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ESTUARINE MANAGEMENT - THE INTEGRATED PICTURE

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ABSTRACT

The management of Gulf coast estuaries is becoming more important every day because of "sunbelt" population growth and corresponding increased conflict between user needs and ecosystem health. There is a developing awareness among both estuarine scientists and environmental managers that these ecosystems do not necessarily function as dictated by historical dogma. Consequently, a definite need exists to generate estuarine management strategies that focus upon integration of the complex interactions between biological, physical, chemical, and geological processes within estuarine systems. This integrative approach, creating a holistic picture of ecosystem function, is the basis for developing predictive models that will improve management decision-making concerning the best uses and survival of estuaries as productive and valuable resources.

The combination of historical data on flora anf fauna standing stocks and recently collected data on interactive processes for south Texas estuaries has provided an understanding of how components of these estuaries interact and demonstrated the utility of integrative strategies to provide useable management tools. These efforts have shown that by taking a holistic approach to understand ecosystem function sound environmental management can be performed that balances ecosystem preservation with societal needs. The intent of this presentation was to demonstrate how the application of these strategies can be used to aid environmental decision-makers in better solving such problems as fishery maintenance, freshwater inflow regulation to estuaries, and navigation dredging. The strategies included identifying relationships between underlying forces that drive the estuarine systems and incorporating this information into a composite scheme of estuarine management. The ultimate goal is to use the research from these various studies to provide a rallying point for all regulating agencies faced with estuarine management responsibilities to focus upon.

1. INTRODUCTION

Decision-makers that are concerned with maintaining the quality of our environment while also allowing for reasonable economic growth to occur usually focus upon a specific problem related to habitat disturbance when environmental alteration is the expected result of man's increased utilization of that habitat. Examples of specific problems focused upon might include changes in population numbers of an endangered species, increases in nutrient concentrations in an aquatic ecosystem, changes in the structure of a major community in the habitat (e.g., species number, abundance, biomass), or decreased production in a population providing an important food resource to man.

Problems related to environmental alteration are usually detected by research programs based on after-the-fact or present condition analysis of the system that provides an empirical data base where quantities are measured, species are identified, organisms are weighed and abundances recorded. Other than obvious direct effects to the biologic or habitat factors monitored, however, conclusions can not usually be drawn from these approaches concerning the composite of effects to an entire ecosystem caused by environmental alteration. If change in the structure of a community is detected through monitoring we can not automatically conclude that the role this community plays in ecosystem function has also changed. In many cases it has not [1,2]. If monitoring suggests that a fishery stocking program has increased the yield of the fishery we can not absolutely assume that the productivity of that aquatic habitat has increased. Often the productivity of the stocked fishery will increase at the expense of some other population in the habitat that either utilizes the same food source as the fishery population, or serves as a food source for the fishery population, thus upsetting the overall balance of the ecosystem [3]. If appropriate baseline studies have been conducted and biotic change is detected, one sees the end result and may determine that the biotic change is linked to environmental alteration. But the mechanism(s) that caused the change remains obscure.

Although monitoring programs are necessary to achieve some management objectives, it is clear that successful environmental management requires much more information than can be provided by the typical monitoring program designed to detect change in environmental factors and plant/animal abundances, as also discussed elsewhere [4]. The incorporation of an ecosystem approach into strategies used to strike a fine balance between preservation of natural resources from degradation while also allowing continued economic growth and development is essential to detect the mechanisms involved and to predict ecosystem alteration from long-term subtle impacts. Taking an ecosystem perspective in management decisions makes control of all components of the environment more feasible and also protects not only the species most directly important to man but also those species at lower trophic levels often forgotten about in the resource yields but without which these yields would not exist.

Good management of Gulf of Mexico estuarine ecosystems is becoming more important every day because of "sunbelt" population growth [5] and corresponding increased conflict between user needs and ecosystem health. There is a developing awareness among both estuarine scientists and environmental managers that these coastal ecosystems do not necessarily function as dictated by historical dogma. It is essential therefore, to generate estuarine management strategies that focus upon integration of the many complex interactions in these systems. Creating a holistic picture of ecosystem function is the basis for developing predictive abilities that will improve the process of determining the best uses and survival of these estuaries as productive and valuable resources.

2. OBJECTIVE OF RESEARCH

Estuaries are typically thought of as highly productive aquatic habitats that sustain important fisheries [6]. In the Texas coastal region of the Gulf of Mexico for example, more than 90% of the commercial and 50% of the recreational fishery yields are comprised of species which spend much of their early lives in estuaries prior to recruitment into the fishery. The Texas coast is also a good example of an area where industrial growth is increasing daily. Characteristics associated with this development are often viewed as incompatible with the maintenance of these coastal areas as natural, productive systems.

Estuaries are also characterized as highly variable environments of varying scales. In order to comprehensively manage these complex ecosystems therefore, detailed knowledge on the dynamics of underlying forces that drive these systems must be developed and an understanding of how the various physical, chemical, and biological components link together into a holistic framework of long-term function must be obtained. By concentrating on key processes in these coastal eocsystems such as nutrient sources, primary and secondary production rates, metabolism, and population dynamics, a comprehensive picture of long-term function can be constructed since all these processes are important to the integrated health of these estuaries.

Using a south Texas estuary as an example, the purpose of this paper was to demonstrate how one can (1) identify environmental characteristics that affect estuarine productivity, (2) isolate specific processes that lead to a holistic perception of ecosystem function, and (3) develop conceptual ecosystem models which can serve as a basic tool in decision-making activities concerning management of the estuarine environment. A long-term data set on this estuary was reconstructed by combining recent ecosystem process measurements with extensive community structure observations, fishery statistics and scattered historical data. This multidisciplinary view of estuarine ecology was contrasted with the climatological record to identify physical forcing characteristics of the estuary. Evaluations of the data set were made to define patterns and mechanisms that explained ecosystem function. The result of these exercises was the demonstration of integrative data evaluation to present conceptual schemes of ecosystem dynamics that could improve the environmental managers decision-making process.

3. METHODS

All measurements discussed in this paper were made in the Corpus Christi Bay estuary, located in the northwestern Gulf of Mexico. This estuary is one of seven major estuaries along the Texas coast and lies in a region characterized by a semi-arid climate. For a more complete description of the Corpus Christi Bay estuary and the study sites from which information was collected for this presentation see recently described studies [7,8]. The development of a long-term data set for this estuary has incorporated all known information on the ecosystem. Included in this data set are hydrography information, climatological records, fluvial flows, water quality and nutrients, nutrient recycling rates, primary production rates (e.g., phytoplankton, seagrasses, saltmarshes, tidal flats), benthic community structure and production rates, and fishery yields.

Benthic macroinfauna distribution data were taken from previous studies on the estuary [8,9] and more recent collections made through October 1983. Methods of collection, which have remained unchanged for 11 years, included replicate benthic samples on a least a quarterly basis using a 0.09 m^2 Peterson grab. Each grab sample was sieved through 0.5 mm mesh screen and the retained organisms identified to lowest possible taxa and counted. Wet-weight biomass was measured on dominant populations and on each total sample. Hydrologic characteristics, measured simultaneously with the collection of benthic samples, included salinity, temperature, dissolved oxygen, and pH (Hydrolab Surveyor 6).

