were: winter = January-April, spring = May-June, summer = previous July and previous August, previous September was by itself, and fall = previous October-previous December.

Annual catches of both species showed poor correlations with annual inflows and with annual inflows of the previous year. The correlation between annual white shrimp catches and annual Lavaca-Navidad River flows for 1961-1976 was better than that with annual adjusted Colorado River

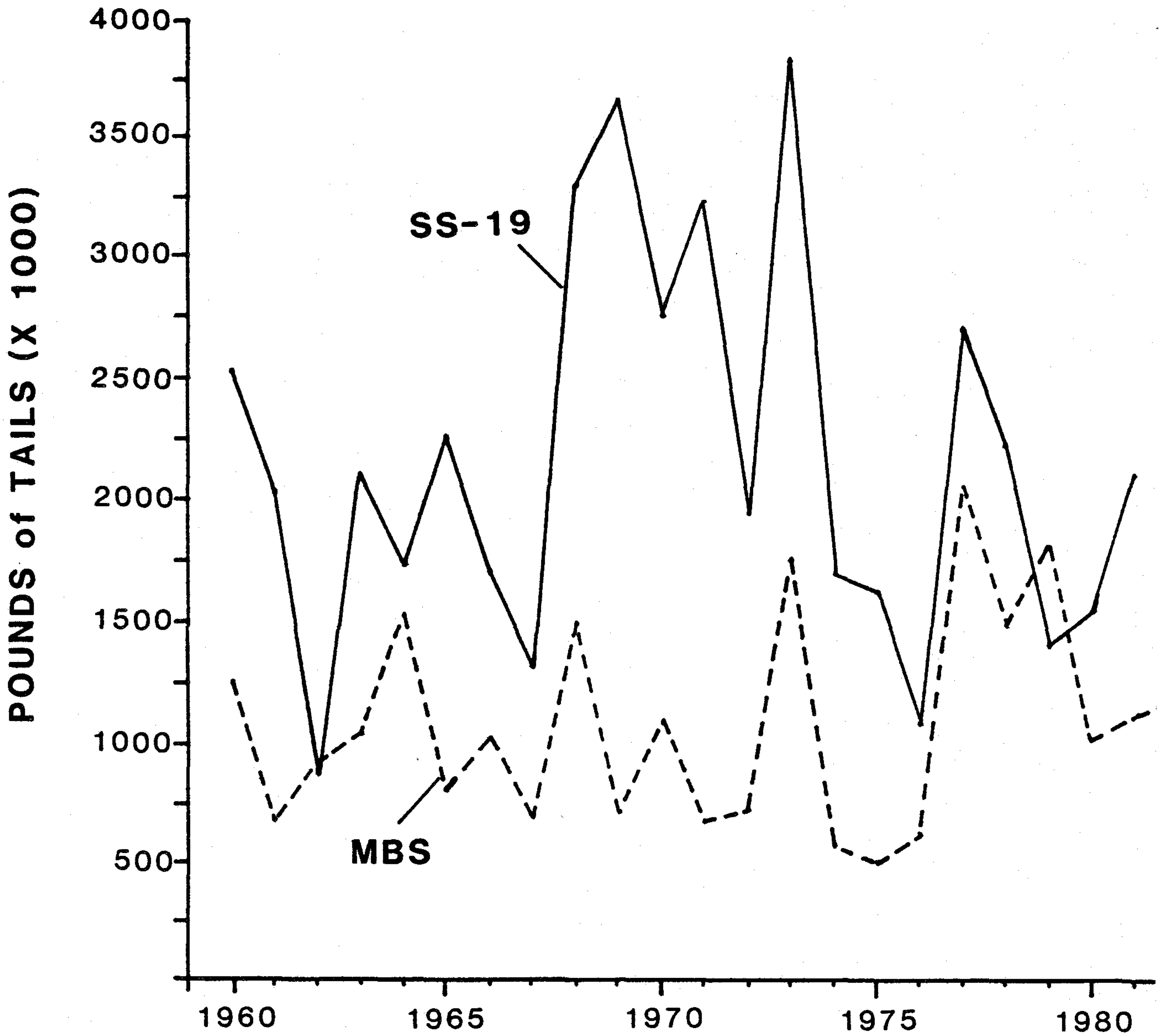


Figure 17. Annual and seasonal catches of white shrimp in statistical subarea 19 (SS-19) and in the Matagorda Bay System (MBS). The annual catch in SS-19 is for a fishery-year, i.e. September through August. The seasonal catch in the MBS includes August through December catches.
Values are for shrimp tails.

Table 14. Annual (=12 months) river flow volumes used in correlation t sts with annual commercial catches of brown and white shrimp in the Matagorda Bay System. Annual flows for brown shrimp include previous August thru current July, and for white shrimp include previous December thru current November. River flows are in thousands of acre-feet.

Y ar	Lavaca R. + Navidad R.		Adjusted Colorado R.	
	Brown	White	Brown	White
1961	1531	1405	2584	2797
1962	740	234	1453	696
1963	155	134	471	401
1964	141	185	229	289
1965	608	721	1133	1261
1966	647	514	1185	1041
1967	86	514	231	389
1968	1440	1039	2434	2370
1969	856	843	1262	1332
1970	535	680	1809	1875
1971	246	409	520	599
1972	1169	851	1239	944
1973	1626	2010	1269	1840
1974	920	1017	1848	1889
1975	1136	679	3231	2338
1976	423	517	1077	1262
1977	994	883	2091	1844
1978	238	639	469	571
1979	1564	1320	1618	1668
1980*	458	261	780	612
1981	653	1433	1440	1982
1982	1425	833	1477	978
Means:	800	778	1340	1317
sd:	502	463	767	729

*Palmetto Bend Reservoir began operations in May 1980.

flows, but neither was statistically significant at the $p<0.10$ level (Appendix D). Correlations between brown shrimp annual catches for 1961-78 and either river's flows were even weaker. The correlation between one-year-lagged annual flows and current year's annual white shrimp catches were negative for both rivers, indicating inverse relationships. Only the correlation using 1962-76 white shrimp catches versus the lagged and adjusted Colorado River flows was significant ($r= -0.49$, $p<0.10$). This negative correlation signifies that if there was a large inflow from the Colorado during the previous year, there would tend to be a lower catch during the current year. However, the relationship is fairly weak, only explaining about 24% of the variability in annual catch. The correlation between brown shrimp annual catches and one-year-lagged annual flows were positive, but not significant for either of the rivers.

Seasonal flows also correlated poorly with annual catches of brown and white shrimp. There were no significant correlations between seasonal river flows of either river and annual catches of brown shrimp for the period 1961-1978. For annual white shrimp catches (1961-76) only spring (April-June) Lavaca-Navidad River flows showed a significant correlation ($r = 0.58$, $p<0.05$).

Analyses using monthly river flows versus annual white shrimp catches yielded several significant correlations. Positive correlations were found for white shrimp annual catches and March ($r = 0.56$, $p<0.05$), April ($r = 0.49$, $p<0.5$) and June ($r = 0.71$, $p<0.01$) monthly Lavaca-Navidad River flows. October monthly flows provided the only significant correlation for the Colorado River and annual white shrimp catches ($r = 0.44$, $p<0.10$). No significant correlations were found between monthly river flow volumes and annual brown shrimp catches. The results from these correlation analyses suggest the use of monthly increments of inflow for establishing inflow-to-harvest relationships.

Regressions of Bay Shrimp Catches with River Flows

Regression tests were performed first for white shrimp residual catches versus monthly flows of the rivers individually and then combined. Both linear and quadratic regressions were used for each case. The same tests were also made using brown shrimp catches.

Statistically significant ($p<0.10$) regression equations were particularly important means of selecting our recommended river flows for maintaining the average shrimp harvest and for enhancing the harvests. Recommended flows for months without statistically significant regressions were made either by using trends shown in regressions where at least 10% of the variation in the catch was explained by the river flow (i.e., multiple $r^2>0.10$) or by accepting the mean monthly flows as general indicators of flows which would support shrimp populations and maintain an acceptable habitat.

White shrimp. Significant regressions between residual white shrimp harvests and monthly flows of the Lavaca-Navidad River were found for March, April, June, September and October (Table 15). Significant regressions between residual white shrimp harvests and adjusted monthly flows of the Colorado River were found only for April and October (Table 16). Similar tests but for the combined river flows yielded significant regressions for March, April, June and October (Table 17). In the months with significant regressions, variations in river flows were able to explain 20 to 63% of the residual harvests depending on the month. The monthly mean flows were recommended for maintaining the mean harvest level of white shrimp for the months without significant regressions (Table 18). Monthly flows for enhancing the white shrimp harvest used thresholding for September and November flows of the Lavaca-Navidad River, and for February, March, July and September adjusted flows of the Colorado River.

Texas Parks and Wildlife Department white shrimp sampling data were not useful for analyses with river inflows.

Table 15. Regression equations for monthly Lavaca-Navidad River flows (x) as they explain changes in residual white shrimp commercial catches (y) in the Matagorda Bay System, 1961-76.

		r^2	Significance p<
Previous December	$Y = 1136 - 4.11x$	.12	n.s.[a]
	$Y = 1171 - 7.23x + 0.03x^2$	.12	n.s.
January	$Y = 966 + 0.75x$	.02	n.s.
	$Y = 1098 - 6.28x + 0.033x^2$	.12	n.s.
February	$Y = 1058 - 1.06x$	.03	n.s.
	$Y = 991 + 2.25x - 0.016x^2$	.06	n.s.
March	$Y = 847 + 4.35x$	.32	.05
	$Y = 908 - 0.10x + 0.028x^2$	.35	.10
April	$Y = 880 + 1.93x$	.25	.05
	$Y = 1020 - 3.41x + 0.015x^2$	.44	.05
May	$Y = 1040 - 0.37x$	.02	n.s.
	$Y = 997 + 0.67x - 0.003x^2$	.04	n.s.
June	$Y = 799 + 1.22x$	.47	.01
	$Y = 848 + 0.33x + 0.001x^2$	.49	.05
July	$Y = 950 - 0.33x$	.00	n.s.
	$Y = 759 + 13.36x - 0.145x^2$	.09	n.s.
August	$Y = 965 - 1.87x$	.01	n.s.
	$Y = 907 + 3.55x - 0.067x^2$	.02	n.s.
September	$Y = 741 - 0.55x$	.05	n.s.
	$Y = 577 + 5.23x - 0.016x^2$	.34	.10
October	$Y = 292 + 2.12x$	.44	.01
	$Y = 365 - 1.75x + 0.018x^2$	.63	.01
November	$Y = 125 + 0.20x$	.01	n.s.
	$Y = 72 + 6.05x - 0.042x^2$	.19	n.s.

[a]not significant, $p > 0.10$

Table 16. Regression equations for monthly adjusted Colorado River flows (x) as they explain changes in residual white shrimp commercial catches (y) in the Matagorda Bay System, 1961-76.

		r^2	Significance $p<$
Previous December	$Y = 1178 - 1.61x$	.12	n.s.[a]
	$Y = 1225 - 2.97x + 0.006x^2$	.13	n.s.
January	$Y = 952 + 0.47x$	.01	n.s.
	$Y = 1098 - 2.57x + 0.001x^2$	.06	n.s.
February	$Y = 1004 - 0.003x$	.00	n.s.
	$Y = 729 + 6.40x - 0.021x^2$	.18	n.s.
March	$Y = 869 + 1.22x$	.10	n.s.
	$Y = 765 + 4.15x - 0.010x^2$	.13	n.s.
April	$Y = 858 + 1.32x$	.11	n.s.
	$Y = 980 - 0.48x + 0.001x^2$	.39	.05
May	$Y = 1020 - 0.15x$	.00	n.s.
	$Y = 980 + 0.48x -0.001x^2$	.01	n.s.
June	$Y = 854 + 0.70x$	.08	n.s.
	$Y = 895 + 0.21x + 0.002x^2$	.08	n.s.
July	$Y = 1014 - 0.86x$	.05	n.s.
	$Y = 909 + 2.68x - 0.013x^2$	.10	n.s.
August	$Y = 1000 - 1.62x$	.02	n.s.
	$Y = 956 + 0.43x - 0.015x^2$	.03	n.s.
September	$Y = 727 - 0.44x$	.03	n.s.
	$Y = 582 + 2.82x - 0.008x^2$	.15	n.s.
October	$Y = 292 + 1.04x$	.22	.10
	$Y = 534 - 4.02x + 0.014x^2$	.59	.01
November	$Y = 135 + 0.02x$	.00	n.s.
	$Y = 84 + 0.83x - 0.002x^2$	.09	n.s.

[a]not significant, $p > 0.10$

Table 17. Regression equations for monthly combined Lavaca-Navidad and adjusted Colorado River flows (x) as they explain changes in residual white shrimp commercial catches (y) in the Matagorda Bay System, 1961-76.

		r^2	Significance p<
Previous December	$Y = 1181 - 1.27x$	.13	n.s.[a]
	$Y = 1231 - 2.35x + 0.003x^2$	.14	n.s.
January	$Y = 954 + 0.30x$	.02	n.s.
	$Y = 1122 - 2.00x + 0.004x^2$	.09	n.s.
February	$Y = 1060 - 0.32x$	.01	n.s.
	$Y = 852 + 2.48x - 0.006x^2$	.13	n.s.
March	$Y = 816 + 1.28x$	.20	.10
	$Y = 907 - 0.65x + 0.005x^2$	.22	n.s.
April	$Y = 813 + 1.10x$	.23	.10
	$Y = 990 - 1.49x + 0.005x^2$	.42	.05
May	$Y = 1036 - 0.14x$	.01	n.s.
	$Y = 964 + 0.72x - 0.001x^2$	.04	n.s.
June	$Y = 773 + 0.66x$	.32	.025
	$Y = 968 - 1.13x + 0.002x^2$	.54	.01
July	$Y = 1006 - 0.57x$	.03	n.s.
	$Y = 858 + 2.68x - 0.009x^2$	.11	n.s.
August	$Y = 1017 - 1.43x$	.03	n.s.
	$Y = 1000 - 0.78x - 0.004x^2$	.03	n.s.
September	$Y = 738 - 0.27x$	.04	n.s.
	$Y = 597 + 1.62x - 0.003x^2$	.21	n.s.
October	$Y = 277 + 0.80x$	.33	.025
	$Y = 439 - 1.44x + 0.004x^2$	.62	.005
November	$Y = 131 + 0.01x$	.00	n.s.
	$Y = 82 + 0.70x - 0.001x^2$	.11	n.s.

[a]not significant, $p > 0.10$

Table 18. Monthly flows (thousands of acre-feet) calculat d to support mean and enhanced white shrimp commercial harvests based on the 1961-76 period of record. Superscripts on the flows indicate which step in Table 1 was used in the selection of each flow value. Flows were derived from equations in Tables 15-17.

A. Flows for mean harvest level.

	Lavaca-Navidad River	Adjusted Colorado River	Combined
January	55[7]	118[7]	173[7]
F bruary	52[7]	123[7]	175[7]
March	50[3]	109[7]	145[4]
April	62[2]	107[2]	169[2]
May	129[7]	176[7]	306[7]
June	156[3]	150[7]	282[2]
July	30[7]	85[7]	115[7]
August	20[7]	42[7]	62[7]
September	103[7]	98[7]	202[7]
October	78[3]	97[2]	144[2]
November	35[7]	120[7]	155[7]
December	31[7]	106[7]	138[7]

B. Flows for an enhanced harvest level.

	Lavaca-Navidad River	Adjusted Colorado River	Combined
January	55[7]	118[7]	173[7]
February	52[7]	150[6]	220[6]
March	172[1]	195[6]	384[4]
April	382[1]	265[5]	607[1]
May	129[7]	176[7]	306[7]
June	849[1]	150[7]	1167[1]
July	30[7]	105[6]	153[6]
August	20[7]	42[7]	62[7]
September	160[6]	180[6]	324[6]
October	237[1]	144[2]	593[1]
November	60[6]	120[7]	310[6]
December	31[7]	106[7]	138[7]

Brown Shrimp. Regression analyses for brown shrimp were similar to those for white shrimp, except only January thru August, and the previous December, were examined (Tables 19, 20 and 21). The later months were dropped because there is little brown shrimp catch in the bay after August, and there is very little expectation of carryover to the next year's catch. The only significant regression found was for adjusted Colorado River flows in June (Table 20). Consequently, the calculated monthly flow volumes for maintaining the mean catch levels were based on mean monthly flow volumes (Table 22). Thresholding was useful in some months for determining the calculated flows for achieving the maximum brown shrimp commercial harvest.

For brown shrimp, the Texas Parks and Wildlife Department sampling data were adequate for use in Tres Palacios Bay, the east arm of Matagorda Bay and the main body of Matagorda Bay. The Tres Palacios Bay trawl sample regression analyses revealed only two significant relationships (Appendix D) and the barseine sample analyses had only one significant equation. For both the trawl and barseine sampling techniques, regressions against May flows yielded significant quadratic equations. Using catches from trawl sampling, the equation calls for the maximum historical flow to achieve maximum production, but using the catches from barseine sampling, the equation requires the minimum historical flow for maximum production. These regressions show opposite inflow requirements and as such require a management decision. Barseine samples are taken near or in the marsh nursery areas, whereas the trawl samples are from the deeper open water portions of the bay. By May many brown shrimp are large enough to begin leaving the marshes. A large inflow could accelerate this process by flushing the shrimp from the marshes into the bay, thus increasing the likelihood of larger catches in trawl samples. Without high flows the shrimp would leave the marshes more slowly, thereby enhancing the barseine catches.

The only other significant relationship is the July quadratic equation for the trawl samples. It indicates that higher than normal flows could enhance productivity. July is a period of possible salinity/temperature

Table 19. Regression equations for monthly Lavaca-Navidad River flows (x) as they explain changes in residual brown shrimp commercial catches (y) in the Matagorda Bay System, 1961-78.

		r^2	Significance p<
Previous December	$Y = 235 + 0.76x$	.08	n.s.[a]
	$Y = 308 - 2.47x + 0.009$	.20	n.s.
January	$Y = 302 - 0.58x$	.03	n.s.
	$Y = 214 + 3.63x - 0.020x^2$	.14	n.s.
February	$Y = 279 - 0.15x$	.00	n.s.
	$Y = 172 + 4.92x - 0.025x^2$	.19	n.s.
March	$Y = 268 + 0.08x$	.00	n.s.
	$Y = 377 - 7.99x + 0.051x^2$	.20	n.s.
April	$Y = 214 + 0.88x$	.14	n.s.
	$Y = 200 + 1.37x - 0.001x^2$	.15	n.s.
May	$Y = 260 + 0.08x$	.00	n.s.
	$Y = 225 + 1.03x - 0.003x^2$	.04	n.s.
June	$Y = 173 + 1.23x$	.07	n.s.
	$Y = 209 - 0.43x + 8.26x^2$	.11	n.s.
July	$Y = 73 - 0.45x$	.02	n.s.
	$Y = 68 - 13.36x - 0.145x^2$	.02	n.s.
August	$Y = 31 - 0.47x$	.01	n.s.
	$Y = 35 - 0.88x + 0.005x^2$	.02	n.s.

[a]not significant, $p>0.10$

Table 20. Regression equations for monthly adjusted Colorado Riv r flows (x) as they explain changes in residual brown shrimp commercial catches (y) in the Matagorda Bay System, 1961-78.

		r^2	Significance p<
Previous December	$Y = 275 - 0.03x$	.00	n.s.[a]
	$Y = 405 - 3.61x + 0.014x^2$	.13	n.s.
January	$Y = 311 - 0.36x$	.02	n.s.
	$Y = 145 + 3.01x - 0.011x^2$	.18	n.s.
February	$Y = 237 + 0.28x$	.01	n.s.
	$Y = 162 + 2.00x - 0.006x^2$	.05	n.s.
March	$Y = 324 - 0.52x$	.05	n.s.
	$Y = 195 + 3.11x - 0.013x^2$	.16	n.s.
April	$Y = 211 + 0.47x$	.08	n.s.
	$Y = 260 - 0.45x + 0.002x^2$	.13	n.s.
May	$Y = 201 + 0.39x$	.07	n.s.
	$Y = 181 + 0.74x - 7.717x^2$	.08	n.s.
June	$Y = 163 + 0.26x$	.04	n.s.
	$Y = 37 + 2.91x - 0.006x^2$	.36	.10
July	$Y = 66 - 0.08x$	.01	n.s.
	$Y = 40 + 0.76x - 0.003x^2$	.07	n.s.
August	$Y = 40 - 0.43x$	.04	n.s.
	$Y = 64 - 1.63x + 0.009x^2$	.08	n.s.

[a]not significant, p>0.10

Table 21. Regression equations for monthly combined Lavaca-Navidad and adjusted Colorado River flows (x) as they explain changes in residual brown shrimp commercial catches (y) in the Matagorda Bay System, 1961-78.

		r^2	Significance p<
Previous December	$Y = 239 + 0.20x$	.02	n.s.[a]
	$Y = 353 - 1.35x + 0.003x^2$	.20	n.s.
January	$Y = 310 - 0.23x$	.03	n.s.
	$Y = 159 + 1.76x - 0.004x^2$	.17	n.s.
February	$Y = 255 - 0.09x$	.00	n.s.
	$Y = 151 + 1.57x - 0.003x^2$	.09	n.s.
March	$Y = 308 - 0.27x$	.02	n.s.
	$Y = 293 + 0.55x - 10.001x^2$	.03	n.s.
April	$Y = 192 + 0.41x$	.14	n.s.
	$Y = 273 - 0.66x + 0.002x^2$	.23	n.s.
May	$Y = 225 + 0.16x$	.03	n.s.
	$Y = 178 + 0.72x -0.001x^2$	.07	n.s.
June	$Y = 161 + 0.15x$	.07	n.s.
	$Y = 150 + 0.25x + 0.00009x^2$	.07	n.s.
July	$Y = 68 - 0.07x$	.01	n.s.
	$Y = 44 + 0.45x - 0.001x^2$	.05	n.s.
August	$Y = 45 - 1.37x$	.01	n.s.
	$Y = 77 - 1.64x + 0.008x^2$	.05	n.s.

