Proceedings of the Shrimp Yield Prediction Workshop

Marine Fisheries

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Edited by
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PREFACE

Shrimp stocks of the Gulf of Mexico represent an extremely valuable commodity whose management falls under the jurisdiction of state and federal fisheries agencies. The Shrimp Yield Prediction Workshop, sponsored by the American Institute of Fisheries Research Biologists, the Texas A&M University Sea Grant College Program and NOAA/National Marine Fisheries Service, traced the evolution of state and federal programs designed to manage shrimp resources. Management strategies and goals of various regulatory agencies' shrimp research programs were discussed. Of particular interest were the various methods used by these agencies to predict shrimp yield and to open and close shrimp seasons. Insight was gained into the significance of abundance and size data obtained by traditional sampling methods, correlations of life history trends and hydrological factors, census data gathered from the bait-shrimp fishery and density information acquired from new quantitative techniques as predictive tools for shrimp resource management. The workshop also assessed the state of the art of predicting shrimp yield and identified critical problems in rendering meaningful predictions.

PREDICTION OF THE CLOSURE DATES FOR THE 1983 TEXAS GULF SHRIMPING SEASON

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ABSTRACT

Brown shrimp (*Penaeus aztecus*) were collected with 18.3-m bag seines along shorelines of seven bay systems and with 6.1-m trawls in five passes leading from the bays to the Gulf of Mexico to determine the closing and opening dates of the 1983 shrimping season in the Texas territorial sea. The purpose of the closed season was to protect small shrimp from fishing pressure until they reached a larger, more valuable size and to minimize waste caused by discarding smaller shrimp during harvest. Based on biological sampling along shorelines in April, the closed season dates were set for 30 minutes after sunset 27 May to 30 minutes after sunset 15 July 1983. Data collected along shorelines in June indicated there was no need to extend or shorten the 15 July opening date. Sampling in passes verified that closure dates and the mean length (90 mm) chosen to predict size at emigration were appropriate, on a coastwide basis, to accomplish the purpose of the closure.

INTRODUCTION

Shrimp are the most valuable commercial seafood product landed in the United States. There were 128.8 million kg (heads-on) with an ex-vessel value of $509 million reportedly landed in 1982 (U.S. Department of Commerce 1983). The value was even greater when the total economic impact is considered. The Gulf of Mexico fishery accounted for 95.2 million kg (74%) and $426 million (84%) of total U.S. landings. Texas landings in 1982 amounted to 32.2 million kg valued at $176 million (Hamilton 1983). This is 25% of the weight and 35% of the value of the U.S. shrimp fishery. Shrimp are the most important commmercial seafood product in Texas, annually accounting for 95% of the value and over 80% of the weight of all seafood landings. Brown shrimp (*Penaeus aztecus*) is the most important species, comprising about 75% of both weight and value of the annual reported landings.

Brown shrimp spawn in the Gulf of Mexico, go through several larval stages and enter the bays during February-April as postlarvae

(Baxter and Renfro 1967; King 1971). They seek the shallow peripheral areas (nursery areas) in the bays where they grow rapidly, migrate to the deeper portions of bays and return to the Gulf in late May or early June at a mean size of about 90 mm total length (Copeland 1965; Trent 1967; Parker 1970; King 1971; Benefield [in press]). Movement back to the Gulf through passes occurs mainly at night near the surface and in association with ebb tide currents during their period of maximum duration (Copeland 1965; King 1971). Movement ceases during daylight and periods of incoming tides. During those periods, shrimp remain on the bottom until the next nocturnal ebb tide. Diurnal tides are mixed, with one low and one high per 24-hour period of maximum range and two highs and two lows per 24-hour period with a minimum range (Collier and Hedgpeth 1950). During their period of maximum range, tides are also of their maximum duration.

Brown shrimp management in Texas is designed to accommodate all users (bait, small food shrimp and large food shrimp fishermen) while protecting the resource and minimizing waste. Supply of large shrimp is ensured by regulating harvest in bays and simultaneously delaying harvest in the Gulf until returning emigrants reach a larger, more valuable size. Shrimp are managed by the Texas Legislature through the Shrimp Conservation Act of 1959 (Parks and Wildlife Laws 1981). This Act established a closed season in the state's territorial waters (16.7 km) during 1 June-15 July each year, but authorized the Texas Parks and Wildlife Commission (TPWC) to adjust closing and opening dates as the total closure was 60 days.

The purpose of this annual closure is to protect small shrimp from fishing pressure until they reach a larger, more valuable size and to minimize waste caused by discarding smaller shrimp during the harvest. Texas has closed its territorial waters for over 20 years, and the statutory 1 June-15 July season was changed in 1967, 1972, 1976, 1981 and 1982. The rationale for adjusting closure dates was detailed by Moffett (1967, 1972), Johnson (1982), Bryan (1983) and Benefield (in press). While small shrimp were protected in state waters by closures prior to 1981, large numbers of small shrimp were still captured and discarded in waters beyond the state's jurisdiction (Berry and Benton 1969; Baxter 1973; Bryan et al. 1982).

The Gulf of Mexico Fishery Management Council's management plan for shrimp was adopted in 1980 and implemented in 1981 (Center for Wetland Resources 1980). Among other options, the plan called for closure of U.S. waters (16.7 to 370.6 km) off Texas to complement the traditional Texas closed season. Total closure of Gulf waters off Texas during 22 May-15 July was believed to have been beneficial by increasing the overall yield and value of the northern Gulf brown shrimp fishery (Jones et al. 1982). This report will document the recommended 1983 dates of closing and opening the Texas territorial sea to shrimping.

MATERIALS AND METHODS

Shoreline samples were collected with bag seines to capture postlarval and juvenile shrimp as they were first recruited to the gear, while otter trawls were used in passes to determine the time and at what sizes shrimp emigrated to the Gulf of Mexico. All samples were collected during daylight.

The 18.3-m wide bag seines had 19.0-mm stretched mesh in the wings and 12.7-mm stretched mesh in the 1.8-m wide bag. Seines were pulled parallel to shore at randomly selected stations for a minimum distance of 15.2 m and a maximum distance of 30.5 m. Ten samples were collected monthly in each of the following bay systems: Galveston, Matagorda, San Antonio, Aransas, Corpus Christi and the upper and lower Laguna Madre. One half of the samples were collected during the first 2 full weeks of each month and one half during the last 2 full weeks each month. Additional sampling details are provided by Hegen (1982).

The 6.1-m wide otter trawls had 39.1-mm stretched mesh throughout and were spread by 0.5 x 1.2 m doors. Tows were 15 minutes in duration. Weekly samples were collected from passes in Bolivar Roads (Galveston Bay), Pass Cavallo (Matagorda Bay), Lydia Ann Channel (Aransas Bay), Corpus Christi Ship Channel (Corpus Christi Bay) and Brazos Santiago Pass in the lower Laguna Madre. Two samples per week were taken in each location parallel with the orientation of the pass. Tow direction (bayward or gulfward) was alternated with each sample. Additional sampling details are provided by Benefield et al. (1983).

All brown shrimp captured in a sample were counted. Total lengths (tip of rostrum to tip of telson) were obtained from a minimum of 19 shrimp (if available) in bag seine samples and 50 in trawl samples.

Catches were expressed as No./ha (bag seines) and No./15 minute tow (trawls). The coastwide mean catch (number and length) in bag seines was weighted by shoreline distance in each bay system (Matlock and Ferguson 1982). Mean shrimp lengths were weighted by the total number caught in each sample. Projected growth rates for combined bays were based on the von Bertalanffy model from Parrack (1979). Sexes were assumed equal since shrimp were not sexed.

The following criteria, procedures and assumptions were used to recommend the 1983 closing of the Texas territorial sea:

1. The mean number of shrimp captured in bag seines during April 1983 was compared to the mean number caught during 1978, 1979 and 1980, when the season was closed on 1 June. Relatively large numbers (April mean for 1978-1979 and 1980 plus 2 SE) of shrimp captured in April were interpreted as indicating good survival and/or early recruitment of postlarvae and therefore a probable earlier than 1 June emigration from bays to the Gulf.

2. The percentage of samples in which brown shrimp occurred was compared to that observed in previous years. A relatively high percentage of samples containing shrimp was interpreted to mean that shrimp were well distributed along the coast.

3. The mean length of shrimp collected during April was determined. If the number of shrimp in samples indicated early emigration, the von Bertalanffy growth model from Parrack (1979) was used to estimate the date that shrimp captured in April would reach a mean length of 90 mm. Growth rate was calculated from 15 April.

4. The periods of maximum duration of ebb tides were determined from National Oceanic and Atmospheric Administration (NOAA) nautical charts for Galveston Bay. The date of the period nearest to the date shrimp were projected to reach 90 mm was determined and recommended as the closure date.

The following criteria, procedures and assumptions were used to recommend the 1983 opening of the Texas territorial sea to shrimping:

The number and mean length of shrimp caught in bag seines during June were compared to those caught in previous years. The season could be set for the 60 days authorized if substantial numbers (a mean of 2 SE greater than average) of small shrimp were still found along shorelines. The season could be shortened if the mean number of shrimp was 2 SE less than average.

RESULTS AND DISCUSSION

Closing Date

Data indicated that an early emigration of shrimp to the Gulf of Mexico in 1983 was probable. Mean number of shrimp captured in April bag seines was similar (1.45/ha) to that in 1982 (1.77/ha), but 2 SE greater than the mean catch rate (0.53/ha) for 1978, 1979 and 1980 (Table 1). The percentage of samples containing shrimp in 1983 was 55.71% compared to a mean of 28.00% for 1978-80, indicating shrimp exhibited a wider than normal distribution.

Mean length of shrimp was 40.73 ± 2.67 mm in April 1983 (Table 1), and growth calculated from 15 April indicated that the mean length would be 90 mm during the last week in May. The periods of maximum ebb tide duration as predicted for Galveston Bay were 15-18 May, 27 May-2 June and 12-15 June. The period of maximum ebb tide duration nearest the date that shrimp were projected to reach a mean length of 90 mm began on 27 May. Therefore, the recommended Gulf closure extended from 30 minutes after sunset on 27 May to 30 minutes after sunset on 15 July.

Opening Date

June bag seine data indicated there was no need to extend or shorten the closed season. Catch rates during June 1983 (2.32 ± 0.33/ha) were similar to the average (2.16 ± 0.23/ha) of previous years (Table 1). The mean length of 63.14 ± 3.51 mm in 1983 was also similar to a mean of 64.36 ± 0.95 mm for 1979-82.

Verification of Closure Date

Trawl samples collected in passes indicated the predicted closure date of 27 May was appropriate (Table 2). The greatest coastwide mean catch rate (121.6/tow) occurred during the week of 30 May-5 June. Highest catches were from Aransas Bay (454.5/tow) and Galveston Bay (25.5/tow). Shrimp appeared to emigrate from the lower Laguna Madre earlier than from the remaining bay systems since the greatest catch rate (27.5/tow) was during the week of 2-8 May. A relatively high catch rate of 45.5/tow in Galveston Bay during 27 June-3 July indicated a later emigration from that area.

The 90 mm mean length used to determine the closure date on a coastwide basis also appeared appropriate. Coastwide mean lengths of shrimp collected in passes ranged from 73 to 106 mm (Table 2). Shrimp in the lower Laguna Madre were smaller (64-92 mm) than those in other bay systems where mean lengths ranged from 83-110 mm.

Table 1. Mean catch rate (No./ha + 1 transformed to Log_{10}) and mean total length (mm) of brown shrimp (*Penaeus aztecus*) collected with 18.3-m wide bag seines along shorelines of Galveston, Matagorda, San Antonio, Aransas, Corpus Christi Bays and the Laguna Madre (upper and lower) during April and June 1978-1983. The mean No./ha and mean percentage of samples containing shrimp for April 1978-1980 was 0.53 ± 0.34 and 28%, respectively. The mean No./ha and mean total length for shrimp in June 1979-1982 was 2.16 ± 0.23 and 64.36 ± 0.95, respectively (ND = no data).

		April			June	
Year	Number of samples/month	Mean No./ha ± 1 SE	Samples containing shrimp (%)	Mean length (mm) ± 1 SE	Mean No./ha ± 1 SE	Mean length (mm) ± 1 SE
1978	42	0.64 ± 0.40	30.95	43.93 ± 2.06	ND	ND
1979	42	0.58 ± 0.38	30.95	41.42 ± 3.87	2.01 ± 0.53	63.29 ± 3.37
1980	42	0.37 ± 0.25	21.43	47.48 ± 9.58	2.43 ± 0.26	65.05 ± 3.28
1981	42	2.03 ± 0.50	76.19	51.83 ± 3.51	1.93 ± 0.52	63.84 ± 2.61
1982	70	1.77 ± 0.35	64.29	47.50 ± 2.20	2.26 ± 0.38	65.24 ± 2.48
1983	70	1.45 ± 0.37	55.71	40.73 ± 2.67	2.32 ± 0.33	63.14 ± 3.51

Table 2. Weekly mean catch rate (No./tow) and mean length (mm) of brown shrimp *Penaeus aztecus* caught at 6.1-m trawl pass stations in selected Texas bay systems during May-July 1983 (Blank = no measurement taken). No shrimp were caught in Corpus Christi Channel.

Month	Date	Number samples[a]	Galveston		Matagorda		Aransas		Lower Laguna Madre		Coastwide	
			No./tow	Length	No./tow	Length	No./tow	Length	No./tow	Length	No./tow	Length
May	2-8	2	0.0		0.0		2.0	90	27.5	72	7.4	73
	9-15	2	0.0		0.5	103	0.0		1.5	69	0.5	78
	16-22	2	13.0	106	0.5	98	7.5	90	4.5	70	6.4	95
	23-29	2	2.0	104	0.0		12.5	103	2.0	64	4.1	98
	30-Jun 5	2	25.5	97	3.5	87	454.5	98	3.0	74	121.7	98
Jun	6-12	2	0.5	83	0.0		0.0		0.0		0.1	83
	13-19	2	3.0	101	0.0		0.0		0.0		0.8	101
	20-26	2	0.0		0.0		0.0		0.0		0.0	
	27-Jul 3	2	45.5	97	0.0		0.0		0.5	92	11.5	97
Jul	4-10	2	0.0		0.5	110	0.5	103	0.0		0.2	106
	11-17	2	0.0		4.5	92	0.0		0.0		1.1	92
	18-24	2	0.0		0.0		2.0	102	0.0		0.5	102
	25-31	2	0.5	98	12.5	109	5.5	106	13.5	84	8.0	98

[a] No./samples per each week in each pass.

Implementation Procedures

Any technique used to establish a closed season should be simple, since it must be employed in a timely manner. The last bag seine samples are not collected until 30 April and 30 June, respectively. Calculations must be made and results presented by memorandum through supervisors and approved by the Executive Director who was delegated the authority to set season dates by the TPWC. The law requires 72 and 24 hours, respectively, public notice for closing and opening dates (Parks and Wildlife Laws 1981). The approved season dates must be published in the Texas Register as public notice and news releases prepared. The National Marine Fisheries Service (NMFS) is notified in order that public notice may be provided concerning the closing and opening of U.S. waters. NMFS must also go through their in-house procedure.

Fishery managers do not always have the luxury of detailed data analysis. In our situation the time lapse from the last day of data collection through approval and public notice is only a few days.

This was the second year in which the described technique was used to determine the season dates and the data indicate it has been a successful method. Since the technique is relatively new, continual improvements may be made as more data are collected and analysed.

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SHRIMP MANAGEMENT IN ALABAMA

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ABSTRACT

The objectives of Alabama's shrimp management program include prediction of relative abundance of brown shrimp (Penaeus aztecus) and white shrimp (Penaeus setiferus), and prediction of the opening day of shrimp season. Initial predictions of current season abundance are made by sampling postlarval shrimp in marshes and comparing monthly catch per unit effort (CPUE) with that in previous years. Juvenile and young adult shrimp are sampled by seine and 16-ft otter trawl to assess and monitor relative abundance and distribution. A monthly CPUE and daily average count or weight are computed. CPUE's are compared with previous years and the average daily count is used to calculate growth rates using an equation of the form $y = ae^{bx}$ where y = the daily average count, x = day, and a and b are regression coefficients. This equation is ultimately used to predict the day when the average size of shrimp will be 68 per pound which is the legal harvestable size in Alabama.

INTRODUCTION

Prediction of Alabama's shrimp harvest is a developing program. Methods are improved yearly as more data accumulate for comparison and statistical manipulation. Attempts are being made to predict shrimp abundance and the opening day of brown shrimp season as far in advance as possible, but the success of this program varies from year to year. The procedures presented here will be those used or developed during 1983. The work is part of Alabama Marine Resources Division's Fisheries Assessment and Monitoring Project funded under P.L. 88-309 through the National Marine Fisheries Service (NMFS).

Samples for evaluating shrimp abundance are obtained throughout Alabama's estuarine waters using a variety of gear. Shrimp are collected at postlarval, juvenile and adult stages. A modification of the Renfro beam plankton trawl (BPL) is used to sample postlarvae in marshes. Fifty-foot bag seines and 16-foot otter trawls with 0.25-inch mesh liners are used to sample juvenile shrimp. Shrimp are separated by species and total number and weight for each species are recorded.

Initially, monthly catch per unit effort (CPUE) values are computed for both postlarvae and juvenile/adult stages by dividing the total number of shrimp caught by the total samples taken in the month. Monthly CPUE is then correlated with averaged environmental data to predict relative abundance and harvest. Daily average size or "count" (the number of heads-on shrimp per pound), determined from the average of all samples each day, is used to calculate brown shrimp growth rate and predict the day on which shrimp will attain Alabama's legal harvest size of 68 count.

Prediction methods are the same for brown shrimp (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*). Pink shrimp (*Penaeus duorarum*) are not considered, although records are kept (pink shrimp comprise an average of only 2% of Alabama's shrimp landings). The following discussion of methods refers to treatment of brown shrimp data.

PREDICTIONS OF RELATIVE ABUNDANCE

Postlarvae

First attempts to predict relative abundance of shrimp during the approaching season is derived from monthly postlarval CPUE. Files of the monthly postlarval CPUE are maintained each year (Table 1) for comparison with current data. The most useful indicator of potential abundance is the peak monthly CPUE of postlarval brown shrimp which normally occurs in March or April. The prediction made at this point is relative to abundances of previous years. In 1983, postlarval brown shrimp abundance was correlated with average monthly salinity and water temperature and reported catch from Alabama's inside waters during June and July. The following indices were used in the correlation.

Salinity (ppt)/temperature (C) index (x): (average March salinity x average March temperature) + (average April salinity x average April temperature), if the sum was less than 500 then x = -1. If the sum was greater than or equal to 500, x = 0. This is a modification of a treatment of salinity and temperature proposed by Sutter and Christmas (1983), based upon the theory that temperature and salinity will tend to have a negative effect below certain averages and little or no effect above those averages.

Brown shrimp postlarval index (y): (average March CPUE + average April CPUE)/2.

Harvest (z): the catch (lbs) from Alabama's inside waters during June and July as reported from National Marine Fisheries

Table 1. Monthly CPUE of brown shrimp (*Penaeus aztecus*) postlarvae caught in Alabama waters per BPL tow 1977-1983.

	SHRIMP PER TOW						
Month	1977	1978	1979	1980	1981	1982	1983
JAN		0.0	0.0	0.3	0.0	0.0	0.0
FEB		0.0	0.0	0.8	0.0	6.3	33.3
MAR		45.5	9.7	9.7	20.2	71.0	23.8
APR	29.0	93.2	4.3	29.2	61.7	65.2	169.2
MAY	22.0	42.0	12.4	22.2	21.3	47.3	17.5
JUN	40.8	13.7	169.0		7.7	14.0	2.0
JUL	36.3	10.7	20.8	6.3	43.3	0.3	25.0
AUG	2.3	4.8	14.8	4.7	14.0	17.3	33.7
SEP	1.3	13.6		11.2	0.3	2.0	4.0
OCT	4.0	1.3		6.7	2.0	5.3	
NOV	6.0	5.7	2.5	16.7	0.0	0.0	
DEC	0.0	0.0	0.0	8.7	0.0	0.3	

Service (NMFS) grids 10.2 and 11.1 by NMFS, Southeast Fisheries Center, Miami, Florida.

Table 2 summarizes salinity/temperature and postlarval indices data used in deriving the equation, and gives predicted annual harvest and the percent error in predictions. The equation describing the relationship is $z = 6488346 + 2313033x - 25572y$. The correlation coefficient r^2 was 0.85.

When 1983 catch statistics became available for June and July for Alabama's inside waters, they were used to check the accuracy of the 1983 prediction equation. Reported landings of brown shrimp in June and July 1983 from Alabama's inside waters were 2,688,353 pounds. The predicted landings calculated from the prediction equation were 1,707,616 pounds representing a 36% error in the prediction. More years of data are necessary to refine this prediction process. Any calculation attempting to correlate biological assessment data to actual harvest depends, in the final analysis, not only upon the accuracy of assessment data collection but also upon the accuracy of catch statistics. Therefore, the Alabama Marine Resources Division has entered into a cooperative agreement with NMFS for improving collection of landing statistics. Alabama now has two port agents working with the two NMFS agents to collect statistics and has hired a fisheries statistician. These personnel should improve both the timeliness and accuracy of landings data.

Juveniles

When juvenile shrimp become abundant in samples (usually April or May), refinements are made of predictions on the upcoming season based upon the comparative juvenile brown shrimp CPUE. This prediction is based upon comparision of relative abundance in the current year with catch in preceding years. The numbers of juvenile brown shrimp in samples during April and May 1983 (Table 3) indicated the poorest harvest of brown shrimp since the beginning of the assessment program in 1977. Later assessment samples and reports from commercial fishermen of actual catch verified this prediction.

To improve prediction of the brown shrimp harvest from inside waters in future years, two mathematical treatments were applied to data in 1983. An attempt was made to correlate the CPUE of juvenile brown shrimp, salinity, and water temperature with the harvest from Alabama's inside waters during June and July. The same variables were used to derive this equation that were used to derive the prediction equation from brown shrimp postlarval CPUE except that April and May monthly averages were used instead of March and April averages.

Table 2. Values used in multiple linear regression comparing postlarval brown shrimp abundance with salinity, water temperature and harvest from Alabama's inside waters during June and July.

Year	Salinity (ppt) Temp. (°C) Index (x)	Postlarval Index (y) (shrimp/tow)	Reported 1/ Catch (lb) (z)	Estimated Catch (lb)	% Error
1979	-1	7.0	4,364,321	3,996,307	-8
1980	-1	19.5	3,308,638	3,676,652	+11
1981	0	41.0	5,270,132	5,439,880	+3
1982	0	68.1	4,916,618	4,746,870	-3
1983	-1	96.5	2,688,353	1,707,616	-36

Prediction Equation: $z = 6{,}488{,}347 + 2{,}313{,}033x - 25{,}572y$, $r^2 = 0.85$

1/ Tidwell 1982. Personal communication, NMFS, Southeast Fisheries Center, Miami, Florida

Table 3. Monthly CPUE 1977-1983 of juvenile and adult brown shrimp (*Penaeus aztecus*) from Alabama waters.

	Shrimp Per Tow						
Month	1977	1978	1979	1980	1981	1982	1983
JAN		0.0	0.1	0.0	0.0	0.0	0.1
FEB		0.0	0.0	0.0	0.0	0.0	0.8
MAR		0.0	0.0	0.2	0.1	0.0	0.8
APR	133.6	9.3	7.3	2.2	17.4	5.5	0.2
MAY	175.2	55.2	45.0	5.2	52.2	48.8	2.9
JUN	72.5	34.8	38.2	19.2	65.1	99.7	82.1
JUL	8.4	20.3	17.6	26.0	17.2	75.6	27.2
AUG	1.1	2.1	8.0	2.2	3.1	9.3	6.9
SEP	3.7	4.3	0.4	0.5	2.2	21.5	1.7
OCT	8.1	3.1	3.2	0.1	0.8	0.1	
NOV	8.8	1.7	2.5	1.0	0.4	0.4	
DEC	10.1	2.5	0.3	0.2	0.3	0.5	

Table 4 lists the values used in the calculation of the multiple linear regression correlation. The equation expressing this relationship was $z = 3640161 + 504506x + 46877y$ ($r^2 = 1.00$). This equation predicted that 3,210,660 pounds of shrimp would be harvested from Alabama's inside waters in June and July 1983. This represented a 19% overestimate of the harvest when compared to the landings reported from the inside waters for that area (2,688,653 pounds). This error, though greater than expected, is well within the level of error in the landing statistics.

In an attempt to address the problem of shrimp survival under various environmental conditions, a correlation was attempted to compare salinity, water temperature and juvenile brown shrimp abundance. Indices used in the multiple linear regression computations were: salinity (ppt) index (x): (average April salinity + average May salinity)/2, and juvenile shrimp abundance (shrimp per tow) index (z): (average April CPUE + average May CPUE)/2.

Table 5 presents the value used in an attempt to determine this relationship. The equation expressing the relationship of these data was $z = -112.7 + 1.88x + 4.86y$. This relationship had an r^2 value of 0.87.

Our multiple linear regression for predictions of catch looks promising, but additional years data are needed to prove the reliability of the method. Initial indications, however, are encouraging. In the future, an attempt is planned to develop mathematical prediction of the survival of shrimp from postlarval stage to the juvenile stage. This is important because of the variable effects of environmental conditions on the growth and survival of shrimp at these stages. Prediction of potential shrimp harvest based upon abundance at the postlarval stage has little value if prediction does not include the rate of survival to harvestable size.

PREDICTION OF OPENING DATES OF THE BROWN SHRIMP SEASON

One management tool has been used effectively in Alabama since 1978 to establish the opening date of the brown shrimping season and aid in the cooperative efforts between Alabama and Mississippi to open the waters of Mississippi Sound in both states simultaneously. Each spring, as soon as sufficient juvenile brown shrimp are collected in samples, an equation is derived to calculate the growth rate and predict the day that the average size will reach the legal size for harvest at 68 shrimp per pound with heads on.

Table 4. Data used in multiple linear regression comparing juvenile brown shrimp abundance to salinity, water temperature and harvest from Alabama's inside waters during June and July.

Year	Salinity (ppt) Temp. (°C) Index (x)	Shrimp Index (y) (shrimp/tow)	Reported Catch (lb) (z)	Estimated Catch (lb)	% Error
1979	-1	26.2	4,364,321	4,363,855	-.01
1980	-1	3.7	3,308,638	3,309,104	+.01
1981	0	34.8	5,270,132	5,271,511	+.03
1982	0	27.2	4,916,618	4,915,239	-.03
1983	-1	1.6	2,688,353	3,210,661	+ 19

Prediction Equation: $z = 3,640,162 + 504,506x + 46,878y$, $r^2 = 1.00$

Table 5. Data used in the multilinear regression to compare April-May averages of brown shrimp CPUE, salinity and water temperature.

Year	Salinity (ppt) (x)	Temperature (°C) (y)	Shrimp Index (z) (shrimp/tow)
1978	12.6	25.6	32.3
1979	7.9	24.2	26.2
1980	8.1	22.5	3.7
1981	18.1	23.4	34.8
1982	13.9	22.6	27.2
1983	4.5	21.5	1.6

Prediction Equation: $z = -112.7 + 1.88x + 4.86,y$, $r^2 = 0.87$

Brown shrimp growth rate is determined by comparing the average size or "count" of shrimp taken on one day with average size on previous days. As the shrimp grow, their count falls. This decrease in count follows the slope of an exponential curve ($y = ae^{bx}$), with rapid growth occurring initially and slower growth occurring as the shrimp get larger.

Often the shrimp taken in samples in early April seem to get smaller day by day. This is because the average daily count is being used to determine size and the change in this average represents the growth rate. Initially, as the juvenile brown shrimp leave the nursery areas, the larger individuals emigrate first. This results in a particular count. If in subsequent samples only shrimp from this initial wave were collected, the count would drop predictably. However, during the first 2 weeks of this emigration, several waves of shrimp move from the nurseries to the open water. Smaller shrimp arrive at sample sites later. When they are included in average count calculations, the average size is smaller. Eventually the shrimp become thoroughly mixed and the average size begins to increase with a resultant drop in count. When three daily counts are available showing a progressive increase in size, these counts are used to extrapolate growth to determine the day that the average size will be 60 shrimp per pound.

