Tampa

BASIS 2

BAY AREA SCIENTIFIC INFORMATION SYMPOSIUM

THE WATERSHED

PROCEEDINGS

TAMPA BAY AREA SCIENTIFIC INFORMATION SYMPOSIUM 2

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STUDENT POSTERS

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PREFACE

The first Tampa Bay Area Scientific Information Symposium (Tampa BASIS) was held in 1982 and emphasized the Tampa Bay estuary. Results from the first symposium identified two critical issues — the need for increased understanding of the watershed surrounding Florida's largest estuary, and the need for informed management of the system as a whole.

These acknowledged needs have stimulated recent escalations in bay management efforts and technical research. Since Tampa BASIS, the Tampa Bay Regional Planning Council created the Agency on Bay Management in 1985 to coordinate the multitude of agencies and organizations involved with Tampa Bay; the Southwest Florida Water Management District's Surface Water Improvement and Management Program was created by the 1987 Florida Legislature to protect and restore surface water bodies; and the Environmental Protection Agency's National Estuary Program was dedicated in 1991 to develop a Comprehensive Conservation and Management Plan. Effective management requires basic research — it is the responsibility of the regulatory and scientific communities to work together to preserve, protect and enhance Tampa Bay.

The primary goal of Tampa BASIS 2 is to bring these communities together for the exchange of ideas and information. Our objectives are to review the status of our understanding of watershed/estuary interactions, to make management decisions based on this understanding, and to disseminate this information to the public.

Sally F. Treat
Peter A. Clark

COASTAL NONPOINT POLLUTION CONTROL
Opening Address

J. W. Rote

It's an honor and a privilege to be with you for BASIS 2. When I was your "rapporteur" for BASIS in May of 1982, I stressed the importance of a watershed approach to the research, planning, and management of Tampa Bay. As your moderator for the next three days, I will be emphasizing nonpoint source pollution control, which I feel is the new frontier in coastal and estuarine water quality management efforts.

INTRODUCTION

From the first Tampa Bay Area Scientific Information Symposium, two critical issues emerged—the need for increased understanding of the watershed surrounding Florida's largest estuary, and the need for informed management of the system as a whole. These acknowledged needs have stimulated a recent surge of scientific and technical research. Given further impetus by the Southwest Florida Water Management District's Surface Water Improvement and Management (SWIM) Program, and the inclusion of Tampa Bay in the National Estuary Program, 1991 is expected to be a year of intense research and management activity.

There has been a flurry of activity over the past decade in addressing water quality and growth-related problems in and around urbanized estuaries. I opened the 1982 BASIS meeting with a paper on the "Science and Management of San Francisco Bay". Recently, a 2020 Chesapeake Bay Growth Management Commission, appointed by the Governor of Maryland, reported on the problems facing the largest estuary on the east coast. Since the 1982 BASIS, just in California, Monterey Bay, San Francisco Bay, Santa Monica Bay, Tomales Bay, and Morro Bay have all held "State of the Bay" conferences.

The dimensions of coastal pollution as a national problem were thoroughly documented in a report by the Office of Technology Assessment, "Wastes in Marine Environments" (April 1987). During the two years following the release of that report, the House Subcommittee on Fisheries and Wildlife Conservation and the Environment and the Subcommittee on Oceanography held a series of nine oversight hearings on many aspects of the coastal pollution problem. In August of 1988, Time and Newsweek magazines both featured cover stories on marine and coastal pollution problems facing the nation.

A major theme which came up frequently at the Congressional oversight hearings was the importance of a "basin-wide approach" to solving coastal pollution problems. This was probably best stated by a witness from Massachusetts, who testified,

> We should keep in mind that the major questions of health of our marine and near coastal waters are best answered through the systems approach. Excellent examples of these include the Chesapeake Bay Program, and the Buzzards Bay and Narragansett Bay Programs with which we work in Massachusetts. These programs assess pollution and its impacts from the broad systems approach and provide a forum to develop coordination of remedial actions. They have allowed us to link EPA and NOAA programs within a given geographical area, to coordinate local, state, and federal efforts to minimize duplication and maximize investments, to link scientists with decision-makers, and to find out just what the citizens/taxpayers want in their coastal waters. (William Eichbaum, Massachusetts Executive Office of Environmental Affairs, March 24, 1988.)

POPULATION GROWTH

At the heart of the coastal pollution problem is simple demographics. People crowded onto the water's edge are both the cause of the decline in coastal environmental quality and one of the major reasons why solving the problem is so critical, because the health and quality of life for so many depend on it. Growing populations along coastal corridors mean more residential, commercial, and industrial development, more roads and infrastructure, and an increase in every type of environmental assault on the land, air, and water of the coastal zone.

Florida and California have a lot in common. Eight coastal counties in the two states will be in the top ten counties in absolute population change between 1988 and 2010. Where there will be some relief in California, with a movement away from the coast toward the inland and central valley counties, the entire state of Florida is considered to be "coastal".

I don't have to tell you that Florida is growing. In 1960, when the state's population was 5 million people, it was the tenth ranked state in the nation. In 1989, the population was 12.5 million, and the state was the fourth most populated, behind California, New York, and Texas. The projected Florida population for 2010 is 16 million people. That would be a 226% increase since 1960. This growth rate compares to 122% in California and 121% in Texas over the same period of time.

Considering the three counties around Tampa Bay (Hillsborough, Manatee, and Pinellas) and Pasco to the north, and Sarasota to the south, the Tampa Bay area is witnessing some of the greatest growth in the entire Gulf of Mexico area. Pinellas County will gain 192,000 people by 2010 (second in the Gulf area); Pasco County, 182,000 (third); Hillsborough County, 158,000 (fifth); and Sarasota, 102,000 (ninth). For Pasco County, this represents a 69% growth between 1988 and 2010, the third highest growth rate in the Gulf area.

In terms of density (population per square mile), by the year 2010 Pinellas County will be first in the Gulf area, with 3,619 people per square mile; Hillsborough will be sixth—924, Sarasota seventh—633, and Pasco ninth—606. Coastal counties in southwest Florida will also have the largest percent increases in population over the next two decades. Ten of the 15 most rapidly growing counties in the coastal zone of the Gulf of Mexico are located in this area.

NONPOINT SOURCES

Nonpoint sources of contaminants are those that are diffuse or poorly defined. They include rainfall or fallout from the air, surface runoff from land, and multiple small inputs such as those from individual houses, businesses, and farms. Monitoring nonpoint source contamination is difficult precisely because it is so diffuse. It is technically challenging both to monitor such contaminant input and to clearly identify sources of elevated levels found in the environment.

Nonpoint sources are attracting greater attention from both regulatory agencies and the public, with most of this attention devoted to storm drains and riverine input. As a result of a steady decrease in the mass emissions from coastal wastewater treatment plants, mass emissions of some chemicals from stormwater runoff now approach those in effluents from coastal wastewater treatment plants. Stormwater and riverine drainage enter the nearshore zone directly, while treated municipal wastewater is discharged two to seven miles offshore, usually in deep water (greater than 100 feet). Potential impacts on recreational beaches may therefore be greater from the land runoff than from offshore discharge of treated wastewater.

In a study I conducted in 1985, the two primary sources of pollutants entering Santa Monica Bay and the surrounding waters of the Southern California Bight were found to be past ocean dumping of industrial chemicals and other waste materials (and some minor present dumping) and municipal wastewater outfalls, past and present. Secondary inputs included: nonpoint source urban runoff (storm drains and flood channels); contaminants from aerial fallout; ocean currents; power generating plants (biocides in cooling water); offshore oil drilling operations (drill muds/cuttings); discharges from ship traffic (hydraulic fluid, bottom paint); dredge spoil dumping; and possible metabolic breakdown (or impurities) in presently used pesticides (Kelthane [Difocol]/DDT-type derivatives).

URBAN RUNOFF

The nonpoint discharge of surface runoff can be an important source of pollutants to nearshore marine waters. Storm drain runoff, flood channels, and agricultural return water, surveyed in California during 1971-72 and 1979-80, were shown to contain high levels of trace metals and chlorinated hydrocarbons. Three major storm channels, and their drainage areas in the Los Angeles Basin (Los Angeles River, San Gabriel River, and Ballona Creek) had high levels of pollutants, with the Los Angeles River averaging approximately 75% of the total storm runoff during the period.

Additional nonpoint source inputs include: fire-fighting wastewater, often containing high concentrations of contaminants; "nuisance" water (wash-down, excess lawn watering, etc.); accidental sewer overflows; and daily, weekly, and other periodic plant and site cleanup and wash-down from business, commercial, and residential sources.

Nonpoint runoff dominates as a source of suspended solids and also contributes half or more of total phosphorus, chromium, copper, lead, iron, and zinc. In addition, it is the overwhelming contributor of fecal coliform bacteria in all areas of the country. Coliform bacteria from dairy cows pose a major problem to shellfish culture operations in California.

NOAA NATIONAL STATUS AND TRENDS PROGRAM

Reports of beaches being closed, trash washing ashore, prohibitions on shellfishing, health warnings to seafood consumers, waste discharges to the sea, ocean dumping, and habitat losses have aroused considerable public concern about the quality of the coastal environment in the United States. To assess the effects of human activities on the quality of coastal and estuarine areas throughout the nation, the National Oceanic and Atmospheric Administration (NOAA) initiated the National Status and Trends (NS&T) Program to monitor trends of chemical contamination in space and time, and to determine biological responses to that contamination.

Since 1984, NOAA's Office of Oceanography and Marine Assessment has monitored, through the NS&T Program, the concentrations of toxic organic compounds and trace metals in bottom-feeding fish, shellfish, and sediments at nearly 300 coastal and estuarine locations throughout the country. Samples collected annually are analyzed to determine levels of synthetic chlorinated compounds (e.g., DDT, polychlorinated biphenyls [PCBs]), polynuclear aromatic hydrocarbons (PAHs), and toxic trace elements (e.g., mercury and lead). The program is the first to use a uniform set of techniques to measure coastal and estuarine environmental quality over relatively large space and time scales, including a "specimen bank" of samples taken each year at 10% of the sites for future, retrospective analyses. A related Bioeffects Program examines the relationship between contaminant exposures and indicators of biological responses in fish and shellfish in areas that are shown to have high levels of toxic chemicals.

A 1990 NOAA report, "Coastal Environmental Quality in the United States — Chemical Contamination in Sediment and Tissues", describes the spatial extent and severity of chemical contamination and changes in concentrations of contaminants over the last decade. On a national scale, it appears that high and biologically significant concentrations of contaminants are limited primarily to urbanized estuaries. In addition, levels of those contaminants have, in general, begun to decrease in coastal waters.

The NOAA study found high concentrations of chemical pollutants rare in the southeast and the Gulf of Mexico area, except for a few sites. High levels at St. Andrews Bay, Florida (Watson Bayou) and Choctawhatchee Bay (Shirk Point) were unexpected and unexplained. Sites in the Tampa Bay area which exceeded "high" concentrations included: Mullet Key Bayou, 5.5 ppb chlordane; Navarro Park, 1.3 ppb cadmium, chlordane; Hillsborough Bay, 87 ppm lead, cadmium, and 200 ppb PCBs; Papys Bayou, 40 ppb DDT chlordane, PCB; Peter O'Knight Airport—lead, DDT, chlordane, PCB; and Old Tampa Bay, 230 ppm chromium.

COASTAL MANAGEMENT SOLUTIONS TO NONPOINT SOURCE WATER POLLUTION

Nonpoint source pollution control was a major item on the environmental agenda of the administration and Congress in 1990. The administration saw an opportunity in the reauthorization of the Coastal Zone Management (CZM) Act to encourage the coastal states to address this significant source of water pollution. Coastal management programs are in a unique position to deal with the land-based causes of nonpoint source pollution through their existing land management capabilities.

SWIM Program

In 1987 and 1988, over $30 million in Florida state funds were directed to water basin monitoring and planning. The Surface Water Improvement and Management (SWIM) Act was signed into law by Governor Martinez on June 29, 1987. This landmark legislation set up a program and provided initial funding to begin the cleanup and restoration of polluted surface water in Florida, along with the preservation of threatened waterbodies within the state. The state's five water management districts are responsible for implementing the law. Each water management district is required to address priority waterbodies named by the legislature within its area and prepare a priority list of other waterbodies in need of restoration, conservation, and/or preservation.

After they identify priority watersheds, each water management district develops a plan to address the identified water quality problem for each watershed. Besides biological and physical descriptions of the waterbody, the plans contain land use and nonpoint source assessments which will help determine overall impacts of land use within the basin and lead to revised best management practices. The plans identify legal frameworks, needed coordination efforts between state and local entities, and public information programs required for the success of the overall effort. The plans include a timetable for bringing all sources into compliance with state water quality standards and a strategy to restore those waterbodies in need of restoration. Finally, the plans will describe projected cost and revenue capability in order to reach each intended waterbody goal.

The Coastal Zone Section within Florida's Department of Environmental Regulation (DER) Bureau of Surface Water Management has played a pivotal role in overseeing the SWIM Program. Coastal Zone staff produced the administrative procedures used to guide the statewide program and administer the SWIM trust fund grants to the water management districts. The coastal zone staff also directly manages the state's review of proposed SWIM plans, including coordination of DER and other state agency comments.

As of August 1989, DER had approved SWIM plans for 18 waterbodies, including (among others) Tampa and Biscayne Bays, Apalachicola River and Bay, and the Suwannee River. Plans for such critical areas as the Everglades National Park and Florida Bay, Indian River Lagoon, and the lower St. Johns River were either conditionally approved or are under development.

Little Manatee River Project

For several years, Coastal Zone Management funds have been a catalyst for interagency investigations to assess the overall health of several major estuarine areas, to identify priority management problems, and to provide direction and leadership for coordinated intergovernmental management. Due to the actions funded through this program, major improvements have been made in Florida's ability to cope with present and future problems affecting these areas. The importance of CZM funding in making these achievements possible is significant.

The Little Manatee River Project is one of four main estuarine areas being funded through the Estuarine Initiative. The objective of this project is to develop a comprehensive, basin-wide management program for the Little Manatee River watershed, involving federal, state, regional, and local agencies. The project will also serve as a prototype for similar efforts in other watersheds in the Tampa Bay system, with the long term goal of enhancing the overall health of the bay.

The Little Manatee River is a priority tributary of Tampa Bay, providing nursery habitat for many fish species, and is critical to the quality of the state aquatic preserve in the area. This area is the last major river of the Tampa Bay system remaining in relatively natural condition. Although there has been considerable state, regional, and local interest in the area, local governments have been unable to develop a comprehensive management plan for the watershed, primarily due to a lack of funding and intergovernmental support.

Phases 1 and 2 of the project have been completed. Work elements completed during Phase 1 include the collection of chemical, hydrological, and biological data from the Little Manatee River, and identification of sources and acquisition of land use information for incorporation into a Geographic Information System (GIS). In Phase 2, riverine data was analyzed to develop a hydrological characterization of the watershed, rating curves and fluxes of dissolved and particulate nutrients, and characterization of biological communities. The land use information was entered into the GIS.

Phase 3 of the project, now underway, involves a coordinated effort by DER/CZM, Department of Natural Resources, Southwest Florida Water Management District, and Hillsborough County to develop the Management Plan for the Little Manatee River. As a result of the progress made using CZM support, this phase of the Initiative is being jointly supported by CZM and the SWIM Program. Project results are intended to improve the overall management of local and state programs affecting the Tampa Bay area and provide the basis for integrating local land use, environmental protection, and stormwater management programs with the ongoing efforts of state agencies charged with water quality and habitat protection.

Coastal Zone Management Act
Nonpoint Pollution Control Program

There is an exciting new game in town. Section 6217 of the Coastal Zone Reauthorization Act Amendments of 1990, entitled "Protecting Coastal Waters", requires each coastal state, with an approved coastal zone management program, to develop a new coastal nonpoint pollution control program for approval by EPA and NOAA. The purpose of this program is "... to develop and implement management measures for nonpoint source pollution to restore and protect coastal waters, working in close conjunction with other state and local authorities" (Section 6217[A]).

The program is to be coordinated closely with existing water quality programs under Sections 208, 303, 319, and 320 of the Clean Water Act, and with state CZM programs. Other sections require states to incorporate these new plans in the 319 programs and require the state CZM programs to contain enforceable policies and mechanisms to implement applicable requirements of the Section 6217 Plan.

This initiative marks a turning point in CZM programs, giving them a larger role in coastal water quality planning, as well as strengthening the new 319 management programs in coastal states with CZM programs. The responsibility for developing and implementing land use management measures rests solely with the states, not with NOAA or EPA. Management measures are reguired to conform to and comply with guidelines established by EPA, as provided under subsection (g) of Section 6217.

CONCLUSION

There is a need to focus more heavily on drainage basin approaches to coastal and estuarine water quality management efforts. Rivers and streams flush pollutants and sediments from upstream areas into our coastal and estuarine waters. At times, the amount of pollution from these sources far exceeds the amounts discharged directly into coastal waters themselves. If we focus only on the point source discharges and ignore the upstream inputs, we will miss a significant part of the overall problem.

The Tampa Bay area is one of the fastest growing regions in the country. Impacts of this growth on the bay's estuarine system have been the subject of numerous scientific investigations and have triggered a variety of efforts related to controlling point sources of pollution, habitat destruction, and other negative activities. The state of Florida recognizes that if it is to be successful, these projects must be better coordinated and must be conducted within a broader, basin-wide management perspective. The state must also focus clearly on controlling nonpoint source pollution, maintaining historic freshwater inflows to the estuary, and integrating consideration of living resource management efforts in local and regional capital improvement programs and comprehensive plans.

WATERSHED MANAGEMENT AND THE IMPORTANCE OF FRESHWATER FLOW TO ESTUARIES

J. A. Browder

ABSTRACT

Freshwater inflow characterizes the estuary, which is identified by Webster as "a water passage where the tide meets the current of a stream." The roles of fresh water in the estuary are discussed. The effect of the watershed on freshwater flow to the estuary is described. The connection between water quality and the hydrologic functioning of the watershed is briefly explained. Freshwater inflow serves many important functions that support estuarine productivity. It establishes a range of habitat in terms of salinity. Spatial variation in salinity partitions the estuary into areas in which individuals are segregated by species and by size and where some predators and parasites are excluded, providing protection for their potential prey. Freshwater inflow furnishes the nutrients to stimulate the growth of primary producers in the estuary and the detrital material to further support the food web. Freshwater inflow influences circulation and sometimes promotes the immigration of postlarval organisms into the estuary from offshore spawning grounds. Under some conditions, freshwater inflow builds ecologically valuable coastal marshes by means of sediment transport and deposition and enhanced growth of marsh vegetation. Freshwater inflow provides dilution--preventing or reducing the severity of stressful hypersalinity. Quantity and timing of freshwater inflow are determined by rainfall and the watershed's hydrologic characteristics. These have been changed by urban and agricultural development and water management. Development of a watershed reduces the opportunity for infiltration and the capacity for dynamic storage, both of which influence the water quality of nonpoint discharges. Restoration of estuarine productivity depends upon taking a watershed approach to management and related applied research. Integrated models are suggested that relate freshwater outflow to watershed structure and salinity and circulation to freshwater inflow. To be useful in evaluating impacts and guiding restoration, these models should be designed to approximate the natural, unaltered system, as well as the present system, so that a comparison can be made of simulations under the two conditions.

INTRODUCTION

Seafood is a major source of world protein, and the demand for fish and shellfish in the United States is increasing as Americans learn the health benefits of seafood and delicious ways to prepare it. Fishing for sport also is growing in popularity, and tourism based on recreational fishing is an important source of income to Florida. It seems ironic that demand is increasing while the ability of our coastal waters to produce marine resources is decreasing. This is particularly a concern in the Gulf of Mexico, where 95% of commercial seafood production and much of the recreational fishery is estuarine dependent (Rounsefell 1975).

ESTUARIES AS NURSERY GROUNDS

Our estuaries serve as nursery habitat for many fishery species, including those caught offshore that may not be thought of as estuarine products. In Florida, the best known estuarine-dependent species include spotted seatrout, striped mullet, red drum, snook, mangrove snapper, tarpon, and penaeid shrimp. Many of these spawn offshore; then newly-hatched larvae or early juveniles move into the estuary. Roughly 20 major commercial species caught offshore inhabit Tampa Bay as juveniles (Sykes and Finucane 1966). Relative densities of juveniles in various types of estuarine habitats suggest that shallow seagrass beds, tidal creeks, emergent marsh vegetation, and mangrove prop roots are optimal juvenile habitat for many species (Yokel 1975, Zimmerman et al. 1984, Thayer et al. 1987). In a number of estuarine-dependent species, postlarvae first settle out of the plankton into a demersal life in the freshest part of the estuary. They then gradually move to more saline areas as they grow.

INFLUENCE OF FRESHWATER INFLOW

Estuarine habitat is being degraded in many ways. Tampa Bay is one of many estuaries that have been made less productive by pollution, bulkheading, causeway construction, and dredging and filling (Comp 1982). But another, less obvious, way that estuaries have been changed is by alteration in freshwater inflow. This may be the most serious problem of all because the importance of fresh water to the estuary is not well recognized, and estuarine water rights are poorly protected.

Fresh water is the basis of estuarine production, establishing the salinity gradients, circulation patterns, and nutrient concentrations that distinguish estuaries from the rest of the coastline. Deegan et al. (1986) showed that fishery production per area of open water around the Gulf of Mexico is roughly proportional to the annual volume of freshwater inflow. The highest seafood landings come from the north central Gulf, which receives the outflow of the Mississippi and Atchafalaya Rivers (Deegan et al. 1986). Gunter (1963) called this area the "fertile fisheries crescent."

Positive statistical relationships have been found between fishery production and freshwater inflow. For instance, Sutcliffe (1973) found positive correlations between seasonal river discharge into the Gulf of St. Lawrence and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*). Browder (1985) found a positive relationship between pink shrimp (*Penaeus duorarum*) production on the Tortugas grounds and an index of freshwater flow from the Everglades to the southwest Florida coast. Da Silva (1985) found a positive relationship between river runoff and the abundance of another penaeid shrimp species, *Penaeus indicus*, off central Mozambique.

Studies in several parts of the world have shown that altering the freshwater inflow to an estuary can damage its production capacity. The most dramatic demonstration occurred with construction of the Aswan High Dam in Egypt. The sardine catch dropped from 15,000 tons in 1964 to 4,600 tons in 1965 and 554 tons in 1966 after the flow of the Nile River was constrained (Aleem 1972). The sardine decline apparently was related to a decline in the phytoplankton they eat. Nutrients transported by the Nile River supported the high phytoplankton concentrations that made possible the high sardine production. Damming the Nile reduced nutrient inputs to the delta.

Rosengurt and Hedgpeth (1989) explain the importance of freshwater flow from the Volga-Kama basin to the circulation and biological productivity of the Caspian Sea. Water projects in the Volga-Kama basin have greatly reduced freshwater flow to the lower Volga-Caspian Sea ecosystem, resulting in a drop in the sea level and a series of negative ecological consequences. Mean annual reduction in runoff is 12%, but the mean spring value has decreased by as much as 37%. As a consequence, the frequency of occurrence of abnormally low spring flows has quadrupled. Spring discharges are particularly important to the production of fishery resources because of the timing of spawning. The decline in runoff has altered the ecosystem in many ways that have all contributed to a reduction in juvenile survival and adult spawning success. Ecosystem characteristics affected by the decrease in freshwater inflow include temperature, salinity, oxygen content, alkalinity, pH, biogenic yield, food resources, circulation patterns, and the size of a nursery ground. Rosengurt and Hedgpeth (1989) provide a detailed account of the decline in fishery production coinciding with the changes in river inflow. Effects have been particularly dramatic in the lower Volga-North Caspian ecosystem. This ecosystem once produced three times as much fish as presently and was capable of maintaining 90% of the world catch of sturgeon. Volga-Kama reservoirs significantly curtailed the water supply to the lower Volga reaches and eliminated an average of about 80% of nursery grounds of sturgeon and other valuable fishes. The fishery production of "normal" or wet years declined to one tenth that supported by the uncontrolled Volga.

Giving an estuary too much fresh water can be as destructive as giving it too little. This was demonstrated by Carter et al. (1973), Colby et al. (1985), and Browder et al. (1986, 1988) in comparisons of Faka Union Bay to other bays in the Ten Thousand Islands of southwest Florida. A large drainage system redirected the flow of 600 km^2 of Collier County into the 2.75-km^2 Faka Union Bay (Fig. 1). Excessive freshwater discharges, especially during the wet season, are thought to be responsible for lower densities of larval and juvenile fish and macroinvertebrates in Faka Union Bay than in nearby bays (Fig. 2).

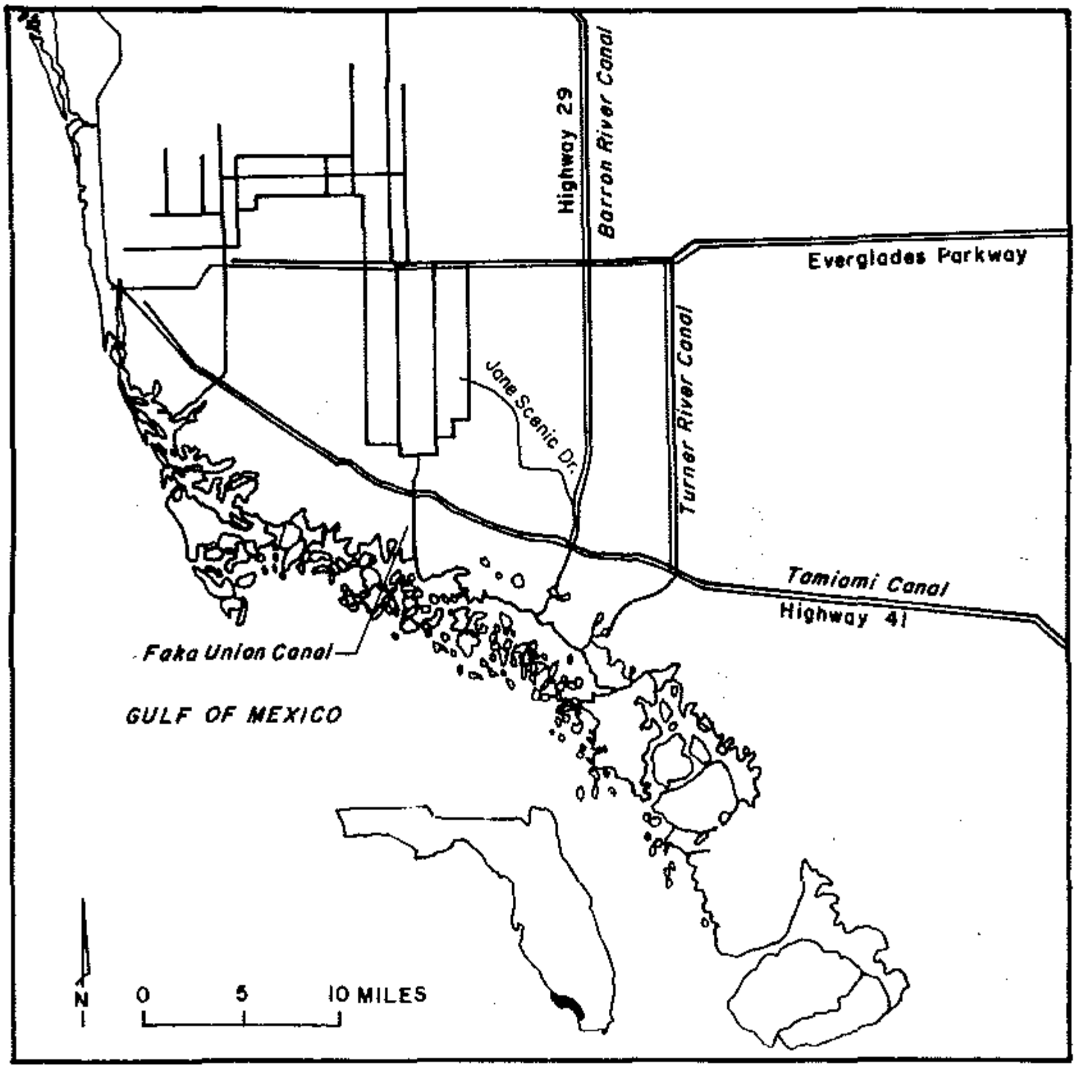

Figure 1. Map of southeastern Collier County showing drainage canals and discharge point (from Browder et al. 1988).

Another example of a Florida estuary receiving too much freshwater flow is the St. Lucie estuary on the lower eastern Florida coast. Water is released from Lake Okeechobee into the St. Lucie Canal to regulate lake stage levels. The canal empties into the St. Lucie estuary. Studies initiated in 1977 (Haunert and Startzman 1985) revealed that continuous experimental flow rates of 2500 cfs (70.8 m^3/s) for three weeks caused substantial changes in the taxonomic composition and abundance of benthos and the distribution of fish in the estuary. The most apparent changes to benthos occurred where salinity was reduced below 5 ppt during the first two weeks of discharge. The number of estuarine organisms in the benthos declined by 44%.

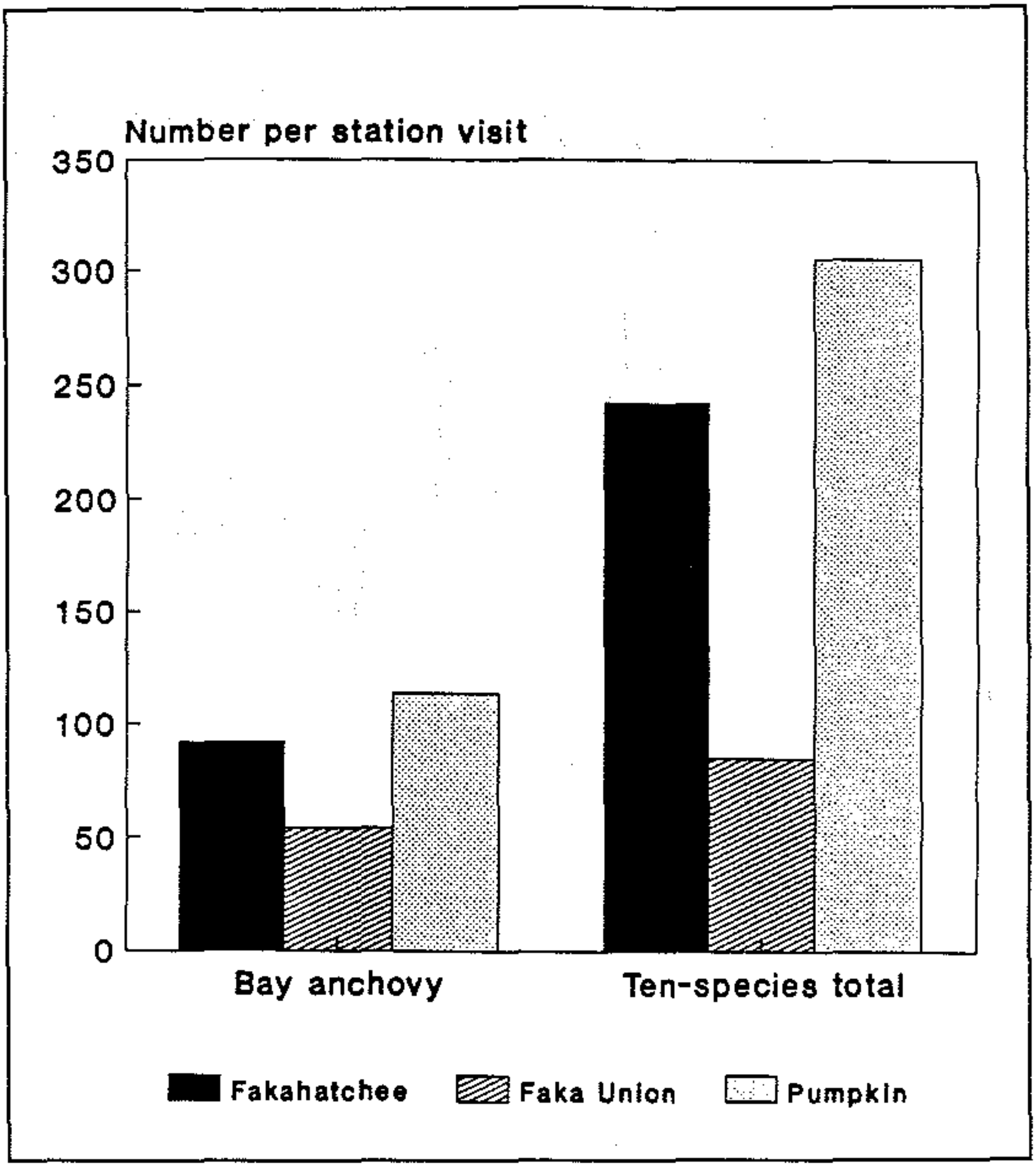

Figure 2. Relative abundance of the bay anchovy and 10 dominant taxa (including bay anchovy) in Fakahatchee, Faka Union, and Pumpkin Bays from October 1982 through June 1984 (from Browder and Wang 1986).

Subsequent modeling studies suggested that, had the discharge continued for an additional week, the oyster bars in the inner estuary might not have survived. The authors concluded that oyster populations in this estuary have been severely reduced due to the continual exposure to fresh water and lack of suitable substrate for settling of oyster larvae when conditions might otherwise be favorable for regeneration. Freshwater discharges approaching 6000 cfs have occurred many times since the canal was enlarged in 1949. This same estuary is stressed by lack of fresh water inflow during the spring of some years (Haunert, undated).

A discharge event in southern Dade County, Florida, provides a dramatic example of the immediate detrimental effect of excessively high freshwater discharges on an estuarine ecosystem. After heavy rains in August 1988, the South Florida Water Management District removed an earthen plug located in the southernmost portion of the C-111 canal, releasing large quantities of fresh water into Manatee Bay and Barnes Sound. The discharge started August 15 and continued into August 23 before efforts to abate the flow began. The peak discharge during the event was estimated at 3840 cfs in background material accompanying a June 8, 1989, dredge and fill permit application for the C-111 Interim Project submitted to the Florida Department of Environmental Regulation by the South Florida Water Management District. The subsequent destruction is briefly described in an October 14, 1988, memo from Renate Skinner to Jim Stevenson of the Florida Department of Natural Resources, as follows:

> The sudden, drastic change in salinity stressed the shallow bays, killing marine life in the vicinity. Eventually, as a result of the discharge, large areas densely vegetated with sea grasses were denuded. The rotting organic matter depleted dissolved oxygen and led to a massive kill of seagrasses, algae, invertebrates, and fishes. Ultimately, the kill extended beyond Barnes Sound into Blackwater Sound and Florida Bay and into John Pennekamp Coral Reef State Park [on the ocean side of the Florida Keys].

Although most estuarine organisms are euryhaline in that they can withstand variation in salinity, Kinne (1964) observes that most euryhaline organisms can tolerate salinity ranges up to only 10-15 ppt. The abrupt and drastic salinity changes associated with large influxes of fresh water are disruptive to most estuarine life. Only a few organisms, which Kinne (1964) refers to as "holeurysaline", can exist in the whole range from pure fresh water to sea water. The rapidity of change also influences the tolerance of euryhaline organisms to salinity changes.

With respect to living resources, there may be an optimum freshwater flow for each estuary that maximizes the area in which favorable salinities coincide with the type of physical structure that is also favorable—for example, a certain type of shoreline configuration, substrate, or bottom cover (Browder and Moore 1981). Figure 3 from Browder and Moore (1981) illustrates this concept. The area of favorable habitat is the "area of overlap" of dynamic (e.g., salinity) and stationary (e.g., bottom type, or shoreline) habitat.

Alteration in freshwater inflow can shift the range of salinities occurring within an estuary, changing the positions of isohalines and reducing the overlap of favorable salinities with favorable stationary habitat. Browder and Wang (1988) used a tidally-averaged computer model to estimate the salinity contours of Faka Union Bay under different freshwater inflow rates. Flows of 200 cfs established a range of salinities from 19 to 24 ppt within the bay (Fig. 4A), whereas at flows of 1500 cfs, the entire bay lay within salinities from 4 to 8 ppt (Fig. 4D). The relative abundance of several fish species in the bay over time was correlated with estimated bay surface area within certain salinity ranges. Browder and Wang (1988) estimated that a flow reduction to roughly 30% of the present variable flow was necessary to optimize fish production in Faka Union Bay. Clearly, alteration in freshwater flow can shift the range of salinities occurring within an estuary, and fish appear to respond to the change.

Estuarine organisms, which have evolved to occupy an area in which salinities vary with tide and season and from one location to another, have a higher tolerance to variable salinities than oceanic organisms. Nevertheless, detailed studies of a few species suggest they occur at highest densities within certain salinity ranges. These desired salinity ranges vary with age in some species. Their postlarvae settle out of the plankton in the upper, fresher reaches of the estuary, then gradually move to deeper, higher salinity areas as they grow (Gunter 1945, Hansen 1970, Rogers et al. 1984).

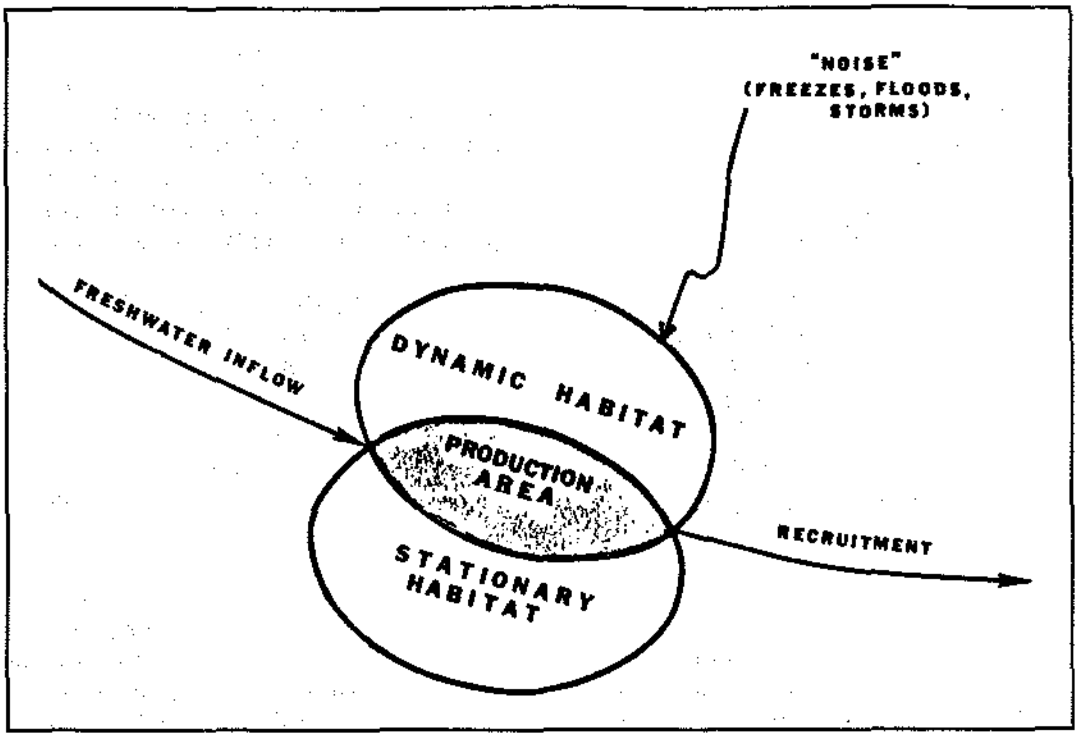

Figure 3. Suggested relationship of freshwater inflow to fisheries production through its effect on area of overlap of favorable dynamic and favorable stationary habitat (from Browder and Moore 1981).

Control of predators, parasites, or competitors may be a major basis for the importance of estuaries as nursery habitat (Gunter 1961). The tolerance of estuarine-dependent species to low and variable salinities provides them with a refuge from predators and parasites that cannot tolerate such conditions, including most species of marine fish.

One might think that the original animal community would be replaced by another in response to a change in the estuary's salinity regime. This was not, however, the case in Faka Union Bay. After more than 10 years to adjust to higher freshwater discharges, the dominant species in Faka Union Bay were the same as those in adjacent bays—just present in reduced number (Browder et al. 1986).

Salinity distributions may affect fish production secondarily by controlling the production of benthic organisms fed on by many estuarine-dependent fish species. Seagrasses and benthic organisms may be particularly vulnerable to changes in salinity regime. In his study of Myakka River, Estevez (1986, 1987) found lowest densities of benthic fauna in the region where salinities ranged from <1 to 10 ppt. Kinne (1971) refers to the salinity range 5-8 ppt as the "horohalinicum" and considers it a significant ecophysiological boundary line characterized by a minimum number of species. The benthic production of an estuary could be greatly reduced by a change in freshwater inflow that increased the bottom area subjected to unfavorable salinities.

The position of isohalines within an estuary varies tidally and seasonally and can also vary with depth (Estevez 1986, 1987). Referring to Florida tidal rivers, McPherson and Hammett (1991) commented that the seasonal movement is usually greater than the daily movement resulting from tides alone. Since seasonal peaks in spawning occur in most estuarine-dependent species, it is important that the area of overlap of favorable salinities with favorable structural habitat is maximized when estuarine nursery grounds are most needed.

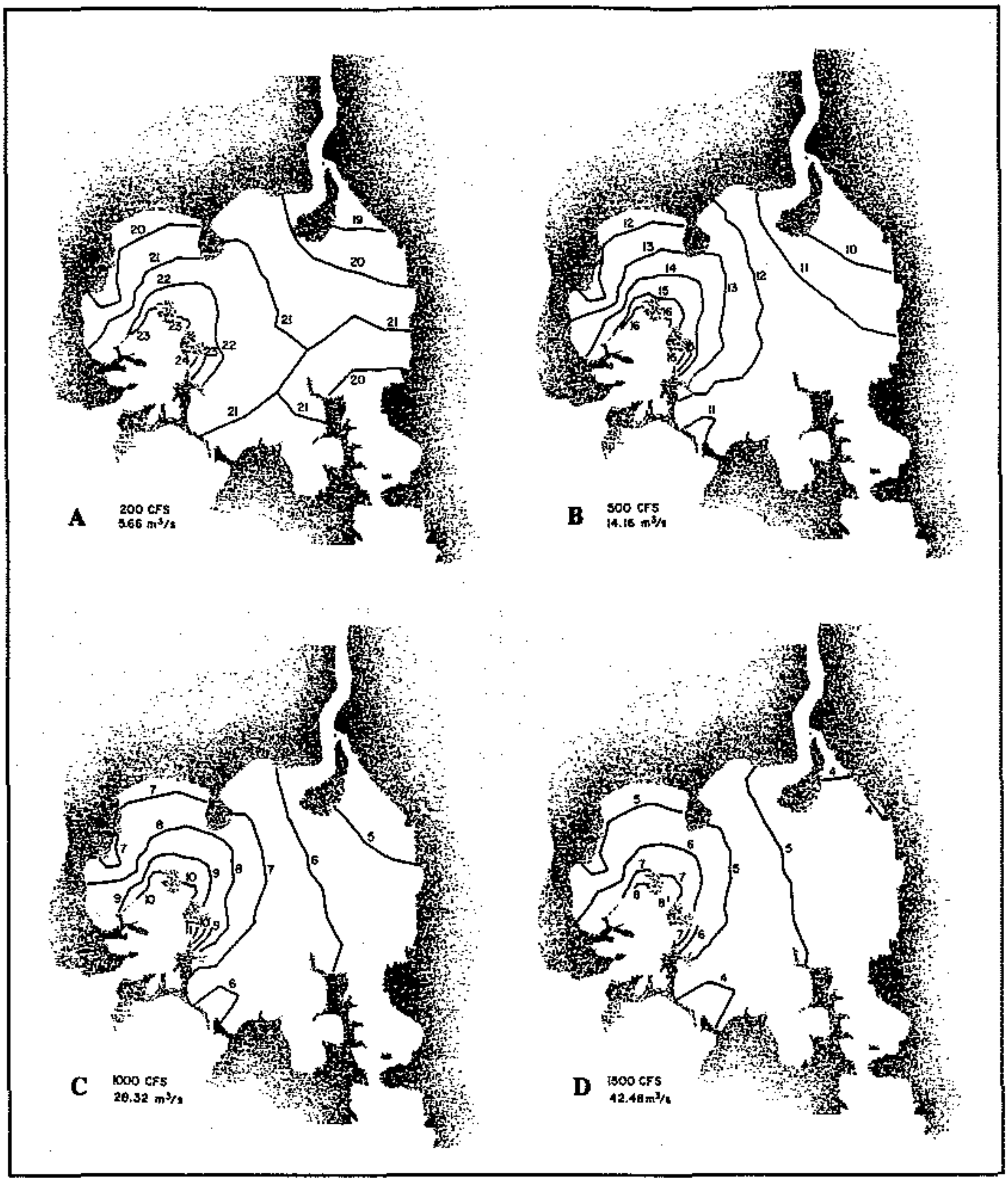

Figure 4. Simulated isohalines (in parts per thousand) in Faka Union Bay for canal discharge rates of A) 200 cfs (5.66 m^3/s); B) 500 cfs (14.16 m^3/s); C) 1000 cfs (28.32 m^3/s); D) 1500 cfs (42.48 m^3/s) (from Browder and Wang 1988).