[a]not significant, $p > 0.10$

Table 22. Monthly flows (thousands of acre-feet) calculated to support mean and enhanced brown shrimp commercial harvests based on the 1961-78 period of record. Superscripts indicate the step in Table 1 used in the selection of each flow value. Flows values were derived from equations in Tables 19-21.

A. Flows for mean harvest level.

	Lavaca-Navidad River	Adjusted Colorado River	Combined
January	54[7]	114[7]	168[7]
February	56[7]	124[7]	180[7]
March	33[7]	103[7]	136[7]
April	66[7]	127[7]	192[7]
May	117[7]	174[7]	291[7]
June	123[7]	145[7]	268[7]
July	28[7]	81[7]	109[7]
August	18[7]	41[7]	59[7]
September	—	—	—
October	—	—	—
November	—	—	—
December	48[7]	112[7]	160[7]

B. Flows for an enhanced harvest level.

	Lavaca-Navidad River	Adjusted Colorado River	Combined
January	90[6]	142[6]	240[6]
February	99[6]	124[7]	180[7]
March	33[7]	118[6]	136[7]
April	66[7]	127[7]	192[7]
May	117[7]	174[7]	291[7]
June	123[7]	230[6]	268[7]
July	28[7]	81[7]	109[7]
August	18[7]	41[7]	59[7]
September	—	—	—
October	—	—	—
November	—	—	—
December	48[7]	112[7]	160[7]

stress (se Appendix F) which could be alleviated by increased inflows. Increased inflows could also act as a flushing mechanism to push shrimp out of shallow marshes into deeper bay areas.

Regression analyses of the east arm of Matagorda Bay trawl catches with adjusted Colorado River flows yielded no significant regressions (Appendix D). The analyses of both Lavaca-Navidad and adjusted Colorado River flows with trawl catches from the main body of Matagorda Bay also resulted in no significant regressions. Overall, the Texas Parks and Wildlife Department sampling data were of limited help in determining freshwater inflow needs.

Spring and early fall flows appear to exert the most influence on shrimp harvest levels. An examination of Tables 15-17, and 19-21 shows that significant correlations and regressions occur for flows of five months: March, April, June, September and October (Critical Flow Months). Spring Lavaca-Navidad River flows versus white shrimp harvest (Appendix D) also show significance. Although we found no significant relationships between shrimp catches and river flows for other months, we feel that the amount of freshwater inflow is still important. Other factors affecting shrimp production could be obscuring the relationships. For the spring period, May is conspicuous in its lack of significant correlations. The data show that both April and June flows are very important, but May flows consistently show a very poor relationship to catch. Small floods on both the Lavaca-Navidad and Colorado Rivers were more frequent in May than in either April or June (Tables 7 and 8) and could be an explanation for this.

Consolidation to Unified Flow Recommendations

To establish unified flow recommendations for the Lavaca-Navidad River and for the Colorado River, the flows calculated for white and brown shrimp were combined by choosing the flow that explained the greatest amount of variability in the shrimp harvest, i.e., the flow with the lowest superscript (Tables 18 and 22). If the superscripts were the same for the two species, an average of the two flows was used. The mean flows used wer for the period 1960-82 (Table 3), except on the Navidad River where no flows were used for the period after Palmetto Dam was closed.

The flows derived using the combined flow analyses are very similar to those derived from the individual river analyses. To facilitate flow apportionment between the rivers, we ignored the results of the Lavaca-Navidad-Colorado combined analyses. For maintaining the mean shrimp harvest, the largest monthly differences between the individual and combined analyses is -39,000 ac-ft in June. The total annual difference is -53,000 ac-ft. Larger monthly differences exist for maximizing the shrimp harvest: +34,000 ac-ft (July), -40,000 ac-ft (April), +56,000 ac-ft (March), and +132,000 ac-ft (November). The large difference in November is an artifact of our methods. The r^2 for the combined November quadratic equation is 0.11 (Table 17), which allows the use of thresholding (#6 in Table 1). The r^2 for residual white shrimp harvest vs adjusted Colorado River flows is .09 (Table 16) which forces the mean flow to be selected. If a threshold flow value is used for Colorado River, the difference is reduced to +15,000 ac-ft.

For maintaining the mean fisheries level the historical mean flows for most months were used for both rivers. For the Lavaca-Navidad River these included the means for January, February, May, July, August, September, November and December (Table 23). The mean flows of these months plus those for March and June were used for the Colorado River. Significant regressions ($p<0.10$) for March, June and October flows of the Lavaca-Navidad River and for October flows of the Colorado River show that flows above the monthly means would be needed, while April flows below the mean would be appropriate for both rivers. When the monthly recommended flows were summed, they totaled 102% of the mean annual flow for the 23-year period—1960 thru 1982.

The recommended flows for maximum shrimp production (Table 23) are at or near the historical highs for several months (Table 3). For the Lavaca-Navidad River these are March, April, June and October, and for the Colorado River they are April and October. These include four of the five Critical Flow Months. These unusually high monthly flow recommendations were derived from significant linear and quadratic regression equations relating white shrimp residual harvests to March, April, June and October river flows and relating brown shrimp residual harvests to June river flows. The high flows during spring months would appear to set up the environment - the marshes and bays - with nutrients, detritus and food organisms for the incoming new-year-class postlarval and juvenile shrimp. The high October flows would appear to act more as a flushing mechanism to

Table 23. Monthly gaged flow recommendations (thousands of ac-ft).

A. Maintaining the mean shrimp harvest in Matagorda Bay.

	Lavaca-Navidad River	Total Colorado River	Adjusted Colorado River[a]
January	63	148	117
February	59	160	122
March	50	130	103
April	62	143	107
May	127	264	182
June	156	248	171
July	30	110	89
August	22	50	43
September	116	130	100
October	78	119	97
November	44	156	118
December	43	124	98
	850	1,782	1,347

Total = 2.632 mil ac-ft = 102 percent of mean flow, 1960-82 (Table 2).

B. Maximizing shrimp harvest in Matagorda Bay.

	Lavaca-Navidad River	Total Colorado River	Adjusted Colorado River[a]
January	90	179	142
February	99	196	150
March	172	197	156
April	382	355	265
May	127	264	182
June	849	334	230
July	30	130	105
August	22	50	43
September	160	234	180
October	237	438	356
November	60	156	118
December	43	124	98
	b	b	b

[a]Adjusted Colorado River flows are appropriate only if total diversion of Colorado River flows into Matagorda Bay is accomplished.

[b]We do not recommend all these high flows in the same year. These are presented to show the potential of increased flows in an individual month.

push the new-year-class subadult shrimp out of the nursery areas and into the main secondary bays and into Matagorda Bay itself.

None of these recommended flows is above the respective month's historical maximum. Data have not been found that enable us to predict the effect on shrimp harvests if two or more months of our recommended high flows were to occur sequentially or even in the same year. It is not necessary, nor would we recommend, that all of these elevated flows occur during a single year to achieve a harvest level above the mean or at a maximum. In fact, it is unlikely that this could occur no matter how upstream reservoirs are operated. These flows are presented to show the potential harvest effects of increased flows in an individual month.

Flooding Needs

Contained within the total monthly flow requirements are allowances for flood events. For the Lavaca-Navidad River we identified flows of 36,000 cfs for flushing upper portions of the delta marsh, and of 33,192 cfs for sediment delivery. Before Palmetto Bend Dam was closed, the Lavaca delta was growing (McGowen et al. 1976a). This indicates that the historic frequency and timing of floods was adequate for the continued viability of the delta nursery habitat. Therefore, our recommendation (Table 24) is to maintain the historic frequency and timing of floods as presented in Tables 5 and 7. Since 49% of the Lavaca delta sediment supply is stopped by Palmetto Bend Dam (U.S. Bureau of Reclamation 1974), the recommended floods will probably not be adequate to maintain the size and health of the delta indefinitely, unless Navidad River sediment-carrying flows are diverted around Lake Texana.

For the Colorado River, we have identified one large flood per year that should accomplish the flooding objectives stated earlier. Its minimum average daily flow should attain 33,000 cfs (Table 24), and it should occur in April, May, June or September. This would be in keeping with the historical record of flooding on the Colorado River.

Smaller floods that would flush the post-diversion delta marshes and also provide sediment, should reach a minimum average daily flow of 10,000 cfs. There should be four per year, and they should occur in the same

Table 24. Flooding recommendations.

Minimum Average Daily Flow (cfs)	Frequency	Timing[1]
	Lavaca-Navidad River	
9,000	2/yr	Mar-June
9,000	1/yr	Sept-Oct
9,000	1/yr	Nov-Feb
35,000	1/2-3 yrs	Apr-June, Sept or Oct
	Colorado River	
10,000	2/yr	Mar-June
10,000	1/yr	Sept-Oct
10,000	1/yr	Nov-Feb
33,000	1/yr	Apr-June or Sept

[1]Emphasis was placed on recommending floods during the Critical Flow Months - see text.

month-groups as given above for the small floods on the Lavaca-Navidad River. These historical patterns were again recommended, because these were the basis for post-diversion delta growth predictions (Coastal Environments Inc. 1980). After full diversion of the Colorado River into Matagorda Bay, these recommended floods should provide adequate sediment for delta growth providing no new reservoirs reduce or cut-off the sediment supply presently being carried by the river.

The three highest September flows in Figure 7 are associated with large floods on the Lavaca-Navidad River (Table 5). We have already noted both the apparent positive influence of fall floods on the next year's catch and the negative influence of large September flows on the remainder of the current year's catch (Figure 10). These conflicting effects of high September flows indicate that it probably is not possible to maintain a maximum harvest in the bay every year.

COMPARISON WITH TEXAS DEPARTMENT OF WATER RESOURCES' RECOMMENDATIONS

The Texas Department of Water Resources (1980) made a d tailed study of the freshwater needs of Matagorda Bay, and included three levels of flow recommendations. These were:

Alternative I - Subsistence
Objective: Minimize annual combined inflow while meeting salinity viability limits and marsh inundation needs;

Alternative II - Maintenance of Fisheries Harvest
Objective: Minimize annual combined inflow while providing freshwater inflows sufficient to provide predicted annual commercial harvest in the estuary of red drum, seatrout, shrimp, and all shellfish combined at levels no less than their mean historical values over the period 1962 through 1976, satisfying marsh inundation needs and meeting viability limits for salinity;

Alternative III - Shellfish Harvest Enhancement
Objective: Maximize the total annual commercial harvest of shellfish (represented by the sum of the harvests of all shrimp, blue crab and oysters) in the estuary while meeting viability limits for salinity, satisfying marsh inundation needs and utilizing an annual combined inflow no greater than the average annual historical combined inflow for the period 1941 through 1976.

In 1984 TDWR produced another level of flow:

Alternative IV - Biotic Species Viability
Objective: Meet monthly salinity viability limits of the estuarine-dependent organisms characteristic of each estuary.

This was defined as a short-term freshwater inflow needs category (TDWR 1984a), but it appears to have gained full stature, equivalent to the previous three alternatives. The 1984 report also slightly changed the flow recommendations for the Lavaca-Navidad River for April, May and June for Alternatives II and III. No explanation was given for the changes.

TDWR's goal for Alternative II was to find the minimal flow that would maintain the average commercial finfish and shellfish harvest, including red drum, spotted seatrout, shrimp, blue crabs and oysters. Our study concentrated on shrimp and their requirements as representative of estuarine organisms and as very important to characterizing an estuary. A comparison of Alternative II flows and our flows to maintain the historical mean harvest of shrimp shows that the total annual recommended flows differ by only 222,000 ac-ft (Table 25). Both sets, 1980 and 1984, of TDWR's recommendations are similar for this alternative. In order to minimize flows, TDWR concentrated 75% (458,000 ac-ft) of the Lavaca-Navidad River annual flow in the months of April, May, June, September and October. This also allowed them to accommodate their flooding requirements in those months. Except for the exchange of May for March, these are the months we identified as Critical Flow Months. So we agree with their approach that if flow is to be minimized, whatever flows remain should be concentrated in the Critical Flow Months and May to maximize the benefit to the commercial shrimp fishery. Of our recommended flow, 63% (539,000 ac-ft) was in those same five months, but because our total flow was larger the flow in those five months was also larger.

Our total flow recommendation for the Lavaca-Navidad River is larger, in part, because the average flows used by TDWR are different from ours. Their period of record is 1941-76, and has an average annual discharge of 614,000 ac-ft. The 1960-82 period we use has an average annual LavacaNavidad River discharge of 795,000 ac-ft (Table 2). Our period corresponds to the span of reliable shrimp harvest records, whereas TDWR's flow period includes many years not used in their harvest data analysis. For the Colorado River our average

Tabl 25. Comparison of gaged flows (thousands of ac-ft) recommended by this study and TDWR studies (1980 and 1984a).

	Lavaca-Navidad River			Colorado River	
	Mean-This study	TDWR Alt. II		Mean-This study	TDWR Alt. II
		1980	1984		
January	63	22	22	148	88
February	59	27	27	160	99
March	50	17	17	130	76
April	62	72	68	143	133
May	127	105	116	264	188
June	156	106	98	248	160
July	30	18	18	110	53
August	22	35	35	50	49
September	116	97	97	130	148
October	78	78	78	119	92
November	44	18	18	156	388
December	43	18	18	124	322
Totals:	850	612[a]	611[a]	1,782	1,798[a]

Totals:

This study	2.632 million ac-ft
TDWR 1980	2.410 million ac-ft
TDWR 1984	2.409 million ac-ft

[a]Rounding of monthly values make this total slightly different than the sum of the column.

annual discharge is 1,798,000 and TDWR's is 1,920,000 ac-ft. The total average annual gaged discharge into the estuary is very similar for the two periods, 2,588,000 for this study versus 2,534,000 ac-ft for TDWR.

Our flow recommendations for the Colorado River are very similar to TDWR's in terms of the annual total for Alternative II (Table 25), but the monthly distribution of flows is very different. Our recommendation retains a pattern similar to that of the Lavaca-Navidad River, with 51% of the flow in April, May, June, September and October. TDWR has only 40% of the flow in those months, but has 39% of the annual flow in November and December compared with our 16%. Their Estuarine Linear Programming Model calculated that these flows are necessary to achieve average harvests of oysters and blue crabs, species that we did not consider. TDWR did not present any details of their Estuarine Linear Programming Model, so we were not able to judge its accuracy. However, for the period 1960-82 TDWR's recommended November flow was met or exceeded only three times, the December flow only once, and the combined November-December flow only once. These flows are very high and do not seem appropriate. In fact, our regression analysis shows a negative relationship for white shrimp harvest versus adjusted Colorado River December flows (Table 16), and for white shrimp harvest versus Lavaca-Navidad-Colorado combined December flows (Table 17).

TDWR's Alternative III is entitled Shellfish Harvest Enhancement. On the surface this would seem to be equivalent to our flows for maximum shrimp production, however, TDWR constrained their model from exceeding historical average flows (1941-76). This prevented them from exploring the full potential of high flows. On the Lavaca-Navidad River they increased spring flows at the expense of fall flows (Table 26). This was especially pronounced in TDWR's 1984 recommendations. Operating within their constraints, we agree with this change, because we also feel that spring flows are more important than fall. Childress et al. (1975) found that high May and June flows were beneficial to white shrimp in nearby San Antonio Bay. For the Colorado River, TDWR decreased spring flows, increased summer flows and r tained their extremely high November and December flows (Table 26). The summer flows were increased because TDWR's salinity model indicated a need for reduced salinities in the east arm of Matagorda Bay in July and August to enhance shellfish habitat conditions. Th salinity model was not displayed for examination, but, as was discussed earlier, this is a potentially critical time for juvenile shrimp and summer salinity conditions were an aspect that we were not able to thoroughly investigate. Oyster habitat considerations would also dictate higher summer flows (see Appendix E). With regard to the reduction in spring flows, our data show that reduction, not enhancement, would occur in shrimp harvest.

TDWR (1980) recommends two floods in the Lavaca delta for the April to June period with a peak discharge of 11,320 cfs. This is very similar to our recommendation of two 9,000 cfs average daily flow floods in March, April, May or June (Table 24). Fall flooding recommendations are also similar. TDWR recommends one 10,370 cfs peak discharge flood for October to January; we recommend one 9,000 cfs averag daily flow for September and October. We also recommend another 9,000 cfs average daily discharge event for the November to February period, for a total of four annual "small" floods versus three recommended by TDWR.

TDWR made no provisions for large floods or for Colorado River floods. As previously stated, large floods flush areas not normally exposed to tidal inundation thereby bringing a new nutrient source to bear on the system. This appears to be reflected in subsequent shrimp harvests (Fig. 10). With the existing isolation of the Colorado delta marshes from the river, flooding is not presently of great importance. However, after diversion of the Colorado River into Matagorda Bay, flooding will be essential to achieve the predicted benefits to the fishery.

We derived no set of flow recommendations equivalent to TDWR's Alternatives I and IV, Subsistence and Biotic Species Viability, respectively. TDWR's flow recommendations for Alternative I on the

Table 26. Texas Department of Water Resources (1980 and 1984a) recommended gaged flows (thousands of ac-ft) for Alternatives I, III and IV.

A. Lavaca-Navidad River

Alternative	I		III		IV
	1980	1984	1980	1984	1984
January	22	22	22	22	9
February	27	27	27	27	9
March	17	17	17	17	6
April	59	26	106	115	18
May	56	116	154	167	16
June	32	32	154	116	9
July	16	16	16	16	6
August	10	10	10	10	7
September	24	14	24	24	17
October	49	18	49	18	13
November	18	18	18	18	7
December	18	18	18	18	10
Totals:	347[a]	343[a]	614[a]	567[a,b]	126[a]

B. Colorado River

Alternative	I	III	IV
January	88	88	10
February	99	99[c]	10
March	76	76	23
April	101	101	100
May	140	140	116
June	105	105	82
July	53	162	33
August	49	110	45
September	148	148	146
October	92	92	94
November	80	384	9
December	82	325	13
Totals:	1,113	1,830	681

[a]Rounding makes this total different than the sum of the column.

[b]In TDWR 1984a, this total is erroneously presented as 617.3. The actual total is 567.3.

[c]In TDWR 1984a, this flow is apparently erroneously presented as 92.1. The total flow for this alternative is the same in both the 1980 and 1984 publications.

Lavaca-Navidad River (Table 26) are less than half of our recommendations for maintaining the mean shrimp harvest (Table 25). Th difference is greatest for June flows, but flows for every month are less than those we recommend. TDWR's Colorado River Alternative I recommended flows (Table 26) are also much less than our recommended flows. TDWR calls for higher flows only in September. The total Alternative I flows are 1.460 million ac-ft compared to our 2.632 million ac-ft.

A permanent reduction to Alternative I flow levels would likely result in a great reduction of the commercial fishery in Matagorda Bay. Salinity levels would be consistently higher and nutrient input greatly reduced. No opportunity is provided for large floods, and even small floods would occur at a much reduced frequency. This would likely cause a steady decline in the vigor of the delta marshes and could easily cause their eventual conversion to open water because of salinity stress and sediment starvation. These same processes have caused substantial wetland losses in Louisiana (Fruge 1981). As TDWR (1984a) noted "extended periods where inflow conditions consistently fall below maintenance levels can lead to degraded estuarine environments, loss of important nursery habitats for sea food species, and a substantial reduction in the potential for natural assimilation of organic matter." Without adequate nutrient input and with the loss of marsh nursery areas, shellfish and finfish productivity could easily fall below levels allowing a profitable commercial harvest.

Alternative IV, Biotic Species Viability, received less discussion by TDWR than did the other three alternatives. We assume that it was meant as the lowest flow that could occur in any single month without the immediate catastrophic loss of estuarine life. We were unable in all cases to determine if the recommended flows are appropriate for that purpose. However, with the possible exception of April, the Alternative IV flows for the Lavaca-Navidad River (Table 26) are so extremely low, that even a single month at those levels could severely stress the estuarine ecosystem. The flows for February, June and July are especially low, and from 1960-82, flows lower than those recommended occurred only 4, 3 and 1 times in these months, respectively. However, flows less than the April recommendation occurred 10 times during the same period.

The Colorado River Alternative IV recommended flows appear to be adequate for the purposes of this alternative in some months, but clearly inadequate in others. The recommended flows for April, June, August, September and October (Table 26) should serve this purpose well. In fact, the September flow is larger than our recommendation for maintaining mean shrimp harvest (Table 25). However, the historical flows from 1960-82 have never been as low as the Alternative IV recommendations for January, February, November and December, and were lower than the March recommendation only twice. To reiterate, the effects of such low flows would be devastating to the fisheries and overall productivity of the bay system. "At this minimum level of inflow, Texas coastal fisheries harvests are projected to decline overall by one-quarter to one-half of the average historical production." (TDWR 1984a).

CONCLUSION

The need for freshwater is continually increasing with a growing population, and Texas is trying to conserve its limited supply of river water by constructing reservoirs. Such reservoirs translate into a reduced flow and an altered character of river water reaching each bay. Reduced flows mean reduced influxes of nutrients, detritus, sediments and freshwater to the bays, and thus a reduction in the elements which promote estuarine productivity.

Using river flow and shrimp fishery data from 1960 thru 1982, we have designed an annual inflow plan to maintain the estuarine environment and the annual brown and white shrimp catch in the Matagorda Bay System. The plan provides recommended monthly flow requirements for the Lavaca-Navidad and Colorado Rivers, and seasonally required floods of specified sizes. The recommended river flows total 102% of the mean annual combined flows of these rivers based on 1960 thru 1982 data. Average historic flows are recommended for most months, but above average flows are recommended for March, June and October for the Lavaca-Navidad River and for October on the Colorado River. Slightly below average flows are recommended for April for both rivers.

Alternative II proposed by TDWR requires only 93% of the mean annual combined flows to maintain the mean annual harvests of shrimp, crabs, oysters and fish in the Matagorda Bay System. Below average flows were proposed for most months. Above average flows were recommended for September, November and December for the Colorado River, and for April, May, June, August and September for the Lavaca-Navidad River.