Primary production rates and benthic processes, including metabolism and nutrient regeneration, were measured in the Corpus Christi Bay estuary between 1981-83. Phytoplankton primary productivity was measured by the ^{14}C method [10]. Quarterly in situ 0.5 and 1.0 m depth incubations were conducted for three years at seven sites that together characterized total estuarine production. Simultaneous measures of water column ammonia-nitrogen were made and analyzed according to phenol-hypochlorite methods [11]. An opaque sediment chamber with circulating water pump was used for incubation of sediments in situ to measure benthic metabolism and sediment nutrient regeneration rates [12]. The chambers were placed by SCUBA divers and incubation occurred for a minimum of 3 hr. Changes in oxygen content of the incubated waters were used to calculate metabolism rates and changes in ammonia-nitrogen concentrations were used to calculate sediment flux rates of nitrogen [13]. Benthic community carbon production was estimated from the metabolism measurements using relationships established previously [14].

Other sources of data used here included gauged freshwater inflow and riverine nitrogen input from the Texas Department of Water Resources [15]. Climatological data were obtained from the NOAA, National Environmental Satellite Data and Information Service. Other data on carbon sources besides phytoplankton production to the estuary were obtained from previous studies on this estuary [16,17]. Fishery catch statistics between 1970 and 1982 were obtained from NOAA (G. Kinkle, National Marine Fisheries Service, Miami, Florida, personal communication). Catch per unit effort adjustments were made to the shrimp data to remove biases in the catch statistics related to difference in effort between years.

4. RESULTS AND DISCUSSION

The Corpus Christi Bay estuary is located in a semi-arid climate where evaporation usually exceeds rainfall, often resulting in extended periods where extuarine salinities equal or exceed oceanic waters (hypersalinity). In addition, the mean tidal range in this region of the northwestern Gulf of Mexico is extremely small relative to estuarine volume and many tidal cycles must occur before the estuary is flushed [18]. Consequently, this estuarine ecosystem is extremely sensitive to climatological changes that cause episodic surges of freshwater input, and the estuary often responds rapidly to such events.

4.1. Estuarine Forcing

Presented in Figure 1 are seven years of hydrologic data on the Corpus Christi Bay estuary. These data illustrated the episodic nature of freshwater input events to the estuary from fluvial flow and/or rainfall. There were no predictable patterns observed in the record with the exception that some years were significantly drier than others. The salinity record (Figure 1) supported the contention stated above that this estuary responded rapidly to large freshwater input. For example, excessive rainfall over a 24-hr interval in September 1979 resulted in 35 cm of rain, the second highest monthly measure in the record (Figure 1). The high intensity and short duration of this rainfall resulted in the lowest recorded salinities in the estuary over the seven-year record, all of which occurred with no increased riverine input.

In contrast, May-June 1981 was characterized by the greatest fluvial input recorded over the 7-yr record (Figure 1) and also exhibited above average rainfall (42% of the annual average). These climatological and hydrological changes again resulted in a significant decrease ($P < 0.01$) in estuarine salinities soon after the changes. The lowered salinities, indicating the ecosystem's response to the environmental changes, lasted for extended intervals after both periods described above, which suggested the magnitude of impact on the ecosystem from these episodic events.

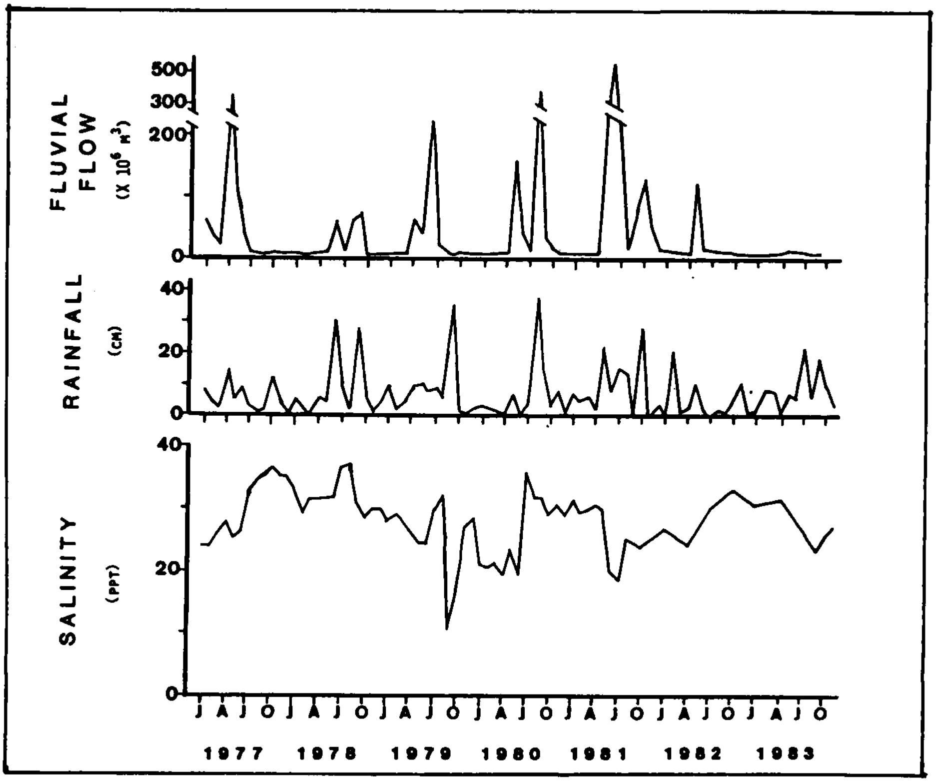

Figure 1. Plots of hydrologic and meteorologic variables measured during the Corpus Christi Bay estuary study, 1977-83.

The main fluvial flow into the Corpus Christi Bay estuary is from the Nueces River, which averaged 7.8 X 10^8 m^3/yr of freshwater input. Net freshwater input on an annual basis, which included the fluvial flow and accounted also for rainfall and evaporation rates, was calculated to be approximately 5.1 X 10^8 m^3/yr [17]. Measured riverine nutrient concentrations [15] indicated that fluvial flow to the estuary could provide an annual mean of 5.46 X 10^5 kg/yr on nitrogen to the estuary [17].

Nutrient regeneration rates measured for the estuarine sediments were observed to provide an annual mean of 23.9 g N/m^2/yr. These measurements, when compared to new nitrogen supplied from the riverine source to the estuary (Table 1), were always significantly greater and indicated that the estuarine sediments were a much more reliable source of nitrogen to the system than the river. The areal estimate for estuarine sediments providing recycled nitrogen to the Corpus Christi Bay estuary was 1.04 X 10^7 kg/yr. As indicated above, fluvial sources of new nitrogen could only provide 5% of the estimated nitrogen recycled by the sediments. Therefore, over the short-term estuarine nutrient concentrations appeared to be maintained by recycling mechanisms rather than inputs of new material.