Freshwater flow drives the circulation of the estuary. According to Sinclair et al. (1985), freshwater inflow into the Gulf of St. Lawrence can move nearly 30 times its own volume. The effect of freshwater inflow on mixing dynamics varies by estuary, depending on the volume of flow within a tidal cycle relative to the tidal prism (Hansen and Rattray 1966). (Tidal prism is the volume of the estuary between high and low tide.) Estuarine mixing dynamics can be affected by changes in freshwater inflow.

Circulation patterns affect retention of plankton within the estuary and the immigration of larval fish and shellfish into the estuary from offshore waters. Different strategies may be required for offshore-spawned ichthyoplankton to move into estuaries with different mixing characteristics. For instance, a wedge of salty bottom water penetrates the inlet of a stratified estuary or the mouth of a stratified tidal river, moving landward, even during ebb tide, while surface water is moving seaward. The best strategy for ichthyoplankton entering this type of estuary might be to stay continuously in the bottom water. On the other hand, the entire water column moves in the same direction with the tide in a well mixed or partially mixed estuary, but the bottom water moves more slowly because of bottom friction. Ichthyoplankton may move vertically with the tide, taking advantage of the differential movement of surface and bottom water, to enter a well mixed or partially mixed estuary. The behavior of migrating larval fish and shellfish may be a factor that determines the estuaries in which they are found. (See Leggett [1984], Miller [1984], and Norcross and Shaw [1984] for reviews concerning larval transport into estuaries.)

Browder et al. (1988) compared ichthyoplankton concentrations in the respective passes leading from the Gulf of Mexico into Faka Union Bay and two adjacent bays receiving lesser volumes of freshwater inflow. Relative concentrations in the transport streams varied differently, depending upon species. But most species were found in higher concentrations in the moderate and low flow streams than in the high flow stream influenced by the canal discharges.

Other planktonic organisms also respond to currents resulting from freshwater inflow. According to Smetacek (1985), various phytoplankton and zooplankton can maintain a geographically constant position within an estuary because of their shape, density, or behavior. Strategies vary by taxon and according to different flow velocities, causing shifts in taxonomic composition that could affect primary production and energy flow through the food web. In northern San Francisco Bay, diatoms were favored by moderate flows but were selected against by high flows (Smetacek 1985). Under moderate flow conditions, the high specific gravity of the dominant diatoms allowed them to sink quickly to the bottom, from which they could regenerate in approximately the same location. On the other hand, high flow conditions flushed them out to sea. Drought periods also selected against diatom blooms, possibly because of changes in mixing dynamics due to lack of fresh water.

The inflow of fresh water to many estuaries varies seasonally. In south Florida, for instance, runoff is greater during summer and fall than during winter and spring. The mixing regime of an estuary thus may vary from one time of year to another. The timing of favorable mixing conditions relative to spawning may be critical to recruitment of larval fish spawned offshore. The timing of spawning, the migration behavior of plankton and larval fish and shellfish, and habitat requirements of juvenile fish may be adapted to the seasonal cycle. Disrupting the timing of flow could be disruptive to these populations. Fishery production may depend upon maintenance of a seasonal flow pattern.

Dams operated for hydroelectric power generation and cooling water for power plants can change the seasonality of outflow with damaging consequences to fisheries. The shrimp fishery in Sabine Lake, Texas, was decimated by the Toledo Bend Dam on the Sabine River (White and Perret 1974). Because of heavy summer demand for air conditioning, high winter discharges were held behind the dam and released in the spring and summer. This schedule of releases interfered with the use of Sabine Lake as a nursery ground by brown shrimp (*Penaeus aztecus*) in the spring and white shrimp (*Penaeus setiferus*) in the summer. Both species required the relatively higher salinities that occurred naturally in Sabine Lake during their nursery periods.

The relative magnitude of dry season flows may be more critical to fishery production than that of wet season flows. The American oyster (*Crassostrea virginica*) is a traditional fishery species in Apalachicola Bay, Florida, and an indicator organism used in evaluating the ecological health of the bay. Wilbur (in prep.) found that oyster production was positively related to the volume of freshwater flow during the dry season two and three years prior to harvest. Predation on oysters is thought to be controlled by salinity, with lower salinities favoring oyster survival (see Browder and Moore [1981] and Wilbur [in prep.] for reviews). The 2- and 3-year delay in effect suggests that higher dry season flows reduced predation on oyster spat.

Estuarine salinities may be particularly sensitive to changes in dry season inflows. In Faka Union Bay, a small change in inflow at the low end of the inflow scale prompted a much greater change in salinity than a flow change at the high end (Fig. 5). If the relationship between salinity and freshwater inflow in Faka Union Bay is typical, then small variations in freshwater inflow during the dry season may strongly affect salinities during that time.

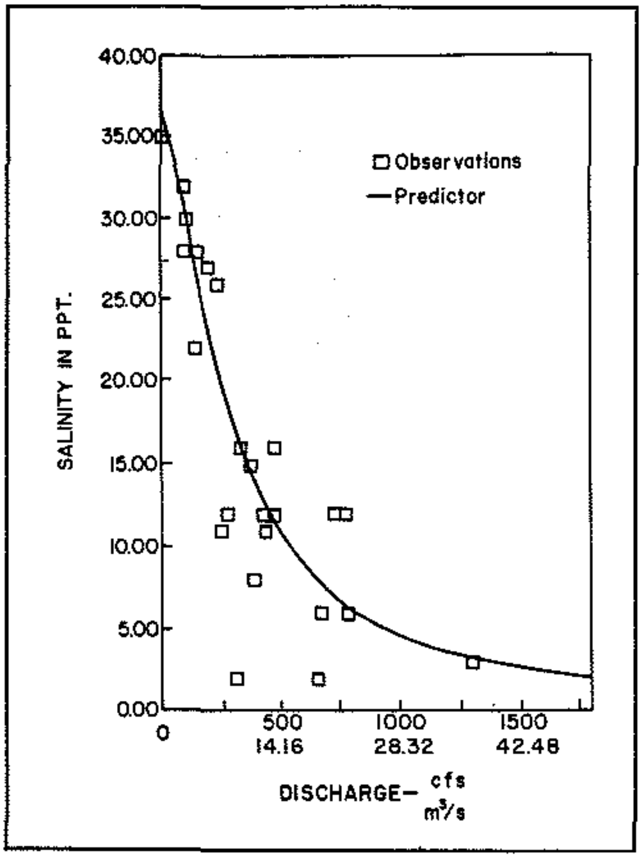

Figure 5. Measured salinity at one station in Faka Union Bay vs. canal discharge, measured for the previous 10 days, with curve of "best-least-squares-fit" hyperbolic function superimposed (from Browder and Wang 1988).

Because of the differential sensitivity of salinities to freshwater inflow, isohalines in tidal rivers and estuaries can be expected to shift a greater distance with a change in freshwater inflow at the low end of the scale than at the high end. The location of isohalines in tidal rivers and the estuaries will be particularly sensitive to change in freshwater inflow during the spring of the year, when flows are lowest and least dependable. A shift in isohalines could eliminate nursery habitat that otherwise would be favorable.

The area of favorable habitat may be particularly vulnerable to natural or man-induced alterations in freshwater inflow in the spring. Peak spawning by many estuarine organisms occurs in the late winter and early spring, when the availability of suitable habitat is least assured.

Evaporation removes fresh water from the estuary, leaving salt behind. Estuaries need enough fresh water to replace evaporative loss just to keep the estuary from becoming hypersaline, particularly if the rate of mixing with oceanic water is low.

THE EFFECT OF WATERSHED ALTERATIONS ON FRESHWATER INFLOW

The volume and timing of freshwater inflow is a function of the watershed—its rainfall pattern and hydrologic structure. Runoff to an estuary usually is directly associated with rainfall over the watershed. In the natural, unmodified, watershed there is a lag between rainfall events and related runoff events. The lag is a function of the amount of storage in the watershed. Some of this is "dynamic" storage in which the water never stops moving and yet moves so slowly, as sheet flow or ground water, that its outflow is substantially delayed. The storage and later, gradual release of wet season surplus provides the base flow that sustains rivers and estuaries during the dry season. This process is very important in areas with seasonal rainfall.

Alterations in the watershed affect the timing and volume of fresh water inflow, as Table 1, adapted from Browder and Moore (1981), describes. Discharge amplitude increases and discharge duration decreases with several types of alteration: 1) reduction in surface permeability or permeable area, as, for instance by construction of parking lots and other paved surfaces; 2) clearcutting or elimination of forested area; 3) agricultural tillage; and 4) increased channelization. Activites such as these decrease the ability of the basin to hold water in dynamic storage. The result is increased wet season flows and total flows, but decreased dry season or base flows. Base flows may be the most crucial flows to survival and growth of many estuarine organisms.

Table 1. Summary of major effects of basin alterations on volume of freshwater inflow.

	INCREASED PEAK FLOW	DECREASED PEAK FLOW	INCREASED DRY SEASON FLOW	DECREASED DRY SEASON FLOW	INCREASED TOTAL FLOW	DECREASED TOTAL FLOW
Dams		P	P*	P*		P*
Consumption		P		P		P
Diversions	P*	P*	P*	P*	P*	P*
Canals	P		P	P		
Deforestation	P			P	P	
Clearcutting	T			T	T	
Roads	P*	T*		P	P*	T*
Paving	P			P	P	

P = Permanent effect
T = Temporary effect
* = Increase or decrease

Dams and upstream water consumption also influence freshwater inflow to the estuary. The effect of dams varies according to their use and the philosophy of their management. A dam can change the seasonality of flow, sometimes drastically and to great detriment, as was the case in Sabine Lake. The operating policy of some dams eliminates freshwater flow to the estuary entirely.

Browder (1976) constructed a simple water model driven by monthly rainfall to study the southwest Florida wetlands that sustain the Wood Stork (*Mycteria americana*). Using the same time series of actual monthly rainfall, I predicted the temporal variation in water table, land surface covered by water, and freshwater runoff under present conditions and in the unaltered watershed prior to drainage. The time series exemplified seasonal and interannual variation in rainfall. Results suggested there was 1) a delay between peak rainfall and peak runoff, 2) a consistently lower volume of annual runoff, and 3) a higher water table and more flow during the dry season in the natural system than in the altered system. The monthly rainfall series used as input and resultant simulated runoff under natural (d) and altered conditions (c) are shown in Figure 6. Wet season flow is highest under altered conditions, but dry season flow is highest under natural conditions. Both runoff and seepage to the coast are functions of water table elevation relative to sea level.

Using models to reconstruct the natural system and evaluate the characteristics of the freshwater flow pattern relative to rainfall under natural conditions is a powerful way to get one's bearings when evaluating impacts of watershed alterations and planning restoration. The Everglades experience demonstrates the usefulness of a model that approximates natural conditions to compare with altered conditions. In a recent cooperative activity involving the University of Florida, the South Florida Water Management District, and Everglades National Park, a hydrologic computer model was used to simulate the natural flow of water through the Florida Everglades to the southwest coast and Florida Bay (Walters et al., in press). The hydrologic functioning of this watershed has been greatly altered by a system of canals, levees, and flow control structures. The model suggested that the base, or dry season, flow toward the coast resulting from a given rainfall pattern would be greater under natural conditions than under present conditions, given the same rainfall. Now federal and state agencies have a better idea what the natural flow pattern was like and how the present flow pattern differs. This information gives direction to their restoration efforts. Although there may not be sufficient water in south Florida to reconstruct wet season flows, it might be possible, through planned new structures and revised operating schedules, to increase dry season flows to a more natural level and to re-establish a more natural seasonal pattern.

Developing a hydrologic model of its watersheds to simulate natural (i.e., pre-development) water flow to Tampa Bay might give added power and direction to Tampa Bay restoration efforts. Then natural flows could be compared to altered flows simulated under the same rainfall conditions. If flows are simulated on at least a monthly basis, then differences in the seasonal variation as well as the total volume of flows under the two conditions—present and natural—could be distinguished. Since groundwater flow from the Floridan aquifer may be an important source of flow to Tampa Bay, this water input should be included in the model. The flow from each river basin should be simulated separately, since each watershed is different and may have been altered in different ways. It is important to simulate natural flows on at least a monthly basis to compare the present seasonal pattern to the natural pattern. It also is important to account for instream alterations to flow, such as impoundment effects.

A second important step would be to use the output of the watershed model as input to a circulation and salinity model of Tampa Bay and the tidal portions of the rivers. One could then see what the historical salinity regime and circulation patterns of each area might have been like and how changes in freshwater inflow may have affected these dynamic characteristics. The models could be used to estimate, for each watershed, the freshwater flow regime that would be necessary to maximize the area in which favorable salinities coincide with favorable structural habitat for juvenile fish and shellfish. The combinations of salinities and structural habitat characteristics that create favorable habitats can be determined from the nearest rivers or estuaries still in relatively undisturbed condition (e.g., the Little Manatee and Myakka Rivers). This information could be used in planning watershed management and in planning a more natural schedule of seasonal releases of water from dams.

HYDROLOGIC EFFECTS ON WATER QUALITY

There is a connection between water quality and the hydrologic characteristics of a watershed. Water quality can be improved by restoring more natural hydrologic functioning. Further water quality degradation can be prevented by preserving natural hydrologic function in land use planning and permitting. High infiltration capability and dynamic storage capacity are essential features of the natural

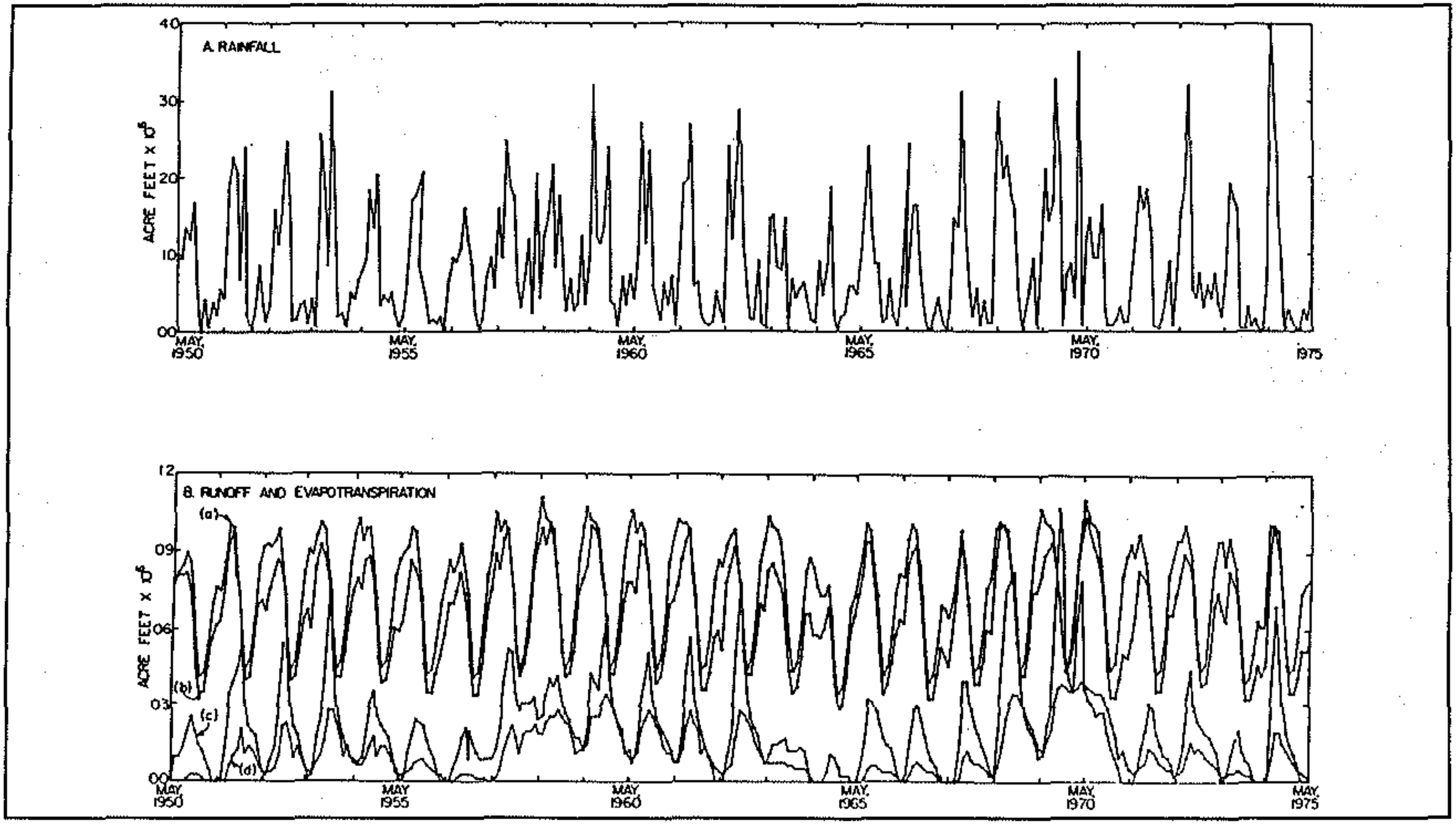

Figure 6. Monthly Ft. Myers rainfall and simulated evapotranspiration and runoff for Collier, Lee, and Hendry Counties under present (1975) and predrainage conditions (from Browder 1976). (a) evapotranspiration under present conditions; (b) evapotranspiration under natural, predrainage conditions; (c) runoff under present conditions; (d) runoff under natural, predrainage conditions.

watershed. Percolation through the top soil is particularly important because of the high concentration of organic material in the top few inches of soil. Nutrients and contaminants adsorb to organic material. Retaining water within the watershed for a longer period not only promotes infiltration but also provides the opportunity for nutrients and contaminants to be removed by plants and soils.

Several landscape structural features and management practices promote infiltration through top soil and increased dynamic storage capacity:

- using pervious surface for parking areas;
- substituting grassy swales for curbs and gutters;
- establishing green belts and corridors;
- establishing buffer strips of canopy vegetation along natural and man-made waterways;
- restoring or creating wetlands; and
- minimizing the number of drainage ditches and canals and their lengths.

Widespread application of these structures and practices should maintain or restore more natural hydrologic functioning and higher water quality.

Permeable surface is a critical factor to infiltration. The amount of permeable surface can be increased by using pervious substrates for parking. The use of pervious pavement increases the ratio of permeable to impermeable surface.

The use of grassy swales for drainage is an effective way of re-establishing a more natural runoff pattern and improving water quality. Substitution of grassy swales for curbs and gutters increases the rate of water infiltration through top soil.

The creation of green belts and corridors is another way to increase or protect permeable surface. Corridors can be particularly effective in re-establishing or maintaining more natural hydrologic function because they can provide a long border of permeable surface adjacent to paved areas. Emphasis should be on native vegetation and natural landscapes that need little or no watering or fertilizer after establishment.

The use of existing and recreated wetlands for dynamic water storage and cleaning is another way to maintain or improve water quality. Aquatic vegetation and organic marsh soils are particularly effective in taking up nutrients and contaminants (Krottje et al. 1981, Dierbert and Brezonik 1985).

Nutrient loading rates can be decreased by decreasing the length of ditches and canals. In an analysis of phosphorus loading to Lake Okeechobee, Fluck et al. (1990) found that the loading rate was positively related to drainage density, the length of streams and canals per unit area of each drainage basin. Conversely, storage of phosphorus within the drainage basin was negatively related to drainage density.

Restoring or preserving the natural hydrologic functioning of the watershed will be beneficial to water quality. Maximizing dynamic storage and infiltration is an effective means of reducing pollutant loading from nonpoint sources.

SUMMARY

1. The demand for seafood is increasing in the U.S.
2. The ability of estuaries to produce seafood is decreasing.
3. Estuaries are nursery habitat for many species that spawn offshore and are harvested offshore.
4. Estuaries have been degraded by man's activities.
5. Changes in freshwater inflow may be the greatest ultimate danger to estuaries because the impacts are poorly recognized and estuarine water rights are poorly protected.
6. Freshwater inflow affects estuarine productivity by establishing salinity, circulation, and nutrient patterns.
7. Relationships between freshwater flow and estuarine production have been identified by studies in the U.S., Africa, and Europe.

8. An estuary can be damaged by getting too much freshwater flow as well as by getting too little.
9. The ideal flow rate for a given estuary may be the one that maximizes the overlap between favorable salinities and favorable bottom and shoreline characteristics.
10. Salinity contours can be modeled as a function of freshwater inflow.
11. If Faka Union Bay is typical, then bay salinities may be more sensitive to change in freshwater inflow near the low end of the inflow range than at the high end.
12. Freshwater inflow affects estuarine circulation. In the Gulf of St. Lawrence, freshwater inflow moved as much as 30 times its own volume.
13. The seasonal distribution of freshwater flow may be important to estuarine organisms. Changing the timing and volume of freshwater inflow may disrupt larval fish immigration and degrade juvenile habitat.
14. Structure and behavioral strategies allow plankton to maintain a fixed geographical location in estuaries and ichthyoplankton to migrate into estuaries. The strategies of existing populations may be suited to natural freshwater flow conditions. Changing the timing and volume of freshwater flow may select against some naturally occurring species.
15. Alterations in the watershed affect the timing and volume of freshwater inflow. Most common alterations increase wet season discharges and the annual volume of flow but decrease dry season flow. Dams and upstream water consumption can decrease annual flow volume and radically change timing.
16. Hydrologic models that simulate freshwater flow from each watershed as a function of rainfall on a monthly (or higher frequency) basis can provide useful perspective on how the present flow pattern differs from the natural flow that supported the estuary.
17. A salinity and circulation model that receives the outflow of the hydrologic models would help determine the most favorable flows for Tampa Bay.
18. The effects of structural modifications to the bay and its tidal tributaries on salinity and circulation patterns need to be examined.
19. Water quality can be improved by creating a more natural pattern of runoff relative to rainfall in the watershed. Some best management practices that accomplish this are: 1) increasing permeable surface by using pervious paving in parking lots, 2) replacing curbs and gutters with grassy swales, 3) creating green corridors and green belts, 4) establishing buffer strips along waterways, 5) restoring or creating wetland, and 6) eliminating ditches and canals.

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PAST, PRESENT AND FUTURE FRESHWATER INFLOW TO TAMPA BAY — EFFECTS OF A CHANGING WATERSHED

H. W. Zarbock

INTRODUCTION

The fact that extensive urban and agricultural land development has occurred in the Tampa Bay watershed is well documented. This paper provides a short, informal discussion of some of the effects of these changes, including the distribution and variation in selected freshwater flow patterns and water quality characteristics that have changed as a result of these development activities.

TAMPA BAY WATERSHED

The Tampa Bay estuary is located on the west central coast of Florida, and opens to the Gulf of Mexico. The tributary watershed, or drainage basin, encompasses approximately 2300 square miles and includes all or parts of six counties. The coastal cities of St. Petersburg, Tampa and Bradenton, and several other urban centers, are located within the watershed.

The land that drains to Tampa Bay contains nine major subbasins and 76 minor subbasins, as delineated for the Tampa Bay Urban Stormwater Analysis and Improvement Study (USAI; Dames & Moore 1990), a SWIM project for the Southwest Florida Water Management District (SWFWMD). The bay's major surface tributaries include the Hillsborough, Alafia, Little Manatee and Manatee Rivers. Minor tributaries include Alligator Creek, Joe's Creek and numerous other coastal streams in Pinellas County; Rocky Creek, Double Branch Creek and Sweetwater Creek in northwest Hillsborough County; the Tampa Bypass Canal, Delaney Creek and Bullfrog Creek in central and south Hillsborough County; and Frog Creek and other coastal streams in Manatee County. Tampa Bay's tributaries and subbasin areas have been previously inventoried and reviewed in detail, most notably by Flannery (1989), Dames & Moore (1990), Lewis and Estevez (1988), Dooris and Dooris (1985) and others.

Tampa Bay, as an estuary, is profoundly influenced by tributary freshwater inflow quantities and patterns, and the resultant interaction of salt and fresh waters. Water quality characteristics and the dependent biotic communities are therefore subject to impacts and changes based on the distribution and variation in freshwater inflows to the bay.

Historical Conditions

Prior to western colonization of the land surrounding Tampa Bay and up to the mid-1800s, these freshwater inflows (including both surface and groundwater sources), were primarily determined by an often long-established set of natural parameters. These features included topography and extent of the watershed, soils distribution, vegetative cover and hydrogeology.

The one major variable in this system was the weather, specifically rainfall. That is, given the set of natural watershed characteristics, the extent and timing of freshwater inflows to Tampa Bay were determined by rainfall patterns. This is a function of rainfall seasonal variation, long-term trends and spatial differences in rainfall patterns. It is well established that the Tampa Bay area experiences distinct seasonal rainfall cycles, with approximately 60% of the annual precipitation falling in the wet season months of June to September. This presents a dynamic state of antecedent conditions and is important for ecological concerns, but becomes unimportant for an analysis of runoff based on annual values.

Recent work by the Southwest Florida Water Management District has indicated that identifiable long term trends in annual rainfall amounts in certain subbasins are insufficient to account for observed changes in freshwater inflow patterns (Flannery, in review). Multi-year cycles can be discerned, but these can be ignored for an analysis that uses the average annual amount for the period of record (up to 50 years for some stations). This strongly suggests that changes in freshwater inflow to Tampa Bay are greatly influenced by anthropogenic factors.

Spatial variation in average annual rainfall for the bay and watershed does exist. Precipitation amounts range from a low of near 50"/yr near Tampa International Airport to highs of near 55"/yr at the northern and southern extremes of the watershed. These area-specific values are used in the determination of runoff loadings as described below.

Beginnings of Significant Inflow Alterations

By the 1950s significant changes had occurred to the watershed. Urban development had begun to spread, resulting in increased land clearing and more impervious surface within the watershed. Drainage patterns had been changed with ditching, canals, channelization of streams and rivers, and by the construction of surface impoundments such as the Hillsborough River reservoir. Additionally, agricultural uses became more intensive, resulting in rural land clearing, draining marginal lands and groundwater pumping, as well as the increased application of pesticides and fertilizers. Finally, large-scale alterations to the watershed landscape began to occur, as associated with phosphate mining. These activities all have far-reaching impacts to freshwater flow to the bay.

This time period is also important because it represents the effective beginning of the accumulation of hydrologic records for the bay and watershed. The U.S. Geological Survey (USGS) and other groups began stream flow, water quality and groundwater elevation monitoring, although often with sparse surviving data, over much of the watershed during these early years of data collection.

Existing Watershed Conditions

Moving forward to the present day, all of the above effects have greatly intensified. During this time, urban development has vastly increased in extent and intensity. Large scale hydrologic alterations are present, such as the Tampa Bypass Canal system, Lake Tarpon Outfall, harbor channel deepening, and the establishment of additional impoundments for potable water sources (such as the Lake Manatee Reservoir on the Manatee River) and industrial uses (such as Florida Power & Light's Point Manatee Power Plant reservoir on the Little Manatee River). Also, numerous minor works such as drainage and mosquito control ditches have been put in place. Many of the previously unused rural areas have been put into agricultural usage, resulting in more land clearing and drainage.

Of great value for investigating the hydrologic effects of these activities is the extensive hydrologic database that now exists for Tampa Bay and its tributaries and watershed. These data include the numerous published reports by USGS, SWFWMD and others addressing issues of the bay, voluminous databases such as WATSTORE and STORET, and forums like the Tampa Bay Area Scientific Information Symposium (BASIS).

POTENTIAL CONSEQUENCES OF WATERSHED ALTERATION

The significance of these watershed changes to the freshwater flows into Tampa Bay includes:

- Another variable has been added to the previously naturally regulated hydrologic system—urban and agricultural development with its relatively swiftly changing land uses and alterations to natural flow patterns.
- Freshwater inflows caused by runoff now react even more rapidly to rainfall events. Naturally varying physical features such as topography, soils and land cover are replaced by uniform characteristics typifying

development—flat, hard, smooth land surfaces and linear, channelized surface water conveyances.

The consequences of these activities to freshwater inflow patterns can be observed, and make it possible to make some predictions about the response of runoff and seepage patterns to these changing land use and water use characteristics:

- The watershed subbasin boundaries can change because of ditching, dikes, or general earthmoving.
- Natural storage in many topographic depressions will be reduced or eliminated.
- Surficial soils are covered over, eliminating or greatly reducing natural storage in soil pore spaces.
- Impervious surfaces reduce vegetative cover and decrease residence time in upstream areas, thus reducing infiltration, evapotranspiration, and settling or uptake of dissolved or suspended water quality parameters.
- Straight, smooth channels encourage faster response time of subbasins to rainfall. Runoff hydrographs are shorter with higher peaks.
- Hardened shorelines reduce bank storage discharge.
- Lowered water table reduces overall groundwater seepage such as bank storage to freshwater tributaries and the bay.

Two major questions to be determined are: 1) how much have urbanization and agriculturalization affected freshwater inflows to Tampa Bay, and 2) can we tell what impacts have occurred, and why?

To answer question 2 first: for our historical period (pre-1850) we can only know about pre-existing conditions through anecdotal accounts and a few pictures—the "travelogue" caliber of discussion. Many travelers, from DeSoto on, have described Tampa Bay as having clear water and an abundance of wildlife.

We can also guess at past freshwater inflow patterns based on our current knowledge of hydrology and historical or reconstructed maps. Using such methods as the Rational Formula or other more sophisticated runoff algorithms, and our best estimate of the type and extent of past natural watershed characteristics, generalized assessments of freshwater flow to the bay can be made. Quantifying these impacts is the subject of ongoing study for both the hydrological and biological research communities in the Tampa Bay area.

DISCUSSION OF SELECTED IMPACTS

Freshwater Flow Response to Development — Steady State

One hydrologic characteristic that can be examined is the overall flow rate of freshwater to Tampa Bay. Using existing data and estimates of past conditions, changes in total flow to the bay can be developed. A Geographic Information System (GIS)/spreadsheet-based model similar to the one used to calculate nonpoint source pollutant loadings to the bay for the SWIM Tampa Bay USAI study was used to estimate pre-development average annual freshwater runoff flows to Tampa Bay.

Using the Environmental Protection Commission of Hillsborough County's map for probable land cover from 1820 and USDA Soil Conservation Service Soil Surveys, a "no-development" runoff loading scenario for the watershed was developed. This scenario uses estimated acreages of upland wooded areas, grasslands, wetlands and open water to determine probable annual runoff volumes generated in the watershed. Figure 1 illustrates the methodology used with this model for runoff calculations. Soils and drainage characteristics, land cover and precipitation values are used to determine runoff rates for each subbasin. This results in runoff volumes that can be expressed as either volume per acre, or volume per time increment, say one year.

Table 1 summarizes the findings of this scenario. Runoff volumes for the current and "no-development" situation are compared to other current flow rate estimates. These results are compatible with some other estimates of average freshwater flow to the bay. Dooris and Dooris (1985) estimated average total flow from seven gaged streams to the bay at 1,792 cfs. Goodwin (1987) estimated total gaged flow to the bay at 1,904 cfs. Hutchinson estimated ungaged flow to the bay at 344 cfs, for a total freshwater flow of 2,245 cfs. Most recently, Flannery (1989) accounted for withdrawals from the major rivers and made an estimate of total tributary flow to the bay of 2,011 cfs.

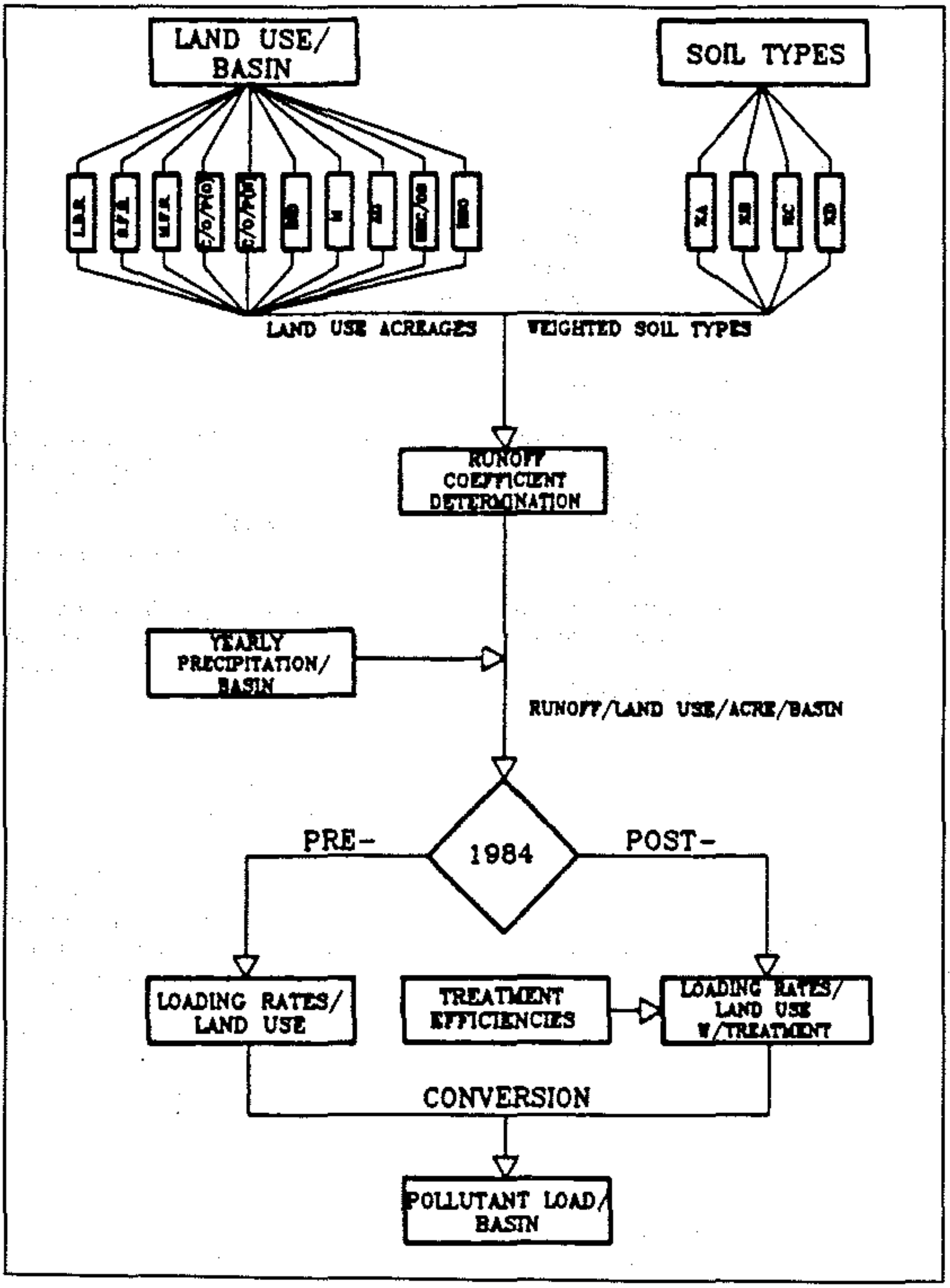

Figure 1. Flow diagram, subbasin analysis.

Table 1. Estimated average daily freshwater inflows to Tampa Bay.

SOURCE	FLOW (cfs)
Current Conditions	
Dooris & Dooris (1985)	1,792
Goodwin/Hutchinson (1987)	2,245
Flannery (1989)	2,011
Dames & Moore (1990)	2,530
Historical Conditions	
Dames & Moore (1991)	2,280*

*Based on annual average rainfall.

These results are interesting for two reasons. First, the estimates for recent or current average daily inflow to Tampa Bay vary over a range of approximately 30% from the low value of 1,792 cubic feet per day (cfs) (Dooris & Dooris) to the high value of 2530 cfs (Dames & Moore). Although this latter estimate is based on flow "off the land" and does not account for routing or travel time in tributaries, it does include all of the watershed, and not only the gaged areas.

The second point is that the spreadsheet model estimates vary on the basis of changing land use and subsequent runoff characteristics. The pre-development value, 2280 cfs, is smaller than the current inflow estimate of 2530 cfs by approximately 10%. In the model, this difference is mainly attributable to changing amounts of impervious area and the reduction over time of the natural soils' infiltration capacity. In this exercise, the spreadsheet model does not directly account for either groundwater seepage or such flow alterations as impoundments or stream withdrawals. However, the average flow rates do not account for such important factors as timing, seasonality, and low-flow regimes.

Therefore, this analysis suggests that development activities, including both urban and agricultural land uses, have affected freshwater flow to Tampa Bay on an annual basis. The lack of impervious surfaces and linear surface water conveyances such as ditches and culverts cause more water to be retained in upstream areas in the watershed, where it can be subject to infiltration, evapotranspiration, and storage. As stated above, this spreadsheet analysis does not account for surface water captured in impoundments or reservoirs. The effects of these impacts need to be factored into the overall water budget for a comprehensive inventory of freshwater inflows.

Nonpoint Source Loadings from the Watershed

In addition to freshwater inflow daily values, various water quality constituent loadings to the bay can be estimated using the GIS/spreadsheet model. For the Tampa Bay USAI study an extensive literature search of stormwater quality monitoring studies from the west central Florida area resulted in the development of a list of pollutant loading rates for typical runoff from ten different land uses as shown in Table 2. These loading rates were factored into the runoff equations to derive potential pollutant loadings from the watershed. This methodology was used to investigate watershed changes as relating to bay loadings.

Using the no-development scenario, loading rates for natural uplands and wetlands were utilized to estimate historical loadings to the bay of total nitrogen (TN), total phosphorus (TP), ortho-phosphate (OP), biochemical oxygen demand (BOD) and total suspended solids (TSS). Although these loading rates were developed from modern land uses and may be influenced by surrounding urban activities, these values represent the most extensive and representative information available for estimating nonpoint source loads to Tampa Bay.

Table 2. Summary of nonpoint source loading rates from central and west central Florida (Tampa Bay USAI; Dames & Moore and Environmental Research and Design, Inc. 1990).

	RUNOFF CONCENTRATION (mg/l)										
PARAMETER	LOW DENSITY RESIDENTIAL[1]	SINGLE-FAMILY	MULTI-FAMILY	LOW INTENSITY COMMERCIAL	HIGH INTENSITY COMMERCIAL	INDUS-TRIAL	AGRI-CULTURAL	REC./ OPEN	MINING	WETLAND	OPEN WATER LAKE
Total N	1.68	2.17	2.28	1.06	2.83	1.79	2.32	1.25	1.18	1.60	1.25
Ortho-P	0.097	0.19	0.38	0.05	0.40	0.13	0.227	0.004	0.05	0.13	0.13
Total P	0.215	0.35	0.51	0.14	0.43	0.31	0.344	0.053	0.15	0.19	0.11
BOD	4.7	8.0	11.5	7.0	17.2	9.6	3.8	1.45	9.6[4]	4.7	1.6
S.S.	16.3	21.5	79.2	71.0	94.3	93.9	55.3	11.1	93.9[4]	10.2	3.1
Total Zn	0.037	0.067	0.060	0.079	0.170	0.122	0.028[2]	0.006[3]	0.122[4]	0.006	0.028
Total Pb	0.038	0.050	0.065	0.166	0.214	0.202	0.025[2]	0.025[3]	0.202[4]	0.025	0.025[3]
Percent Imp.	14.6	27.6	67.4	89.7	97.5	84.6	0.00	1.50	23.0	0.00	0.00
Runoff Coefficient	0.272	0.369	0.678	0.828	0.0887	0.793	0.304	0.175	0.361	0.225	0.500

[1]Average of single-family and recreational/open space loading rates.
[2]Runoff concentrations assumed equal to open water/lake values for these parameters.
[3]Runoff concentrations assumed equal to wetland values for these parameters.
[4]Runoff concentrations assumed equal to industrial values for these parameters.

Table 3 summarizes estimated potential nonpoint source TN, TP, OP, BOD and TSS loadings resulting from an analysis of the undeveloped watershed and from the circa 1950 scenario. These values are compared to estimates of current and future nonpoint source loads as calculated for the SWIM Tampa Bay USAI study. The current estimates account for the treatment of stormwater in permitted developments that are subject to surface water management rules, which were enacted in 1987.

Table 3. Estimated nonpoint source loadings from the Tampa Bay watershed (in million pounds per year).

	NONPOINT SOURCE LOADS				
TIME PERIOD	TN	TP	OP	BOD	TSS
circa 1820	4.05	0.17	0.04	4.98	36.2
circa 1950	8.50	1.07	0.75	24.3	187
1990	10.3	1.39	0.95	31.6	243
2020	10.4	1.37	0.96	36.8	238

It can be seen that total loadings for all parameters increase significantly between undeveloped and current conditions. Also, between current and future conditions, TN, OP and BOD increase, and TP and TSS decrease. This decrease is a function of similar loading rates between different land uses and the projected efficiency of surface water management systems now mandated for most new development. The increased values for some future scenario parameters suggest that even with surface water management regulations in place, the increased acreage of land uses with higher loading rates will offset the efficiencies of treatment facilities.

Freshwater Flow Response to Development — Event Response

Another indication of developmental impacts to freshwater flow can be seen in the response of runoff within an individual subbasin as a function of changing land use and drainage characteristics. Subbasins with more natural land cover are often characterized by slower overland flow and longer stream travel times, with moderate runoff hydrograph peaks after rainfall events and slowly receding flows as uplands drain and bank storage discharges through pervious river banks. In subbasins with more developed conditions surface flow can be expected to travel more quickly over impervious surfaces and through straight, smooth conveyance facilities. Individual subbasins can be studied to detect changes in runoff patterns that occur with increased urbanization.

An appropriate subbasin for such an analysis must meet several criteria. Land use in the subbasin must have undergone an extensive shift from a majority of undeveloped land to containing significant acreages of urban or agricultural land. Second, the period of record for hydrologic data collection must extend far enough into the past to include the time of significant land use changes. Finally, other factors must be generally constant or factored out, such as rainfall, the subbasin limits, and any overriding new features such as a large reservoir or other major drainage work.