The two plans have thus arrived at nearly the same annual river flow requirements, but have partitioned the flow into different monthly volumes. We question TDWR's reduced Colorado River flows during the spring and their elevated flows in November and December, as the former may be detrimental to the brown and white shrimp populations and the latter would seem to have no particular value.

We were unable to find a strong statistical or even graphical relationship between the bay shrimp fishery and that of the area of the Gulf of Mexico adjoining the Matagorda Bay System. With the greatly increasing fishing effort on brown shrimp in the bay, one may expect to see some reduction in brown shrimp catches in the Gulf. Our concern is that this situation could be exacerbated if the carrying capacity of the bays - primary, secondary and even tertiary bays - is reduced by the loss of river water inflows. It is necessary to reiterate the importance of large floods to an estuarine system such as the Matagorda Bay System. These floods bring in large amounts of sediments, nutrients, detritus and freshwater, plus provide the mechanical action needed to flush nutrients and detritus from bordering marshes into the bays where they fertilize an important food chain which supports shrimp, crabs and fish.

In any study of an issue as complex as freshwater-inflow needs, there always remain other avenues of investigation that could be explored. The most logical expansion of this study would be to determine the freshwater inflow requirements for crabs, oysters and finfish. Even a more detailed inspection of the freshwater needs of shrimp coupled with other factors such as temperature extremes, tidal extremes, wind and rainfall could prove very useful. Managers may have to choose the species they can afford in costs of freshwater if required volumes and schedules of delivery vary substantially among species. In this regard we would like to point out that more fisheries independent data and long-term productivity information from secondary and tertiary bays in each bay system could greatly reinforce the fisheries dependent data. Our thanks to the foresight of the leaders of the Texas Parks and Wildlife Department who maintained their fisheries independent shrimp sampling of Texas bays from 1963 through 1980.

Of particular importance to any future analyses of the impacts of freshwater inflows to a bay and its biota would be a salinity model for that bay. Such a model could predict the salinity in critical habitats of the bay based on freshwater inflow, circulation patterns, rainfall, evaporation, tides, wind and barometeric pressure. The Texas Department of Water Resources has made excellent strides in formulating such models for most bay systems in Texas, but unfortunately these models have not been finalized nor published. With such a model, salinities in nursery areas could be predicted, and salinities within the range allowing optimum productivity of both animals and plants could be maintained.

Current reservoir proposals on the Lavaca and Colorado Rivers have the potential to greatly reduce freshwater inflows to the Matagorda Bay System.

These reductions, if great enough, would adversely effect the productivity of both the estuarine system and the adjacent Gulf of M xico. The biological, economic and social impacts of freshwater inflow reduction make wise water management decisions critical to the continued prosperity of the Texas coast. We hope this report will be of some assistance to the managers of freshwater inflows to Texas bays.

LITERATURE CITED

Armstrong, N. E., M. O. Hinson, Jr., J. H. Collins and E. G. Fruh. 1975. Biochemical cycling of carbon, nitrogen, and phosphorus in saltwater marshes of Lavaca Bay, Texas. Report to the Texas Water Department Board. Center for Research in Water Resources, Austin.

Baxter, K. N. and W. C. Renfro. 1967. Seasonal occurrence and size distribution of postlarval brown and white shrimp near Galveston, Texas, with notes on species identification. Fish. Bull. U.S. 66:149-158.

Berry, R. J. and K. N. Baxter. 1969. Predicting brown shrimp abundance in the northwestern Gulf of Mexico. FAO Fish. Rep., No. 57, 3:775-798.

Blum, J. L. 1969. Nutrient changes in water flooding the high salt marsh. Hydrobiologica 34:95-99.

Bomar, G. W. 1983. Texas weather. University of Texas Press, Austin. 265 p.

Bouma, A. H. and W. R. Bryant. 1967. Rapid delta growth in Matagorda Bay, Texas. Laguna Costeras, un Simposio. Mem. Simp. Inter. Lagunas Costeras: 171-183.

Chapman, C. R. 1966. The Texas basins project. Pages 83-92. In: American Fisheries Society Special Publication No. 3.

______. 1971. The Texas Water Plan and its effect on estuaries. Pages 40-57. In: Smith, R. F. (ed.). A Symposium on the Biological Significance of Estuaries. Sport Fishing Institute, Washington, D.C.

Childress, R., E. Bradley, E. Hegen and S. Williamson. 1975. The eff cts of freshwater inflows on hydrological and biological parameters in the San Antonio Bay system, Texas. Texas Parks and Wildlife D partment, Austin. 190 p.

Coastal Environments Inc. 1980. Delta building potential of the Colorado River central Texas. Appendix I In: Corps of Engineers. 1981. Mouth of the Colorado River, Texas Phase I General Design Memorandum and Environmental Impact Statement (Diversion Features). U.S. Army Engineer District, Galveston, TX.

Cook, H. M. and M. J. Lindner. 1970. Synopsis of biological data on the brown shrimp *Penaeus aztecus* Ives, 1891. FAO Fish. Rep. 4(57).

Corps of Engineers. 1977. Mouth of the Colorado River, Texas Final Environmental Statement. U.S. Army Engineer District, Galveston, TX. 77 p.

_____. 1981. Mouth of the Colorado River, Texas Phase I General Design Memorandum and Environmental Impact Statement (Diversion Features). U.S. Army Engineer District, Galveston, TX. 211 p.

Dawson, A. J. and N. E. Armstrong. 1975. The role of plants in nutrient exchange in the Lavaca Bay brackish marsh system. Report to the Texas Water Development Board, Center for Research in Water Resources, Austin, TX. 115 p.

Day, J. W., W. G. Smith and C. S. Hopkinson, Jr. 1973. Some trophic relationships of marsh and estuarine areas. Pages 115-135. In: Chabreck, R. H. (ed.). Proc. Coastal Marsh and Estuary Management Symposium. Louisiana State University, Baton Rouge.

Diener, R. A. 1975. Cooperative Gulf of Mexico estuarine inventory and study-Texas: area description. NOAA Technical Report NMFS CIRC-393. 129 p.

Dury, G. H. 1969. Relation of morphometry to runoff frequency. Pages 419-430. In: Chorley, R. J. (ed.). Water, Earth and Man. Methuen & Co. Ltd., London.

Espey, Huston and Associates. 1976. A study of the placement of materials dredged from Texas ports and waterways. Volume I. General Land Office, Austin, TX. 385 p.

_____. 1977. Marsh plant production and potential detritus in Lavaca, San Antonio and Nueces Bays. Report to Texas Water Development Board, Document No. 17688. 53 p.

_____. 1979a. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas Phase I final report: Subunit 1 (Matagorda Bay). Report to U.S. Fish and Wildlife Service, Houston, TX. 196 p.

_____. 1979b. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas Phase I final report Subunit 2 (Lavaca Bay). Report to U.S. Fish and Wildlife Service, Houston, TX. 169 p.

_____. 1979c. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas: Appendix A, Climatology of Matagorda Bay. Report to U.S. Fish and Wildlife Service, Houston, TX. 25 p.

_____. 1979d. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas: Appendix B, Hydrology of Matagorda Bay. Report to U.S. Fish and Wildlife Service, Houston, TX. 107 p.

_____. 1979e. Studies of the eff ct of alterations of fr shwater inflows into Matagorda Bay area, Texas: Appendix F, study species-general biology and ecology. Report to U.S. Fish and Wildlife Service, Houston, TX. 356 p.

_____. 1979f. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas: Appendix H, Preliminary assessment of perturbations. Report to U.S. Fish and Wildlife Service, Houston, TX. 59 p.

_____. 1982. Studies of the effects of alterations of freshwater inflows into Matagorda Bay area, Texas Phase 3 final report. Report to U.S. Fish and Wildlife Service, Houston, TX. 222 p.

Fruge, D. W. 1981. Effects of wetland changes on the fish and wildlife resources of coastal Louisiana. Pages 387-401. In: Cross, R. D. and D. L. Williams (eds.). Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U.S. Fish and Wildife Service, Offic of Biological Services. FWS/OBS-81/04. 2 Vol.

Gaidry, W. J. III. 1974. Correlations between inshore spring white shrimp population densities and offshore overwintering populations. La. Wildl. Fish. Comm. Tech. Bull. 12, 18 p.

Gazey, W. J., B. J. Gallaway, R. C. Fechhelm, L. R. Martin, L. A. Reitsema, K. F. Benney, R. Schroeder and D. Chester. 1982a. Shrimp mark-release and post interview sampling survey of shrimp catch and effort with recovery of recaptured tagged shrimp. Vol. I. In: Jackson, W. B. (ed.). Shrimp population studies: Bryan Mound brine disposal sit off Freeport, Texas, 1981-1982. NOAA/NMFS Final Report to DOE. 291 p.

____. 1982b. Shrimp mark-release and post interview sampling survey of shrimp catch and effort with recovery of recaptured tagged shrimp. Vol. III. In: Jackson, W. B. (ed.). Shrimp population studies: West Hackberry and Big Hill brine disposal sites off southwest Louisiana and upper Texas coasts, 1980-1982. NOAA/NMFS Final Report to DOE. 306 p.

Gilmore, G., J. Dailey, M. Garcia, N. Hanebaum and J. Means. 1976. A study of the effects of freshwater on the plankton, benthos, and nekton assemblages of the Lavaca Bay system, Texas. Texas Parks and Wildlife Department, Austin, TX. 112 p.

Goldstein, A. L. 1978. Nutrient contributions from the Colorado River to Matagorda Bay. Texas Department of Water Resources. Austin, TX. 11 p.

Gunter, G. and H. H. Hildebrand. 1954. The relation of total rainfall of the state and catch of the marine shrimp (Penaeus setiferus) in Texas waters. Bull. Mar. Sci. Gulf Carrib. 4:95-103.

Hackney, C. T. 1978. Summary of information: Relationship of freshwater inflow to estuarine productivity along the Texas coast. U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-78/73.1 25 p.

Heald, E. J. 1969. The production of organic detritus in a south Florida estuary. Ph.D. Dissertation. University of Miami, Miami, FL. 110 p.

Heinle, D. R. and D. A. Flemer. 1976. Flows of material between poorly flooded tidal marshes and an estuary. Mar. Biol. 35:359-373.

Hildebrand, H. H. and G. Gunter. 1952. Correlation of rainfall with the Texas catch of white shrimp, Penaeus setiferus (Linnaeus). Trans. Am. Fish. Soc. 82:151-155.

Holloway, S. L. and L. F. Sullivan. 1982. P na id shrimp tagging experiments in Louisiana, 1979. NOAA Tech. Memo. NMFS-SEFC-89. 101 p.

Houston Lighting and Power Company. No date. South Texas project units 1 and 2: environmental report. Volume 2. Houston Lighting and Power Company environmental report to the Nuclear Regulatory Commission. Houston.

_____. 1978. Environmental report-operating license stage. South Texas project units 1 and 2. Houston Lighting and Power Company environmental report to the Nuclear Regulatory Commission. Houston, TX. 2 Vol.

Jones, L. L., J. W. Adams, W. L. Griffin and J. Allen. 1974. Impact of commercial shrimp landings on the economy of Texas coastal regions. Texas Agricultural Experimentation, Texas A&M University, TAMU-SG-75-204.

King, B. D., III. 1971. Study of migratory patterns of fish and shellfish through a natural pass. Tex. Parks and Wildl. Dept., Tech. Ser. No. 9. 54 p.

Klima, E. F. 1980. The National Marine Fisheries Service shrimp research program in the Gulf of Mexico. Pages 47-76. In: Proceedings of the working group on shrimp fisheries of the northeastern South America. West. Cent. Atl. Fish. Comm. Rep. 28.

Leopold, L. B., M. G. Wolman and J. P. Miller. 1964. Fluvial processes in geomorphology. Witt Freeman and Co., San Francisco. 522 p.

Liebow, E. B., K. S. Butler, T. R. Plaut, V. L. Arnold, G. H. Ford, T. D. Kahn, M. A. Klein, C. Alday-Bondy and V. Parker. 1980. Texas barrier islands region ecological characterization: a socioeconomic study. U.S. Fish and Wildlife Service, Office of Biological Services; FWS/OBS-80/19. 2 Vols.

Lindner, M. J. and H. L. Cook. 1970. Synopsis of biological data of the white shrimp, Penaeus setiferus (Linnaeus) 1767. FAO Fish Rep.: 4(57).

Livingston, R. J. 1981. River-derived input of detritus into the Apalachicola estuary. Pages 320-329. In: Cross, R. D. and D. L. Williams (eds.). Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-81/04. 2 Vols.

Longley, W. L. and M. Wright. In preparation. Texas barrier island region characterization. U.S. Fish and Wildlife Service, Biological Services Program, Slidell, LA.

Lyon, J. M. and C. J. Boudreaux. 1983. Movement of tagged white shrimp, Penaeus setiferus, in the northwest Gulf of Mexico. La. Dept. Wildl. Fish. Tech. Bull. No. 39.

Matthews, G. A. 1981. The effects of floods on the zooplankton assemblage of San Antonio Bay, Texas. Pages 509-525. Vol. I. In: Cross, R. D. and D. L. Williams (eds.). Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-81/04. 2 Vols.

_____, D. B. Koi and R. L. Benefield. 1984. A users guide to the inshore shrimp and hydrographic data collected by the Texas Parks and Wildlife Department from 1963 through 1980. NOAA Technical Memorandum NMFS-SEFC-140. 74 p.

McGowen, J. H. and J. L. Brewton. 1975. Historical changes and related coastal processes, Gulf and mainland shorelines, Matagorda Bay area, Texas. University of Texas at Austin, Bureau of Economic Geology, Special Report. 72 p.

McGowen, J. H., C. V. Proctor, Jr., L. F. Brown, Jr., T. J. Evans, W. L. Fisher and C. G. Groat. 1976a. Environmental geologic atlas of the Texas coastal zon : Port Lavaca area. University of Texas at Austin, Bureau of Economic Geology. 107 p.

McGowen, J. H., L. F. Brown, Jr., T. J. Evans, W. L. Fisher and C. G. Groat. 1976b. Environmental geologic atlas of the Texas coastal zone--Bay City-Freeport. University of Texas at Austin, Bureau of Economic Geology. 98 p.

McGowen, J. H. and R. A. Morton. 1979. Sediment distribution, bathymetry, faults and salt dispairs on the submerged lands of Texas. University of Texas at Austin, Bureau of Economic Geology, Special Publication. 31 p.

Minello, T. J. and R. J. Zimmerman. 1983. Fish predation on juvenile brown shrimp, Penaeus aztecus Ives: the effect of simulated Spartina structure on predation rates. J. Exp. Mar. Biol. Ecol. 72:211-231.

Moore, K. A. 1974. Carbon transport in two York River, Virginia tidal marshes. M.A. Thesis. University of Virginia, Jamestown, VA. 102 p.

Nadeau, R. L. 1972. Primary production and export of plant materials in the salt marsh ecosystem. Ph.D. Dissertation. Rutgers University, N w Brunswick, NJ. 167 p.

Nixon, S. W., C. A. Oviatt, J. Garber and V. Lee. 1976. Diel metabolism and nutrient dynamics in a salt marsh embayment. Ecology 57:740-750.

Odum, E. P. and A. A. de la Cruz. 1967. Particulate organic detritus in a Georgia salt marsh-estuarine ecosystem. Pages 383-388. In: Lauff, G. H. (ed.). Estuaries. Amer. Assoc. Adv. Sci., Publ. No. 83. 757 p.

Odum, W. E., T. J. Smith III, J. K. Hoover and C. C. McIvor. 1984. The ecology of tidal freshwater marshes of the United States east coast: a community profile. U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-83/17. 113 p.

Ranwell, D. S. 1964. Spartina salt marshes in southern England, II. rate and seasonal pattern of sediment accretion. J. Ecology 52:79-94.

Schelske, C. L. and E. P. Odum. 1962. Mechanisms maintaining high productivity in Georgia estuaries. Proc. Gulf Caribb. Fish. Inst. 14:75-80.

Schumm, S. A. 1974. Geomorphology. In: Yearbook of Science and Technology. McGraw-Hill, New York, NY.

Sheffield, W. J. and M. T. Walton. 1981. Loss of Colorado River inflows to Matagorda Bay, Texas and efforts for restoration. Pages 216-229. In: Cross, R.D. and D. L. Williams (eds.). Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-81/04. 2 Vols.

Shisler, J. K. and D. M. Jobbins. 1977a. Salt marsh productivity as affected by the selective ditching technique. Mosq. News 37:631-636.

_____. 1977b. Tidal variations in the movement of organic carbon in New Jersey salt marshes. Mar. Biol. 40:127-134.

Teal, J. M. 1962. Energy flow in the salt marsh ecosystem of Georgia. Ecology 43:614-624.

Texas Department of Health. 1983. Classification of shellfishing areas. Division of Shellfish Sanitation Control. Austin, TX. 13 maps.

Texas Department of Water Resources. 1977. Continuing water resources planning and development for Texas. Phase I—planning methods, revised estimates of present water demand and availability, projections of future water needs, and identification of some potential sources of water supply for use in modifying and amending the Texas water plan. Volume 2. Texas Department of Water Resources, Austin, TX. 814 p.

_____. 1978. Hydrological and biological studies of the Colorado River delta, Texas. Texas Department of Water Resources, LP-79. Austin, TX. 164 p.

_____. 1980. Lavaca-Tres Palacios Estuary: a study of the influence of freshwater inflows. Texas Department of Water Resources, LP-106. Austin, TX. 325 p.

_____. 1981. Lavaca-Tres Palacios Estuary: an analysis of bay segment boundaries, physical characteristics, and nutrient processes. Texas Department of Water Resources, LP-78. Austin, TX. 549 p.

_____. 1984a. Water for Texas: A comprehensive plan for the future. Texas Department of Water Resources, GP-4-1. Austin, TX. 2 Vols.

_____. 1984b. The state of Texas water quality inventory. Texas Department of Water Resources, LP-59. Austin, TX. 557 p.

Texas Water Development Board. 1968. The Texas Water Plan. Austin, TX. 502 p.

U.S. Bureau of Reclamation. 1974. Final environmental impact statement, Palmetto Bend Reservoir, Texas. Amarillo, TX. 163 p.

U.S. Department of Commerce. 1960-82. Climatological Data, Texas. Vol. 65 No. 1 to Vol. 87 No. 10. National Oceanic and Atmospheric Administration, Weather Bureau.

_____. 1961-1984. Gulf Coast Shrimp Data, Annual Summary 1960 thru 1982. National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

_____ and Texas Parks and Wildlife Department. 1961-1984. Texas Landings, Annual Summary 1960 thru 1982. National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

U.S. Fish and Wildlife Service. 1979. Reestablishment of Colorado River flows into Matagorda Bay, Texas supplemental fish and wildlife report. Albuquerque, NM. 52 p.

U.S. Geological Survey. 1978. Water resources data for Texas water year 1977. Water-Data Report Tx. 77-3. 561 p.

Ward, G. H., Jr. 1982. Pass Cavallo, Texas: Case study of tidal prism capture. Waterway, Port, Coastal and Ocean Div., American Soc. Civ. Engr., Vol. 108 (WW4):513-525.

_____ and N. E. Armstrong. 1980. Matagorda Bay, Texas: its hydrography, ecology and fishery resources. U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-81/52. Washington, D.C. 230 p.

Williams, D. L., P. G. Rowe, H. C. Ellison, J. B. Blackburn, Jr., J. M. Dietzmann, W. G. Handel, B. Justice, K. Kreger, S. J. Mixon, W. M. Mugler, E. Paransky, J. L. Reynolds, F. M. Setzer, C. P. Sharpe, K. A. Shuley, N. Sulkowski, W. F. Timmer, T. L. Watson, V. Wendt and P. Woods. 1976. Texas Gulf Coast Program. Rice Center for Community Design and Research, Research Report 1. Houston, TX. 262 p.

Wolman, M. G. and J. G. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. J. of Geology 68(1).

Woodruff, C. M., Jr. 1975. Resources of the Texas coastal region. Texas General Land Office, Coastal Management Program. Austin, TX. 45 p.

Woodwell, G. M., D. E. Whitney and D. W. Juers. 1977. The flax pond ecosystem study: exchanges of carbon in water between a salt marsh and Long Island Sound. Limnol. Oceanogr. 22:833-838.

Zimmerman, R. J. and T. J. Minello. 1984. Densities of Penaeus aztecus, P. setiferus, and other natant macrofauna in a Texas salt marsh. Estuaries 7(4A):421-433).

_____ and G. Zamora, Jr. 1984. Selection of vegetated habitat by brown shrimp, Penaeus aztecus, in a Galveston Bay salt marsh. Fish. Bull. U.S. 82(2):325-336.

Appendix A. Gaged River Flows for Tributaries to the Matagorda Bay System, 1960-82.