Table 1. Comparison of nitrogen sources to the Corpus Christi Bay estuary between sediment recycling and fluvial flow. Nutrient recycling is based upon three sampling sites and expanded over 432.9 km^2 surface area. Riverine nitrogen is represented by maximum mean values over a five-year study period.

	January	April	July	October
Nueces River Total Inorganic Nitrogen Input (10^4 kg/day)	0.090	0.069	0.139	0.436
Estuarine Sediment Ammonia-Nitrogen Regeneration (10^4 kg/day)	1.119	3.852	4.280	0.994
Percent River Contribution, Contrasted to both Sources Combined	7.4	1.7	3.2	30.5

Table 2. Multivariate regression analysis results of the dependent variable water column ammonia-nitrogen compared with other measured independent variables that potentially served as a source of ammonia-nitrogen to the water column. Number of sampling cases was 16 over a three-year period of measurement in the Corpus Christi Bay estuary.

Independent Variable	Multiple Correlation Coefficient	R^2	Simple Correlation Coefficient	Significance
		UPPER-ESTUARY (Station 2)		
Riverine Flow	0.6403	0.4103	0.6403	0.034
Wind Speed	0.8907	0.7933	0.4015	0.002
Rainfall	0.9135	0.8345	0.5228	0.004
		MID-ESTUARY (Station 7)		
Sediment Regeneration	0.7290	0.5314	0.7290	0.011
Wind Speed	0.8338	0.6952	0.3563	0.009
Riverine Flow	0.8545	0.7302	0.1252	0.021

Evidence further supporting this conclusion comes from comparison of changes in water column nutrient concentrations with changes in fluvial flow rates and sediment nutrient regeneration rates (Table 2). Only at upper-estuary sites were there significant correlations noted between estuarine nutrient concentrations and fluvial flow. At mid-estuary sites nutrient concentrations were significantly correlated with sediment recycling rates and not correlated with fluvial flow rates.

Annual phytoplankton production in the Corpus Christi Bay estuary was measured to be 174.1 g C/m^2/yr. This annual rate was characterized by large seasonal variation [19] as well as extensive spatial variation, as illustrated by the data presented in Figure 2. Productivity was observed to usually be greater further away from the riverine source during most measurement periods over the three years of study. Much of the decreased productivity closer to the riverine source was related to shallower waters and greater turbidity in the water column, causing light limitation on photosynthesis. Increased productivity of the mid-estuary region was linked to a more constant supply of nutrients from the sediments since it was demonstrated above (Table 2) that this region relied on the mechanism of sediment recycling for its nitrogen supplies. In contrast, the upper-estuary water column nutrient concentrations more closely paralleled fluvial flows than recycling of nitrogen from the sediments.

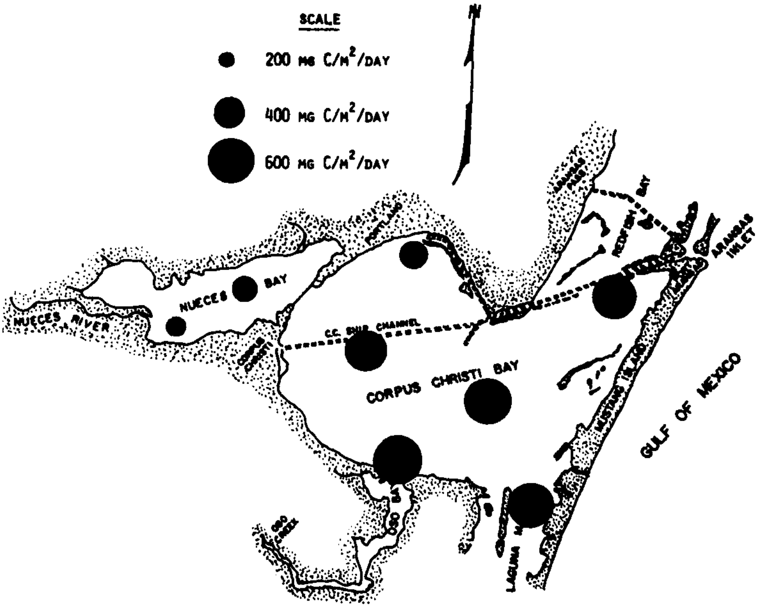

Figure 2. Spatial variation in mean daily phytoplankton production estimated for the entire study period in the Corpus Christi Bay estuary (1981-83).

Using the ratio of 6.6 for C:N content of phytoplankton [20], it was calculated that sediment recycling of nutrients in the Corpus Christi Bay estuary was able to supply approximately 90% of the nitrogen needed to support measured phytoplankton production annually. In contrast, new nitrogen contributed from riverine input to the estuary could only support 5% of this photosynthesis, further emphasizing the greater reliance of this estuary upon the recycling of nitrogen for maintenance of productivity.