Located in northwest Hillsborough County, the Rocky Creek subbasin appears to meet all these criteria. Much of the stream has been channelized, and the watershed area has undergone substantial urbanization within the past 25 years, with urban uses spreading and agricultural uses becoming more intensive (i.e., range land converted to citrus or row crops). Also, the period of record for USGS stream flow and quality data extends back to 1953. This ensures that hydrologic data has been collected during the period including the majority of developmental activities that have occurred in this subbasin.

Although other factors such as any point source inflows may influence the absolute values of the following analysis, the relative scale of such factors is not so significant as to invalidate the following work, which investigates the changes in one subbasin's runoff response to rainfall events over time with changing land use and stream channel morphology.

Figure 2 shows daily discharge values for water year 1989 for the USGS stream gage no. 02307000, Rocky Creek near Sulphur Springs. Several flow peaks are evident, indicating periods of higher flow in the creek caused by stormwater runoff. Figures 3 and 4 show daily discharges from the same site for water years 1954 and 1955. Although with a casual observance the three hydrographs look very similar, there are significant differences between the 1954-55 and the 1989 flow patterns.

A simple analysis was completed to determine if any change in stream flow in response to runoff can be detected between the 1954-55 and 1989 data. For this exercise, individual rain event runoff hydrographs were examined for the three years. Total precipitation and average flow for each year were noted. The hydraulic characteristic that was investigated was the rate of recession of the runoff hydrograph. The reduction in flow from hydrograph peak to pre-storm levels during the days after a rainfall event (with no additional rain) was examined to determine rate of reduction in stream flow per day.

This simple linear differential resulted in an interesting set of results, summarized in Table 4. We might expect the runoff hydrograph to rise and fall more quickly under developed conditions than undeveloped. For the noted number of observations, this was indicated to be the case. For events generating more than 10 cfs of additional flow, the fall in stream flow was 2 to 3.5 times as rapid for developed conditions. For flows of 10 cfs or under, the fall in stream flow was 2 to 4 times more rapid with developed conditions.

Although many factors may play a part in this observed difference in hydraulic behavior, it is suggested that the major reasons for the observed change in recession rates for the runoff hydrographs for Rocky Creek observed above are consistent with the previously discussed potential consequences of increased development within the watershed.

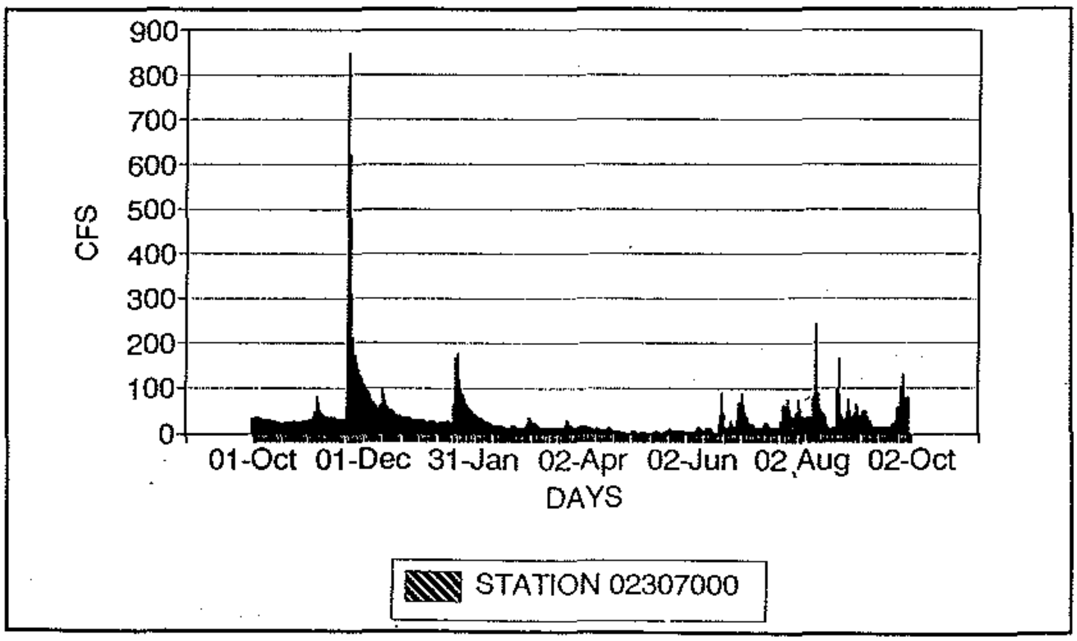

Figure 2. Rocky Creek daily average flow, 10/1/88 - 9/30/89.

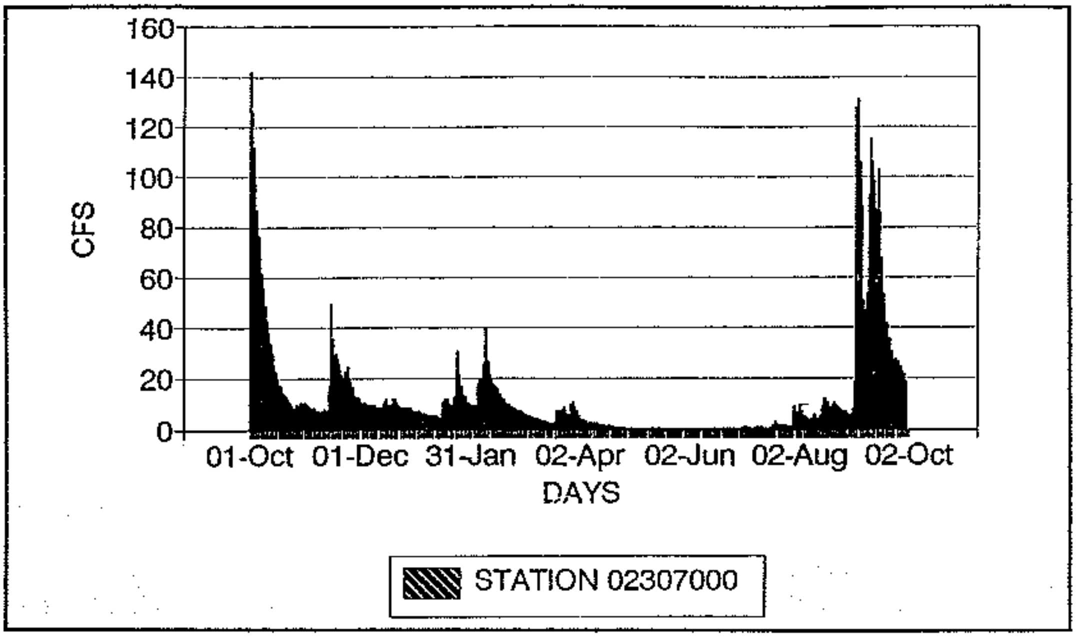

Figure 3. Rocky Creek daily average flow, 10/1/54 - 9/30/55.

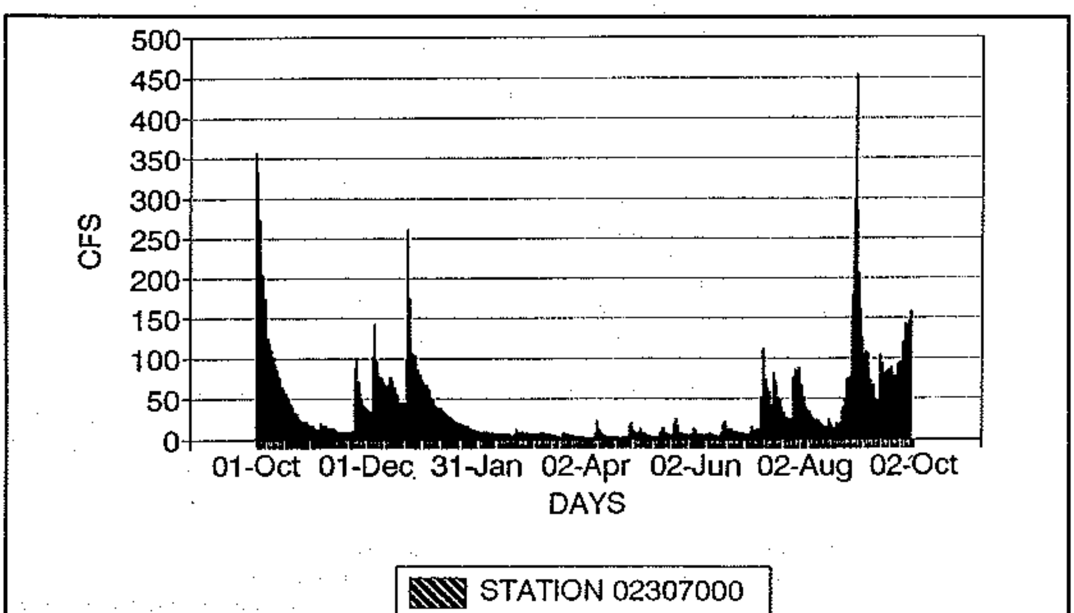

Figure 4. Rocky Creek daily average flow, 10/1/53 - 9/30/54.

Table 4. Comparison of runoff hydrograph recession rates, Rocky Creek near Sulphur Springs, Florida.

WATER YEAR	AVERAGE ANNUAL FLOW (cfs)	TOTAL ANNUAL PRECIP. (TIA) (in)	CHANGE IN STREAM FLOW PER DAY (cfs): FLOW >10 cfs	NUMBER OBS.	FLOW <10 cfs	NUMBER OBS.
1954	42.8	51	4.8	6	0.62	6
1955	14.4	47	2.8	5	0.30	5
Average (rural/undev.)	28.6	49	3.8		0.46	
1989	39.7	47	9.6	8	1.12	5

In summary, the major influences of increased urban and agricultural activities on freshwater inflow in the Tampa Bay watershed are:

1. Changes in net flow reaching the bay—increases from higher runoff rates and decreases from potable and industrial water use withdrawals;
2. More rapid rise and recession of runoff hydrographs results in a "spike" response to rain events, in addition to other temporal variations to runoff rates; and
3. Pollutant loadings change with runoff rates and land use types.

The overall effects of freshwater inflow variations and the resultant effects to the living resources of Tampa Bay are ongoing themes in the local scientific community. Current work by SWFWMD, USGS and the Tampa Bay National Estuary Program will further address this important issue. Recommended topics for future research include the development of an ongoing assessment of the Tampa Bay water budget, and the effects of altered freshwater flows on the local biota.

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DATA COLLECTED DURING THE N.O.S. CIRCULATION SURVEY OF TAMPA BAY

R. G. Williams
M. C. Connolly
H. R. Frey

ABSTRACT

In June 1990, the Estuarine and Ocean Physics Branch in NOAA's National Ocean Service (NOS) began a 15-month survey of Tampa Bay currents, water levels, water structure, and meteorological parameters. The data will be used to make new predictions, and to provide the necessary input to calibrate and verify a three-dimensional numerical circulation model.

Currents are measured primarily by RD Instruments Acoustic Doppler Profiler (ADCP), known as RADS (Remote Acoustic Doppler Sensing) in NOS. The RADS systems used in current meter stations are mounted on the bottom scanning upward. A downward-scanning RADS is towed from a surface vessel to map spatial current patterns. Currents in very shallow water are measured with InterOcean's S4 electromagnetic current meters. Water levels are measured with a standard NOS tide gage, the Leupold & Stevens Analog-to-Digital Recorder. Meteorological measurements are made with Coastal Climate's Weatherpak. Time series of conductivity and temperature at depth are measured with Sea-Bird Electronics' SeaCat recorders; conductivity-temperature-depth (CTD) profiles are made with Sea-Bird's SBE-9 profilers.

Six long-term current-temperature-salinity stations representing conditions throughout and just outside the bay have been occupied since August 1990, with only short breaks for maintenance and data recovery. Three separate deployments of two months duration each concentrating on a specific region of the bay, have been made since the start of the survey. Nearly continuous water level measurements have been made along the shoreline of Tampa Bay since June 1990. Meteorological data is being collected at several sites in the bay region. Shipboard CTD surveys of the bay were made in August and November, and a towed RADS survey was made in November.

A permanent physical oceanographic real-time system (PORTS) is being installed in Tampa Bay, primarily to provide timely information for navigation and environmental management. The first component of PORTS, a current profiler and weather station, was installed at the new Sunshine Skyway Bridge in June 1990. Completion is scheduled for 1991, including three current profilers, three water level gages, and the meteorological station.

Measurement and data quality control procedures are given, along with statistics on the quantity and quality of data collected. Data availability will be discussed including temporary and archive media and data formats. Survey data and information products will include revision of NOAA's tide and current prediction tables; special predictions of Tampa Bay currents and water levels; an archived circulation survey data set; reports on the circulation survey, and an interpretive report on the physical oceanography of Tampa Bay.

INTRODUCTION

The Tampa Bay Oceanography Project (TOP), conducted by NOAA's National Ocean Service, has the objective of providing improved current and water level data and predictions for safer and more cost-effective navigation of ships, management of hazardous material spills, search and rescue operations, and management of the estuarine environment. There are three major components of TOP:

- an extensive 15-month circulation and water level survey;
- calibration and validation of a numerical circulation model;
- installation, test, and evaluation of a physical oceanographic real-time system (PORTS).

Detailed TOP objectives, schedules, location maps, and participating agencies are given in NOS 1990a. In this paper, we discuss progress in the TOP survey, including field activities, amount and type of data collected, installation and operation of the PORTS, data management and data availability.

THE MEASUREMENT PROGRAM

The survey includes extensive observations of currents, water levels, temperature, salinity, and atmospheric variables. The survey was designed to collect sufficient data cost-effectively to:

- derive the astronomical tidal constituents needed for new predictions;

- calibrate and validate the numerical circulation model;
- investigate the wind- and density-driven components of currents, and
- gain insight to the dynamic processes of the Bay.

The survey includes fixed (long term) stations that will be occupied for the duration of the project to provide continuous synoptic coverage, and stations that will be occupied for two months to provide detailed regional coverage.

There is a total of 38 current meter stations, 19 water level stations, five weather stations, and three moored conductivity-temperature stations. In addition to the fixed stations, five transects for conductivity-temperature-depth measurements, and six transects for towed current profiler measurements will be made five times during the survey. The PORTS data will also be included in the survey data set.

Oceanographic Instruments

The principal instrument used to measure current profiles is RD Instruments' Acoustic Doppler Current Profiler (ADCP), also known as RADS (Remote Acoustic Doppler Sensing) in the NOS. RADS systems use the Doppler principle to infer the velocity from the frequency shift of acoustic signals backscattered from minute plants and animals moving at the mean speed of the water column.

The RADS systems are deployed on the bottom in platforms which provide protection, and permit instrument leveling by divers. One RADS is towed in a downward configuration on a stable catamaran. The towed RADS scans the water column from the top down, and enables the preparation of space-time maps of currents.

For water depths less than about 3 m, InterOcean's S4 is used. The S4 operates on the principle of modulation of electromagnetic fields due to fluid flow. They are attached to aluminum masts seated in concrete pads resting on the bottom. The height of the S4 is adjustable by means of holes and locking pins in the mast.

Water level measurements are made with the standard NOS tide gage, the Analog-to-Digital Recorder manufactured by Leupold & Stevens, Inc. This mechanical system consists of a stilling well-and-float that automatically records water levels every six minutes with a precision of .01′. Digitized water levels are stored on punched paper tape that is removed from the gage on a monthly basis and processed. The water level is also measured visually on a graduated staff and recorded each day to provide an independent check on the values punched on the paper tape.

Fixed-depth conductivity and temperature (CT) measurements are made using SeaBird's SeaCat SBE-19 and SBE-16 CT sensors, which are attached to the RADS platforms or to fixed navigation aids. Surface-to-bottom profiles of conductivity, temperature, optical transmissivity and dissolved oxygen are made from ships with SeaBird's SeaCat SBE-9 conductivity, temperature, and depth (CTD) sensors at stations along prescribed transects.

Weather data are collected at approximately 12 m above the sea surface using Coastal Climate Weatherpaks in both the real-time and self-recording modes. Data include wind speed and direction, atmospheric temperature and pressure, and, at the PORTS location, relative humidity, and near-surface temperature.

Field Operations

Current meters were deployed on the bottom beginning in June 1990. The field work was supported by the research vessels RV *Bellows* and RV *Suncoaster*, of the Florida Institute of Oceanography. Conductivity-temperature-depth stations were also deployed off the mouth of the bay and in Hillsborough Bay. The station locations are shown in Figures 1-3. Both the RADS and S4s were programmed to provide 10-minute vector averages of current velocity. The RADS provide velocity measurements at 1 m depth increments over at least 85% of the water column, whereas the S4s provide data at one depth. These instruments are retrieved and re-deployed every two months, to meet the TOP schedule and to permit data extraction and maintenance.

Divers inspected the instruments on site in early July and found biofouling to be severe on all underwater instruments. It was decided to schedule monthly underwater inspection and cleaning of all instruments in addition to the bimonthly recycling for data retrieval and dockside maintenance.

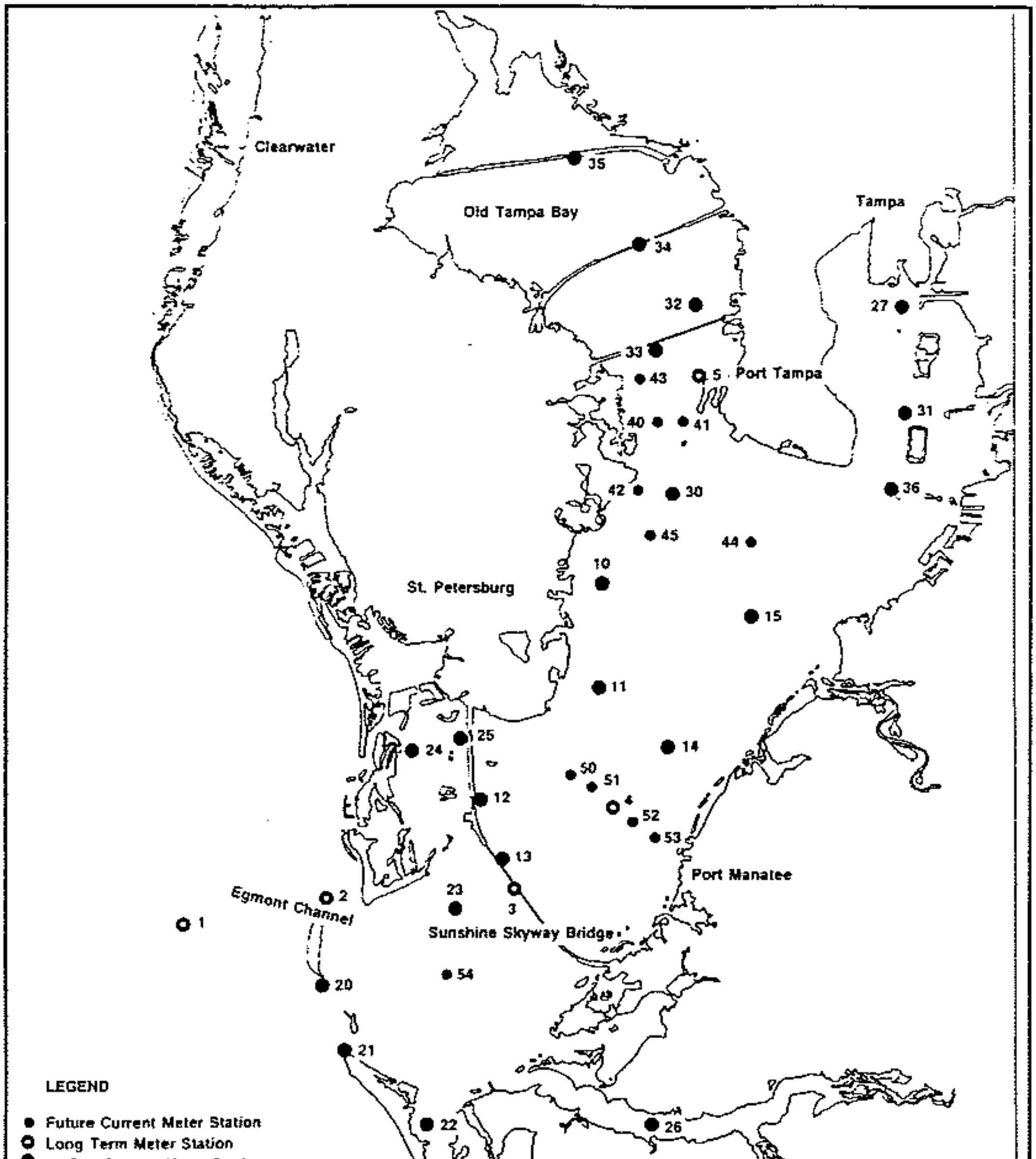

Figure 1. Location map of TOP current meter stations.

In August, a detailed CTD mapping of the Bay was made from the RV *Bellows* and RV *Suncoaster* (Figure 4). A 24-hour transect was made at the mouth of the bay by the *Bellows*, while *Suncoaster* made a section offshore perpendicular to the coast, and then up the axis of the channel. The *Bellows* took CTD casts approximately every 0.25 nautical miles across Egmont Channel, and then every 0.5 nautical miles at the two northern sections. The *Suncoaster* took CTD casts every 0.5 nautical miles. A total of 225 CTD casts were made during this mapping.

In November, a generally similar CTD mapping of the Bay was made from the NOAA ship *Ferrel*. The towed RADS was deployed for the first time to make six sections along the axis of the shipping channel, and perpendicular to it (Figure 4).

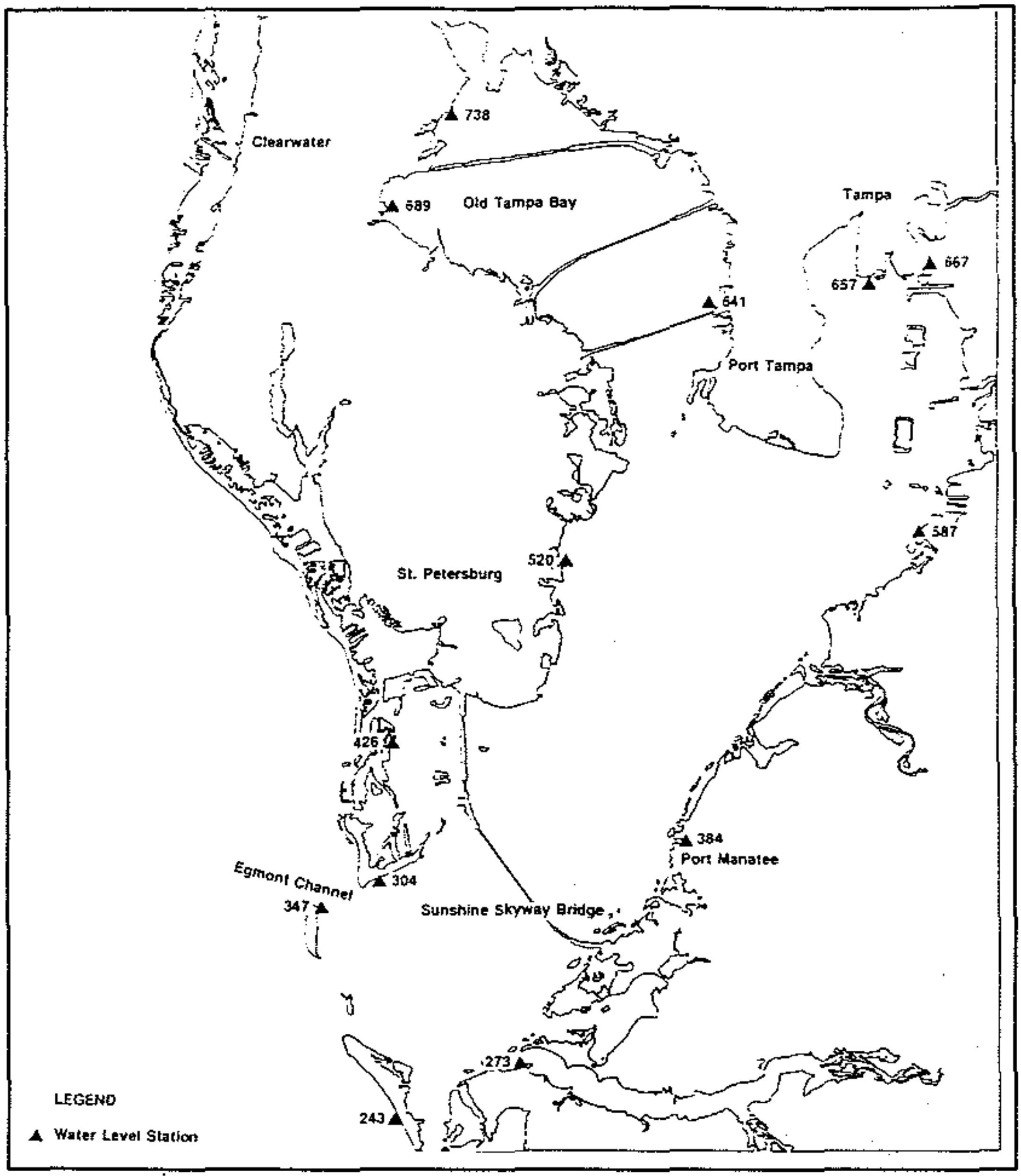

Figure 2. Location map of TOP water level stations.

THE PHYSICAL OCEANGRAPHIC REAL-TIME SYSTEM (PORTS)

PORTS—the Nations's first fully integrated physical oceanographic real-time system—is a major component of TOP (Figure 5). It also provides data to the circulation survey. The Tampa PORTS, when fully implemented, will provide not only real-time currents, but also water levels and weather data for several locations. It has a fully integrated Data Acquisition System (DAS) and Information

Dissemination System (IDS). When fully operational, it will be turned over to a host state agency.

Installation of the electronic/transmitting system and the first of three planned real-time ADCP's at station C-3, in the navigation channel under the new Sunshine Skyway Bridge (Figure 1), was completed in June 1990. However, useable data was not transmitted until August because the undersea telemetry cable was cut, probably by a fishing trawler shortly after installation. A buoy has since been installed to mark the cable crossing.

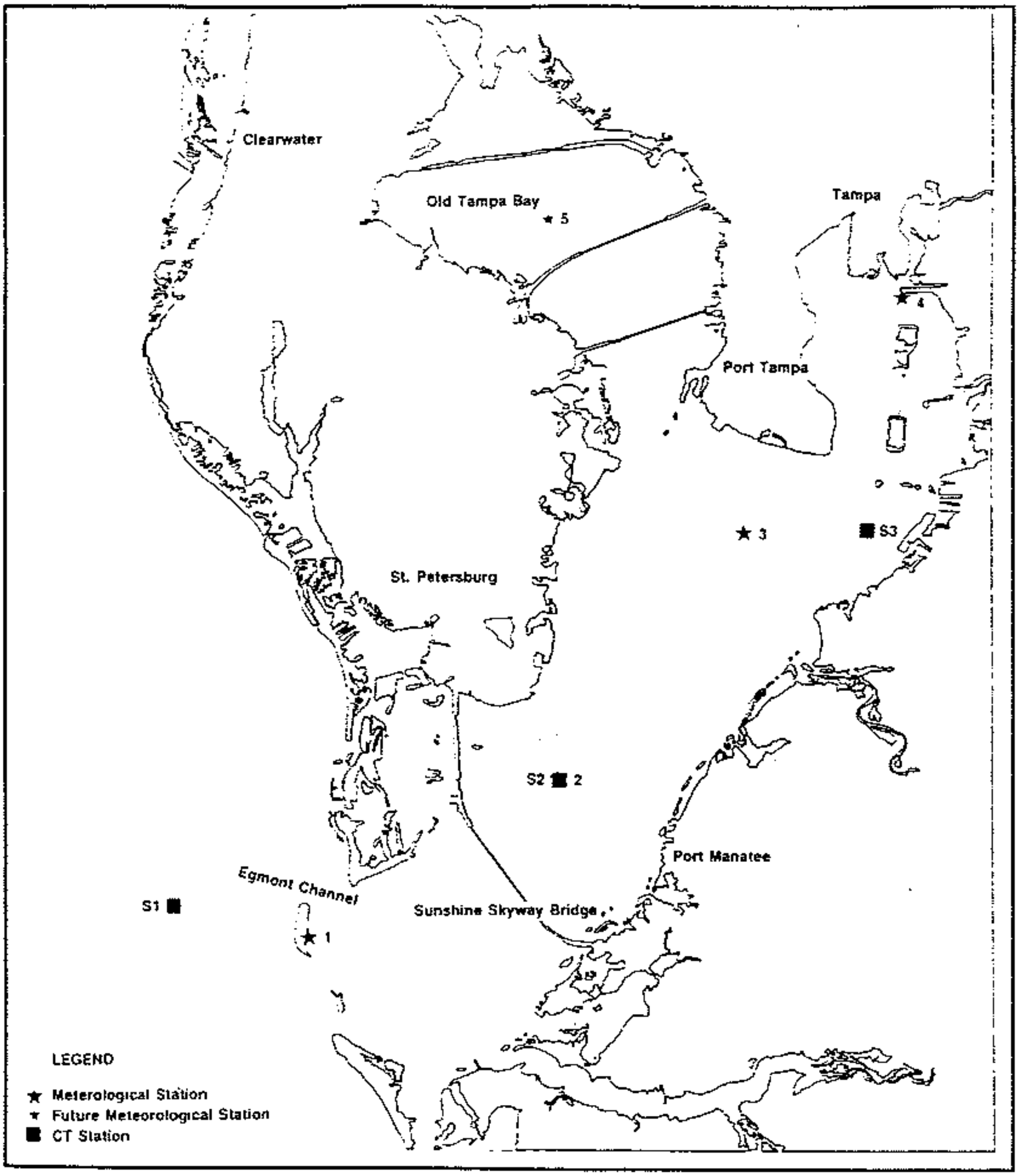

Figure 3. Location map of TOP meteorological and conductivity-temperature-depth stations.

PORTS measures water speed and direction, and is equipped with a sensitive pressure transducer to measure water pressure, from which depth is computed. The unit has a special naval bronze case for durability and resistance to biofouling. Its supporting platform is a low-profile concrete housing which would provide some protection if hit directly by a trawl door, anchor, or other hazard. A real-time weather station (M-2) located nearby measures wind speed, wind direction, air temperature and barometric pressure. Real-time communications were established and all current and weather data are now received at the DAS in the U.S. Coast Guard operations center at St. Petersburg.

PORTS Data Acquisition and Dissemination Systems

Data collected by the PORTS instruments is transmitted to the PC-based DAS. Data from the RADS, the pressure gage, and the weather station, each consisting of 10-minute averages, are received every 10 minutes and saved in ASCII files. The latest data sample is displayed as a formatted text screen displayed on the DAS console.

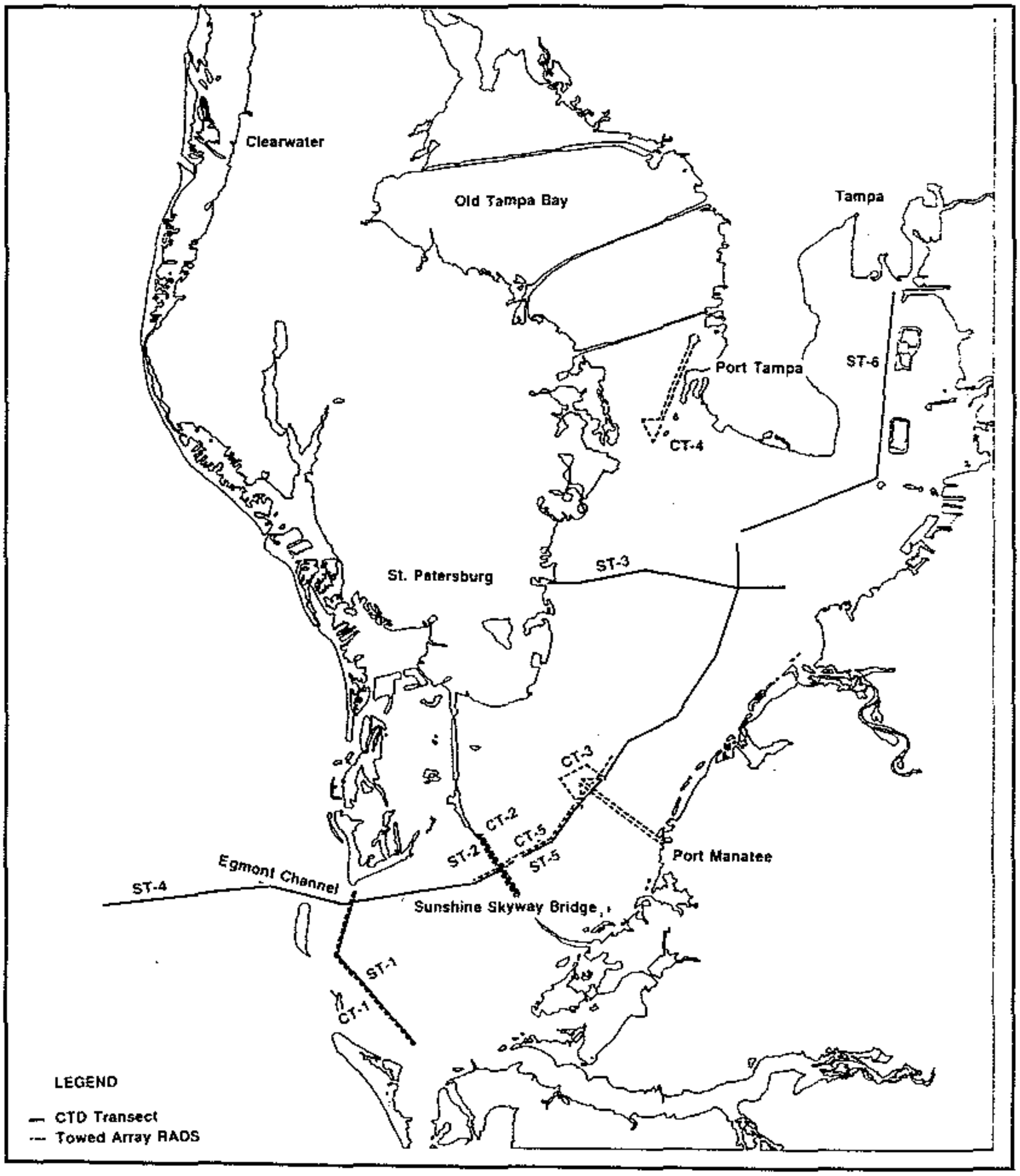

Figure 4. Location map of TOP towed RADS transects and CTD transects.

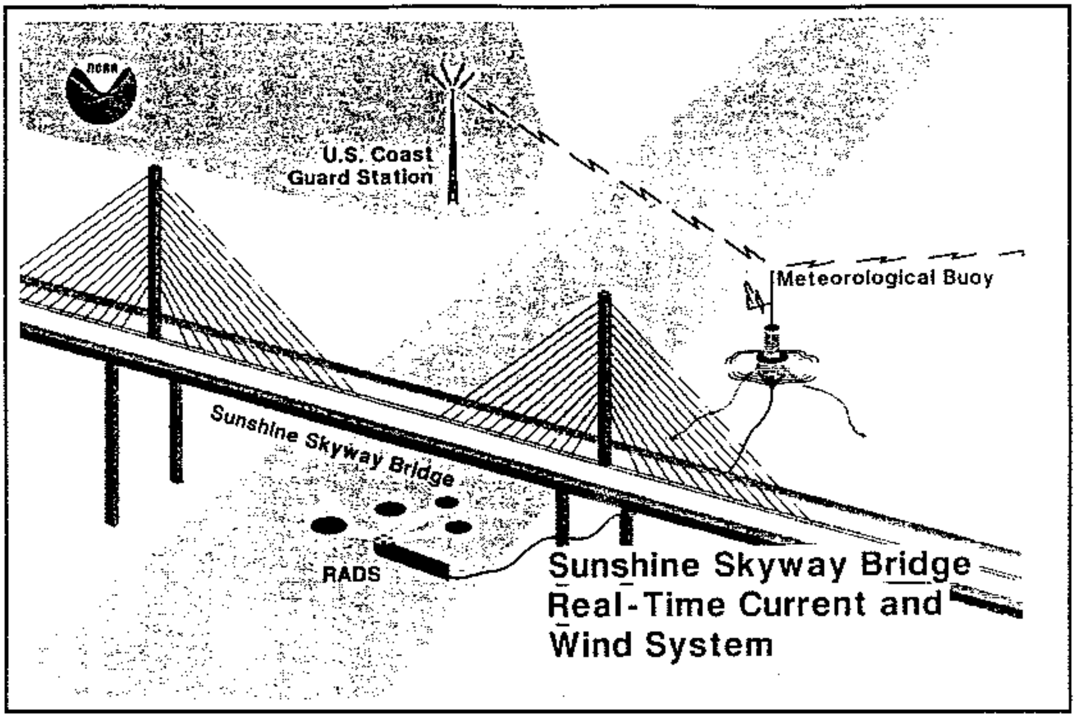

Figure 5. Tampa Bay physical oceanographic real-time system (PORTS).

The voice response system was installed in November 1990. The voice messages will be enhanced over time to include new kinds of information that can be derived from the data. NOS will be working closely with the Tampa Bay Pilots and the Coast Guard in developing voice menus. The National Weather Service and the Hazardous Materials Office now access the voice response system. It is anticipated that further dissemination of the information through NOAA Weather Radio and possibly local cable television will occur.

MEASUREMENT QUALITY CONTROL

All new and refurbished or upgraded instruments were inspected and tested prior to acceptance. The 1200 kHz RADS and S4s were calibrated in the tow tank at the David Taylor Naval Research and Development Center. The 600 kHz and 300 kHz RADS were calibrated in the manufacturer's lakeside facility in San Diego, California. All RADS and S4 compasses were calibrated on shore by rotating the instruments in stable mounts and taking comparative bearings between the instrument compass and a high quality laboratory compass.

Immediately following deployment and at one month intervals, divers inspect, level, and check each instrument for proper clearances, removing any obstructions. Many of these inspection dives include underwater photography of instruments to permit evaluation in the laboratory.

CTs and CTDs are calibrated prior to shipment from Sea-Bird Electronics. All instruments are recalibrated at the Northwest Regional Calibration Center both before and after major field deployments. Several instruments were sent for calibration checks following retrieval in December 1990.

Meteorological instruments pass an in-house inspection and testing prior to deployment in the field. Once installed, they are inspected monthly.

DATA COLLECTED

Water level data collected since the beginning of the project is displayed in Figure 6. Station numbers can be located on the station location map (Figure 2). Most of the large gaps in some of the station data are the result of vandalism. One station, at Port Manatee, was damaged during Tropical Storm Marcos.

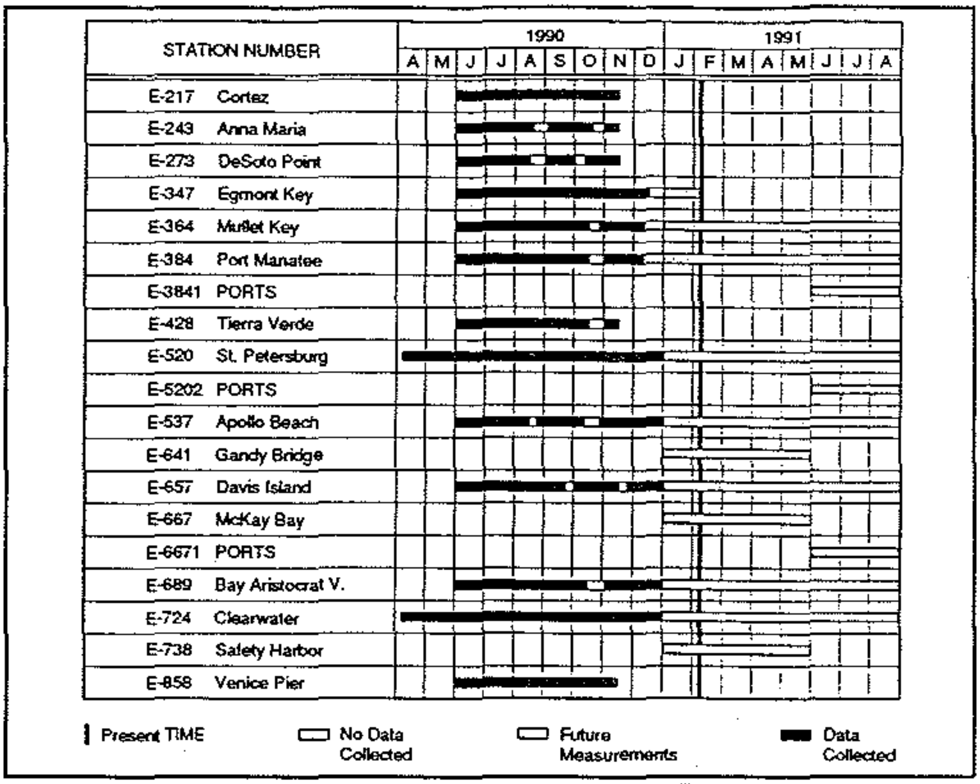

Figure 6. Schedule for TOP water level gage deployments.

Current meter data is shown in Figure 7. The long-term stations, C-1 through C-6 have a good record of data collection. C-1 did not collect data for the first period of its operation due to the failure of circuit boards, possibly the result of high ambient temperatures.

The S4 data collected at the very beginning of the project is suspect because of high biofouling. In some cases, S4 data was not collected because the instruments were hit by propeller blades of vessels passing overhead.

Towed RADS data were not taken in August, as originally scheduled, because additional testing of the instrument was required. The towed RADS is not yet an operational system, and the data requires additional study before it can be released.

CT and CTD data collected are presented in Figure 8. CT sensors at sites S-1 and S-3 were both hit by vessels during deployment periods resulting in loss of data.

As of October 1990, 91.6% of planned RADS data was recovered, 43% of planned S4 data, and 80% of CTD data. Eighty-seven percent of water level data for this period is considered to be of high quality.

Meteorological data was collected at the PORTS station M-2 for the period August 22 through the present with only very small breaks, on the order of minutes. The data from station M-3 was degraded for much of this same period of operation due to lightning strikes. Stations M-2 and M-3 (Figure 3) have only recently been deployed. Station M-5 has not yet been deployed.