Table A.1. Monthly river flows for the Lavaca River gaged near Edna, Texas, at hydrologic unit 12100101 of the U.S. Geological Survey from January 1960 thru December 1982. Values are in thousands of acre-feet.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	11.5	12.8	5.1	6.9	5.2	64.5	11.3	39.3	4.7	223.3	50.7	36.5
1961	58.5	63.8	10.0	6.9	5.7	81.2	34.7	5.0	123.3	9.7	65.3	7.7
1962	5.9	5.4	4.5	37.2	5.9	14.2	3.4	1.3	9.2	3.6	2.1	3.7
1963	5.1	17.7	3.0	1.8	1.8	1.7	4.4	0.5	9.4	0.3	1.2	2.4
1964	2.2	4.2	5.5	4.4	1.9	17.6	1.1	1.6	11.5	2.5	0.6	0.9
1965	36.6	55.9	5.1	4.2	99.7	40.8	3.0	2.0	1.2	5.4	48.7	17.2
1966	7.6	16.1	9.2	34.9	45.2	8.5	5.3	2.8	2.1	1.2	1.1	1.4
1967	1.5	1.2	1.7	4.4	2.3	0.7	0.3	1.2	112.2	51.7	5.0	2.8
1968	61.4	8.8	10.1	13.2	83.7	114.8	12.8	3.8	6.6	2.8	2.9	12.4
1969	6.9	62.8	44.2	83.5	87.6	6.7	3.0	2.3	3.1	7.6	3.8	18.3
1970	16.6	4.1	22.5	4.8	76.9	26.2	3.7	2.7	21.8	16.2	2.5	2.1
1971	2.0	2.1	2.3	1.8	1.5	5.4	1.2	39.7	83.2	22.2	4.8	34.1
1972	22.0	26.6	14.0	3.8	191.1	23.6	6.6	6.6	2.9	2.4	2.4	2.2
1973	4.4	9.5	65.3	153.6	34.1	297.8	23.7	10.0	14.5	110.2	12.9	7.9
1974	68.1	13.3	7.6	5.9	31.0	50.8	3.9	6.6	90.4	8.9	37.9	17.3
1975	10.4	9.6	5.9	35.0	106.2	28.9	27.4	6.0	4.6	3.5	2.8	12.8
1976	3.1	2.5	3.3	31.5	50.8	17.0	18.1	2.5	4.1	55.1	22.6	147.6
1977	21.2	60.7	11.4	55.6	13.0	17.6	4.0	2.3	4.0	1.7	9.5	2.9
1978	9.3	9.3	6.5	15.2	2.6	8.4	2.6	1.2	169.1	7.7	8.0	4.5
1979	96.2	45.0	24.1	63.9	151.2	90.1	10.3	4.5	49.4	4.0	2.9	3.6
1980	31.9	13.7	4.9	4.1	52.8	3.5	1.8	1.3	2.3	2.0	1.4	1.7
1981	2.4	1.6	2.1	9.8	14.4	137.9	23.0	4.6	141.3	16.6	103.7	8.7
1982	6.1	33.0	10.1	6.4	199.2	9.2	3.9	1.9	3.6	3.1	64.3	11.2

Table A.2. Monthly river flows for the Navidad River gaged near Ganado, Texas, at hydrologic unit 12100102 of the U.S. Geological Survey from January 1960 thru April 1980. Values are in thousands of acre-feet.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	33.2	38.0	8.3	14.8	23.1	206.7	40.9	80.3	17.1	164.8	94.7	65.2
1961	93.8	164.7	12.2	7.6	5.1	144.9	65.3	10.3	263.0	7.3	65.5	5.7
1962	6.3	7.2	4.7	39.7	9.4	21.2	14.6	4.5	16.6	2.6	0.8	10.9
1963	14.7	17.1	2.4	1.8	3.0	4.1	21.4	4.9	4.5	1.2	6.1	12.4
1964	2.7	15.6	9.7	2.2	3.2	29.4	7.2	7.1	30.2	7.0	3.2	0.9
1965	35.0	44.7	3.2	4.4	156.9	43.2	9.3	6.1	10.4	14.4	88.5	33.8
1966	20.7	40.4	21.8	53.3	110.8	29.6	16.1	18.8	11.3	4.9	0.6	1.1
1967	2.2	1.0	1.1	6.6	7.7	4.0	6.2	22.2	213.2	60.5	4.4	1.9
1968	167.5	14.4	13.9	15.3	124.2	291.9	32.6	8.7	21.8	13.7	9.9	29.0
1969	17.1	112.9	75.8	97.3	130.7	10.1	6.0	5.5	14.2	12.7	8.8	27.2
1970	28.3	3.8	66.2	9.1	122.1	32.3	15.3	6.2	71.7	77.4	3.9	1.8
1971	1.7	2.4	1.5	3.8	4.2	3.2	6.3	42.0	114.3	56.2	3.1	55.8
1972	29.3	57.1	16.0	4.3	256.0	39.7	23.8	12.9	11.3	4.8	4.2	1.7
1973	10.4	21.5	106.4	228.5	39.1	551.6	28.5	28.5	102.0	126.4	26.8	10.3
1974	119.7	15.6	11.0	20.0	58.3	54.0	11.6	19.8	251.0	16.8	97.0	32.6
1975	17.7	12.9	5.4	37.4	157.6	69.4	34.0	21.6	20.6	9.5	2.8	33.3
1976	3.0	2.3	2.5	34.3	54.7	48.3	33.8	2.4	10.4	42.4	26.4	209.7
1977	24.6	82.2	7.4	101.0	13.0	47.6	11.6	3.0	9.0	8.5	16.5	1.7
1978	42.2	24.5	4.2	14.4	1.9	29.5	7.8	1.3	239.4	13.5	15.3	6.3
1979	162.2	74.8	38.1	104.8	169.5	45.8	21.8	5.9	135.7	5.7	3.4	3.0
1980	103.3	15.0	4.4	4.0	Palmetto Bend Reservoir Closed.							

Table A.3. Releases from the Palmetto Bend Reservoir to Lavaca Bay from May 1980 thru April 1984. Values are in thousands of acre-feet.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1980					nr*	nr	nr	nr	2.99	2.99	1.70	0.01
1981	0.01	0.01	0.01	0.01	30.41	338.62	76.31	16.72	185.99	114.81	211.84	6.58
1982	0.04	55.55	6.21	12.26	267.60	0.95	4.01	0.19	1.86	13.47	114.29	17.33
1983	33.34	143.03	121.69	1.81	46.69	8.58	153.08	15.67	86.58	178.48	66.82	5.00
1984	47.78	14.85	3.72	0.35								

*nr = no release.

Table A.4. Monthly river flows for the Colorado River gaged near Bay City, Texas at hydrologic unit 12090302 of the U.S. Geological Survey from January 1960 thru December 1982. Values are in thousands of acre-feet.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	258.5	284.9	227.1	227.9	362.7	530.1	157.8	119.8	66.2	304.0	420.0	228.0
1961	298.1	460.3	287.9	218.5	115.4	512.5	471.9	176.9	663.9	106.8	280.5	220.1
1962	164.3	58.7	43.0	33.5	21.0	70.4	35.8	16.9	52.9	50.9	40.5	83.5
1963	60.2	90.9	35.5	23.0	21.9	22.9	39.1	19.2	23.4	21.6	18.9	21.1
1964	15.8	27.7	49.2	7.4	14.0	30.0	7.1	7.0	52.2	47.1	41.3	35.2
1965	137.3	269.3	47.6	21.9	384.3	378.7	84.2	11.6	26.6	62.6	206.1	252.2
1966	116.2	109.2	95.7	128.2	401.6	67.2	26.3	35.8	5.6	36.2	50.6	18.2
1967	16.6	13.7	15.8	19.3	27.8	17.5	0.1	19.2	159.2	67.7	79.1	41.6
1968	505.9	385.4	363.3	408.2	622.7	717.0	207.6	45.4	113.5	47.9	37.3	151.0
1969	54.1	222.2	232.0	254.3	342.2	53.7	22.8	12.3	19.4	91.0	215.1	164.8
1970	172.1	179.8	453.2	324.9	429.6	254.5	131.5	54.6	79.8	233.7	41.8	28.2
1971	36.4	19.0	17.4	33.3	32.8	9.2	17.2	48.9	154.2	103.5	206.0	300.2
1972	117.2	88.0	46.0	21.0	279.0	50.6	56.8	19.1	25.3	47.2	52.9	30.6
1973	106.2	151.5	223.7	345.7	149.3	489.7	54.0	88.0	173.5	547.5	159.2	151.2
1974	394.4	105.4	75.7	54.1	149.8	48.6	35.1	66.9	447.6	279.7	801.4	312.6
1975	211.6	434.3	231.5	161.1	807.7	598.2	273.4	85.4	46.9	55.9	55.1	62.1
1976	41.8	26.6	32.5	234.5	241.1	134.2	256.0	78.4	77.5	154.2	167.4	430.6
1977	133.4	299.6	107.9	798.1	458.0	186.5	56.0	30.1	55.6	33.0	49.2	33.0
1978	61.9	64.9	24.6	48.2	20.2	59.8	41.4	27.8	162.6	33.5	72.7	47.4
1979	284.9	213.2	125.7	226.5	410.7	391.5	117.1	53.9	235.4	36.5	28.8	33.2
1980	105.0	58.3	45.5	55.9	191.9	26.5	39.0	21.5	37.2	48.4	43.0	54.5
1981	59.9	40.7	140.5	86.7	120.1	986.4	283.2	51.6	265.6	136.7	456.6	99.4
1982	64.7	81.8	74.2	87.7	456.9	68.2	114.0	53.9	43.4	40.5	60.6	46.8

Table A.5. Monthly river flows for Tres Palacios Creek gaged near Midfield, Texas, October 1970 thru September 1981. Values are in thousands of acre-feet.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1970										44.3	.7	.5
1971	.3	.4	1.2	3.1	3.0	2.7	3.6	5.0	30.3	6.6	1.0	21.3
1972	3.8	3.0	1.3	2.0	31.9	5.2	4.0	2.7	5.3	2.3	8.3	.4
1973	3.0	10.0	2.8	36.2	14.0	40.6	4.3	6.2	75.9	26.7	8.4	1.2
1974	11.0	3.2	5.5	4.1	23.7	5.6	2.8	10.0	10.5	2.3	29.2	11.2
1975	3.0	1.0	1.6	3.4	11.3	19.8	4.8	6.2	4.3	1.8	1.9	18.6
1976	.8	.4	.6	2.6	1.9	7.4	14.4	1.0	4.0	3.0	12.5	24.7
1977	2.9	3.2	.9	6.2	2.3	3.8	3.7	2.3	6.0	7.4	7.2	.6
1978	9.3	10.2	.9	3.3	1.2	8.8	3.6	1.4	10.8	1.8	5.4	4.7
1979	32.2	18.9	19.2	9.5	15.8	7.8	24.2	5.0	77.8	1.8	1.0	4.8
1980	13.4	3.8	3.3	1.5	34.1	1.5	3.4	1.8	5.9	7.7	.7	.5
1981	1.2	.8	.5	2.2	21.0	26.4	38.3	7.0	21.1			

Appendix B. Temperature and Rainfall Data for the Matagorda Bay Area, 1960–82.

Table B.1. Total rainfall for each month. Values were computed as means from data obtained from stations: Point Comfort, Port Lavaca No. 2, Port O'Connor, Palacios FAA Airport and Matagorda No. 2. Values are in iches.

Year	J	F	M	A	M	J	J	A	S	O	N	D	Sum
1960	2.6	3.6	3.0	1.7	2.4	19.0	1.0	9.4	1.3	11.0	4.2	8.9	68.1
1961	3.2	5.1	0.4	2.7	0.4	9.4	5.2	4.9	7.2	0.4	5.0	1.1	45.0
1962	0.9	0.2	0.4	4.7	2.6	6.3	0.3	1.0	4.6	3.8	1.4	4.4	30.6
1963	0.6	1.9	0.3	0.5	0.4	6.8.	1.2	1.6	2.2	0.3	6.6	2.6	25.0
1964	3.8	2.4	3.1	0.2	1.8	7.0	1.6	5.1	8.3	1.0	2.4	3.2	39.9
1965	2.1	3.9	1.6	0.4	2.9	3.2	0.3	2.3	2.6	2.8	2.1	5.9	30.1
1966	4.0	3.2	0.6	4.9	6.4	6.8	3.6	1.9	4.4	1.6	0.5	1.9	39.8
1967	2.6	1.5	0.6	0.0	4.3	0.0	3.1	8.1	18.9	8.3	1.5	0.5	49.4
1968	4.4	2.9	2.1	1.0	6.1	15.5	3.7	3.0	4.4	2.8	1.4	1.8	49.1
1969	0.5	4.2	2.2	4.0	3.3	1.4	0.8	4.2	4.3	4.4	3.6	3.2	36.1
1970	2.4	1.8	4.1	3.2	5.3	2.6	3.9	1.8	9.7	6.4	0.2	0.9	42.3
1971	0.4	2.5	0.3	2.4	3.1	2.9	0.2	6.6	13.7	6.3	2.1	6.2	46.7
1972	3.8	1.8	0.9	2.2	6.4	0.7	4.7	3.6	10.0	12.1	4.3	0.3	50.8
1973	2.9	2.2	0.5	3.4	0.8	7.7	0.3	4.4	11.6	8.2	0.6	0.9	43.5
1974	4.2	1.4	3.3	4.1	11.1	3.7	0.5	6.6	4.7	1.7	5.0	2.6	48.9
1975	1.6	1.4	0.2	0.3	5.1	4.7	1.6	6.9	5.5	1.4	1.0	2.2	31.9
1976	0.3	0.1	1.0	6.3	3.8	2.3	16.1	1.6	5.6	5.0	4.9	5.9	52.9
1977	2.5	1.4	1.2	4.6	5.9	6.7	0.5	2.9	5.1	4.6	6.2	0.5	42.1
1978	3.4	4.6	0.3	2.4	0.1	5.0	2.5	0.7	7.5	3.6	3.6	2.6	36.3
1979	7.2	3.2	3.5	3.8	4.4	2.6	12.2	3.7	17.5	1.0	0.7	1.2	61.0
1980	4.3	1.3	3.0	0.6	5.4	0.0	2.1	5.2	4.6	1.6	1.5	0.9	30.5
1981	3.0	2.1	1.5	1.4	13.0	9.9	4.0	5.3	1.1	7.1	1.6	4.8	54.8
1982	0.5	9.0	0.5	2.0	4.0	1.6	1.4	2.4	1.8	3.7	8.0	1.3	36.2
Means:	2.7	2.7	1.5	2.5	4.3	5.5	3.1	4.1	6.8	4.3	3.0	2.8	43.1

Table B.2. Average daily temperatures (^{o}F) for each month. Values were computed as means from data obtained from stations: Point Comfort, Port Lavaca No. 2, Port O'Connor, Palacios FAA Airport and Matagorda No. 2.

Year	J	F	M	A	M	J	J	A	S	O	N	D
1960	53.6	52.6	57.2	71.1	74.3	82.0	84.3	83.5	79.5	75.3	63.8	53.2
1961	49.4	57.2	65.4	68.7	77.3	81.2	83.1	82.0	80.4	72.9	61.5	57.4
1962	48.5	64.1	60.0	69.4	77.0	81.5	84.8	85.5	82.4	77.2	63.0	55.4
1963	47.8	54.0	66.5	76.0	78.4	82.5	84.6	84.7	81.5	76.4	67.2	49.6
1964	53.0	52.2	61.2	72.3	78.6	81.9	84.8	85.4	81.1	69.6	67.0	55.9
1965	57.3	54.4	58.2	72.2	77.7	83.1	85.6	84.0	82.5	71.0	70.0	59.5
1966	49.5	52.2	62.4	71.4	75.5	80.9	83.6	83.6	79.6	71.4	66.3	55.9
1967	53.2	55.4	67.1	76.6	76.3	83.4	84.0	81.1	78.2	71.1	65.7	55.4
1968	52.0	51.8	59.0	69.8	77.2	80.6	82.8	84.4	78.8	75.0	62.4	56.4
1969	50.8	56.1	57.8	71.0	75.4	82.5	87.4	86.2	82.7	75.1	63.6	60.4
1970	59.6	58.0	59.9	71.5	74.2	81.1	83.9	85.2	81.8	71.4	61.6	64.1
1971	59.3	59.8	64.5	70.1	77.4	83.9	86.3	84.2	80.4	75.3	67.2	63.6
1972	49.8	59.4	68.4	74.6	76.4	83.2	83.4	84.8	83.1	74.2	60.3	53.4
1973	56.1	54.1	66.7	67.6	76.8	81.8	86.5	83.2	82.0	77.0	73.2	59.4
1974	57.8	57.4	68.8	72.0	79.2	82.5	84.1	83.9	76.9	73.7	63.9	56.0
1975	53.8	57.6	64.4	69.7	77.2	81.0	82.8	82.5	79.7	73.7	65.7	55.7
1976	47.3	64.0	66.3	70.2	73.8	81.4	82.0	83.6	79.8	65.1	55.8	52.3
1977	48.0	56.3	65.4	70.2	76.8	82.6	84.7	85.4	83.6	75.0	67.0	59.0
1978	47.9	48.6	61.6	69.1	78.2	83.2	85.4	85.3	81.2	73.3	67.6	56.7
1979	57.9	53.2	64.7	71.4	74.6	81.4	83.4	83.5	77.6	75.7	61.6	54.8
1980	54.1	53.7	62.1	67.5	76.3	84.6	85.7	84.3	83.8	71.8	60.7	58.5
1981	54.1	55.1	62.7	73.6	76.2	81.8	84.8	84.4	80.1	75.9	68.0	59.4
1982	54.6	56.2	65.0	70.6	76.7	83.5	85.4	85.3	82.2	73.2	64.2	59.0
Means:	52.8	55.8	63.3	71.2	76.6	82.2	84.5	84.2	80.7	73.5	64.7	57.0

Table B.3. Low temperature days. Values were computed as means from data obtained from the Port Lavaca No. 2 and Port O'Connor weather stations.

Year	Number of days the temperature reached 32°F or below.					Number of days in April the temperature reached 68°F or lower.
	Prev. Nov.	Prev. Dec.	Jan.	Feb.	Mar.	April
1960	0.0	2.0	1.5	3.5	0.0	20
1961	0.0	2.0	4.5	1.5	0.0	19
1962	0.0	3.0	8.0	0.0	2.0	24
1963	0.0	3.0	10.5	4.0	0.0	11
1964	0.0	0.0	5.0	2.0	0.0	20
1965	3.0	6.0	1.0	3.0	3.0	18
1966	0.0	0.0	8.0	2.0	1.0	23
1967	0.0	1.0	1.0	3.0	0.0	14
1968	1.5	0.0	5.5	2.0	0.5	19
1969	0.5	0.0	3.0	0.0	0.0	25
1970	0.0	0.0	4.0	1.5	0.0	18
1971	0.0	1.0	2.5	3.5	1.0	21
1972	0.0	2.5	4.0	1.5	0.0	16
1973	0.0	0.0	5.0	3.0	0.0	22
1974	0.5	0.0	2.0	3.0	0.0	18
1975	2.5	2.0	3.0	4.0	0.0	20
1976	0.0	1.0	3.0	0.0	0.0	24
1977	0.0	2.0	6.0	0.0	0.0	26
1978	0.5	1.0	8.0	2.0	1.5	25
1979	0.0	1.5	9.5	2.5	0.0	24
1980	0.0	0.0	0.0	0.0	0.0	30
1981	0.0	1.0	0.0	2.0	0.0	14
1982	nd*	nd	6.0	1.0	0.5	21

*no data.

Appendix C. Commercial Shrimp Harvest and Shrimp Sampling Data.

Table C.1. Monthly commercial catches of brown shrimp, *Penaeus aztecus*, from Matagorda Bay. Values are in thousands of pounds of tails.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	0	0	0	0	0	0	0	1.6	0	0	0	0
1961	0	0	0	0	19.1	0	4.8	4.9	0	0	0	0
1962	0	0	0	0	12.1	4.9	110.8	10.4	0	0	0	0
1963	0	0	0	0	7.3	74.3	23.5	0	0	0	0	0
1964	0	0	0	0	26.4	87.2	4.8	0	0	0	5.2	0
1965	0	0	0	0	78.6	242.2	31.0	274.3	0	0.8	38.2	2.3
1966	0	0	0	0.2	33.2	117.2	42.3	0	0	3.6	0	2.0
1967	0	0	0	1.1	88.9	13.2	16.1	6.5	6.0	0	0	0
1968	0	0	0	0	1.3	49.7	0	0	0	0	0	0
1969	0	0	0	0	7.4	48.1	12.0	0	0	0	0	0
1970	0	0	0	0	26.1	81.3	1.0	0	0	0	0	0
1971	0	0	0	0	27.1	95.6	12.2	0	0	0	0	0
1972	0	0	0	5.7	97.2	39.3	5.7	0	0	0	0	0
1973	0	0	0	0	73.0	354.2	116.8	0	0	0	0	0
1974	0	0	0	0	123.3	103.5	54.5	0	0	0	0	10.5
1975	0	0	0	4.0	197.4	194.4	51.4	23.0	0	0	12.0	5.8
1976	0	0	0	0	208.9	308.4	33.4	0	0	0	0	0
1977	0	0	0	1.4	123.4	466.9	29.0	0	0	0	0	0
1978	0	0	0	11.4	81.1	265.8	117.6	1.9	0	2.0	0	0.2
1979	0	0	0	4.7	277.1	819.5	304.2	0	7.4	0	0	0
1980	0	0	0	0.5	284.1	766.7	213.2	0.6	10.2	5.2	0	0
1981	0	0	0	2.6	306.6	382.6	98.0	0	0	0	0	0
1982	0	0	4.0	0.6	241.2	645.0	208.1	5.3	0.5	0.3	0	0