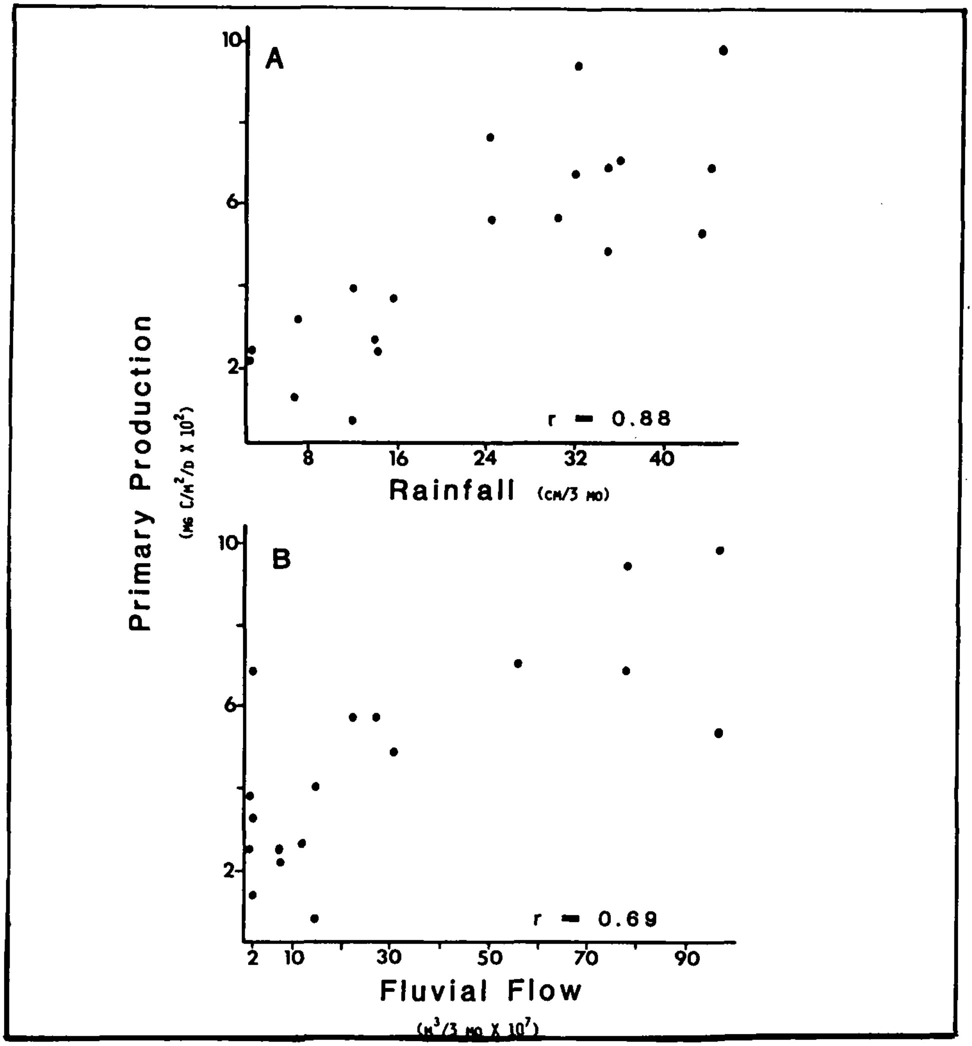

Figure 3. Scatter plots of daily phytoplankton production with (A) total rainfall for a three-month interval preceding measurement and (B) total fluvial flow for a three-month interval preceding measurement. Correlation plots for each plot are indicated.

Deviations from this pattern were observed in the data base however, and were related to the episodic climatological events discussed previously. Data in Figure 3 best illustrated the effect of these climatological changes to the estuary with respect to phytoplankton production. Whenever excessive rainfall or fluvial flows to the estuary were observed during a three-year study interval, productivity rates responded, exhibiting increased production of carbon. Furthermore, mutiple regression analysis indicated that these two environmental variables together accounted for 84% of the total variation (increases) in primary production in the Corpus Christi Bay estuary during 1981-83.

For years it has been thought that the river deltas and tidal marshes were the most important contributors of nutrients to the coastal estuarine ecosystem [6,15,21]. Contrary to these beliefs, evidence is now accumulating suggesting a general feature of estuaries is that nutrient recycling is important in sustaining production [22,23]. Data from the study described here further supported this conclusion. I believe we have learned from the Corpus Christi Bay data base that although many of the processes controlling productivity are related to recycling, periodic forcing from episodic climatological events is required to cause an "over-shoot" in production, above the steady state level, which replaces materials lost through recycling mechanisms and maintains a relatively constant long-term pattern of estuarine production. If this is the case then the contribution of nutrients from river deltas for example, becomes important from a perspective of the episodic nature of this contribution rather than the continued reliance of the ecosystem on this contribution.

4.2. Biological Responses

The documentation of trophic levels above primary producers responding to episodic changes in the estuarine environment has also been possible through the examination of the Corpus Christi Bay estuarine data base. An 11-yr period of observation on benthic macroinfaunal abundance and biomass in this estuary (Figure 4) has indicated several intervals of change in the benthic community related to both climatological changes and man-made alterations. For example, a significant increase ($P < 0.001$) in both abundance and biomass of benthic fauna was observed in early 1980. This correlated with the intensive rainfall event of September 1979 which was followed by a 9-mo interval of decreased estuarine salinities described previously and illustrated in Figure 1. It was believed that the benthos of the estuary responded to the increased production of the ecosystem, stimulated by increased nutrient inputs from the rainfall event, by exhibiting record measures for abundance and biomass of its populations, which were never equalled in the 11-yr study period (Figure 4).

Also illustrated in Figure 4 are two intervals of channel dredging that occurred in the Corpus Christi Bay estuary, within the vicinity of the benthic collections during the 11-yr study. In both instances the dredging activities surpressed the annual peaks in benthic macroinfaunal abundance and biomass that were usually observed in the winter and spring of each study year. It was concluded that channel dredging was capable of producing short-term effects on benthic communities near the dredging activities. In both instances return to average measures for these variables was noted the following year.

There are few direct indications from estuarine data bases of links between production in different trophic levels. To a degree, this is the result of instantaneous measurements in highly time-dependent systems. But it also reflects the variability and patchiness inherent in these estuarine systems.

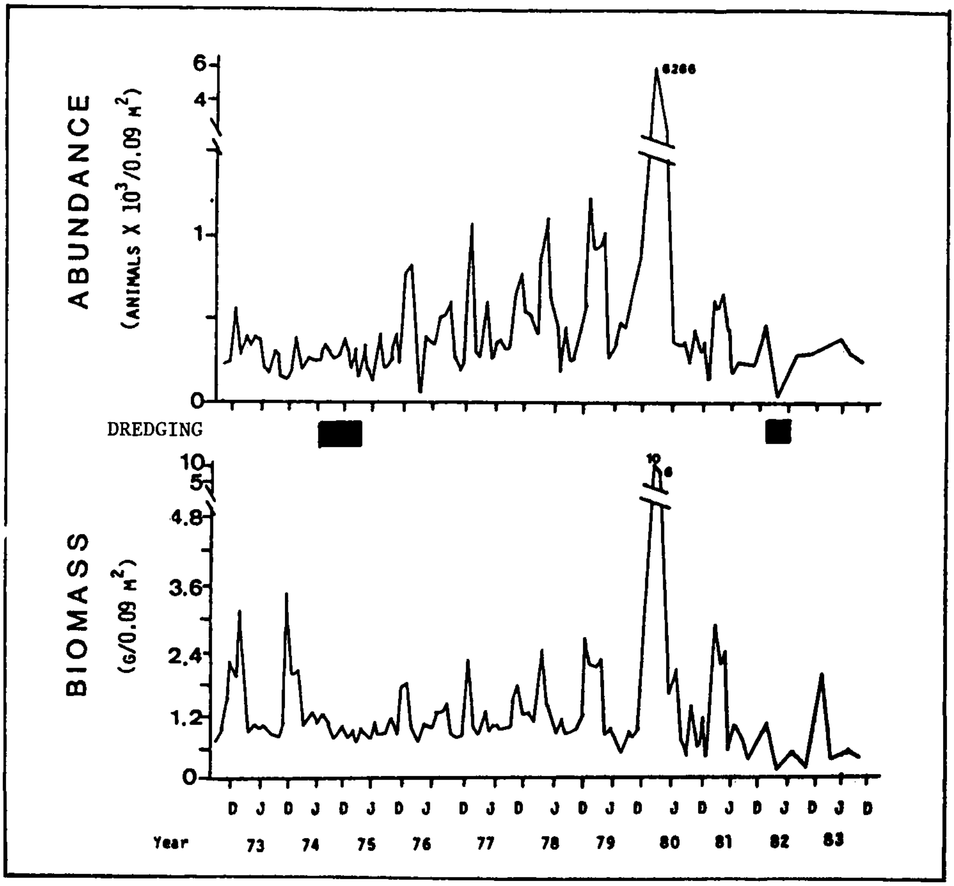

Figure 4. Plots of mean macrobenthic infaunal abuncances and biomasses from October 1972 to October 1983 in the Corpus Christi Bay estuary. Dredging intervals are indicated on the plots.