The date on which the initial prediction can be made varies year to year depending upon the environmental conditions. During the period 1978-83, initial predictions were made from 3 to 8 weeks prior to the opening day of the shrimping season. Predictions are generally made 5 weeks before opening day. These initial predictions have averaged within 5 days of the final date decided upon for opening. In each case, the opening of the shrimping season was set several days beyond the predicted date to allow for coordination with Mississippi. As additional samples are taken during the spring, the new data are added to the calculations to update and improve the prediction. This allows for adjustments due to environmental developments such as spring flooding and lower than expected water temperatures which tend to reduce growth rates.

Each year, the accuracy of the shrimp size predicted opening day is verified either by direct observation of commercial catches on board the boats on opening day or from field samples from selected stations. In each year during 1978-83, shrimp size verified on the shrimping grounds has met or exceeded the legal requirements for opening on the date predicted.

LIMITATIONS TO PREDICTIONS

This growth rate calculation and prediction can not, however, predict shrimp movement and subsequent changes in size composition due to emigration of small shrimp from nursery areas. Therefore, sampling must continue up to the opening date in order to correct, if necessary, for sudden emigration of smaller shrimp into the shrimping ground from nursery areas.

Shrimp management in Alabama is dynamic like the system which it attempts to manage. This is a necessity since additional data reveal ways to improve prediction of shrimp growth and production. With the improvement expected in landing statistics provided by the cooperative agreement between Alabama and NMFS, prediction of the shrimp harvest from Alabama's inside waters should continue to improve in coming years. Continued work on relationships between shrimp and hydrologic conditions should increase expertise in the prediction not only of shrimp growth, but also shrimp movement.

One problem which exists when trying to move from a simple manipulation of in-house data to correlation of data to actual harvest by the commercial sector is the question of effort. Calculations based simply upon total pounds of shrimp caught can be misleading because the success of the shrimp harvest depends upon the effort expended. This effort is represented by both the number and length of trips, which, in turn, is affected by weather and economic factors. Calculations based upon catch per trip are also unreliable because, by NMFS definition, a single trip is recorded whether the boat is out one day or 30 days. Therefore, a certain number of trips one year may produce more shrimp harvested than many more trips in another year simply because the average length of each trip was longer during the year with fewer trips. Obviously any variation and combination of effort can occur. One solution to this problem is an increase in the percentage of interviews by port agents collecting landings data and in the reliability of data concerning the number of hours fished.

SUMMARY

The attempt to predict eventual shrimp harvest from available sample data collected in the winter and spring is an evolving process in Alabama. The methods discussed in this paper represent the earliest attempts. As more data become available, the methods will be refined. To date the CPUE of postlarval and juvenile brown shrimp is used to predict the relative abundance. Average sizes of shrimp taken in trawl samples are plotted by sample day and the resultant exponential curve can be extrapolated to predict the day when the average size will reach 68 shrimp per pound. This growth rate prediction has proved very useful for setting an opening day for the brown shrimp season. However, because the average size determined in this manner is a result of both shrimp growth and mingling of shrimp of various sizes, the prediction equation can not entirely take the place of field sampling just before the season opens. If a large number of small shrimp is prematurely driven from the nursery areas or the larger shrimp suddenly move to the Gulf of Mexico, the average size of shrimp on the traditional bay shrimping grounds will become smaller rapidly and unpredictably.

Nonetheless, the prediction methods presented here are useful to the biologists and administrators of Alabama's Marine Resources Division. With the insight gained using these methods we have been able to better inform the resource users about the size and quantity of the resource on a timely basis. The growth rate prediction has successfully been used to coordinate the selection of the opening day of the brown shrimp season with the state of Mississippi for several years.

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FORECASTING OFFSHORE BROWN SHRIMP CATCH FROM EARLY LIFE HISTORY STAGES

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ABSTRACT

A prediction of adult brown shrimp harvest, based on an index derived from Galveston Bay bait fishery CPUE, is issued to the industry by the National Marine Fisheries Service Galveston Laboratory every June. This prediction has been the most reliable index of future shrimping success, but it is available only weeks before the shrimping season begins. Studies are underway to develop an earlier forecast by establishing valid abundance indices at the advanced postlarval and early juvenile stages of the brown shrimp life cycle.

Postlarval shrimp are sampled with a beam trawl twice weekly at the entrance of Galveston Bay. Predictions based on postlarval abundance have been quite variable, but the regular sampling yields information regarding timing and magnitude of shrimp immigration. Future work will attempt to improve predictions at this life stage, which would give the earliest information to the fishery.

Juvenile brown shrimp abundance has been evaluated at several Texas coastal ponds. Preliminary data from these mark-recapture studies suggest that there may be a relationship between juvenile shrimp standing stock and subsequent offshore abundance. If a prediction could be developed from juvenile stage shrimp it would be available as much as a month earlier than the bait index prediction.

INTRODUCTION

Biologists at the National Marine Fisheries Service (NMFS) Galveston Laboratory began studies in the early sixties to investigate possibilities of predicting the annual abundance of brown shrimp (*Penaeus aztecus* Ives). This work was based on the premise that the number of postlarval shrimp collected during their movement from the Gulf to coastal bays and the density of juvenile shrimp in estuarine areas are proportional to subsequent offshore densities of adult brown shrimp. Other fishery biologists, working under contract with the Galveston Laboratory or independently, have pursued the same approach along various parts of the Gulf and south Atlantic coasts. Detailed reports include those of Baxter (1963), St. Amant et al. (1963), Louisiana Wildlife and Fisheries Commission (1964), Christmas et al. (1966), St. Amant et al. (1966), Baxter and Renfro (1967), Berry and Baxter (1969), Christmas and van Devender (1981), and, most recently, Sutter and Christmas (1983).

In the Gulf of Mexico, brown shrimp postlarvae enter the bays and passes when they are 10 to 14 mm long. Mass movements of postlarvae into nursery areas generally occur in March and April after water temperatures reach or exceed 15.6 C (60 F). Collections of young postlarvae from the Galveston Entrance are used as early indicators of the upcoming crop for the offshore fishery. Shrimp abundance is measured as the postlarvae grow into juveniles and enter the bay and bait shrimp fisheries. Our best estimate of brown shrimp abundance is derived from data collected from the Galveston Bay bait shrimp fishery during May and early June.

The Gulf of Mexico shrimp fishery is one of the most valuable fisheries in the United States. Approximately half of the catch is landed in Texas. The annual shrimp catch is variable, however, and fluctuations in catch and value can cause economic hardship to the industry in poor years. Early prediction of offshore shrimp catch has become increasingly important to fishermen and processors so that they can plan their economic strategies in advance of the fishing season. Following, we describe how each life stage index is evaluated to form a prediction of offshore catch.

Postlarval Shrimp Abundance Index

A continuing survey to investigate seasonal changes in the movement of postlarval shrimp through the principal entrance to Galveston Bay (Fig. 1) began in November 1959 as part of an expanding shrimp research program. Initially, stations were located on Galveston Beach as well as at the Galveston Entrance to determine if the beach zone was a postlarval shrimp habitat. When no mean size difference was detected compared with Galveston Entrance samples, it was assumed that shrimp moved directly to estuaries. Shrimp near the shoreline of the entrance were sampled twice weekly with a hand-drawn beam trawl (Renfro 1963). Tows were made alternately in the morning and afternoon in an effort to sample during both ebb and flood tides each week. Penaeid shrimp were separated from the catch, identified, and counted at the laboratory. Details of sampling procedures and species identification were provided by Baxter (1963) and Baxter and Renfro (1967).

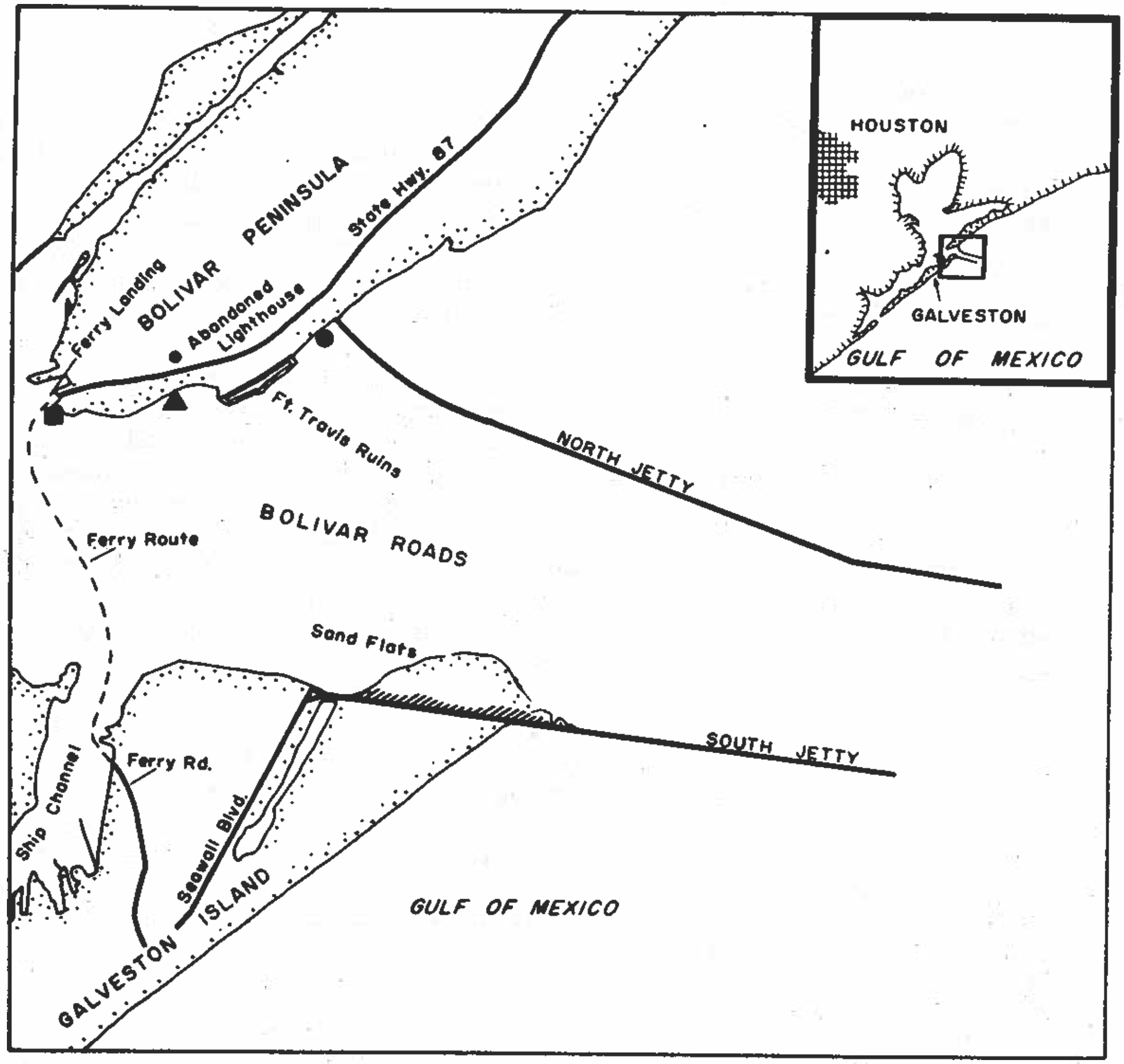

Figure 1. Postlarval brown shrimp sampling data site (filled black circle) at North Jetty and Galveston Bay Entrance (from Baxter 1963).

The significance of postlarval catch gathered between November 1959 and May 1961 became apparent when we found high numbers of postlarvae caught in early spring 1960 were followed by a near record brown shrimp catch in the offshore commercial fishery during the summer months. Catches of postlarvae in 1961 were small as were later commercial harvests, suggesting that catch data on postlarvae were indicative of brown shrimp abundance.

Semiweekly sampling for postlarvae was initiated in August 1961 with a new objective - to investigate the possibility of predicting relative abundance of commercial shrimp from postlarval catches. Sampling procedures were not changed because we believed that a simple and inexpensive predictive technique would be more acceptable to shrimp management agencies than would complex sampling schemes. With the exception of a brief interruption caused by Hurricane Carla in September 1961, a routine schedule was followed until sampling terminated in November 1974. Sampling was again initiated in February 1983, continuing through May 1983, the months when brown shrimp enter Galveston Bay (Baxter and Renfro 1967).

Over the years, the postlarval index has provided a rough estimate of the number of postlarvae entering the bay system; however, it has not been a consistent indicator of future offshore abundance. Largest numbers of postlarvae are generally taken in March and April, declining in May, but abundance and timing vary year to year. For example, the 1983 postlarval counts were quite low compared with the 16-year (1960-75) average, and offshore catch also was low (Table 1). In contrast, 1963 counts were much higher than the 16-year average, but subsequent landings that year were less than the 1960-82 average of 27.5 million pounds. The 1967 total postlarval count was only about half of the 1963 count, yet the offshore catch was a record 42.7 million pounds.

Postlarval brown shrimp are most vulnerable to environmental conditions. They depend on the tidal and wind-driven currents to carry them into the bays and within the estuaries, and are subject to wide variation in salinity and temperature. Although postlarval brown shrimp can tolerate a wide range of temperature and salinity, the combination of low temperature and low salinity is detrimental (Zein-Eldin and Aldrich 1965). The postlarval index has great potential as a predictor if environmental variables can be quantified in the model and the prediction adjusted for changes in the variables. Sutter and Christmas (1983) showed that incorporating a salinity index, a salinity-temperature interaction index, and a postlarval shrimp index into a multilinear regression equation yields a model that accounts for 80% of the variability of June and July brown shrimp commercial harvest from Mississippi waters.

Table 1. Monthly average number of postlarval brown shrimp per tow at Galveston Bay Pass and subsequent offshore catch of adult brown shrimp.

		Averages		
	1960-75	1963	1967	1983
Feb	75	0	200	80
March	202	304	217	116
April	192	503	30	71
May	86	62	12	31
Subsequent Offshore Catch (10^6 lb)	27.5*	24.6	42.7	17.5

*1960-1982 average

Berry and Baxter (1969) examined several potential sources of variability: the reliability of their sampling gear, the effects of tides on postlarval catches, and the possibility of diel differences in catches. They found that the beam trawl provided a satisfactory sample, and that the total variation of samples taken over a 4-day period was almost as great as that from collections made during 6 months. In fact, the range in numbers of postlarvae at a given location can change from zero to several thousand within several hours. No correlations were found between postlarval catch and time of day or tide stage at the North Jetty location leading the investigators to believe that their station was probably in a position where water movements differed from recorded tide level. Collections of postlarvae made at Rollover Pass (East Galveston Bay) in spring 1965 showed that numbers of postlarvae varied with water movements when currents were strong. Berry and Baxter (1969) presumed that postlarvae caught during ebb tide had been carried into the bay on a previous flood tide, and that conditions affecting water flow can influence the numbers of postlarvae carried past the sampling station. These conditions may include tide changes, storms, and freshwater runoff from land.

Juvenile Brown Shrimp Standing Stock

We are currently evaluating the potential of juvenile brown shrimp population density in a Texas coastal pond as a predictor of offshore abundance. A predictor based on this pre-bait life stage would be more timely than the bait index prediction, though possibly not as accurate. This predictor would likely be more accurate than the postlarval index because of the lower amount of mortality occurring between the juvenile stage and entry to the fishery, but would be available somewhat later in the season.

The juvenile brown shrimp population of Sydnor Bayou, a tertiary tidal marsh in Galveston Bay, was first estimated from results of a Petersen mark-recapture study conducted before shrimp emigration from estuarine nursery areas to bay and offshore areas in May 1970. Mark-recapture experiments were conducted in June and July 1971 in five Texas coastal ponds from Galveston to the Port Lavaca area (Fig. 2). We returned to Sydnor Bayou in May 1983 to estimate standing stock of juvenile shrimp (Sullivan et al. in press).

There appears to be a direct relationship between juvenile population density and offshore abundance. Population densities for the three years studied were highest in years with above average offshore catch (1970 and 1971). The 1983 density in Sydnor Bayou was extremely low (37% of the 1970 level) and the prediction for the offshore catch was 9.7 million pounds less than the 1960-82 average

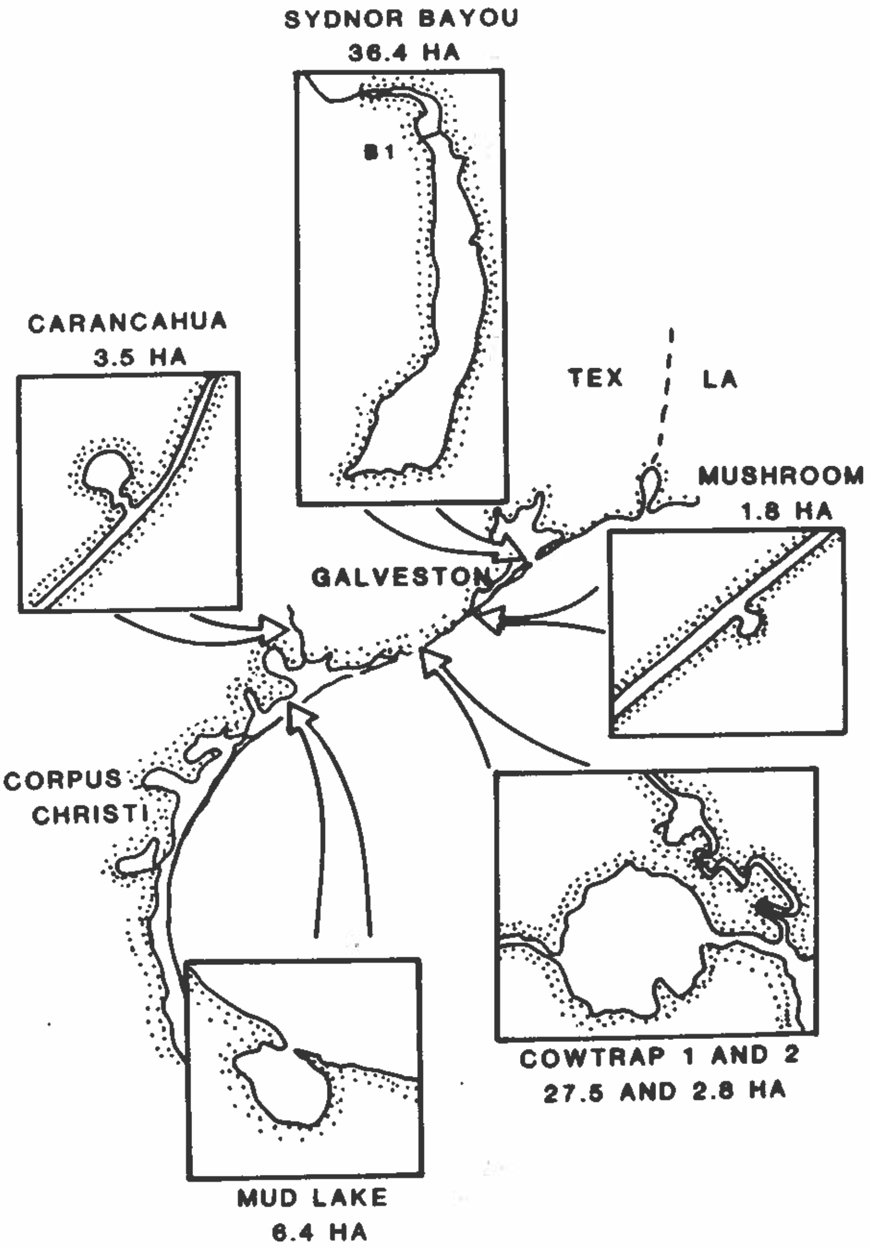

Figure 2. Sites of juvenile brown shrimp mark-recapture studies: Sydnor Bayou (1970, 1983); Carancahua, Mushroom, Cowtrap and Mud Lakes (1971) (from Sullivan et al. in press).

of 27.5 million pounds (Table 2). We do not have sufficient data to attempt a prediction using this index.

Bait Shrimp Index

Our most reliable index of future shrimping success is developed from the bait shrimp fishery data. Young shrimp grow to a size of 70 to 100 mm (total length) from 6 to 12 weeks after entering estuaries. These juveniles are harvested by a seasonal bait shrimp fishery which operates in Galveston Bay to supply sport fishermen with live bait. The shrimp are harvested with otter trawls towed by small trawlers.

A survey of the bait shrimp fishery of Galveston Bay began in 1957 (Chin 1960). Statistics of fishing effort have been gathered since June 1959, along with data on landings and species composition from five strata in the Galveston Bay system (Fig. 3). Interviews are obtained from at least half of the bait shrimp dealers and fishermen in the bay area, and visual check is made of other bait shrimp stands to determine how many are open for business. Total landings and fishing effort are estimated from this information. Species and size composition of landings are assessed from samples of shrimp purchased weekly from a random selection of dealers.

The bait index, derived from the average weekly catch per unit effort for the weeks including 25 April through 12 June, is directly related to the offshore catch (Fig. 4), with a correlation coefficient $r^2 = 0.847$ for data from 1960 through 1980. Bait index and offshore catch data for 1981 to the present are not included in the regression because the Texas Closure management measure has altered the fishing season since 1981. Bait indices for 1966, 1975 and 1979 were not included in the regression. CPUE's for 1966 and 1979 were inflated due to floods which may have concentrated shrimp in lower bay areas or forced early emigration. It was obvious early in the 1966 and 1979 seasons that the bait CPUE's were unrealistic. Weekly collections of bait samples showed an absence of bait in the upper bays, with unusually high catches in the lower bay. No data were collected in 1975.

Predictions from this model (Table 3) were very good for 1982 and 1983, and have been useful in evaluating the impact of the Texas Closure in 1981, 1982 and 1983 (Klima et al. 1982, 1983, and 1984). The assumption that the Galveston Bay bait fishery is indicative of the entire Texas coast is important to successful predictions. For example, in years such as 1973 when lower level abundance was due to heavy rainfall and runoff into the system and resultant lowered salinites, the bait index was low, and the prediction was therefore low. Subsequent production was 3.9 million pounds higher than

Table 2. Juvenile brown shrimp population estimates of shrimp larger than 40 mm TL for several Texas coastal ponds.

Location	Start Date	40 mm + population per acre	95% CI	Offshore Production (10^6 lb)
Sydnor Bayou 90 Acres	5/31/83	2,309	2,010-2,608	17.5
	5/21/70	6,163	5,111-7,215	30.7
Mud Lake 16 Acres	6/3/71	3,015	2,800-3,230	34.5
Carancahua 9 Acres	6/7/71	6,314	5,753-6,874	34.5
Mushroom 5 Acres	7/2/71	5,750	5,451-6,048	34.5

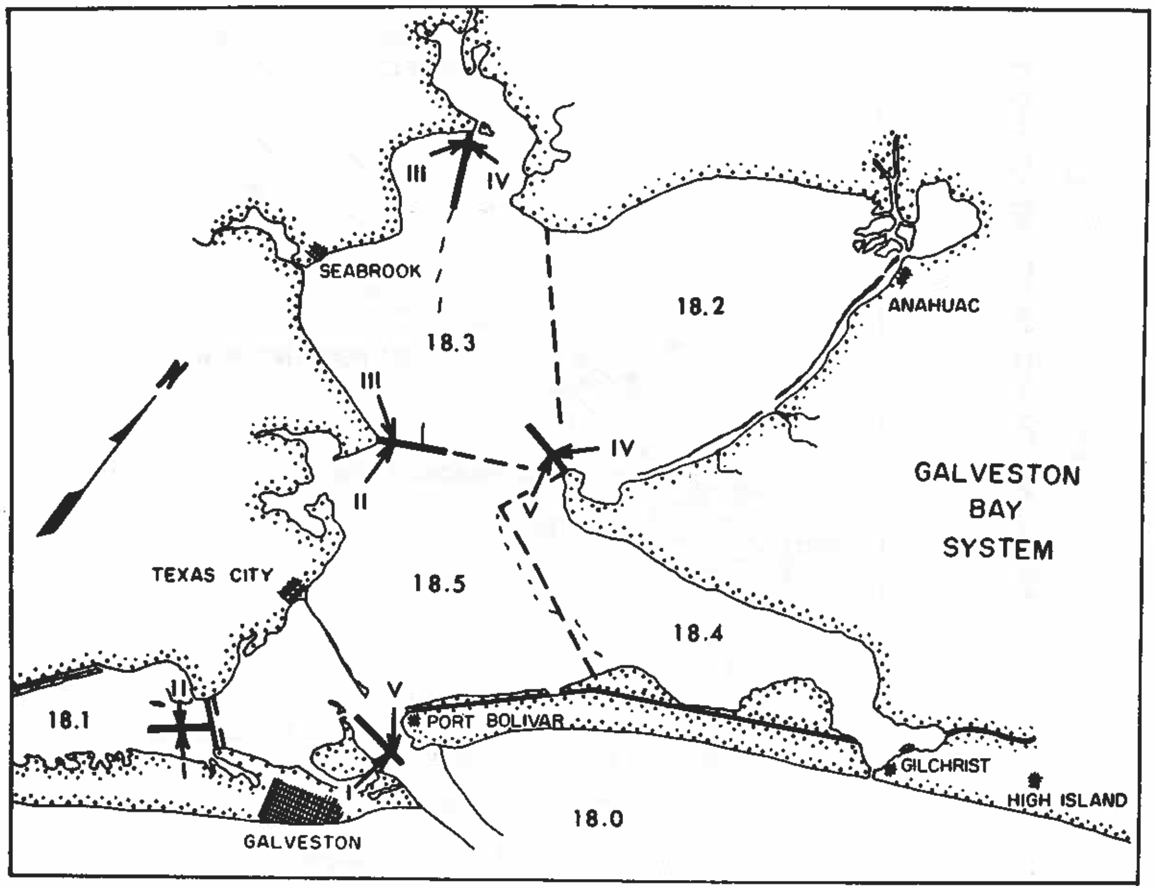

Figure 3. Statistical areas and five bait shrimp strata in Galveston Bay. Dealerships are grouped in geographic areas: I-Galveston Island (29 dealers); II-Virginia Point to Eagle Point (36 dealers); III-Eagle Point to Morgan Point (4 dealers); IV-Houston Ship Channel to Smith Point (6 dealers); and V-Bolivar Peninsula to High Island (23 dealers). Fishing areas are designated as: 18.1 - West Bay; 18.2 - Trinity Bay; 18.3 - Upper Galveston Bay; 18.4 - East Bay and 18.5 - Lower Galveston Bay. Numbers of dealers are for 1983.

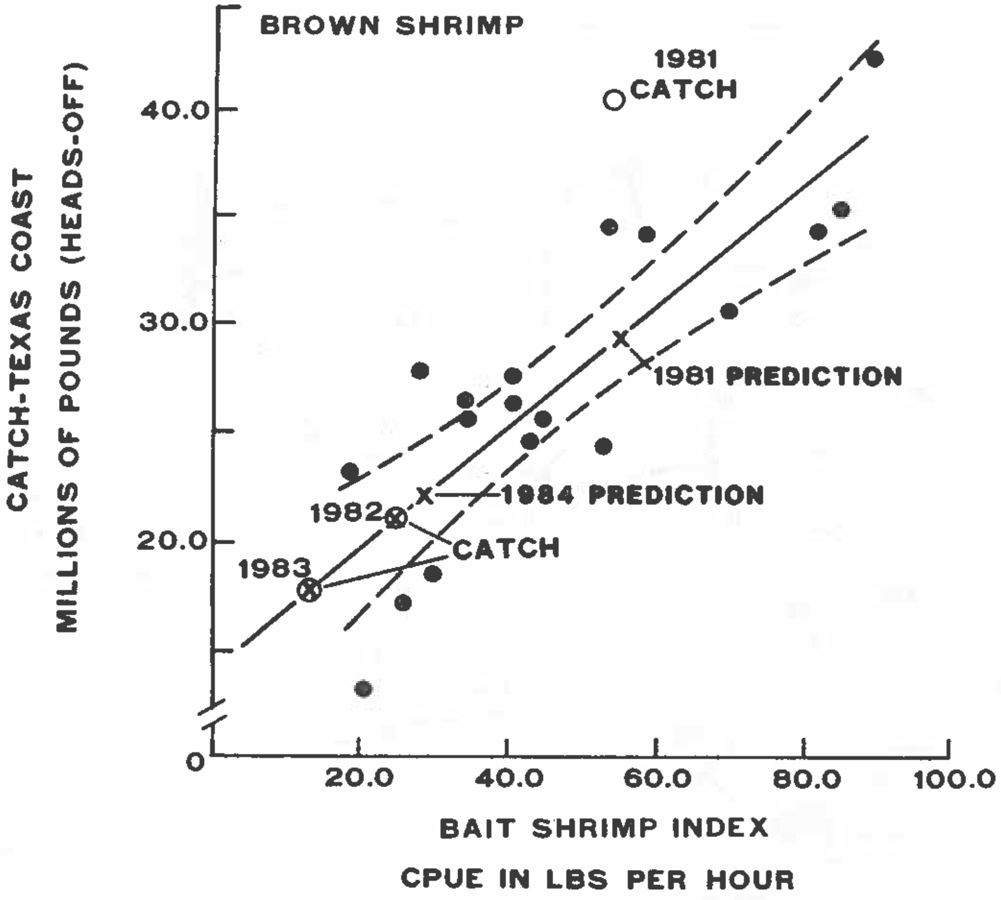

Figure 4. Bait shrimp index prediction model.