Table C.2. Monthly commercial catches of white shrimp, *Penaeus setiferus*, from in Matagorda Bay. Values are in thousands of pounds of tails.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	0	0	0	0	0	0	0	403.7	408.8	311.5	123.8	6.4
1961	0	0	0	0	74.9	8.1	7.9	237.6	120.5	151.4	126.1	47.1
1962	0	0	0	0	0	0.2	0	422.3	206.5	171.9	111.0	0.4
1963	0	0	0	0	1.0	0.1	9.0	294.8	378.0	262.6	92.8	10.6
1964	0	0	0	0	12.8	8.7	34.7	504.1	557.0	301.2	159.1	4.0
1965	0	0	0	6.5	8.3	5.4	9.6	60.3	316.1	276.0	150.4	5.4
1966	0	0	0	0	20.0	7.6	5.5	441.1	344.2	204.9	43.5	0
1967	0.4	0	0	0	3.3	0.2	0	125.6	121.2	272.1	111.6	51.2
1968	27.6	0	0.3	3.7	10.4	0	1.3	437.7	418.6	512.1	133.6	0
1969	0	0	0	7.8	98.0	28.0	9.6	153.2	271.1	192.9	96.0	0
1970	0	0	0	3.7	26.5	51.1	12.3	263.7	433.9	321.5	71.0	0
1971	0	0	0	0	4.0	6.4	1.2	42.2	160.4	357.9	122.7	0
1972	0	0	0	19.6	50.0	34.9	18.0	212.8	208.3	256.2	40.7	0
1973	0	0	0	3.3	27.3	86.8	30.1	193.4	572.2	448.4	388.9	156.3
1974	29.4	22.2	36.2	57.0	119.0	42.7	43.4	253.6	140.8	117.9	26.0	33.1
1975	0.8	0	0	4.5	65.2	19.8	6.6	86.7	136.3	165.9	89.1	22.9
1976	1.5	0	0	2.7	10.8	16.5	14.7	171.0	285.4	147.4	17.3	0
1977	0	0.3	0	2.5	24.5	44.6	53.2	373.2	846.5	438.1	204.2	197.6
1978	4.0	4.5	0	4.5	12.7	4.1	0.3	254.8	496.8	450.7	187.1	104.5
1979	6.8	0	0	32.9	23.3	23.4	1.2	644.5	380.0	389.8	314.0	82.3
1980	0	0	0	12.2	53.5	42.6	2.4	289.6	289.8	306.5	128.9	10.2
1981	1.8	0	0.3	8.0	24.4	0.9	0.2	118.8	257.2	349.1	205.0	191.8
1982	27.3	0	0	5.5	19.8	3.9	1.7	235.2	339.9	231.0	306.1	81.5

Table C.3. Monthly catches of brown shrimp in statistical subarea 19 off the Texas coast. Values are in thousands of pounds of tails.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1960	119	47	220	215	293	143	4078	4114	2862	2449	797	118	15455
1961	64	102	146	144	358	397	1373	1681	410	329	212	210	5426
1962	159	267	48	86	77	128	716	1280	1953	1558	688	428	7388
1963	58	50	23	36	183	505	2782	4255	2745	1835	489	165	13126
1964	29	39	67	162	192	284	1806	2570	2064	977	286	183	8659
1965	233	73	36	147	101	260	3215	2954	2620	1727	1599	1181	14146
1966	294	98	178	81	93	225	1063	2911	3966	1662	992	1040	12603
1967	164	98	87	103	320	2706	4752	5015	2767	1582	812	672	19078
1968	183	140	74	114	171	554	2683	3881	2220	1742	1350	613	13725
1969	294	244	168	124	345	428	1795	2922	1433	719	633	736	9841
1970	167	211	170	264	334	600	1886	3151	2977	1457	1368	918	13503
1971	299	233	98	180	164	342	3216	4352	2459	1651	1153	492	14639
1972	280	126	120	52	236	794	4378	5230	3454	1436	604	722	17432
1973	93	33	80	107	170	395	1222	1480	840	743	388	285	5836
1974	261	218	161	84	159	381	1196	1106	619	277	184	132	4778
1975	81	46	64	23	85	402	1746	1800	1064	640	387	390	6728
1976	58	85	52	62	23	196	1798	1954	1491	1235	593	166	7713
1977	37	44	48	91	110	212	2989	2511	939	708	1487	831	10007
1978	183	364	46	20	293	317	1930	2085	1166	901	559	740	8604
1979	150	104	226	101	143	342	829	1033	649	572	769	312	5230
1980	157	77	15	44	154	337	1264	1583	2175	1629	827	424	8686
1981	77	33	8	30	45	2	5451	5200	1990	1264	1278	597	15975
1982	202	155	43	26	89	43	2851	2446	985	856	522	167	8385
MEAN:	158	126	95	100	180	434	2392	2848	1906	1215	782	501	10738
SD:	88	90	66	64	101	527	1313	1338	982	556	416	313	4217

Table C.4. Monthly efforts directed at brown shrimp in statistical subarea 19 off the Texas coast. Values are in days (1 = 24 fishing hours).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1960	187	79	419	594	845	452	2828	4005	3375	3053	1167	254	17258
1961	264	597	384	437	1104	1123	2678	2944	610	501	317	328	11287
1962	256	556	134	351	329	380	1625	3040	3059	2823	1175	780	14508
1963	156	153	95	137	645	899	3284	5509	3776	2613	714	235	18216
1964	56	110	144	450	619	607	2581	4733	3774	1627	530	355	15586
1965	507	193	127	479	381	328	3179	3740	3136	2134	2115	1586	17905
1966	538	263	414	305	270	640	1500	3656	5354	2499	1542	1604	18585
1967	370	288	252	582	922	2151	3345	4529	2664	2084	1212	1239	19638
1968	397	425	223	451	440	885	3589	4733	3311	2891	2017	1047	20409
1969	839	1180	1113	1221	2203	2386	5259	4619	2317	2415	1079	1453	26084
1970	375	592	492	883	974	1148	2293	3107	3519	2202	1751	1339	18675
1971	614	620	248	487	502	648	3529	5516	3201	2344	973	781	19463
1972	534	410	264	252	0	1459	3228	5442	4693	2236	827	1200	20545
1973	601	89	199	661	758	644	1438	3406	2625	1605	737	557	13320
1974	274	0	0	419	439	754	1538	1338	652	483	509	347	6753
1975	270	0	0	0	348	580	2005	2699	1817	1322	747	777	10565
1976	149	261	161	209	81	357	2000	3186	2209	1691	1317	631	12252
1977	86	303	313	378	718	486	2639	2812	1122	1150	2373	1523	13903
1978	366	833	337	63	1310	627	1829	2819	1742	2356	1478	1956	15716
1979	453	341	842	185	518	583	1177	1781	999	848	1077	902	9706
1980	792	870	202	133	275	4922	4314	3507	4107	7724	4902	2580	34328
1981	299	85	4	55	111	0	2110	3666	1904	1255	1321	1145	11955
1982	389	436	102	90	307	78	2350	3556	1903	1525	1048	441	12225
Means:	381	378	281	384	613	962	2623	3667	2690	2147	1345	1003	16473
SD:	207	303	261	287	481	1036	1000	1107	1256	1418	935	606	5867

Table C.5. Monthly catches of white shrimp in statistical subarea 19 off the Texas coast. Values are in thousands of pounds of tails.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1960	2	0	10	138	47	12	99	111	511	636	599	140	2305
1961	29	88	185	42	124	18	84	78	60	561	615	424	2308
1962	84	65	49	14	36	5	99	16	133	111	377	20	1009
1963	1	0	39	16	78	5	61	33	47	372	399	510	1561
1964	78	14	81	144	179	77	120	77	180	349	366	169	1834
1965	11	50	125	158	89	70	128	36	45	496	308	143	1659
1966	108	75	348	128	402	74	106	29	132	376	368	160	2306
1967	57	52	186	58	90	54	139	29	71	278	199	162	1375
1968	64	18	71	97	72	45	107	136	723	878	523	180	2914
1969	50	62	119	118	222	86	200	134	646	667	868	80	3252
1970	14	14	156	105	418	261	335	98	368	1128	323	145	3365
1971	17	57	86	89	246	116	134	49	164	575	536	201	2270
1972	219	117	237	220	380	189	301	88	100	314	677	86	2928
1973	48	61	95	95	165	56	117	128	718	909	571	306	3269
1974	197	159	142	136	292	114	196	59	182	306	333	154	2300
1975	32	72	118	110	190	110	51	36	68	142	461	156	1553
1976	58	137	165	68	86	64	97	117	145	293	291	52	1573
1977	22	4	55	62	54	29	42	34	418	566	798	255	2339
1978	172	12	103	86	85	54	88	71	143	794	570	166	2344
1979	36	19	72	110	145	54	110	15	123	488	322	126	1620
1980	32	34	43	16	37	31	130	30	202	270	458	152	1435
1981	29	38	54	62	43	8	145	81	112	514	605	153	1844
1982	35	76	126	51	168	92	68	105	152	695	487	197	2252
Means:	61	54	116	92	159	72	129	69	237	509	481	180	2157
SD:	60	43	75	50	118	62	71	40	216	256	168	109	657

Table C.6. Total number of Texas Parks and Wildlife Department Matagorda Bay barseine and trawl samples examined for brown and white shrimp relative abundance and size information.

Bay/Gear Month:	J	F	M	A	M	J	J	A	S	O	N	D
Tres Palacios/Barseine 1963-80	0	3	13	69	63	14	11	11	11	10	11	3
Tres Palacios/Trawl 1963-80	0	4	17	68	63	27	31	37	28	24	18	11
Turtle/Trawl 1972-80	0	3	4	21	19	15	12	15	10	10	8	8
Carancahua/Trawl 1968-80	0	2	3	27	27	18	17	20	16	13	8	9
Lavaca/Trawl 1972-80	0	6	9	13	13	12	20	21	21	18	11	12
East arm, Matagorda/Trawl 1966-80	0	0	6	39	37	11	17	19	14	6	6	1
Matagorda/Trawl 1963-80	0	8	47	142	111	50	59	59	54	50	47	20
Trawl Totals	0	23	86	310	270	133	156	171	143	121	98	61

Table C.7. Mean abundance and lengths of brown shrimp in Texas Parks and Wildlife Department Matagorda Bay System samples, 1963-80. A barseine catch is the number of shrimp caught in a 500-ft drag. Trawl catches were standardized to the equivalent number of shrimp caught by a 25-ft net dragged for 15 min.

Bay/Gear		BROWN SHRIMP - MEAN #/SAMPLE										
	J	F	M	A	M	J	J	A	S	O	N	D
Tres Palacios/Barseine	ns[a]	0	2	60	61	20	1	3	8	12	12	16
Tres Palacios/Trawl	ns	1	6	64	159	145	58	12	7	3	1	2
Turtle/Trawl	ns	0	0	106	205	84	48	1	5	2	6	0
Carancahua/Trawl	ns	0	0	56	80	84	51	1	0	1	0	0
Lavaca/Trawl	ns	0	1	26	88	66	35	8	1	0	0	0
East arm, Matagorda/Trawl	ns	ns	58	43	172	111	43	16	2	2	1	0
Matagorda/Trawl	ns	0	10	25	97	107	67	11	7	4	2	2
Trawls only: Percent	—[b]	0	3	15	36	27	14	2	1	1	1	0
Rank	—	11	5	3	1	2	4	6	7	8	9	10

Bay/Gear		BROWN SHRIMP - MEAN LENGTHS										
	J	F	M	A	M	J	J	A	S	O	N	D
Tres Palacios/Barseine	ns	—	23	28	37	42	41	36	27	35	39	40
Tres Palacios/Trawl	ns	23	71	42	61	70	75	61	49	60	73	58
Turtle/Trawl	ns	—	—	33	57	72	92	44	40	22	62	—
Carancahua/Trawl	ns	—	—	44	62	78	73	78	—	26	—	—
Lavaca/Trawl	ns	—	78	61	78	78	80	66	71	—	—	—
East arm, Matagorda/Trawl	ns	ns	80	45	67	76	78	76	73	69	52	—
Matagorda/Trawl	ns	—	80	57	70	79	79	77	66	73	74	73

[a]ns = no sample

[b]— = no shrimp caught

Table C.8. Mean abundance and lengths of white shrimp in Texas Parks and Wildlife Department Matagorda Bay System samples, 1963–80. A barseine catch is the number of shrimp caught in a 500-ft drag. Trawl catches were standardized to the equivalent number of shrimp caught by a 25-ft net dragged for 15 min.

Bay/Gear	J	F	M	A	M	J	J	A	S	O	N	D
	WHITE SHRIMP - MEAN #/SAMPLE											
Tres Palacios/Barseine	ns[a]	0	0	0	0	28	136	92	64	51	30	39
Tres Palacios/Trawl	ns	0	2	3	3	157	296	179	107	161	78	8
Turtle/Trawl	ns	0	9	14	4	113	295	217	161	143	324	26
Carancahua/Trawl	ns	0	1	6	1	66	376	301	214	274	172	8
Lavaca/Trawl	ns	0	12	23	18	112	259	235	146	245	30	1
East arm, Matagorda/Trawl	ns	ns	2	12	5	41	151	222	82	45	90	50
Matagorda/Trawl	ns	0	1	3	3	4	46	61	31	20	25	20
Trawls only: Percent	—[b]	0	0	1	1	9	25	21	13	16	13	2
Rank	—	11	10	8	9	6	1	2	4	3	5	7
	WHITE SHRIMP - MEAN LENGTHS											
Bay/Gear	J	F	M	A	M	J	J	A	S	O	N	D
Tres Palacios/Barseine	ns	—	—	—	—	26	40	35	33	37	43	46
Tres Palacios/Trawl	ns	—	102	112	140	46	67	92	84	82	74	72
Turtle/Trawl	ns	—	90	108	145	66	74	86	89	81	56	63
Carancahua/Trawl	ns	—	106	116	146	48	64	76	77	61	62	56
Lavaca/Trawl	ns	—	93	120	141	65	77	93	92	81	87	102
East arm, Matagorda/Trawl	ns	ns	114	113	139	87	87	96	93	81	76	69
Matagorda/Trawl	ns	—	100	117	150	101	83	109	108	104	88	77

[a]ns = no sample

[b]— = no data to form a value.

APPENDIX D. Additional Correlations and Regressions.

Table D.1. Correlations (r=) between annual river flow volumes and annual commercial shrimp catches in the Matagorda Bay system. Annual river flow volumes were summed monthly volumes from August of the previous year thru July for brown shrimp, and from December of the previous year thru November for white shrimp.

	Lavaca River		Colorado River[1]	
Brown Shrimp	r	Signif. p<	r	Signif. p<
Previous 12 months				
1961-1978	.07	n.s.	.10	n.s.
1979-1982	.41	n.s.	.14	n.s.
1961-1982	.26	n.s.	.03	n.s.
Lag 1 year				
1962-1978	.03	n.s.	.21	n.s.
1979-1982	.17	n.s.	-.11	n.s.
1962-1982	-.00	n.s.	-.15	n.s.
White Shrimp				
Previous 12 months				
1961-1976	.39	n.s.	.08	n.s.
1977-1982	.23	n.s.	.44	n.s.
1961-1982	.38	n.s.	.12	n.s.
Lag 1 year				
1962-1976	-.17	n.s.	-.49	.10
1977-1982	-.42	n.s.	-.28	n.s.
1962-1982	-.16	n.s.	-.37	.10

[1]Colorado River flows are adjusted to include only the amount estimated to be entering the bay.

Table D.2. Correlations (r=) between annual commercial shrimp catches in th Matagorda Bay System and seasonal river flow volumes.

Brown Shrimp	Lavaca River 1961-78	Colorado River[1] 1961-78
Winter	.13	.05
Spring	.20	.26
Summer	-.18	.04
Early Fall	-.15	-.06
Fall	-.04	-.00
White Shrimp	**1961-76**	**1961-76**
Winter	.11	.05
Spring	.58*	.19
Summer	-.06	-.18
Fall	-.06	.02

Seasons	for Brown Shrimp	for White Shrimp
Winter	January-April	Prev. December-March
Spring	May and June	April-June
Summer	Prev. July & Prev. August	July and August
	Prev. September	
Fall	Prev. Oct.-Prev. Dec.	September-November

*Significant ($p < = .05$).

[1]Colorado River flows are adjusted to include only the amount estimated to be entering the bay.

Table D.3. Correlations (r=) between monthly river flow volumes and annual commercial catches of shrimp in the Matagorda Bay System.

A. Brown Shrimp

Months	Lavaca River 1961-78	Adjusted Colorado River 1961-78
Prev. Aug.	-.27	-.05
" Sept.	-.15	-.06
" Oct.	-.26	-.04
" Nov.	-.07	.03
" Dec.	.28	-.01
January	-.17	-.14
February	-.04	.12
March	.02	-.22
April	.38	.28
May	.05	.26
June	.20	.20
July	.01	.06

B. White Shrimp

Months	Lavaca River 1961-76	Adjusted Colorado River 1961-76
Prev. Dec.	-.34	-.35
January	.14	.12
February	-.19	.00
March	.56*	.32
April	.49*	.33
May	-.12	-.06
June	.71**	.29
July	-.01	-.21
August	-.09	-.08
September	-.20	-.07
October	.37	.44+
November	-.16	-.20

+Significant (p< = .10).
*Significant (p< = .05).
**Significant (p< = .01).

Table D.4. Regression equations for monthly Tres Palacios Creek flows (x) as they explain changes in residual brown shrimp trawl samples catches (Y) from Tres Palacios Bay, 1972-80.

		r^2	Significance p<
January	$Y = 465 - 7.03x$	.07	n.s.[a]
	$Y = 372 + 15.92 - 0.692x^2$	.14	n.s.
February	$Y = 488 - 16.46x$	.15	n.s.
	$Y = 415 + 16.38x - 1.692x^2$	.19	n.s.
March	$Y = 464 - 16.10x$	.15	n.s.
	$Y = 430 + 5.85x + 1.095x^2$	.16	n.s.
April	$Y = 626 - 56.10x$	.14	n.s.
	$Y = 967 - 224.19x + 15.219x^2$	.44	n.s.
May	$Y = 252 + 4.94x$	.10	n.s.
	$Y = 437 - 43.81x + 1.431x^2$	.68	.05
June	$Y = 463 - 43.74x$	.36	n.s.
	$Y = 645 - 132.42x + 8.522x^2$	.43	n.s.
July	$Y = 49 + 1.88x$	.02	n.s.
	$Y = -136 + 56.27x - 2.086x^2$	.62	.10

[a]n.s. = $p > .10$

Table D.5. Regression equations for monthly Tres Palacios Creek flows (x) as they explain changes in residual brown shrimp barseine catches (Y) from Tres Palacios Bay, 1971-80.

		r^2	Significance p<
January	$Y = 114 - 3.01x$	.28	n.s.[a]
	$Y = 126 - 6.61 + 0.113x^2$	.31	n.s.
February	$Y = 117 - 5.00x$	.29	n.s.
	$Y = 125 - 8.90x + 0.215x^2$	.30	n.s.
March	$Y = 109 - 4.99x$	.26	n.s.
	$Y = 141 - 25.27x + 1.014x^2$	.43	n.s.
April	$Y = 108 - 2.48x$	.22	n.s.
	$Y = 136 - 11.00x + 0.221x^2$	.29	n.s.
May	$Y = 72 - 1.63x$	.34	n.s.
	$Y = 103 - 9.38x + 0.229x^2$	.90	.05

[a]n.s. = $p > .10$

Table D.6. Regression equations for monthly adjusted Colorado River flows (x) as they explain changes in April and May brown shrimp trawl sample catches (Y) in the east arm of Matagorda Bay, 1966-77.

		r^2	Significance $p<$
Dec mber	$Y = 226 - 0.22x$	.04	n.s.[a]
	$Y = 235 - 0.42x + 7.122x^2$	.05	n.s.
January	$Y = 164 + 0.26x$	.06	n.s.
	$Y = 226 - 0.89 - 0.003x^2$	.13	n.s.
February	$Y = 242 - 0.33x$	.09	n.s.
	$Y = 167 + 1.20x - 0.005x^2$	.24	n.s.
March	$Y = 193 + 0.03x$	.01	n.s.
	$Y = 235 - 0.90x + 0.003x^2$	.05	n.s.
April	$Y = 210 - 0.07x$	.01	n.s.
	$Y = 183 + 0.26x - 6.59x^2$	.04	n.s.

[a]n.s. = $p > .10$

Table D.7. Regression equations for monthly Lavaca River flows (x) as they explain changes in April and May brown shrimp trawl sample catches (Y) in the main body of Matagorda Bay, 1963-80.

		r^2	Significance p<
December	$Y = 119 + 0.07x$	.01	n.s.[a]
	$Y = 127 - 0.37x + 0.001x^2$	.02	n.s.
January	$Y = 132 - 0.16x$	.02	n.s.
	$Y = 127 + 0.05 - 8.522x^2$	.02	n.s.
February	$Y = 133 - 0.23x$	.02	n.s.
	$Y = 128 + 0.05x - 0.002x^2$	.02	n.s.
March	$Y = 138 - 0.47x$	.07	n.s.
	$Y = 155 - 1.68x + 0.008x^2$	.10	n.s.
April	$Y = 139 - 0.25x$	.08	n.s.
	$Y = 157 - 0.87x + 0.002x^2$	.15	n.s.

[a]n.s. = $p > .10$

Tabld D.8. Regression equations for monthly adjusted Colorado River flows (x) as they explain changes in April and May brown shrimp trawl sample catches (Y) in the main body of Matagorda Bay, 1963-80.

		r^2	Significance p<
December	$Y = 123 - 0.01x$	.00	n.s.[a]
	$Y = 138 - 0.46x + 0.002x^2$	.01	n.s.
January	$Y = 145 - 0.21x$	.05	n.s.
	$Y = 169 - 0.71 + 0.002x^2$	.07	n.s.
February	$Y = 163 - 0.35x$	.12	n.s.
	$Y = 145 + 0.075x - 0.005x^2$	.14	n.s.
March	$Y = 154 - 0.34x$	.12	n.s.
	$Y = 201 - 1.60x + 0.005x^2$	.23	n.s.
April	$Y = 137 - 0.117x$	.03	n.s.
	$Y = 170 - 0.73x + 0.001x^2$	.19	n.s.

[a]n.s. = $p > .10$

Appendix E. Salinity Requirements of the American Oyster, *Crassostrea virginica*

by Sammy M. Ray
Texas A&M University at Galveston
5007 Avenue U
Galveston, TX 77550

Salinity Requirements of the American Oyster, *Crassostrea virginica*

By Sammy M. Ray

Large populations of the American oyster (*Crassostrea virginica*) characteristically occur in estuarine systems that are fed by major rivers. The Louisiana coastal area and Chesapeake Bay are prime examples of the direct association of high oyster production with high freshwater inflow. The vast flow of the Mississippi River is directly responsible for the large areas of highly productive oyster reefs, both east and west of the Mississippi delta. With regard to Texas, the greatest oyster production generally occurs in the Galveston Bay system, whereas little or no production occurs in the Laguna Madre. This difference in production is directly associated with the difference in freshwater inflow. The Galveston Bay system is fed by two major rivers, the Trinity and San Jacinto Rivers. On the other hand, no major rivers enter the Laguna Madre.