A comparison of benthic macroinfaunal biomass observations in the Corpus Christi Bay estuary with shrimp fishery yields in this same estuary between 1973-82, however, indicated an interesting pattern (Figure 5). Experimental observations elsewhere have shown that penaeid shrimp obtain at least part of their nutrition from organisms living in the benthos [24]. The parallel pattern observed for annual benthic biomass and annual shrimp fishery yields in Figure 5 suggested that either these two components of the estuarine foodweb were responding to the same environmental changes or they were responding to each other, since a correlation of r = 0.82 was measured between the two variables. In addition, the increased production of benthic biomass discussed above for the period following the September 1979 rainfall event (Figure 4) was also evident in Figure 5 and the shrimp fishery exhibited parallel increased yields in biomass. Thus, the suggestion that estuarine productivity is maintained by episodic climatological events over the long-term was further supported by yet another component of the Corpus Christi Bay estuarine ecosystem.

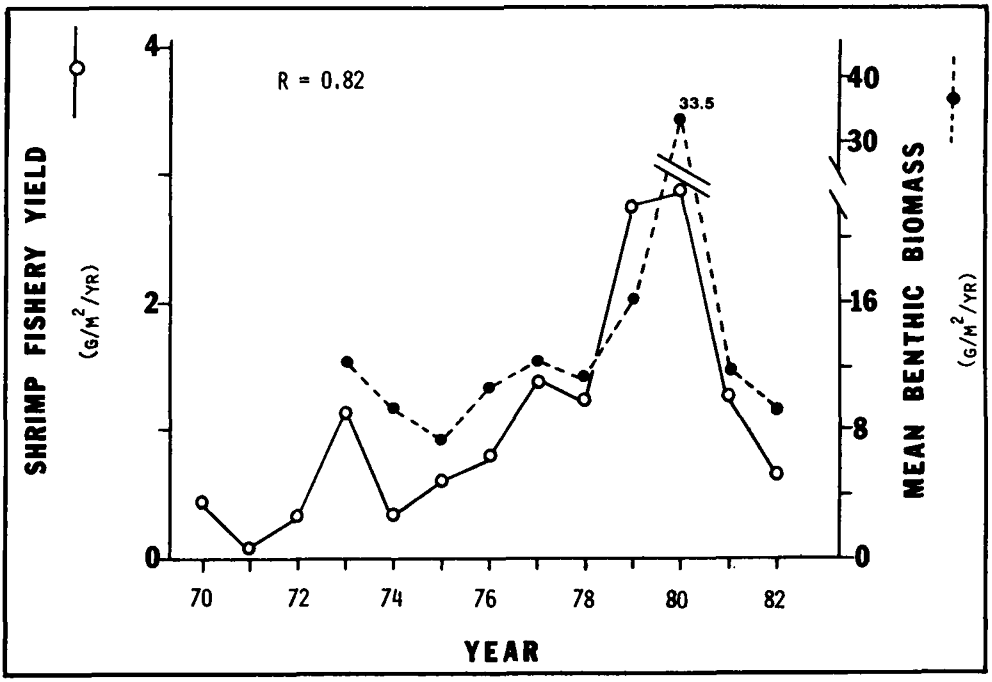

Figure 5. Comparison of macrobenthic infaunal annual biomass and shrimp fishery yields for the Corpus Christi Bay estuary. The correlation between the two variables is indicated.

All estuaries contain chemical gradients between their saline and fresh sources of water input. Frequently, there are other gradients found in estuaries such as in temperature, sediment structure, particulate materials, and metabolism. The spatial variability of these estuarine characteristics is as important to understand as the temporal variability discussed above with respect to episodic climatological events if one wishes to adequately manage an estuarine ecosystem and make decisions based upon sound scientific judgement.

Illustration of the spatial variability in mean daily phytoplankton primary production for the Corpus Christi Bay estuary (Figure 2) provided a good example of gradation with respect to a basic food source to estuarine consumers. Sediment metabolism, which is an indicator of the health of animals inhabiting the estuarine bottom and a measure of carbon production by the most important primary consumer component of the estuary, also varied significantly in moving from riverine to oceanic regions of this estuary (Figure 6). In the upper-estuary large temporal variability was observed and greater sediment metabolism was linked to periods of greater freshwater input (r = 0.86). In the mid-estuary region greatest overall metabolic rates were observed and these rates were more closely linked to differences in sediment texture, kinds of benthic communities present, and primary production rates of the overlying waters than to allochthonous effects such as freshwater input. The further away from fluvial flow effects that metabolic measures were made, the more able these measures were

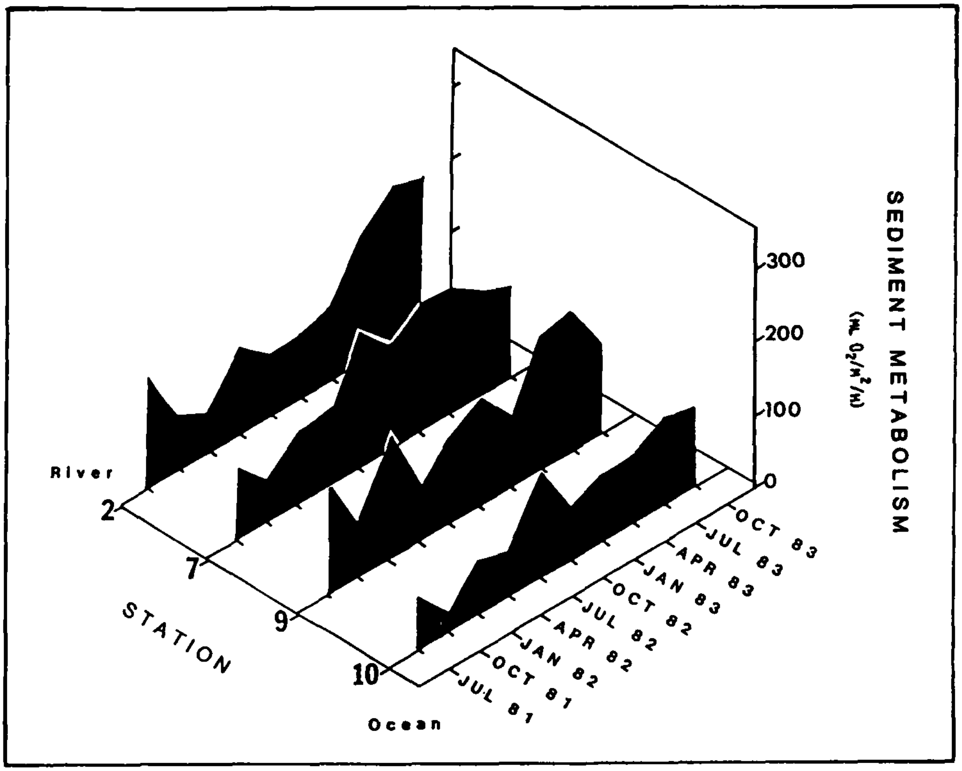

Figure 6. Temporal and spatial variation in benthic sediment metabolism in the Corpus Christi Bay estuary at four stations representing an estuarine gradient in salinity.

to reflect seasonal variations that would be expected in an estuarine ecosystem (Figure 6).