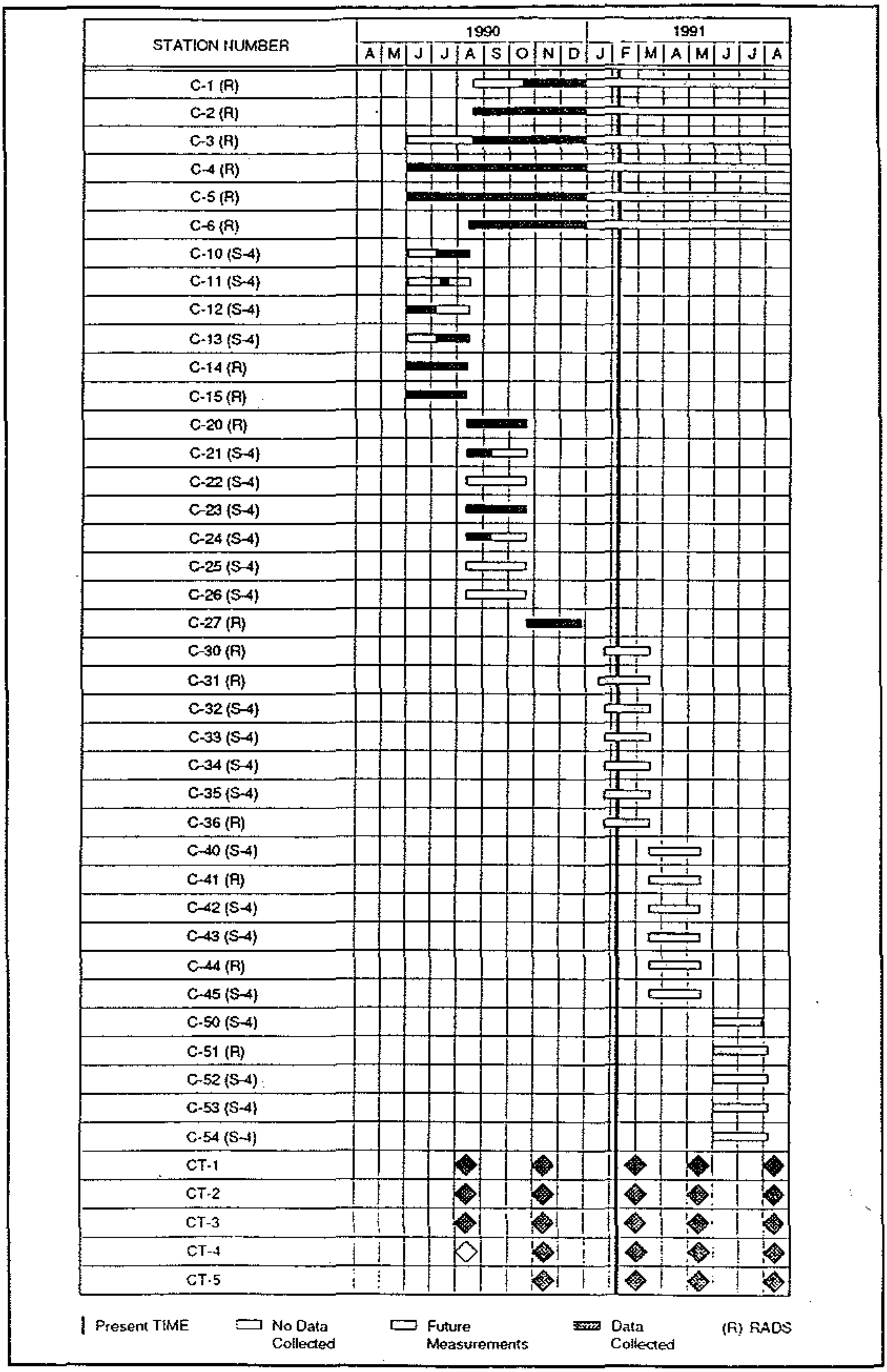

Figure 7. Schedule for TOP current meter deployments; RADS moorings are denoted by (R); towed RADS transects are shown by diamonds.

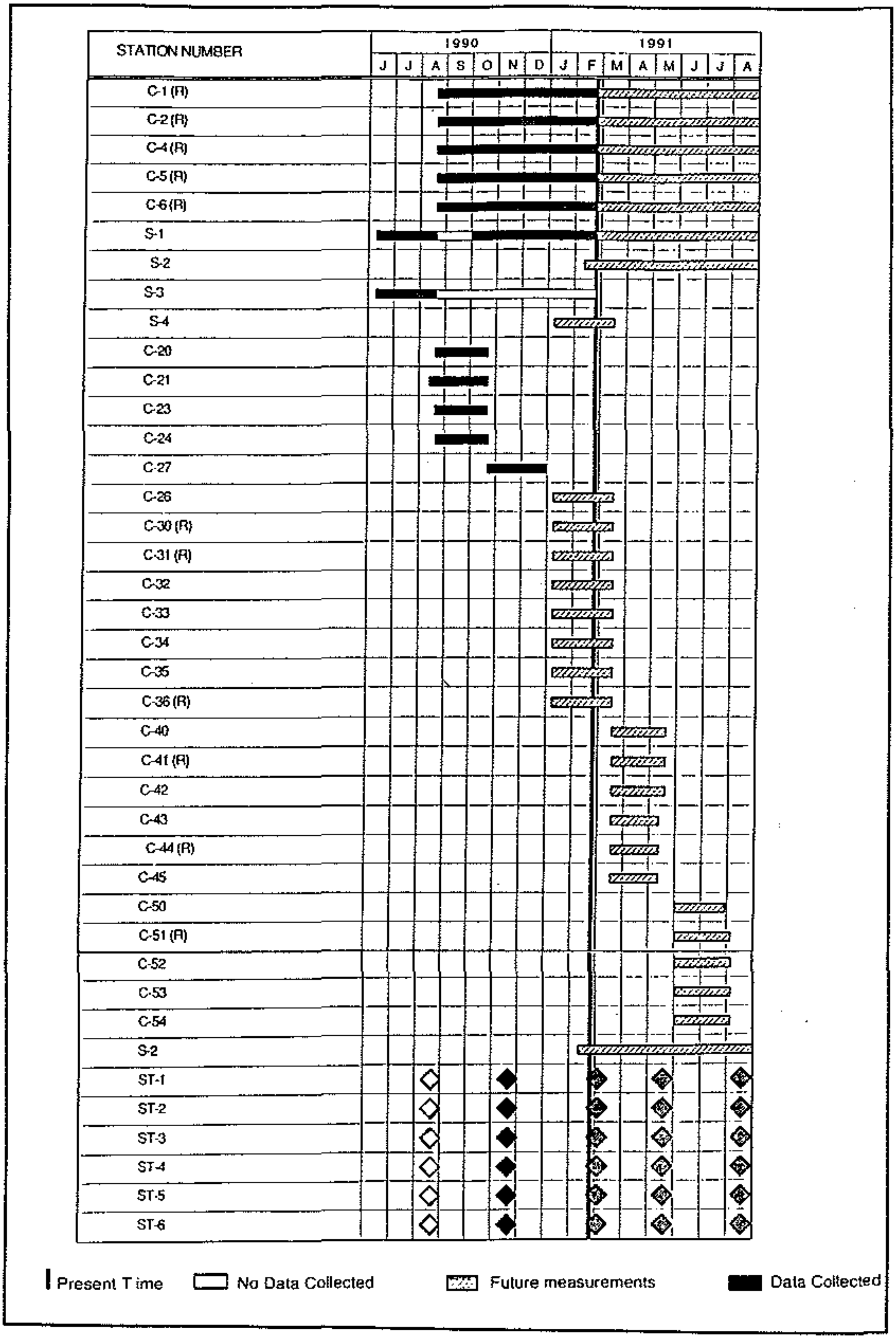

Figure 8. Schedule for TOP conductivity-temperature-depth gage deployment.

DATA PROCESSING - DATA QUALITY CONTROL

The detailed data processing and quality control (QC) procedures are documented in a field refence guide (NOS 1990c). QC procedures include time series plots of selected current meter, CT, CTD, and weather data records. The plots are examined for noise, outliers, offsets, drifts, physical reasonableness, and consistency with data from neighboring instruments. Questionable data is flagged for subsequent detailed review.

The RADS records a number of special parameters for QC monitoring. An "error velocity" signal is calculated from the velocity data of each of the four beams. Under ideal conditions of uniform fluid velocity, this error velocity should be zero. Under actual field conditions, it is small (less than a very few centimeters per second) if the instrument is perfoming correctly. If the echo amplitude of the received signal is outside prescribed limits, performance of the instrument is suspect. Examples of the QC plots are shown in Figure 9, where it is seen that error velocity is very small, and echo amplitude is behaving as expected.

Data from all water level stations is processed and tabulated using NOS standard operating procedures. These include a preliminary evaluation of data quality using a visual scan, as well as comparison with a tide observer's daily observations of water level with a graduated staff adjacent to the ADR gage. Statistical staff-to-gage relationships are established and applied to the data before tabulation.

DATA ANALYSIS

A primary purpose of the data is to develop new predictions for Tampa Bay. Traditional methods of harmonic analysis will be used to derive the astronomical tidal constituents for making new predictions. The new predictions will be compared with data to assess their quality. The large amount of data, including long time series of water levels and currents, will facilitate detailed predictions at numerous locations in the bay, in contrast to the single reference station at Egmont channel used for present predictions.

Analysis of the non-tidal components of currents and water levels will be made in order to model these forces in prognostic numerical circulation models. Information on the forcing of the circulation in the Bay by wind stress, runoff, and offshore currents will be used in order to make forecasts of the total current (Hess, this volume).

Real-time data from PORTS will be analyzed for the purpose of providing comparison with NOAA tables, and with new predictions, as well as for determining the feasibility of making short term forecasts of water levels and currents at sites of concern to mariners.

DATA AVAILABILITY

Oceanographic data collected during the 15-month circulation survey will be available to mariners, managers, and scientists after it has been quality controlled by NOS. Data that passes the QC criteria will be available to the public following the completion of the project. Raw instrument data will be temporarily archived by NOS on magnetic media in both ASCII and binary formats. Data are available during the survey from:

TOP Data Manager
Estuarine and Ocean Physics Branch, N/OMA 13
NOAA/National Ocean Service
6010 Executive Boulevard
Rockville, MD 20852
(301) 443-8510

After completion of the survey, when data analyses indicate no serious undetected errors, the data will be transmitted to NOAA's National Oceanographic Data Center (NODC), Washington, D.C., for archiving. Since an archival format for

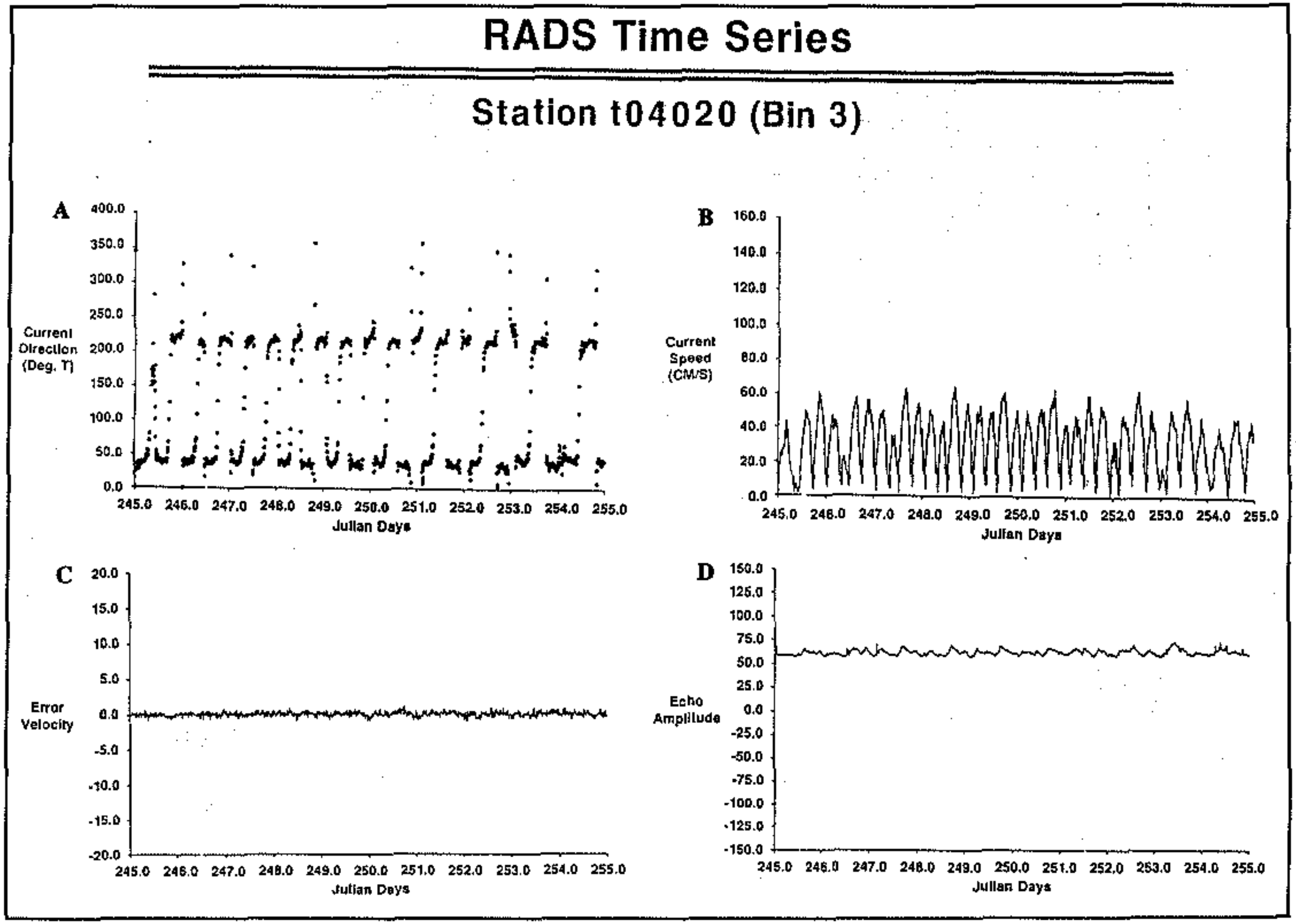

Figure 9. Time series of data for quality control (from the PORTS RADS): A) current direction; B) current speed; C) error velocity; D) echo amplitude.

RADS data has not been determined, these data may be transferred at a later time. The transferred data will be generally available from NODC upon request by June 1992, from:

User Services Branch E/OC21
National Oceanographic Data Center
NOAA/National Environmental Satellite
Data and Information Service
Washington, D.C. 20235
(202) 673-5549

Meteorological data will be transferred to NOAA's National Climatic Center (NCDC) for archiving. The transferred data will be available from NCDC upon request by June 1992, from:

Information Services Division E/CC4
National Climatic Data Center
NOAA/National Environmental Satellite
Data and Information Service
Federal Building
Asheville, NC 28801
(704) 259-0871

Raw water level data will be retrieved from the gages at the end of each month and processed. Analyzed water level and bench mark data will be available three months after retrieval and may be obtained from:

Tidal Datum Quality Assurance Section, N/OMA 123
Sea and Lake Levels Branch
NOAA/National Ocean Service
Rockville, MD 20852
(301) 443-8467.

INFORMATION PRODUCTS AND SERVICES

Information products and services will be available approximately one year after the conclusion of the field survey. Included are:

- a circulation survey data set and survey report;
- revision of NOAA's tide and current prediction tables, and special detailed prediction tables for Tampa Bay;
- model-generated products, including a circulation and water level forecast atlas, and simulations of circulation and water levels for various scenarios (see Hess, this volume); and
- a technical report on the physical oceanography of Tampa Bay and model validation.

REFERENCES

National Ocean Service, 1990a: Tampa Bay Oceanography Project - Plan for FY 1990 to FY 1992. NOAA, National Ocean Service, Office of Oceanography and Marine Assessment, Rockville, Maryland. 68pp.

National Ocean Service, 1990b: Tampa Bay Oceanography Project - Progress Report for FY 1990. K. W. Hess, Editor. NOAA, National Ocean Service, Office of Oceanography and Marine Assessment, Rockville, Maryland. 38pp.

National Ocean Service, 1990c: Computer Based Field Reference Guide for Instrument Data Management. B. Rotondi, Editor.

ADDRESS: NOAA-National Ocean Service, 6010 Executive Boulevard, Rockville, MD 20852.

INITIAL FINDINGS ON THE CIRCULATION OF TAMPA BAY

R. H. Weisberg
R. G. Williams

ABSTRACT

Initial findings on the circulation of Tampa Bay, Florida, are presented, using data from the U.S. Department of Commerce, NOAA, National Ocean Service, Tampa Oceanography Project (TOP). Located on Florida's west coast, Tampa Bay is the largest of Florida's drowned river valley estuaries. The bay has been described as vertically well mixed, a description that has been used to justify vertically averaged models as tools for guiding water quality sampling and analysis. However, while Tampa Bay is vertically well mixed in salinity, it does have dynamically significant horizontal salinity (density) gradients, owing to the distribution of inflowing fresh water, particularly along its eastern shore. These horizontal gradients and surface wind forcing both imply a fully three-dimensional circulation. The TOP is presently providing the first data set capable of facilitating a better description of the flow field for Tampa Bay. Evidence so far shows three major components of the circulation, driven by tides, buoyancy and winds, respectively. The dynamics and thermodynamics of the estuary are therefore fully three-dimensional, a fact which should be recognized for future data collection, analysis and numerical modeling.

INTRODUCTION

Tampa Bay, located on Florida's west coast, is the largest of this state's drowned river valley estuaries. Tampa Bay is a significant marine resource for the State of Florida. It provides major ports of commerce, supports a variety of fisheries and offers important recreational opportunities for Florida's residents and visitors. Given its location between the cities of St. Petersburg and Tampa, with adjacent agricultural and mining land uses, Tampa Bay comes under competing utilizations, stretching its ability to maintain the water quality that is ultimately necessary for sustaining these utilizations. As is the case with other estuaries, it is of increasing importance to understand the factors which control water quality so that sound management decisions can be made.

Water quality derives from a multitude of physical and biogeochemical factors. Variations in any constituent water property depend upon advective and diffusive transports (the physical factors) and sources and sinks (the biogeochemical factors). For examples, nutrient concentrations depend upon all of these factors. Sampling the bay to determine water quality and modeling the bay to gain management insight have both been impeded by the view that, by virtue of well mixed salinity, the bay could be sampled and modeled as if the physical factors were all vertically uniform.

The U.S. Department of Commerce, NOAA, National Ocean Service (NOS), Tampa Bay Oceanography Project (TOP) is presently providing the first data set that can be used to describe the flow field and its variations within the bay. Presented herein are some preliminary findings from the initial TOP data returns. Empirical evidence from the first two months of velocity, observed beneath the Sunshine Skyway Bridge, shows three types of circulation, driven by tides, buoyancy and winds, respectively. These findings are preliminary in so far as the data have not yet been fully screened by the NOS for quality control; the record lengths are short (the initial two months of a longer collection effort), and data have only been analyzed from one of several locations. While further extensive analyses will be performed, these data are sufficient to conclude, consistent with estuarine circulation physics, that the circulation within Tampa Bay is fully three-dimensional.

The paper is organized as follows. The first section provides a conceptual background for the physics of estuarine buoyancy-driven convection. The relevant forcing for this convection is baroclinic, defined as the non-coincidence between isolines of density and pressure, owing to river inflow-induced horizontal density (salinity) gradients. This mode of circulation, commonly referred to as estuarine circulation, e.g., Pritchard (1956) and Cameron and Pritchard (1963), is an important way in which river water passes through the estuary en route to the sea. Along with this "estuarine circulation" are the astronomically-driven tidal currents and the wind-driven non-tidal currents. The data pertinent to these three types of circulation are presented in the next section. The last section then provides a summary and a set of recommendations.

CONCEPTUAL PHYSICS

The role of buoyancy in driving a non-tidal circulation within Tampa Bay has in the past been neglected because of the observation that bay water salinities appear to be vertically well-mixed. This salinity observation is approximately correct; however, it does not imply that the velocity should be similarly uniform with depth. The present section attempts to provide a conceptual basis for the role of horizontal density gradients in driving a convective mode of circulation. This type of circulation is not new. It has been described by several authors over the past three decades, including a parametric analytical study by Hansen and Rattray (1965). The starting point for discussion is the recognition that, in the steady state, the sum of the torques acting upon a fluid must balance. If we consider motions within a vertical plane, slicing through the center of the estuary from its head at Tampa to its mouth at the Gulf of Mexico, then the buoyancy and frictional torques normal to that plane must balance. Otherwise fluid will accelerate to produce such a balance. A buoyancy torque arises by the integral, over the plane, of the "baroclinic vector" and a frictional torque arises (in the absence of wind stress) by the frictional force of fluid rubbing along the bottom. The baroclinic vector is defined as the vector product of the pressure gradient and the density gradient. If the pressure and density gradients are co-linear then the baroclinic vector is zero and the fluid is barotropic. However, if the isolines of density and pressure are not co-linear then the resulting baroclinic vector will tend to produce a buoyancy-driven convection.

The component of the baroclinic vector (B.V.) normal to the plane of interest is:

$$B.V. = 1/\rho^2[(\partial p/\partial z)(\partial \rho/\partial x)-(\partial p/\partial x)(\partial \rho/\partial z)],$$

where p is the pressure, ρ is the density, x is the along-axis direction, z is the vertical direction and ∂ denotes a partial derivative. Considering the case where the pressure is hydrostatic and the density is constant with depth, the baroclinic vector becomes:

$$B.V. = -g/\rho(\partial \rho/\partial x),$$

where g is the acceleration of gravity. This term is the dominant baroclinic term pertinent to estuarine circulation, even if density varies with depth. Clearly, with salinity varying from relatively fresh water values near the estuarine head to sea water values at the estuarine mouth, the along-axis density gradient, $\partial\rho/\partial x$, is large. Figure 1 illustrates this point. The solid lines represent lines of constant pressure and the dashed lines represent lines of constant density. In case A they are parallel, so despite a large vertical density difference, the baroclinic vector is zero. In case B they are perpendicular, so despite the fact that there is no vertical density difference, the baroclinic vector is a maximum. Case B is the pertinent case for the vertically well mixed salinity observation of Tampa Bay. A second way of illustrating this point is to utilize the Knudsen Hydrographic Theorem (e.g. Neumann and Pierson 1966). For the case of a two layered flow in which the incoming and outgoing water fluxes and salinities are defined by T_i, T_o, S_i, S_o, respectively and the river inflow by R, then the following balances are obtained from water and salt conservation:

$$T_i = [S_o/(S_i-S_o)]R,$$

and

$$T_o = [S_i/(S_i-S_o)]R.$$

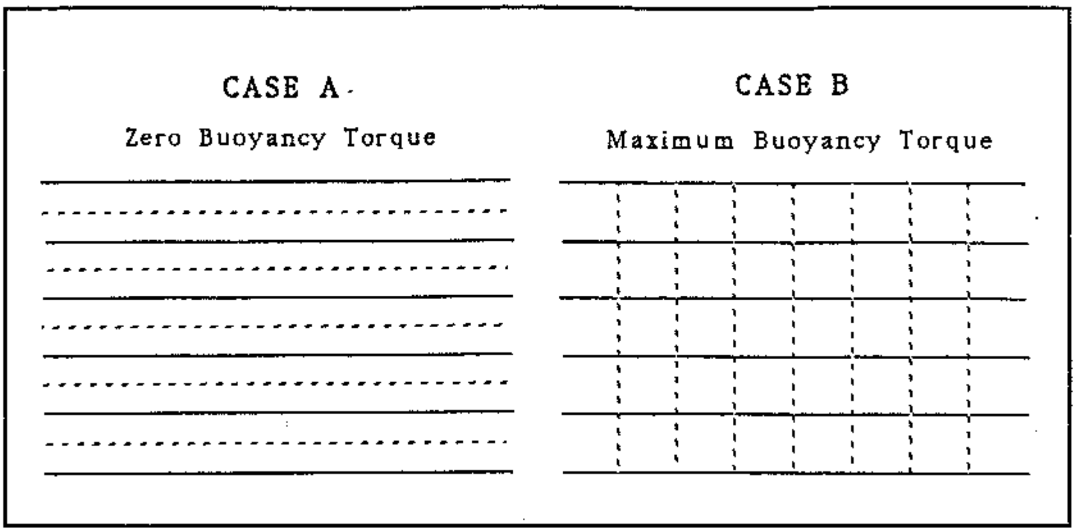

Figure 1. Sketches showing the relationship between lines of constant density and lines of constant pressure for barotropic and baroclinic flows. Case A represents a barotropic field in which the isolines of density and pressure are co-linear. Case B represents a baroclinic field in which the isolines of density and pressure intersect at an angle, resulting in a buoyancy torque.

These relationships show that the inflow and the outflow volume fluxes are small if the vertical density difference is large, and conversely. The implication for Tampa Bay is that the buoyancy-driven convection should be large.

The simplest formulation for the buoyancy-driven convection problem, which yields an analytical solution, consists of force balances between the horizontal pressure gradient and friction in the along-axis direction of the estuary, and between the vertical pressure gradient and gravity in the vertical direction. These equations are:

$$1/\rho(\partial p/\partial x)=A(\partial_2 u/\partial z^2)$$

and

$$1/\rho(\partial p/\partial z)=-g,$$

where A is a constant eddy diffusivity for momentum. If the along-axis density (salinity) gradient is assumed to be independent of depth then these equations may be integrated directly, using the boundary conditions:

$$u=0 \text{ at } z=0 \text{ (no slip at the bottom)},$$

and

$$\partial u/\partial z=0 \text{ at } z=S \text{ (no stress at the sea surface)}.$$

Constraining the volume flux of water to equal the river inflow yields a solution for the vertical distribution of the buoyancy-driven mean flow in terms of the horizontal density gradient as:

$$u(z)=\{(3R/SW)[(z/S)-(1/2)(z/S)^2]\}+\{(1/48)(g/A)(\partial\rho/\partial x)S^3[-6(z/S)+15(z/S)^2-8(z/S)^3]\},$$

where W is the width of the estuary. Evaluating this expression at the surface, z=S, then results in the time averaged buoyancy-driven along-axis surface flow as:

$$u(S)=(3/2)(R/SW)+(1/48)(g/A)(\partial\rho/\partial x)S^3.$$

The first term represents the barotropic effect of the river inflow and the second term represents the baroclinic effect of the along-axis density gradient. Substituting representative numbers into this equation shows that the first term is insignificant and the second term is of order 10 cm/sec. These equations may also be solved for the along-axis surface slope, $\partial S/\partial x$, which follows from the volume flux constraint. This yields:

$$\partial S/\partial x=-(3A/\rho g S^3)(R/W)-(3/8)(S/\rho)(\partial\rho/\partial x),$$

where again, the first term is the barotropic effect of the river inflow and the second term is the baroclinic effect of the along-axis density gradient. Substituting representative numbers into this equation shows that the first term is insignificant and the second term is about 0.09 cm/km, which translates into a sea level difference between the head and the mouth of the estuary of about 5 cm. It is this small, but dynamically significant, pressure head that drives fluid out of the estuary on average near the surface. The distribution of the pressure gradient force with depth is given by:

$$\partial p/\partial x=-(3AR/WS^3)+gS(\partial\rho/\partial x)[5/8-z/S],$$

showing that the along-axis density gradient causes the sign of the pressure gradient force to reverse at a distance of $z=(5/8)S$ from the bottom, resulting in a force which drives fluid into the estuary on average over the lower portion of the water column. Figure 2 summarizes the vertical distributions of the along-axis velocity component and the along-axis pressure gradient from this model of buoyancy-driven estuarine circulation.

Tampa Bay is certainly more complicated than this model implies. It has complex topography which gives rise to non-linear interaction terms, non-uniform freshwater inflow concentrated on the east shore, and the assumption of uniform density gradient, decoupled from the flow field, is overly simplistic. However, this simplest of estuarine buoyancy-driven convection models does contain the essential physics; predicting, by virtue of the horizontal density gradient, that buoyancy-driven convection is an important component of the flow field in Tampa Bay. In contrast, vertically averaged models, by excluding the physics of the buoyancy-driven convection, are incapable of describing this dynamically significant type of estuarine circulation. Since the above model is linear, the effects of tidal currents and wind-driven currents may be added. But rather than pursue this with an overly simplified model, let us just see what the initial TOP data show.

VELOCITY OBSERVATIONS FROM THE SUNSHINE SKYWAY BRIDGE

The data collection effort of the NOS TOP is described in detail in this volume by Williams et al. For this presentation, an initial set of analyses using the real-time velocity measuring system deployed within the main shipping channel beneath the Sunshine Skyway Bridge has been prepared. Additional data will be included in a more extensive analysis as they become available. The data to be presented here consist of: 1) a two-month long record of water velocity, sampled hourly, at 1 m intervals between depths of 1.9 m from the bottom and 3.6 m from the surface, over a total mean water depth of 15.5 m; and 2) simultaneous wind velocity, sampled at the Tampa International Airport (TIA). These data span the time interval of August 15 to October 15, 1990.

The water velocity data are sampled using an RD Instruments Acoustic Doppler Current Profiler (ADCP), which measures velocity acoustically using the Doppler effect. Sound, transmitted at a specific frequency, when reflected from anything moving with the water, will return at a slightly different "Doppler shifted" frequency. By sensing this Doppler shift, the instrument calculates and then records water velocity. A velocity profile is obtained by range gating the echo returns over time intervals corresponding to an acoustic path length of 1 m. In the present case, with

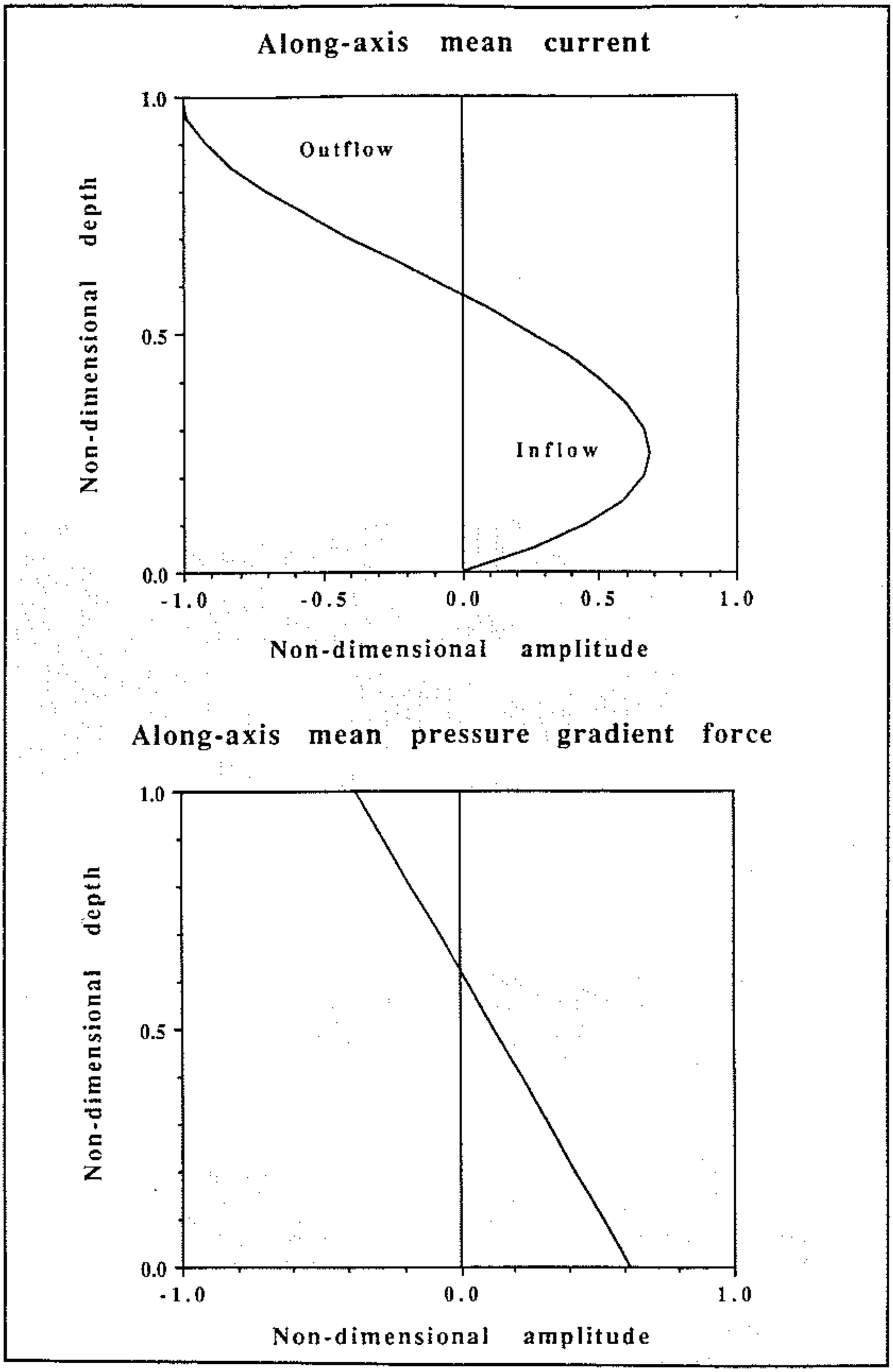

Figure 2. The vertical distribution of along-axis mean flow and along-axis pressure gradient for a simplified analytical model of buoyancy-driven estuarine circulation.

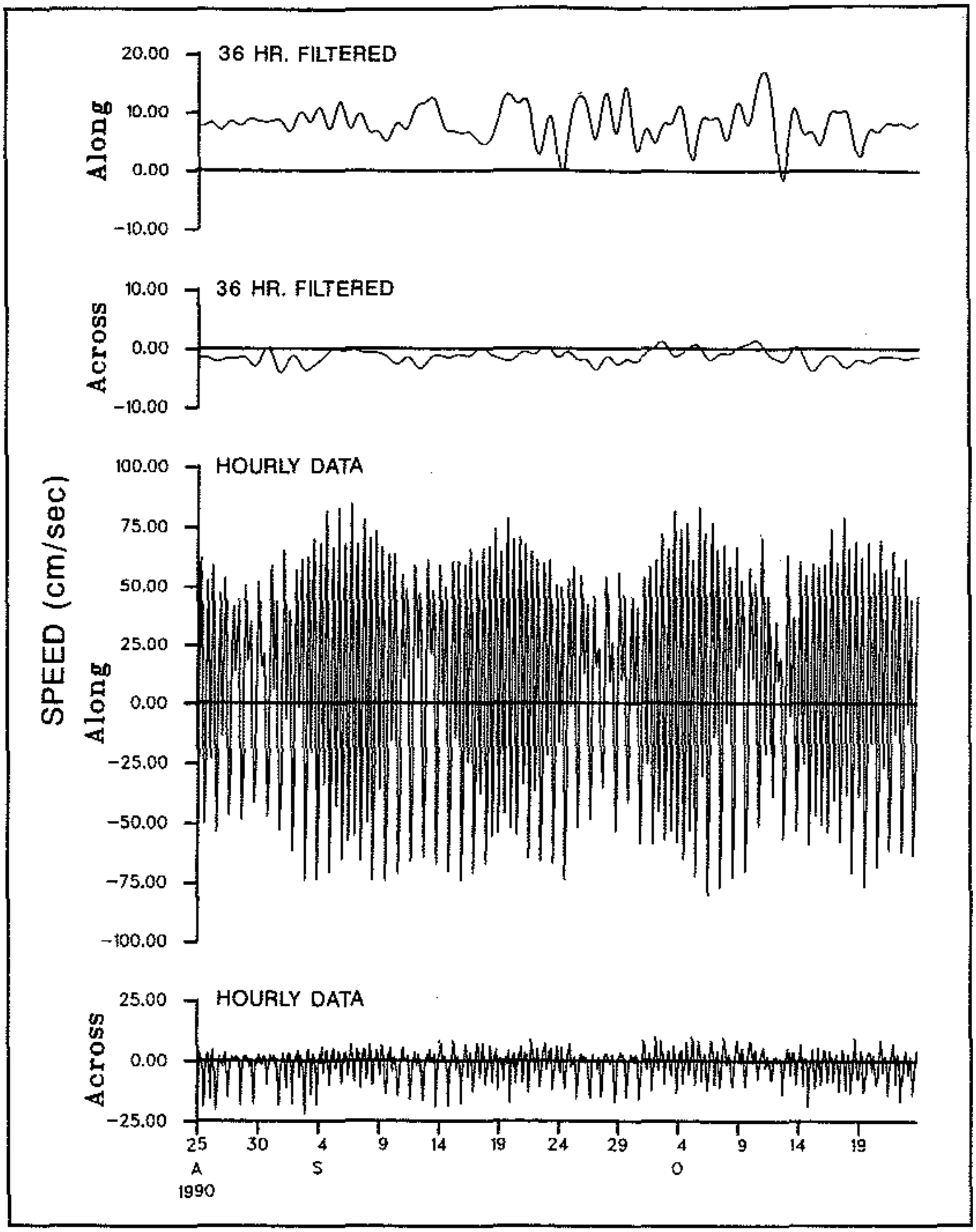

Figure 3. Along- and across-axis components of velocity measured at a depth of 1.9 m from the bottom under the Sunshine Skyway Bridge using an RD Instruments Acoustic Doppler Current Profiler. The two sets of time series represent the original data sampled hourly and data low-pass filtered to exclude tidal and other fluctuations occurring on time scales shorter than 36 hours. Positive along- and across-axis currents are directed toward 062°T and 332°T, respectively, where 062°T is the local orientation of the navigational channel.

the ADCP deployed on the bottom looking upward, the array geometry is such that data are obtained between 1.9 m from the bottom to 3.6 m from the surface. Figure 3 shows the data collected at the 1.9 m bin. Four time series are presented. The lower two are the hourly sampled horizontal velocity components relative to a Cartesian coordinate system oriented along and across the channel axis. As taken from a navigational chart of the bay, the channel axis at this location lies along the direction of 062°T. Thus, in Figure 3, positive along-axis flow is directed toward 062°T and positive across-axis flow is directed toward 332°T. The overall flow is nearly rectilinear; however, there is a non-zero across-axis component that is both depth and frequency dependent. The hourly data show distinctive tidal oscillations of the mixed semidiurnal and diurnal form, with peak speeds of about 75 cm/sec. Upon filtering out the tidal oscillations, the upper two time series represent the non-tidal portion of the flow. For this purpose filtering was performed using a truncated Fourier transformation with a cut-off frequency of 1/36 hours. The non-tidal flow shows both a mean value and oscillations about the mean occurring at time scales of several days. The mean flow, with magnitude of about 10% of the tidal fluctuations, is hypothesized as due to buoyancy-driven convection and the non-tidal fluctuations about this mean are hypothesized as due to local winds.

Tidal Currents

The data from all of the 11 depth bins appear very similar to those shown in Figure 3. The kinetic energy density spectra show that the semidiurnal and diurnal spectral peaks are the largest, as expected, and a vector spectral analysis shows that the principal axis of variance is aligned nearly with the channel axis, but not quite. For the tidal currents at this location, the orientation of the semi-major axis of variance for both the semidiurnal and diurnal species is nearly uniform with depth and aligned along 057°. This orientation coincides with the overall bathymetry of the lower bay, as opposed to the local channel axis which changes along the bay; however, the difference between these directions is small (005°).

A description of the spatial distribution of the individual tidal harmonics, including error analyses, will follow from the additional data that are presently being collected. For now, an analysis is presented for two broad spectral bands, encompassing all of the semidiurnal and all of the diurnal species, respectively. Using the technique of frequency domain empirical orthogonal function analysis, the amplitude and relative phase distribtution with depth, calculated separately for the semidiurnal and diurnal tidal bands, are shown in Figures 4 and 5, respectively. The analysis consists of calculating the eigenvectors of the cross-spectral matrix averaged over a specified frequency band. Mode 1 refers to the first eigenfunction, which in both cases accounts for over 99% of the variance summed over the water column. This high percentage of variance contained in a single mode reflects the fact that the tidal currents are very coherent vertically. These figures show that the semidiurnal and the diurnal tidal species are distributed nearly uniformly with depth, both in amplitude and phase, with the semidiurnal species on average being roughly twice as large as the diurnal species at this location. Both the semidiurnal and the diurnal tidal currents are very nearly rectilinear, and if we were to rotate the coordinate system by the 005° determined above, the across-axis components shown in Figures 4 and 5 would become very small and the along-axis components would become slightly larger.

Tidal current amplitudes are expected to have a nearly uniform distribution with depth since they are driven by a barotropic (uniform with depth) pressure gradient imposed upon the bay by astronomically driven Gulf of Mexico sea level oscillations. The phase uniformity with depth is surprising however, as the effects of friction predict a phase lead near the bottom which has been observed in other estuaries (e.g., Weisberg and Sturges 1976). Since the structure of the flow field within the bottom boundary layer is important for turbulent dissipation, further analyses from different locations in the bay will be very important toward understanding the dissipation and correctly modeling the overall flow field.

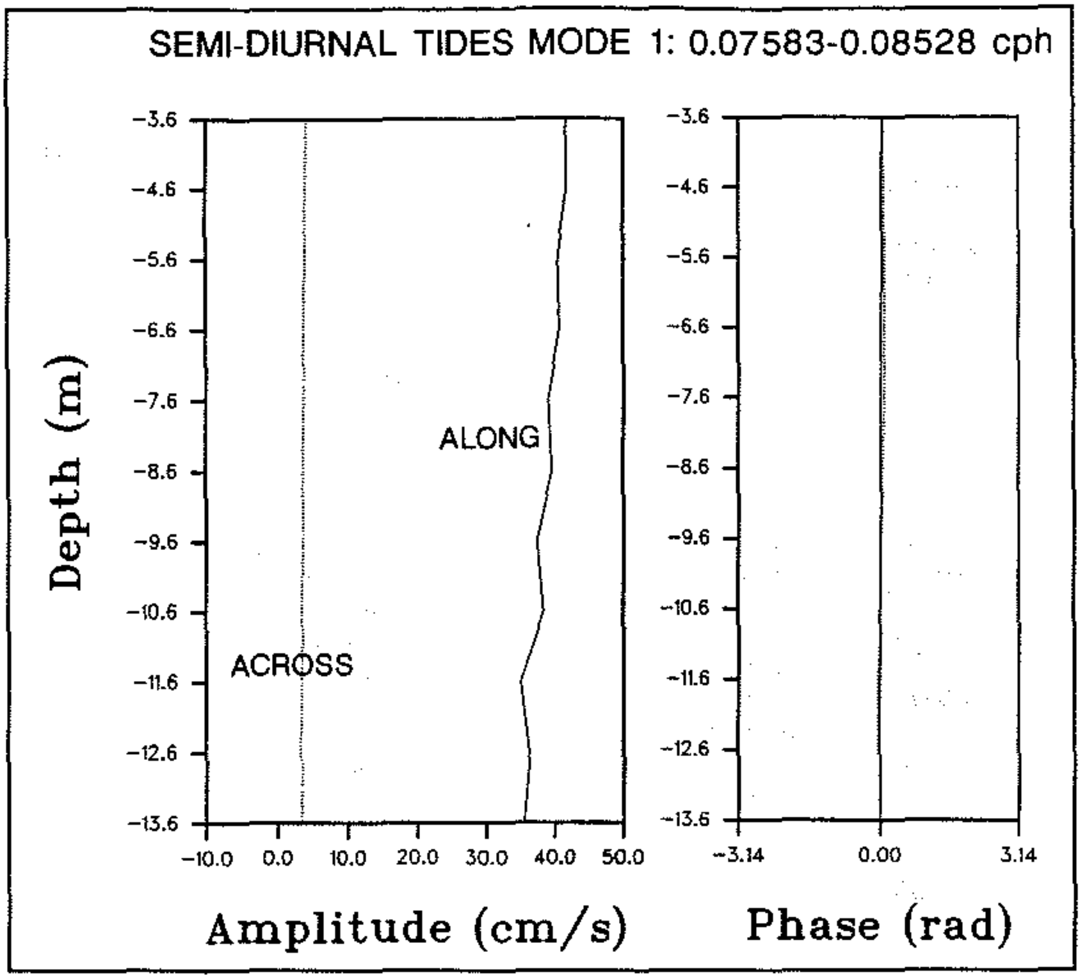

Figure 4. The amplitude and relative phase distribution with depth (between 1.9 m from the bottom and 3.6 m from the surface, in a total mean water depth of 15.5 m) for the first empirical orthogonal function mode, determined over the bandwidth 0.07583-0.08528, inclusive of all of the semidiurnal tidal species. For the along-axis (solid lines) and across-axis (dashed lines) components, the first mode accounts for 99.9% and 98.9% of the variance summed over the water column, respectively.