Oysters are euryhaline organisms that tolerate a wide range of water salinity. According to Chanley (1957) the optimum salinity for *C. virginica* is between 15 and 22.5 parts per thousand (ppt). Galtsoff (1964) reported the range of favorable water salinity for oysters to be 5 to 30 ppt. He further noted that prolonged exposure to water salinities of less than 10 ppt or more than 34 ppt is unfavorable. Only marginal populations exist at the extremes of the salinity range (5-40 ppt). In Chesapeake Bay the optimum salinity for oysters is from 10 to 28 ppt (Galtsoff 1964), whereas the optimum salinity for growth and survival in Louisiana is much lower, 5 to 15 ppt (Galtsoff 1964, St. Amant 1964). Thus, American oysters in more northern latitudes appear to be more tolerant of high salinity levels than those in more southern latitudes (Van Sickle et al. 1976). With such a wide range of salinity tolerance, oyster reefs may form from the upper to the lower reaches of a bay.

On the one hand, oysters at the upper end (area of major freshwater introduction) of a bay are generally plagued by freshwater kills and siltation resulting from floods, which generally occur in late winter and spring. On the other hand, the oyster populations at the lower end (area of major seawater entrance) of the bay are threatened by predatory and disease-causing organisms. Since optimal conditions for oyster propagation and survival are likely to exist more often in the middle region than at either the upper or lower region of a bay, it also follows that the greatest area of oyster reefs will occur in the middle region. An examination of a map of the Galveston Bay oyster reefs (Fig. 3, Hofstetter 1977) will show this to be the case.

Natural factors such as prolonged droughts, planned reduction of freshwater inflow and deepwater channels within bays are among the major factors that enhance the intrusion of high salinity waters into estuarine systems. Increased intrusion of high salinity waters effectively shifts the optimum condition for oyster production towards the upper bay. Such a shift upward from the middle region of a bay generally results in a reduction in area of suitable reefs or substrate for setting of oysters. In addition to reduced substrate, oysters growing at the upper extremity of a bay are much more vulnerable to freshwater kill and siltation than those in the middle region of the bay.

As previously mentioned, biological agents (predators, parasites and pests) that are detrimental to oysters are most prevalent in areas where salinities consistently exceed 20 ppt. Furthermore, the adverse effects of most of the detrimental organisms are exacerbated at water temperatures in excess of 20°C. For example, oyster mortality is considerably greater in water of 25 ppt salinity and 25°C temperature than at lower levels of either hydrographic parameter. Furthermore, the degree of damage is directly related to the length of time oyster populations are subjected to elevated salinity and temperature. Also, the reduction or elevation of the level of any one of these two hydrographic features will either ameliorate or enhance the adverse effects of the other factor with regard to oyster mortality. Thus reduced freshwater inflows will result in more damage to oyster populations in July and August when temperatures are high than in the cooler months of December and January.

As noted earlier, floods and prolonged freshets pose a constant threat to oyster populations. Nevertheless, an adequate influx of freshwater is absolutely essential to provide nutrient-rich waters and sediments to nourish the estuarine syst m, including the marshes. Ther fore, a failure to carefully consider the total role played by freshwater introduction in estuarine productivity, may result in long term changes that could be disasterous to populations of sessile organisms such as oysters. It has been suggested by some that controlled reduction of freshwater influx during the "wet" season may be useful in minimizing the adverse effects of low salinity on spawning and setting as well as freshwater kills of oysters. However, under such a regime, salt water intrusion into the stuary may become more pronounced with a resultant gradual increase in oyster enemies. Moreover, once freshwater is retained behind a barri r, it will probably be very costly and difficult to arrange for releases in sufficient volume and duration to provide the purging and flushing effects of natural floods.

LIFE HISTORY

This brief account of the life history of the American oyster in Texas coastal waters is taken primarily from Galtsoff (1964) and Hofstetter (1977 and 1983). As a result of more than 30 years of study by Robert P. Hofstetter, oyster biologist with the Texas Parks and Wildlife Department at Seabrook, Texas, the biology and ecology of oysters are better known from the Galveston Bay system than for any other Texas bay. Much of the results of Hofstetter's studies in Galveston Bay is summarized in his 1977 publication dealing with trends in oyster population in Galveston Bay from 1952 to 1972. In a subsequent publication, Hofstetter (1983) records the oyster population trends in Galveston Bay for 1973–1978.

In recent years, with one exception, the major harvest of Texas oysters has come from the Galveston Bay system (Hofstetter 1977 and 1983). Between 1961 and 1978, 60% to 90% of the total Texas oyster harvest was from this bay system. However, in 1978–79, San Antonio Bay produced 75% of the Texas harvest, whereas the Galveston Bay harvest fell to 2% of the total harvest. This drop in production came as a result of shortening the 1978–79 Galveston Bay season to 45 days in order to protect the large supply of small seed oysters from dredging damage. This action led some

Galveston Bay oystermen to shift their operation from Galveston Bay to San Antonio Bay (Hofstetter 1983).

Spawning and Setting

Oysters with ripe gonads are common in Galveston Bay from April through September. Hofstetter found a few ripe individuals in winter at a temperature range of 17 - 20°C. Mass spawning of Galveston Bay oysters probably occurs between May and August. Eighty to 100% of the large oysters appear to be sexually mature at this time (Hofstetter 1977).

Frequent spat-set failure in the Galveston Bay system appears to be related to late winter and spring floods. Over a 23-year period, Hofstetter (1983) found that best spat sets usually occurred when spring salinities ranged between 17-24 ppt and that there was little spat set when salinity fell below 8 ppt. In other field and laboratory studies, Butler (1949) found that gametogenesis and spawning were suppressed by prolonged exposure to salinity levels of less than 6 ppt, and the return to normal gonadal activity is delayed for three to four months following salinity increases. Butler attributed the suppression of gonadal activity to variations in food supply rather than direct effect of less saline water. Hofstetter (1977) has observed milky oysters in Galveston Bay in late spring and early summer when salinities were below 5 ppt. He considered that these oysters may have matured before the salinities were depressed by river flooding. Moreover, he had no evidence that these oysters ever spawned. Galtsoff (1964) states that *C. virginica*'s free swimming larval stage may last for 2 to 3 weeks, depending upon temperature, salinity and other factors. Hofstetter provided no information of the length of the larval oyster stage in Galveston Bay.

During a 20-year period (1953-1972), Hofstetter observed initial spat sets most often in May and June. In some years, however, initial sets were observed as early as April and as late as August. In mid-Galveston Bay (Redfish Reef) setting first began when salinity values averaged 14 ppt, with a range of 5-24 ppt, and the mean monthly temperature was 26°C (21-29°C range).

Although peak annual oyster spat sets generally occurred in June and

July, some peaks were observed in May, August and October during the 20-year period. At Redfish Reef the salinity averaged 16 ppt (4-24 ppt range), and the mean temperature was 27°C (21-29°C). P ak sets did not occur during the same months in all areas of the Galveston Bay system. Generally peak sets occurred in upper and middle Galveston Bay in June and in East Bay during July and August. Moreover, secondary peaks of setting occurred at some stations in the Galveston Bay system. Hofstetter noted such secondary peaks took place seven times between 1962 and 1972, with October being the month of most common occurrence.

Growth and Survival

Hofstetter (1977) provided some data on growth and survival of oysters in Galveston Bay. At Todd's Dump in mid-Galveston Bay the average monthly growth was 6.9 mm for spat of the 5-10 mm size range and those of the 10-21 mm range showed an average monthly growth of 6.3 mm. During the 1962-72 period, Hofstetter found that spat usually reached seed oyster size within three months following setting; and sub-market and market sizes (minimum length of three inches) were reached in 7-10 months and 13-17 months, r spectively. The time required for spat to reach minimum legal mark t size varies with time of setting. May-June spat reach market-size in 13-15 months, whereas July-August spat require more time, 15-17 months. Hofstetter was unable to determine the time for September-October spat to become market size. In tray studies conducted in Galveston and East Bays, Hofstetter observed growth rates similar to those he reported for naturally growing populations. May spat of 1965 and 1967 reached market size in 16 months following setting; July spat of 1969 became market size in 14 months; and October spat of 1966 reached market size in 13 months.

Survival rates of oyster in the Galveston Bay system during the 1961-72 period have been determined by Hofstetter (1977). He determined the survival rates by comparing the average annual number of seed and submarket oysters with the average annual number of spat (per bushel sample) obtained from all sample stations. In summarizing the data obtained during the 1961-72 period, Hofstetter determined that about 85% of the spat became seed oyster size and that about 63% and 41% became sub-market and market-size oysters, respectively. Furthermore, he found that survival rates were greater in light-spat-set years than in heavy-spat-set years. During light-spat-set years, averaging 50 spat per sample, 74% of the spat reached seed size, whereas in heavy-spat-set years, averaging 400 spat per sample, 37% of the spat reached seed oyster size. With regard to quantity, seed oysters averaged 150 per sample in heavy-spat-set years compared with 40 seed oysters per sample in light-spat-set years; and sub-market oysters averaged 90 per sample in heavy-spat-set years compared with 35 per sample in light-spat-set years.

Moreover, Hofstetter (1977) found that the average annual Trinity River flow influenced oyster survival rate. During years of low flow (averaging 2,109,000 ac-ft per year) the oyster survival rate was greater than during years of high flow (averaging 6,975,000 ac-ft per year). In low flow years, 89% of the average annual number of spat reached seed oyster size, 71% reached sub-market size and 45% reached market size, whereas in high-flow years 75% of the spat reached seed oyster size, 56% reached sub-market size and 36% became market size. Also, in low-flow years the average number of market-size oysters was 35 per sample compared with 26 per sample in high-flow years.

Although Hofstetter's studies show a relationship between low Trinity River flow and relatively high oyster population levels in the Galveston Bay system, he further states (Hofstetter 1977) that this relationship should not lead one to conclude that reduced river flow is necessarily beneficial to oysters. Hofstetter (personal communication, March 25, 1985) is of the opinion that minimum water salinities of 10-15 ppt are necessary during spring and early summer for successful spawning and setting of oysters in most Texas bays, except Galveston Bay. He feels that a higher minimum spring salinity range, 15-20 ppt, is more suitable for spawning and setting in the Galveston Bay system. As previously noted, Hofstetter (1983) found that the best spat sets usually occurred in Galveston Bay when spring salinities ranged from 17-25 ppt.

In Louisiana, Chatry et al. (1983) recommended a somewhat lower salinity regime for good seed production. For 11 years (1971-1981) Chatry and his colleagues studied the relationships of salinity and spatfall to seed oyster production in the prime state-controlled seed ground east of the Mississippi River. They found that the salinity regime during the year in which spatfall occurred was closely related to the seed oyster production for the next year. With 11 years of data from three stations in the seed grounds, they determined an optimum annual salinity regime for good seed production. The critical period within the optimum salinity regime appears to be May through September. Optimum salinities for May are from 6-8 ppt, and salinities should average 13 ppt in June and July. Salinities should not exceed 15 ppt until late August and should not average more than 20 ppt in September. Chatry et al. (1983) recommended that this salinity regime be used in managing proposed freshwater diversions to increase seed oyster production in Louisiana.

Interestingly, Chatry et al. (1983) found an inverse relationship between spat set and seed production. Years with heavy spat set were followed by years of poor seed production, whereas lighter sets often resulted in better seed production. These results differ somewhat from those obtained in Galveston Bay by Hofstetter (1977), who found greater seed production following heavy spat sets. There is no doubt that higher salinities in spring and early summer favor higher spat production, but continued high salinities in excess of 15-20 ppt during the summer months is likely to result in poor survival as a result of predation. Thus, light sets of spat under salinity conditions that enhance their survival are probably sufficient to sustain a commercial fishery.

EFFECTS OF FLOODS

Floods and prolonged freshets play a major role in controlling oyster populations. According to Hofstetter (1977 and 1983) two major (1957 and 1973) and three minor floods (1961, 1966 and 1968) occurred in the Galveston Bay system between 1952 and 1978. Although the 1957 flood is considered to have been more severe than the 1973 flood, Hofstetter (1977) is of the opinion that the 1973 flood possibly caused greater damage to the oyster resource.

In May-June 1957 there was almost a total kill of oysters in Trinity

Bay and the eastern end of Redfish Reef (Hofstetter 1977). Severe mortality, however, was not observed on the central and western end of Redfish Reef. Moreover, East Bay appears to have escaped severe damage since oysters were harvested from this bay in the 1957-58 season. Also, the greatly reduced salinities in 1957 resulted in delayed spawning. In the central Galveston Bay area peak spawning did not occur until October. Other consequences of the 1957 flood appeared to be slower growth and poorer survival of oysters than usual. In various areas of the bay, 22 to 26 months were required for the 1957 spat to reach market size and the survival rate of these spat was rather low: 1% on Vingt-et-un Reef (lower Trinity Bay) and 3% on Todd's Dump (mid-Galveston Bay).

Although oyster sampling was restricted to Todd's Dump and Redfish Reef, both in central Galveston Bay, as well as Hanna's Reef (East Bay), no oyster mortality attributable to flooding was observed during 1961. There was no delay of spat setting, which began at all three stations in June and peaked in July. The 1961 spat reached market size in 16 to 20 months, and the survival rate of the spat to market size was 8% on Redfish and Hanna's Reefs and 10% on Todd's Dump.

During the 1966 flood, the oysters were killed in Trinity Bay. In central Galveston Bay, excessive mortality (30-40%), was limited to the eastern portion of Redfish Bar (Bart's Pass). Hofstetter (1977) reported on unpublished data obtained by Richard L. Benefield (Biologist, Texas Parks and Wildlife Dept.) in his studies of the effects of the 1966 flood on oysters in Trinity and upper Galveston Bays. Benefield found that oysters survived for two to three weeks in salinities of less than 5 ppt. However, more than 90% of the oysters died when exposed to salinities below 2 ppt at temperatures between 24° and 27°C. Benefield also noted that small oysters appeared to survive better than those of market size. Hofstetter (1977) found some spat set at all stations in June and July, but peak setting did not occur until October. Light to moderate sets occurred in mid-Galveston Bay and the set was light in East Bay. The spat reached market size on Redfish Bar in 11 months after setting, and those in East Bay became market size in 12-13 months.

During the 1968 flood, low (0-1 ppt) salinity persisted for several months (March-July) in Trinity Bay. The salinities showed a rang of 0-3 ppt in upper Galveston bay, 0-7 ppt in mid-Galveston Bay and 2-7 ppt in East Bay. In 1968 the sampling was limited to middle Galveston Bay and East Bay. In middle bay, flood-related mortalities ranged from 8% at Redfish Reef to 90% at Bart's Pass. In East Bay the mortality ranged from 19% to 32%. The spat set was delayed until September in upper Galveston Bay, August-September in middle Galveston Bay and July-August in East Bay. In the middle bay area, 1968 spat reached market size about 14 months aft r setting. Market-size oysters reached their peak in East Bay 15-16 months after setting.

According to Hofstetter (1977) the 1973 flood was similar to that of 1957, but the flooding period was more prolonged in 1973. In 1973 the spring flood lasted for four months and the fall flood lasted for three months, whereas in 1957 these floods persisted about one month less in both seasons. In April 1973 the salinity values were less than 10 ppt at all stations except those in East Bay (range 9-11 ppt). By mid-May the salinities dropped to 0-2 ppt at upper bay stations, 1-6 ppt at middle bay stations and 3-4 ppt at East Bay stations. During June and July the salinities did not exceed 3 ppt at any stations in the system except those in East Bay (3-4 ppt). The adverse effects of low salinities on oysters wer aggravated by the high water temperatures, which had increased from 20°C in May to 27°C in late June and 28°C in early July.

By mid-July oyster mortality reached 100% on Beezley's Reef (lower Trinity Bay), and by this time nearly all of the oysters in Trinity Bay were killed. In July 90% mortality occurred on Bart's Pass at the eastern section of Redfish Bar. Mortality in other sections of Redfish Bar decr ased from 30% to 15% from east to west. West of the Houston Ship Channel mortality of oysters was greater than that at the western portion of Redfish Bar due to flooding on the local watershed. In Dickinson Bay about 40% of the oysters were lost. The mortality in East Bay varied from 15 to 40%. Hofstetter found that oysters survived at salinities of 2 ppt or l ss for at least four weeks at temperatures ranging from 20-27°C. However, exposure to such low salinity for more than four weeks at water temperatures of 25-28°C resulted in severe mortality. Spat set, which was generally light, did not occur until September-October.

Hofstetter (1983) presented data on population trends in central Galveston Bay for the 1973-78 period. Although recovery from the 1973 flood was slow, sufficient set occurred in 1973 and 1974 to provide a relatively abundant oyster population in late 1974 and early 1975. However, light sets in 1975, 1976 and 1977 led to a decline of market oyster populations, which reached the lowest level recorded in 23 years by the summer of 1978. Fortunately, an abundant set in 1978 resulted in a great increase in small oysters (26-75 mm) in the summer of 1978. Although large populations of small oysters were found in all areas of the Galveston Bay system, the greatest number occurred along the west shore and central area of Galveston Bay. Hofstetter (1983) commented that the sharp increase in the number of small oysters following the good set of 1978 was a good indication of the ability of depressed oyster populations to recover rapidly with the return of favorable conditions. In order to protect the abundant crop of small oysters, the 1978-79 oystering season was closed for the entire Galveston Bay system on December 15, 1978.

In commenting on the effects of floods on spat set, Hofstetter (1977) notes that increased setting has been shown to follow flooding. He points out that such was the case shortly after the flood waters receded in 1957. Hofstetter considers that such increase might be due to increase in cultch derived from the relatively clean shells of dead oysters. The efficiency of "boxes" (dead oysters with both valves attached) as spat collectors is well known. Hofstetter noted further that in recent years the trend has been for a longer delay between flooding and more abundant spatfall. He thinks this trend may indicate the presence of some inhibiting agent or agents.

I concur with Hofstetter's comments (1983) regarding the effects of flooding on oyster populations in the Galveston Bay system. Hofstetter notes that despite the fact that flooding inhibits spatfall, low salinity often results in increased survival of market-sized oysters by reducing oyster drill predation as well as the spread of lethal disease organisms such as <u>Perkinsus</u>. Furthermore, he points out that low salinities enhance the survival of seed and market-sized oysters in central Galveston Bay, which is the ar a with the greatest amount of suitable substrate or shell in the entire Galveston Bay system.

MAJOR BIOLOGICAL ENEMIES OF OYSTERS

Populations of C. virginica on the coast of the Gulf of Mexico are plagued by numerous predators, parasites and pests (competitors and commensals). This report deals only with those biological agents that are known to cause serious mortality on the Gulf coast and in Texas in particular.

Pests (Competitors and Commensals)

The pests of oysters include numerous organisms that become attached to or bore into the shell of oysters. Many of these are fouling organisms that compete with oysters for food and setting space. Shell borers may weaken the shell structure and thus require the expenditure of excessive energy in shell repair. Among the major oyster pests on the Gulf coast are boring sponges (Cliona), boring clams (Dilplothyra), mud worms (Polydora), slipper shells (Crepidula), tunicates, bryozoans, barnacles, mussels (Ischadium = Brachidontes) and a variety of algae. Although competitors and commensals may be harmful to oysters when they occur in great abundance, none are considered to be major factors as mortality agents. For a general account of the pests of C. virginica the readers are referred to the section entitled: "Commensals and Competitors" in Galtsoff (1964).

Predators

Predation at all stages in the life cycle is a major cause of oyster mortality. The larval stages are destroyed by many grazing organisms such as ct nophores, coelenterates, ciliates, worms, barnacles, tunicates, various bivalves and fishes (Hofstetter 1977). The sessile stages are preyed upon by flatworms, crustaceans, molluscs, echinoderms, fishes, birds and mammals (Galtsoff 1964, Hofstetter 1977). The major predatory species found on the Gulf coast include flatworms (Stylochus), various fishes (black drum, Pogonias cromis; sheepshead, Archosargus probatocephalus; and various skates and rays), various species of crabs (blue crabs, Callinectes sapidus; stone crabs, Menippe mercenaria; and several species of smaller xanthid crabs) and the southern oyster drill, Thais haemastoma. Crabs, especially blue and stone crabs, are often as serious predators as drills (Hofstetter 1959). See Galtsoff (1964) for a general discussion of predators of the American oyster and see Hofstetter (1977) for a general account of the oyster predators of Galveston Bay, Texas. Also, see Butler (1985) for an excellent synoptic review of the literature on the southern oyster drill.

Worldwide, carnivorous gastropods are the most destructive predators of oysters. Many estuarine areas of the world are excluded from successful oyster propagation by predatory snails. Similar to most oyster predators, these snails are most abundant in more saline waters. There is little doubt that the southern oyster drill (Thais haemastoma) is the most destructive oyster predator on the Gulf coast and as such causes great economic loss to the industry. Drills feed on oysters and other molluscs by rasping the edge of shell or by drilling a hole in the shell and then removing the flesh with an extensible proboscis. Drills attack many sessile organisms such as mussels, barnacles, clams, hydroids and small oysters in preference to mature oysters (Butler 1954).

Thais haemastoma is a highly fecund organism and larval production is quite high (Galtsoff 1964). Each egg capsule may contain several hundred to several thousand eggs and each female may deposit from 50 to 150 capsules (Butler 1954). Unlike some predatory snails, the larvae escape from the egg capsules as free-swimming veliger larvae rather than very small, crawling juvenile snails. The planktonic stage lasts for 30 to 60 days (Butler 1954). Thus, T. haemastoma is easily and widely distributed by currents. In the Galveston Bay system, Hofstetter (1977) found drill egg capsules from April through August, but they were most common from May through July. During a wet year (1969), egg capsules were not found at Hanna Reef (East Bay) until September and no drills were collected in the prior months. In a dry year (1972), Hofstetter also noted late deposition of egg capsules in July-August at South Redfish Reef.