4.3. Interdisciplinary Patterns

A question often posed when physical, chemical, and/or biological alterations of an estuary are considered is: what effect will this have on the biota, especially those directly used by man? The only reliable approach to this question must involve several levels of biota, ecosystem components, and processes and cannot be fully successful without interdisciplinary linkage to physical and chemical components with their corresponding changes in ecosystem function. As a simple example, consider the summary of data from a three-year study in the Corpus Christi Bay estuary presented in Figure 7 that demonstrates how various interdisciplinary components can be integrated into a perception of total ecosystem function. In 1981 salinity was low (Figure 7) because of the high net freshwater input with associated nutrients as verified by Figure 1. Nutrient regeneration rates were also very high compared to other years (Figure 7). These physical-chemical features resulted in both high primary production

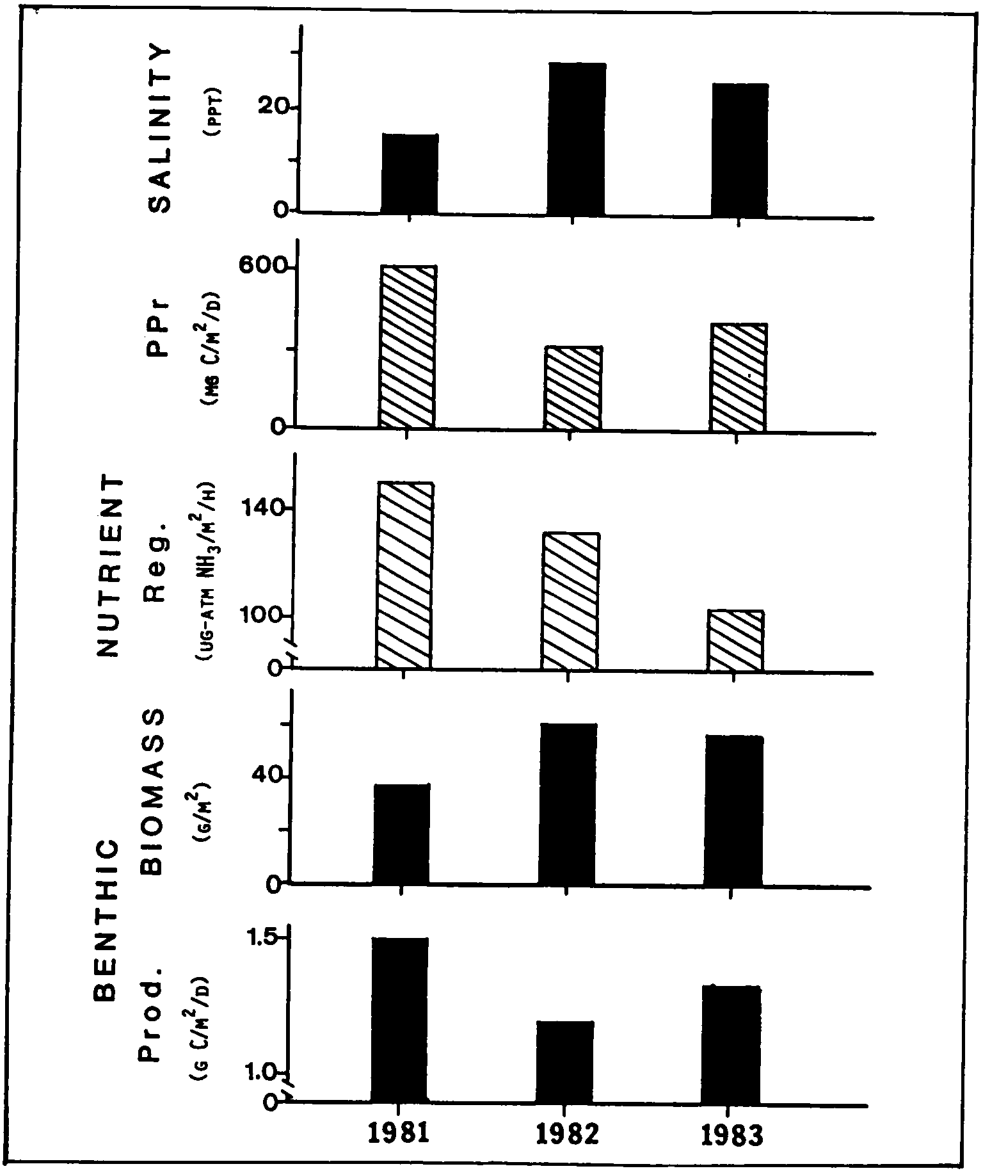

Figure 7. Annual mean measures for salinity, primary production, sediment nutrient regeneration, and benthic biomass and production for the Corpus Christi Bay estuary during a three-year study interval.

and high secondary production, as exhibited by benthic communities. The significantly higher primary production of 1981, with the majority of carbon input to the sediments [25], was enough to sustain benthic standing stock biomass in the estuary for the next two years (Figure 7) even though production decreased over those next two years.

Estuarine-wide salinities decreased again during 1983 (Figure 7) because of increased rainfall (Figure 1) with assumed nutrient supplies. Annual primary production, however, did not show much of an increase over the previous year (1982). Larger standing stocks of benthic populations along with increased production of these populations in 1983 (Figure 7) did not leave a large excess of phytoplankton-derived carbon for remineralization in the sediments and thus, nutrient regeneration rates were very low [23]. Lower recycling rates of nitrogen from the sediments negated the increased supply of new nutrients from greater freshwater input and resulted in less primary production than might have otherwise been expected.

In order to demonstrate how the various biological components of an estuary are linked together and can potentially affect one another, a conceptual scheme of material flow for the Corpus Christi Bay estuary was constructed (Figure 8). All secondary consumer level production estimates in Figure 8 came from fishery harvest yields where biomass was converted to carbon production using a conversion of wet weight to carbon content of 6% [25]. Ten percent transfer efficiencies were assumed here for carbon flow between trophic levels [6].

All sources of known carbon to the estuary equalled an annual input of 372.2 g C/m^2/yr (Figure 8). The small amount of calculated transfer to the pelagic foodweb indicated that the majority of primary-produced carbon was diverted to the benthic habitat. The benthos therefore, served as a major link between the primary sources of carbon and transfer of this carbon to secondary consumers. The annual benthic production rate (504 g C/m^2/yr) was calculated to be more than sufficient to support all other secondary and tertiary consumer production in the Corpus Christi Bay estuary (Figure 8). A paradox arose, however, concerning an adequate supply of carbon from primary producer sources to support the measured benthic production in the estuary. A potential solution to this paradox might be that the 504 g C/m^2/yr of benthic infaunal production in itself actually represented three different trophic levels: microfauna (bacteria, etc.), meiofauna, and macrofauna [26]. If this were the case, then the needed input of carbon to the benthos would be considerably reduced and have to support an initial benthic consumer level yielding 287.3 g C/m^2/yr. This initial benthic trophic level would then support two other trophic levels (meiofauna and macrofauna) producing 144.6 and 71.8 g C/m^2/yr respectively, assuming a 50% transfer efficiency between benthic trophic levels [26].