Buoyancy-driven Flow

The record length mean values for the along-axis and across-axis components of the flow are shown in Figure 6. The magnitudes of the means are about 10% the magnitudes of the tidal currents. Unlike the tidal currents, however, the mean currents do not reverse every 12 to 24 hours; rather, they provide a persistent flux of water, which, at this location, is directed into the estuary over the entire portion of the water column sampled. The shape of the along-axis distribution with depth agrees with the shape of the curve in Figure 2, with maximum inflow near the bottom and decreasing inflow towards the surface. Unlike Figure 2, however, the along-axis mean flow does not show a flow reversal between the bottom and 3.6 m from the surface. This presents a dilemma, since the large quantity of water flowing on average toward the head of the estuary must be balanced by a return flow elsewhere. This return may occur closer to the surface or in combination with near surface flows concentrated on the eastern shore where most of the fresh water enters Tampa Bay. Presently, data are not available to answer this question. What is clear, however, is that a large mean flow component exists, directed into the estuary at this location, and that this mean inflow is consistent in magnitude and shape of its vertical distribution with that predicted by buoyancy-driven convection theory.

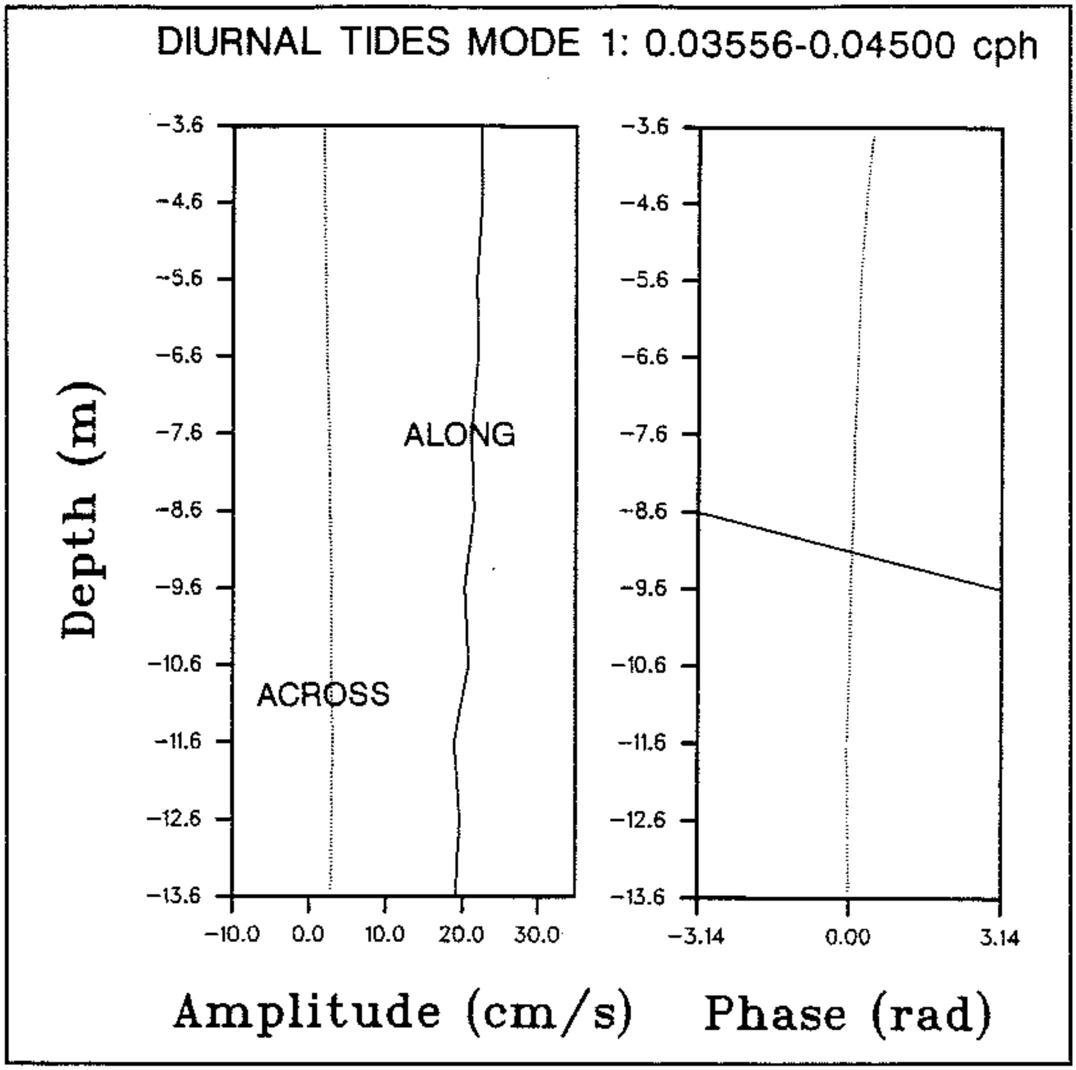

Figure 5. The amplitude and relative phase distribution with depth (between 1.9 m from the bottom and 3.6 m from the surface, in a total mean water depth of 15.5 m) for the first empirical orthogonal function mode, determined over the bandwidth 0.03556 cph-0.04500 cph, inclusive of all of the diurnal tidal species. For the along-axis (solid lines) and across-axis (dashed lines) components, the first mode accounts for 99.9% and 97.1% of the variance summed over the water column, respectively.

Wind-driven Flow

Figure 7 shows the low-pass filtered time series of along-axis velocity component at 2 m intervals between 1.9 m from the bottom and 3.6 m from the surface. Inspection of these non-tidal along-axis velocity component fluctuations shows that like the tidal currents the non-tidal fluctuations also occur uniformly with depth over the portion of the water column sampled. To quantify this distribution, a time domain empirical orthogonal function analysis was performed by calculating the eigenvectors of the cross-covariance matrix between the low-pass filtered time series sampled at all 11 depths. This analysis was performed separately on the along-axis and the across-axis components. The results for the first mode, which accounted for 97% and 72% of the variances in the along-axis and across-axis components, respectively, are shown in Figure 8. Amplitude distributions with depth are shown at the top and time evolution functions are shown at the bottom. Multiplication of the amplitude function by the associated time evolution function gives the portion of the observed non-tidal current that is accounted for by the first mode. For the along-axis component, this first mode representation is essentially identical with the data at each depth sampled. Two questions present themselves: 1) what causes these non-tidal velocity fluctuations, and 2) do they represent vertically uniform non-tidal fluctuations or are they indicative of a fully three-dimensional non-tidal circulation? The answers to both of these questions follow from analyses of the non-tidal fluctuations in relationship to the local wind fluctuations.

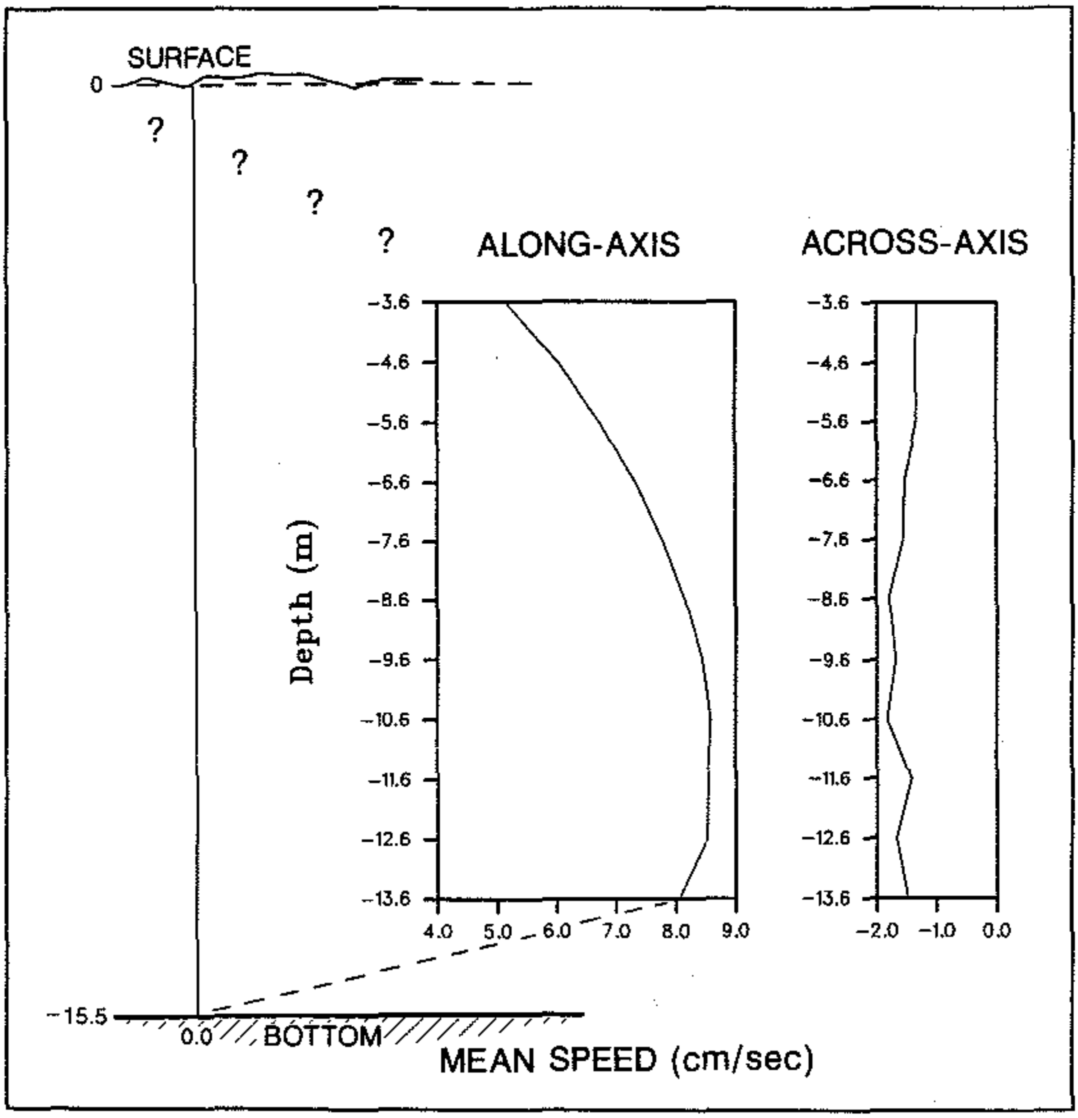

Figure 6. The vertical distribution with depth (between 1.9 m from the bottom and 3.6 m from the surface in a total mean water depth of 15.5 m) of the record length (August 15 - October 15, 1990) mean values for the along-axis and the across-axis components of velocity measured in the main shipping channel beneath the Sunshine Skyway Bridge. Positive along-axis component values are directed into the estuary. The bottom boundary condition requires that the flow goes to zero at the bottom. Whether or not the flow reverses within the upper 3.6 m at this location remains unknown.

Wind velocity time series for the August 15 through October 15, 1990 time period, as recorded at the Tampa International Airport (TIA), were obtained from the National Weather Service archive in Asheville, N.C. Figure 9 shows the TIA wind velocity components in a Cartesian coordinate system oriented along 060°T and 150°T, wherein the time series have been low-pass filtered in the same way as the non-tidal currents and the time base has been shifted to GMT to coincide with the

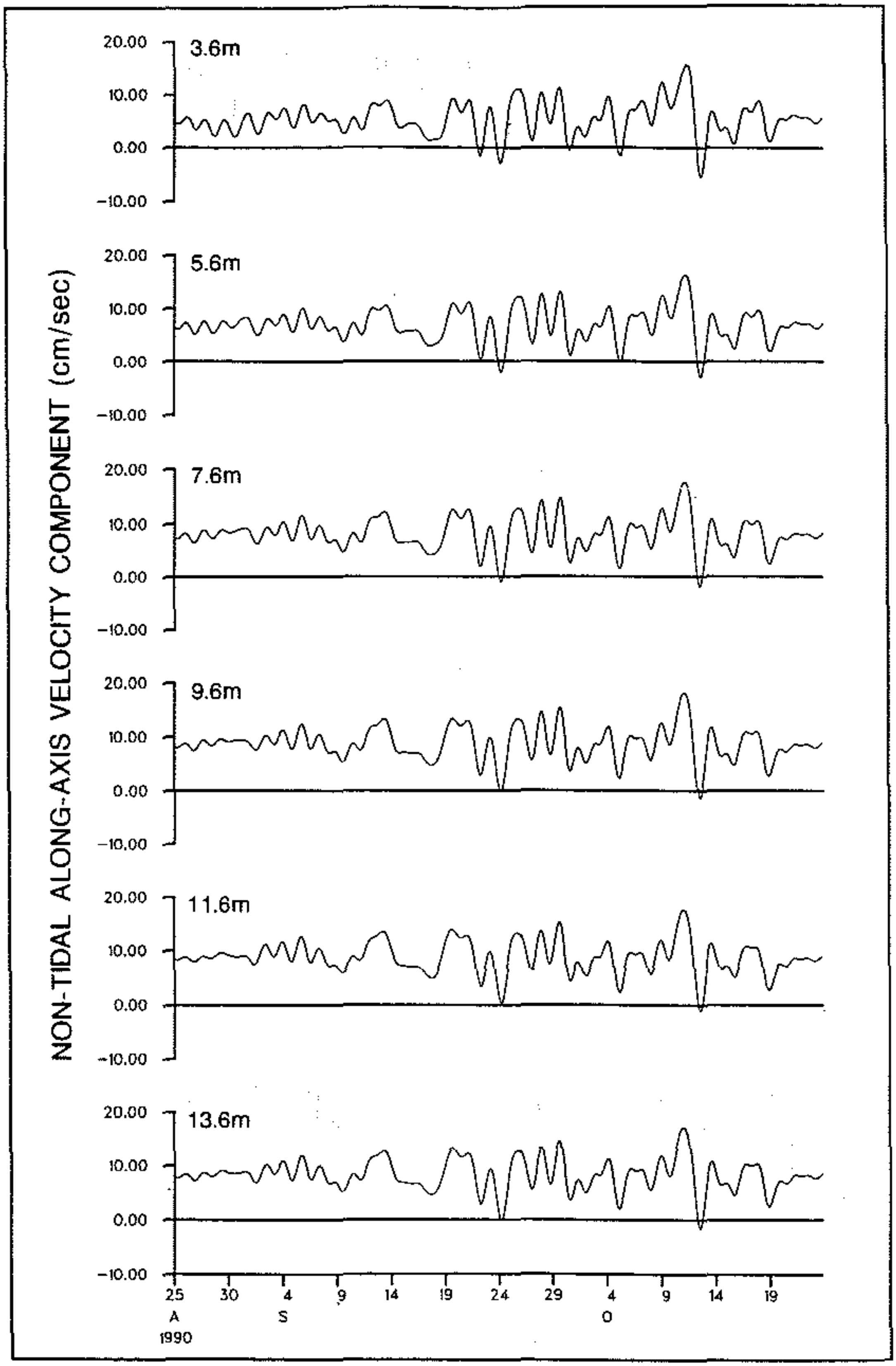

Figure 7. Time series of along-axis velocity component measured in the main shipping channel beneath the Sunshine Skyway Bridge at 2 m depth increments between 1.9 m from the bottom and 3.6 m from the surface, low-pass filtered to exclude oscillations at time scales shorter than 36 hours.

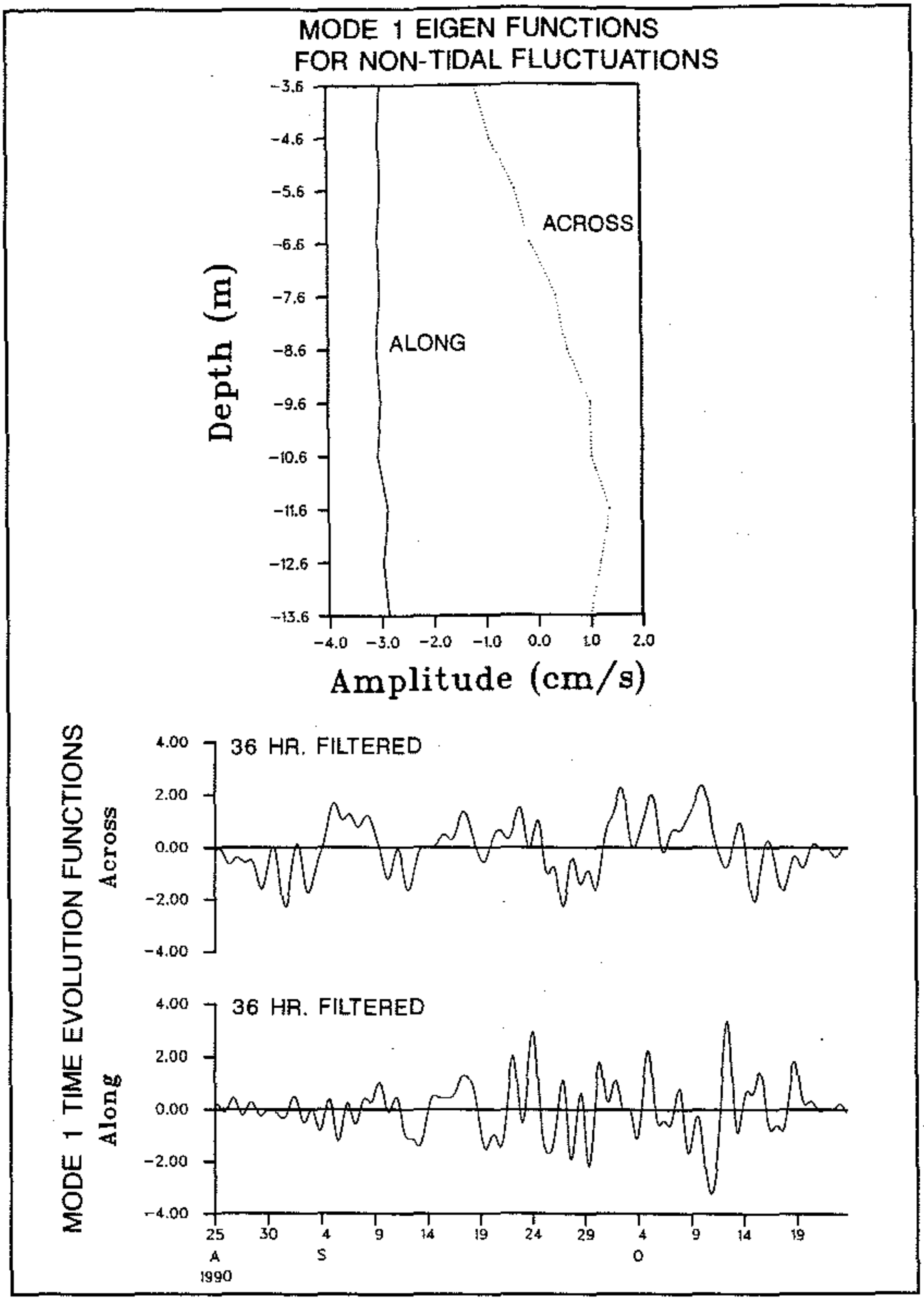

Figure 8. The amplitude distribution with depth (between 1.9 m from the bottom and 3.6 m from the surface, within the main shipping channel beneath the Sunshine Skyway Bridge) of the first mode empirical orthogonal function computed separately for the along-axis (solid line) and the across-axis (dashed line) components of non-tidal current, and their associated time evolution functions. The first mode accounts for 97% and 72% of the variance summed over the water column for the along-axis and the across-axis components, respectively. Multiplication of the time evolution function by the amplitude distribution with depth gives the portion of the time series at each depth that is accounted for by the first mode.

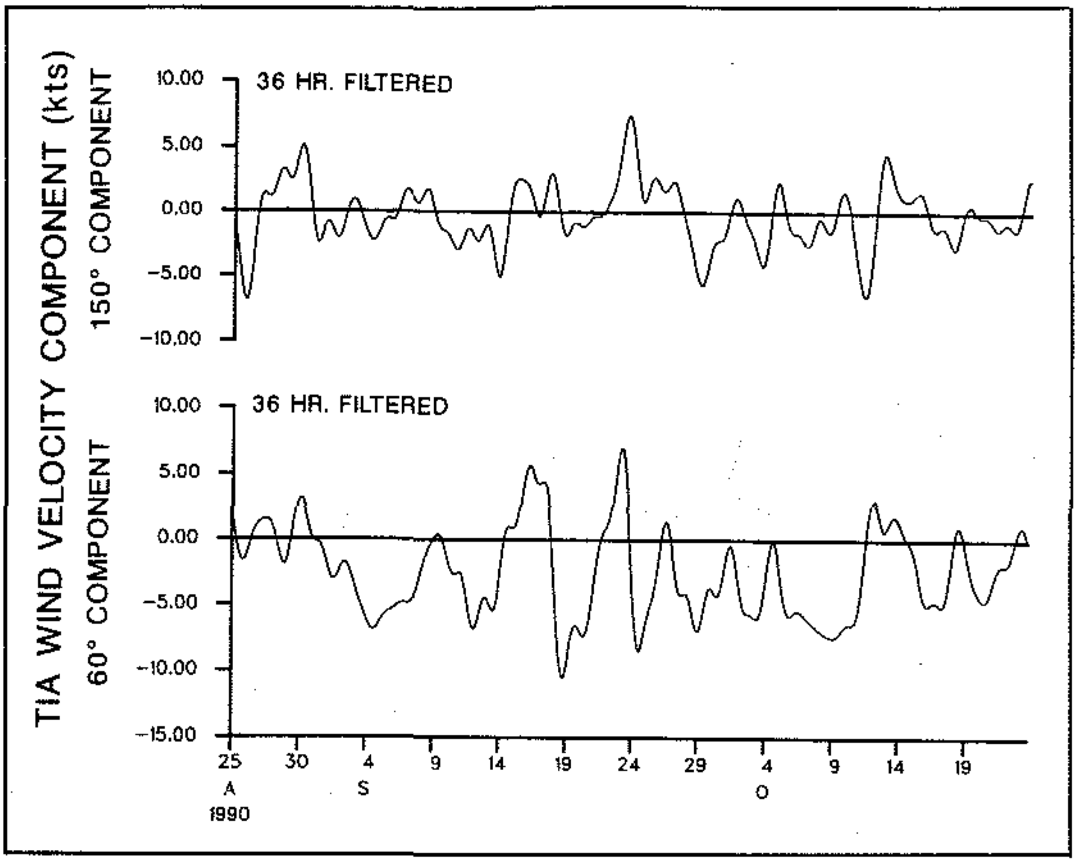

Figure 9. Wind velocity components relative to 060°T and 150°T sampled at the Tampa International Airport, low-pass filtered to exclude fluctuations at time scales shorter than 36 hours. The time base has been adjusted to GMT to coincide with the water velocity data.

TOP data. As a first analysis of the relationship between the along-axis currents and the winds, coherency was calculated between the wind velocity and the first mode along-axis current time evolution function for different wind velocity vector orientations. The results are shown in Figure 10 as contours of coherence squared as a function of wind velocity component orientations between 000°T and 180°T and frequency. Coherence squared, in this calculation, is the portion of the variance in the along-axis component of current that may be accounted for by a linear relationship with the component of wind velocity oriented along a given direction. The analysis shows that the along-axis component of current is highly coherent with the wind velocity at TIA. This coherence is highest over the frequency band that includes the synoptic scale wind fluctuations, i.e., those fluctuations that are associated with well organized weather patterns, having time scales of several days and space scales large compared with Tampa Bay, and for which the wind fluctuations observed at TIA are indicative of winds over the bay. Within this synoptic band, the wind velocity component that is most coherent with the along-axis non-tidal current component is the component that is oriented at approximately 060°T. Thus, along-axis winds are most effective in driving along-axis currents. Note that a secondary peak in coherence squared lies along an orientation of 000°T, which coincides with the orientation of the west Florida coast line.

Having established that the non-tidal along-axis component of current is coherent with the local wind velocity, the next set of analyses addresses how well the non-tidal current fluctuations can be accounted for in terms of the local winds. A statistical model is applied which seeks a set of transfer functions that minimize the

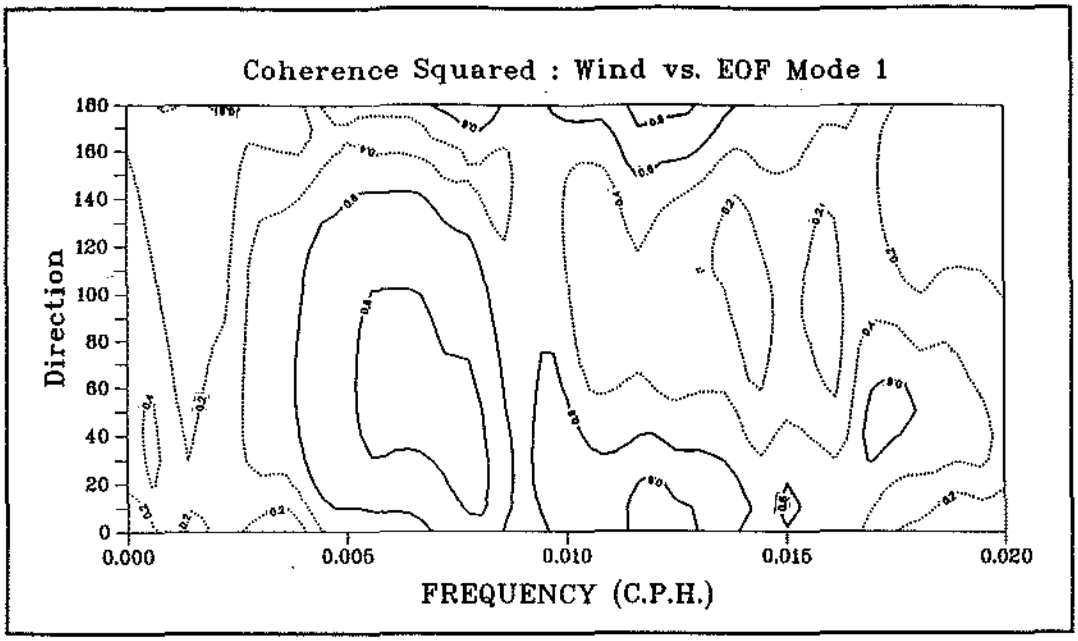

Figure 10. Coherence squared as a function of wind velocity component orientation and frequency. The calculation was performed over a bandwidth of 0.00417 cph resulting in approximately 12 degrees of freedom for which the 90% significance level is 0.44. Contours encompassed by solid lines therefore represent significantly coherent wind and water velocity component fluctuations. Note that maximum coherence occurs over the synoptic scale wind fluctuation frequency band and in the along estuarine axis direction.

mean squared error between the observed non-tidal currents and the portion of the non-tidal currents that can be estimated by linear operations upon the local wind velocity components. The natural coordinate system to work in, based upon the results of Figure 10, is the coordinate system aligned with the along-axis direction of approximately 060°T. The results of the linear mean square estimation analysis are given in Figure 11. Multiple squared coherence (top) is the portion of the non-tidal along-axis component of current variance that is accounted for by linear operations upon both orthogonal wind velocity components. The figure shows that over the synoptic weather band some 90% of the along-axis current fluctuations are accounted for by the local winds. Within this range, the transfer function amplitude for the along-axis component of wind velocity translates to approximately 6 cm/sec of current for every 10 kts of wind. The phase relationship is such that a wind velocity fluctuation directed into the estuary (toward 060°) produces a non-tidal velocity component fluctuation directed out of the estuary, with the wind velocity fluctuation leading the water velocity fluctuation by several hours. This suggests a causal relationship between the wind velocity fluctuations and the non-tidal current fluctuations, and to see how well this statistical model works, Figure 12 shows the observed mode 1 along-axis velocity component time series and its estimated counterpart using the transfer functions of Figure 11. The time series are nearly identical. We caution that these results are based upon short records with a limited number of degrees of freedom. They will be refined and extended as more data become available. However, the results are encouraging and they seem to offer clear answers to the two questions that were posed earlier. First, the cause of the non-tidal along-axis current fluctuations is primarily the local wind fluctuations and in particular the component of the local wind velocity that lies along the axis of the bay. Second, since the phase relationship between the along-axis winds and the along-axis non-tidal currents is such that winds blowing into the bay cause currents in the channel (between depths of 3.6 m from the surface and the bottom) to flow out of the

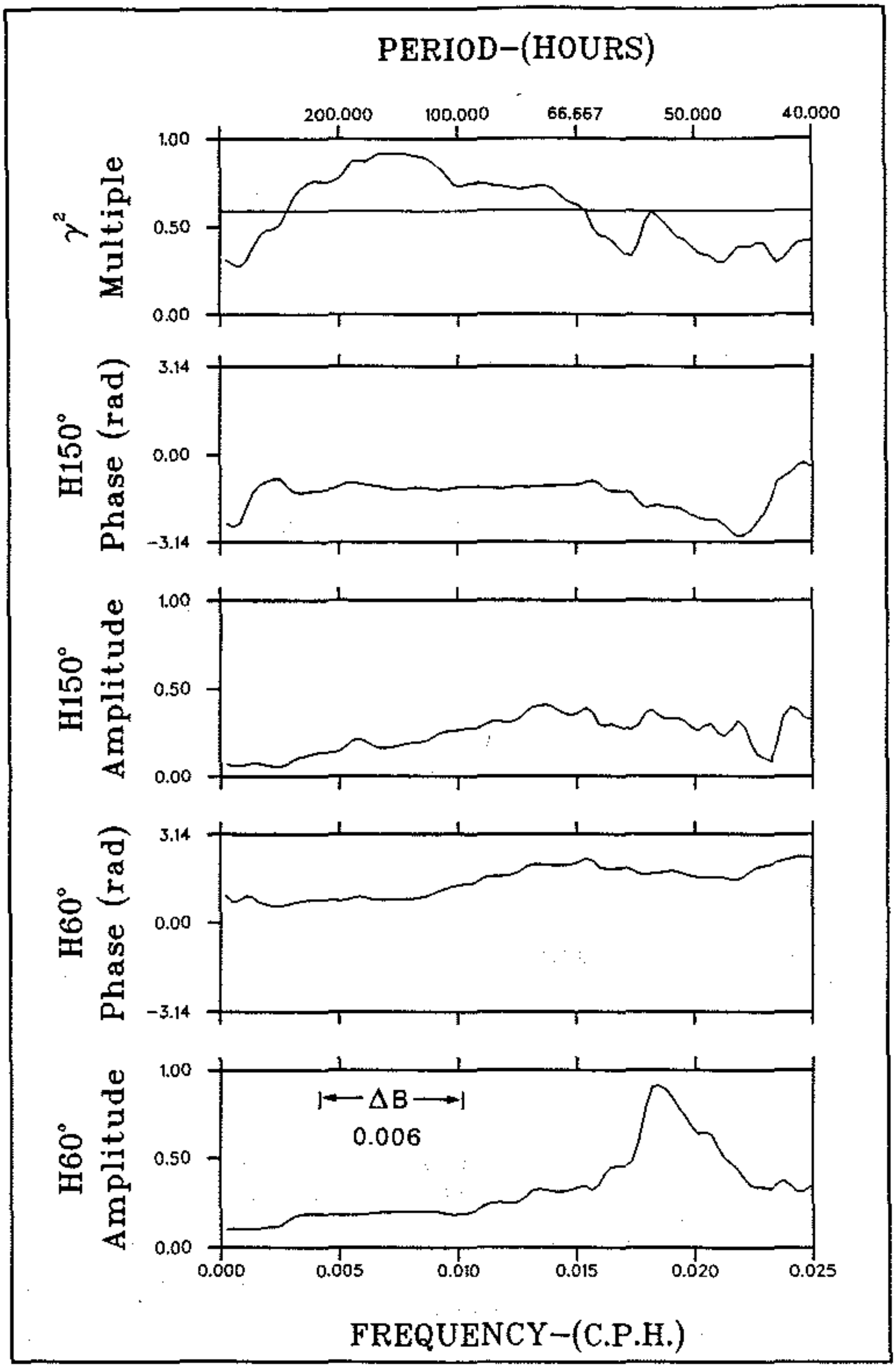

Figure 11. Results, in the frequency domain, of a multiple input (two orthogonal wind velocity components) single output (along-axis water velocity component time evolution function) linear mean square estimation analysis. From top to bottom, as a function of frequency, are the multiple coherence squared, the transfer function amplitude and phase for the across-axis wind velocity component and the transfer function amplitude and phase for the along-axis wind velocity component. Averaging was performed over a bandwidth of 0.0064 for approximately 18 degrees of freedom and the associated 90% significance level on multiple squared coherence is 0.59. Error bars will eventually be added to the transfer functions upon inclusion of additional data.

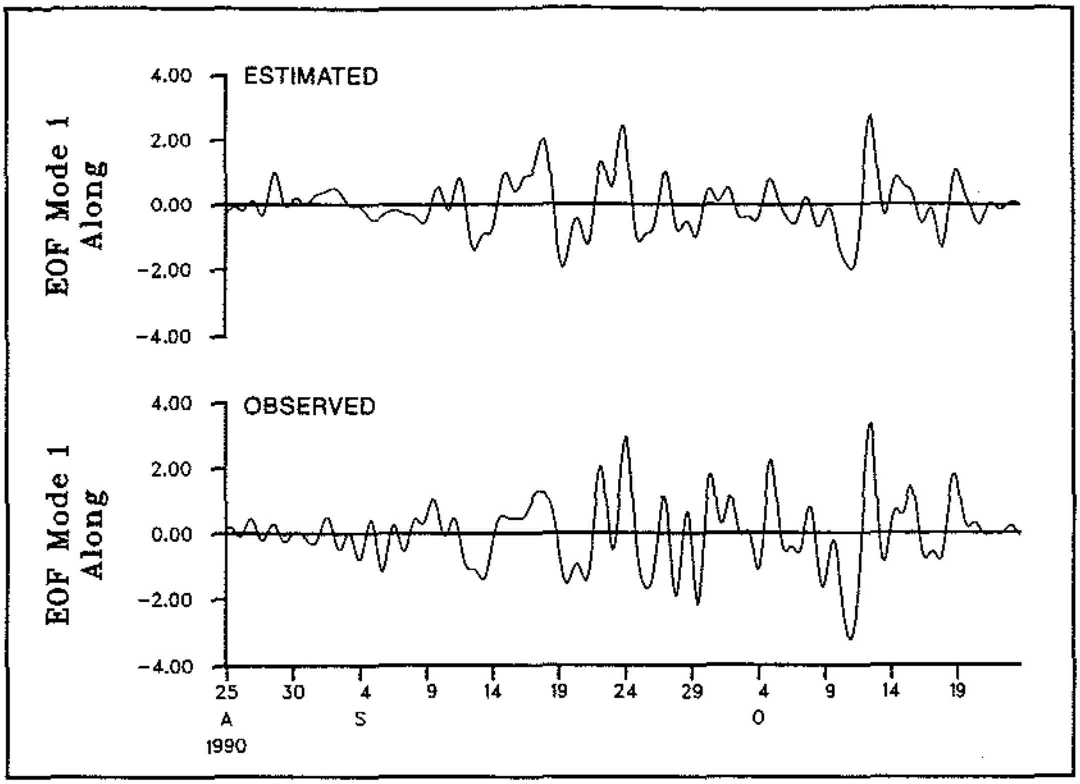

Figure 12. The results, in the time domain, of the linear mean square estimation procedure. Two time series are compared: 1) the observed first mode (accounting for 97% of the variance) time evolution function for the non-tidal along-axis water velocity component and 2) its counterpart estimated via linear operations upon the two orthogonal wind velocity components.

bay, and conversely, the wind-driven, non-tidal circulation must be fully three-dimensional. A similar result was found for Narragansett Bay by Weisberg (1976) and the effects of winds aligned with the coastal ocean were shown for Chesapeake Bay by Wang and Elliott (1978).

SUMMARY AND RECOMMENDATIONS

State and local agency concerns over the deteriorating water quality of Tampa Bay have led to considerable sampling and restoration efforts, as reported during the two successive Bay Area Scientific Information Symposia BASIS and BASIS 2. Little attention, however, has been given to the circulation of the bay since it has been assumed, by virtue of vertically well mixed salinity, that the circulation is vertically uniform also. The NOAA/National Ocean Service Tampa Bay Oceanography Project (TOP), presently in progress, is providing the first comprehensive data set capable of describing the three-dimensional aspects of the circulation in Tampa Bay. The present paper has discussed initial findings from the first two months of TOP velocity data collected at a long term measurement station located within the main shipping channel beneath the Sunshine Skyway Bridge. Empirical evidence is given for three important types of circulation, driven by tides, buoyancy and winds, respectively. The primary conclusion is that the circulation of the Tampa Bay estuary is fully three-dimensional.

As a region in which river waters mix with sea water, estuaries develop a particular mode of circulation, commonly referred to as "estuarine circulation", which is driven by the horizontal variation of salinity from relatively fresh to relatively salty water between the estuary's head and the coastal ocean. These horizontal salinity gradients promote a buoyancy-driven convection irrespective of the vertical salinity gradient at any point along the estuary. A conceptual basis for this buoyancy-driven convection has been discussed here, along with a simplified analytical model. Estuaries are also influenced by non-tidal wind-driven flows and, of course, tidal currents. The TOP data show these three components of the circulation as described here, which may be summarized as follows. At the Sunshine Skyway Bridge, the tidal currents are nearly uniform with depth with peak speeds of about 1.5 kts; there exists a vigorous buoyancy-driven mean flow directed into the estuary with a magnitude of about 10% of the tidal currents; winds blowing into the bay cause currents to flow out of the bay, and conversely, with these non-tidal current fluctuations predictable by techniques of linear mean square estimation. The buoyancy- and wind-driven flow findings provide a conundrum. With water steadily flowing into the bay between depths of 1.9 m from the bottom and 3.6 m from the surface by buoyancy forcing and with water fluctuating uniformly into or out of the bay between these depths for several days at a time by wind forcing, where do the return flows occur in order to balance mass? These return flows must occur either above 3.6 m, or on the sides, or by a combination of both. Inspection of a bathymetric map of the bay shows that from an areal perspective, about half of the estuary has depths less than 3.6 m, the uppermost TOP measurement depth under the Sunshine Skyway Bridge. It is conceivable therefore that a considerable return flow can occur above this depth over a large areal extent. Also important is the fact that most of the river inflow to the bay occurs distributed along the east shore. It is conceivable therefore that a considerable portion of the return for the buoyancy-driven convection part of the flow occurs on the east side of Tampa Bay, although for river water uniformly input at the head, the Coriolis force would favor the opposite shore. As a conundrum we can only speculate until further measurements aimed at answering these important questions are made. The following recommendations follow from these findings:

1. Tampa Bay should be viewed as a fully three-dimensional estuary for water quality considerations.
2. The TOP data set should be extensively analyzed for tidal, buoyancy and wind driven modes of circulation.
3. Additional measurements should be implemented to answer the questions raised by TOP data; essentially how are the non-tidal buoyancy- and wind-driven circulations closed?
4. With Tampa Bay fully three-dimensional and time dependent, and with spatially inhomogeneous fresh water and nutrient inputs, sampling strategies must be careful to avoid temporal and spatial aliasing and biasing.
5. With complicated bottom topography and inhomogeneous inputs, a fully three-dimensional and time dependent numerical model (see Galperin et al. and Hess et al., both in this volume) will be required to fully explore the flow field and to address the water quality issues that are linked to the flow field.
6. While such numerical models are necessary they are not sufficient. They must be carefully tested against a data set that is complete enough to elucidate the relevant processes and pathways. Once tested and validated, a set of scientific questions may be posed, numerical experiments conducted and results analyzed.

ACKNOWLEDGEMENTS

We wish to express our appreciation to Dr. H. Frey, Chief, Estuarine and Ocean Physics Branch, National Ocean Service, NOAA, for his cooperation in making these data available is such a timely manner. The TOP field program represents a major undertaking by skilled NOS scientists, engineers and technicians, all of whom are collectively recognized here.

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NUMERICAL CIRCULATION MODEL CALIBRATION AND VALIDATION FOR TAMPA BAY USING N.O.S. CIRCULATION SURVEY DATA

K. Hess

ABSTRACT

The Estuarine and Ocean Physics Branch in NOAA's National Ocean Service is presently conducting the Tampa Bay Oceanography Project (TOP), including development and application of a three-dimensional, time-varying, curvilinear-grid circulation model of the bay (NOS 1990). A version of the Princeton numerical circulation model is being used to understand the local oceanography and to study the tidal water level response characteristics throughout the bay. The model depicts the vertical water current profile at numerous locations throughout the bay, allowing for a predictive capability that includes the combined effect of tides, winds and density gradients on water levels and currents. Bathymetric data for the bay were obtained from NOAA's National Geophysical Data Center in both gridded and non-gridded format for model input. Validation studies are being carried out on a medium resolution grid that includes comparison of modeled and predicted astronomical tides in Tampa Bay during times when wind effects were not dominant, and for uniform water density.

INTRODUCTION

The Estuarine and Ocean Physics Branch (EOPB) in NOAA's National Ocean Service (NOS) is presently conducting the Tampa Bay Oceanography Project (TOP). TOP consists of three major components: 1) an intensive, 15-month survey of currents, water levels, water temperature and salinity, winds, and other meteorological parameters in Tampa Bay, Florida (Figure 1); 2) development and application of a sophisticated three-dimensional, time-varying, curvilinear-grid circulation model; and 3) installation of the nation's first fully integrated Physical Oceanographic Real-Time System (PORTS), including information on currents, water levels, and winds at locations where these data are critical for safe navigation.

The TOP circulation survey was designed in part to gather sufficient oceanographic data in a cost-effective way to gain insight to the dynamic processes of the bay, and calibrate and validate the numerical circulation model. The survey began in June 1990, and includes 38 fixed current meter station locations. Instrument resources include seven remote acoustic Doppler sensors (RADS) and five electromagnetic current meters. There are 16 water level gage locations, five meteorological instrument stations, three moored conductivity-temperature arrays, and several transects for towed RADS and conductivity-temperature-depth meters (see Williams, this volume).

EOPB has a version of the Princeton three-dimensional numerical circulation model for the project. This model is being applied to the bay to understand the local oceanography and to study the tidal water level response characteristics throughout the bay. The model depicts the water current profile over the vertical and at numerous locations throughout the bay between current meter stations, allowing for a predictive capability that includes the combined effect of tides, winds and density gradients on water levels and currents. The extensive data set collected during the circulation survey will be used for model calibration and validation.

The data and information products and services that will result from the model study are: 1) a model-generated circulation and water level forecast atlas; 2) model-generated simulations of circulation and water levels available to the public on magnetic media; and 3) a technical report on the physical oceanography of Tampa Bay and model validation.

PAST OCEANOGRAPHIC AND MODELING STUDIES OF TAMPA BAY

Tampa Bay has been the object of numerous oceanographic studies over the years. Dinardi (1978) described an extensive circulation survey of the bay in 1963.

These data have been used for the NOAA Tidal Current Tables and the Tidal Current Charts for Tampa Bay.

Goodwin and Michaelis (1976) report on a water level study carried out by the U.S. Geological Survey during 1971-1973. During the study period, the maximum tide at St. Petersburg was recorded at 1.5 m during Hurricane Agnes and the minimum tide was recorded at 0.9 m below mean sea level.