T. haemastoma become sexually mature when they are about one year old.

Based on data obtained from studies at Pensacola, Florida, Butl r (1954) postulated a minimum life span of about 5 years and a maximum of about 10 years. Under laboratory conditions he found that mortality averaged about 12% per year. In consideration of the adult snail's longevity, low mortality rate, high reproductive potential and sparcity of natural enemies, Butler further concluded that larval mortality must be high or oysters would not be able to survive in our coastal waters. It is likely that the relatively long pelagic life (30-60 days) contributes to high larval mortality.

The distribution of T. haemastoma in estuaries is salinity depend nt. This snail is usually absent from areas in which the sustained salinity level is less than 15 ppt (Butler 1954, Chapman 1954). At salinity levels of 10 ppt this organism is immobilized, and a salinity of 7 ppt for one or two weeks is lethal (Schechter 1943, Galtsoff 1964). Breithaupt and Dugas (1979) reported that epidemic populations of Thais were eliminated from the Louisiana "State Seed Ground" east of the Mississippi River in 1975 by major freshets, which reduced the salinities to less than 15 ppt. No measurable quantities of drills were noted in the study area for at least 24 months.

Although floods that cause low salinities kill many drills on reefs, significant populations of the snails may survive in deep pockets of salt water (Butler 1954). During the 1950 flood of Mississippi Sound, Butler observed that the freshwater conditions, which prevailed for about 6 weeks, killed many oysters and drills, yet large numbers of drills survived in the deep channel and they repopulated the entire area by the next year.

In addition to salinity, the drill's activity, including feeding, is dependent upon water temperature (Butler 1954). Drills stop feeding and become inactive at 12°C and they enter a state of hibernation at less than 12°C. During hibernation they usually burrow into the bottom substrate.

Presently, freshwater is the only practical means of controlling the spread of the southern oyster drill in estuarine systems (Butler 1954, Galtsoff 1964, Breithaupt and Dugas 1979). Breithaupt and Dugas (1979) proposed the introduction of freshwater from the Mississippi River to the Louisiana "State Seed Grounds" east of the river to control salt water intrusion. These authors suggest that the flow of freshwater should be controlled to achieve an optimum salinity in the 10 to 15 ppt range. They noted that a salinity of at least 10 ppt is required for oyster larvae to survive and that an upper limit of 15 ppt will keep drill populations in check. In addition to controlling oyster drill populations, Breithaupt and Dugas pointed out that the controlled introduction of Mississippi River water would allow nutrient-rich waters to revitalize the marsh while maintaining an optimum salinity for spat fall. It is my opinion that the approach suggested for Louisiana by Breithaupt and Dugas is applicable to Texas estuarine systems such as Matagorda Bay and Galveston Bay during dry years.

One must keep in mind that the timing of such controlled freshwater introduction is most important. In addition to *Thais*, *Perkinsus marinus*, another major cause of oyster mortality on the Gulf coast, is most active during the warm periods (summer and early fall) of the year. Thus, freshwater introduction during this time of year will be most effective in controlling the two most important oyster mortality agents on the Texas coast. Unfortunately, this time of year would probably be the most difficult in which to obtain the controlled release of freshwater from reservoirs into the estuaries because of reduced river flow, especially during dry years, and increased upstream demand for water during this period.

Parasites and Diseases

The American oyster serves as host for numerous parasites, which belong to several different taxonomic categories. Included among oyster parasites are bacteria, spirochaetes, fungi, protozoans, trematodes, cestodes and copepods. The great majority of these parasites are not known to be highly pathogenic to oysters. The most commonly reported parasites of oysters from the coasts of Texas and Louisiana include a protistan, *Perkinsus marinus* (=*Dermocystidium marinum* = *Labyrinthomyxa marina*); a trematode, *Bucephalus*; a small gastropod, *Boonea* (=*Odostomia*); and two species of a gregarine protozoan, *Nematopsis* (Mackin 1962, Hofstetter 1977, Van Sickle et al. 1976). For a general account of parasites and diseases of the American oyster the reader is referred to Galtsoff (1964) and Mackin (1962).

P rkinsus marinus is the only one of the above mentioned parasites that is known to be an economically important pathogen of oysters on the Gulf coast. This protistan parasite was first d scribed by Mackin et al. (1950) as Dermocystidium marinum. Culture studies by Ray (1954) and Mackin (1962) suggested that this organism is a fungus. Further culture work by Mackin and Ray (1966) indicated that this parasite was related to the fungus genus, Labyrinthomyxa and was reclassified as Labyrinthomyxa marina. El ctron microscope studies of the motile zoospore stage of the parasite by Levin (1978) led to the assignment of this organisms to a new genus in the protozoan phylum Apicomplexa. The organism is now classified as Perkinsus marinus.

P rkinsus marinus was first associated with widespread epidemic mortality of oysters during warm seasons in high salinity waters of Louisiana during the late 1940's. Since 1950 P. marinus has been found to be widely distributed in the high salinity waters of all the Gulf states and ext nsive studies by many investigators have shown this organism to be the most destructive oyster parasite on the Gulf coast and in some areas along the south Atlantic coast. Mortalities ranging up to 95% have been frequently report d as occurring in summer and early fall under conditions of high temperature and high salinity.

Th study of the distribution and pathogenicity of P. marinus was greatly stimulated by the development of the rather simple thyioglycollate culture technique (Ray 1952a and 1952b), which was later modified (Ray 1966). This technique provides a rapid assay method for accurately determining the incidence and intensity of infection. For general accounts of the biology, ecology, epizootiology and pathogenicity of P. marinus see Ray (1954), Ray and Chandler (1955), Mackin (1962), Mackin and Boswell (1956), Galtsoff (1964), Andrews (1965), Andrews and Hewatt (1957) and Perkins (1976).

Although salinity is an important factor in controlling the distribution of the contagious oyster disease caused by P. marinus, temperature is the most important environmental factor affecting the incidence as well as the intensity of infection in oysters. Generally, in Louisiana the degree of inf ction is low in the spring, but rises sharply in areas of moderate to high salinities (> 18 ppt) when water temperatures consistently exceed 20°C (Ray 1954, Mackin 1962). In endemic areas the intensity of infection and oyster mortality remain at a high level until the water temperatures fall below 25°C in autumn. The greatest development of Perkinsus infection occurs at temperatures ranging from 25°C to maximum summer temperatures. When temperatures consistently remain in the low twenties the mortality drops sharply; likewise the intensity of infection in live oysters declines, although not as sharply as does the mortality rate.

The seasonal pattern of infection in Texas (Galveston Bay) appears to be slightly different from that observed in Louisiana. In Galveston Bay, Hofstetter (1977) found that the incidence of infection increased from a winter low to a mid-spring high, declined in early summer as salinities decreased, and then climbed to an annual peak in late summer. Infections remained at light to moderate intensities through December.

The host is able to eliminate a large portion of the parasites during winter and early spring. However, the winters on the Gulf coast are generally too mild to cause the complete elimination of the parasites from most of the hosts. In colder areas, such as Chesapeake Bay, infections are detected much less frequently in winter and spring; they almost disappear until June (Andrews and Hewatt 1957).

Epizootics by Perkinsus probably do not develop in areas where the mean salinity falls below 12 to 15 ppt (Mackin 1962, Andrews 1979). During a 10-year study (1962-1972) in Galveston Bay, Hofstetter (1977) found intensity of infection to be directly related to salinity levels. The highest infection levels occurred at salinity ranges between 21-25 ppt and there was some decline of infection intensity at salinities of 26-30 ppt.

A comparative study of the survival of experimentally infected oysters held at low salinity (10 to 15 ppt) and high salinity (24 to 29 ppt) indicated that development of acute infection of Perkinsus was delayed by about one month by low salinity (Ray 1954). Although the oysters held at low salinity lived longer than ones held at high salinity, all low-salinity oysters died of acute Perkinsus infections. Since this study demonstrated that low salinity (10 to 15 ppt) is not physiologically unfavorable for development of Perkinsus infections, the exact role of salinity is uncertain. Mackin (1962) suggested that correlation of Perkinsus infections with salinity is not due solely to adverse physiological effects on either the host or parasite, but is due in part to the numerical dilution of infective elements by the influx of freshwater and the subsequent flushing of the bays.

Hofstetter (1977) observed the effects of a "killing flood" on Perkinsus infections in oysters on Bart's Pass (mid-Galveston Bay). In spring 1968, oysters on Bart's Pass were lightly infected when a Trinity River flood caused a heavy oyster kill. Oysters that developed after the flood, first examined in September 1969, remained free of Perkinsus infection until September 1971. Through May 1972 less than 50% of oysters were infected. The infection level had reached 90% by June 1972 and 100% by August 1972. Thus on Bart's Pass, the post-flood oysters apparently remained free of Perkinsus infection for three years or more. However, Hofstetter (1977) feels that this long delay in re-establishment of Perkinsus infection on Bart's Pass may be unusual, since oysters on the adjacent areas of Redfish Reef were consistently infected during this period.

Based on studies conducted in Louisiana, Mackin (1951) found that young oysters, especially those less than a year old were not as susceptible to infections as market-sized oysters. Further studies conducted in Louisiana (Ray 1953 and 1954) showed that June spat held in an area of high endemicity for Perkinsus were highly refractive to infections. Only two of 275 (less than 1%) of the spat examined between June 12 and September 19, 1952 were infected. The infection level remained below 10% through January 1953 then there was a gradual rise to almost 40% in June 1953, about one year after the initiation of the study. However, under the same conditions as noted for the spat study, uninfected oysters about one year old showed infection levels of about 60% by September 19, 1952.

Later studies in Texas (Hofstetter 1971 and 1977) suggest that small oyst rs are more susceptible to Perkinsus infection than Mackin and Ray observed in Louisiana. Hofstetter found July-August spat infected at ages of 3-5 months at Hanna Reef (East Bay) in 1971, at a salinity range of 20-29 ppt. Moreover, in 1966 Hofstetter usually did not find a marked difference in incidence and intensity between young oysters (averaging 50-62 mm long) and large market-sized oysters (averaging 83-95 mm long) at Redfish Reef (Galveston Bay). The reasons for differences observed in susceptibility of young oysters to Perkinsus infections in Louisiana and Texas are not known. Possibly the intensity and proximity of the focus of infection in the study areas may have differed.

Another possible explanation for the difference in the results of the Louisiana and Texas studies may be related to difference in the culture methods employed. The original thyioglycollate method (Ray 1952a, 1952b and 1954), employing penicillin and streptomycin as antimicrobial agents, was used in the Louisiana studies, whereas the modified culture method (Ray 1966), employing Chloromycetin and Mycostatin, was used in the Texas investigations. The modified method in general appears to be somewhat more sensitive than the original method (Ray 1966). The results of comparative studies between the two methods showed that generally more enlarged Perkinsus cells are observed with Chloromycetin and Mycostatin than with penicillin and streptomycin.

With regard to susceptibility of young oysters to Perkinsus infections, recent studies by Ray (unpublished data) in West Bay of the Galveston Bay system confirm the positive findings of Hofstetter (1971 and 1977). During the period July through October 1985, a large number of spat were tested for Perkinsus infection by the modified thioglycollate culture technique (Ray 1966). Spat attached to live oysters taken from Marsh Reef, Confederate Reef and Mid Reef were sampled at approximately monthly (July through October) intervals. It should be noted that the incidence of Perkinsus infections, as shown by monthly samples of market-sized oysters, has been very high on Marsh and Confederate Reefs since 1983. No monthly sample showed less than 90% (the great majority were 100% infected) infection for three years (1983-1985) at Confederate Reef and the same level of infection was encountered for two years (1984-1985) at Marsh Reef. The Perkinsus infection level in oysters from Mid Reef was not as high as those of the other two West Bay reefs. However, the incidence was 96% or more during the spat sampling period.

Perkinsus infections were found in spat from Confederate and Mid Reefs as early as July 1985. No spat wer found on these reefs prior to July 1985. Moreover, no spat were obtained from Marsh Reef in July. Two of four spat (between 5-10 mm long) from Confederat Reef and one of seven spat (<5 mm long) from Mid Reef were very lightly infected. The August spat samples showed that all 10 spat (10-30 mm long) from Condeferate Reef, six of seven spat (20-30 mm long) from Marsh Reef, and eight of 10 spat (14-24 mm long) from Mid Reef were infected with Perkinsus. The infection intensity was light in most cases for August. However, the intensity had reached moderate-heavy in some spat from Marsh and Confederate Reefs at this time. In September the incidence levels for spat samples were 70% (10 individuals, 20-25 mm long) on Confederate Reef; 100% (10 individuals, 20-30 mm long) on Marsh Reef; and 40% (5 individuals, 25-30 mm long) on Mid Reef. The intensity of infection in spat varied from very light to moderate-heavy in September. In October the incidence levels were: 100% for three individuals (approximately 20 mm long) from Confederate Reef and 40% for five spat (<20 mm long) from Marsh Reef. Some of the spat collected in October 1985 showed intensities of infection that were greater than moderate. Two spat, one from Confederate Reef and one from Mid Reef showed an infection intensity of heavy.

A fourth oyster reef, Carancahua, in the middle of West Bay, was sampled for Perkinsus in spat on only one occasion, September 1985. On this occasion five spat (approximately 20 mm long) were negative for Perkinsus. Although the adult oysters sampled from this reef were 100% infected in June 1985, the infection level had dropped to 50% by Sept mber 1985.

It is of interest to note that the intensity of infection in spat from Mid Reef, which appears to maintain less intense infections of Perkinsus than either Confederate Reef or Marsh Reef, was much less than that noted for these two West Bay reefs. Only one of 16 infected spat from Mid Reef showed an infection intensity of more than light. The data obtained during the 1985 study in West Bay suggest that levels of Perkinsus infection in spat on a particular reef is related to the level of infection in the adult oysters populating that reef. These data leave little doubt that young oysters are highly susceptible to Perkinsus infections when associated with adult oysters that are highly infected with this parasite.

In addition to temperature and salinity, the close proximity of infected populations to uninfected or lightly infected populations appears to be an important factor in the spread of P. marinus. Thus maintenance of epizootics is dependent on the density and continuity of oyster populations. On the other hand, the degree of isolation of populations is important in slowing the spread of epizootics (Mackin 1962, Andrews 1965 and 1979). There is overwhelming evidence that direct transmission of waterborne infective cells from oyster to oyster is the primary mechanism for spreading the infectious disease caused by this parasite (Ray 1954, Ray and Chandler 1955, Mackin 1962, Andrews 1965, 1967 and 1979 and Perkins 1976). Recently White et al. (in press) have demonstrated that the ectoparasitic snail, Boonea (=Odostomia) impressa may directly transfer P. marinus from infected oysters to uninfected ones. This report provides the first substantial evidence that an intermediate (transfer) host may also be involved in the spread of this oyster disease. Current evidence indicates that all stages of Perkinsus that occur in oysters are capable of initiating infections. In laboratory studies, Mackin (1962) found that a minimum dosage of 100 infective cells was required to initiate a lethal infection. Infective cells may enter the host by way of gill, mantle or gut epithelia (Ray 1954, Mackin 1962).

Dead and dying oysters, the great majority of which are heavily infected at death, appear to be much more important in the spread of Perkinsus than infected live oysters (Andrews and Hewatt 1957, Andrews 1965 and 1979). Although it is possible for infective cells to be transmitted a great distance by water currents (Mackin 1962), Andrews (1965 and 1979) believes that most infections occur from dying oysters that are in close proximity, within 15 meters, of uninfected hosts. Furthermore, without residual infected populations of oysters, P. marinus spreads very slowly into new areas or new beds (Andrews 1979).

Further evidence implicating the importance of dead oysters in the spread of this parasite was provided by Hoese (1962). He found live P. marinus in the intestinal tract of an oyster drill (Urosalpinx cinerea), in the intestinal tract and on the bodies of three fishes (Gobiosoma bosci, Chasmodes bosquianus and Opsanus tau) and from the bodies, especially the s ta , of two crabs (Neopanope t xana and Rhithropanopeus harrisii). Hoese further concluded that most dying oysters are consumed by scaveng rs before they can decay. Therefore, most of the Perkinsus cells from dying oysters must pass through the digestive system of scavengers.

The effects of isolation in slowing the spread of Perkinsus within West Bay (Galveston Bay system) appear to be supported by current studies (Ray, unpublished data). Since March 1983 the incidence and intensity of infection has been monitored monthly in market-sized oysters on two large West Bay reefs, Confederate and Carancahua. Carancahua Reef is located near the center of West Bay and Confederate Reef is located in the eastern portion of the bay about 4.5 nautical miles from Carancahua Reef. There appear to be no major oyster reefs between these two reefs nor immediately west of Carancahua Reef. The salinity and temperature values obtained along with the monthly oyster samples were similar at both reefs. At sampling times the salinity ranged from a low of 16 ppt to a high to 33 ppt during the two-year period. The salinity values were 20 ppt or more except for two or three months following Hurricane Alicia, which hit the West Bay area in late August 1983. In March 1983 the incidence and weighted incidence (average infection intensity per live oyster in sample) of infection were 100% and 1.3 on Confederate Reef and 4% and 0.12 on Carancahua Reef, respectively. During the remainder of the year the incidence ranged from 96% to 100% and the intensity ranged from a low of 2.2 in May to a high of 3.6 in October on Confederate Reef. On Carancahua Reef, however, the incidenc and intensity remained below 10% and 0.25, respectively, except for August (32%/0.44) and October (24%/0.56).

During 1984 the high incidence and intensity of infection prevailed in Confederate Reef oysters, and the incidence and intensity gradually incr ased on Carancahua Reef. From January 1984 through March 1985 the incidence was at least 96% on Confederate Reef with an intensity of infection above 2.0 except for January 1984 (1.8) and February 1985 (1.2). The maximum intensity for 1984 was 3.4 in August. On Carancahua Reef both the incidence and intensity increased from a low of less than 25% and 0.25, respectively, in January and February 1984 to a high of 76% incidence and

2.5 intensity in August 1984. By December 1984 the incidence (96%) and intensity (1.8) on Carancahua Reef were similar to that on Confederate Reef (incidence 100%, intensity 2.0). However, the winter water temperatures of 1984 and 1985 appeared to be more effective in reducing the incidence on Carancahua Reef (44%) than on Confederate Reef (100%) by March 1985.

Apparently the persistence of such a high level of *Perkinsus* infection on Confederate Reef is due to an intense focus of infection that exists in the eastern portion of West Bay. Moreover, it appears that a similarly intense focus of infection is developing on Carancahua Reef. West Bay, which is a high salinity bay, has a history of sporadic commercial production of oysters. Unfortunately, the Gulf Intracoastal Waterway diverts much of the freshwater flow to either end of West Bay. Thus West Bay lacks a good source of freshwater inflow to control drills and *Perkinsus* infections. Several years of little or no commercial production may occur between periods of good production, such as that which occurred during 1982, 1983 and the winter and spring of 1984. Despite the presence of extensive oyster shell reefs, it is my opinion that oyster populations in West Bay generally remain at low levels because of drill predation and *Perkinsus* infections. Once high levels of *Perkinsus* develop in West Bay, it is my further opinion that oyster populations must be reduced to low levels by extensive harvest without excessive damage to the shell substrate and/or natural mortality before substantial commercial populations will be reestablished. Andrews (1965 and 1979) has stressed that in Virginia "fallowing and isolation" are important aids in controlling *Perkinsus* infections on planted beds.

Although low salinity *per se* inhibits the activity and spread of *Perkinsus*, low salinity does not eradicate the parasite from oysters (Mackin 1962, Andrews 1979). As pointed out by Andrews (1965 and 1979) persistent low salinity for long periods and/or the absence of oyster populations will be required to eliminate *Perkinsus* disease from an area once it becomes established. As indicated by Hofstetter's (1977) studies in Galveston Bay, killing floods may serve an important natural role in controlling *Perkinsus* epizootics by periodically removing the focus of infection through the elimination of the parasite's host.

The presence of factors that inhibit the development of Perkinsus infections in oyst r populations in areas characterized by consistently high water salinities (>30 ppt) has been hypoth sized by Hoese (1963). He noted that oyster populations in such areas as the Seaside of Virginia; Harbor Island, Texas; and Alligator Harbor, Florida usually are free of Perkinsus infections despite the fact that physical parameters appear to be suitable for the development of this parasite. Moreover, he found that medium prepared with waters from such high salinity areas as Seaside of Virginia, Port Aransas and Harbor Island of Texas inhibited the enlargement of Perkinsus hypnospores in oyster tissues. According to Hoese, the absence of Perkinsus in such high salinity areas is correlated with the presence of Spartina salt marshes.

Studies by Ray (unpublished) in West Bay of the Galveston Bay system do not appear to support Hoese's hypothesis. For several years I have monitored the Perkinsus infection level in a small oyster reef (Marsh Reef) on the south shore of West Bay, which usually has salinities ranging from 25 to 33 ppt during the summer and fall months. The infection rate in market-sized oysters, even in winter and early spring months, seldom drops below 100%. This reef is almost completely surrounded by an extensive stand of smooth cordgrass, Spartina alterniflora.

Furthermore, Hoese (1963) suggested that the hypothesis concerning the inhibitory influence of Spartina marshes should be tested by sampling for P rkinsus in areas of extensive Spartina marshes, such as those in South Carolina and Georgia, where Perkinsus does not appear to be a severe cause of oyster mortality. However, early in 1986, the author received verbal reports of extensive oyster kills, which have been attributed to Perkinsus, in both South Carolina and Georgia. These oyster kills have been reported to have followed prolonged periods of drought in those two states.

Data (unpublished) obtained from recent surveys (1984 and 1985) by Eric Powell and Marie White (Oceanography Department, Texas A&M University, College Station, Texas) indicate that varying degrees of Perkinsus infection occurred in most of the oyster populations in Redfish and Aransas Bays near Port Aransas, Texas. One of the areas surveyed in 1984 was Big Slough on Harbor Island. One sample of 10 small oysters (40-50 mm long) taken in

April showed two very lightly infected oysters. Another sample of ten oysters collected from the same population in June showed a 30% incidence of infection and the intensity of infection was greater than moderate in each of the three infected individuals.