4.4. Management Application

Data from the long-term Corpus Christi Bay estuarine data set that provided insight toward integrated ecosystem function were summarized on an annual basis and combined into Figure 9. The purpose of this exercise was (1) to understand how components of the estuary interacted and (2) to illustrate how information on fauna (e.g., life history cycles, standing stocks) within the ecosystem could be combined with information on ecosystem processes (e.g., benthic production, nutrient regeneration) in a holistic picture that provided a useable management tool to the decision-maker.

As an example of how this scheme could be applied as a decision-making aid, consider the regulation of freshwater inflow to estuaries. When benthic nutrient recycling rates were at a minimum in the fall (Figure 9) nutrient input from the riverine source was at its peak, thus maintaining primary production at reasonable levels. In contrast, when riverine input was low during the

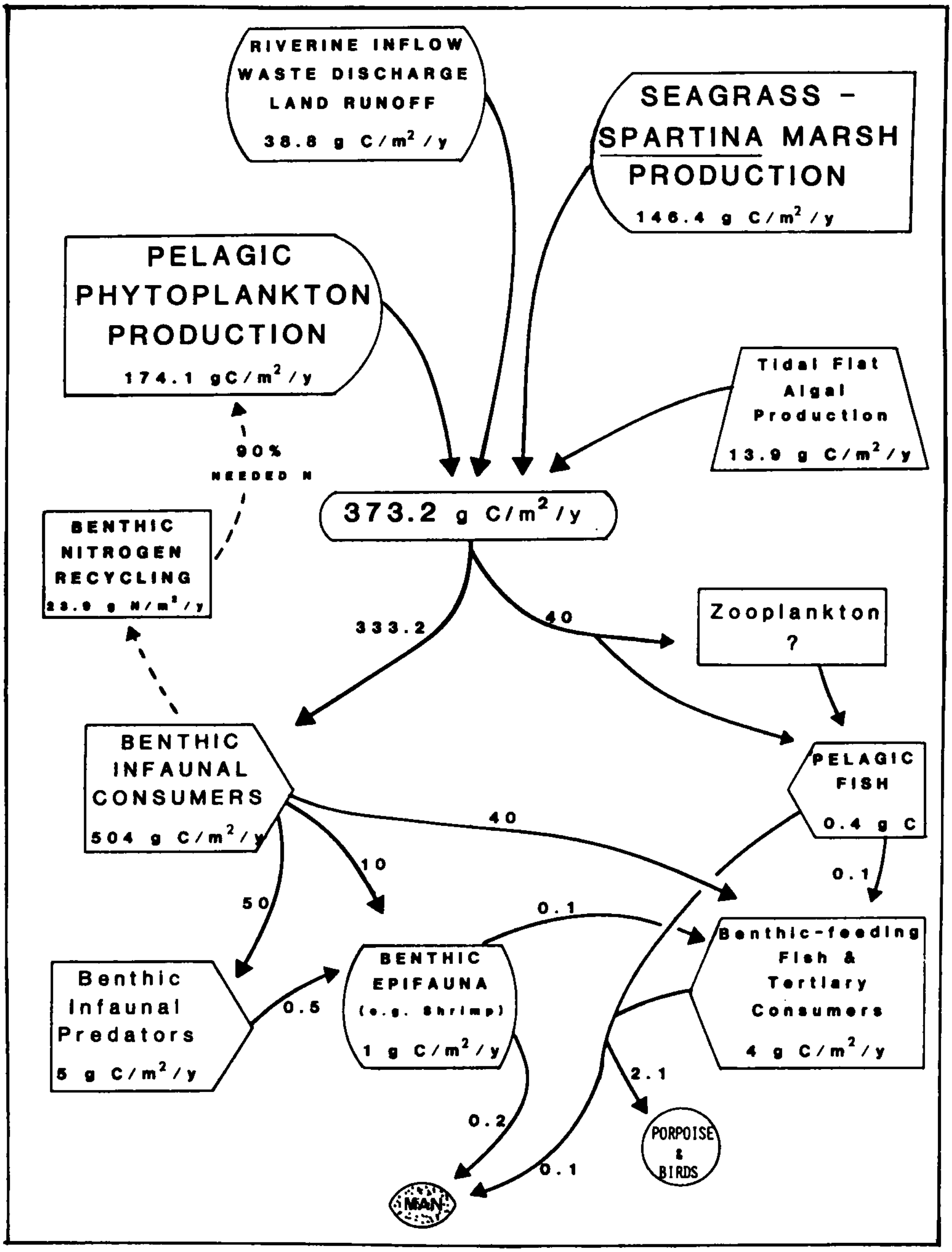

Figure 8. Foodweb for the Corpus Christi Bay estuary showing flow of carbon between trophic levels. The flow rates are expressed in g $C/m^2/yr$. Benthic nitrogen recycling rates are also illustrated.