Table 3. Galveston Bay bait shrimp index from 1960 through 1983.

Year	Bait index	Texas Offshore Catch June-July (10^6 lb) Predicted	Actual	Difference (10^6 lbs.
1960	53.6	29.1	34.5	+ 5.4
1961	20.8	20.0	13.2	- 6.8
1962	26.1	21.5	17.3	- 4.2
1963	53.0	29.0	24.6	- 4.4
1964	30.2	22.6	18.6	- 4.0
1965	41.0	25.6	26.5	+ 0.9
1967	89.4	39.0	42.7	+ 3.7
1968	28.0	22.0	27.9	+ 5.9
1969	43.5	26.3	24.7	- 1.6
1970	70.0	33.7	30.7	- 3.0
1971	82.3	37.1	34.5	- 2.6
1972	85.6	38.0	35.5	- 2.5
1973	18.7	19.4	23.3	+ 3.9
1974	34.3	23.8	26.4	+ 2.6
1976	34.1	23.6	25.7	+ 2.1
1977	58.5	30.3	34.3	+ 4.0
1978	40.5	25.5	27.7	+ 2.2
1980	45.0	26.7	25.7	- 1.0
1981	54.3	29.3	40.0	+10.7
1982	26.3	21.5	21.8	+ 0.3
1983	12.7	17.8	18.2*	+ 0.4

*Preliminary data

predicted in 1973 because estuaries along the central and lower coast of Texas had good crops of brown shrimp and production was high in subareas 20 and 21, while the upper Texas coast (subareas 18 and 19) recorded the lowest catch ever up until that time.

SUMMARY

The three indices described here must meet three criteria to be considered "good" predictors. They must be precise, timely, and cost effective. The bait shrimp index is the most accurate predictor because the shrimp abundance is evaluated just prior to the offshore fishery season. Consequently, it is also the least timely. The bait index predictors have been fairly accurate; and the data collection is accomplished by one person. Because of the time factor, studies are underway to develop an earlier forecast by establishing valid indices at the advanced postlarval and early juvenile stages of the brown shrimp life cycle.

An index of postlarval abundance, while most satisfactory as an early predictor, is least accurate; however, the sampling itself is simple, requires one person's time and minimal equipment. Quantification of environmental effects may improve the accuracy of predictions from the postlarval index.

A prediction based on juvenile brown shrimp abundance is not as timely as the postlarval index, but more precision is gained. The mark-recapture method is labor intensive, but only for short periods of time, and requires more equipment than postlarval sampling. The accuracy of a prediction at this stage has yet to be determined because of limited data.

ACKNOWLEDGEMENTS

Many people have contributed to the prediction studies at Galveston over the years. We especially thank Mr. Carlton Furr for collecting bait fishery information and samples over the last 25 years, Mr. Dennis Emiliani for his efforts in field studies and data quality control, and Mr. Frank Patella for computer programming and data base maintenance.

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MEASUREMENTS OF ESTUARINE SHRIMP DENSITIES APPLIED TO CATCH PREDICTIONS

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ABSTRACT

New methodology was used to determine densities of brown shrimp (*Penaeus aztecus*), white shrimp (*P. setiferus*) and other species in a Galveston Bay salt marsh. These density measurements permitted comparisons of abundances between habitats and realistic estimates for projections of standing stocks. The data were obtained using a cylindrical drop sampler that encloses 2.8 m of marsh bottom. The method was compared against other techniques traditionally employed in estimating shrimp abundances. In side-by-side shallow water sampling on bottoms without vegetation, a 1-m wide beam trawl, 5.5-m wide bag seine and 3.7-m wide otter trawl were 82, 33 and 17% as efficient, respectively, as the drop sampler in catching shrimp. With marsh vegetation present, the 1-m wide beam trawl was 23% as efficient as the drop sampler. Standing stock estimates extrapolated from drop sampler density measurements to 90 acres were similar to mark-and-recapture estimates covering the same area. In a small pond (172 m) with 1,200 white shrimp, the stock estimate using six drop samples was 1,166. The major disadvantage for estimating stocks is that drop sampler data reflect natural patchiness in distributions, which often results in higher variances than methods that integrate patches.

INTRODUCTION

The size and success of the shrimp fishery in the northern and western Gulf of Mexico each year depend upon the number of postlarvae recruited into estuaries and upon the growth and survival of juveniles in estuarine nurseries (Gunter 1950; Chin 1960; Loesch 1965; St. Amant et al. 1966; Barrett and Gillespie 1973; Gaidry and White 1973; Johnson 1975). In accordance, the abundances of juvenile shrimp in estuaries can provide an estimate of future yield for fishermen (Berry and Baxter 1969).

The primary impediment to predicting annual shrimp yield is the reliability of data upon which predictions are based. At the core of the problem is acceptance of relative abundance estimates, without qualification, from traditional sampling techniques. Commonly used sampling devices, such as trawls and seines, vary in catch efficiency depending upon circumstances, and the resulting errors are incorporated into abundance data. These errors translate into poor estimates of standing stock for shrimp and other fishery species. Using such data, spatial and temporal comparisons are virtually impossible. Our aim has been to examine this sampling problem and develop methodology that can accurately depict shrimp densities as well as reliably assess stocks in estuarine habitats.

Several predictive techniques have been used that focus on the early life-stages of shrimp. One of the earliest and most commonly used is the postlarval index devised by Baxter (1963) to measure the relative abundance of postlarvae immigrating into estuaries from the Gulf through major passes (Baxter and Renfro 1967). A modification of the technique (Pullen et al. 1968) has extended abundance assessment to older postlarvae and juveniles in shallow-water nursery areas. Abundances of yet larger bait-sized juveniles are also assessed for prediction using different methods (Klima et al. 1982) in deep-water estuarine and bay areas. Each of these techniques relies upon trawls, seines or nets of various types to sample not the actual number of shrimp present but a relative number indicative of abundance. Such samples are acquired under a variety of environmental circumstances during a period when life stage and behavioral characteristics of the shrimp are changing rapidly. The effect of many unaccountable variables on catch efficiencies has made it difficult to compare relative abundance data (for use in prediction) among techniques or across conditions. Some relationships, however, can be established. First, it is apparent that the accuracy in predictive resolution for each technique is greatly dependent upon consistency in measurement of relative abundances. Whatever the circumstances, the mechanical error in sampling (catch efficiency) must remain the same or be corrected for as changes occur. The second is that measurements of abundance for future yield prediction from later life stages (such as bait-sized juveniles) will be better than measurements from earlier stages (such as postlarvae), simply due to nearness in time to harvest. Third, fishery dependent measurements used for prediction are likely to be biased reflecting catch rather than abundance.

Since one or all of the above may confound prediction of shrimp yield, changes should be considered to determine where corrective measures in technique are appropriate or possible. Variability in relative abundances due to changing efficiency of sampling gear and the inability to standardize catchability between samples, even when using the same sampling gear, appears to be the biggest impediment to good prediction. The simple solution may be to apply sampling that reliably measures actual densities. In a recent study (Zimmerman et al. 1984; Zimmerman and Minello in press), a drop sampler technique was used in an attempt to measure actual densities of brown shrimp (Penaeus aztecus) and white shrimp (P. setiferus) in a Galveston Bay salt marsh. The technique was designed to permit valid comparisons of shrimp densities between differing shallow-water habitats. The measurements provided a reference for evaluating other methods that estimate shrimp population size including those using trawls, seines, and mark-recaptures. In the following, the merits and disadvantages of applying such methodologies to predicting shrimp yields are discussed.

METHODS

A cylindrical drop sampler enclosing 2.8 m^2 (Fig. 1) was designed for obtaining accurate measurements of natant macrofauna in marsh habitats. A descriptive account of the sampler and methods, the salt marsh study site, and the study design are given in Zimmerman et al. (1984). To partly evaluate effectiveness, recovery of shrimp enclosed by the drop samplers was tested. Fifty juvenile shrimp, of sizes from 23 to 91 mm in total length, were marked by clipping a uropod and placed into samplers deployed in vegetated and nonvegetated habitats. After a 30-minute adjustment period, the procedure for removing organisms was followed and recovery was recorded. The test was repeated four times in each habitat. In another different test, the accuracy of the drop sampler was evaluated by comparing an estimate of population size extrapolated from drop sampler measurements taken in a shallow pond containing 1,200 white shrimp. Prior to the test, the 8.5 x 20.2 m (172 m^2) pond (uniformly sloping to 85 cm in depth along the long central axis) was drained and all organisms were removed. Shrimp from a nearby natural marsh area were collected with an otter trawl and placed in the refilled artificial pond. Six drop sampler cylinders (2.8 m , each; Fig. 2) were deployed to equally sample the ends, sides and middle of the pond. Mean density, calculated from the samples, and total area were used to estimate population size and compare against the actual number of shrimp present. Since samples were stratified, density contours were also plotted to evaluate nonrandomness in the shrimp distribution pattern. This provided a useful assessment of error attributable to variation in densities among patches of shrimp.

In other evaluations, densities of shrimp derived using drop samplers in a natural marsh system were compared against relative abundances over areas swept by a 1-m wide beam trawl, a 5.5-m wide bag seine, and a 3.7-m wide otter trawl. Initially, eight pairs of samples from vegetated (Spartina alterniflora) and nearby non-vegetated (sandy mud) habitats were taken using both the 1-m beam

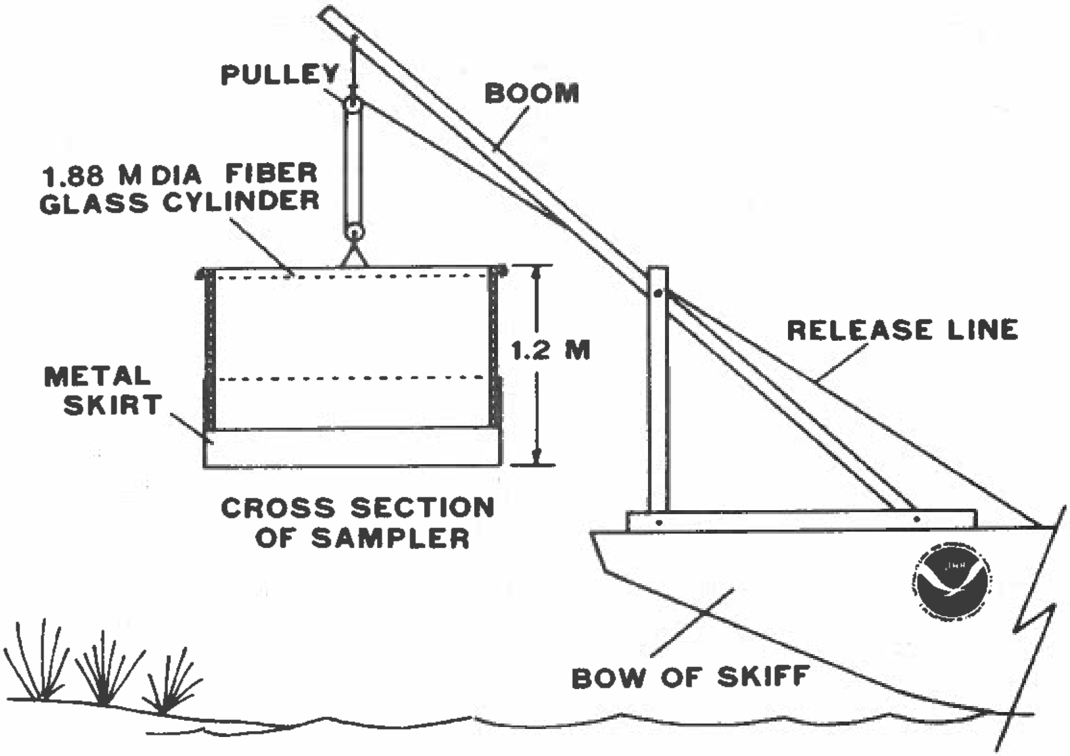

Figure 1. A cylindrical drop sampler used to measure shrimp densities in shallow water (from Zimmerman et al. 1984).

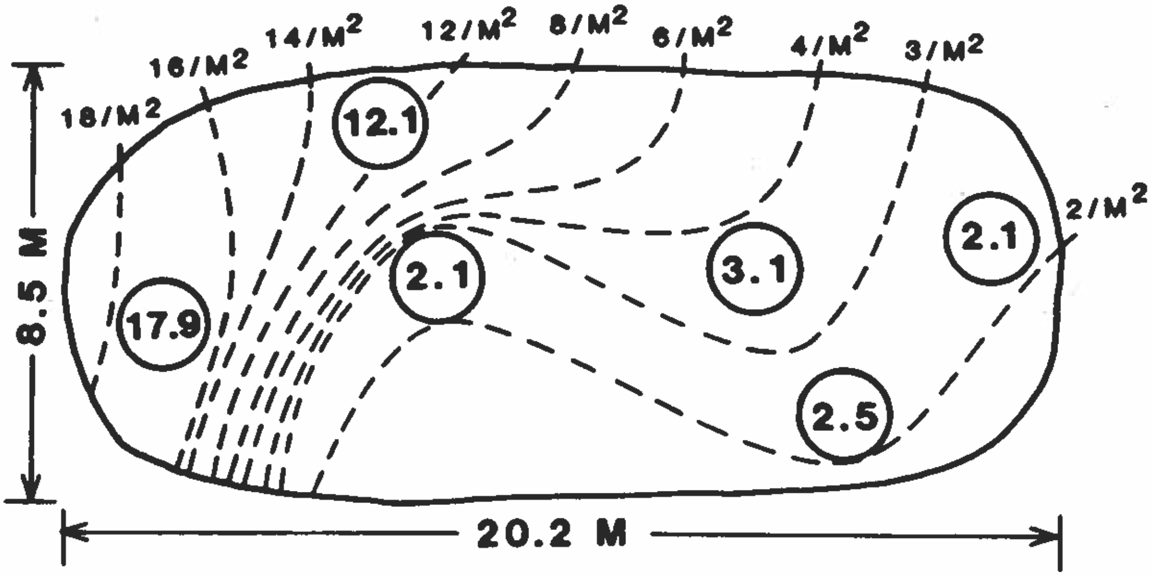

Figure 2. Density contours of white shrimp within a small pond contaning 1,200 individual shrimp. Shrimp densities (number/m^2) were obtained using 2.8 m^2 drop samplers (circles) and extrapolated to give an estimate of population size (1,166 shrimp).

trawl (3.0 m^2 per sample) and the drop sampler (2.8 m^2 per sample) at flood tide. The beam trawl was held on the bottom by hand, using one person on either side of the device, and pulled over a distance of 3.0 m. Water depth during sampling was approximately 35 cm intertidally and 65 cm subtidally. In separate tests that followed, 10 nonvegetated samples were each obtained with the drop sampler, the 5.5-m bag seine (110 m^2 per sample) and the 3.7-m otter trawl (75 m^2 per sample). Sets of samples from each gear were taken at random and simultaneously within the same area, and the catch per unit area for each of the seine and trawl collections was calculated and efficiencies estimated relative to the drop sampler. Comparisons were done within a large subtidal cove (approximately 250,000 m^2) with uniform water depth (80 cm), the same sediment type (muddy sand), and at low tide. Trawl and seine replicates were pulled over premarked distances of 20 m each. Typically, two drop cylinders were deployed about 10 m apart and the trawl was pulled on one side of the cylinders, about 30 m away, in one direction then on the opposite side in the other direction. Seine hauls were made parallel to the trawls over undisturbed bottom. For each gear type only those shrimp larger than 40 mm in total length were used in density calculations, since smaller shrimp were not effectively retained by the mesh in the otter trawl (13 mm^2) or bag seine (6 mm^2). The 1 mm^2 mesh in the beam trawl and drop sampler collection nets retained shrimp of all sizes.

Extrapolation of drop sampler densities to estimate shrimp population size was also compared to mark-recapture estimates within a natural bayou. In a study by Sullivan et al. (in press), 4,000 marked shrimp were released in a 36.4 ha temporarily closed bayou, and 5% were recaptured among unmarked shrimp after 18 h. These data were used to calculate total population size by the Petersen ratio (Bailey 1951). During the study, 16 drop samples were obtained from Spartina and nonvegetated habitats (equally divided) in the pond to measure densities. The resulting habitat-related densities were used to estimate population size for the entire area of the bayou. The methods and results of drop sampler versus mark-recapture comparisons are fully discussed in Sullivan et al. (in press).

RESULTS AND DISCUSSION

Recovery of marked shrimp from the drop sampler was 91% (SE = 3.3%, n = 4) in Spartina habitat and 98% (SE = 1.3%, n = 4) in nonvegetated habitat, and a t-test revealed no significant difference ($P > 0.1$) in recovery between habitats. The overall recovery mean (both habitats) was 94% (SE = 2.1%, n = 8). Error due to avoidance or entrainment during sampler deployment was not estimated. However, catch efficiency and accuracy of the technique appear to be high as reflected by our pond density estimate and comparison with mark-recapture methodology. Actual mean density of captive shrimp in our 172 m^2 pond was 6.99/m^2. Calculated mean density from 6 drop sampler replicates was 6.78/m^2 (SE = 2.71). The relatively high standard error was apparently due to nonrandom distribution of shrimp within the small pond as demonstrated by density contours (Fig. 2). In a 36.4 ha bayou, the estimated shrimp population was 207,786 using mark-recapture and 245,000 using 16 drop cylinder samples. The 95% confidence intervals were between 180,884 and 234,688 for mark-recapture, and 91,300 and 731,000 for drop sampler (Sullivan et al. in press).

Compared against drop sampler densities, the 1-m beam trawl was 23% as effective in Spartina vegetation for catching shrimp and 82% as effective on nonvegetated bottom (Table 1). Given equivalent area sampled, coefficients of variation (CV) from beam trawl densities were higher (in vegetation CV = 100%, nonvegetated bottom CV = 185%) than the coefficients of variation from drop sampler estimates (in vegetation CV = 42%, nonvegetated bottom CV = 100%).

In comparisons with other sampling gear, shrimp densities on nonvegetated bottom were 0.30 shrimp per m^2 using the drop sampler, 0.10 shrimp per m^2 with the 5.5-m bag seine, and 0.05 shrimp per m^2 with the 3.7-m otter trawl. Compared to the drop sampler, catchability coefficients were 33% (n = 10) for the bag seine and 17% (n = 10) for the otter trawl (Table 1).

The otter trawl is ineffective as a quantitative sampling device as confirmed by our data and those of others (Loesch et al. 1976; Kjelson and Johnson 1978). Loesch et al. (1976) compared P. aztecus densities in Louisiana from mark-recapture estimates against estimates obtained with a 4.9-m wide otter trawl, and found trawl efficiency to be about 44.8%, varying between 36% and 53%. Shrimp catchability in trawls may be expected to vary temporally and spatially dependent upon shrimp behavior (burrowing, swimming, feeding) and environmental conditions (bottom type, water clarity, current structure, light intensity). In at least one study, water clarity has been shown to significantly influence catchability by an otter trawl (Nielsen 1983). Since otter trawls are difficult to standardize against variables that affect catch efficiency, they should not be used for quantifying stocks and predicting yields.

Seines are also used for quantification of estuarine populations (Modde and Ross 1983) and shrimp stock assessment (Benefield and Baker 1980; Benefield 1982). Kjelson and Johnson (1974) used a 354-m seine to sample marked fish in a shallow-water estuarine area and measured catch efficiency at 31 to 54% (95% confidence interval). These investigators noted that increased crew experience improved sampling efficiency from 10 to 47%. Despite the large area of each sample (10,000 m^2), which presumably reduces error due to patchiness

Table 1. Comparative gear efficiencies for sampling *Penaeus aztecus* in a West Galveston Bay salt marsh (from Zimmerman *et al.* 1984).

	Mean Efficiency			
Habitat Type	^{1}Drop Sampler	^{2}Beam Trawl	^{3}Bag Seine	^{4}Otter Trawl
Spartina vegetation				
% Efficiency	94%	23%	not	not
(Shrimp count, mean/m^2 + SD)	(8.9±3.7)	(2.2±2.2)	operable	operable
Nonvegetated				
% Efficiency	98%	82%	33%	17%
(Shrimp count, mean/m^2 + SD)	(0.30±0.30)	(0.25±0.46)	(0.10±0.06)	(0.05±0.04)

Area sampled and number of replicates for each device were:

^{1}2.8m^2(n=22); ^{2}3.0m^2(n=12); ^{3}109m^2(n=10); ^{4}72m^2(n=10).

in natural distributions, Kjelson and Johnson (1970) were not able to greatly lessen variability and increase sampling precision (CV = 100%, n = 10). In another study, Weinstein and Davis (1980) estimated seine catch efficiency for three abundant fish species at 60.6 to 78.0% (respective standard deviations were 19.4 and 9.4%). Seining captured 70.3% of fish species present compared to 92.1% from a Rotenone sample. Our data (Table 1) suggest that for sampling shrimp, catch efficiency of seines is better than that of otter trawls, but it is not precise and also may be difficult to standardize. For purposes of yield prediction, seine data may not be adequate. Bay seine estimates of shrimp abundances taken by the Texas Parks and Wildlife Department throughout Texas bays, to evaluate size class structure (Benefield et al. 1983), do not appear to correlate closely with offshore catch given by Hämilton (1983, also see Bryan 1983).

Small bottom-nets, such as a 1-m wide beam trawl (Renfro 1963), 0.5-m wide marsh net (Pullen et al. 1968) or push nets (Allen and Inglis 1958), are probably better than large trawls for estimating shallow-water shrimp densities because area covered can be effectively measured and the small mesh in these nets can include smaller shrimp. With these devices, catch efficiency is relatively high (Table 1) and variability within sample sets (CV) is more likely to represent patchiness in distributions rather than error due to factors influencing catchability. Extending density estimates of small bottom-nets used in marshes to yield prediction appears to be feasible (Table 2, Table 3, Sutter and Christmas 1983), if tows are long enough to integrate sampling sites and conditions (such as bottom type and tidal stage) are carefully standardized. Since shrimp are juvenile transients in estuaries, sampling to estimate standing stock will be more effective in locations that are occupied for longer periods. For example, a 1-m beam trawl may be a better estimator of future yield when applied within nursery habitats (Sutter and Christmas 1983) than in migratory passes (Baxter 1963). Even in estuarine nurseries, however, conditions affecting densities and catch efficiency may vary. Since shrimp are often attracted to intertidal marshes (Zimmerman and Minello in press), densities on nearby subtidal bottom may vary according to tidal stage. In addition, brown shrimp burrow less at low light intensities (Lakshmi et al. 1976) making them more accessible for sampling at night and on cloudy days. Beam trawls and other small nets are designed for staying on the bottom, but an uneven seafloor can also cause some areas to be poorly sampled. These kinds of problems lead to variability in catch efficiency and loss of precision and accuracy when estimating population size. Under these circumstances, it may be advisable to restrict devices which estimate relative abundances to areas of uniform bottom without vegetation during night hours when the tide is low. An alternate solution is to avoid use of measurements with low catch efficiences and use methodology which

Table 2. Marsh net and drop sampler estimates of estuarine postlarval brown shrimp densities (latter part of March only) in selected Galveston Bay marshes compared to offshore catch.

Year	Marsh (number/m^2)	Offshore catch (tails x 10^6 lbs
1979	**0.9	*18.8
1980	**8.7	*28.1
1981	**5.0	*40.0
1982	*0.9	*22.0
1983	*0.5	*17.0

*from National Marine Fisheries Service, Southeast Fisheries Center, Galveston, Texas.

**from Texas Parks and Wildlife Department, Coastal Fisheries Branch, Austin, Texas.

Table 3. A comparison of sampling gear and methods used to estimate juvenile shrimp abundances for predicting future yield.

Method	Advantages	Disadvantages
3.7 m otter trawl (relative abundance, area swept)	Simple operation; standard fishing gear; low manpower requirement; low cost; incorporates a large area; integrates natural variation in density patterns; may be used in deep water.	Low catch efficiency (30%), inaccurate, selective; may not always stay on bottom and area swept is difficult to ascertain; effectiveness is variable and highly dependent upon environmental circumstances; not useful in very shallow water or on vegetated bottoms; does not sample smaller shrimp sizes due to large mesh size; burrowed shrimp missed; cannot assure standard operation; nor distinguish between natural and mechanical sampling variability.
5-5m bag seine (relative abundance, area swept)	Simple operation; standard gear; low manpower requirement; low cost; incorporates a moderately large area; integrates natural variation in density patterns.	Low catch efficiency (50%), inaccurate, selective; effectiveness is variable and dependent upon operation and environmental circumstances; restricted to shallow-water; smaller shrimp may not be sampled by larger mesh sizes; burrowed shrimp missed; cannot distinguish between natural and mechanical sampling variability.
1-m beam trawl (relative abundance, area swept)	Simple operation; simple construction; low manpower requirement; low cost; stays on bottom; can measure area covered accurately; samples all sizes of shrimp; integrates natural variation in densities or samples discrete patches depending on length of tow; can be used in deep and shallow water.	Moderate catch efficiency (70%); selective; variable effectiveness dependent upon environconditions; burrowed shrimp missed; active avoidance by shrimp possible due to small mouth of net; ineffective on vegetated bottoms.

Table 3. continued

Method	Advantages	Disadvantages
$2.8m^2$ drop sampler (actual abundance, area enclosed)	High catch efficiency (95%) in all shallow water habitats including those with vegetation; actual densities measured; all shrimp sampled including those burrowed; natural patchiness in densities can be measured.	Operation and construction complex; high manpower requirement; high cost; each sample covers a small area and samples one patch; many samples needed to reduce variance term; restricted to shallow water.
Mark and recapture (actual abundance, indirect estimate)	Highly effective; accesses total population across all habitats and conditions; not restricted by water depth.	Operation complex; high manpower requirement; high cost; need population without immigration or emigration during measurement; estimates only among sizes captured; requires 10% recapture of marked animals; requires measurement of mortalities.
Commercial bait-shrimp index (relative abundance, indirect measurement)	Highly effective for shrimp within one month prior to harvest; low manpower requirement; low cost; no field sampling required; widespread coverage; numerous data points.	Requires monitoring of commercial bait fishery; uses otter trawl data and incorporates fishery biases; does not predict from early juvenile stocks.
Post-larval Index (relative abundance, direct measurement)	Simple operation; low manpower; low cost; provides earliest indicator of abundance using beam trawl or plankton net data; can be at immigration passes or in nursery areas.	Post larval abundance does not reflect future survival rates; temporal and spatial patchiness difficult to integrate during immigration; may need many samples.

consistently provides accurate density estimates through high catch efficiency (Table 3).

In vegetated habitats, such as marsh grasses and seagrasses, bottom nets are very inefficient (Table 1). Past recognition of this problem stimulated the development of a sled-mounted suction sampler (Allen and Hudson 1970) and drop net methodology (Hoese and Jones 1963; Gilmore et al. 1976). The drop cylinder sampler (Zimmerman et al. 1984), designed for estuarine marshes, combines valuable advantages of the suction sampler and drop net technique. Since it is possible to remove all organisms once enclosed by the drop sampler (including burrowed shrimp), valid comparisons of abundance relationships can be established between different shallow-water habitats regardless of bottom type.

The technique has greatly improved the accuracy of density measurements, but variability may be high for the drop sampler within sample sets (coefficients of variation). In this case error represents natural patchiness (Fig. 1) rather than variability in gear catch efficiency. At present, the problems posed by the technique are those created by the relatively small area sampled ($2.8\ m^2$) and the effort required to obtain each sample. As presently designed, the drop sampler serves well for measuring densities in a small area and may be useful in calibration of catch efficiency for other techniques. However, the number of drop samples needed for estimating population size may not be practical for generating shrimp yield prediction. Yield prediction depends upon low variance among samples that measure densities. Due to the magnitude of natural density differences between patches of shrimp, and the variable number and size of patches, the number of drop samples needed to reduce variance is often large. Therefore, methods which cover larger areas (incorporate more patches) may be preferable. Use of a well calibrated 1-m beam trawl, redesigned to improve catch efficiecy, may be the best candidate for increasing precision and accuracy which is cost effective for shrimp yield prediction (Table 3).