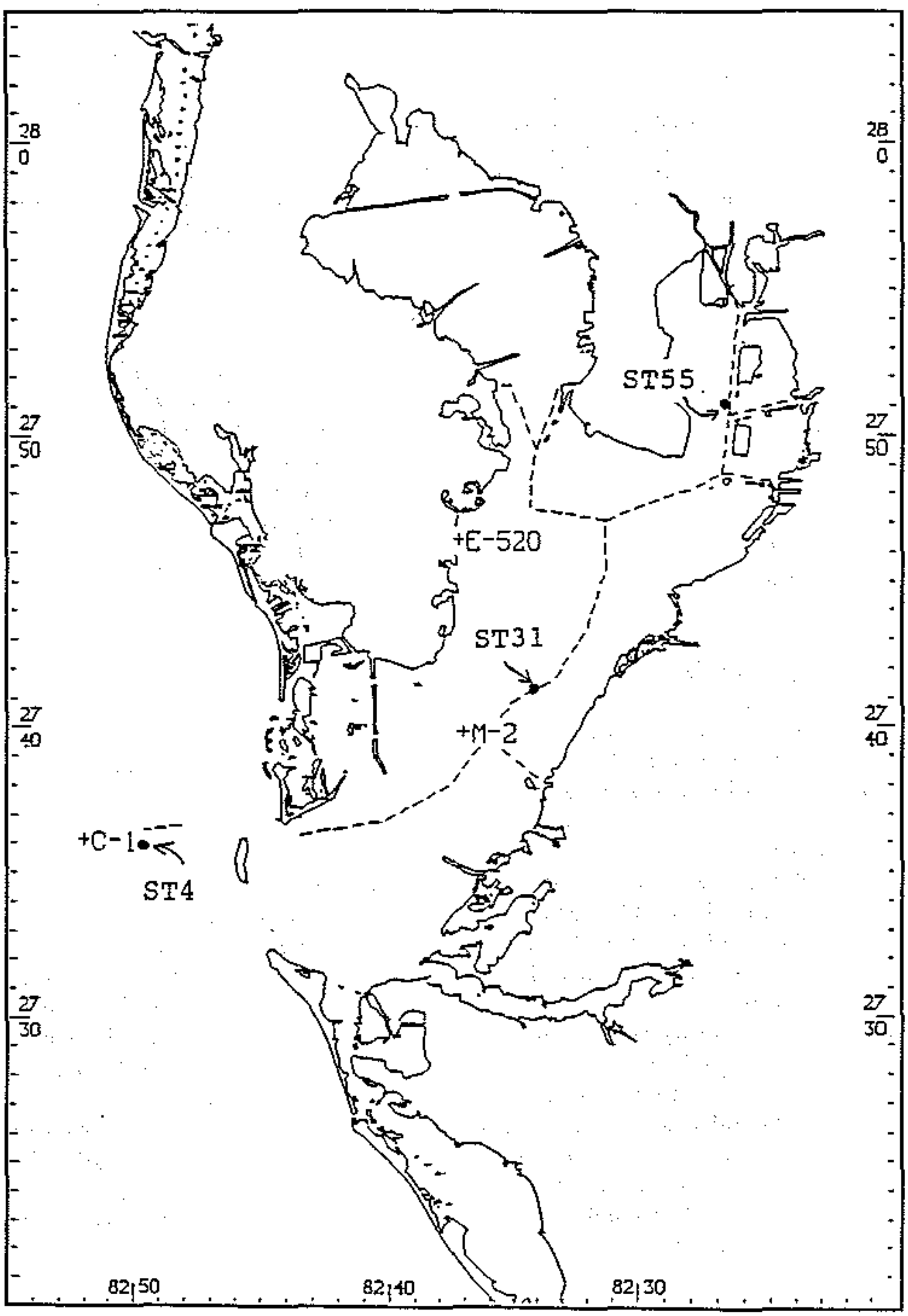

Figure 1. Location map of the Tampa Bay region showing salinity-temperature profile stations ST4, ST31, and ST55; current meter and pressure transducer station C-1; water level station E-520; and meteorological station M-2.

Ross (see Goodwin 1987 and Spaulding et al. 1988) has carried out several numerical modeling studies of tidal residual circulation and water quality in Tampa Bay. He and his associates used vertically-averaged horizontal momentum equations, but ignored horizontal shear stresses and density gradients. The residual circulation was determined to be an important component in flushing the bay.

Goodwin and Ross (1984) made comparisons of tidal amplitudes, residual tidal circulation, and storm surges on Tampa Bay using their respective vertically averaged numerical models. They estimated changes in circulation likely to occur after the completion of pier protection islands near the new Sunshine Skyway Bridge. While the overall circulation in the bay was not altered significantly, there were noticeable changes in current vectors near the bridge.

Goodwin (1977, 1980, 1987) made highly detailed numerical simulation of currents to simulate the effects of dredging to the flushing of the Tampa Bay and Hillsborough Bay. He used a two-dimensional, vertically integrated numerical model with a grid cell size as small as 500 m to produce relatively accurate estimates of the tidal currents. Goodwin (1987) achieved an average standard error of 3 cm between modeled and observed half-hourly water levels at 11 locations, although only 1.5 days of data were used. He also achieved an average standard error of 3 cm/s for a 40-hour period when comparing currents measured at a distance above the bottom equal to 40% of the total water depth and the model's vertically averaged currents. These studies demonstrated the importance of residual circulation in flushing the bay.

Shaffer et al. (1986) describe the National Weather Service's storm surge modeling program for the U.S. east and Gulf coasts. Model basins include one developed for Tampa Bay. The vertically-integrated surge model operates on a polar grid that covers the central portion of the southwest Florida coast with a grid cell size of 4 km, and has higher resolution (cell size approximately 1 km) inside the bay. This model does not, however, simulate astronomical tidal variations.

To achieve an objective, quantitative assessment of the accuracy of NOAA's current predictions, a Quality Assurance (QA) Miniproject was recently conducted (Williams et al. 1989). Measurements were made during deployment periods from December 1988 through February 1989 at the reference station for current predictions (Egmont Channel), the new Sunshine Skyway Bridge, the intersection of B-Cut and Manatee Channel, and the intersection of K-Cut and Port Tampa Channel, where data had been collected during the 1963 survey. Statistical analysis of the published NOAA predictions and those computed from the new measurements showed that differences in the times of slack waters and maximum ebb and flood currents sometimes exceed acceptable standards.

THE NOS NUMERICAL CIRCULATION MODEL

The Princeton three-dimensional numerical circulation model (Blumberg and Mellor 1987) is being applied to the bay understand the local oceanography and to study the tidal water level response characteristics throughout the bay. The model depicts the vertical water current profile at numerous locations throughout the bay between current meter stations, allowing for a predictive capability that includes the combined effect of tides, winds and density gradients on water levels and currents. Since significant horizontal and vertical salinity and temperature gradients have been observed by NOS in Tampa Bay during the survey (Figure 2), it is important that the model be capable of simulation in three dimensions.

The model includes a dimensionless sigma vertical coordinate, the level 2-1/2 turbulence closure representation, and an orthogonal curvilinear horizontal coordinate system. Occasional problems arising from the use of sigma coordinates (Sheng et al. 1990) are alleviated by using uniform sigma intervals, avoiding large bottom slopes, subtracting the mean water density from the local density, and using a carefully selected horizontal pressure gradient. The code is structured to take advantage of high-speed vector processing. The model will provide a theoretical basis for unifying

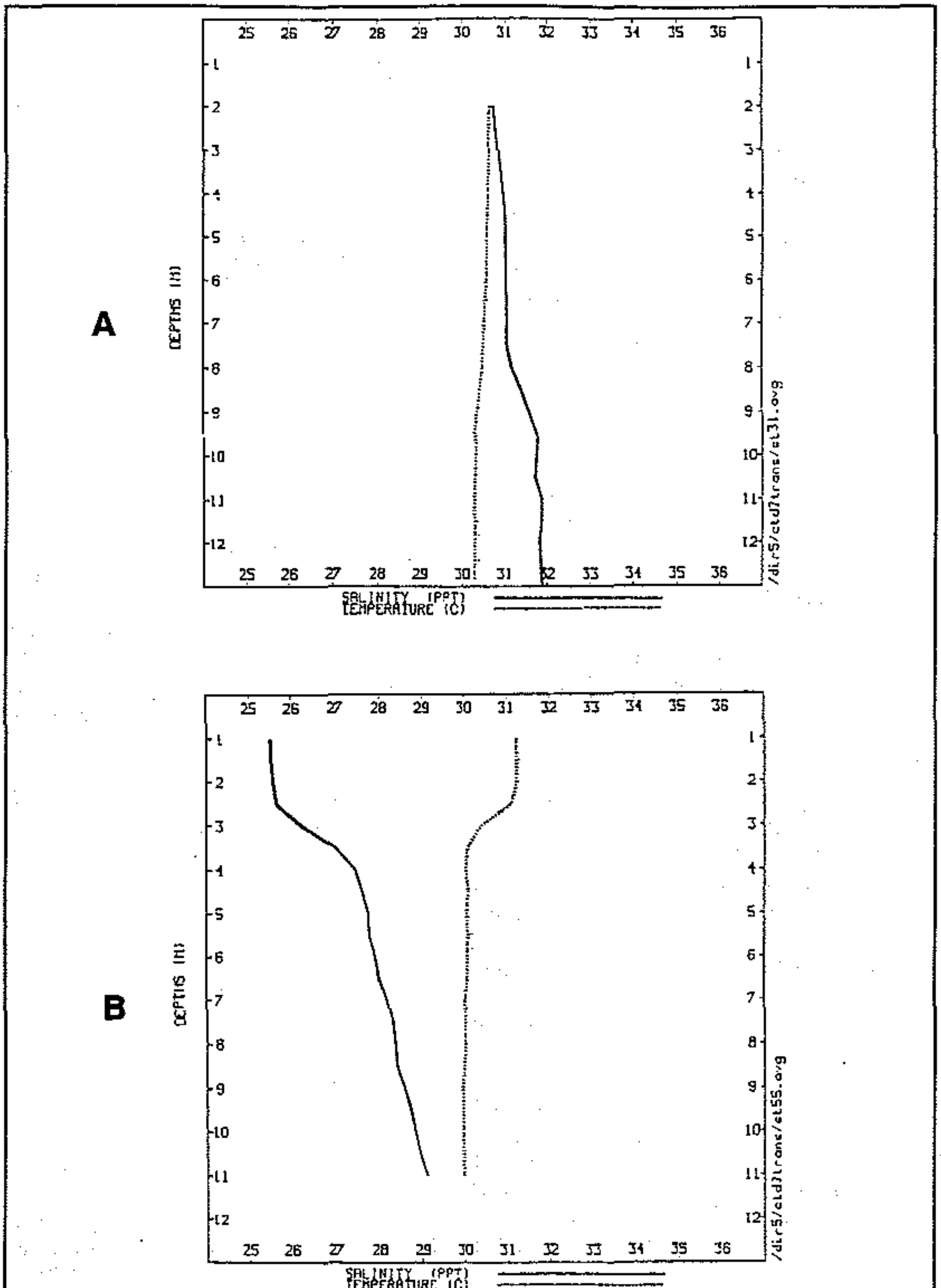

Figure 2. Salinity and temperature profiles at (A) station ST31 (mid-bay), and (B) station ST55 (Hillsborough Bay); see Figure 1 for locations.

model outputs will again be quantified and compared to criteria for an assessment of accuracy.

MODEL CALIBRATION AND VALIDATION STUDIES FOR WATER LEVELS

The simulation chosen for the initial study was a comparison of observed and modeled (hindcast) water levels at St. Petersburg for a 10-day period in August 1990. Input data needed to include water levels at the model boundary outside the bay, wind velocity data, and freshwater inflow data.

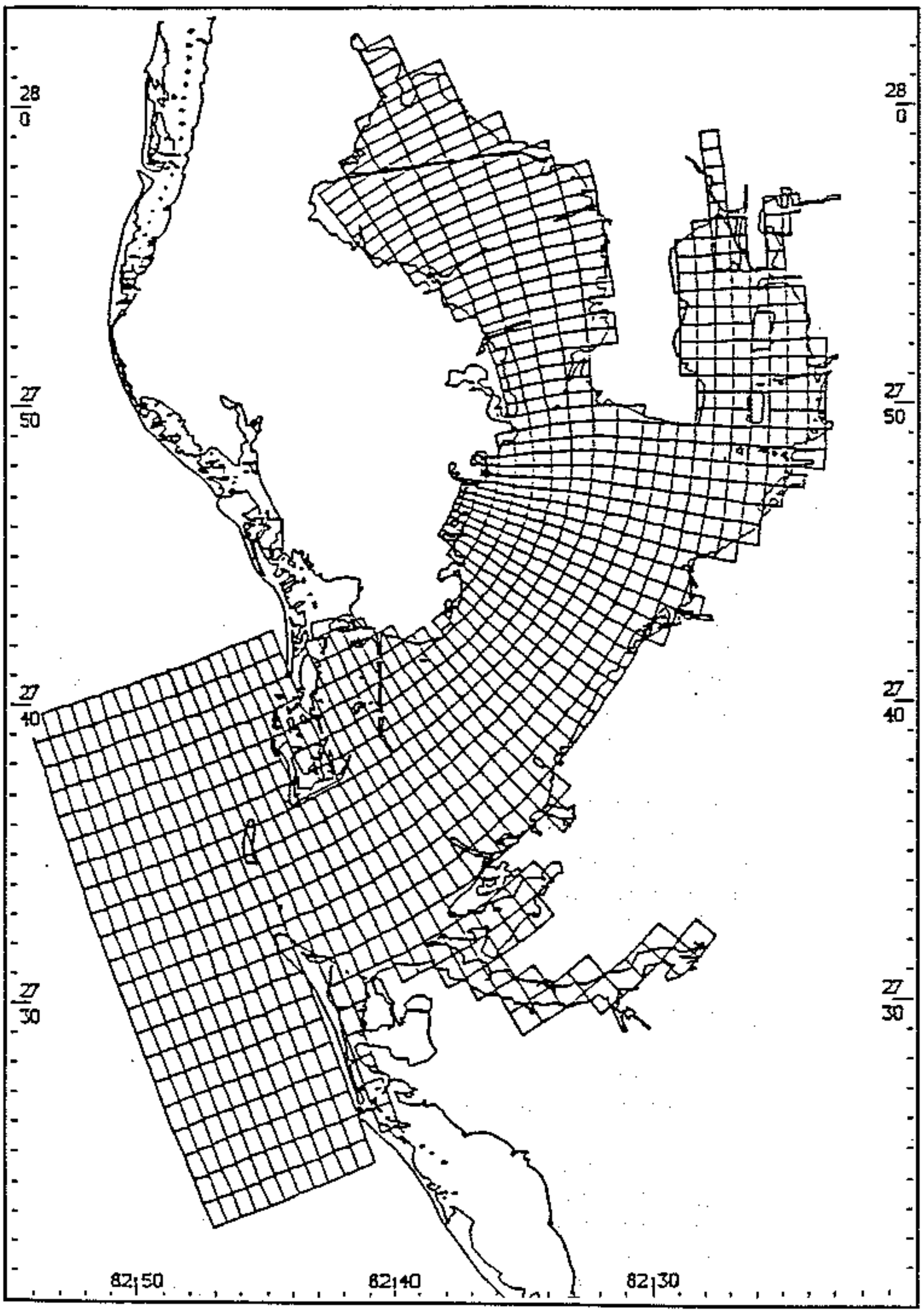

Figure 3. Medium resolution numerical model grid for Tampa Bay.

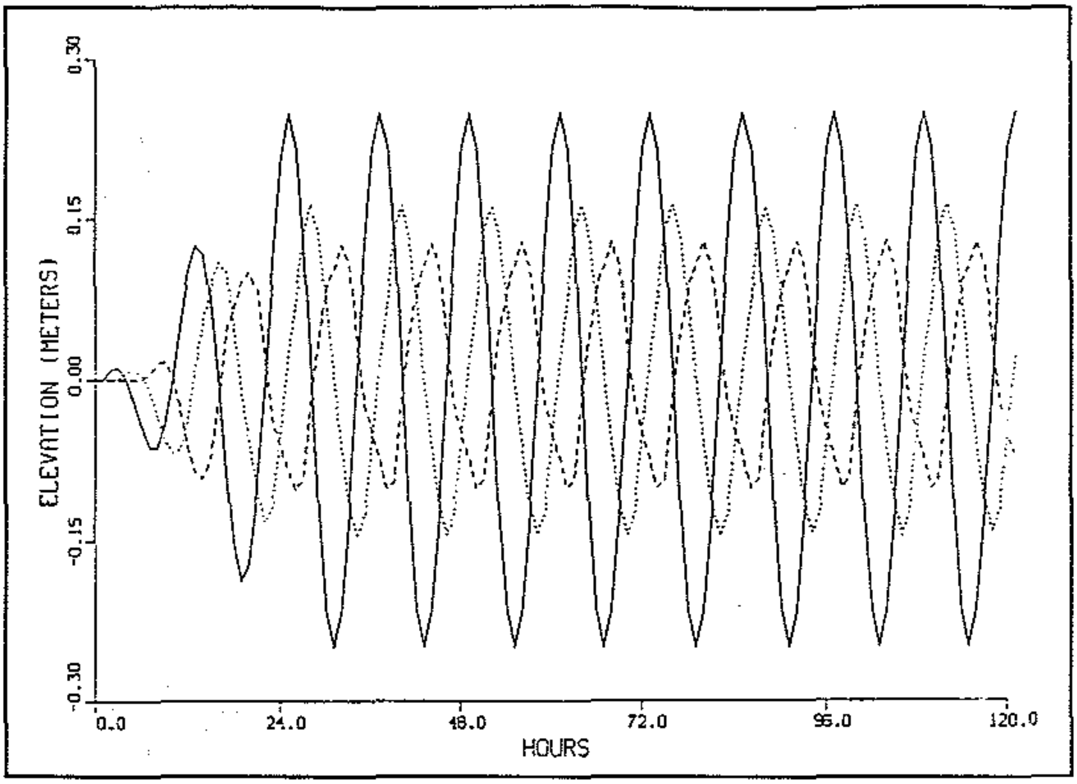

Figure 4. Results of a spin-up experiment. Solid line is the ocean boundary tide, the dotted line is the modeled tide at St. Petersburg, and the dashed line is the modeled tide at Davis Island.

Water levels at the model boundary needed to drive the tidal currents throughout the bay have been obtained from a long-term installation of a pressure transducer fixed to a bottom-mounted RADS unit positioned approximately 15 km west of the entrance to Tampa Bay at station C-1 (see Figure 1). Water level values were obtained by converting pressure values to water column heights (without correcting for density effects) for all 10-minute observations and subtracting the mean. (In the future, harmonic analysis of these data will provide the constituent tides for modeling purposes. Additional tide data outside the bay is available north at Clearwater Beach and south at Venice Pier.)

Wind data has been collected as part of TOP at four locations around the bay, including Egmont Key which represents more coastal conditions. Wind speed and direction at the PORTS site (station M-2; see Figure 1) is to estimate the wind stress for the entire bay.

River flow data for the present consists of monthly climatological averaged discharges for four major rivers (Flannery 1989). These data have been interpolated to give daily values.

Water levels at St. Petersburg (station E-520; see Figure 1) were measured during TOP and processed at 6-minute intervals. These data are used to check the model's performance.

The results of a 10-day simulation are shown in Figure 5. Phase information is very good, although amplitudes are less accurate. (In the future, an effort will be made to quantify the relationship between the observed and the modeled time series.)

As a check on the input conditions, the observed and computed water levels at Egmont Key are compared; the goodness of fit indicates that the input condition is sufficiently accurate.

data from short-term observational programs and the conceptual knowledge of the important physical processes in the bay. Model output can be used to develop new relationships for prediction and to assist in designing observational networks.

This model is presently being used in EOPB for Long Island Sound tidal, wind, and density current simulations, and will be used for the Charleston Harbor, South Carolina, circulation and modeling project. It has also been used by others in Delaware Bay (Galperin and Mellor 1990) and other coastal regions. The EOPB model runs on the National Institute for Science and Technology's Cyber 205 supercomputer at Gaithersburg, Maryland. Analysis of model output can be made either on the Cyber, or on EOPB's Hewlett-Packard 9000/825 or Silicon Graphics 4D/340SGX minicomputers. Extensive display graphics utilities exist on all machines.

TAMPA BAY GRID AND BATHYMETRY

The Princeton circulation model includes an orthogonal curvilinear coordinate transform capability, so the grid can be fitted to the bay's lateral boundaries. Development began on an Fortran program, GEN, to generate an orthogonal curvilinear grid for Tampa Bay, based on principles in Thompson et al. (1985) and Blumberg and Herring (1987). A 23 x 83 cell curvilinear grid was generated and plotted for Tampa Bay, using the navigation channel for the centerline and the bay's shorelines for the two lateral boundaries (Figure 3). The output grid consists of a file containing the latitudes and longitudes of cell corners and is easily plotted along with the digitized coastline for the Tampa Bay-Sarasota Bay region.

Bathymetric data for Tampa Bay were obtained from NOAA's National Geophysical Data Center in both gridded and non-gridded format. Preliminary coding and testing was completed on a computer program, FILLGRID, that, given a two-dimensional grid in earth coordinates, will fill cells with depth values obtained from a bathymetric file. The input bathymetric data is a subset of the NGDC data gridded at 15-second intervals. Some user decisions are required to set a minimum water depth and the minimum water/land ratio allowed per water cell. This labor-saving approach allows rapid generation of trial grids.

MODEL SENSITIVITY STUDIES

The numerical model is now undergoing a period of sensitivity testing to determine the best set of parameters (timestep, grid configuration, water depths, and bottom roughness) for Tampa Bay simulations. During the sensitivity analysis, the important input parameters are varied to see how the computed solution changes. Turbulence parameters have been established by theoretical and experimental studies and they remain constant for these simulations.

Present model runs use an internal mode timestep of 200 seconds and an external mode time step of 20 seconds. With 972 water cells in the horizontal and 8 vertical levels, the simulation of one day requires approximately four minutes on a Cyber 205. Early results show that for sinusoidal water level forcing, interior water levels reach a condition of repeatability after about a 48-hour spinup period (Figure 4).

Generally speaking, during the calibration phase certain model inputs will be adjusted so the computed solution matches the observed data to the greatest extent possible. For the Tampa Bay study, data from several distinct time periods from the 15-month survey will be used. Differences between data and model outputs will be quantified, and the calibration process will continue until predetermined criteria are reached. Since the bay's dominant currents are tidally driven, it is desirable to select calibration and validation data, depending on the results of the field survey, for periods when wind and other forcings are both negligible and strong.

During the validation process, the adjustable input variables are fixed at their calibration values, and the model is rerun for one or more time periods different from those used during the calibration phase. Differences between observational data and

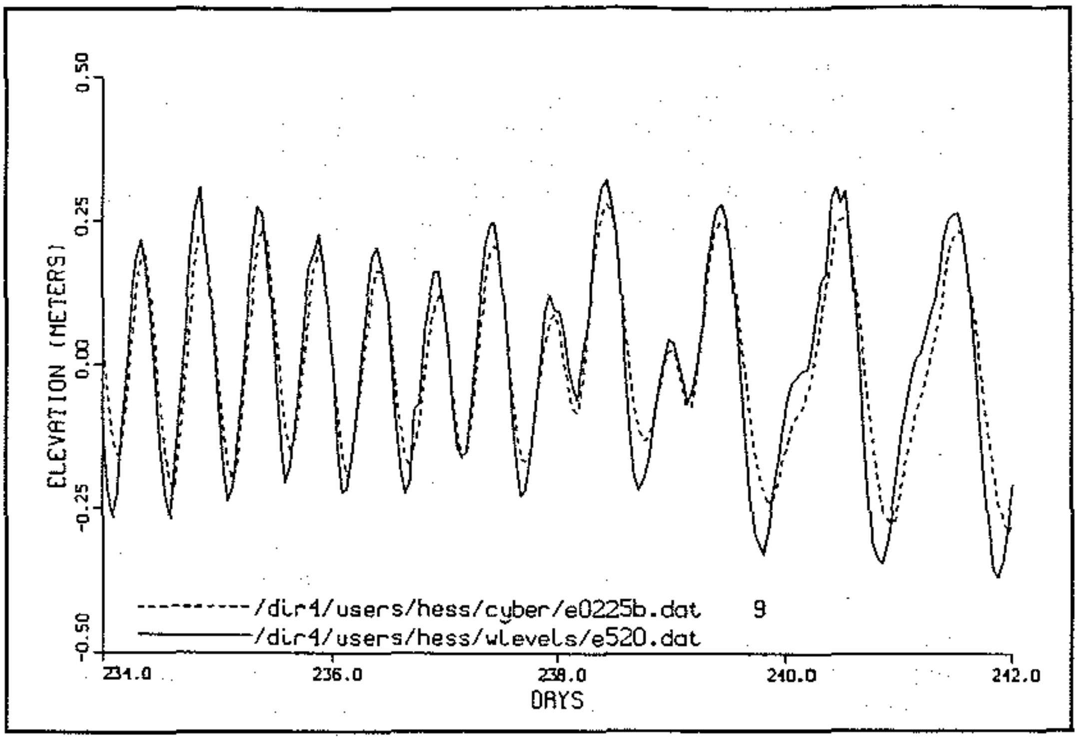

Figure 5. Water level results for August 12 - August 30, 1990. The solid line is the observed water level at St. Petersburg (station B-520), and the dashed line is the modeled water level.

FUTURE SIMULATIONS

Model calibration and validation will eventually include comparisons between model output and data from all the TOP survey locations. The tidal response must be determined first to isolate and understand the wind's contribution. Later, water level variations due to wind influence will be simulated using the collected data. Wind data will be collected at five locations around the bay, including Egmont Key which represents more coastal conditions. Wind speed and direction will be measured and used to estimate wind stress. The vertical atmospheric temperature gradient will be estimated from measurements at two levels to indicate the stability of the air column and to estimate drag coefficients. Standards of accuracy will be similar to those for tides (especially for water levels) as they may apply, but given the aperiodic variation in wind events the acceptability limits will be less restrictive.

Density currents are expected to be of low order, but are important in certain localized regions such as the navigation channel and river discharges. These currents can be determined from the analysis of current meter and conductivity-temperature-depth (CTD) data.

Horizontal and vertical temperature and salinity distributions will be estimated from the CTD transects and compared with the model output. The location of a conductivity-temperature (CT) mooring just outside the bay's entrance for 15 months will provide boundary conditions. Heat fluxes will be estimated from bulk exchange relationships using measured air and sea surface temperatures, relative humidity, atmospheric temperature gradients, and incoming solar radiation.

An attempt to quantify the model's performance will be initiated. For example, a statistical comparison of differences between model and observational tidal phases and ranges can be made. Further comparisons can be made between observational and modeled subtidal variability. The goal is to produce an objective measure of the model's skill as opposed to a subjective conclusion based on the inspection of graphs.

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A TIME-DEPENDENT THREE-DIMENSIONAL MODEL OF CIRCULATION IN TAMPA BAY

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R. H. Weisberg

ABSTRACT

A three-dimensional time-dependent ocean circulation model of the Blumberg-Mellor type has been applied to study the dynamics and thermodynamics of Tampa Bay. This is the first attempt to use a three-dimensional hydrodynamic model for that estuarine system. This study concentrates on subtidal circulation where effects of density and wind forcing (baroclinicity) are most transparent and the importance of resolving the vertical structure is most obvious.

The model is forced by a tidal signal comprised of six astronomic constituents at the mouth of the bay, climatological freshwater runoff from four major rivers on the east side of the bay (Manatee, Little Manatee, Alafia and Hillsborough Rivers), and steady unidirectional winds. The vertical and horizontal salinity distributions are reconstructed by the model from an initial state compiled from available observational data. The temperature was assumed constant and equal to 30°C which corresponds to the summer conditions.

After spinning up the model for 120 days from the initial state and establishing a steady pattern of circulation, the model was run for 30 more days with various wind scenarios. Residual circulation on the time scale of 30 days was considered. It was found that without wind, the subtidal circulation in Tampa Bay has the classical two-layer pattern with surface, fresher currents flowing seaward while heavy, bottom currents flow into the bay. The most intense bottom currents are found along the navigational channels and in Hillsborough Bay. The northeasterly winds intensify the two-layer circulation while southwesterlies weaken this pattern. Also, southwesterly winds create strong northeastward currents along the east bank of Tampa Bay which can advect pollutants and floating substances from the mouth all the way into Hillsborough Bay.

The three-dimensionality of subtidal circulation in Tampa Bay has often been overlooked in the previous studies which assumed that the bay is well mixed and can be adequately simulated by a two-dimensional, vertically integrated model. This study demonstrates that even though the salinity does not change much in the vertical, the two-layer subtidal circulation still prevails. The cause of this circulation is the horizontal density gradient which always exists in estuarine systems.

This study describes the initial implementation of a three-dimensional circulation model for Tampa Bay; more research and data collection are clearly necessary. These preliminary simulations lead us to believe that the circulation is quite complex and markedly three-dimensional. The three-dimensionality of the subtidal circulation may have important implications for the biological, ecological and water quality modeling of that estuarine system.

INTRODUCTION

This paper describes the results of the first application of a three-dimensional, time-dependent, hydrodynamic model to Tampa Bay to assess the importance of the density- and wind-induced residual circulation in that estuary. The well established Blumberg and Mellor (1980, 1987) circulation model with orthogonal curvilinear coordinates as introduced by Blumberg and Herring (1987) and enhanced by Blumberg and Galperin (1990) has been used in this study.

The next section provides a brief description of physical oceanography of Tampa Bay, followed by the summary of the current status of numerical modeling of that estuary. Then, the application of the three-dimensional circulation model is detailed, with description of the numerical model, computational grid and applied forcing. The final sections describe numerical results, compare them with other simulations, and provide conclusions and recommendations for future research.

PHYSICAL OCEANOGRAPHY OF TAMPA BAY

The largest of the Florida drowned river valley estuaries, Y-shaped Tampa Bay is located in the west central part of the Florida peninsula, at 28°45′N and 82°30′W. The northwestern and northeastern compartments of the estuary are known as Old Tampa Bay and Hillsborough Bay, respectively; the central part is referred to as Middle Tampa Bay and the region adjacent to the West Florida shelf is called Lower Tampa Bay (Fig. 1). The bay extends about 60 km northeastward from about the 8-

km wide mouth that connects it to the Gulf of Mexico. The width of Tampa Bay is about 15 km and the total open water area is about 1,030 km^2 (Clark and MacAuley 1989, Lewis and Whitman 1985).

The bay bathymetry has been undergoing significant manmade modifications during the last century. A major shipping channel has been dredged from the mouth to the upper reaches of Lower Tampa Bay, where it splits into two branches, one entering Old Tampa Bay and the other going into Hillsborough Bay.

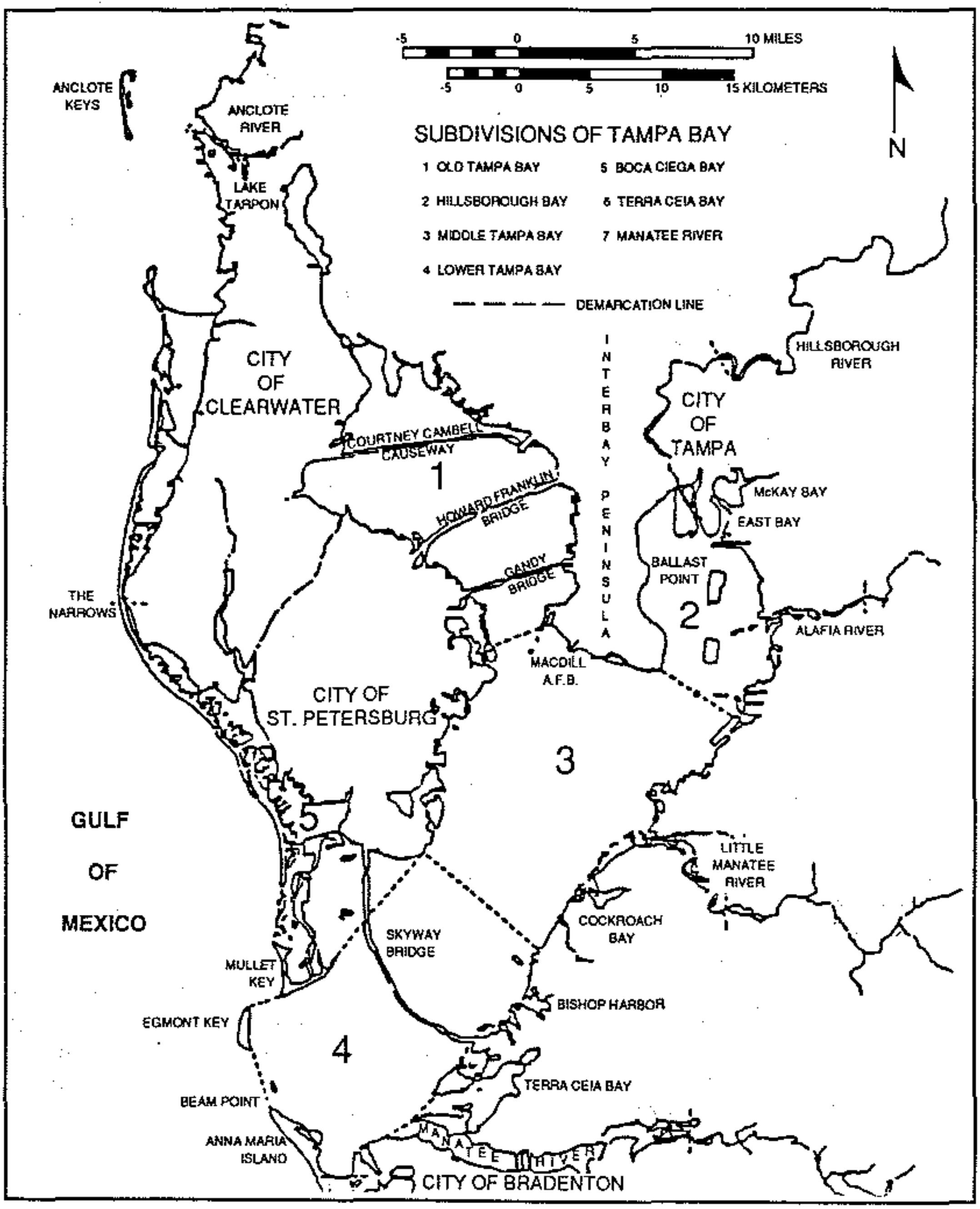

Figure 1. Geographic map of the Tampa Bay area (from Lewis and Whitman 1985).

Tampa Bay is a relatively wide and shallow estuary, its average depth being about 4 m. Inside the bay, the depth generally does not exceed 10 m except within the navigational channels dredged to about 15 m. Since these channels run the full length of Tampa Bay, while narrow, their increased depth can be very important for the distribution of water properties.

The watershed area of Tampa Bay covers about 4,600 km^2; it encompasses parts of Manatee, Hillsborough, Pasco, Pinellas, Sarasota and Polk Counties, and delivers a total annual mean freshwater runoff of about 63 m^3/sec into the estuary. The primary sources of the fresh water are four major tributaries—the Hillsborough River (15 m^3/sec), Alafia River (13 m^3/sec), Little Manatee River (6 m^3/sec) and Manatee River (10 m^3/sec)—that comprise about 70% of the total discharge. The remainder comes from smaller creeks, streams, marshes and land (Flannery 1989, Lewis and Estevez 1988).

The tidal forcing of Tampa Bay is mixed; predominant astronomic constituents are the lunar semi-diurnal (M_2) and solar diurnal (O_1) (Goodwin and Michaelis 1976, Goodwin 1987). Superposition of these signals produces two high and low unequal tides daily. Typically for mixed tides, the tidal range has significant temporal variability; the average range is about 0.7 m. Inspection of sea level records from long term measurement sites such as St. Petersburg or nearby coastal stations shows that synoptic scale variability due to storms and seasonal variability due to a combination of steric and wind effects are often large. The seasonal difference between relatively high sea level in summer and relatively low sea level in winter is about 0.3 m.

The amplitude of the tidal currents in Tampa Bay varies from 1.2-1.8 m/sec at the mouth to about 0.15 m/sec in Hillsborough Bay. The flood tide enters Tampa Bay in the vicinity of Egmont Key and propagates to the upper reaches of Middle Tampa Bay where it bifurcates, following the navigational channel, and enters Hillsborough and Old Tampa Bays. This pattern reverses during the ebb tide. Although the duration of the ebb cycle is shorter than the flood, the maximum ebb velocities exceed the corresponding flood velocities. It takes the flood tide 3.5 hours to propagate from the mouth to the upper reaches of Tampa Bay.

Studies in other coastal plain estuaries have shown that winds substantially affect estuarine circulation. Weisberg and Sturges (1976) demonstrated that the effects of local winds upon the tidal residual flow in Narragansett Bay were typically as large, or larger, than the baroclinically driven residual flows. Thus, the local winds could even reverse the direction of the residual flow. Weisberg (1976a, b) then showed that these effects could be quantified using linear mean square estimation techniques and offered a means for determining the record length of measurement that would be necessary for calculating a mean value with a given degree of confidence. Wang and Elliott (1978) further demonstrated that along with the local wind effects, the effects of wind setup on the adjacent coastal ocean was also important for the residual circulation of the Chesapeake Bay. These findings have been borne out by all subsequent estuarine circulation studies and have equal bearing upon Tampa Bay, where the annual mean wind is easterly and the synoptic scale (variations occurring over several day intervals) variations are very large due to the passage of fronts, particularly during the fall to spring seasons. Winds are generally weakest in summer, with the exception of afternoon thunderstorms when they are locally intense, and during tropical storms.

The climate of Tampa Bay region is subtropical, exhibiting a transitional pattern from continental to tropical Caribbean. Long, warm and humid summers are typical, as well as mild, dry winters.

The annual average bay area temperature is about 23°C and the total yearly rainfall is about 135 cm. More than half of this rainfall takes place between June and September, mostly due to the thunderstorms (Lewis and Estevez 1988).

Temperature and salinity profiles in Tampa Bay show little vertical variation (Dinardi 1978, Goodwin 1987). The relatively weak vertical stratification can be attributed to the small freshwater runoff, relatively large tidal volume and shallow depth.

Tampa Bay borders three counties—Pinellas, Hillsborough and Manatee; its drainage area serves a population of over four million annually, among them over one million permanent residents and over three million tourists (Palmer and McClelland 1988). Tampa Bay is heavily used for commercial and recreational navigation and fishery. Port Tampa and Port Manatee are major sources of employment for bay area residents (Clark and MacAuley 1989).

PREVIOUS HYDRODYNAMIC MODELING OF TAMPA BAY

To date, Tampa Bay circulation modeling has been limited to the two-dimensional vertically-integrated approach. The rationale behind this kind of modeling has been an intuitive assumption that in a shallow, vertically well mixed estuary like Tampa Bay the density driven mode of circulation is not important. The major factors determining flushing and residual circulation have been believed therefore to be tidal action and throughflow of freshwater (Ross 1973, Palmer and McClelland 1988, Goodwin 1989). Two vertically integrated, barotropic circulation models have been developed and applied to Tampa Bay over the years; one of these models was designed by Dr. B. Ross and his colleagues (Ross et al. 1984) at the University of South Florida and the other one was implemented by Dr. Carl Goodwin and his group (Goodwin 1984, 1987, 1989) at the U.S. Geological Survey, Tampa.

Although both models are based on similar physical assumptions, their numerical algorithms are different. The Ross approach goes back to an explicit integration of the finite difference equations in the horizontal as introduced by Reid and Bodine (1968) based on the work by Dronkers (1964). The Goodwin model uses a computationally more efficient implicit integration algorithm based on Leendertse's (1967) approach. As well known from standard stability analysis, explicit integration schemes are conditionally stable and their time step is limited by the CFL (Courant-Friedrichs-Levy) condition while implicit schemes are unconditionally stable and employ larger time steps than equivalent explicit schemes. Both models have been used for simulation of tidal and subtidal circulation of Tampa Bay; they were found to predict the tidal stage at different locations inside the bay reasonably accurately. The tidal currents were not generally well reproduced by either model.

The subtidal circulation pattern revealed by both models is quite complicated; it is dominated by gyres virtually everywhere in Tampa Bay (Fig. 2). These gyres are assumed to be responsible for trapping sediments, particles and other substances, causing an increase in flushing time and ultimately affecting the quality of water in Tampa Bay. However, neither theoretical nor numerical analysis of the relationship between the modeled Eulerian gyres and the mass transporting, Lagrangian circulation has been performed such that it is not clear how important these gyres are for Tampa Bay flushing. In addition, the very existence of these gyres has not been confirmed observationally; their sensitivity to winds has not been revealed. Furthermore, the density-induced residual circulation in Tampa Bay has never been addressed. Even though this estuary is vertically well mixed most of the time, it exhibits significant salinity variation in the horizontal, from about 33 ppt at the mouth to approximately 20 ppt at the upper reaches of Hillsborough Bay (Estevez 1989, Boler 1986). Based on the classical theory of estuarine circulation (Pritchard 1956), one would expect that density-induced (baroclinic) residual circulation in Tampa Bay would be at least as important as its tidally induced counterpart. The investigation of the wind driven and baroclinic modes of circulation of Tampa Bay is the subject of the present study.

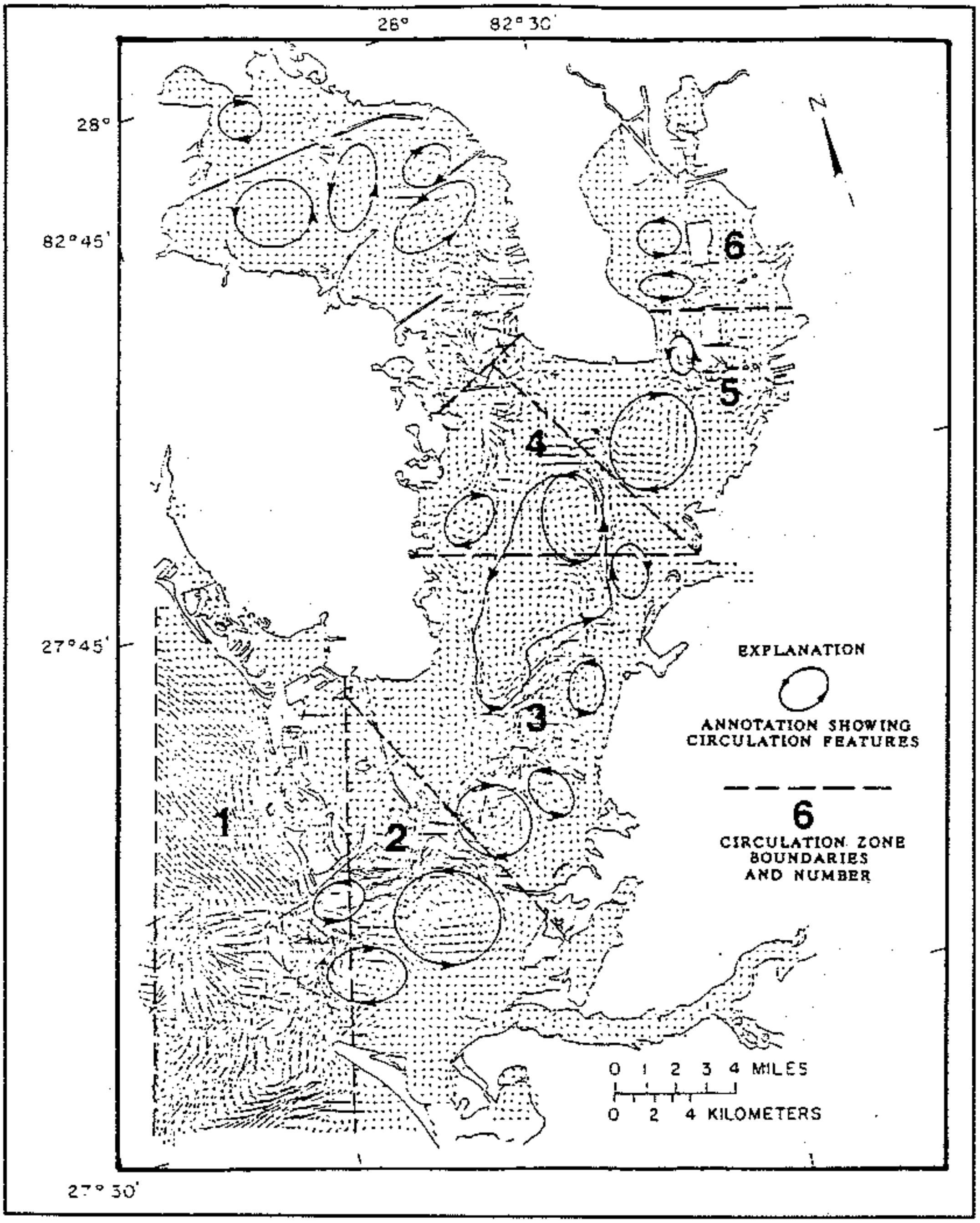

Figure 2. Tidally-averaged flow pattern in 1985 calculated by Goodwin (1989) using a vertically-integrated, barotropic model. Residual "gyres" and circulation zones defined by Goodwin are also shown (from Goodwin 1989).