While it is quite possible that inhibitory substances may exist in areas where consistently high salinity conditions prevail, it is this author's opinion that the existence of nearby foci of infected oysters as well as the continuous recruitment of uninfected oysters are necessary to foster the maintenance and spread of *Perkinsus* infections. Furthermore, influxes of oceanic waters, which do not support large oyster populations because of predation, may dilute infective elements of *Perkinsus* as postulated for freshwater influxes by Mackin (1962).

In 1962-1963, Mackin (unpublished data) discovered a new oyster parasite in Aransas Bay, Texas. This parasite, which is known as Aransas Bay Organism (ABO), is not well known. Unfortunately, this organism does not respond to the thioglycollate culture technique. Thus its detection and identification require the use of histological techniques, which are costly and time consuming. This brief account of ABO is taken from Hofstetter (1977). This organism is highly virulent and is lethal to oysters of all sizes. The organism was first noted in Aransas Bay under hypersaline conditions and it disappeared in 1966 when salinities were reduced by normal rainfall. Between 1962 and 1966, ABO appears to have spread into San Antonio and Matagorda Bays. According to Hofstetter (1977) ABO has not been found in Galveston Bay. Schlicht (1969) reported that ABO had replaced *P. marinus* in Aransas Bay. Schlicht's histopathological studies suggested that ABO and *P. marinus* were related organisms. This finding led him to tentatively place ABO in the genus *Labyrinthomyxa*. The extent of the distribution of ABO on the Texas coast and its importance as an oyster mortality agent are uncertain at this time.

LITERATURE CITED

Andrews, J. D. 1965. Inf ction xperiments in nature with Democystidium marinum in Chesapeake Bay. Chesapeake Sci. 6:60-67.

_____. 1967. Interaction of two diseases of oysters in natural waters. Proc. Natl. Shellfish. Asoc. 57:38-49.

_____. 1979. Oyster diseases in Chesapeake Bay. Mar. Fish. Rev. 41:45-53.

_____ and W. G. Hewatt. 1957. Oyster mortality studies in Virginia II. The fungus disease caused by Dermocystidium marinum in oysters of Chesapeake Bay. Ecol. Monogr. 27:1-25.

Br ithaupt, R. L. and R. J. Dugas. 1979. A study of the southern oyster drill (Thais haemastoma) distribution and density on the oyster seed grounds. Louisiana Wildl. Fish. Comm. Tech. Bull. No. 30. 20 p.

Butler, P. A. 1949. Gametogensis in the oyster under conditions of depressed salinity. Biol. Bull. 96:263-269.

_____. 1954. The southern oyster drill. Proc. Natl. Shellfish. Assoc. 44:67-75.

_____. 1985. Synoptic review of the literature on the southern oyster-drill Thais haemastoma floridana. NOAA Technical Report NMFS-SSRF-35. 9 p.

Chanley, P. E. 1957. Survival of some juvenile bivalves in water of low salinity. Proc. Natl. Shellfish. Assoc. 48:52-65.

Chapman, C. R. 1954. Oyster drill (Thais haemastoma) predation in Mississippi Sound. Proc. Natl. Shellfish. Assoc. 49:87-97.

Chatry, M., R. J. Dugas and K. A. Easley. 1983. Optimum salinity regime for oyster production on Louisiana's state seed grounds. Contr. Mar. Sci. 26:81-94.

Galtsoff, P. S. 1964. The American oyster, Crassostrea virginica (Gmelin). U.S. Fish Wildl. Serv., Fish. Bull. 64:1-480.

Hoese, H. D. 1962. Studies on oyster scavengers and their relation to the fungus Dermocystidium marinum. Proc. Natl. Shellfish. Assoc. 53:161-174.

_____. 1963. Absence of Dermocystidium marinum at Port Aransas, Texas with notes on an apparent inhibitor. Tex. J. Sci. 15:98-103.

Hofstetter, R. P. 1959. The Texas Oyster Fishery. Texas Parks and Wildl. Dept. Bull. No. 40. 39 p.

_____. 1971. Galveston Bay oyster studies: 1971. Texas Parks and Wildl. Dept. Coastal Fish. Proj. Rept. 1971, 107-124.

_____. 1977. Trends in population levels of the American oyster, Crassostrea virginica Gmelin on public reefs in Galveston Bay, Texas. Texas Parks and Wildl. Dept. Tech. Series. No. 24. 90 p.

_____. 1983. Oyster population trends in Galveston Bay 1973-1978. Texas Parks and Wildl. Management Data Series. No. 51. 33 p.

Levine, N. D. 1978. Perkinsus gen. n. and other new taxa in the protozoan phylum Apicomplexa. J. Parasitol. 64:549.

Mackin, J. G. 1951. Histopathology of infections of Crassostrea virginica (Gmelin) by Dermocystidium marinum Mackin, Owen, and Collier. Bull. Mar. Sci. Gulf Carib. 1:72-87.

_____. 1962. Oyster disease caused by Dermocystidium marinum and other microorganisms in Louisiana. Publ. Inst. Mar. Sci. Univ. Tex. 7:132-229.

_____ and J. L. Boswell. 1956. The life cycle and relationships of Dermocystidium marinum. Proc. Natl. Shellfish. Assoc. 46:12-115.

_____, H. M. Owen and A. Collier. 1950. Preliminary note on the protistan parasite, Dermocystidium marinum n. sp. in Crassostrea virginica (Gmelin). Science. 111:238-329.

_____ and S. M. Ray. 1966. The taxonomic relationships of Dermyocystidium marinum Mackin, Owen and Collier. J. Invert. Path. 8:544-545.

Perkins, F. O. 1976. Dermocystidium marinum infection in oysters. Mar. Fish. Rev. 38:19-21.

Ray, S. M. 1952a. A culture technique of the diagnosis of infection with Dermocystidium marinum Mackin, Owen, and Collier in oysters. Science. 116:360-361.

_____. 1952b. A culture technique for the diagnosis of infection with Dermocystidium marinum in oysters. Natl. Shellfish. Assoc. 1952 Convention Addresses: 9-13.

_____. 1953. Studies on the occurrence of Dermocystidium marinum in young oysters. Natl. Shellfish. Assoc. 1953 Convention Addresses: 80-92.

_____. 1954. Biological studies of Dermocystidium marinum, a fungus parasite of oysters. The Rice Institute Pamphlet, Monograph in Biology, Special Issue. 114 p.

_____. 1966. A review of the culture method for detecting Dermocystidium marinum, with suggested modifications and precautions. Proc. Natl. Shellfish. Assoc. 54:55-69.

_____ and A. C. Chandler. 1955. Dermocystidium marinum, a parasite of oysters. Exp. Parasitol. 4:172-200.

St. Amant, L. 1964. Louisiana leads in oyster production. Louisiana Wildl. Comm. Wild. Educ. Bull. No. 84. 11 p.

Schechter, V. 1943. Tolerance of the snail Thais floridana to waters of low salinity and the effect of size. Ecology. 24:493-499.

Schlicht, F. G. 1969. The populations and distribution of the oyster pathogen Labyrinthomyxa marina (Mackin, Owen and Collier) and the relation of these populations to the pathogen of oyster, the Aransas Bay Labyrinthomyxa. Ph.D. Dissertation, Texas A&M University. 94 p.

Van Sickle, V. R., B. B. Barrett, T. B. Ford and L. J. Gulick. 1976. Barataria Basin: Salinity changes and oyster distribution. Sea Grant Publ. No. LSU-T-76-02. LWFC Tech. Bull. No. 20. 22 p.

White, M. E., E. M. Powell, S. M. Ray and E. A. Wilson. Host to host transfer of Perkinsus marinus in oysters (Crassostrea virginica) populations by the ectoparasitic snail Boonea impressa (Pyramidellidae). (Accepted for publication by J. Shellfish Res.).

Appendix F. Environmental Effects Related to Penaeid Shrimp Populations.

by Zoula P. Zein-Eldin
National Marine Fisheries Service
4700 Avenue U
Galveston, TX 77551-5997

Environmental Effects Related to Penaeid Shrimp Populations

By Zoula P. Zein-Eldin

Penaeids in general have a wide range of tolerance to most environmental factors (excluding such poisons as certain heavy metals and insecticides). Two environmental factors, however, have been more studied than all others. These are salinity and temperature, both separately and, to a lesser extent, in combination. Both abundance data (sampling within estuaries, bays, inlets, etc) and more limited experimental data show that the two penaeids most common in Texas, the white shrimp (*Penaeus setiferus*) and the brown shrimp (*Penaeus aztecus*) both occur and grow in a broad range of environmental conditions commonly used to delineate water type. Thus both species have been reported in salinities of less than 1 to 45 ppt, and in temperatures of 5.2 to 38°C. Indeed, *P. aztecus* has been caught in salinities of 60 and 70 ppt. Unfortunately, most reports do not give the size range of the animals observed. Reported occurrences of smallest sizes (6-15 mm) of both species in Texas appear to be limited to a narrower salinity range (15-35 ppt), because most of these animals have been taken in entrances or inlets to bays during sampling designed to determine the precise date at which postlarvae are entering the estuary (Baxter, 1963; Baxter and Renfro, 1967; Copeland and Truitt, 1966). Caillouet et al. (1971), however, document the presence of postlarvae of both species in Vermilion Bay, Louisiana in salinities less than 1 ppt, and experimental data have shown that postlarvae of both species survive and grow at salinities constantly as low as 5 ppt within a wide range of temperatures, and that growth does occur at even lower salinities (Zein-Eldin, 1963; Zein-Eldin and Aldrich, 1965; Zein-Eldin and Griffith, 1969).

Both species occur in wide temperature ranges as well. Survival is reduced at low temperatures, and numerous reports document the winter kill of shrimp following cold fronts. Effects of high temperatures are less well explored, but juveniles of both species are reported to occur in water warmed by thermal effluents (Chung and

Strawn, 1984), and laboratory studies have shown that growth of postlarvae of both species increases with temperature up to 33°C (Zein-Eldin and Griffith, 1969). Survival of smaller juvenile brown shrimp decreases with temperatures above 30° (Zein-Eldin and Griffith, 1966), while small white shrimp continue to grow and survive up to constant temperatures approaching 35°C (Zein-Eldin and Griffith, 1969).

Laboratory studies indicate that interactions of salinity with t mperature may have more significant effects than either factor alon , particularly under somewhat extreme conditions of either. For both species, combinations of low temperature with low salinity are more detrimental than other combinations. Both species are most susceptible to low temperatures (11-15°C) at salinities 5 ppt or less, and appear to be somewhat protected against low temperature effects when salinities are nearer to those of the open Gulf, 25, 35 and 40 ppt. Postlarvae and small juvenile brown shrimp seem to be more str ssed by constant high temperature (greater than 30°C) than do white shrimp, and again survival is noticeably reduced by combinations of these temperatures with salinities of 5 ppt or less; white shrimp at these constant warm temperatures are adversely affected only by the high salinities. White shrimp appear to grow less well and survival is decreased at salinities of 35 ppt (as compared to 25 ppt); salinities between 5, 15, 25 and 35 have not been examined in detail, nor have juvenile shrimp (initial size greater than 25 mm) been tested in these higher salinities. These patterns suggest that water flow requirements into nursery areas for penaeids would need to be varied with time of the year, and perhaps adjusted for the particular year e.g. early or late entrance of postlarvae into a given system.

Interactions of these easily measured factors with others more difficult to analyze have not been attempted by many. Little is known of the effect of sea water intrusion on the other biota, some of which may be predators or food for the penaeids. Thus the effects on shrimp of the increase in numbers of crabs (Parker, 1955) as salinity increases have not been evaluated nor have there been studies relating parasites to salinity. Such ecological studies might result in a reduction of the broad biological tolerance range of the two species.

Changes in species composition during periods of high salinity have been recorded (Parker, 1955; Hoese, 1960), but neither competition, effects on vegetation and cover, nor predation have been well studied. Unlike the oyster, in which the physiological tolerances far exceed the ecological tolerance of the species established by interactions with parasites and predators, little is known of ecological interactions affecting penaeid shrimp. Increase in salinity may be responsible for the introduction of marine predators and competitors which are better able to make use of the environment than young penaeids already stressed (indicated by decreased growth) at higher salinities.

Correlations of shrimp abundance with river flow or rainfall have been made for the white shrimp in Texas (as a crop) but do not appear to be valid in some other Gulf states, nor do they apply to catches of the brown shrimp. Nor are there adequate studies evaluating the effects of combinations of environmental factors including natural riverine sediments and turbidity related to changes in salinity associated with increases in water flow.

Historical evidence (Gunter and Hildebrand, 1954; Copeland and Bechtel, 1974) and laboratory studies agree, however, that young white shrimp occur more frequently and grow faster when nursery areas are of lower salinity. This would require the release of sufficient water to maintain nursery salinities below 25 ppt, and perhaps less during the warmer months (August-September) of the year. It is noteworthy that white shrimp juveniles did not die at salinities of 35-40 ppt after 30 days continuous exposure, but that growth was retarded (Zein-Eldin and Griffith, 1969). The decrease in abundance and commercial catch recorded (Gunter and Hildebrand, 1954) during drought may indicate more complex ecological or biological relationships.

Based on interaction of only temperature and salinity, without regard to other ecological tolerances, salinity reductions would appear to be more important in nursery areas used by white shrimp. In fact, low salinity runoff during colder periods, as in early spring when postlarval brown shrimp may be in the estuari s and marshes in large numbers, may be detrimental to that population, as at times of "blue northers" accompanied by heavy spring rains. Under such conditions, retention of water until temperatures have increased would probably benefit the brown shrimp population.

Based on the limited data for juvenile shrimp, it would appear that water flow could be restricted during the early spring months when cold fronts are still likely, to minimize the negative effects of the combination of cold and low salinity on young brown shrimp. Conversely, water inflow would be most necessary during the late spring and summer in the presence of young white shrimp needing salinities less than 20-25 ppt. As temperatures decrease in the fall, control of water flow might again be important, since it appears that in postlarvae of both species, survival is better at higher salinities than at 5 ppt or less as temperatures decrease to 18°C or less.

Rate of change and length of exposure to the new conditions are also to be considered in the design of discharges. Gradual release is pr ferred so there may be time for the animals to acclimate to the new regime, and an additional stress from current effects would not occur.

Although all of these factors; salinity, temperature, water flow, vegetative cover, food supply, presence of predators and parasites, concentration of pollutants (heavy metals, etc.); need to be evaluated for a determination of the amount of water required for commercial and sports fisheries in the various bays, practicality may demand that only the most stressful factors be included. Thus, consideration must be given not only to 1) the total volume of water to be released but the time of release in relationship to the arrival of young of the year; 2) the interaction of temperature and salinity: maintain higher salinities in cold temperatures, but simultaneously provide marsh areas with sufficient covering water, for the young; while lowering salinities (less than 20-25 ppt) during hotter summer months when young white shrimp are most numerous in the estuarine areas.

In summary, the biological tolerances to commonly measured environmental factors of both species of penaeid shrimp appear to be broad. The ecological interactions of the animals with other fauna and flora are less well understood, and these latter may play important roles in determining the success of the species in nursery areas and bays, particularly during periods of stress from temperature or salinity. Thus ideally outflows should be planned to minimize stress to penaeid species by careful monitoring of the time of entry of the young shrimp together with the evaluation of actual conditions in the areas of planned waterflow. Thus temperature records would be important during late February through early April so that effects of low temperature-low salinity interaction upon the brown shrimp population could be reduced. Similarly, estuarine and marsh salinity records during August and September would determine outflow necessary to protect the population of white shrimp.

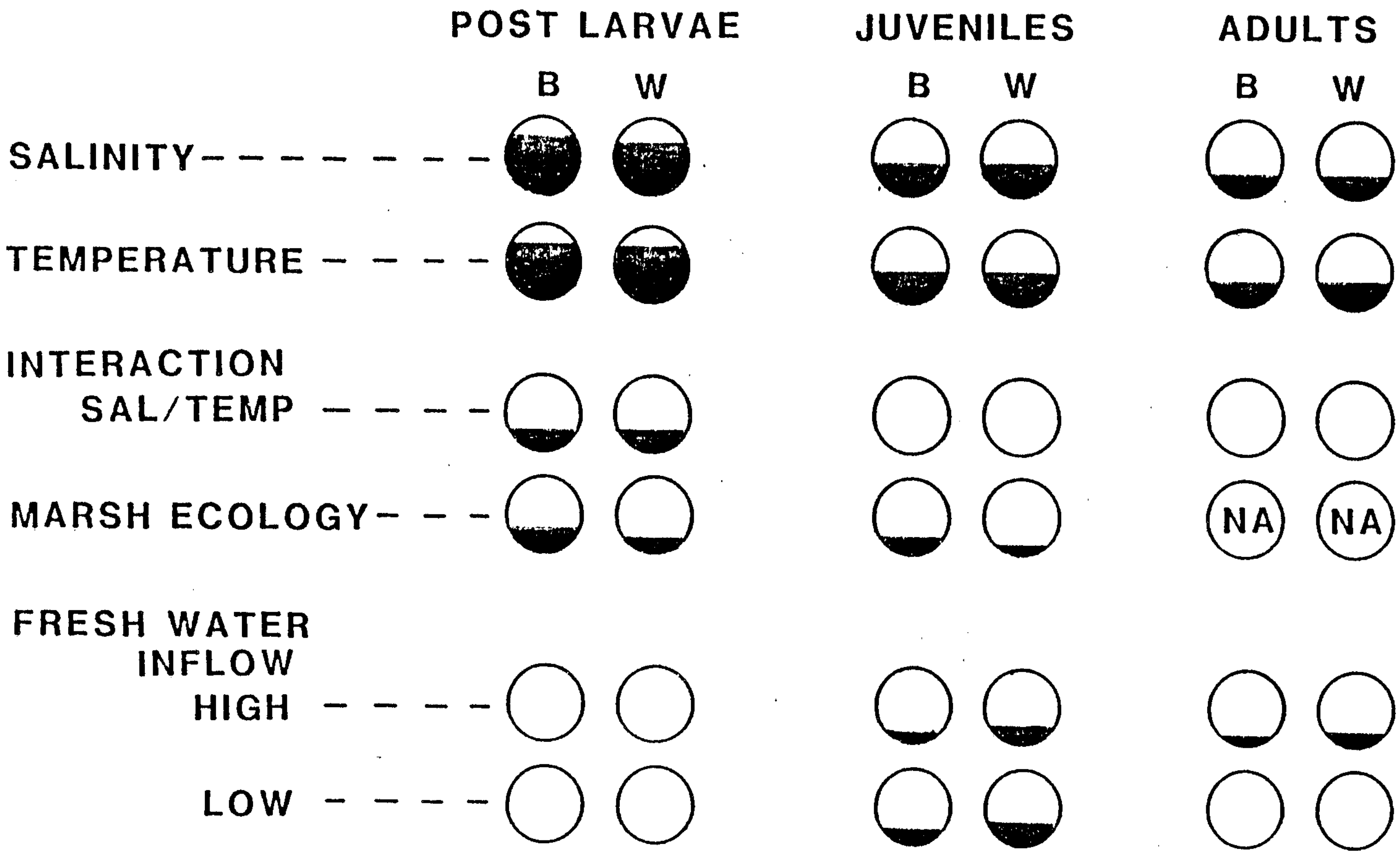


Figure F.1. The status of knowledge regarding the effects of various environmental parameters on shrimp. B= brown shrimp, and W= white shrimp. An all black circle would represent complete knowledge.

Literature Cited

Baxter, K. N. 1963. Abundance of postlarval shrimp--an index of future shrimping success. Proc. Gulf Carib. Fish. Inst., 15:79-87.

_____ and W. C. Renfro. 1967. Seasonal occurrence and size distribution of postlarval brown and white shrimp near Galveston, Texas, with notes on species identification. Fish. Bull. U.S. 66:149-158.

Caillouet, C. W., Jr., B. J. Fontenot, Jr., W. S. Perret, R. G. Dugas and H. F. Hebert. 1971. Catches of postlarval white shrimp, Penaeus setiferus (Linn.), and brown shrimp, P. aztecus Ives, and temperature and salinity observations in Vermilion Bay, Louisiana, March 1963 to April 1967. U.S. Dept. Commerce, COM-71-01055, Data Report 64, 39 pp.

Chung, K. S. and K. Strawn. 1984. Seasonal change in thermal tolerance of common estuarine crustaceans. Bull. Jap. Soc. Sci. Fish. 50:451-456.

Copeland, B. J. and T. J. Bechtel. 1974. Some environmental limits of six Gulf coast estuarine organisms. Contrib. Mar. Sci. 18:169-204.

_____ and M. V. Truitt. 1966. Fauna of the Aransas Pass Inlet, Texas. II. Penaeid shrimp postlarvae. Tex. J. Sci. 18:65-74.

Gunter, G. and H. H. Hildebrand. 1954. The relation of rainfall of the state and catch of the marine shrimp (Penaeus setiferus) in Texas waters. Bull. Mar. Sci. Gulf Carib. 4:95-103.

Hoese, H. D. 1960. Biotic changes in a bay associated with the end of a drought. Limnol. Oceanogr. 5:326-336.

Parker, R. H. 1955. Changes in the invertebrate fauna, apparently attributable to salinity changes, in the bays of central Texas. J. Paleontology 29:193-211.

Zein-Eldin, Z. P. 1963. Effect of salinity on growth of postlarval penaeid shrimp. Biol. Bull. 125:188-196.

_____ and D. V. Aldrich. 1965. Growth and survival of postlarval *Penaeus aztecus* under controlled conditions of temperature and salinity. Biol. Bull., 129:199-216.

_____ and G. W. Griffith. 1966. The effect of temperature upon the growth of laboratory-held postlarval *Penaeus aztecus*. Biol. Bull. 131:186-196.

_____. 1969. An appraisal of the effects of salinity and temperatur on growth and survival of postlarval penaeids. FAO Fish. Rep. No. 57, 3:1015-1026.