There are other techniques available for estimating abundances and predicting yield, but most have restrictive limitations (Table 3). Estimation of population size by mark and recapture can be quite accurate (Hutchins et al. 1980; Sullivan et al. in press), but the necessary assumptions are often difficult to meet. This technique works best in a closed system where immigration and emigration are impossible during the mark-recapture event. Sullivan et al. (in press) blocked the entrance to a dead-end bayou on Galveston Island with a 46-m net (6-mm mesh) and estimated juvenile brown shrimp numbers by mark-recapture. Population size obtained using the Petersen ratio (Bailey 1951) agreed closely with our independent estimate acquired using the drop sampler. In another investigation, Hutchins et al. (1980) checked mark-recapture estimates of shrimp numbers in experimental ponds against actual densitites. They found estimates to be inflated by about 12% but within error limits (SE = 9.1%). Aside from the few sites available within any estuarine system for applying mark-recapture methodology, the technique is often costly and requires an intensive effort. In addition, smaller shrimp are usually not marked (tagging is rarely practiced on individuals less than 40 mm in length); therefore, assessment does not include the entire population. Enclosing nets and drop nets also have been used to estimate sizes of estuarine populations (Hellier 1958; Hoese and Jones 1963; Kjelson et al. 1975; Matlock et al. 1982), but with limited success. The main problem has been ineffectiveness in removing organisms once entrapped. Application of toxic substances, such as rotenone for fish, appears to improve resolution of estimates but even these are not entirely effective (Weinstein and Davis 1980, Matlock et al. 1982). A successful bait shrimp index also has been developed for predicting yield (Klima et al. 1982) but it has diminished value since data are required just before (within 1 month) shrimp attain sizes large enough for the primary commercial harvest. The most useful estimators of predictive yield will target postlarvae and early juveniles several months prior to entry into the fishery.

Shrimp yield prediction must be precise to be reliable, and improved precision incorporates low variance and consistency in measuring population size. By acquiring such estimates on early recruits together with measurements of environmental factors that influence shrimp survival (Saila et al. 1982; Sutter and Christmas 1983) perhaps the best yield projections can be made. For most predictors, the precision of estimates is highly dependent upon gear bias and circumstances of use. All sampling devices that measure relative abundances assume that catch efficiency is uniform in time and space. This assumption, as has been reviewed in our investigation, is usually untrue. Catch efficiency is usually low and rarely standardized for consistency. The result is that errors are incorporated into estimating population size, and both precision and accuracy in predicting future yield are lost. The best methods are those which have high catch efficiency and low variance and access the early juvenile population (Table 3).

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INCORPORATING CLIMATIC AND HYDROGRAPHIC INFORMATION INTO SHRIMP YIELD FORECASTS USING SEASONAL CLIMATIC COMPONENT MODELS

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ABSTRACT

Year to year variations in Ekman transport, river discharges, and temperature and salinity conditions were summarized on a seasonal basis to incorporate climatic and hydrographic information into shrimp yield using seasonal principal components as predictor variables in regression equations.

Preliminary results indicate that conditions were favorable for offshore brown shrimp production in the vicinity of the Texas and Louisiana boundary when there were strong northward winds (and eastward Ekman transport) during the winter, followed by a dry spring. These conditions may have resulted in higher survival rates for postlarvae and juvenile stages in the estuaries. High springtime river discharges and resulting low salinity in nursery areas reduced offshore brown shrimp yields regardless of wind direction.

White shrimp landings were positively correlated with summer river discharges in the region. Strong winds toward the northwest (and northeast Ekman transport) in the spring and summer during periods of spawning and larval transport into nursery areas correlated with decreased offshore yields of white shrimp. In the fall, strong easterly winds, low river discharge and relatively cold water temperatures correlated with increased offshore white shrimp landings.

INTRODUCTION

This paper describes a method of general use in relating climatic and hydrographic variations to fluctuations in annual brown and white shrimp yields. The specific application described in this paper concerns an analysis of annual fluctuations in offshore yields of brown and white shrimp in the vicinity of the Texas and Louisiana boundary. The northeastern Texas and southwestern Louisiana coastal region represents a transition zone in an east-west gradient from high rainfall and river discharge in Louisiana to low rainfall and river discharge in Texas. The region of interest is a zone between peak brown and peak white shrimp abundance (Fig. 1).

The reason for focusing on the Texas and Louisiana boundary is related to offshore brine disposal activities conducted as part of the Strategic Petroleum Reserve (SPR) program. The intent of the program, administered by the Department of Energy, is to develop a secure national storage for up to 1 billion barrels of crude oil. For some of the needed capacity, underground storage facilities for crude oil are being created in salt domes and mines using solution-mining techniques. In the process of solution mining, a by product is a saturated brine solution which is discharged at variable rates (approximately 100,000 barrels/day) into the Gulf of Mexico through diffusers offshore (Fig. 2). Brine discharge sites have been selected offshore of the southwest Louisiana coast and upper Texas coast. At the time of the research, the West Hackberry salt dome had been selected as an oil storage facility and the Big Hill salt dome was a candidate site being considered for expansion of the reserve from 578 to 758 million barrels.

Because of the potential impacts of the brine on commercial shrimp fisheries, studies of shrimp populations were conducted as part of a joint Department of Energy/National Oceanic and Atmospheric Administration/National Marine Fisheries Service project. One of the objectives of the funded research was to develop statistical techniques for relating environmental variations to temporal and spatial variations in shrimping success in statistical areas within which brine diffusers are located, so that the hypothesis that brine disposal had no adverse impact on shrimp yields could be tested. Shrimp landings data for the region of interest have been obtained from the Gulf Coast Shrimp Data which were compiled by the Southeast Fisheries Center, Technical Information and Management Services of the National Marine Fisheries Services, and by its predecessor prior to 1970, the Bureau of Commercial Fisheries, Department of the Interior.

SHRIMP LIFE CYCLE

One critical aspect in attempting to relate climatic fluctuations to shrimp yields is the choice of the spatial and temporal aggregation of the shrimp data sets. The Gulf Coast Shrimp Data contain information on monthly landings in a range of size classes and depth zones within each statistical area. Annual variations in total offshore yields in a given area are analyzed in this paper. Our rationale for this aggregation was that any major environmental influence on shrimp yield by whatever mechanism would be manifest in the total landings for the year. However, to interpret possible linkages between environmental forcings and annual

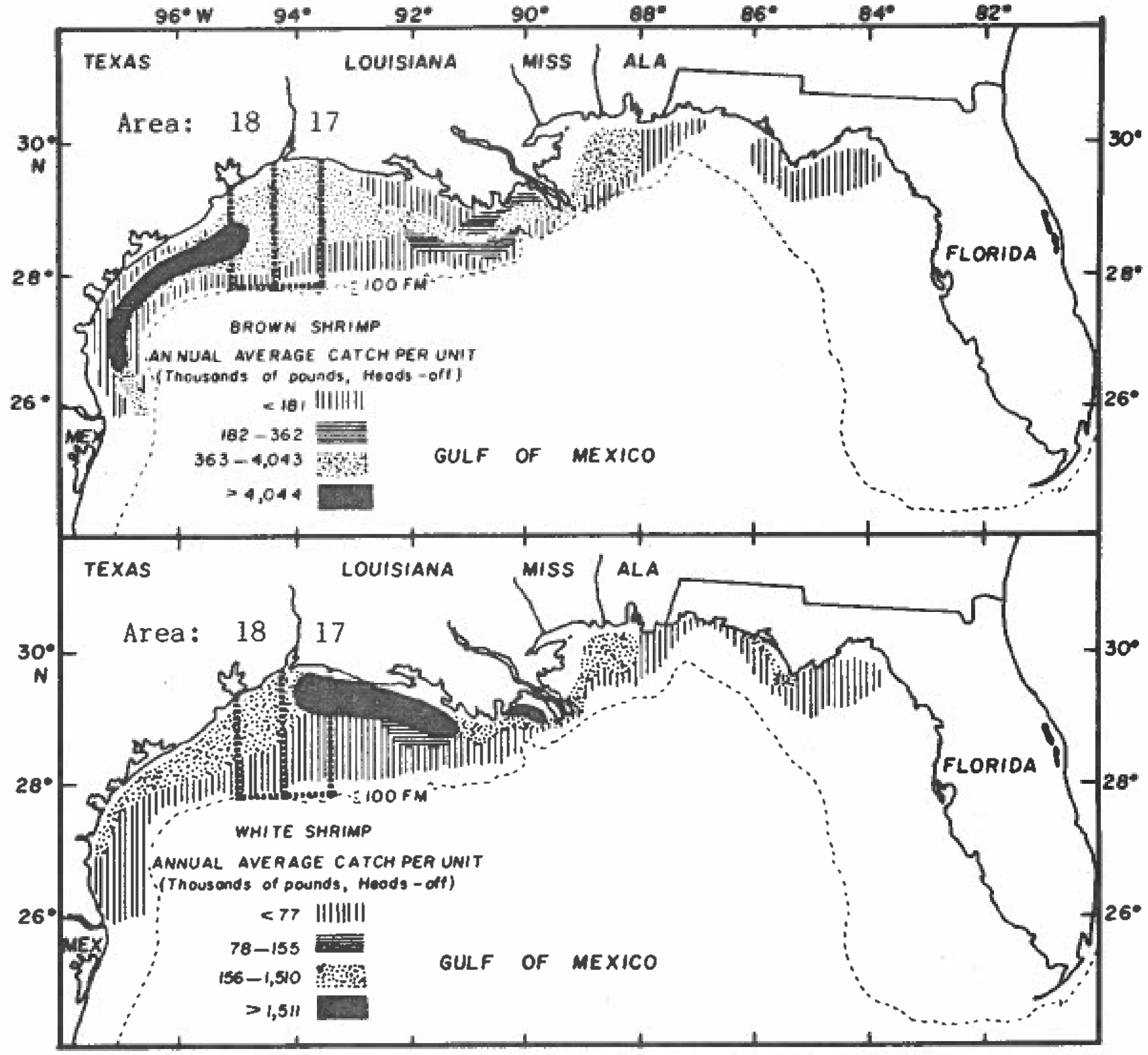

Figure 1. Distribution of reported offshore catches of brown and white shrimp (1959-1963). A unit represents the combination of one 9-meter depth stratum and one statistical area (from Etzold and Christmas 1977).

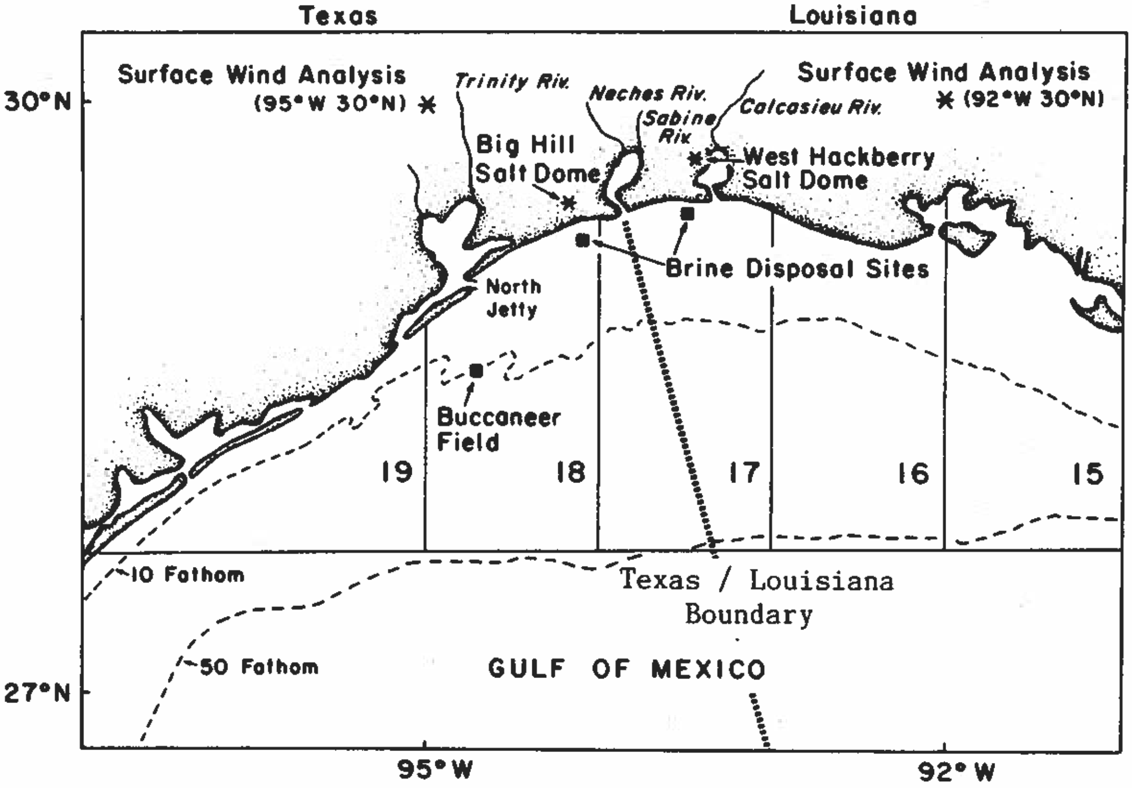

Figure 2. Texas and Louisiana boundary study area.

variations in shrimp yield, it is necessary to consider that timing of brown and white shrimp life cycles (Fig. 3). Major differences in the brown and white shrimp life cycles are due to shifts in time and space at which various life stages reach maximum abundance. The approximate timing of various life stages is illustrated in Figure 4. For brown shrimp, key references on the timing of peak density of various stages include: Copeland (1965), Renfro and Brusher (1965), Baxter and Renfro (1967), Gaidry and White (1973), Christmas and Etzold (1977), White and Boudreaux (1977), GMFMC (1980a,b), and Reitsema et al. (1982). Key references for white shrimp are: Linder and Anderson (1956), Renfro and Brusher (1964), Joyce (1965), Bryan and Cody (1975), GMFMC (1980a,b), and Reitsema et al. (1982). It may be inferred from Figure 4 that factors affecting brown shrimp larval transport would be operating during the fall and winter, a period of peak brown shrimp spawning and postlarval shrimp movement inshore to estuarine and near coastal nursery areas. For white shrimp, spring is an analogous period in which transport conditions might be important.

SEASONAL ASPECTS OF CURRENT PATTERNS AND HYDROGRAPHY

Seasonal aspects of current patterns and hydrography in the region were examined to choose the temporal partitioning to be used to summarize the environmental data. A detailed description of the current patterns and hydrography in the northwestern Gulf of Mexico can be found in Armstrong (1979, 1980) who described a 4-year study of the waters in the region of the Buccaneer Gas and Oil Field which is located in statistical area 18, near the Texas - Louisiana boundary (Fig. 2). Armstrong found that annual temperature and salinity cycles closely paralleled conditions described by Temple et al. (1977). In general, water temperatures followed air temperatures (Fig. 5), and salinity reached maximum values in winter, decreasing through the spring in response to combined river discharge from streams as far east as the Mississippi River. Currents in the Buccaneer Field were typically directed along the shore, with mean flow toward the southwest. However, layered flow developed in late spring and summer, with subsurface currents flowing toward the east. The salinity minimum in late spring (Fig. 5) was attributed to the spring increase in river discharge from the Mississippi and Atchafalaya Rivers, with a 2-month lag and from the Trinity and Sabine Rivers with a 1-month lag (Temple et al. 1977, Armstrong 1980). The fall decrease in salinity (Fig. 5) was attributed by Armstrong (1980) to the seasonal reversal in subsurface currents which transported freshened water from the east into the Buccaneer Field area. Variability in hydrographic conditions and currents was largely due to variations in atmospheric conditions. Maximum currents measured during the Buccaneer Field study (as high as 180

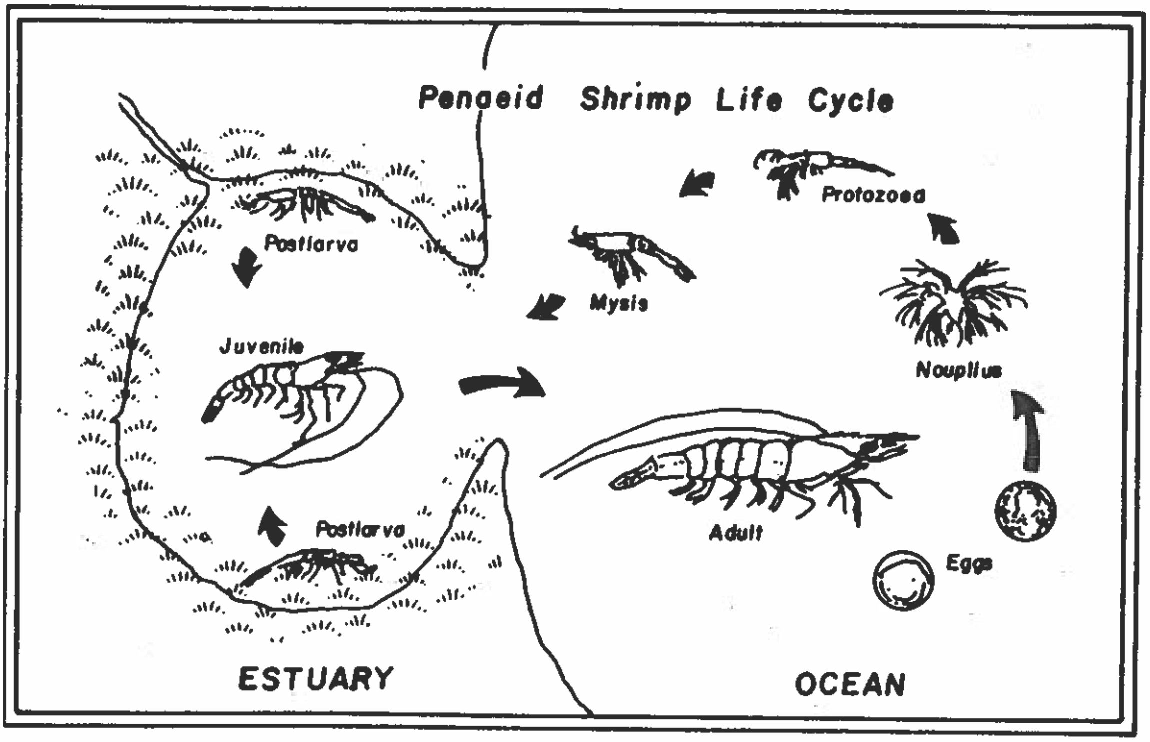

Figure 3. Penaeid shrimp life cycle (from Etzold and Christmas 1977).

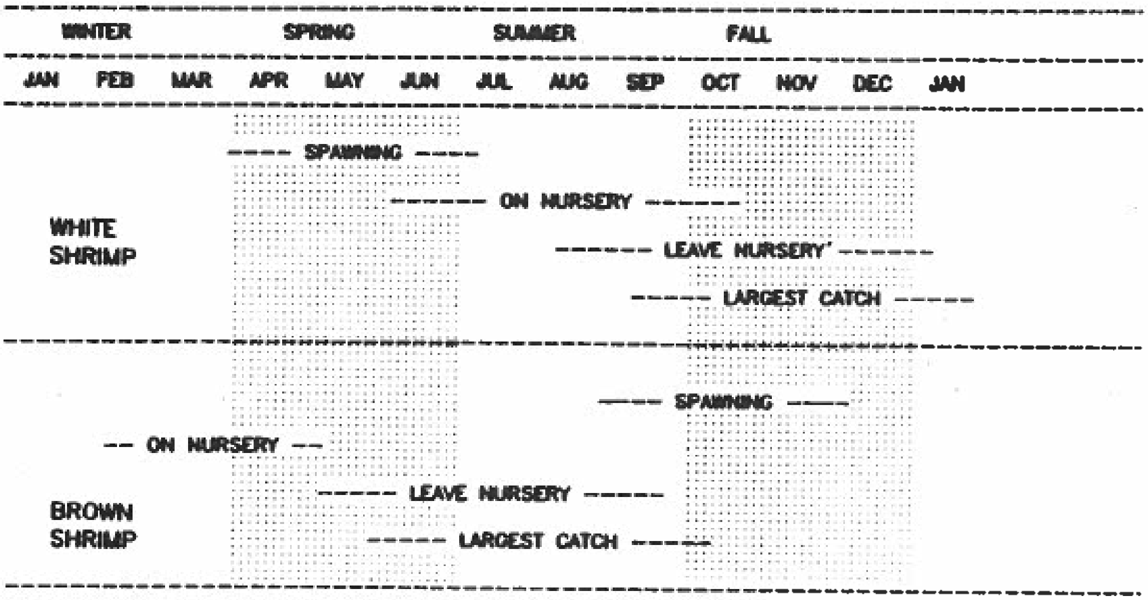

Figure 4. Approximate timing of shrimp life cycle (adapted from Knopf 1970).

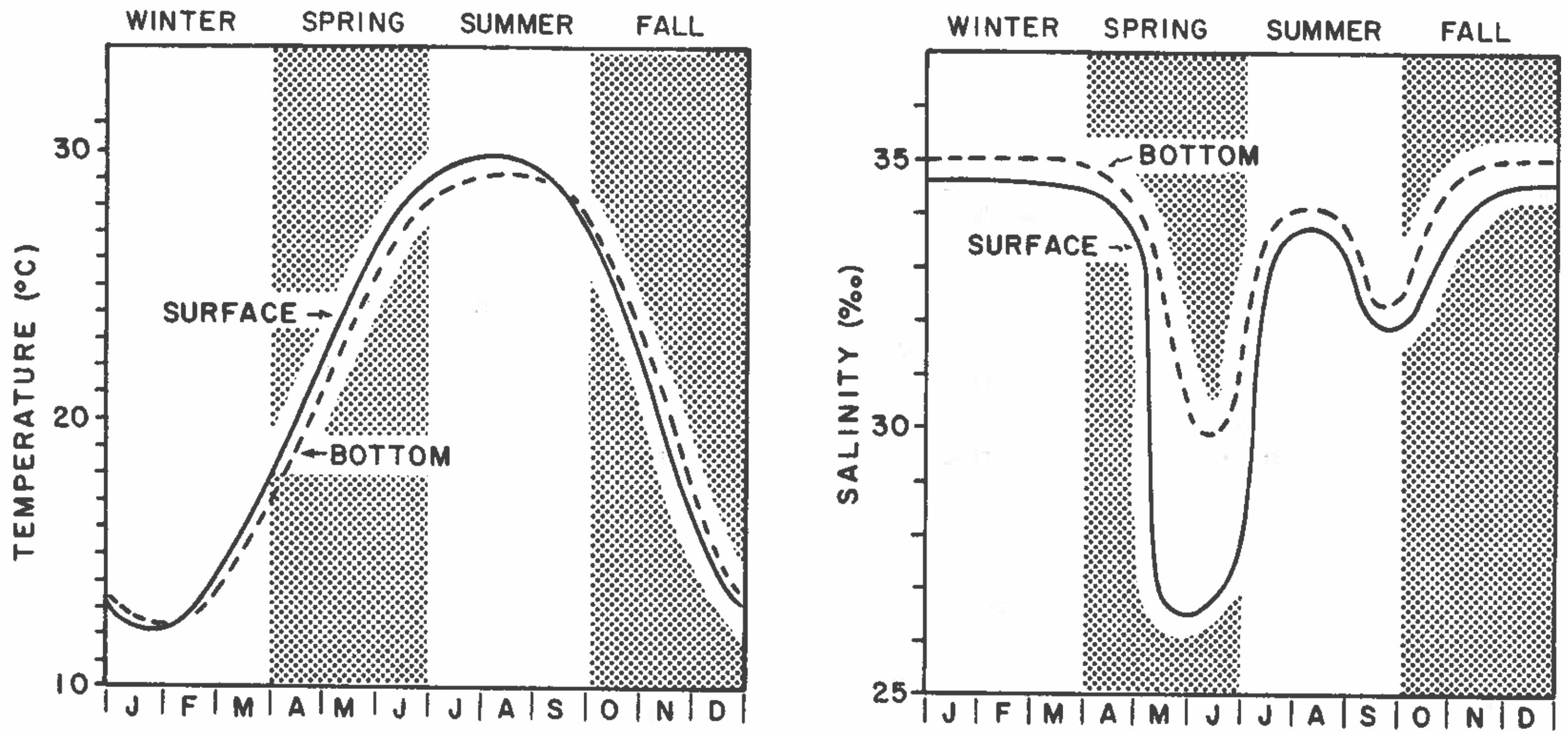

Figure 5. Seasonal cycles in temperature and salinity in the Buccaneer Field off Galveston, Texas (adapted from Armstrong 1980).

cm/sec) occurred during the passage of cold fronts (Armstrong 1979, 1980). In many cases, year to year variability in hydrographic conditions was related to variations in the passage of frontal systems.

Since the Buccaneer Field is located in statistical area 18, we have used Armstrong's (1979, 1980) study as the basis for partitioning the environmental data into four seasons. Seasons were defined on the basis of the calender year: winter included January - March, spring included April - June, summer included July - September, and fall included October - December for the analyses discussed in this paper. This partitioning of the calender year was justified in terms of water temperature cycles and salinity conditions offshore of Galveston Bay (Fig. 5), and because seasons defined in this fashion can be related to the approximate timing of major stages in brown and white shrimp life cycles (Figs. 3 and 4).

CHOICE OF ENVIRONMENTAL VARIABLES FOR PREDICTING SHRIMP YIELDS

Ideally, it would be desirable to have an extensive data set to exhaustively describe estuarine, coastal, and shelf environmental conditions, e.g. dynamic maps of temperature and salinity distributions, current patterns, stratification, subpynocline oxygen levels, etc. In practice, such detailed information is not available, but sufficient information is still available over a long enough period of time to present the investigator with some difficult choices when attempting to determine linkages between environmental forcings and shrimp yields. We chose to consider wind induced transport, coastal river discharges, and coastal water temperature and salinity conditions. A brief discussion on the selection of the initial variables used in the analysis follows.

Wind Driven Transport

Oceanographic conditions in the northwestern Gulf of Mexico are quite variable because a down coast (southwestward) current off of Louisiana may be opposed by an upcoast wind driven current which develops during the winter off of the Texas coast. This shift in coastal currents can be related to a shift in the wind field from prevailing easterly winds (toward the north) in the summer (Fig. 6) as the Bermuda high pressure center develops over the North Atlantic (Bryson and Hare 1974). Both Smith (1980) and Cochrane and Kelly (1982) have observed that the coastal currents are best correlated with the alongshore component of the wind stress (Rezak et al. 1983). Figure 7 illustrates the pattern of coastal currents that would be set up on a cuspate shore, such as the northwestern Gulf of Mexico,

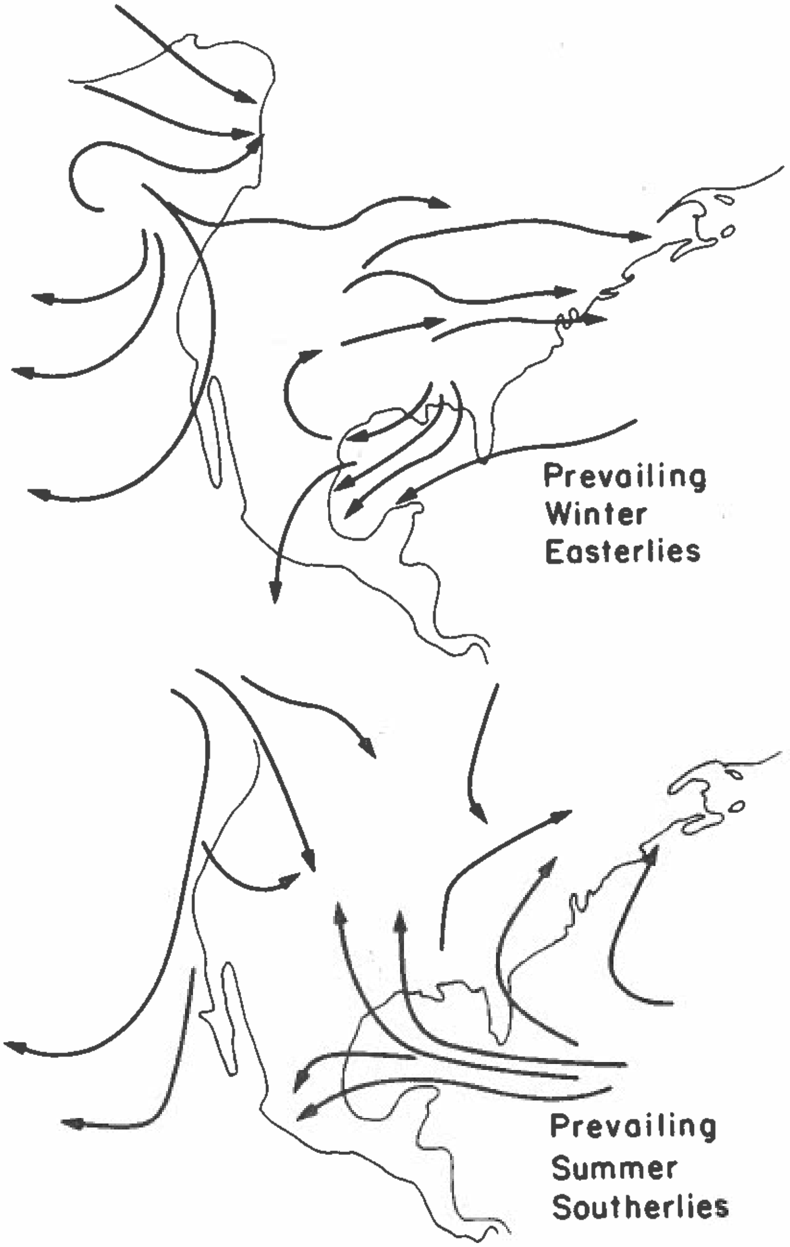

Figure 6. Prevailing winter and summer winds (adapted from Bryson and Hare 1974).