THE THREE-DIMENSIONAL MODEL OF TAMPA BAY

To investigate the effects of density variations on circulation in Tampa Bay, the fully three-dimensional time-dependent hydrodynamic model by Blumberg and Mellor (1980, 1987) has been used. This model has a long history of successful applications in other estuaries (Oey et al. 1985a, b, c for the Hudson-Raritan estuary; Blumberg and Goodrich 1990 for Chesapeake Bay; Galperin and Mellor 1990a, b, c for Delaware Bay, River and adjacent continental shelf; and Blumberg and Galperin 1990 for New York Bight). The model solves a coupled system of differential prognostic equations describing conservation of mass, momentum, heat and salinity at each horizontal and vertical location determined by the computational grid. It incorporates a sophisticated turbulence closure sub-model that provides eddy viscosity and eddy diffusivity (Mellor and Yamada 1982, Galperin et al. 1988). The model employs a bottom and free-surface following σ-coordinate system in the vertical that allows a better resolution of surface and bottom boundary layers. In the horizontal, the model uses an orthogonal curvilinear coordinate system, first introduced by Blumberg and Herring (1987) and enhanced by Blumberg and Galperin (1990). The model recognizes fast barotropic external waves and slow baroclinic internal waves, and solves corresponding barotropic and baroclinic equations with different time steps, thus increasing computational efficiency (the so-called mode splitting technique). It is clear therefore that in water systems with constant density, this three-dimensional circulation model reduces to a barotropic model. Such a three-dimensional barotropic model, moreover, is more accurate than the vertically integrated models described previously because it resolves the vertical structure of the circulation and produces realistic estimates of the bottom shear stress (Oey et al. 1985b). For example, the model is capable of realistic reproduction of opposite, in the vertical, tidal currents during tidal reversals (e.g., Weisberg and Sturges 1976) and turbulent mixing induced by surface wind and bottom stresses.

Figure 3 shows a plane view of Tampa Bay, its bathymetry, and the curvilinear orthogonal coordinate system designed for the present study. This system has 30 points in the I direction, 40 points in the J direction and 11 σ-levels in the vertical. The vertical spacing in this model is the same as in studies of Hudson-Raritan estuary (Oey et al. 1985a, b), Delaware Bay (Galperin and Mellor 1990a, b, c) and New York Bight (Blumberg and Galperin 1990), with higher resolution in the bottom and surface boundary layers. The grid is relatively denser in the vicinity of navigational channel and in Hillsborough Bay while resolution decreases in Old Tampa Bay. The Manatee River is fully included in the model grid.

When the 3-D circulation model is forced by a comprehensive data base, it can produce very detailed and realistic information on dynamic and thermodynamic processes in the water body of interest (see Galperin and Mellor 1990a, b, c describing simulations of the Delaware Bay complex). Since the present study is only an initial assessment of the importance of baroclinicity in Tampa Bay circulation, the forcing data base has been grossly simplified and included only very basic parameters, such as typical tides and freshwater runoff. Tidal amplitudes and phases at Egmont Key were provided by the National Ocean Service. Six astronomical constituents were used to generate the tidal forcing; they included the S_2 (amplitude 6.7 cm, period 12.00 hr), M_2 (17.7 cm, 12.42 hr), N_2 (3.4 cm, 12.66 hr), K_1 (14.6 cm, 23.94 hr), P_1 (4.9 cm, 24.06 hr) and O_1 (14.0 cm, 25.82 hr) constituents. It was assumed that the free surface elevation is constant along the mouth of Tampa Bay and equal to that at Egmont Key. Considering the narrowness of the mouth, this is a reasonable assumption. Freshwater runoff from the Hillsborough, Alafia, Little Manatee and Manatee Rivers was assumed constant in time and equal to the mean annual values as specified by Flannery (1987). These values are 15, 13, 6 and 10 m^3/sec, respectively. One may anticipate an interesting pattern of density-driven residual circulation specific to Tampa Bay since most of the freshwater input comes from the east bank of the estuary.

Vertical and horizontal temperature variability in Tampa Bay is not very significant on 10- to 20-day time scales and was neglected in this study. The water temperature was set at 30°C, in accordance with the prevailing conditions for July (Dragovich and Sykes 1967).

As was mentioned earlier, the horizontal salinity variation is expected to be a major factor determining long-term circulation and considerable effort was expended in the specification of a realistic three-dimensional salinity field based on the average

July data reported in Dragovich and Sykes (1967). Salinity at the Hillsborough, Alafia, Little Manatee and tidal head of Manatee Rivers was assumed zero.

The three-dimensional circulation model code was executed at the Department of Marine Science, University of South Florida, on a Silicon Graphics mini-supercomputer, 4D/280GTXB. Computationally, the code proved to be very efficient and could easily be parallelized to run on the available eight CPUs. With an external time step of 30 sec and an internal time step of 300 sec, 30 days of simulated time took about 3 hours of CPU time.

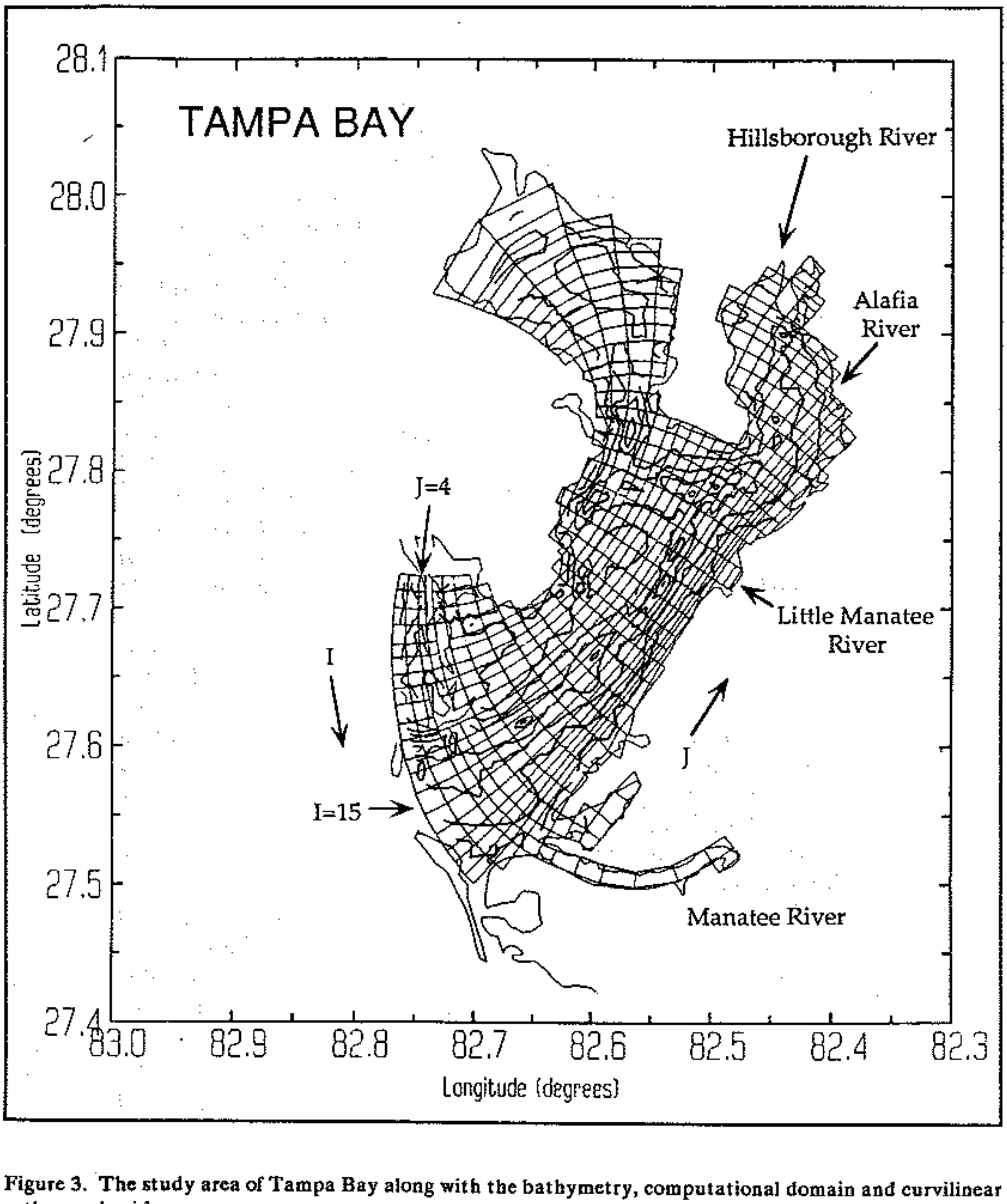

Figure 3. The study area of Tampa Bay along with the bathymetry, computational domain and curvilinear orthogonal grid.

RESULTS OF THREE-DIMENSIONAL SIMULATIONS

A large number of simulations were carried out with the three-dimensional model of Tampa Bay. The model was run for 120 days to establish an initial data base which was then used for a variety of 30-day simulations. In most cases, the results of the 30-day simulation were averaged over the entire length of the run to filter out the tidal signal and thus reveal the nature of the net nontidal (subtidal or residual) circulation.

The first simulation conducted with the model was directed at a comparison with the barotropic results produced by Ross and Goodwin using the vertically integrated models mentioned previously. For this purpose, the present three-dimensional model was executed with zero salinity everywhere. The resultant surface elevations, maps of surface and near-bottom currents and two velocity crossections, along the row, J=4, and the column, I=15, are shown in Figures 4a and 5. One can see in Figure 4a that there is very mild setup of the surface elevation along the Bay, only about 1.5 cm. Figures 5a and b show that surface and near-bottom currents are usually in the same direction. The magnitude of the surface residual currents inside Tampa Bay does not exceed 2-3 cm/sec while the bottom currents, decelerated by the bottom friction, are weaker by at least a factor of two. The currents generated by the three-dimensional model follow approximately the same pattern as the vertically integrated residual currents calculated by Goodwin (1989). One can identify multiple "gyres" which generally have the same location, size and sense of rotation as those found by Goodwin (1989) and shown in Figure 3. Cross-sections J=4 and I=15 (Fig. 5c, d) exhibit a weak residual circulation in the Manatee River and Hillsborough Bay as well as very small vertical motion. Current intensifications seem to be correlated with local topographic irregularities. A general conclusion that can be drawn from these comparisons is that the major features of the barotropic residual circulation of Tampa Bay as derived from two-dimensional and three-dimensional models are quite similar.

Results of baroclinic simulations using realistic spatial density field but no winds are depicted in Figures 4b, 6 and 7. Figure 4b shows that not only the distribution of nontidal free surface elevation changes markedly when compared to the barotropic case (Fig. 4a) but also that the associated longitudinal barotropic pressure gradient increases by about a factor of three. This results in significant increase in surface currents, which reach about 10 cm/sec (Fig. 6a). Figure 6a also illustrates a dramatic change in the character of residual circulation, which is now comprised of two layers. The surface, fresher water forced by the barotropic pressure gradient due to the surface elevation setup flows seaward, while bottom, saltier water, forced by the baroclinic pressure gradient generated by the salinity differences in the horizontal, flows landward. This is the classical pattern of density-driven, residual circulation in estuaries (Pritchard 1956). The landward-flowing near-bottom currents are largest inside the ship channels because the larger depths produce stronger baroclinic pressure gradients. This effect is clearly evident in Lower Tampa Bay and in Hillsborough Bay. The circulation in Old Tampa Bay is relatively weak. The residual gyres, easily identifiable in barotropic simulations, have been overwhelmed by the density induced residual flow. The surface currents have a tendency to converge towards the navigational channel, particularly in the lower portion of Tampa Bay. This is opposite to the near-bottom currents that diverge towards the banks. Residual circulation in Tampa Bay is more intense near the east bank and in Hillsborough Bay than in other parts of the bay because of the specifics of the freshwater supply. One can also see that the Manatee River develops a strong two-layer circulation resulting from the close proximity of its one end to the mouth of the bay where the water is saltier, and from the throughflow of freshwater coming from the other end. Residual near-bottom currents in Tampa Bay are generally weaker than their surface counterparts by about a factor of two.

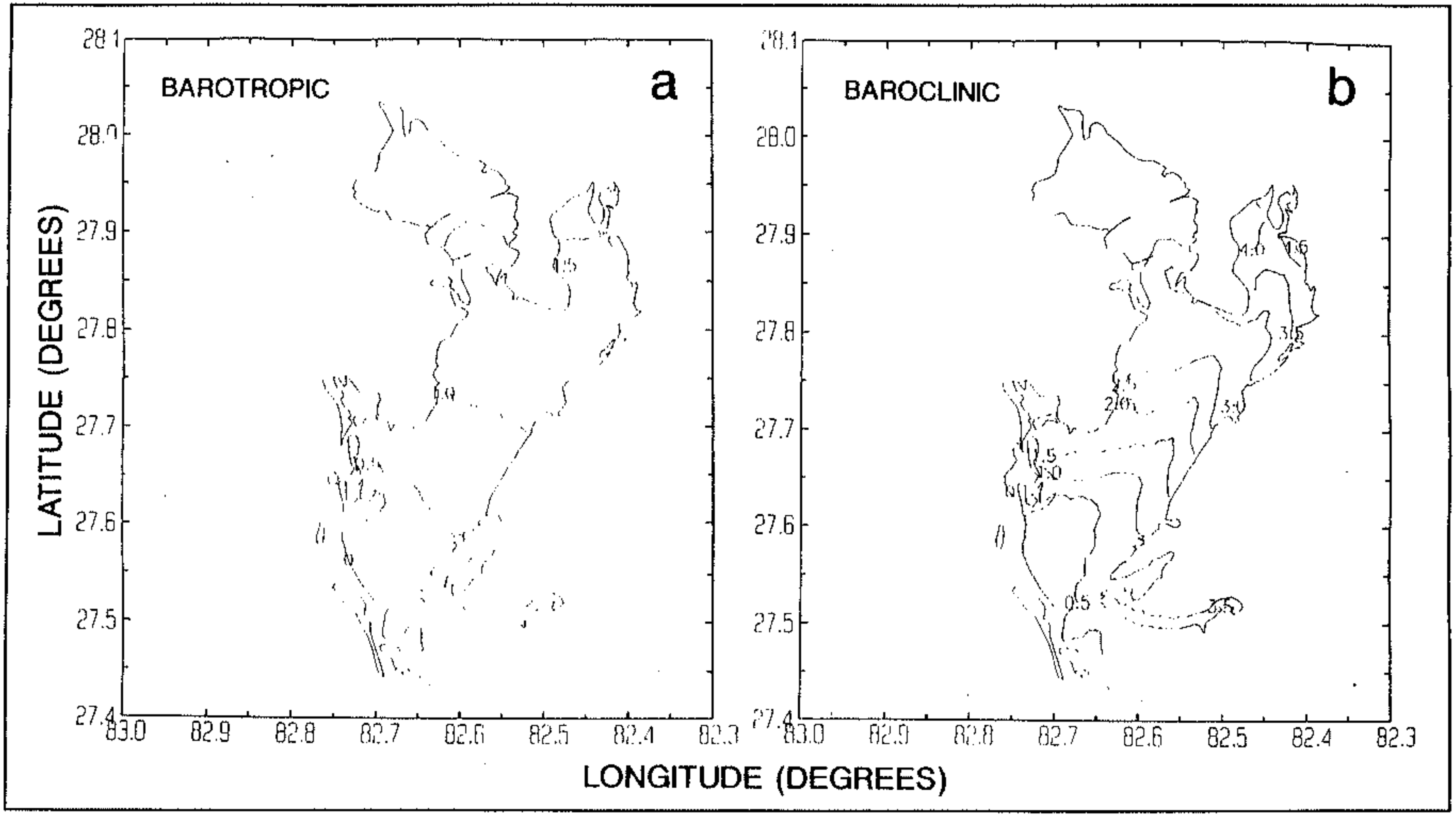

Figure 4. Monthly-averaged free surface elevation calculated by the three-dimensional model in barotropic (a) and baroclinic (b) cases. Contour interval 0.5 cm.

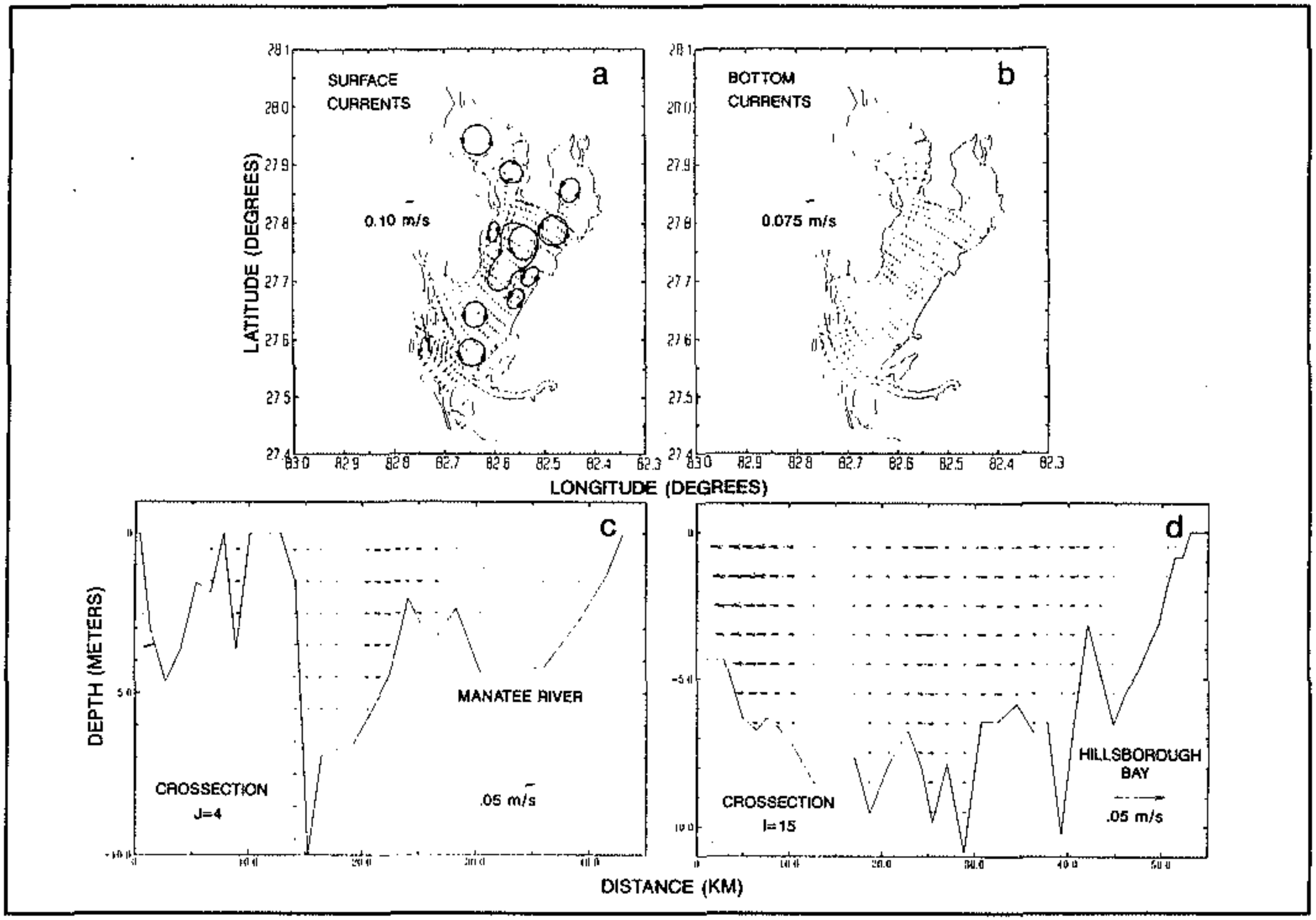

Figure 5. Monthly-averaged currents calculated by the three-dimensional model in the barotropic case: surface (a), near-bottom (b), along the lateral cross-section, J=4 (c), and along the longitudinal cross-section I=15 (d). Note weak residual circulation in Manatee River and Hillsborough Bay.

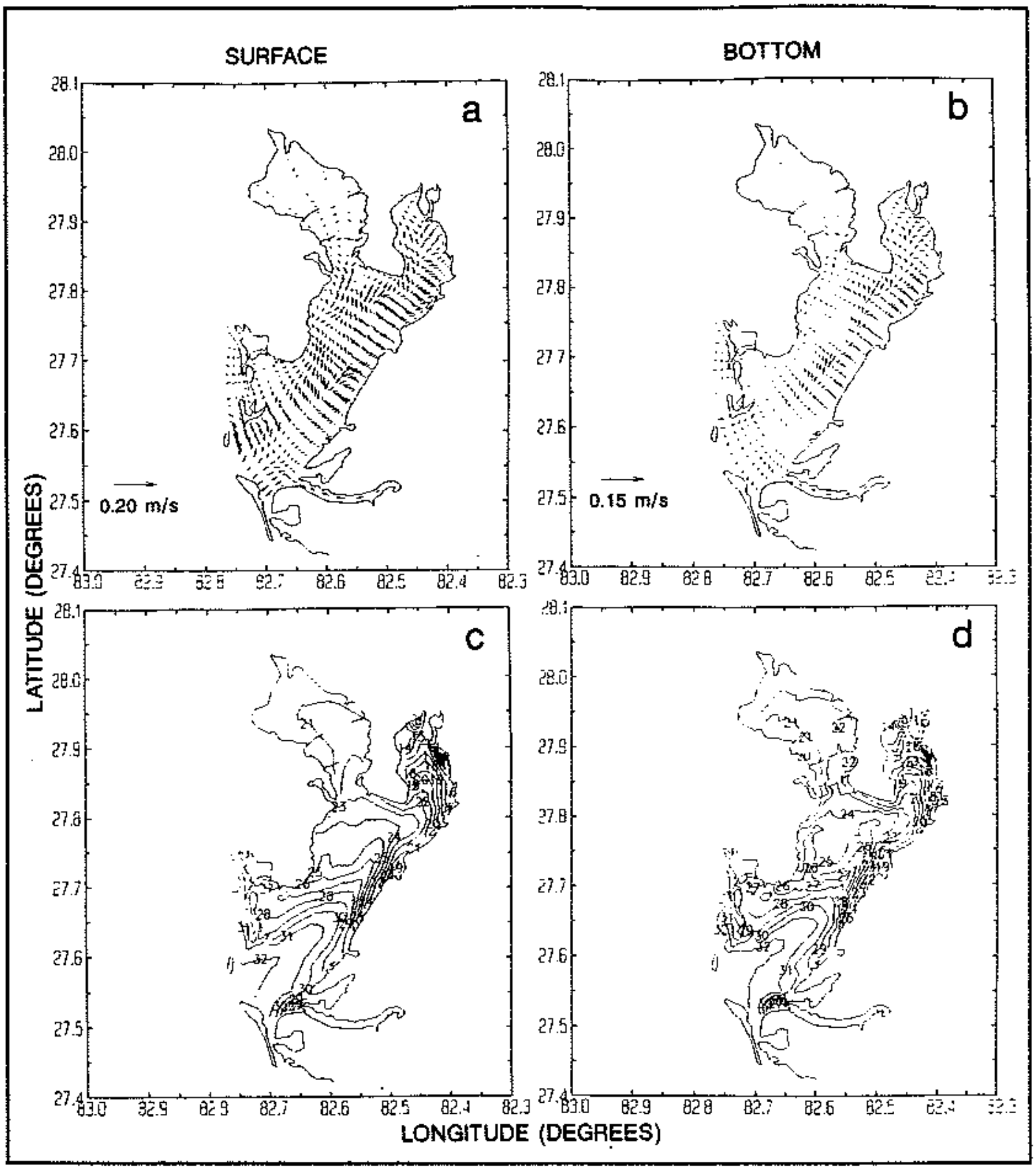

Figure 6. Plane views of monthly-averaged currents and salinity calculated by the three-dimensional model in the baroclinic case: surface (a) and near-bottom (b) currents, and surface (c) and near-bottom (d) salinity. Note change in scale for currents compared to the barotropic case, Figure 5. Contour interval for salinity 1 ppt.

Figures 6c and d show horizontal maps of surface and near-bottom subtidal salinity distributions. They illustrate significant horizontal density gradients which drive a baroclinic residual circulation. Additionally, the maps show large salinity tongues penetrating deep into the bay along the deep channel both at the surface and near the bottom. These tongues are due to advection and dispersion of salt along and around the channel carried out by strong near-bottom currents and turbulent mixing. Sharp salinity gradients near the east bank of Tampa Bay and in Hillsborough Bay are produced by the freshwater input concentrated along the east bank of Tampa Bay. In the vertical, salinity differences rarely exceed 1-2 ppt, in agreement with various estimations collected in Tampa Bay over the years.

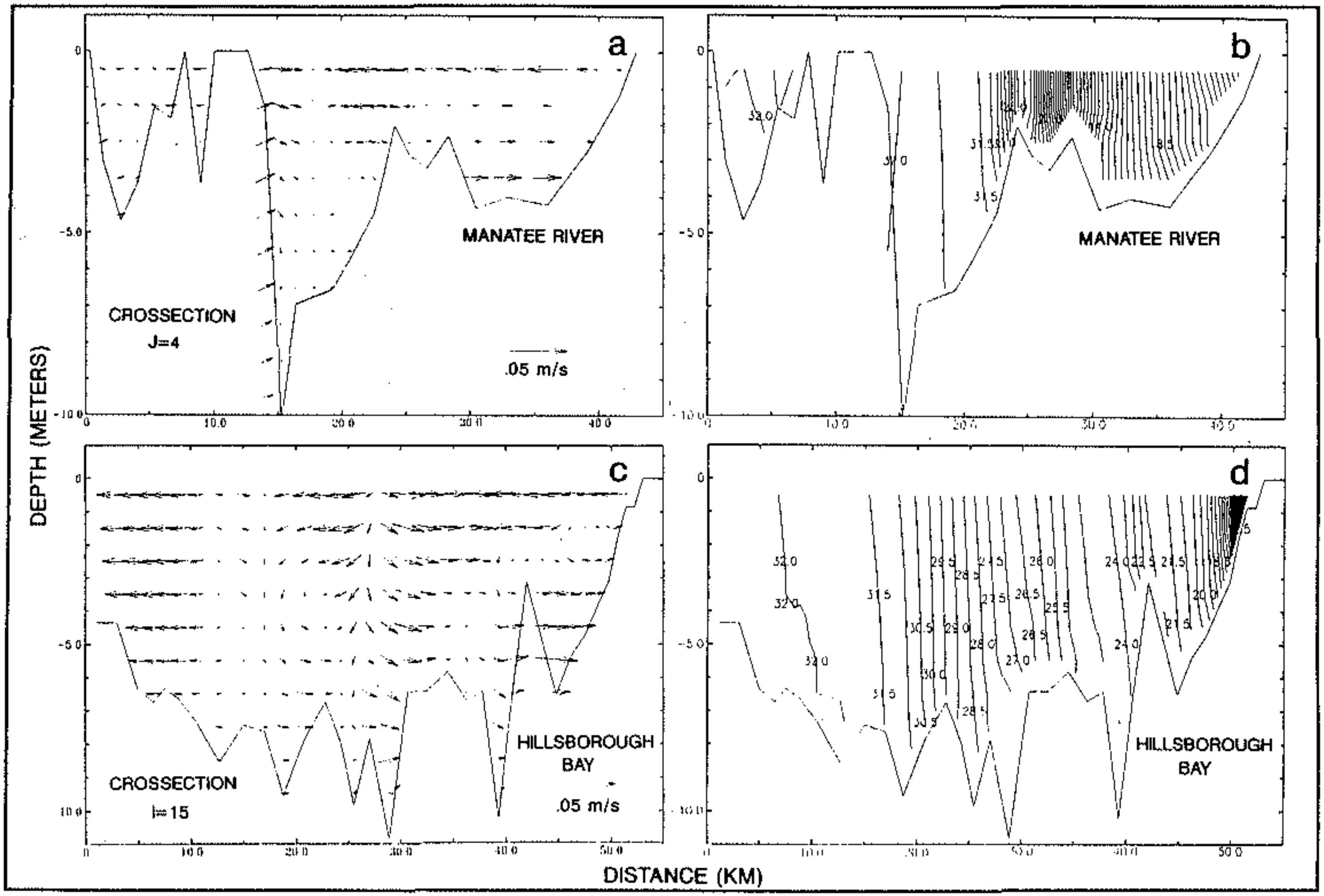

Figure 7. Monthly-averaged currents and salinity calculated by the three-dimensional model in the baroclinic case: currents (a) and salinity (b) along the lateral cross-section, J=4; currents (c) and salinity (d) along the longitudinal cross-section, I=15. Note strong two-layer circulation in Manatee River and Hillsborough Bay. Contour interval for salinity 0.5 ppt.

Figure 7 shows two cross-sections of residual currents and salinity along the row J=4 and the column I=15. Compared to the barotropic case (Fig. 5c), the flow in the Manatee River (Fig. 7a) is much intensified and has a strong two-layer signature. Longitudinal circulation in the estuary is also significantly enhanced; two-layer patterns prevail in Lower and Middle Tampa Bay and Hillsborough Bay (Fig. 7c). Regions with amplified vertical velocity are an indication of an increased exchange between surface and bottom waters which may have important implications for biological and ecological processes in the bay.

Contrary to the rich and complex subtidal dynamics, salinity cross-sections (Figs. 7b, d) exhibit little vertical variability, only about 1 ppt over the entire water column. Based on this, one would be tempted to characterize Tampa Bay as a well mixed estuary. However, such a classification would apply to the vertical salinity distribution only; the present simulations indicate that the large horizontal salinity gradients dominate the residual circulation in Tampa Bay and determine its structure, intensity and two-layer character.

Along with the baroclinicity, winds are known to play a crucial role in subtidal variability of estuaries; this was shown observationally (Weisberg 1976a, b; Weisberg and Sturges 1976; Wang and Elliott 1978) and numerically (Oey et al. 1985b, Galperin and Mellor 1990b). However, despite their potential importance, the effects of the wind forcing on Tampa Bay residual circulation have never been quantified.

The present study is the first account of the wind-driven mode of residual circulation in Tampa Bay. Four different idealized scenarios were simulated using steady winds with magnitude 5 m/sec blowing from the northeast, southeast, southwest and northwest. The initial conditions were identical to those used in the baroclinic zero-wind calculations described earlier such that the present results describe the superposition of the density- and wind-induced circulation. As was shown earlier, the barotropic component of the residual circulation is much smaller than its baroclinic counterpart such that a separate study of the barotropic response on winds would not be very informative and was not attempted.

Figure 8 shows surface elevations for all four simulated wind scenarios. Most evident is that the distributions are dramatically different from each other and from the zero-wind case (Fig. 4b). Northeasterlies (Fig. 8a) cause surface elevation to drop inside the bay and to rise at the mouth (the so-called set-down); while the elevation does not vary much along Lower and Middle Tampa Bay, a slight lateral gradient is present. In the other three cases, the winds orient the elevation isopleths normal to their own direction and lead to a piling up of the water against the banks of the bay which creates a barotropic pressure gradient opposing the winds. For southeasterlies (Fig. 8b) and southwesterlies (Fig. 8c), the elevation difference between the mouth and the upper reaches of Tampa Bay approaches 6-8 cm, thus exceeding the baroclinic windless case with values of 4-5 cm (see Fig. 4b). Northwesterlies (Fig. 8d) create a rather interesting dynamic pattern depressing elevation in Old Tampa Bay (it becomes equal to that at the mouth of the bay) and piling water up against the east bank, accompanied by the development of a strong salinity front (depicted in Figs. 12c, and d). Examining the changes in free surface elevation brought about by the winds, one concludes that wind effects are at least as important in shaping the structure of residual circulation of Tampa Bay as the effects of baroclinicity.

Figure 9 shows surface and near-bottom currents and salinities induced by northeasterlies. These winds significantly intensify surface seaward flow which is accelerated now by the directly applied wind stress. Strong seaward currents develop along the east bank of Middle and Lower Tampa Bay. The barotropic pressure gradient, opposing its baroclinic counterpart in the zero-wind case (Fig. 4b), has diminished (Fig. 8a) such that the near-bottom currents grew stronger compared to the no-wind case (Fig. 6b). Generally, Figure 9 indicates that northeasterlies enhance two-layer residual circulation in all compartments of Tampa Bay.

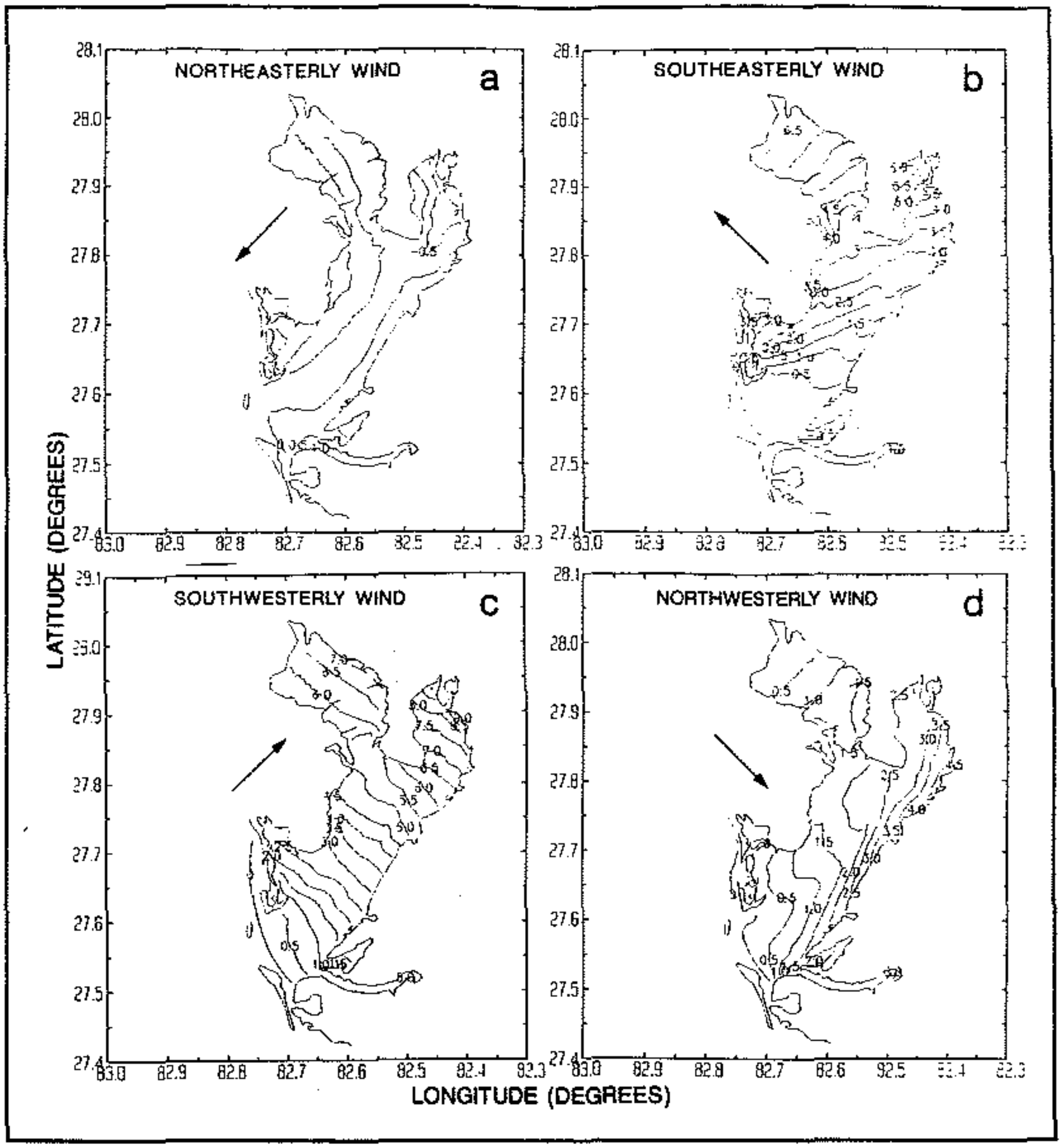

Figure 8. Monthly-averaged free-surface elevation for four wind scenarios: northeasterly (a), southeasterly (b), southwesterly (c) and northwesterly (d). Contour interval 0.5 cm. The arrows show wind direction.

The stronger near-bottom currents facilitate farther penetration of high salinity west Florida shelf water into the Tampa Bay interior. The saltier bottom waters are transported and mixed vertically inside the bay, ultimately increasing surface salinity values. Figure 9 exhibits such an increase, of about 2 ppt, when compared to the zero-wind case (Figs. 6c, d) in the surface and near-bottom salinities in lower Tampa Bay and in Hillsborough Bay. The increased salinity in the bay interior produces sharper gradients in the vicinity of the east bank because the values of salinity at the bank itself are strongly constrained by the freshwater runoff.

The importance of freshwater runoff on the baroclinic circulation is highlighted in Figure 9; Old Tampa Bay, receiving no fresh water, exhibits a weak residual circulation and is void of salinity structure. On the other hand, Hillsborough Bay, receiving much fresh water, has a rich subtidal structure and a well developed two-layer circulation. Also, following the near-bottom currents, salinity tongues, extending to the upper reaches of Middle Tampa Bay, "chose" to enter Hillsborough Bay where they can be compensated by the outflowing fresher water.

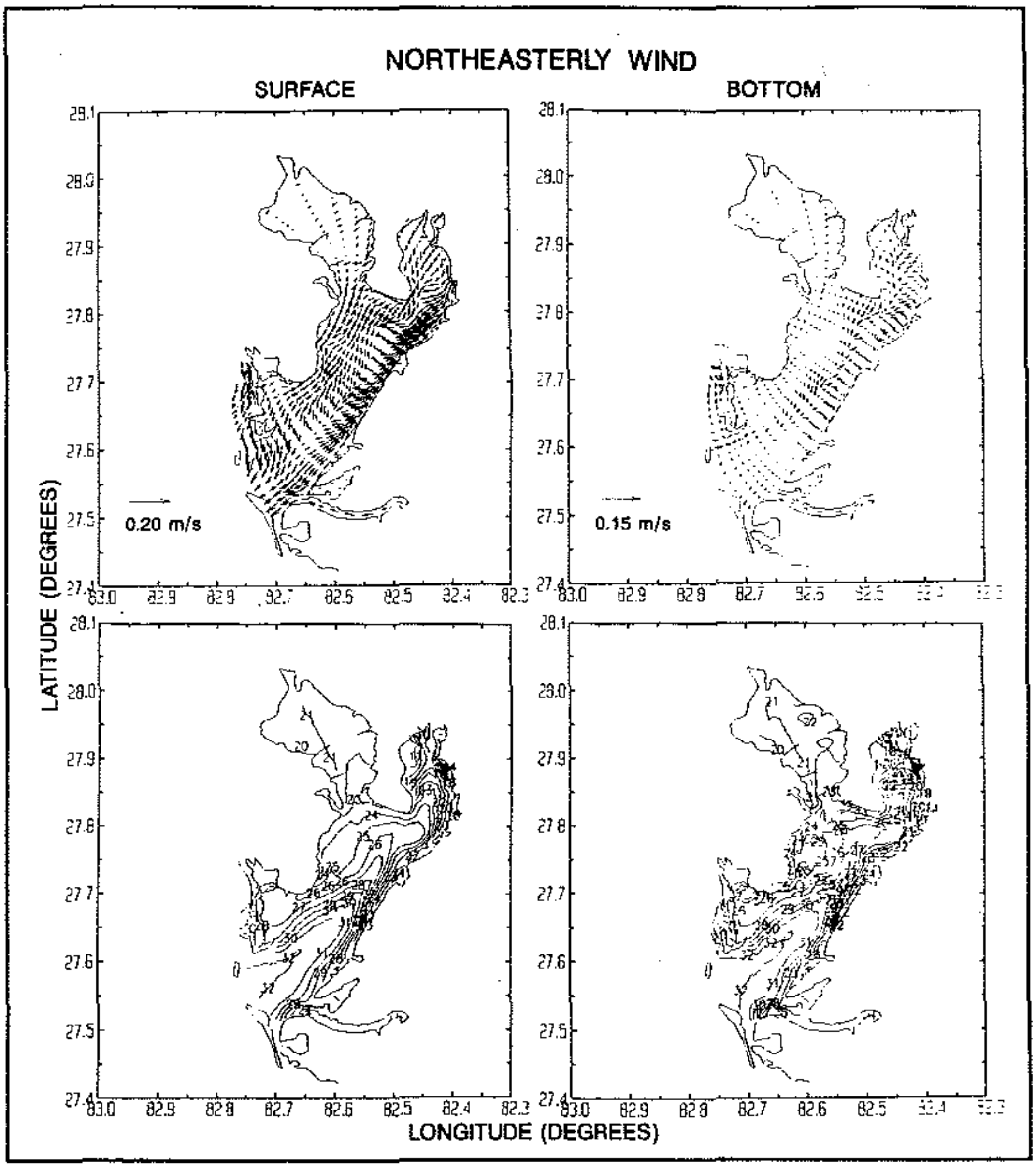

Figure 9. Plane views of monthly-averaged surface and near-bottom currents and salinity calculated by the three-dimensional model in the baroclinic case with steady, 5 m/sec northeasterly wind. Contour interval for salinity 1 ppt.

Southeasterlies (Fig. 10) steer the surface currents in their own direction by virtue of the surface stress while the barotropic pressure gradient forces the water seaward. Westward currents at the upper reaches of Middle Tampa Bay may advect salt, biological species, and pollutants from Hillsborough to Old Tampa Bay, thus intensifying the communication between the compartments of Tampa Bay. The near-bottom circulation is affected significantly compared to the no-wind case (Fig. 6b); a minor change is the current reversal in the upper reaches of Middle Tampa Bay. An interesting two-layer circulation pattern develops in Old Tampa Bay, where surface water flows landward while near-bottom currents flow into Middle Tampa Bay. Old

Tampa Bay lacks significant density structure in both the horizontal and the vertical but develops a considerable barotropic pressure gradient (Fig. 8b). The two-layer circulation inside that compartment of Tampa Bay is the result of the joint action of the surface wind stress and barotropic pressure gradient. Similarly to the surface currents, near-bottom currents in the upper Tampa Bay are directed from Hillsborough to Old Tampa Bay. The southeasterlies remove fresh water from the east bank of Tampa Bay and advect it into the interior, thus decreasing salinity gradients near the east bank.