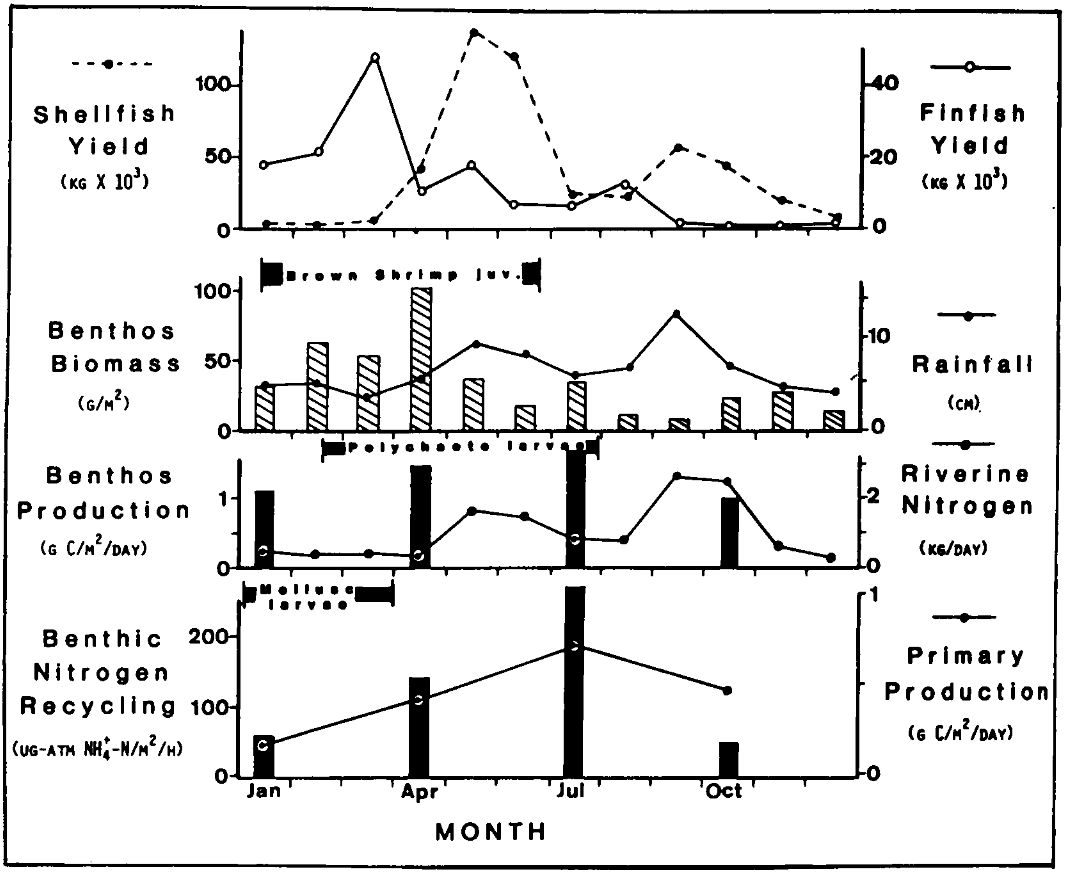

Figure 9. Mean values from a multiyear data base on the Corpus Christi Bay estuary for benthic macroinfaunal biomass and production, sediment nutrient regeneration, phytoplankton production, riverine nutrient input, and rainfall, along with fishery yields and periods of peak brown shrimp abundance and larval colonization to the sediments.

summer, benthic nutrient recycling rates were high and peak primary production levels occurred. An appropriate period to divert freshwater inflow from the estuary for upland use while minimizing impact to the estuary, therefore, would be during the fall when the riverine input was most needed by the estuary. In addition, the winter and spring periods were times of important phases of benthic life stages, when larvae were colonizing the sediments and juvenile shrimp were utilizing the estuary for nursery grounds (Figure 9). These were also periods of peak benthic standing stock and peak fishery harvests. Thus, the best period of the year to divert freshwater from the Corpus Christi Bay estuary, according to the data in Figure 9, appeared to be during the summer. Although primary production peaked during this period, benthic nutrient recycling was also at its peak and could compensate for nutrient losses resulting from freshwater diversion.

Another example demonstrating the utility of this approach came from consideration of the need for dredging in our estuaries. As indicated in Figure 9, standing stocks of benthic fauna were much lower during the fall than other periods of the year. Secondary production rates were also lowest during the fall, as were phytoplankton production rates. Benthic nutrient regeneration rates were lowest during rhe fall when peak supplies of nitrogen came from fluvial input. Since the winter to early summer was important for benthic larvae, juvenile shrimp, and peak fishery yields, the environmental manager could decide to conduct dredging activities during the fall when the seafloor communities would be least impacted by the disturbance. There may be other considerations not covered by the conceptual scheme in Figure 9, but these examples demonstrated how integrated information could aid environmental managers in making decisions, based upon sound scientific judgement.

Another environmental characteristic that should be considered in respect to the above decision-making examples is resiliency after a disturbance. If for example, it was concluded that the fall would be the period of least impact from dredging, then the resiliency of impacted components need be considered. Processes and communities should not be perturbed long enough to significantly affect their contribution to ecosystem function. Data presented in Table 3 indicated how resilient the benthic community of the Corpus Christi Bay estuary

Table 3. Benthic community data from a channel station in the Corpus Christi Bay estuary prior to channel dredging (1974-82) and after dredging (1982-83) occurred in April 1982, to illustrate resiliency of the benthic species assemblages in this ecosystem.

Sampling Date	Infaunal Abundance (animals/m^2)	Infaunal Species Number	Infaunal Biomass (g/m^2)
January 1982	5,055.6	26	4.59
April 1982 [1]	214.8	9	1.39
July 1982	2,833.3	28	14.81
Average January	6,305.2 ± 2,031.2	29.7 ± 12.5	10.56 ± 4.83
Average April	5,873.3 ± 1,900.1	36.0 ± 17.4	16.86 ± 6.26
Average July	2,022.5 ± 1,242.3	38.9 ± 15.5	17.29 ± 6.04

[1] Sampling conducted two weeks after dredging completed.

was after a period of dredging in April 1982. The January 1982 benthic characteristics of infaunal abundance, species number and total biomass were normal for this time of year [8]. The April 1982 measures for these same characteristics, taken immediately after the dredging event, were far below the average for April of other years. By July 1982, however, these same benthic measures were similar to average observations for that month of other years. The benthos of Corpus Christi Bay were resilient enough to show characteristics normal for these fauna three months after the dredging disturbance to the estuary.

5. CONCLUSIONS

Many past efforts of managing estuarine ecosystems, striving for a balance between preservation and economic growth, have relied upon information from research addressing after-the-fact or instantaneous analyses of the system that do not usually provide predictive abilities. To develop these predictive abilities, however, in order to improve environmental management, more attention needs to be focused upon understanding the processes involved in ecosystem function. By utilizing specific examples from estuarine environmental assessment in south Texas, the study described here has demonstrated how a holistic perception of ecosystem function can improve environmental understanding.

Combining recent study results on mechanisms that regulate ecosystem dynamics with historical data on water quality and biota changed our perception of estuarine function in south Texas. Documented environmental changes in the Corpus Christi Bay estuary were correlated with changes in primary productivity rates, benthic community structure and fishery yields. This information coupled with high measured rates of nutrient regeneration from the estuarine sediments caused us to conclude that the ecosystem relies heavily on the recycling of materials and requires episodic climatological changes in order to replace materials lost from recycling and to maintain a steady state in estuarine production. With this refined perception of the relationship between episodic inputs of freshwater and ecosystem function it became more apparent that net production of the estuary, above the long-term steady state levels, could only be realized through these episodic events.

In addition, the development of material flow schemes and integration of several physical, chemical, and biological components into holistic displays significantly enhanced our understanding of estuarine dynamics. The integration of interdisciplinary data increased our knowledge of how various processes linked the biologic components of the system. The illustration of carbon flow through the system biota demonstrated the importance of the estuarine benthos serving as a link between primary producers and almost all secondary consumers in the ecosystem. These trophic analyses also indicated the sensitivity of the benthos to changes in carbon supply to the estuary since there appeared to be no excess carbon contributed to the system, above that required to support measured benthic production.

The long-term data set for the Corpus Christi Bay estuary has laid a reliable base upon which to develop estuarine management strategies. Predictive modelling can use this kind of ecosystem characterization and the conceptual schemes that are developed from it for model verification and refinement in order to improve our ability to detect and predict change in estuaries. It has been suggested [27] that potential environmental disturbances be evaluated by means of an interdisciplinary problem-solving approach. The integration of various estuarine ecosystem components into a conceptual scheme able to be visualized by the environmental manager, as demonstrated here, is a dramatic improvement over the trial-and-error management approaches followed in the past. It also brings us closer to quantitatively modelling these kinds of environments. Our economic interests in estuarine resources are too great to allow us to continue without considering these potential improvements in our decision-making process.

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