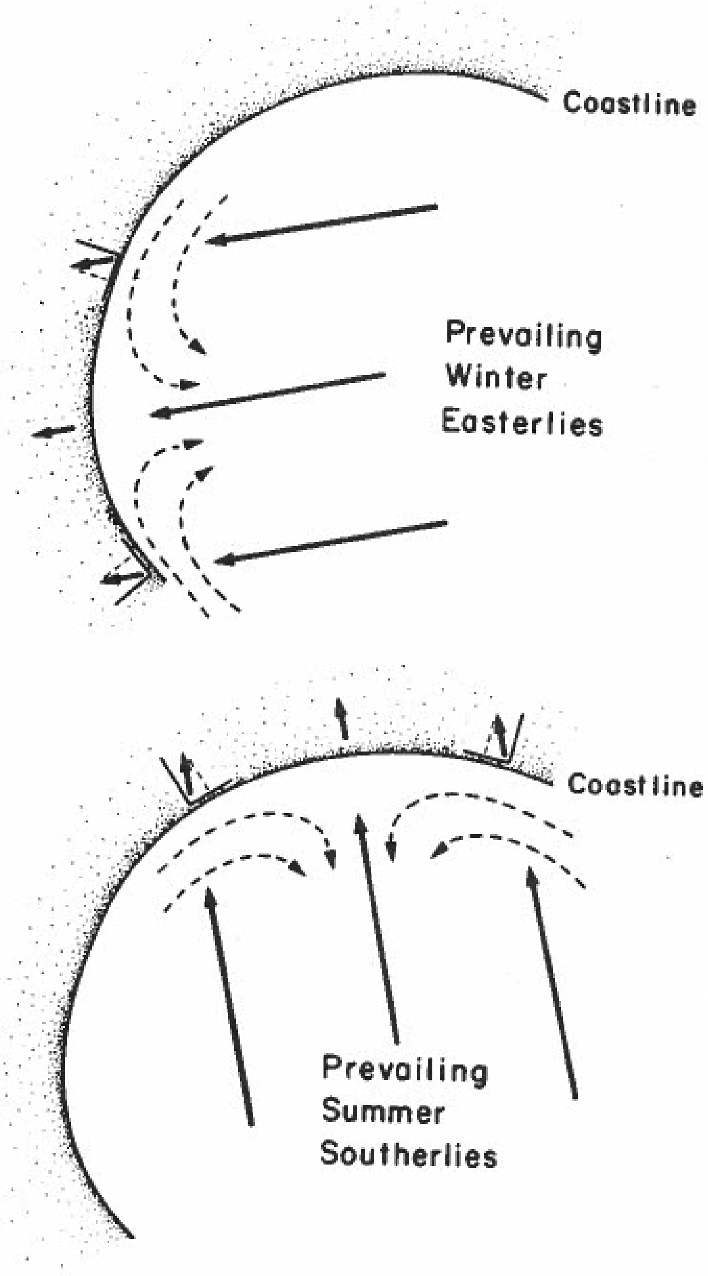

Figure 7. Wind driven coastal currents on a cuspate shore (adapted from Smith 1980).

in the absence of other forcings (such as pressure gradients set up by coastal river discharge). Based on this simple model suggested by Smith (1980), it can be inferred that the seasonal rotation from prevailing easterlies in the winter to prevailing southerlies in the summer could cause a northeastward shift in a zone of convergence in the coastal current field.

In a detailed study of the alongshelf component of the wind stress at the coast, Kelly et al. (1983) noted a convergence between upcoast and downcoast components in the wind field occurring in southern Texas (between Port Isabel and Port Aransas) in January. In an average year, this zone of convergence in the wind field migrated upcoast reaching a position in southwestern Louisiana (east of Calcasieu River) in July (Fig. 2). This usually resulted in a convergence between upcoastal currents off Texas and downcoastal currents off Louisiana with the zone of convergence in coastal currents migrating upcoast in a fashion similar to the convergence in the wind field. The migration of this convergence zone in the wind field occurred during seasons when brown and white shrimp spawn and move into nursery areas (Fig. 4). Interestingly, the average summertime position of the zone of convergence in the wind field occurs at the boundary between peak brown and white shrimp densities (Fig. 1).

Farther offshore, wind direction influences ocean currents in a different fashion. According to Ekman's theory, the effect of wind direction on water transport (integrated from the surface to the Ekman depth) results in mass transport in a direction 90 degrees to the right of the surface wind vector. Thus if Ekman theory holds in offshore areas, prevailing winter easterlies would result in northward mass transport at a time when brown shrimp are spawning. Prevailing summer southerlies (toward the north) would result in mass transport to the east in offshore areas at a time when white shrimp are spawning.

It seems likely that seasonal wind driven shifts in the location of a zone of coastal current convergence may influence larval transport, and thus affect the biogeographic distribution of shrimp stocks. If so, it may be possible to correlate year to year variations in the magnitude and timing of the seasonal rotation in the wind field to fluctuations in shrimp abundance in a given area.

An attempt was made to infer wind driven transport from monthly mean atmospheric pressure fields, since coastal currents have not been measured directly for most of the period of interest in this study. The data set used for this purpose was generated by the Pacific Environmental Group of NMFS according to a methodology developed for the west coast of North America (Bakun 1973). Monthly mean pressure fields from the Fleet Numerical Weather Center were interpolated on to a three degree mesh grid and differenced to approximate the first derivative of pressure. An estimate of the wind speed and direction near the sea surface was then formed by rotating an estimated geostrophic wind vector by 15 degrees toward the lower pressure, and reducing its magnitude by 30% to approximate boundary layer effects. Bakun (1973) goes on to calculate Ekman mass transport indices which were estimated to be 90 degrees to the right of the adjusted surface wind vector. Ekman's solution for wind driven transport assumed 1) no boundaries, 2) infinitely deep water, 3) a constant vertical eddy viscosity, and 4) a barotropic condition. All four of these assumptions were seriously compromised in the Gulf of Mexico (Anderson 1983). However, the calculated values may be sufficiently precise to characterize major variability in currents from year to year on a seasonal basis (Bakun, personal communication).

It does not matter if the estimated surface wind vector or the Ekman transport vector is used, from the point of view of statistical prediction based on correlation analysis. In our analysis we have chosen to use Bakun's Ekman transport indices from the two grid positions (Fig. 2) closest to the Texas and Louisiana study area (located at 30 N latitude - 92°W and 95°W longitude). Seasonal mean Ekman vectors for the period 1960 - 1976 are illustrated in Figure 8 for both locations. Based on an idealized Ekman ocean, an interesting feature illustrated in Figure 8 was that a seasonal shift in wind driven transport occurs, with average springtime Ekman transport toward the northeast. This shift in transport corresponds to the change from prevailing easterly winds in the winter to prevailing southerly winds in the summer (Fig. 6).

River Discharge

Relationships between river discharges and shrimp abundance in large sections of the Gulf of Mexico have been documented by many authors. Hildebrand and Gunter (1953) and Gunter and Hildebrand (1954) related variations in annual white shrimp landings in Texas to rainfall in the previous two years and found that higher landings were correlated with periods of heavier rainfall. This type of relationship did not hold for annual white shrimp landings in Louisiana and Mississippi River discharges. However, river discharges in Louisiana in the previous two years were found to be negatively correlated with Louisiana brown shrimp landings. A casual relationship was inferred since brown shrimp are adapted to areas with higher salinities, and may not survive lower salinity conditions in estuaries during periods of high river discharges.

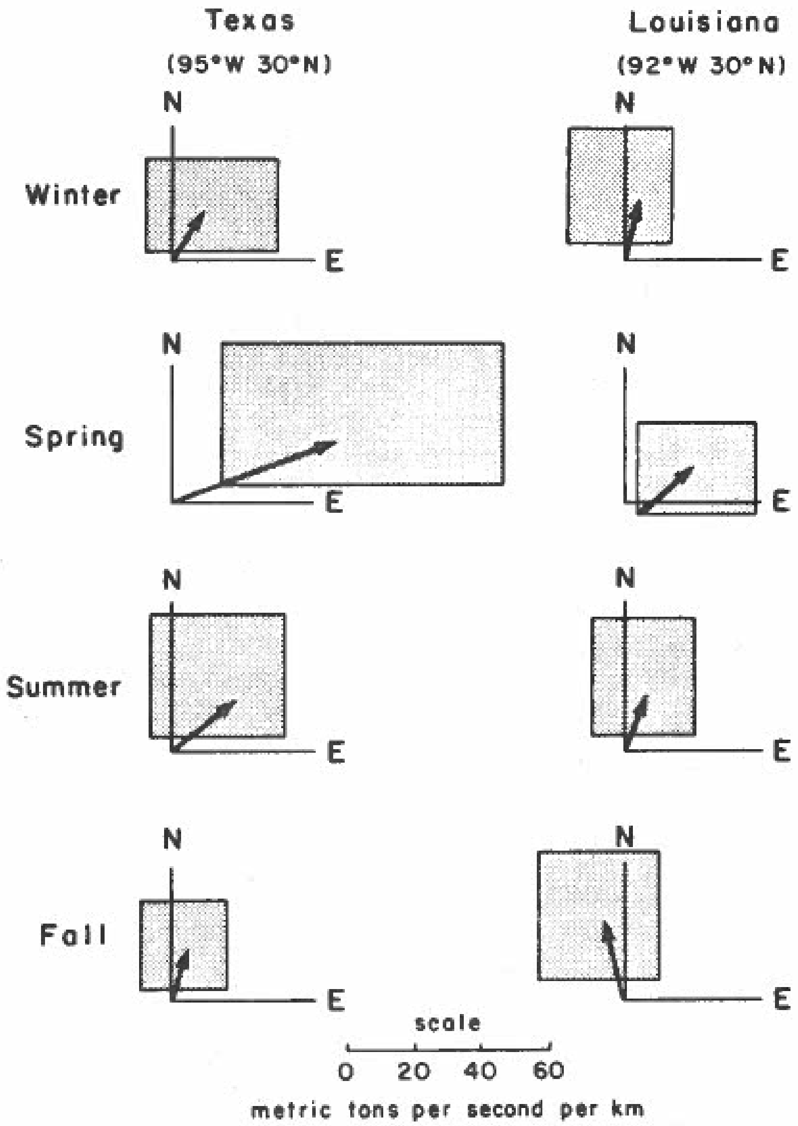

Figure 8. Seasonal variation in Ekman transport. Mean vectors indicated by arrows. Minimum and maximum values indicated by boxes.

Gunter and Edwards (1969) used the same methods with a longer time series in an attempt to confirm and extend these results. They confirmed that there was a correlation between catch of white shrimp in Texas and the average Texas rainfall of the previous years, and the fact that this relationship was not apparent between Louisiana catches and the combined discharges of the Atchafalaya and Mississippi Rivers. The relationship between annual Louisiana brown shrimp landings and Atchafalaya and Mississippi discharges for the same and previous years was found to be negative but quite weak. The correlation between annual brown shrimp landings in Texas and Texas rainfall was even weaker. Barrett and Gillespie (1973, 1975) refined the above analyses for Louisiana landings by distinguishing between spring and summer river discharges. They found a negative correlation between river discharge in the spring and brown shrimp landings, and another negative correlation between white shrimp landings and summer river discharge. Although the relationship between river discharge and brown shrimp production in Louisiana is similar to that previously described, the relationship for white shrimp was related to the fact that excessive river discharges in the summer could also limit available nurseries with appropriate salinites.

For this analysis, we chose to consider average quarterly river discharges from the Mississippi and three rivers in the vicinity of the Texas - Louisiana boundary: the Sabine, Neches, and Trinity Rivers. Although the Mississippi is 450 km from the Texas - Louisiana boundary, it was included in the analysis because it can influence the coastal currents and salinity conditions in the region. The Atchafalaya River discharge is highly correlated with the Mississippi discharge, and since it was thought that it would not contribute significant additional information, it was not included in the analysis. The Sabine, Neches and Trinity Rivers empty into estuaries that discharge into NMFS statistical areas 17 and 18.

Water Temperature and Salinity

A number of studies have related water temperature to commercial catches of penaeid shrimp. Williams (1967) used coastal air temperatures expressed as net heating degree days to distinguish between years with good and poor catches. Barrett and Gillespie (1973, 1975) noted that the cumulative effect of the number of hours below 20 C after the first week in April may be a critical factor, and is negatively correlated with Louisiana brown shrimp production. In support of this claim they cite work by Zein-Eldin (1963, 1965) who found in controlled laboratory conditions that at temperatures below 15 C postlarval brown shrimp developed a decreasing tolerance to low salinities. Further experimental work under controlled laboratory conditions indicated that postlarval brown shrimp burrowed into the substrate when temperatures fell in a range of 12 to 17 C and emerged when temperatures reached 18 to 21.5 C (Aldrich et al. 1968; Barrett and Gillespie 1973).

The most consistently sampled temperature and salinity record we were able to obtain near the Texas - Louisiana boundary was a series of measurements made at the North Jetty in Galveston Bay by NMFS Southeast Fisheries Center (Fig. 2). Because we felt that temperature and salinity extremes might be as important as quarterly averages, quarterly minimum, median, and maximum temperatures and salinities were included in the analysis.

PRINCIPAL COMPONENT ANALYSIS ON A SEASONAL BASIS

Principal component analysis was used to achieve a parsimonious characterization of the major correlations among the chosen environmental variables. The method produces uncorrelated linear combinations of the original variable set which have maximum variance subject to certain constraints described below. The new linear combinations are referred to as Principal Components or PC's, and are determined independently of the shrimp yield data. The PC's are then related to fluctuations in shrimp yield. The advantage of this approach is that covariation among environmental conditions can be utilized to advantage in developing predictive models. For example, Barrett and Ralph (1976) note that in Louisiana cool or cold fronts are usually preceded by heavy rainfall, and the associated north winds force the freshwater in the upper estuaries gulfward causing salinity dilutions. A large number of variables could be used to describe this sequence of events, but the major components of variation in the system may be described by one or two PC's. Parsimonious description of the environmental forcings becomes very important when analyzing short time series of catch statistics for environmentally induced variations.

A separate principal component analysis was conducted for each season because the correlations among the environmental variables do change from one season to the next. Also, it was thought that it might be possible to interpret correlations between seasonal aspects of brown and white shrimp life history cycles. This would not be possible if environmental data from all quarters were analyzed together.

The analyses included data from 1960 through 1976, i.e. 17 years of data. For each season, the analysis included: four variables related to quarterly average transport (the north and east components of estimated Ekman transport at two locations), four variables related to river discharge (quarterly average discharge from the Mississippi, Sabine, Neches and Trinity Rivers), three variables related to salinity (quarterly minimum, median and maximum salinity at the North Jetty in Galveston Bay), and three variables related to sea water temperature (quarterly minimum, median and maximum temperature, also measured at the North Jetty in Galveston Bay). Thus, 14 variables were used to describe climatic conditions in each of four seasons. Principal component analysis can not be conducted if there are more variables than the number of observations used in the analysis. Sites used for estimating surface winds, the North Jetty site at the mouth of Galveston Bay, and the local rivers used in the analyses are indicated in Figure 2. Since we were analyzing a 17-year time series, there was a practical limit to the number of environmental variables that could be included in an analysis of this type. Thus subjective choices, as described above, were required to reduce the number of independent variates to a manageable subset prior to conducting the principal component analyses for each season.

The seasonal aspect of our model formulation represents a variation of Draper and Smith's (1981) description of principal component regression. The following notation will be used. For a given season let Zi, i = 1,...p, represent p independent variables, and PCj, j = 1,...p, represent the p PC's defined by the eigenvectors of the p x p correlation matrix of the independent variables:

$$\begin{array}{cc} & \begin{array}{ccccc} PC1 & PC2 & PC3 & \cdots & PC14 \end{array} \\ \begin{array}{c} Z1 \\ Z2 \\ Z3 \\ \vdots \\ Z14 \end{array} & \left[\begin{array}{ccccc} \gamma_{1.1} & \gamma_{1.2} & \gamma_{1.3} & \cdots & \gamma_{1.14} \\ \gamma_{2.1} & \gamma_{2.2} & \gamma_{2.3} & \cdots & \gamma_{2.14} \\ \gamma_{3.1} & \gamma_{3.2} & \gamma_{3.3} & \cdots & \gamma_{3.14} \\ & & & & \\ \gamma_{14.1} & \gamma_{14.2} & \gamma_{14.3} & \cdots & \gamma_{14.14} \end{array} \right] \end{array}$$

The first principal component (PC1), was defined as

$$PC1 = \gamma_{1.1}Z1 + \gamma_{1.2}Z2 + \gamma_{1.3}Z3 + \ldots + \gamma_{1.14}Z14$$

The eigenvalues (λ_i) associated with the PC's (or eigenvectors) are estimated under the constraint

$$\sum_i (\gamma_{i.j})^2 = \sum_j (\gamma_{i.j})^2 = 1.0$$

Thus, the squared elements of the eigenvectors $(\gamma_{i.j})^2$ were interpreted as either the percent of the total variance of an original variable Zi that is accounted for by a given principal component PCj or the percent of the PCj variance accounted for by a given variable Zi. The sum of the eigenvalues is constrained to equal the number of independent variables p used in the analysis. Thus the ratio (λ_i)/p can be interpreted as the percent of the system variance accounted for by a given PC axis of equal importance. Computations were done using the PRINCOMP procedure in SAS. Since a separate principal component analysis was done for each season, the notation PCj.Qk will be used to identify the j-th PC from the k-th quarter, where k can equal 1, 2, 3 or 4 during winter, spring, summer and fall, respectively.

To interpret the relationships among the independent variables and the dependent variables, the signs and magnitudes of the coefficients of the eigenvectors need to be interpreted. An interpretation of the results of the principal component analyses for each season can be found in the appendix.

SELECTING THE PRINCIPAL COMPONENT REGRESSION EQUATIONS

Multiple linear regression equations were estimated using the first three principal components from each quarter as independent or predictor variables in order to determine possible relationships between annual landings and seasonal climatic fluctuations. The percent of the total variance explained by the first three PC's in each quarter was: winter 77%; spring 75%; summer 69%; and Fall 77%. Including only the first three PC's from each quarter for further analysis was another subjective choice. The choice was based on the rationale that the PC axes accounting for the greatest year to year variance would be good candidates for predicting annual variance in shrimp yields. A possible weakness in this approach is that the chosen factors may not optimally describe the climatic and hydrographic factors and interactions which actually influence annual variability in shrimp landings.

As with many multiple regression approaches, a problem arises due to correlations among the independent variables. In this case correlations among PC's within a given season are constrained to be zero. Thus, within season colinearity problems are avoided, which is a major advantage of the approach we have adopted. However, correlations between PC's in different seasons occurred (Table 1). In particular, the first PC from all four quarterly analyses was significantly intercorrelated. To an extent, this was due to the fact that wet and dry years occur, resulting in correlations between river discharges and salinity conditions between seasons. From the interpretations of the PC's available in the appendix, it is apparent that a wet year would occur if the evaluation for the first principal component in the winter (PC1.Q1) was positive, the first principal component in both spring and summer analyses (PC1.Q2 and PC1.Q3) was negative, and the first principal component in the fall (PC1.Q4) was positive. This explains the signs of the PC1 intercorrelations in Table 1.

In this study, a best subset selection technique was used to determine how many and which variables to retain. The regression for Y was first worked out on every subset of the k variables. The best subset was then selected on the basis of Mallow's criterion, Cp, which can be considered to be an estimate of the total mean square error of the predictions made for new Y's from the chosen regression. The SAS procedure RSQUARE was used for computation. The reader should recognize that a large number of possible models are evaluated in this procedure. We have included that first three PC's from each season, i.e. 12 independent variates. Thus, there are 66 models based on a subset of 2 PC's, 220 models based on a subset of 3 PC's, etc. Furthermore, the selection procedure has no way of guarding against identifying spurious relationships. Thus, we may only have confidence in the models if they make oceanographic and biological sense. Examples of results of model selection and estimation are presented in the next two sections for prediction of annual brown and white shrimp landings in NMFS statistical area 18 off of the Galveston, Texas coast (Fig. 2).

PREDICTING ANNUAL BROWN SHRIMP LANDINGS IN STATISTICAL AREA 18

The best regression for predicting annual brown shrimp landings from area 18 on the basis of Mallow's Cp criterion involved only three of the seasonal PC's and explained 56% of the variation in landings observed during 1960-1976. Although additional variables contributed to an increase in R-square values, the implication from Mallow's criterion was that these regressions were outfitted, and would thus be less reliable for prediction. The interested reader can refer to Saila et al. (1982) for alternate models and their corresponding Cp values. Regression coefficients presented in Table 2 were interpreted as follows. Since the regression coefficient associated with PC2.Q1 is positive, landings for brown shrimp would

Table 1. Correlation among seasonal principal components.

		Winter			Spring			Summer			Fall		
		PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
WINTER	PC1	1.0											
	PC2	0.0	1.0										
	PC3	0.0	0.0	1.0									
SPRING	PC1	-0.54*	0.16	0.49*	1.0								
	PC2	0.06	-0.01	0.03	0.0	1.0							
	PC3	0.42	0.09	0.29	0.0	0.0	1.0						
SUMMER	PC1	-0.70*	-0.21	0.27	0.76*	0.01	-0.21	1.0					
	PC2	0.39	-0.11	0.62*	0.12	-0.08	0.57*	0.0	1.0				
	PC3	-0.18	-0.17	0.33	-0.01	0.07	0.23	0.0	0.0	1.0			
FALL	PC1	0.51*	0.18	-0.44	-0.45	0.02	0.20	-0.67*	0.07	-0.01	1.0		
	PC2	0.27	0.06	0.27	-0.13	-0.44	0.45	-0.13	0.47	0.08	0.0	1.0	
	PC3	0.00	-0.44	0.21	-0.06	0.03	0.03	0.25	0.34	0.15	0.0	0.0	1.0

Table 2. Regression equations based on seasonal principal components.

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------------------------------------------------------------------------
    The regression equation for brown shrimp landings (metric tons)
    in statistical area 18 is:

    Landings = 3202 + 479 PC2.Q1 + 239 PC1.Q2

                                          ST. DEV.     T-RATIO =
         COLUMN        COEFFICIENT        OF COEF.     COEF/S.D.
                          3202.1            517.9          6.18
         PC2.Q1            478.6            237.2          2.02
         PC1.Q2            239.4            100.5          2.38

                    ANALYSIS OF VARIANCE
          DUE TO       DF             SS        MS=SS/DF
         REGRESSION     2        9511746         4755873
           PC2.Q1           1        4174990
           PC1.Q2           1        5336755
          RESIDUAL    14       13164586          940328

    R-SQUARE   = 41.9 PERCENT
------------------------------------------------------------------------
    The regression equation for white shrimp landings (metric tons)
    in statistical area 18 is:

     Landings = 1415 - 395 PC2.Q3 - 100 PC3.Q3 - 129 PC1.Q4

                                          ST. DEV.     T-RATIO =
         COLUMN        COEFFICIENT        OF COEF.     COEF/S.D.
                          1414.8            108.7         13.02
         PC2Q3           -394.83            80.64         -4.90
         PC3Q3           -100.15            29.39         -3.41
         PC1Q4           -129.43            28.76         -4.50

                    ANALYSIS OF VARIANCE
          DUE TO       DF             SS        MS=SS/DF
         REGRESSION     3        1134863          378288
            PC2Q3           1         579973
            PC3Q3           1         119294
            PC1Q4           1         435596
         RESIDUAL      13         279569           21505

   R-SQUARE    = S80.2 PERCENT
------------------------------------------------------------------------
(PCi.Qj refers to the ith principal component from the jth quarter)
```

be expected to be larger for the years where the evaluation of PC2.Q1 was large. This occurred in the winter quarter (Q1) when the east component of Ekman transport at both stations was high, the north component of Ekman transport at both stations was low, and when the median and maximum temperatures at the North Jetty were high. This would correspond to a winter with relatively warm southerly winds (toward the north). Since the regression coefficient associated with PC1.Q2 is positive, landings would be expected to be lowest for those years when the evaluation of PC.Q2 takes on large negative values. This occurred when springtime river discharges were high and salinities at the North Jetty were low. According to Mallow's criterion, PC2.Q4 should be retained in the model. However, climatic factors operating in the fall should not have a major affect on brown shrimp landings, since peak landings occur in the summer (Fig. 3). When PC2.Q4 was excluded from the model, the remaining two PC's accounted for 42% of the variance in brown shrimp landings in area 18, with an average absolute error of 0.73 metric tons.

These regression results may be interpreted as follows. When the winter east component of Ekman transport increased, PC2.Q1 increased and annual landings for brown shrimp in area 18 increased. This could be due to the fact that the major concentration of brown shrimp is off Texas (Fig. 1). High eastward Ekman transport in January through March would favor the movement of larval brown shrimp toward nursery grounds on the eastern edge of their range. Alternative causal explanations are possible. For example, southerly winds could enhance transport of larval shrimp into the estuaries. The evaluations of the PC's that were retained for prediction of brown and white shrimp landings are included in Table 3. We infer that favorable transport years occurred when the evaluation of PC2.Q1 was greater than 1.0, including the winters of 1967, 1971, 1973, 1974, 1975, and 1976. However, juvenile brown shrimp stages may not survive low salinity conditions in nursery grounds. When springtime river discharges were low in this region, PC1.Q2 was high and landings were above average. Springtime river discharges were high (PC1.Q2 < -1.0) in 1968, 1969, and 1973 (Table 3). Thus, even though we suspect that transport conditions were favorable in 1973, high springtime river discharges could have caused major mortalities in the estuaries, resulting in a poor yield in 1973. A reviewer of this manuscript also indicated that 1973 was the year of the first major international oil crises which may have resulted in a reduction of the fishing effort. Years that included favorable eastward transport in the winter and favorable low river discharges in the spring include 1967, 1971, 1974 and 1976. On the basis of high springtime river discharges, 1968, 1969, and 1973 could be expected to be poor yield years.

The fit of observed and predicted values from 1968 through 1976

Table 3. Evaluations of the principal climatic components used to predict brown and white shrimp landings.

(PCi.Qj refers to the ith principal component from the jth quarter)

	BROWN SHRIMP		WHITE SHRIMP		
YEAR	PC2.Q1	PC1.Q2	PC2Q3	PC3Q3	PC1Q4
1960	-2.1413	0.6643	0.9132	0.45649	-0.3937
1961	-1.1776	-1.0985	1.6442	4.07486	-0.1055
1962	-2.0291	-0.5196	1.9829	-0.59545	1.5271
1963	-2.2094	1.8453	1.0803	0.92335	2.8081
1964	-2.2574	-0.1596	1.4492	-0.22615	1.6709
1965	-2.2224	-1.3442	1.5402	-1.11260	1.9134
1966	-3.5355	-1.6997	1.6883	-1.00906	1.6726
1967	-1.5990	0.6810	1.1885	-0.21007	1.5695
1968	-3.4943	-4.0672	1.8304	-0.51186	0.1491
1969	-2.4575	-4.9891	1.0142	-0.93174	2.1334
1970	-3.2667	-0.3959	0.7067	-1.01808	0.9101
1971	-2.0275	1.6707	0.9366	0.13919	-0.0512
1972	-1.3813	0.5958	1.6095	-1.46947	0.7852
1973	-1.4801	-6.7552	1.6994	-0.19735	-2.6221
1974	-0.1561	-1.0411	0.2634	0.81082	-0.9568
1975	-0.6049	-4.1659	1.1345	-0.57559	0.9138
1976	-0.1274	-0.3259	0.9507	-1.12662	0.3585

was very good on the basis of the regression model including only two PC's (Fig. 9). The regression model underestimated 1960 brown shrimp landings by approximately 1 metric ton. This underestimation was largely due to a low score for PC2.Q1 as a result of below average eastward Ekman transport, above average northward Ekman transport, and below average median and maximum temperatures. Thus, on the basis of the regression model and the interpretations in the previous paragraphs, it would appear that transport of larval stages during the winter of 1960 may have been unfavorable. The springtime estuarine salinity in 1960 at the North Jetty was above average as a result of below average river discharge in the region. Thus, conditions in the nursery areas during 1960 may have been favorable for the survival of juvenile brown shrimp.

The model overestimated shrimp landings during the period 1961-1964 by an average of 1.15 metric tons. The evaluation of the winter Ekman transport component, PC2.Q1, was close to zero during this period (Table 3). Since the regression equation has the form:

$$Y = a + b(PC2.Q1) + c(PC1.Q2) + e,$$

the term b(PC2.Q1) is equal to zero when PC2.Q1 equals zero. Thus the regression equation did not utilize the Ekman transport information during the years 1961-1964. Springtime river discharges during this period were low, indicated by positive values for PC1.Q2 (Table 3) and resulted in the overestimation of the 1961-1964 landings. The model also failed to predict the exceptionally high landings observed in 1967. From the lack of fit, it can be inferred that the regression model may not adequately balance the relative importance and possible interactions between transport to nursery areas and salinity conditions in nursery grounds.

PREDICTING ANNUAL WHITE SHRIMP LANDINGS IN STATISTICAL AREA 18

The best model, on the basis of Mallow's criterion, explained approximately 80% of the variation in white shrimp landings in statistical area 18. Regression coefficients are presented in Table 2 and can be interpreted as follows. As the north component of Ekman transport and the minimum and median temperature at the North Jetty increased, PC2.Q3 increased, and white shrimp landings in the area decreased. When the summer east component of Ekman transport was high and median and maximum salinities at the North Jetty were low, PC3.Q3 increased and landings decreased. Additional predictive information is contained in PC1.Q4. This component explained approximately 40% of the variation in the 14 climatic and hydrographic variables in the fall. This season corresponds to a period when white shrimp are leaving the estuarine nursery areas and

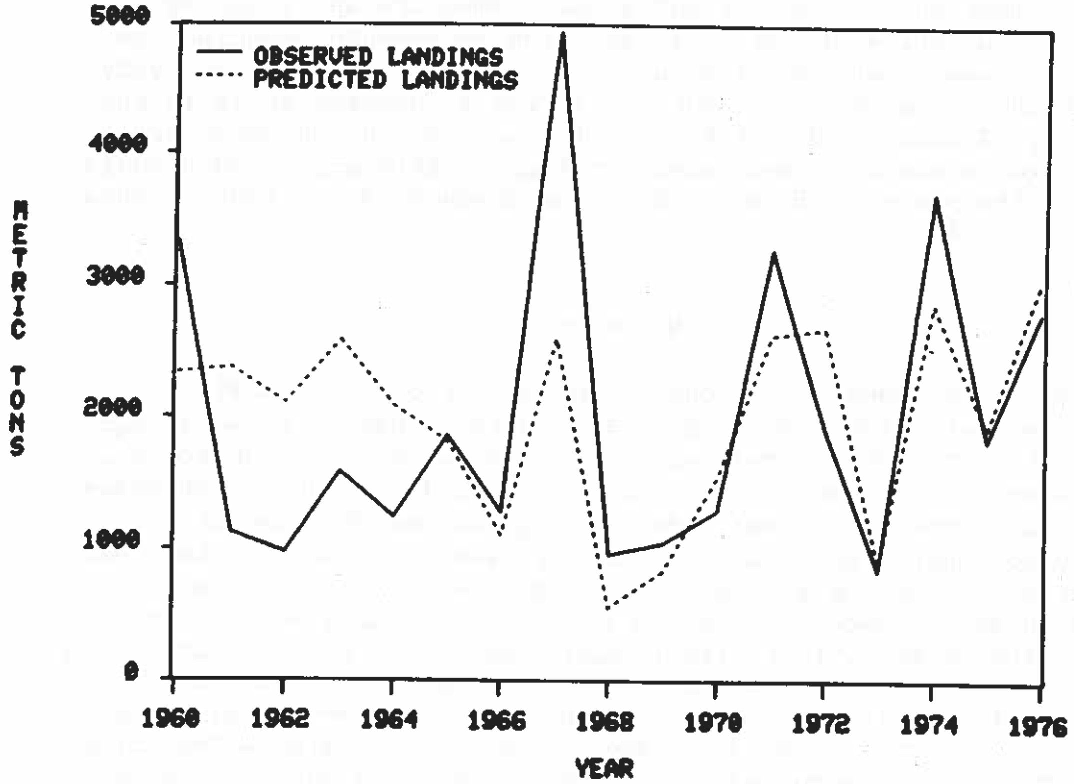

Figure 9. Brown shrimp landings - Area 18.

the largest offshore landings occur. This Ekman transport was high and the salinity, median and maximum temperature, and northward Ekman transport were low (appendix Table 8). A high score on PC1.Q4 would indicate favorable conditions for offshore catches of white shrimp. In fact, a drop in water temperature has been known to trigger the fall migration of white shrimp out of the estuaries. Observed and predicted values for white shrimp landings from statistical area 18 are illustrated in Figure 10.

The importance of spring and summer Ekman transport may be related to the white shrimp life cycle and geographic distribution. Spring and summer correspond to a period of major spawning activity offshore and subsequent transport of larvae to nursery areas in the estuaries. Transport during this period toward the northeast was found to correlate with decreased landings in this area. This could be due to the presence of major spawning grounds to the east of area 18 (Figs. 1 and 2).

CONCLUSIONS

Predicting annual variaions in shrimp yield on the basis of seasonal climatic components appears to offer a number of advantages compared to more traditional regression approaches. In particular, within season collinearity problems are avoided. However, inferences concerning causal mechanisms based on regressions on seasonal climatic components still need to be validated against data that have been gathered since 1976. Specific inferences based on these regression models should be tested against other data sets. For example, the effected recruitment should be tested against variations in indices of inshore recruitment for this region. Furthermore, although offshore larval transport conditions have been implicated as an important forcing function, transport conditions also affect other factors such as average tidal levels in the marshes which could be a major factor influencing inshore growth and survival.

One of the reasons the regressions on seasonal principal components worked as well as they did was the information entered into the regression equations when seasonal climatic and hydrographic conditions departed from average seasonal conditions. In a given year, when climatic factors were close to the 17-year seasonal averages, the corresponding PC's were evaluated as being close to zero, and thus these terms dropped out of the prediction equations. It should be emphasized that, according to Marr (1972), empirical relationships between the physical environment and organisms are often only precise in extreme conditions and, that when conditions are average, the strongest variance is often linked to biotic factors such as competition, etc. (Garcia and Le Reste 1981). If all

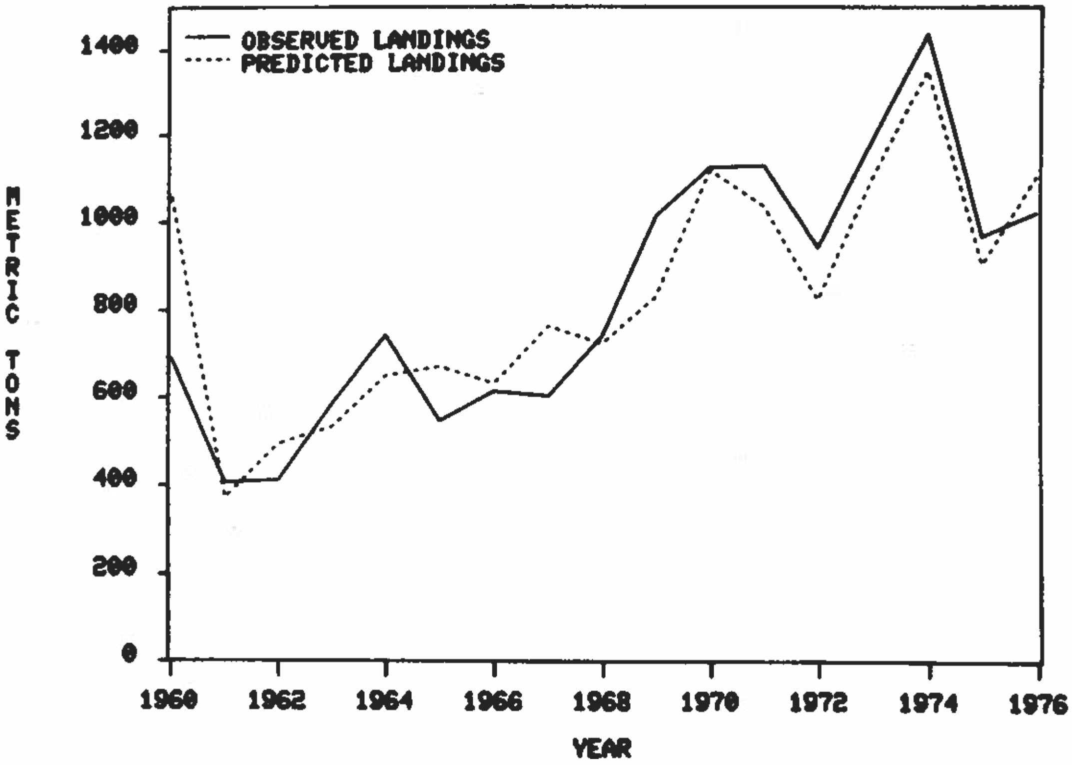

Figure 10. White shrimp landings - Area 18.

seasonal climatic and hydrographic conditions were close to the 17-year averages, all of the PC's would be close to zero, and all of the terms on the right hand side of the regression equations would drop out. Predicted landings in such a case should then simply be close to the average landings for the 17-year period. One of the reasons the regression models did not work better was that significant interactions between seasonal components were not included as crossproduct terms in the regression equations. This could be done relatively easily, but the merits of this additional complexity would only be justified if the prediction accuracy was much improved.

A method of deriving confidence intervals on individual yield predictions is included in Saila et al. (1982). Since the method is empirical, it should not be used if environmental variations are outside of the range observed during 1960 to 1976. The confidence intervals require the specification of a confidence level, (e.g. 95%), and can be used for hypothesis testing. It would only be possible to reject the hypothesis that brine disposal operations have had no affect on shrimp yields in statistical areas 17 and 18 if the observed landings were lower than the lower bounds on the predicted confidence intervals, given the environmental conditions that have been observed. Other interventions could be tested as well, as long as they are not confounded.

An assumption underlying the principal component analysis was that shrimp densities would fluctuate in response to environmental forcings, and fishing effort would adjust in such a fashion that the stock would continue to be fished as long as it was profitable. If this assumption is valid, fishing effort would not have to be included in the annual yield prediction models. However, changes in offshore fishing effort or economics which affect annual offshore shrimp yields independently of environmental forcings would bias the analysis. To determine if this has occurred, it would be necessary to have an independent estimate of stock size, perhaps based on research trawls or the inshore bait fishery. These stock size estimates could then be predicted on the basis of climatic components. One could also predict offshore yields from these estimates of stock size and determine if significant additional variance in offshore yield could be attributed to changes in offshore fishing effort. To do this would require the design of a standardized measure of fishing effort. Brunenmeister (1981) has made significant progress along these lines.

The effect of the size of the reproductive shrimp stock on subsequent yields is another variable that has not been included in the analyses. If reproductive stock size data were available, one could reanalyze the climatic component models including reproductive stock size as an additional predictor to determine if significant additional variance in yield could be accounted for.

For management purposes, it would be desirable to ask, and answer the question: "If the environmental affects on shrimp stock sizes are accounted for, is there evidence that suggests that changes in fishing effort or management practices regulating that effort have significantly affected yields in concurrent and subsequent years?" The confidence with which one can answer this question depends on the accuracy and precision with which one can estimate fishing effort and stock size in a given year, and the amount of annual variance in fishing effort and stock size that can be accounted for on the basis of environmental conditions. The principal component regression techniques described in this paper may significantly improve our ability to account for environmentally induced variations in fishing effort and stock size, and thus improve our ability to understand yield fluctuations and manage the fishery.

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APPENDIX

Principal Component Analysis for Each Season

Principal component analysis for the winter quarter (Q1): The correlation matrix and results of the principal component analysis for the winter quarter (Q1) are presented in Appendix Tables 1 and 2. The first three principal components described 77% of the variance in the original 14 independent variables.

On the basis of the magnitude of the elements of the first eigenvector, the first principal component (PC1.Q1) was interpreted as a river discharge-salinity component. From the signs on the eigenvector coefficients, it can be seen that this component was positively correlated with annual variations in quarterly averaged Neches, Sabine, and Trinity River discharges and negatively correlated with the minimum and median salinity at the North Jetty during the winter. River discharges and salinity information jointly accounted for 93% of the variance of PC1.Q1.

The second principal component (PC2.Q1) was interpreted as representing the annual variations in Ekman transport during the winter and was related to the median and maximum temperatures at the North Jetty (appendix Table 2). From the signs of the second eigenvector coefficients, it can be seen that PC2.Q1 was positively correlated with the east component of Ekman transport at both locations and positively correlated with the median and maximum temperatures at the North Jetty. PC2.Q1 was also negatively correlated with the north component of Ekman transport at both locations. Thus, scores from this principal component were highest when the east component of Ekman transport at both stations was high, the north component of Ekman transport at both stations was low and when the median and maximum temperatures at the North Jetty for the winter quarter were high. The winter transport indices jointly accounted for 70% of the variance of PC2.Q1. An additional 22% was accounted for by the median and maximum water temperature at the North Jetty in the winter. This component was found to be useful for predicting variations in brown shrimp landings.

The third principal component (PC3.Q1) was positively correlated with annual variations in the maximum water temperature observed at the North Jetty during the winter. PC3.Q1 was also negatively correlated with the Mississippi River discharge. This principal component was labeled as the one primarily describing quarterly maximum temperature observed at the North Jetty, which by itself accounted for 50% of the PC3.Q1 variance.

Appendix Table 1. Correlation matrix.

Winter Quarter

EK.EAST.LO	1.0													
EK.EAST.TE	0.84*	1.0												
EK.NORTH.LO	-0.83*	-0.69*	1.0											
EK.NORTH.TE	-0.56*	-0.70*	0.59*	1.0										
SALIN.MIN	0.21	0.44	-0.27	-0.24	1.0									
SALIN.MED	-0.18	0.02	0.20	0.23	0.69*	1.0								
SALIN.MAX	0.05	0.18	0.02	0.05	0.46*	0.72*	1.0							
TEMP.MIN	-0.07	-0.16	0.02	-0.15	-0.41	-0.51*	-0.36	1.0						
TEMP.MED	0.68*	0.63*	-0.57*	-0.34	0.21	-0.30	-0.10	0.04	1.0					
TEMP.MAX	0.46	0.40	-0.33	-0.14	0.10	-0.25	0.18	-0.17	0.50*	1.0				
MISSIP.	0.36	0.04	-0.25	-0.18	-0.48*	-0.50*	-0.44	0.08	0.16	-0.22	1.0			
NECHES	0.14	-0.07	-0.17	-0.08	-0.79*	-0.83*	-0.49*	0.31	0.05	0.20	0.51*	1.0		
SABINE	0.19	-1.0	-0.16	-0.08	-0.84*	-0.88*	-0.60*	0.39	0.13	0.15	0.58*	0.95*	1.0	
TRINITY	-0.20	-0.47	0.12	0.17	-0.79*	-0.78*	-0.63*	0.60*	-0.15	-0.01	0.31	0.76*	0.77*	1.0

North and east components of Ekman transport at the Louisiana wind analysis site (92°W, 30°N) and the Texas wind analysis site (95°N, 30°W)

Minimum, median and maximum salinity and water temperature at the North Jetty, Galveston, Texas

River flow

* Indicates significance at α = 0.05

Appendix Table 2. Principal component analysis: winter quarter.

	EIGENVALUES				
	5.33	4.16	1.26	1.05	0.68
	EIGENVECTORS				
EAST EKMAN COMPONENT (LOUIS.)	0.016	0.458	-0.046	0.141	0.053
EAST EKMAN COMPONENT (TEXAS)	-0.099	0.443	-0.085	-0.026	0.097
NORTH EKMAN COMPONENT (LOUIS.)	-0.022	-0.421	0.120	-0.008	-0.076
NORTH EKMAN COMPONENT (TEXAS)	-0.013	-0.345	0.344	0.298	-0.353
MINIMUM SALINITY	-0.374	0.153	-0.072	-0.172	-0.211
MEDIAN SALINITY	-0.402	-0.113	-0.088	0.125	0.103
MAXIMUM SALINITY	-0.313	0.013	0.216	0.108	0.638
MINIMUM TEMPERATURE	0.233	-0.038	-0.133	-0.713	0.119
MEDIAN TEMPERATURE	0.027	0.384	0.214	-0.103	-0.521
MAXIMUM TEMPERATURE	0.009	0.267	0.712	-0.008	0.036
MISSISSIPPI RIVER	0.253	0.120	-0.431	0.482	-0.100
NECHES RIVER	0.388	0.064	0.148	0.174	0.279
SABINE RIVER	0.411	0.065	0.076	0.149	0.127
TRINITY RIVER	0.385	-0.125	0.111	-0.165	0.041

Principal component analysis for the spring quarter (Q2): The correlation matrix and results of the principal component analysis for the spring quarter (Q2) (appendix Tables 3 and 4) were similar to those for the winter quarter, but with a few interesting differences. The first three principal components described 75% of the variance in the original 14 variables.

Once again, the first principal component, PC1.Q2, was interpreted as a salinity-river discharge component. However, unlike the case of the winter quarter, the signs associated with the eigenvector coefficients were negative for the rivers and positive for salinity. Thus, PC1.Q2 was negatively correlated with river discharges. It should be recognized that any of these components could be redefined by changing the sign of the eigenvector coefficients. This would simply reverse the orientation of the principal axis in the hyperspace. The important thing to realize was that for this component, as defined, increases in river discharge resulted in lower scores, while the opposite was true for PC1.Q1 in the winter quarter analysis. The four river discharge variables and three salinity variables jointly accounted for 81% of the PC1.Q2 variance. Springtime salinity-river discharge conditions, as described by this component, were also useful for predicting variations in brown shrimp landings.

The second principal component for the spring, PC2.Q2, was interpreted as representing Ekman transport, but with a slight shift in the major axis of variation. The four transport variables accounted for 73% of the PC2.Q2 variance. An additional 16% was accounted for by the maximum salinity and median temperature at the North Jetty in the spring. Unlike the transport component for the winter, the eigenvalues positively weighted the north and east components of Ekman transport at both locations. From an inspection of the eigenvector coefficients it was seen that this principal component was positively correlated with the north and east components of Ekman transport at both locations. In addition, this principal component was negatively correlated with maximum salinity at the North Jetty. Inspection of the correlation matrix of the original variables for the spring quarter (appendix Table 3) indicated a slight negative correlation between maximum salinity and the east component of Ekman transport at both locations. Variations in PC2.Q2, interpreted as primarily representing transport conditions, apparently contained information useful for predicting year to year variations in white shrimp landings.

The third principal component was interpreted as a temperature component. Median and maximum temperature at the North Jetty jointly accounted for 78% of the PC3.Q2 variance.

Appendix Table 3. Correlation matrix.

Spring Quarter

EK.EAST.LO	1.0													
EK.EAST.TE	0.85*	1.0												
EK.NORTH.LO	0.59*	0.52*	1.0											
EK.NORTH.TE	0.60*	0.71*	0.83*	1.0										
SALIN.MIN	0.39	0.46	0.10	0.24	1.0									
SALIN.MED	0.14	0.26	0.05	0.15	0.77*	1.0								
SALIN.MAX	-0.02	0.07	-0.23	-0.14	0.58*	0.83*	1.0							
TEMP.MIN	0.07	0.19	0.04	0.12	0.34	0.40	0.19	1.0						
TEMP.MED	0.43	0.46	0.36	0.43	0.33	0.27	0.00	0.16	1.0					
TEMP.MAX	0.06	0.10	-0.12	-0.12	0.02	0.02	0.16	-0.12	0.37	1.0				
MISSIP.	0.06	-0.14	0.02	0.00	-0.47	-0.68*	-0.61*	-0.35	-0.15	-0.43	1.0			
NECHES	-0.43	-0.46	-0.17	-0.28	-0.73*	-0.84*	-0.75*	-0.30	-0.27	-0.09	0.63*	1.0		
SABINE	-0.32	-0.37	-0.08	-0.13	-0.70*	-0.83*	-0.75*	-0.24	-0.20	-0.19	0.69*	0.95*	1.0	
TRINITY	-0.31	-0.35	0.01	-0.18	-0.85*	-0.81*	-0.74*	-0.20	-0.19	0.09	0.37	0.81*	0.74*	1.0

North and east components of Ekman transport
at the Louisiana wind analysis site (92°W, 30°N)
and the Texas wind analysis site (95°W, 30°N)

Minimum, median and maximum
salinity and water temperature
at the North Jetty,
Galveston, Texas

River flow

* Indicates significance at $\alpha = 0.05$

Appendix Table 4. Principal component analysis: spring quarter.

	EIGENVALUES				
	6.01	3.11	1.43	1.01	0.74
	EIGENVECTORS				
EAST EKMAN COMPONENT (LOUIS.)	0.197	0.407	-0.005	-0.234	0.184
EAST EKMAN COMPONENT (TEXAS)	0.237	0.379	-0.051	-0.081	0.139
NORTH EKMAN COMPONENT (LOUIS.)	0.099	0.456	0.057	0.113	-0.490
NORTH EKMAN COMPONENT (TEXAS)	0.153	0.459	0.089	0.095	-0.290
MINIMUM SALINITY	0.349	-0.028	0.121	-0.047	0.312
MEDIAN SALINITY	0.364	-0.167	0.090	0.095	-0.053
MAXIMUM SALINITY	0.298	-0.312	0.023	-0.145	-0.092
MINIMUM TEMPERATURE	0.156	-0.025	0.142	0.830	0.270
MEDIAN TEMPERATURE	0.167	0.257	-0.396	0.135	0.428
MAXIMUM TEMPERATURE	0.058	-0.052	-0.789	-0.085	0.021
MISSISSIPPI RIVER	-0.266	0.213	0.312	-0.290	0.394
NECHES RIVER	-0.384	0.054	-0.040	0.085	0.141
SABINE RIVER	-0.365	0.123	0.040	0.110	0.193
TRINITY RIVER	-0.343	0.102	-0.245	0.253	-0.219

Principal component analysis for the summer quarter (Q3): The correlation matrix and results of the summer principal component analysis are summarized in appendix Tables 5 and 6. The first three principal components described 69% of the year to year variance of the original 14 independent variables. The first principal component, PC1.Q3, was interpreted as a salinity-river discharge component. It was negatively correlated with all river discharges and positively correlated with minimum, median, and maximum salinity at the North Jetty. The river discharge and salinity variables jointly account for 89% of the PC1.Q3 variance.

The remaining principal components were quite different from those obtained from either the winter or spring quarters. The relationship among the original Ekman transport variables had changed again. During the winter quarter, the north component and east component of Ekman transport were negatively correlated at both locations (appendix Table 1). This pattern changed to a positive correlation between the north and east Ekman components in the spring at both stations (appendix Table 3). The pattern changed again in the summer quarter where there was a very weak correlation between the quarterly average north and east component of Ekman transport at both locations (appendix Table 5).

The second principal component for the summer (PC2.Q3) heavily weighted the north component of Ekman transport at both locations and minimum and median temperatures at the North Jetty (appendix Table 6). All of these variables were positively correlated with this principal component. The implication was that in the summer when the north component of Ekman was high the quarterly minimum and median temperatures at the North Jetty increased. This correlation pattern is suggested in appendix Table 5.

The third summer principal component heavily weighted a number of variables: the east component of Ekman transport at both locations, median and maximum salinity and median temperature at the North Jetty. This principal component scored highest when eastward Ekman transport was high and median and maximum salinity at the North Jetty were low. It should be recognized that the salinity information that entered this principal component was conditioned on the information that had already been extracted by the first principal component. For this reason, a simple interpretation may be difficult. Starting with the inspection of the correlation matrix among the original variables (appendix Table 5), there was a slight positive correlation among median and maximum salinity at the North Jetty and the east component of Ekman transport at Location 2 in Texas. Except for maximum salinity, these variables were negatively correlated with river discharges. Thus, in addition to the general salinity-discharge component (PC1.Q3), this component (PC3.Q3)

Appendix Table 5. Correlation matrix.

Summer Quarter

EK.EAST.LO	1.0														North and east components of Ekman transport at the Louisiana wind analysis site (92°W, 30°N) and the Texas wind analysis site (95°W, 30°N)
EK.EAST.TE	0.63*	1.0													
EK.NORTH.LO	0.27	-0.16	1.0												
EK.NORTH.TE	0.38	-0.03	0.93*	1.0											
SALIN.MIN	0.34	0.51*	0.11	0.15	1.0										Minimum, median and maximum salinity and water temperature at the North Jetty, Galveston, Texas
SALIN.MED	-0.09	0.29	0.05	0.06	0.56*	1.0									
SALIN.MAX	-0.05	0.20	-0.04	0.04	0.54*	0.75*	1.0								
TEMP.MIN	0.37	0.09	0.38	0.49*	-0.04	-0.13	-0.11	1.0							
TEMP.MED	0.07	-0.16	0.50*	0.48*	-0.09	0.40	0.19	0.64*	1.0						
TEMP.MAX	0.09	0.09	0.03	0.08	0.14	-0.01	0.11	-0.28	-0.23	1.0					
MISSIP.	-0.20	-0.53*	0.24	0.13	-0.23	-0.37	-0.12	0.08	-0.06	-0.28	1.0				River flow
NECHES	-0.23	-0.51*	-0.05	-0.10	-0.90*	-0.71*	-0.58*	-0.09	-0.20	-0.05	0.45	1.0			
SABINE	-0.09	-0.55*	0.13	0.07	-0.69*	-0.69*	-0.49*	0.03	-0.09	-0.11	0.55*	0.93*	1.0		
TRINITY	-0.17	-0.34	0.19	0.17	-0.63*	-0.51*	-0.57*	0.16	0.19	-0.20	0.34	0.66*	0.62*	1.0	

* Indicates significance at $\alpha = 0.05$

Appendix Table 6. Principal component analysis: summer quarter.

	EIGENVALUES				
	4.93	2.97	1.75	1.29	0.99
	EIGENVECTORS				
EAST EKMAN COMPONENT (LOUIS.)	0.128	0.246	0.567	-0.019	0.177
EAST EKMAN COMPONENT (TEXAS)	0.288	-0.015	0.462	-0.206	0.052
NORTH EKMAN COMPONENT (LOUIS.)	-0.022	0.501	-0.036	0.346	0.005
NORTH EKMAN COMPONENT (TEXAS)	0.013	0.517	0.045	0.315	-0.038
MINIMUM SALINITY	0.375	0.041	0.058	0.194	0.359
MEDIAN SALINITY	0.354	0.039	-0.367	-0.026	-0.132
MAXIMUM SALINITY	0.309	-0.001	-0.343	0.148	0.119
MINIMUM TEMPERATURE	-0.017	0.438	0.101	-0.389	0.019
MEDIAN TEMPERATURE	0.050	0.427	-0.302	-0.276	-0.332
MAXIMUM TEMPERATURE	0.081	-0.097	0.212	0.615	-0.488
MISSISSIPPI RIVER	-0.253	0.099	-0.225	0.197	0.643
NECHES RIVER	-0.422	-0.068	0.055	0.059	-0.070
SABINE RIVER	-0.406	0.045	0.042	0.122	0.076
TRINITY RIVER	-0.344	0.125	0.028	-0.110	-0.169

related the eastward Ekman transport to salinity changes at the North Jetty. The regression analysis discussed above suggested that this component also contained information useful for predicting annual variations in white shrimp landings in the vicinity of the Texas-Louisiana boundary.

Principal component analysis for the fall quarter (Q4): The correlation matrix and results of the fall principal component analysis are summarized in appendix Tables 7 and 8. The first three principal components described 77% of the variance in the original 14 variables for this quarter.

An interesting correlation pattern appeared in the fall. The north and east components of Ekman transport were negatively correlated as they were in the winter. However, a consistent and positive correlation occurred between the east component of Ekman transport at both locations and river discharges (appendix Table 7). An intriguing aspect of this was that the correlations were opposite in sign from the correlations observed between the east component of Ekman transport at both locations and river discharges in the spring (appendix Table 3).

From the magnitude of the eigenvalue associated with the first principal component, PC1.Q4 (appendix Table 8), it was seen that PC1.Q4 summarized 41% of the covariation among the environmental factors in the fall. This principal component positively weighted the east component of Ekman transport at both locations, river discharges, and minimum and median temperatures at the North Jetty. It negatively weighted the north component of Ekman transport and minimum, median and maximum salinity. It thus scored highest when river discharge and eastward Ekman transport and median temperatures were high and salinity and northward Ekman transport were low. The fall corresponds to the time of peak offshore white shrimp landings, and the regression analysis suggested that this component was useful for prediction. The remaining principal components with eigenvalues > 1 combined Ekman transport data with temperature or salinity data at the North Jetty.

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Appendix Table 7. Correlation matrix.

Fall Quarter

EK.EAST.LO	1.0														North and east components of Ekman transport at the Louisiana wind analysis site (92°W, 30°N) and the Texas wind analysis site (95°W, 30°N)
EK.EAST.TE	0.91*	1.0													
EK.NORTH.LO	-0.44	-0.34	1.0												
EK.NORTH.TE	-0.49*	-0.39	0.77*	1.0											
SALIN.MIN	-0.11	-0.29	-0.01	-0.26	1.0										Minimum, median and maximum salinity and water temperature at the North Jetty, Galveston, Texas
SALIN.MED	-0.31	-0.38	0.41	0.23	0.70*	1.0									
SALIN.MAX	-0.46	-0.44	0.32	0.38	0.29	0.63*	1.0								
TEMP.MIN	0.22	0.12	-0.24	-0.33	0.02	-0.34	-0.70*	1.0							
TEMP.MED	0.76*	0.73*	-0.31	-0.40	0.08	-0.26	-0.57*	0.46	1.0						
TEMP.MAX	0.06	0.24	0.01	0.30	-0.20	0.03	0.05	-0.40	-0.10	1.0					
MISSIP.	0.44	0.34	-0.37	-0.19	-0.26	-0.41	-0.27	0.02	0.21	0.05	1.0				River flow
NECHES	0.41	0.54*	-0.25	0.02	-0.68*	-0.78*	-0.30	0.18	0.40	0.02	0.38	1.0			
SABINE	0.43	0.49*	-0.25	0.06	-0.63*	-0.74*	-0.44	0.16	0.38	-0.02	0.46	0.88*	1.0		
TRINITY	0.38	0.42	-0.16	-0.04	-0.56*	-0.58*	-0.33	0.37	0.41	-0.24	0.23	0.72*	0.69*	1.0	

* Indicates significance at $\alpha = 0.05$

Appendix Table 8. Principal component analysis: fall quarter.

	EIGENVALUES				
	5.76	2.53	1.68	1.20	0.92
	EIGENVECTORS				
EAST EKMAN COMPONENT (LOUIS.)	0.311	-0.221	0.317	0.177	0.163
EAST EKMAN COMPONENT (TEXAS)	0.318	-0.102	0.376	0.246	0.064
NORTH EKMAN COMPONENT (LOUIS.)	-0.217	0.290	-0.078	0.537	0.016
NORTH EKMAN COMPONENT (TEXAS)	-0.166	0.489	0.015	0.329	-0.063
MINIMUM SALINITY	-0.216	-0.459	0.022	0.108	0.180
MEDIAN SALINITY	-0.336	-0.181	0.187	0.253	0.239
MAXIMUM SALINITY	-0.293	0.146	0.200	-0.109	0.548
MINIMUM TEMPERATURE	0.193	-0.234	-0.499	0.201	-0.278
MEDIAN TEMPERATURE	0.286	-0.263	0.113	0.433	0.053
MAXIMUM TEMPERATURE	-0.017	0.169	0.569	0.049	-0.562
MISSISSIPPI RIVER	0.218	0.029	0.199	-0.406	0.106
NECHES RIVER	0.334	0.290	-0.004	-0.008	0.183
SABINE RIVER	0.333	0.276	-0.026	-0.016	0.138
TRINITY RIVER	0.298	0.190	-0.219	0.163	0.336

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A REVIEW OF THE PRESENT STATUS OF KUWAIT'S SHRIMP FISHERIES WITH SPECIAL REFERENCE TO THE NEED FOR EFFORT LIMITATION

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INTRODUCTION

The shrimp fisheries of the Gulf which lies between Iran and the Arabian Peninsula have shown considerable fluctuations in landings since their inception in the early 1950's. Figure 1 shows a map of Kuwait waters and the general locality of Kuwait in the Gulf. FAO (1982) reviewed the available knowledge of these fisheries and showed that landings peaked in 1967-68 at 17,600 metric tons (t) of whole shrimp. By 1974-75, the last year for which full data were available, total landings had fallen to 12,400 t. Kuwait's shrimp fishery is, in many ways, typical of the shrimp fisheries of the Gulf as a whole, landings peaked in 1966/67 at 3,202 t (FAO 1982) and in 1967/68 were slightly lower (2,735 t). However, by 1975-76 they had fallen to an all time low of 1,027 t. This long-term decline in landings was associated with major economic problems related to overfishing, which, in 1972-73, led to the closure of several shrimp fishing companies (Mathews 1981a). General concern for the welfare of Kuwait's shrimp stocks (which, together with the finfish stocks, are Kuwait's second natural resource after petroleum), led to the establishment of the Shrimp Fisheries Management Project in 1978 with a view to protecting the stocks from further decline. A Shrimp Culture Project was established in 1971 to restock shrimp in Kuwait waters and thereby increase commercial landings. The Shrimp Fisheries Management Project was intended to maintain or, if possible, to increase landings from the shrimp stocks through stock assessment and the introduction of appropriate fisheries management measures. Restocking was eventually suspended after analysis of the results (Farmer 1981) showed that insufficient knowledge of the life cycle of Penaeus semisulcatus, the species then thought to dominate Kuwait landings, was available for restocking to be feasible.

The studies initiated in 1978 have been conducted continuously to the present with two main objectives. The first objective was to obtain data on catch (C), effort (E) and catch per unit (C/E) suitable for surplus yield analysis to be carried out. These could be used to formulate a management strategy designed to prevent any future overcapitalization and economic losses to the shrimp fishing

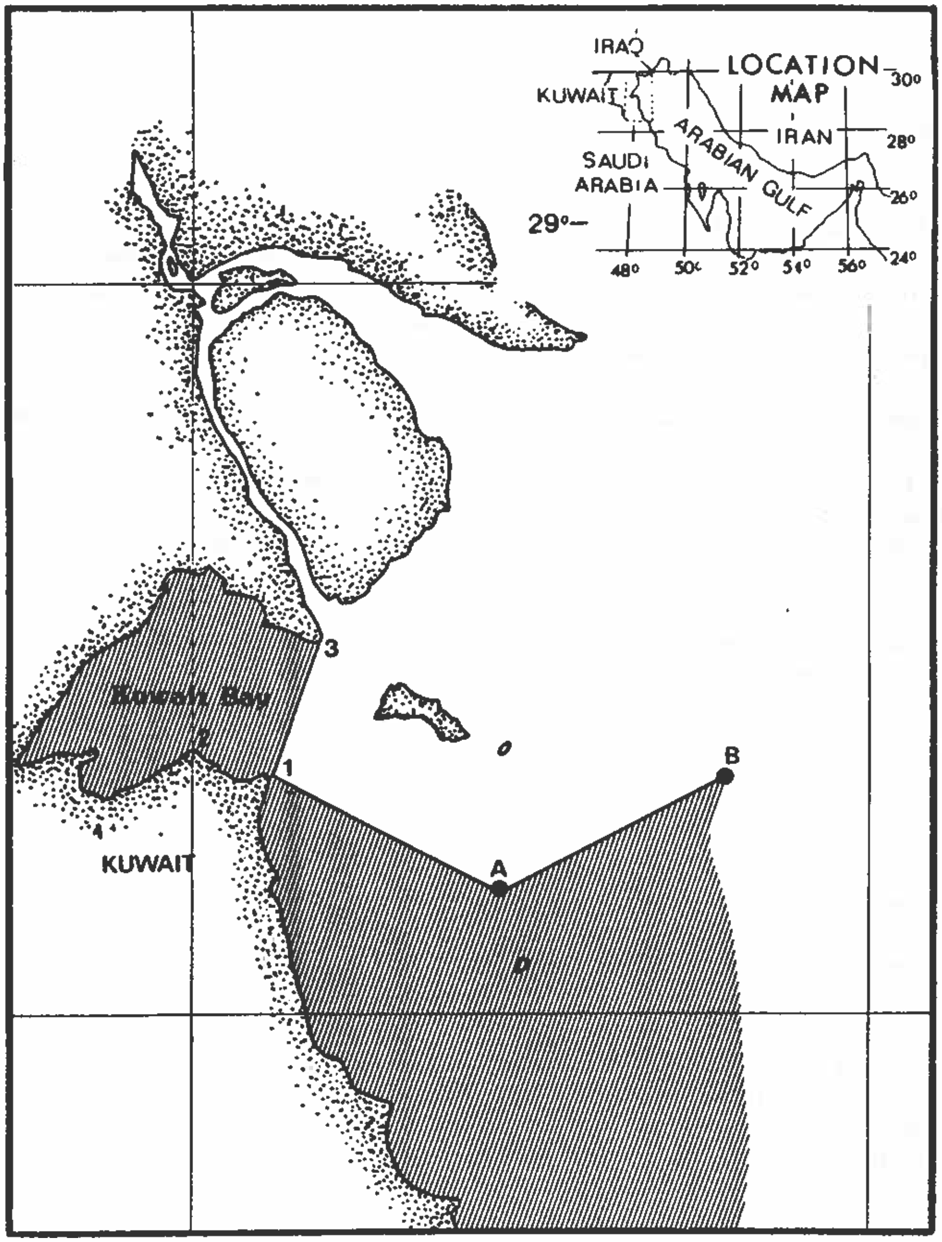

Figure 1. The closed area designed to protect Penaeus semisulcatus nursery and fishing grounds (cross hatched): Ras Al-Ard: 1, Ras Al-Ajuzza: 2; and Ras Sabiyah: 3. The open area east of Kuwait Bay and north of the remaining shaded area delineated by Ras Al-Ard and points A and B is the area in which the closed season fishery for Metapenaeus affinis is allowed to take place.

industry such as occurred in 1972-73. A system for obtaining estimates of landings and effort expended was established in 1978 and has been in operation ever since (Zalinge 1981).

The second objective was to obtain estimates of mortality and growth rates suitable for use in dynamic pool models. The dynamic pool and surplus yield approaches were used simultaneously because it was felt that management measures based on independently collected data and independent analytical techniques would be more likely to succeed than any measures based upon only one or other of these approaches. A system for monitoring the biological characteristics of the penaeids landed in Kuwait's dhow shrimp fisheries was also established in 1978 so as to obtain the basic data needed to estimate growth and mortality and has been maintained continuously since then (Mohamed et al. 1981a). In 1981, it was extended to cover the industrial fishery (Bedford 1981a) following comments from the industry that the species composition of the industrial landings was not 90% *P. semisulcatus* as had been believed until then (Salah Yazbeck, in Mathews 1981a). These systems have been maintained continuously since their inception in 1978 and 1981. The two objectives have been met, and both surplus yield and dynamic pool models have been applied independently to Kuwait's fisheries.

From 1980 onwards, a considerable amount of research into the life cycle, spawning and recruitment of *P. semisulcatus* was conducted by Al-Attar (1981). Some of the results of this work combined with the results obtained from the catch and effort sampling system are now used in the management of Kuwait's shrimp fisheries (Morgan 1984). Recently, extensive studies of recruitment in Kuwait's penaeid fisheries were started with a view to establishing an index of recruitment which can be used as a management tool in predicting the landings to be obtained. This work is not yet complete.

Most of the work conducted on Kuwait's shrimp stocks since 1978 has been presented in a series of unpublished reports. Mathews (1981b), Mohamed et al. (1981a,b), Al-Shoushani (1984), El-Musa (1984), Mathews (1984a), Mathews and Al-Hossaini (1984) have covered various aspects of Kuwait's shrimp fisheries. Work reported includes a detailed analysis of the growth and mortality estimates so far available, a description of the various segments of the fishery and of its history and the geographical extent of Kuwait's shrimp stocks. Al-Attar (1981) and Mathews (1981c) suggested that two cohorts occurred in the life cycle of *P. semisulcatus* and FAO (1982) confirmed this. Morgan and Garcia (1982) developed an indirect recruitment index, assuming the landings were 100% *P. semisulcatus*, and showed that strong fluctuations had occurred from 1965-1980, with higher recruitment in the earlier years for which data were available; changes in effort levels did not appear to influence recruitment levels. Recruitment trends were similar in both the Saudi Arabian and Kuwait fisheres even though effort trends differed. Morgan (1984) applied this knowledge of recruitment patterns to Kuwait's shrimp fishery and suggested that because more direct estimates of recruitment to the fishery were significantly higher in the spring of 1982 than they were in 1981, the 1982-83 shrimp fishery should be allowed to extend for 9 months instead of only the 6 to 7 months allowed during the previous 2 years. Mathews (1981b) and unpublished data provide evidence that recruitment to the fishery in July 1982 was higher than in any previous years for which records were available (1978-1982).

FAO (1977) drew attention to the serious fall in shrimp landings in the whole area, and suggested the imposition of a closed season so as to protect recruits to the fishery. This advice was followed by a general 5-month closed season on shrimp fishing in Kuwait, Saudi Arabia, Bahrain, Qatar, United Arab Emirates, Iraq and Iran in 1980-81 and 1981-82, although with different levels of enforcement. Mathews (1981b) drew attention to the over-exploitation of Kuwait's shrimp resource in particular by a fleet which was historically too large, and especially to the economic consequences of expending high effort levels in Kuwait's shrimp fishery. At the Third Shrimp & Finfisheries Management Workshop held 19 June 1982 (Mathews 1984b) specific recommendations for managing Kuwait's shrimp fishery included:

1. Reduction of the 5-month closed season (1 February - 30 June) to a 3-month closed season (1 April - 30 June).

2. Substitution of a fixed closed season for a flexible closed season that will be determined each year some time between July and December based on the recruitment studies carried out from March to June, i.e. during the period preceeding the opening of the fishery.

3. Recognition of the existence of two unit stocks, *Penaeus semisulcatus* and *Metapenaeus affinis*, which can be managed separately. Figure 1 shows the closed area (covering the *P. semisulcatus* stocks) and the open area (covering the *M. affinis* stocks) chosen for the 1982-83 closed season when 10 industrial boats were allowed to fish the *M. affinis* stocks as an experiment. The open area coincides with the area occupied by *M. affinis*, although Farmer and Ukawa (1980) showed that *P. semisulcatus* used to be found in a large part of it. According to more recent work, *P. semisulcatus* is now rare in this area

(Abdul-Ghaffar and Mathews 1984).

The object of this paper is to provide an assessment of the success of the new management measures, and to consider the situation created by the unexpectedly high expenditure of effort in the fishery during the last two seasons. This paper also focuses attention on the dual concepts of yield in weight or mass, i.e. "biomass yield" (expressed as Y^b/R), and economic yield, i.e. "biovalue" yield expressed as Y^e/R, (Y and R indicate yield and number of recruits, respectively, and the suffixes b and e indicate the biomass and economic aspects of yield).

Work on shrimp in Kuwait has been carried out using the biological year starting on 1 July and ending the following 30 June. The biological year is referred to as 1981/82, 1982/83 and is used here unless otherwise indicated.

Although work on recruitment is an essential component of Kuwait's shrimp fisheries management research, it is premature to provide results of this work.

CATCH(C), EFFORT(E) AND CATCH PER UNIT EFFORT (C/E)

Historical Analysis

Mathews (1981b) provided a detailed analysis of the history of this fishery. The industrial fleet was established in the late 1950's in the Shuaiba area of Kuwait, and exploited Kuwaiti and other shrimp stocks. During the early 1970's overcapitalization led to closure of some shrimp fishing companies and the establishment of a smaller industrial fleet in Kuwait. The dhow fleet was not active until 1969, when dhow boats of traditional design began to exploit Kuwait's shrimp stocks regularly. In 1980, the managers of the Shuaiba industrial fleet (consisting of two fishing companies), accepting the idea that effort levels were too high for a fleet aimed principally at the exploitation of Kuwait waters, sold many of its vessels to independent operators. A new industrial fishery became established in the Sief area; its vessels are composed of old, steel hulled, mechanized industrial vessels shed by the industrial fleet at Shuaiba. Al-Hossaini (1984) and Shalash et al. (1984) described the development of this fleet from three boats to about 25 boats in 1983.

Data on landings, E and C/E for the different elements in Kuwait's shrimp fisheries since the beginning of the data series (Table 1) show changes in landings and C/E with effort during this

Table 1. Catch, effort and catch per unit effort of whole shrimp in Kuwait's fishery 1965-1982.

YEAR	INDUSTRIAL CATCH(t) (Shuaiba)	INDUSTRIAL CATCH(t) (Seif)	DHOW CATCH(t)	TOTAL CATCH(t)	C/E (kg/d)	EFFORT (STANDARD DAYS)
1965/66	2747			2747	678	3129
1966/67	3158			3158	965	3273
1967/68	2697			2697	745	3620
1968/69	2357			2357	787	2995
1969/70	1716		56	1772	446	3973
1970/71	993		111	1104	396	2788
1971/72	1580		224	1804	530	3404
1972/73	1506		479	1985	421	4712
1973/74	664		773	1437	573	2508
1974/75	848		747	1595	430	3709
1975/76	355		657	1012	427	2370
1976/77	1125		843	1968	505	3897
1977/78	423		661	1084	326	3325
1978/79	662		740	1402	212	6613
1979/80	560		655	1215	188	6463
1980/81	1000		515	1515	470	3223
1981/82	1006	261	432	1699	192	8854
1982/83	1006	514	385	1905	219	8687

This table differs from that published in FAO (1982) because extra data for some years are included and also because of use of a more precise conversion factor from tails to whole shrimp calculated from Farmer (1980): tail weight = total weight x 0.6338.

period. These data exclude shrimp caught and discarded at sea (Zalinge et al. 1981).

Excepting the first few years of the fishery which show markedly higher catch rates, probably corresponding to the much higher recruitment observed by Morgan (1984), there is a very wide range of effort (2,500 - 9,000 days per year) over which a narrow range of catches (1,000-2,000 t/yr) occurs (Fig. 2). The result of this is that very high effort levels cause marked reductions in C/E without producing an increase in total landings. It has been suggested that the very high catch rates typical of the early years (1965-1969) were associated with a schooling phase of P. semisulcatus, since reduced by a combination of overfishing and disturbance of the environment, to a demersal phase showing much lower catch rates (Penn 1981; Mathews 1981b). FAO (1982) also suggested that strong fluctuation in recruitment had occurred during the life of the fishery because of the marked fluctuations in total catch over a rather narrow effort range (Fig. 2). Because of this possibility and Morgan's (1984) observation that recruitment was higher during these early years, data from 1965-1968 were excluded from further analysis as they may have been atypical.

A simple surplus yield model was fitted to the data from 1969-1970 onwards. It was based on the relation between C/E and total effort. The estimated yield (MSY) occurs at 6,500 d/yr. Points representing the early period of very high catches, although excluded from the analysis, are shown for comparison and are situated above the line. This suggests that either schooling (Penn 1981) or higher recruitment (Morgan and Garcia 1982) or a combination of these factors operated so that data for the early years of the series are not comparable with the data from 1969-1970 onwards. Therefore, only the later time series of data was used to generate the curve shown in Figure 3. The roughly flat right hand section of the middle curve in Figure 3 shows that nearly the same catches can be had for effort levels varying from 4,000-10,000 d/yr. It would be economically advantageous to harvest shrimp at the lower end of this range.

Hopkins et al. (1984) estimated that the cost of running a single industrial export-oriented vessel was KD 51,300 per year. Table 2 shows preliminary estimates of total expected catches, total fishing costs, total value of the catch and net profits for shrimp fishing in Kuwait. (This procedure assumes that all landings were obtained by industrial fishing units; the artisanal fishery faces a rather different structure, but it is only a small component of the overall fishery).

Figure 4 shows the results obtained from this economic analysis: while MSY occurs at 6,500 days at a level of 1,720 t/yr, maximum

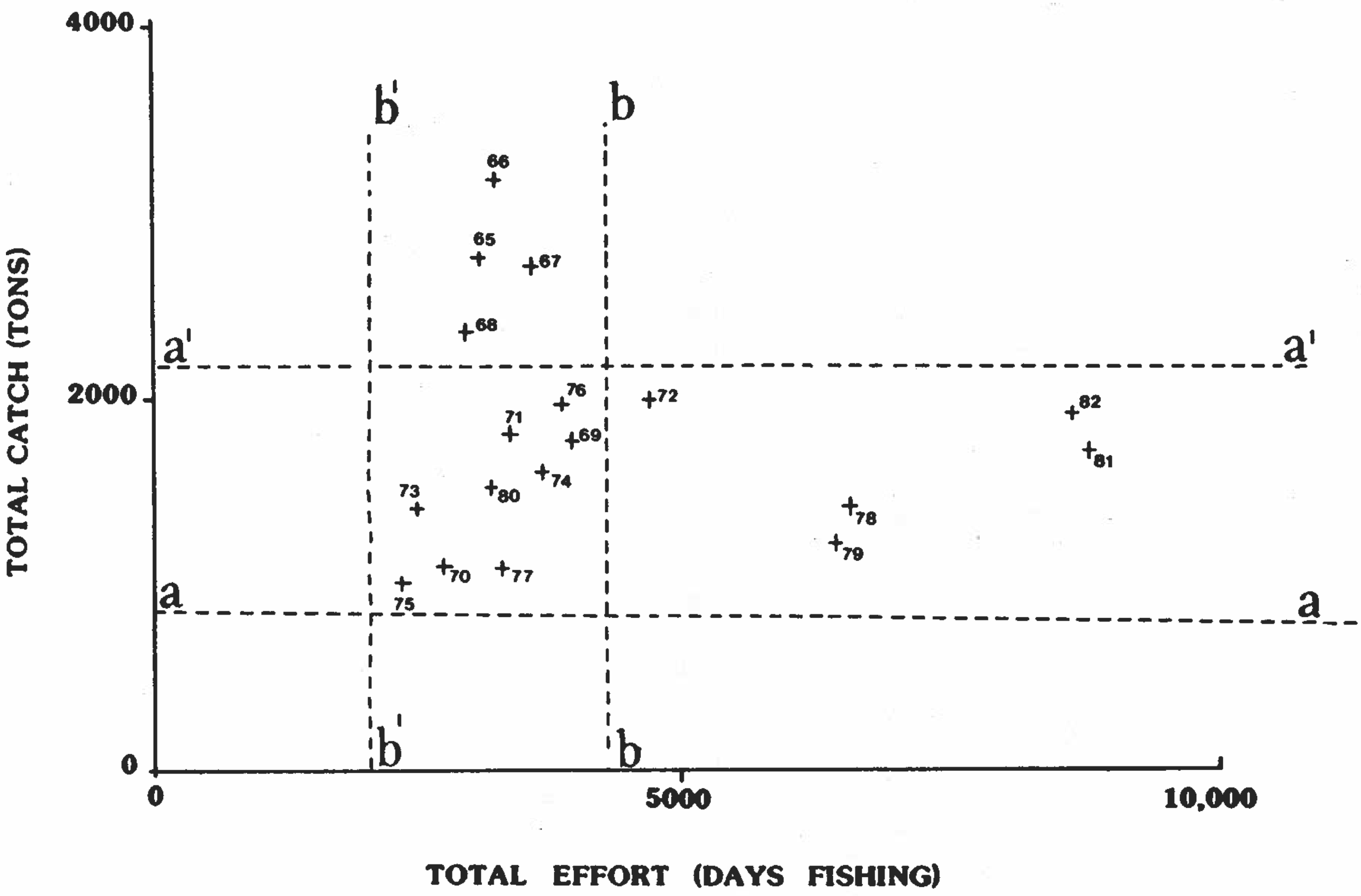

Figure 2. The relation between total catch and total effort in Kuwait's shrimp fishery. The numbers indicate the shrimp seasn starting on 1 July 1982. Lines a-a and a' - a' enclose data incuded in this study. Lines b-b and b' - b' include data consistent with changing levels of recruitment (e.g., FAO 1982). Points for 1965/66 to 1968/69 are excluded from the analysis.

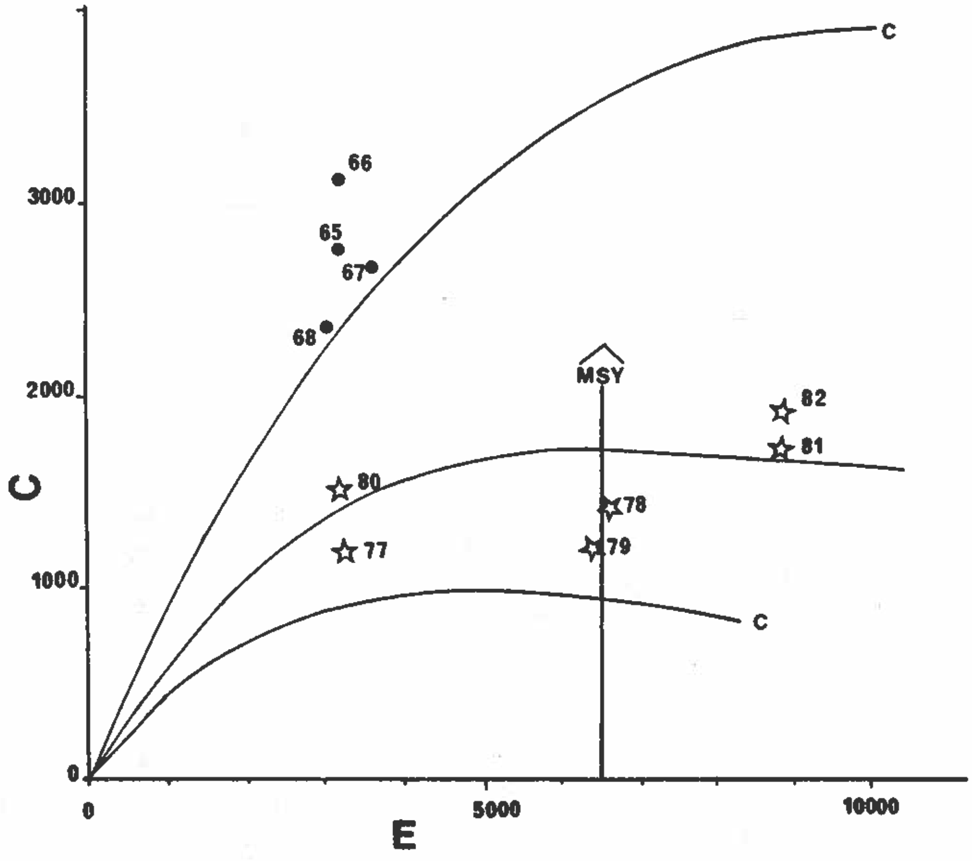

Figure 3. Surplus yield model for Kuwait's shrimp fishery.

Table 2. Estimates of total cost of fishing, total volume of landings and the net profit obtained from fishing shrimp in Kuwait.

TOTAL EFFORT thousands of days	ESTIMATED NO. OF BOATS (to the nearest boat)	TOTAL CATCH (from Fig. 3) thousands of kg	TOTAL COST OF FISHING thousands of KD*	TOTAL VALUE OF SHRIMP CATCH thousands of KD*	NET PROFIT (-10% for sales cost) thousands of KD*
0	0	0	0	0	
2	11	1,076	570	1,345	698
3	17	1,365	860	1,706	760
4	22	1,570	1,140	1,963	741
6	33	1,718	1,710	2,148	394
6.5	36	1,720	1,853	2,150	267
9	44	1,671	2,280	2,089	-210
10	55	1,524	2,850	1,905	-1,040

Assuming: Cost of running one boat = KD 51,300/yr in 1981-82 (from Hopkins et al. 1984). Total cost of fishing is based on calculation to the nearest 0.1 of a boat, rounded to the nearest KD 10,000. Whole shrimp price was 1.25 KD/kg in 1981-82 (after conversion from tails to whole shrimp; Hopkins et al. 1984). One boat fishes 180 d/yr during a nine month fishing season (Mathews 1981b).

*KD, the Kuwaiti Dinar; KD 1.000 was approximately US$ 3.43 in 1982.

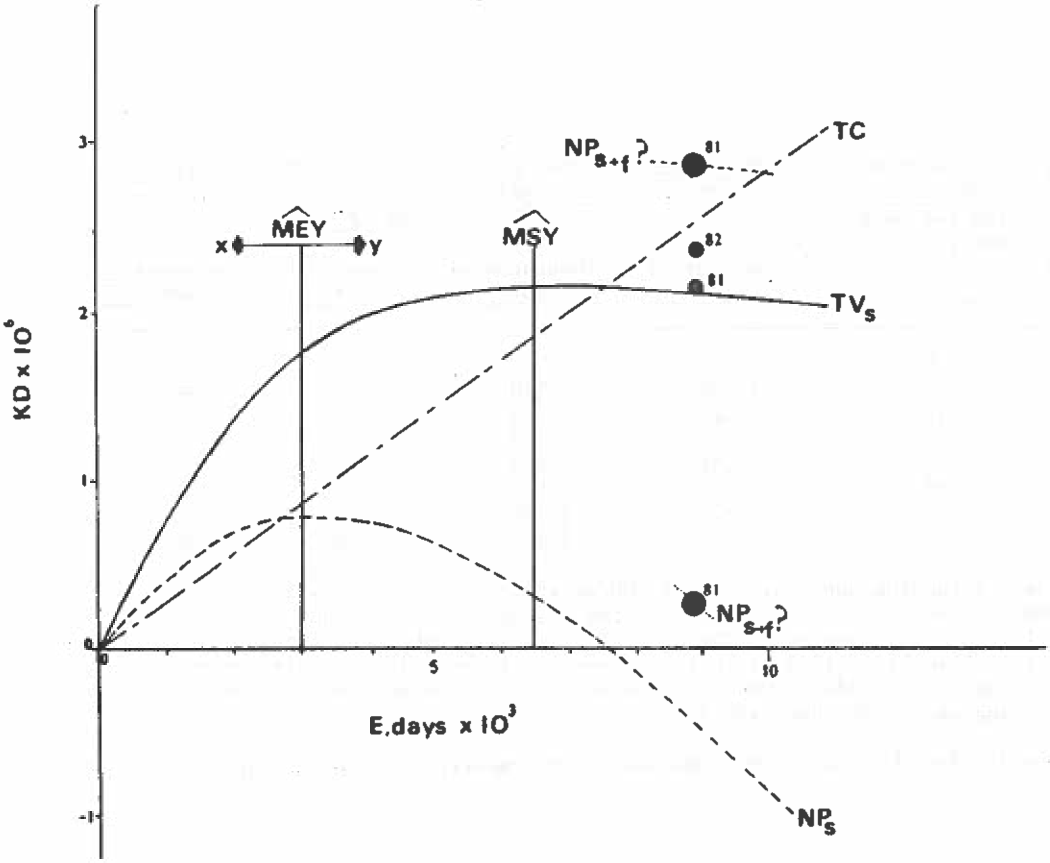

Figure 4. Relations between total value of the shrimp landed (TVs) and total cost of running the shrimp fleet (TC). The net profit (NP) is also shown. The subscripts s and s + f indicate shrimp landing or shrimp and finfish landings combined, respectively.

MSY: Maximum Sustainable Yield
MEY: Maximum Economic Yield
numbers indicate the season
X and Y: the range for which net profit is KD 700,000/year.
All economic data refer to 1982.

economic yield (MEY) occurs at 3,000 d/yr, although a profit of KD 720,000 (at 1982 prices) could be made at levels of 2,000 to 4,000 d/yr. Also, at all levels of fishing from 5,000 to 10,000 d/yr about the same total value can be landed with a total cost of fishing varying from KD 1,000,000 to KD 3,000,000. Total value and total cost are equal at 7,500 d/yr; at effort levels above this, a net economic loss will be experienced in this fishery (although the more efficient units or fleets will make a profit). If the value of the finfish bycatch is included, zero profit does not occur until 10,000 d/yr, and the significance of finfish sales for the economics of the shrimp fishery is seen to be considerable. In fact, rational management of the shrimp fishery at high effort levels may depend on prudent exploitation of trawlable finfish stocks by the shrimp fishery.

This analysis must be treated with caution as several simplifying assumptions have been made. But it is not essentially different from that presented on 17 January 1981 at the first Shrimp Fisheries Management Workshop in Kuwait when Mathews (1981b) suggested that zero profits would occur at 10,000 days effort. Since that date, the fishing effort expended has increased from 3,200 d/yr with C/E of 470 kg/d to 9,000 d/yr with C/E of 190 kg/d; i.e., a fall of 2.5 x in C/E occurred together with an increase in effort of 2.8 x; it seems that the fall in C/E was largely, if not entirely, caused by the increase in effort and that a policy of limiting effort, e.g. to a maximum of 6,500 d/yr of standard effort (if not at an even lower level), would protect the incomes of the various elements in the fishery. At the very least, it would certainly appear appropriate to prevent entry of more vessels in the fishery than actually fished in 1982-1983.

This surplus production analysis is based on the assumption that the general recruitment level does not vary very much. Morgan and Garcia (1982), however, showed that recruitment levels have varied very considerably in the past, although their data also show that variations from 1969-1970 onwards have been relatively smaller than they were prior to this date. They found that parallel trends in the recruitment index for the Saudi Arabian and Kuwaiti shrimp fisheries occurred in spite of the different data bases used and the different effort trends which occurred in the Kuwaiti and Saudi Arabian fisheries. It is not yet known what changes in recruitment levels are related to; it is therefore possible that significant increases (or decreases) in recruitment may occur in Kuwait in the future, which could cause corresponding increases (or decreases) in landings. Such changes could be viewed as shifting the position of the surplus yield curve shown in Figure 3 so that it rises to higher (or falls to lower) levels in some years than in others. Figure 3 also shows two possible surplus yield curves that might represent the surplus yield function at higher or lower levels of recruitment or at different levels of carrying capacity due, for instance, to environmental changes, e.g. landfill or long-term trends (Mathews 1981b; Doi 1981). Mathews (1981b) also suggested a bimodal surplus yield curve with a high mode at low effort levels based on a fishery targeted toward schooling shrimp and a lower mode at a higher level of effort based on fishing demersal shrimp. This would be consistent with the exclusion of data from 1966-1969 if heavy schooling of shrimp occurred in the early years of the fishery in Kuwait (Penn 1981), and now no longer occurs (Hamdan and Mathews 1981a; Mathews 1981a).

A full analysis of the importance of recruitment in Kuwait's shrimp fishery lies outside the scope of this paper. Nevertheless, management of Kuwait's shrimp fishery poses two interesting problems. On the one hand, the high level of effort and the low CE during the last decade suggest that a reduction of effort could produce significant economic gains to the fishery. On the other hand, the occurrence of some years in which very much larger harvests are possible than in others suggests that the possibility of maintaining a capability for making high landings should be considered even at the cost of low catch rates in some years. The biological basis for Kuwait's shrimp fishery therefore tends to lead toward two opposite strategies, and the successful management of Kuwait's fisheries depends on the satisfactory resolution of these two pressures. Historically, serious economic losses and disruption to the fisheries sector have occurred in spite of any benefits which may have accrued from occassional high landings caused by high recruitment in some years. Control of harvesting capacity is therefore more important than retention of a residual capacity to harvest these occasional high levels of shrimp.

The 1982-1983 Fishery

Table 3 summarizes data on Kuwait's 1982-1983 shrimp fishery, including its various segments, and compares them with the relevant data for 1981-1982. There was a small increase in C/E from 1981-1982 to 1982-1983 (192 to 219 kg/d). Because different fishing areas, fishing gear and fleets are involved, it seems unlikely that this change could have been caused by the increased efficiency of the fishing gear or of the fleet's operations; and it seems probable that C/E increased from biological causes. Morgan (1984) suggested that increased recruitment in May and June of 1982 should lead to higher landings, and this may have occurred. The closed season in 1981-1982 prevented fishing of the P. semisulcatus stock during February and March 1982. The shorter closed season in 1982-1983 allowed fishing in February and March of 1983, and during this period 265 t of shrimp were landed. The overall effort expended during the 7-month season of 1981-1982 and the 9-month season of 1982-1983,

Table 3. Catch (C), effort (E) and catch per unit (C/E) in Kuwait's shrimp fisheries.

	1982/83 TOTAL C (t)	1982/83 TOTAL E (d)	1982/83 C/E (kg/d)	1981/82 TOTAL C (t)	1981/82 TOTAL E (d)	1981/82 C/E (kg/d)
Seif Industrial	514.3	1,878.0	273.9	261.3	1,187	220.1
Shuaiba Industrial	1,000.8	4,586.2	219.3	1,005.7	5,242	192.0
Artisanal	385.0*	43,845.9*	8.78*	432.0*	50,360*	8.58*
Artisanal (using standard units)	385.0	1,756.0	219.3	432.0	2,250.2	192.0
Open Season Fishing Total	1,905.0	8,686.0	219.3	1,699.0	8,854	191.97

For the industrial fishery at Seif, one day's fishing is assumed to equal 14.9 h fishing (Al-Hossaini 1984); weight of whole shrimp x 0.6338 = weight of headless shrimp.

*Based on effort estimated in hours fishing.

however, was the same (8,500-9,000 days); so it is probable that in spite of the change in duration of the season, the increase in C/E was caused by a modest increase in recruitment.

The Fishery Directed at M. affinis During the Closed Season

Abdul-Ghaffar and Mathews (1984) provided the basic data for assessing the experimental fishery on M. affinis during the closed season. Catch rates in the fishery varied from 440-205 kg per day from March to June 1983. Even the lowest value compares favorably with the mean catch rates obtained during the open season (Table 1: 190-220 kg/d from 1981-1983) whereas the higher values of C/E achieved (440 kg/d) were comparable to mean values obtained from 1974-1978 during the open season fishery at effort levels of about one-third of those observed from 1980-1982 (Table 1).

One objective of the fishery directed towards M. affinis was to increase the harvest of the industrial boats without damaging the P. semisulcatus stock. A second objective was to allow harvesting of M. affinis without damaging this stock. The relatively high C/E recorded in the M. affinis fishery suggests that the number of boats fishing the M. affinis stock, arbitrarily limited to 10 during the closed season, was held to a rather low number. This number was chosen on the basis of the area available for fishing and an estimate of the swept area the fleet could apply to this area. No data were available for application of any surplus yield model to the M. affinis stock, separately from the P. semisulcatus stock. Until a separate surplus yield model can be fitted for the M. affinis stock, it will not be possible to determine the optimum catch and effort levels it can sustain, but is seems likely that effort expended on the M. affinis stock can be substantially increased. An extension of the experimental fishery directed on M. affinis during the closed season is suggested for 1983-1984, with a substantial increase in the number of boats being allowed to fish (Abdul-Ghaffar and Mathews 1984). Data obtained in the future may make it possible to determine more adequately the best management policy to be applied to this stock. Biological studies need to be continued because C/E is influenced by many factors other than effort expended. It is, however, clear that a substantial fishery can be maintained by the M. affinis stock during the closed season for P. semisulcatus.

The fishery directed towards M. affinis during the closed season was established with the objective of harvesting the M. affinis available from the spring recruiting cohort (Mathews 1984a). These shrimp were being lost to the fishery under the previous management regime (complete closure of shrimp fishing during the closed season). Out of a total of 251 t landed by the fishery based on the M. affinis stock, only 12 t, i.e. 4.8%, was P. semisulcatus. It is clear that the objective of the experimental fishery (to allow harvesting of *M. affinis* and, to a lesser extent, of *Parapenaeopsis stylifera* while providing protection for *Penaeus semisulcatus*) was achieved.

Timing of the Closed Season

Peak catch in numbers of *Penaeus semisulcatus* fished per hour in the dhow fishery occurs in Kuwait Bay in June or July and peak C/E in kg/h occurs in July or sometimes August (Mathews 1981b; Mathews et al. 1982) in the dhow fishery. Recruitment of *P. semisulcatus* does not start until May in females and June in males for the industrial fishery. This was also true for both the dhow and the industrial fisheres from 1978 to 1980 (Al-Houssaini 1981). During this period there was no closed season and data are available from May and June for both fisheries.

Since recruitment of *P. semisulcatus* to the fishery does not start until May, the closed season could possibly be reduced by one more month, e.g. a 2-month closed season from May to June. If the sole objective of the closed season is to protect pre-recruits, a 2-month closed season would be adequate. Other effects of a 2-month closed season would be to increase total effort and to expose large spawning shrimp to the fishery. These factors should be taken into account when devising a management strategy.

Size at Entry into the Fishery

The size of small, early juvenile shrimp at entry to the fishery is regulated; until the autumn of 1983, a smaller mesh size (30 mm stretched mesh) was allowed for the artisanal fishery than for the industrial fishery (40 mm stretched mesh). These sizes were chosen arbitrarily, however, and Mathews (1981d,e) showed how the introduction of mesh size regulations into a fishery without scientific justification may be counterproductive. Al-Hossaini et al. (1984) summarized the results of selectivity studies conducted over 3 years and concluded that the 50% selection point and the selection range are not clearly related to mesh size, perhaps because of the large amount of bycatch and rubbish caught during shrimp trawling. This suggests that mesh size regulations may not be very effective.

However, Zalinge et al. (1981b) reported that discards of small *P. semisulcatus* and other species in the dhow fishery varied from 18 to 65% of the total numbers caught (Fig. 5). The discarding practices of the dhow fleet result in the loss of large numbers of small *P. semisulcatus* which would have grown to much larger sizes. There is no detailed study of the discarding practices of the industrial boats, but they are known to land *P. semisulcatus* even in

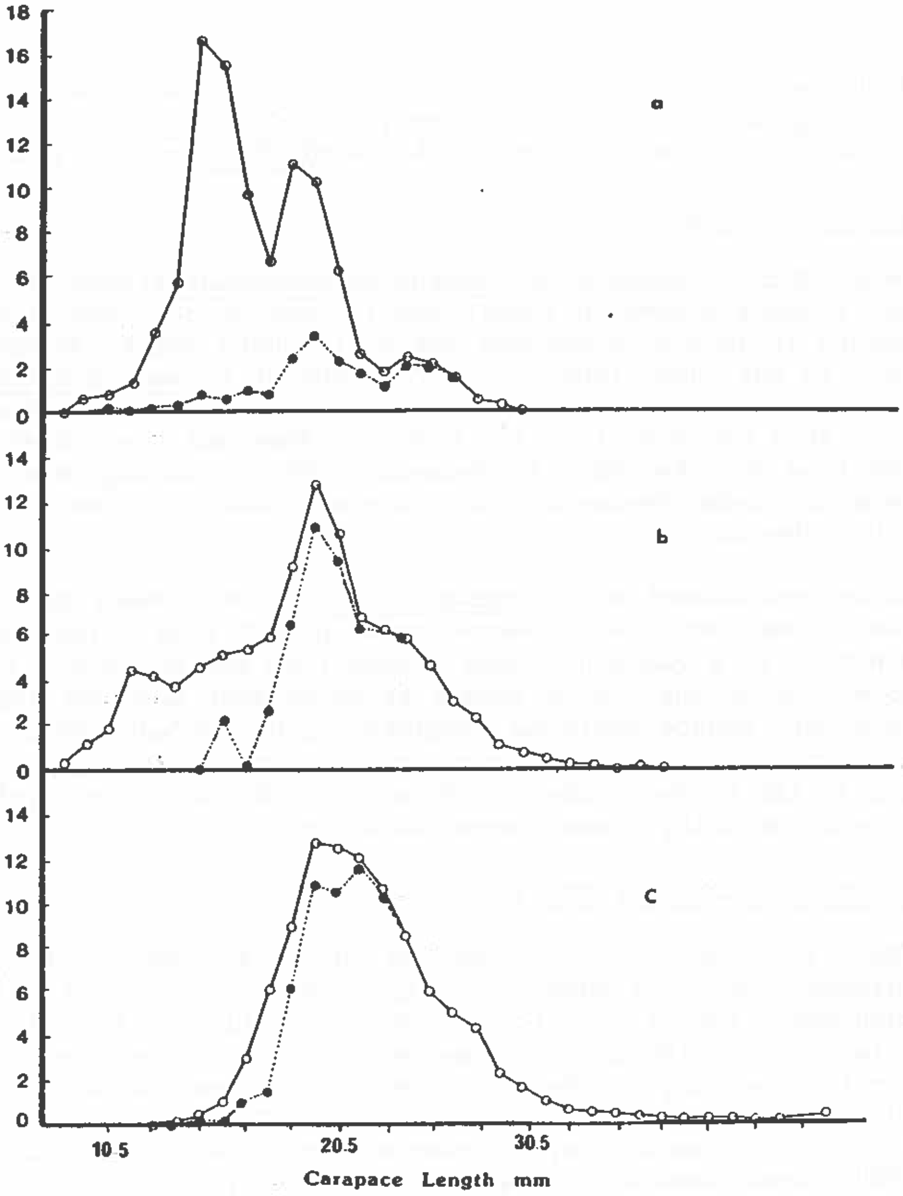

Figure 5. Discards from the artisanal fishery:
a: Parapenaeopsis stylifera
b: Metapenaeus affinis
c: Penaeus simisulcatus
○———○: caught
●———●: landed (where different from the shrimp caught) after Van Zalinge et al. 1981.

the 110+ tails/lb size categories, and it is believed that virtually all *M. affinis* and *P. semisulcatus* harvested are landed.

The dhow and industrial fleets tend to fish in different areas with the dhow boats fishing in shallow waters, nearer inshore, especially in Kuwait Bay (Fig. 1). Because the smaller shrimp which occur inshore on the dhow fishing grounds migrate further offshore where they become accessible to industrial fishing (Mohammed 1981a, Al-Shoushani 1984; Shalash et al. 1984), there may be good reason to require industrial and dhow boats to use nets of the same mesh, i.e. at least 40 mm stretched mesh. Discarded shrimp die before they are returned to the water, so the significant numbers of shrimp are likely to be available for harvesting later in the year, at a larger size, if the number of discards in the artisanal fishery can be reduced. A regulation requiring a minimum mesh size of 40 mm stretched mesh was recently established for all trawlers operating in Kuwait waters.

Extent of the Closed Area

The boundaries of the closed area were chosen to coincide with the area of distribution of *P. semisulcatus* as it is now known to be. The precise boundary of the closed area chosen for Kuwait Bay was a straight line joining Ras-Al-Ard to Ras Sabiyah. Hamdan and Mathews (1981b) show the precise distribution of *M. affinis* and *P. semisulcatus* in Kuwait Bay; a substantial portion of the best fishing ground for *M. affinis* is excluded. It is suggested that a more appropriate boundary to the closed area would be a straight line joining Ras Al-Ajuzza to Ras Salmiyah. This would allow fishing more of the *M. affinis* stock without allowing significant fishing of *P. semisulcatus*.

MORTALITY ESTIMATES AND APPLICATION OF A DYNAMIC POOL MODEL

Mathews and Al-Hossaini (1984) reviewed all previous estimates of mortality and growth so far available for Kuwaiti penaeids. For *P. semisulcatus*, they suggested that estimates of the instantaneous rate of total mortality (Z), based on length related catch curves, were probably the most useful; estimates of Z based on the technique of Jones and Van Zalinge (1981) were biased because several of the basic assumptions of the technique were violated. Mathews and Al-Hossaini (1984) obtained estimates of M, the instantaneous rate of natural mortality, using Pauly's (1982) technique, but found that it gave unrealistically high values. The estimates they provided were $Z = 5.0$, F (the instantaneous rate of fishing mortality) $= 3.0$, $Z-F = M \sim 2.0$. The estimated exploitation rate is therefore 60%.

Mathews and Al-Hossaini (1984) decided that the growth estimates of El-Musa (1984), based on modal progression analysis, were sufficiently reliable for stock assessment purposes. Using values of L and K (the von Bertalanfly growth parameters) obtained for *P. semisulcatus* males and females separately from 1978-1982, they estimated that values of L_∞ and K were 46.3 mm carapace length (CL) and 1.5 (on a yearly basis), respectively. These estimates were based on the mean values of L_∞ and K for male and female *P. semisulcatus* taken over the five full cycles for which data are available.

Using these estimates, it is possible to construct a yield surface (Fig. 6) for the *P. semisulcatus* stock. The yield surface shows that for values of $\overline{F} > 3.0$, biomass yield per recruit (Y_b/R) increased to values of $l_c = 30$ mm CL; Y_b/R declines slowly as l_c increases from 30-35 mm CL and very sharply as l_c increases from 35 mm to 40 mm CL (this last feature is not shown in Fig. 6). For values of $F \sim 2$, Y_b/R reaches a maximum at $l_c \sim 25$ mm and at values of $F < 1.5$ it reaches a maximum at $l_c \sim 15$ mm. The present value of $l_c \sim 18$ mm would be applicable only at very substantially lower effort levels ($F = 0.5$-1.5) than are presently in effect ($F = 3.0$). Presently, the open season on Kuwait's fishery starts on 1 July of each year. The modal size of shrimp landed in July has varied over the last 6 years from 41-50 tails/lb to 21-25 tails/lb. Figure 6 provides evidence that a size of 26-30 tails/lb, corresponding to 30 mm CL, would be the most appropriate for Kuwait's fishery. Table 1 shows that over the last few years there has been a trend for total effort to increase. Therefore, at all likely levels of F (3.0 and above), Y_b/R will be increased by increasing the size at entry to the fishery.

Work is presently underway on recruitment of *Penaeus semisulcatus* in Kuwait, and one possible application of this work and of the results of yield per recruit analysis might be a variable opening date for the fishery instead of a fixed date, with the timing chosen so as to capture shrimp at a larger entry than has occurred in some years.

The present position of the fishery in 1982-1983 is shown in Figure 6 (at A). An increase in F from 3.0 to 6.0 (change from A to O, Fig. 6) would lead to a small decrease in Y_b/R from 16.4 g/R to 14.5 g/R, i.e. by $\sim$ 12%. A decrease from $F \sim 3.0$ to $F \sim 1.0$ (a change from A to O') would lead to a change in Y_b/R from 16.4 to 12.5, i.e. to a decrease of 24%. However, $(Y_b/R) \div F$ would change from 5.47 at A to 12.5 at O; i.e. the catch rate would increase by 229% (x 2.29) if fishing mortality was decreased by about two thirds, while if F was increased from 3.0 to 6.0 (a change from A to O in Fig. 6), $(Y_b/R \div F)$ would change from 5.47 to 2.42, i.e. the catch

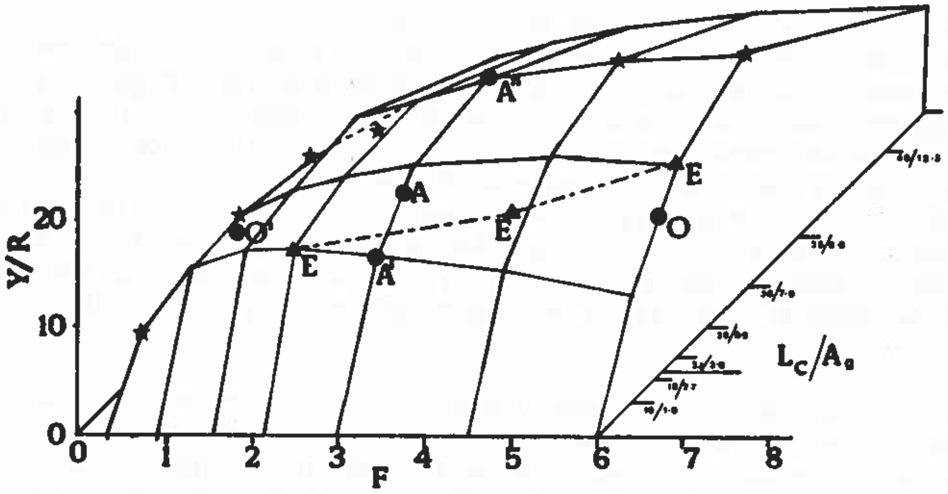

Figure 6. Yield surface for <u>Penaeus</u> <u>semisulcatus</u>.

Y_b/R: Yield per recruit (i.e. yield in biomass)
F: Fishing Mortality
l_c: Length at entry to the fishery in carapace length (mm)
A_g: Age in months; 30/7.0 indicates 30 mm CL and 7.0 months old
O: Y/R at present size at entry but higher effort
O': Y/R at present size at entry and lower effort
A: Y/R at present effort and size at entry
A': Y/R at present effort and lower size at entry
A": Yield per recruit at present effort and higher size at entry
E: Points on the eumetric curve, i.e. points at which Y/R is a maximum for the effort level shown
★: Points at which Y/R is ghighest for a particular effort level (The point shown at A" is also one of these points)

rates would be decreased to 44% (x .44) of their present level. The position of $F \sim 2.0$, not shown in Figure 6, shows that the value of Y_b/R would be very similar to that at A (15.4 g/R instead of 16.4 g/R).

Figure 6 shows the effects of increases or decreases in F obtained from dynamic pool analysis. These are in close agreement with the results obtained from surplus yield modeling (Figs. 3 and 4) which suggest that optimization of net profit occurs at 3,000 days, i.e. at an amount one-third of the current effort level of 9,000 d/yr, and that a reduction in effort by one third (i.e. to 6,000 d/yr) would result in no significant decrease in total shrimp catch. The two models using entirely separate data bases, assumptions and methodologies have produced essentially similar conclusions about the relation between effort, yield and landings and catch per unit effort.

Only the changes in biomass yield per recruit Y_b/R have been discussed. Changes in the economic value of the yield per recruit (Y_e/R) with increase in 1_c would be much greater because of the increase of price per unit weight with the increase in size. Work on the construction of yield surfaces in terms of the economic value of the yield is presently underway. Surplus yield modeling does not provide for changes in the value of the landings with changes in the size of shrimp landed as does the yield per recruit provide a very satisfactory solution to this problem. Work on a model which includes fluctuations in mean value of landings as a function of the size mix of the shrimp landed and of the seasonal price fluctuations is underway in Kuwait.

This application of the yield per recruit model to the fishery is based upon the assumption of a steady state equilibrium in the population. Attention has already been drawn to the fact that major changes in recruitment have probably occurred in the past; Mathews (1981a) also noted the assumption of constant values for the various mortality and growth parameters is not necessarily true, especially if major changes in effort (and presumably in fishing mortality) occur over a period of several years. Work is continuing on possible effects of changes in recruitment, long-term changes in the environment associated with such changes, and of the effects of possible changes in Z, F and M on landings and yield per recruit in Kuwait's shrimp fisheries.

CONCLUSIONS

1. Two entirely independent analyses, using independent data bases, were applied to Kuwait's shrimp stocks. Both surplus yield analysis, based on C, E and C/E data, and dynamic pool analysis, based on growth and mortality rates, showed that Kuwait's shrimp fishery is presently subjected to effort levels that are unnecessarily high, both in terms of catch rates and the economic value of the catch rates achieved. A significant reduction in effort could be carried out without significantly reducing landings.

2. Significant reductions in the cost of fishing, accompanied by significant increases in net profit, could be obtained by reducing the amount of effort expended. A simple economic yield model showed that MEY occurs at much lower effort levels (∿3,000 days) than MSY (∿6,500 days).

3. Profitability of Kuwait's shrimp fishery depends on prudent exploitation of the bycatch.

4. The dynamic pool analyses suggested that significant increases in biomass yield per recruit and in economic yield per recruit could be brought about by increasing the size at entry, 1 , to the fishery.

5. Continuation of the experimental two stock management policy is justified. The *P. semisulcatus* stock is protected during the closed season. An increase in effort on the *M. affinis* stock during the closed season on the *P. semisulcatus* fishery would probably result in increased landings from the *M. affinis* stock.

6. 516 t of shrimp were landed from 1 February to 30 June 1983; these landings would not have been made had the reduced closed season and the two stock management policy (including the experimental fishery directed at *M. affinis* during the closed season for *P. semisulcatus*) not been implemented. The value of these landings was KD 645,000 (i.e. US $2,200,000), an amount substantially larger than the total investment in shrimp fisheries research in Kuwait from 1977 to 1984 (KD 450,000, i.e. US $1,500,000).

7. Recruitment studies, not yet sufficiently advanced to be included in this review, are also an essential part of Kuwait's shrimp fisheries management work.

8. Shrimp restocking work was suspended pending a more detailed knowledge of the recruitment process and may be undertaken once again in the future if a more detailed knowledge of the life cycle and/or recruitment ever justifies such a step. Further work on restocking would require socio-economic as well as biological justification.

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