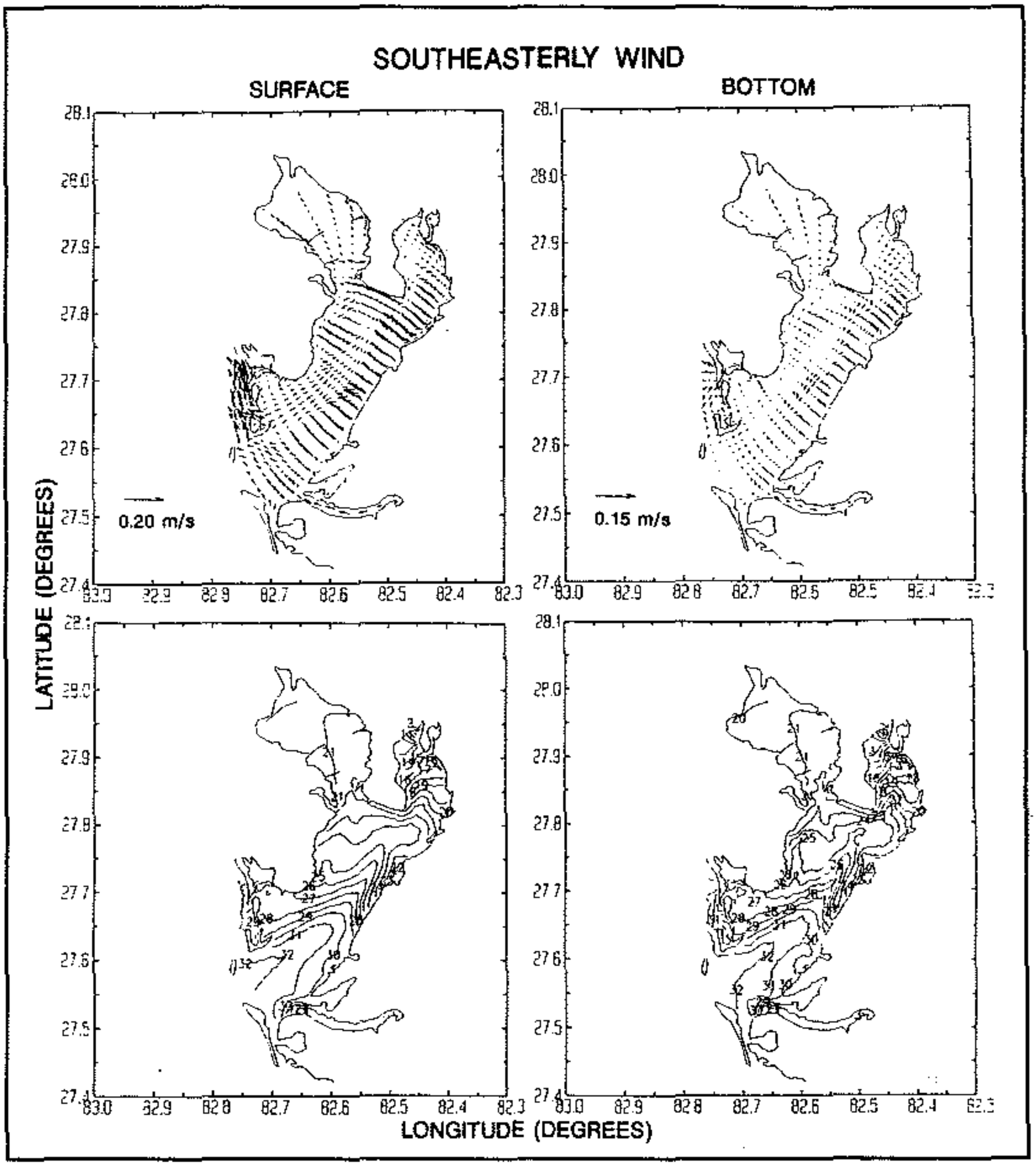

Figure 10. As in Fig. 9 but with southeasterly wind.

Southwesterlies (Fig. 11) generally drive the surface currents landward, opposite to the zero-wind case and against the barotropic pressure gradient. Interesting features of residual circulation are strong northeastward currents along both the east and west banks of Tampa Bay that may enhance the advection of salt, biological species, and pollutants from the mouth of Tampa Bay into Hillsborough and Old

Tampa Bay. As mentioned earlier, southwesterlies increase the barotropic pressure gradient which opposes its baroclinic counterpart. Thus, the total pressure gradient driving near-bottom circulation decreases and near-bottom landward currents diminish. Recalling that the surface currents in this case are also directed landward, one concludes that the southwesterlies destroy the pattern of two-layer circulation in Middle and Lower Tampa Bay. However, the axis and the coastline orientation of Hillsborough Bay are such that the baroclinic circulation survives there.

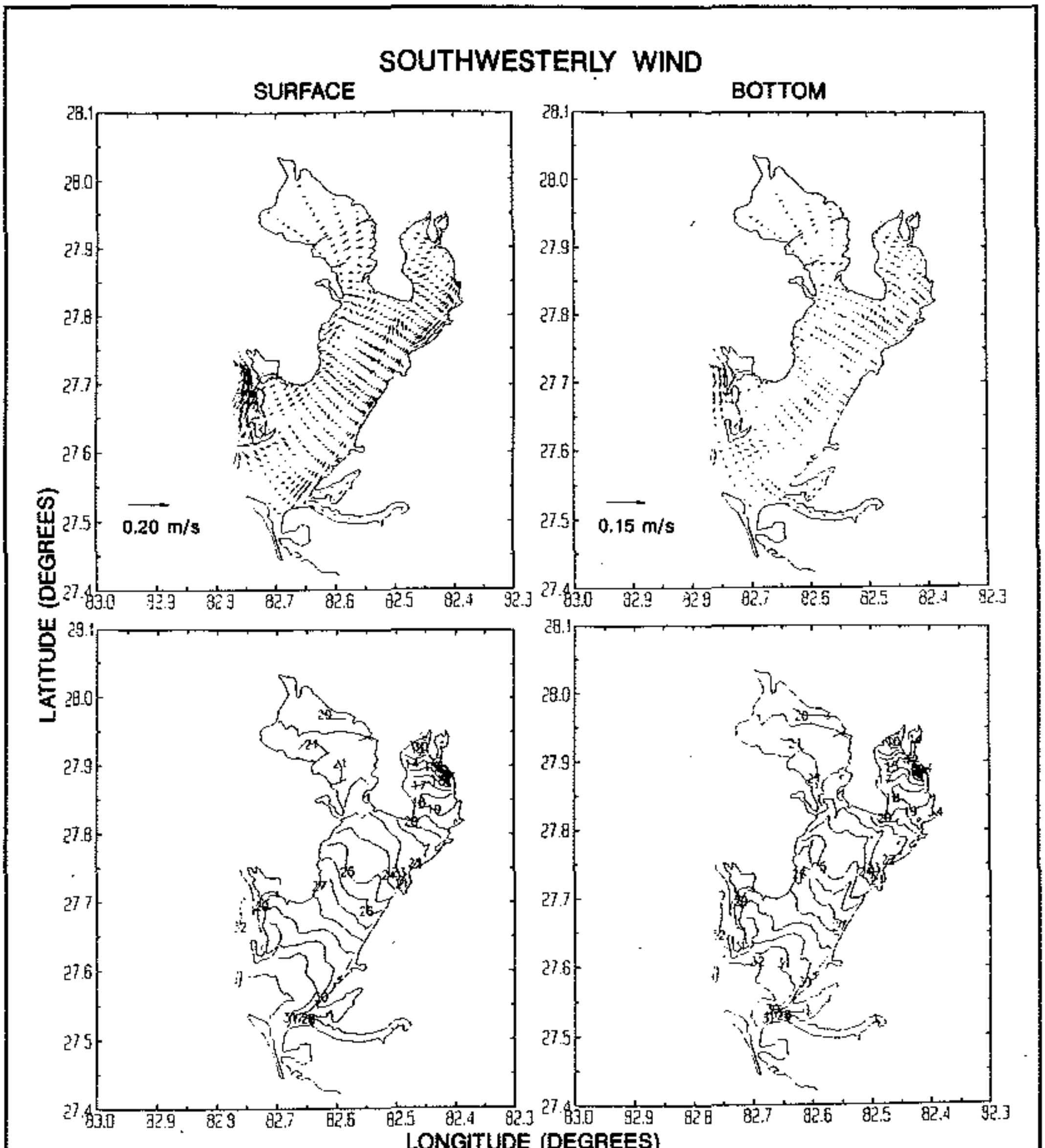

Figure 11. As in Figure 9 but with southwesterly wind.

The destruction of the two-layer circulation by southwesterlies results in salinity distributions similar to those that would have been produced by a barotropic model. These distributions are markedly different from the zero-wind case (Figs. 6c, d) and from the three other wind scenarios. Salinity isopleths are roughly parallel to those of the surface elevations (Fig. 8c), while all the sharp gradients disappear. The rich salinity structure in Hillsborough Bay reflects the presence of baroclinicity there.

Northwesterlies (Fig. 12) align the surface flow in their own direction in the western part of Tampa Bay while induced by the setup of the free surface elevation barotropic pressure gradient forces the water seaward near the east bank. The associated near-bottom circulation in Lower and Middle Tampa Bay is slightly intensified. An interesting two-layer pattern develops in Old Tampa Bay, where the surface current flows into Middle Tampa Bay while near-bottom current flows landward. This two-layer circulation is a product of a combination of the wind stress driving surface water into Tampa Bay and the opposing barotropic pressure gradient generated by the setup of surface elevation (Fig. 8d). Figure 12 also depicts the enhancement of the salinity fronts near the east bank of Tampa Bay by the northwesterlies. Effects of baroclinicity in Old Tampa Bay are not significant. Due to the orientation of the Manatee River, northwesterlies have an effect on its circulation similar to that of the southwesterlies on Tampa Bay, decreasing the flow and making it quasi-barotropic.

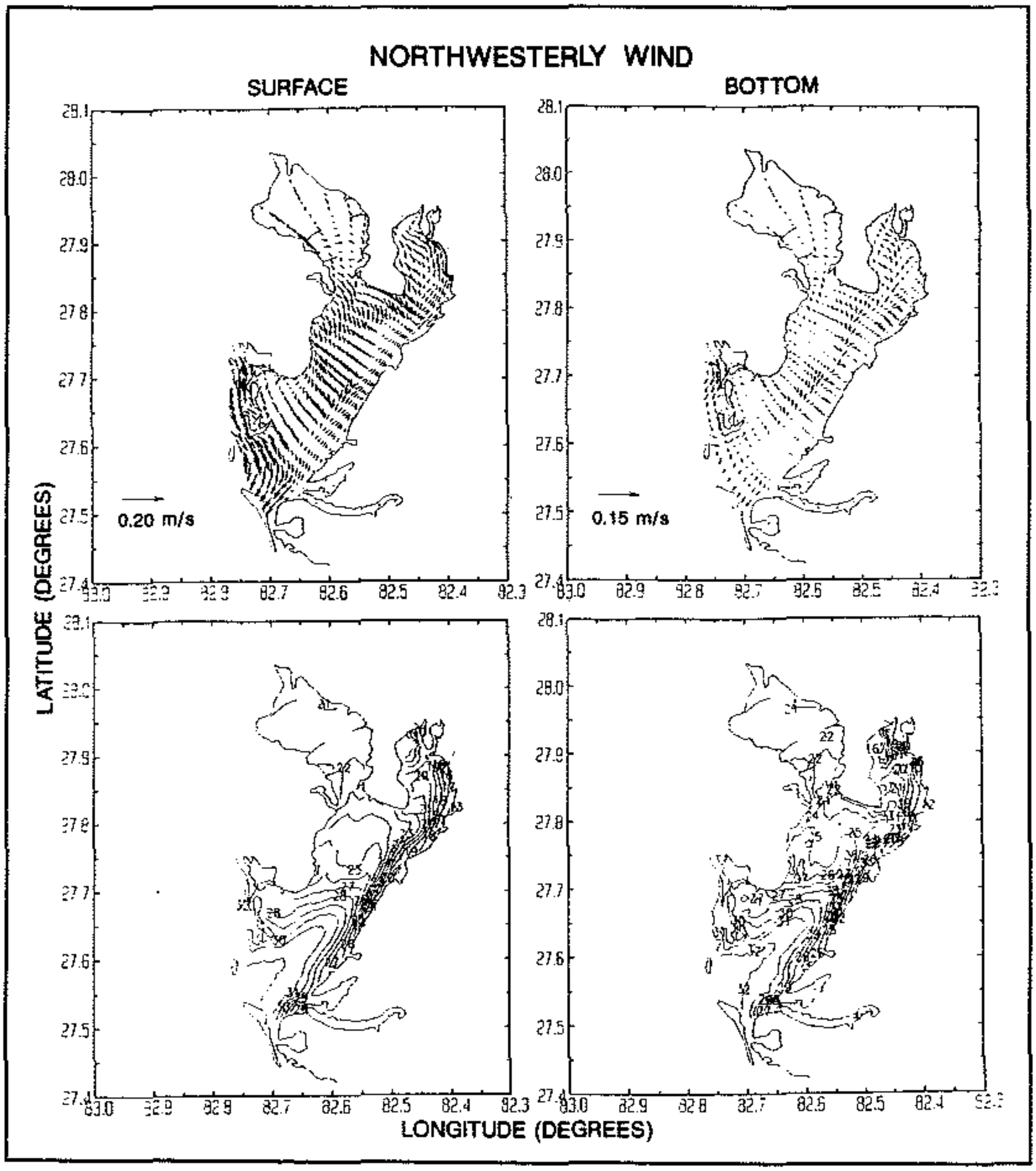

Figure 12. As in Figure 9 but with northwesterly wind.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

To date, Tampa Bay has been referred to as a well mixed estuary, and vertically-integrated, two-dimensional, barotropic modeling of its circulation has been accepted as an adequate approach by the agencies entrusted with bay management. Despite several attempts over the past several years at arguing for the importance of buoyancy driven convection upon the residual circulation for Tampa Bay and for the importance of fully three-dimensional wind effects, the horizontal salinity differences existing in Tampa Bay have never been considered as an important dynamic factor. From the analysis of other estuaries and from the theory, however, it has been known that the horizontal density structure (baroclinicity) can induce complex three-dimensional residual circulation equal to or exceeding that due to the tides. An investigation into the potential importance of baroclinicity for Tampa Bay circulation was a primary motivation for the present study. The approach chosen in this study for addressing the density-driven baroclinic circulation is the application of a three-dimensional circulation model allowing, among other things, for the interaction between the barotropic and baroclinic modes of circulation. Such a model has been developed and applied to Tampa Bay; this paper provides some preliminary results from that ongoing study. One should keep in mind that very little observational information is available at the present time to calibrate and validate the model; the presented results are mostly qualitative, and further simulations and analysis are clearly needed. A circulation study of Tampa Bay is currently being conducted by the National Ocean Service (NOS) and it should produce a data base useful for calibrating and validating the model.

The present modeling study has yielded a number of important findings. The results of the three-dimensional barotropic simulations (zero salinity everywhere) indicate that the residual barotropic circulation is relatively weak (2-3 cm/sec) and is dominated by multiple gyres. Location, size and rotation of these gyres are approximately the same as those obtained with two-dimensional barotropic models. When baroclinic effects are included, the residual circulation changes markedly. The flow pattern intensifies to about 10 cm/sec and forms the classical two-layer signature, with surface, fresher water flowing out of the bay and onto the shelf and saltier, heavier water flowing into the bay. Wind-induced modifications of residual circulation are also found to be very significant. Winds redistribute surface elevation thus affecting barotropic pressure gradients. They can modify the entire density structure of Tampa Bay, resetting horizontal depth-dependent pressure gradients ultimately affecting the baroclinic circulation. Winds also have direct effect on surface currents communicated through the interface stress. Winds at certain directions can enhance or suppress the two-layer circulation in Tampa Bay; they can lead to creation or disappearance of salinity fronts.

Three modes of residual circulation can be identified in Tampa Bay: barotropic, baroclinic and wind-driven. The barotropic mode is the weakest; its associated currents are smaller, by at least a factor of three, than the currents related to the other two modes. The previous models that dealt only with the barotropic mode have obviously missed the most important components of the subtidal dynamics in Tampa Bay and are clearly inadequate for either circulation or related water quality studies.

As to the present model, the following improvements and extensions can be envisioned:

- conduct extensive calibration/validation exercises;
- incorporate the surface heat flux including the diurnal cycle;
- include time-dependent, realistic freshwater runoff;
- provide better forcing at the mouth of the bay by specifying observations, and not tidal constituents;
- improve the parameterization of the crossmouth exchange with west Florida shelf;
- rigorously determine model forecasting skill.

Many other possible directions of research can be conceived. One of the most important and exciting is the possibility of developing a coupled hydrodynamic-water quality-ecological model of Tampa Bay that could be used for interdisciplinary studies of the bay or, by local and state authorities, for bay management. It is clear that the engine for such a model will be a three-dimensional time-dependent circulation model of the kind described in this study.

ACKNOWLEDGMENTS

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LIGHT ATTENUATION AND LIGHT AVAILABILITY IN TAMPA BAY

V. A. Levesque
D. H. Schoellhamer
B. F. McPherson
R. L. Miller

ABSTRACT

The availability of photosynthetically active radiation (PAR) in estuarine waters is fundamentally important for the health and growth of seagrass meadows. The availability of PAR is determined by the intensity and angle of incoming solar radiation and the attenuation of light in the water column. The U.S. Geological Survey is conducting studies in Tampa Bay to determine causes of light attenuation in the water column and to estimate availability of PAR for different attenuation coefficients.

In Tampa Bay, short-term periods (hours) of increased light attenuation have coincided with an increase in non-chlorophyll suspended materials, and long-term periods (weeks) of increased light attenuation have coincided with summer increases in chlorophyll *a* and color. During the current collection period (1988-1990), Tampa Bay light attenuation coefficients typically ranged from 0.4 to 2.4 l/meter and have been as high as 3.6 l/meter in Hillsborough Bay. Chlorophyll *a* concentrations seldom exceeded 10 mg/m^3; however, concentrations usually increased during warmer months, with maximum values of 21 to 36 mg/m^3 occurring in Hillsborough Bay and Old Tampa Bay during late summer and early fall in 1988.

The availability of PAR will be assessed with a model that uses incoming solar radiation, solar elevation angle, and attenuation coefficients to predict the length of time during a day that PAR exceeds a threshold intensity at a given depth. Increased information about light attenuation and availability is necessary and will be useful for the protection and management of seagrass meadows in Tampa Bay.

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CHANGES IN CLIMATE, SEA LEVEL, AND TAMPA BAY

D. Fletcher

ABSTRACT

During the last ice age, sea level was about 100 m (330') lower than it is today, and the Gulf of Mexico was located about 160 km (100 mi) west of the mouth of Tampa Bay. The climate was colder. As we emerged from the ice age, there was a particularly rapid rise in sea level that did not slow until about 3,000 years ago. However, since 1931, the observed sea level in Florida has been rising at a rapid pace again, and is expected to accelerate in the future. By the year 2030, the increase is forecast to be most likely 20 cm (7.8"). An analysis of temperature and precipitation for Tampa since 1900 shows the past 30-year period to be both the coolest and dryest of the century. The future climate likely will be warmer by 1°C (1.8°F) or less. Based on current global models, it is impossible to categorize a trend for future rainfall.

INTRODUCTION

The climate of the earth and the level of the sea have been in a constant state of evolution. By human standards of time, most of the changes have been so slow that the average person's view is that sea level is constant. However, there has been a rise in sea level that scientists believe will be increased by greenhouse gases and global warming in the future. There is much debate over the magnitude of the changes. However, the consequences for coastal areas and estuaries such as Tampa Bay may be significant and widespread.

PAST CLIMATE CHANGES

Before we can look to the future, we need to understand the past climate and the changes that have evolved into our current conditions. The succession of ice ages over the last two million years have been attributed fundamentally to variations in the earth's orbit. Credit for developing this modern theory is given to Yugoslavian astronomer Multin Milankovitch. It includes changes in the shape of the orbit, the tilt of the axis, and the wobbling of the earth's axis. The cycle of wobbling, or precession, is about 26,000 years. Now the earth's axis points to Polaris, which is called the North Star. About 13,000 years ago, during the last ice age, the earth's axis was pointed toward the star Vega, making it the North Star. Then, the orbital positions of the winter and summer solstices were reversed. The Northern Hemisphere winter occurred when the earth was farthest from the sun, and summer at the closest position. The seasonal contrasts were much greater—winters were colder, summers warmer (Lutgens and Tarbuck 1989).

TAMPA BAY AND FLORIDA IN THE LAST ICE AGE

The earth was in the declining stages of the last great ice age about 12,000 years ago. Then, more of the earth's water was frozen in glaciers that covered large portions of the Northern Hemisphere. Sea level was about 100 m (330') lower than it is today. The Gulf coast was located 130 to 160 km (80-100 mi) west of what is now the mouth of Tampa Bay. The climate was cooler by 5-10°C (9-18°F), and was described as similar to the present climate in the state of North Carolina.

As glaciers retreated, the rise in sea level drowned vast amounts of Florida's low-lying land. State underwater archaeologist W. A. Cockrell has found artifacts at several submerged locations, including Warm Mineral Springs at Venice, Florida. Tampa Bay was created as the sea moved inland. Large quantities of shells dredged from the floor of the bay have contained artifacts of what Cockrell calls Paleo-Indians, who lived and hunted in the area 10,000 years ago (Cockrell 1980).

RATE OF SEA LEVEL RISE

Studies from geological records of the past 7,000 years in south Florida show that sea level was rising at a rate of about +0.25 cm/yr until about 3,000 years ago. During this period, there was a rapid retreat of the shoreline. The increase slowed drastically about 3,200 years ago, to about +0.04 cm/yr. The slow rate allowed shorelines to stabilize or expand, and many shallow marine environments to build (Maul 1990).

To examine the recent past, a composite sea level record from 1898 to 1988 was constructed by Maul and Hanson (1990) using data from the earliest Florida site, Fernandina Beach, and data from Charleston, S.C., for the years 1924-1938 when Fernandina did not operate. This composite shows that sea level was falling at about -0.11 cm/yr before 1931. But since then, it has been rising at about +0.25 cm/yr. Maul and Hanson note a similar behavior at two other Florida stations, Cedar Key and Key West. Data for St. Petersburg, available for the period 1947-1986, shows a trend of +0.22 cm/yr, which is consistent with most other Florida stations analyzed by Maul et al. (1991). This much faster rate of sea level rise is similar to the earlier period between 3,000 and 7,000 years ago, when the shoreline retreated rapidly.

Since south Florida is tectonically stable, the relative sea level rises are representative of oceanic variability, rather than a combination of both land subsidence and sea level rise. A straightforward linear projection of the St. Petersburg trend of +0.22 cm/yr would amount to an increase of about 9 cm (3.5") by the year 2030. However, the predicted rise in temperature due to the greenhouse effect shows the increase could be more than three times higher, or 32 cm (12.5"). The most likely scenario places the increase at 20 cm (7.8") (Maul et al. 1991).

IMPLICATIONS OF THE PREDICTED RISE IN SEA LEVEL

The physical consequences of sea level rise can be classified into three broad categories: shoreline retreat, temporary flooding, and salt intrusion. The biggest loss may take place in wetlands. The ability of a wetland to sustain vertical growth is a balance between sedimentation and sea level rise. The loss of wetland economies such as shellfish industries may occur with the 20-cm sea level rise scenario (Maul 1990). The development of areas adjacent to wetlands, and the hardening of shorelines with seawalls and other barriers, will result not only in the loss of the wetlands but will also prevent new marshes from forming (EPA 1988).

Sandy shorelines retreat landward. The actual amount of erosion may be several meters for every centimeter of sea level rise (EPA 1983). In some states, planners have recognized the impact of erosion, and have recommended set-back limits rather than sand replenishment (Hendry 1990).

Sea level rise is assumed to shift the water table and the freshwater/saltwater boundary upward by the amount of sea level rise, and landward in accordance with shoreline retreat. Overpumping of coastal aquifers also has resulted in intrusion, and in many cases dwarfs the possible impact of sea level rise (EPA 1983).

TEMPERATURE AND CLIMATE

Variations in climate often are measured by grouping statistics into 30-year "normals". An analysis of temperature and precipitation records in Tampa since 1900 shows that the 30-year period 1930 to 1959 was a modest 0.3°C (0.6°F) warmer than the previous 30 years or the following 30 years. The average temperature for 1900-1929 was 22.29°C (72.12°F); for 1930-1959, it was 22.61°C (72.7°F); and for 1960-1989, it was 22.28°C (72.1°F). The warmer middle 30-year period agrees with similar temperature studies for the southeastern region of the United States (Virginia, North and South Carolina, Georgia, Alabama, and Florida) by Maul and Hanson (1990). Rainfall averaged 1197 mm/yr (47.15"/yr) for the period 1900-1929. It reached a maximum in the second 30-year period, 1930-1959, averaging 1302 mm/yr (51.27"/yr). For the last 30 years, 1960-1989, the average rainfall was 1141 mm/yr (44.95"/yr).

Mean global warming aver the next 40 years is expected to be in the range of 0.4-1.8°C (0.7-3.2°F). Regional scale changes in climate can be only estimated using general circulation models. Wigley and Santer (1990) state the only modeling result that one can place confidence in is a general warming in all seasons for the region. Allowing for uncertainties in the sensitivity of the models, the regional warming is likely to be in the range of 1-3°C (1.8-5.4°F) between now and 2040-2060.

Studies of air temperature at several locations in the wider Caribbean region have led Maul (1990) to conclude an increase less than 1°C (1.8°F) appears to be more plausible for the area by 2025. At this rate, it would be many decades before such a regional-scale change could be distinguished from the noise of natural variability.

For precipitation changes, Wigley and Santer (1990) say there is some evidence of decreased winter/spring rainfall in the northern part of the Caribbean basin. However, results from four models are often diametrically opposed. Wigley and Santer state there is little they can say about future precipitation changes.

TROPICAL STORMS AND HURRICANES

Higher sea surface and air temperatures in the Atlantic, Caribbean, and Gulf of Mexico may increase the overall frequency and strength of tropical storms and hurricanes. Shapiro (1990) uses historical data to link a rise in sea surface temperatures of 1.5°C (2.1°F) to a possible 40% increase in the annual number of storms. However, he cautions that the projection is subject to substantial uncertainty, adding that the likely impact on any particular region is quite uncertain.

CONCLUSION

Maul (1990) points out that there is little doubt that the climate is changing, but there is an important difference now—human activity is strongly involved. However, the effects are difficult to isolate from other natural moods in the earth's climate. In fact, Maul et al. (1991) note that falling sea level prior to 1931 is inconsistent with simple arguments of human effects on global climate. Greenhouse gases have been added to the earth's atmosphere in significant quantities since the start of the industrial revolution, but the evidence is tenuous that there is a cause and effect relationship on global sea level. More study is needed.

In an analysis of the global warming debate, S. H. Schneider of the National Center for Atmospheric Research notes (1990) that public responses typically come in two categories, adaptation and prevention. Flexibility of adaptive measures need to be considered now. Schneider asks that even if only small changes occur, what would be lost by improving the flexibility of water supply systems? After all, nature will continue to give us wet and dry years. This makes sense, considering the present state of our water supply and demands in west central Florida. The other management response is prevention—simply slowing down the rate at which climate-modifying gases are produced.

The best strategies, according to Schneider, should have high leverage or tie-ins that help to solve more than one problem. The single most important tie-in strategy involves energy. Using it efficiently not only will reduce the prospect of rapid climate change, but also will reduce acid rain, air pollution in cities, dependency on foreign energy supplies, and improve the competitiveness of manufactured products. Schneider and other experts call for enhanced research, to establish a firmer factual basis for decision making, whether adaptive or preventive.

ACKNOWLEDGEMENTS

I wish to thank G. A. Maul of the National Oceanic and Atmospheric Administration, Miami, and P. Clark of the Tampa Bay Regional Planning Council for their assistance in providing some of the reference material.

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PINELLAS COUNTY ACID DEPOSITION STUDY

V. E. Molesch

INTRODUCTION

While there are no ambient air quality standards for acid deposition, acid deposition is an environmental concern which has been under investigation during the 1980s. In Florida, the major work in this field of study has been done under the auspices of the Florida Electric Power Coordination Group, Inc. The purpose of this study is to contribute additional information on an issue of growing concern to the Tampa Bay area.

The approach and methodology utilized in this study follow the same analysis methodology and analysis units that were employed in the Florida Acid Deposition Study (FADS). The major finding of this study is consistent with the findings of the FADS. As rainfall amounts decrease, the mean rainfall acidity increases and pH levels decrease. Additional results for Pinellas County included:

- The peak monthly deposition rate for sulfates can be translated into a total monthly deposition of 19 tons per square mile per month.
- Thundershowers are efficient sulfur dioxide scrubbers with a removal rate between 15% to 50% of the local anthropogenic emissions of sulfate.
- The natural component to chloride deposition was determined to be 95%.
- Nitrogen dioxide is both an important ozone precursor and an important acid rain precursor.

METHODS

Pinellas County operates one acid deposition sampling site at Cross Bayou near the Clearwater Airport. This site was established in May 1984. During 1985, the site collected reliable data only for pH and conductivity of rainfall. The temporary lack of a rain gauge at the site resulted in only 1985 and later data for pH as being reliable enough to establish a rainfall acidity baseline.

Samples at the site are collected in a special wet/dry collector. During dry periods a lid covers the wet sampler and dust collects in the dry side. When it rains, the lid switches by means of electronic sensors to cover the dry side, allowing the wet side to collect the rain sample. The site was also equipped to measure rainfall levels and record rain events.

During 1985 and 1986, data obtained at the site included pH, conductivity, sulfate, nitrate, chloride, and ammonia with all but the first two variables determined through wet-chemistry methodologies. Metals including calcium, magnesium, potassium, and sodium were analyzed by atomic absorption methods. A significant number of the weekly samples taken during 1985 and 1986 were not analyzed for metals, with the result that quantitative estimates of deposition from anthropogenic as opposed to natural sources are not possible to determine. In August 1986, an ion chromatograph was purchased and installed. Subsequently, analytical procedures were revamped and resulted in near 100% data completion in 1987 and 1988 through ion chromatography methodologies.

RESULTS AND DISCUSSION

Pinellas County is downwind of sources on the peninsula to the east and, due to the higher emissions of acid rain precursors like sulfur dioxide and oxides of nitrogen, it is not surprising that Pinellas' volume-weighted mean pH was measured at 4.57. Figure 1 shows the variation of rainfall acidity as a function of weekly sample rainfall amount. Since the weekly rainfall collected in the sampler varies considerably from one week to the next during the year, a logarithmic x scale was chosen in this analysis. The results are consistent with the findings of the Florida Acid Deposition Survey;

as rainfall amounts decrease, the mean rainfall acidity increases and pH levels decrease. As rainfall increases to 10" per week mean acidity levels increase to a pH of 5.0, while for amounts of 0.1" or less, pH levels decrease to less than 4.0. Extreme acidity levels approach 3.0, or about the acidity of sour pickles or soft drinks.

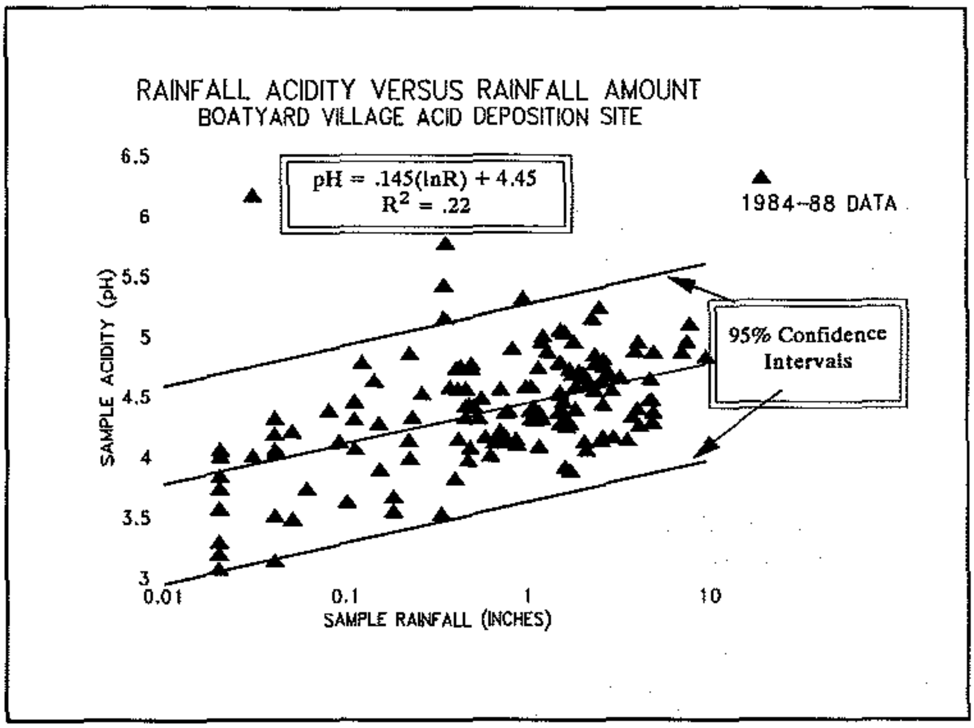

Figure 1. Rainfall acidity vs. rainfall amount, Boatyard Village site, 1984-1988.

Figure 2 shows the monthly variation in pH levels at the Cross Bayou site. The peak rainfall acidity levels occur during the summer thundershower season with prevailing easterly winds causing thunderstorms to form frequently over the Pinellas peninsula. Sulfur dioxide and nitrogen dioxide emissions are also higher during the summer. During the winter, the volume-weighted mean pH varies from 4.5 to 5.0, while in the summer, the volume-weighted mean pH is as low as 3.4.

The volume-weighted mean concentrations of each of the acid deposition ions were calculated in terms of equivalents per hectare or moles per 10,000 m^2. The 1987 and 1988 monthly variation of total sulfate and nitrate deposition is presented in Figure 3. Again, consistent with the analysis of monthly variations in pH, peak sulfate and nitrate wet deposition occurs in the June through September time frame, with peak values of 70-80 equivalents per hectare. Nitrate wet deposition is directly proportional to sulfate deposition. Molar total deposition rates are close to one to one. Of this total sulfate and nitrate deposition, 84% is due to anthropogenic sources and 16% due to natural sources (based on the methodology used in the FADS).

The peak monthly deposition rate for excess sulfates—sulfates in excess of natural rates of deposition due to sea salt—was 69 equivalents per hectare, possibly due to industrial sources. This is slightly higher than obtained in the Florida Acid Deposition Study. The peak monthly deposition rate for sulfates cited translates into a total monthly deposition of 19 tons per square mile per month. The rate of wet deposition alone over a land area the size of Pinellas County (240 square miles) would be sufficient to account for 50% of the total daily emissions rate for sulfur dioxide in Hillsborough and Pinellas County. However, this assumption may not be valid, since Cross Bayou may be an acid rain hotspot relative to surrounding deposition rates, and

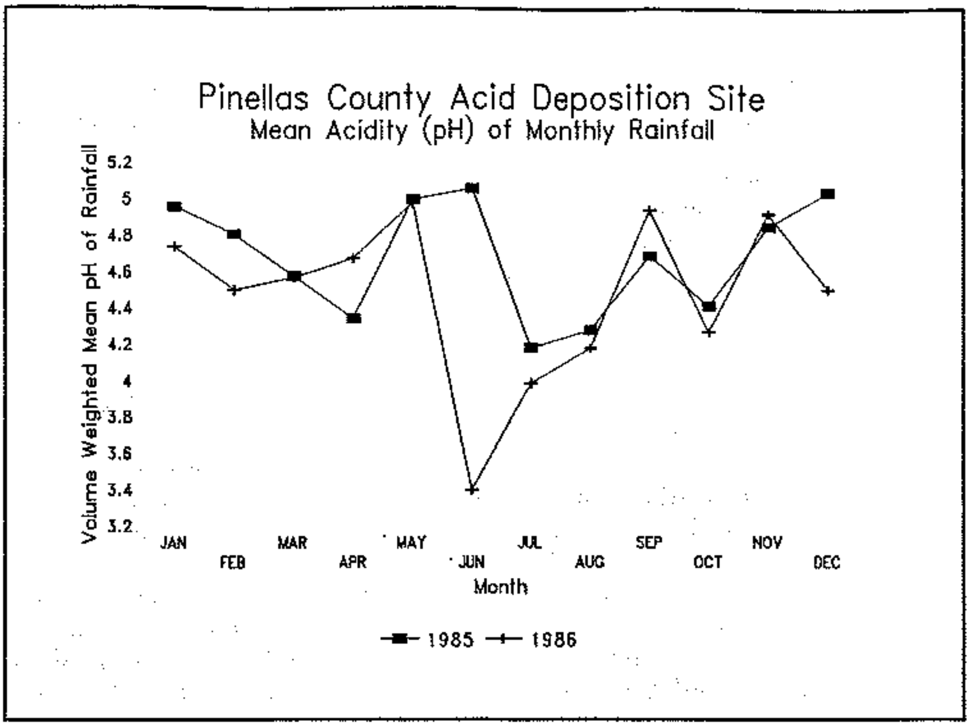

Figure 2. Pinellas County acid deposition site, mean acidity of monthly rainfall.

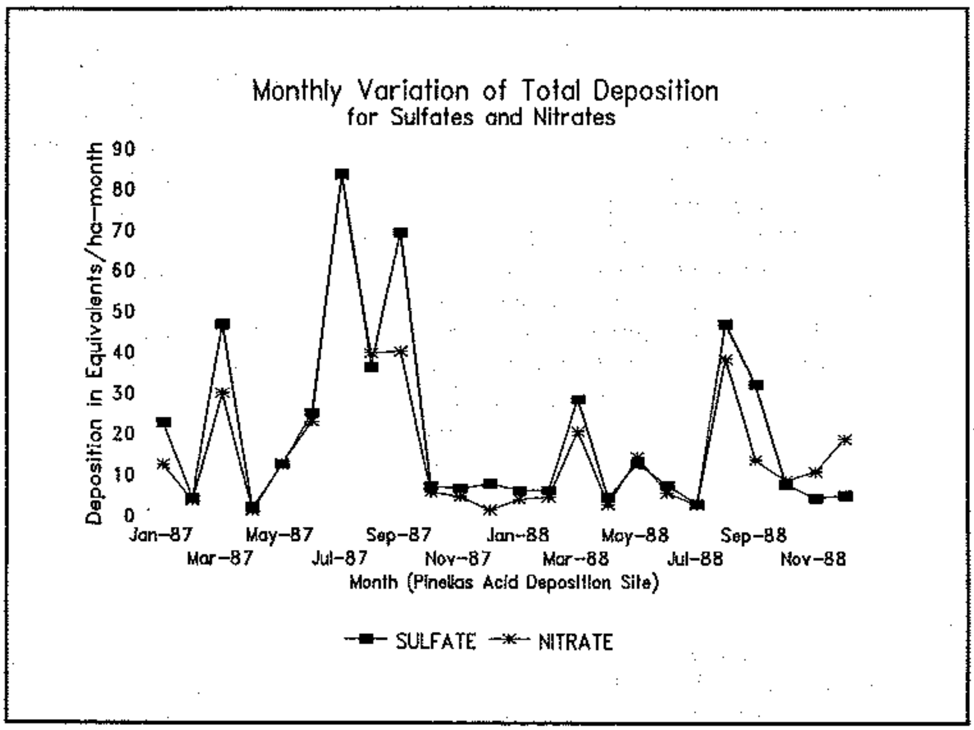

Figure 3. Monthly variation of total deposition: sulfates and nitrates.

rainfall patterns in the bay area are highly variable. Qualitatively, one may draw the conclusion that thundershowers are efficient sulfur dioxide scrubbers with a removal rate between 15% and 50% of the local anthropogenic emissions of sulfate.

The main natural source of acid deposition is the creation of sea salt ions which form an important source of condensation nuclei for maritime precipitation. As a result, the proportion of ions in sea salt closely matches the proportion of the elements in sea water. Sea water contains 19.0 g/l chloride, 10.5 g/l sodium, 1.35 g/l magnesium, 0.885 g/l sulfur, 0.40 g/l calcium, 0.38 g/l potassium and 0.065 g/l bromine. Other than elemental carbon, strontium, boron and silicon, all other elements present in sea water have concentrations of less than 0.001 g/l. Sodium is used as the tracer element to determine sea salt content in acid rain, and as a consequence, analysis of sodium is vital for acid deposition analysis.

By this tracer method, the natural component to chloride deposition in Pinellas County was determined to be 95%. The deposition due to anthropogenic sources or excess deposition is only 5% of total deposition. This is opposite to the pattern for sulfate and nitrate deposition. For potassium, the anthropogenic component was 52%, while for magnesium, the anthropogenic component of acid deposition was less than 2%. Magnesium deposition, like chloride deposition, is dominated by sea salt from the Gulf of Mexico and from the Atlantic Ocean. In the case of calcium, the excess deposition was 85% of total deposition. The deposition patterns for magnesium are similar to chloride, while calcium deposition is dominated by anthropogenic sources. Figure 4 shows the monthly variation for sodium and chloride in 1987 and 1988. As one would expect, during the winter season the majority of precipitation in the area is of maritime origin, and sea salt from the ocean produces a peak of deposition during the December to March time frame. Peak deposition is 200 moles chloride content per hectare during late winter. On the other hand, summertime deposition rates are at 5-10% of peak winter deposition. Summertime precipitation is Florida peninsula in origin, and the lower mean wind speeds during this time period reduce the quantity of sea salt nuclei production. As with sulfate and nitrate deposition, sodium deposition is directly proportional to total chloride deposition. Natural deposition dominates anthropogenic sources of sodium and chlorides primarily due to Pinellas County's geography of being surrounded on three sides by salt water. Figure 5 shows the monthly total deposition for magnesium, calcium, and potassium. Magnesium and calcium have seasonal deposition patterns similar to sulfates, while potassium exhibits a lower degree of pronounced seasonal variations. Peak total deposition for these three ions is much less than the deposition for sulfates or nitrates. Peak monthly deposition is 20 equivalents per hectare for magnesium, 12.3 equivalents per hectare for calcium, and 8 equivalents per hectare of potassium.

The results of this study indicate a significant north-south gradient of total acidity and total deposition with the highest levels in northern Florida. However, there has been no comparable analysis of the east-west gradients of acid deposition. The climatological analysis that was completed during Pinellas County's Ozone Transport Study suggests that the rain belts on Florida's east and west coasts may result in local acid deposition hotspots due to higher rainfall levels under the sea breeze convergence zones and entrainment of acid rain precursor-laden air in the recirculation zones along Florida's coast.

The seasonal variation of acid deposition is opposite to the monthly variation of mean ozone concentrations as shown in Figure 6. Ozone primary and secondary peaks in April and October of 1987 correspond with acid deposition minima during the same months. Conversely, the acid deposition peak during the July through September rainy season corresponds with a three-month low ozone period. This seasonal pattern suggests that during the spring and fall dry seasons a higher percentage of the regional nitrogen oxide emissions is washed out of the atmosphere during the summer months by thundershowers, while during the spring and fall seasons more of the regional

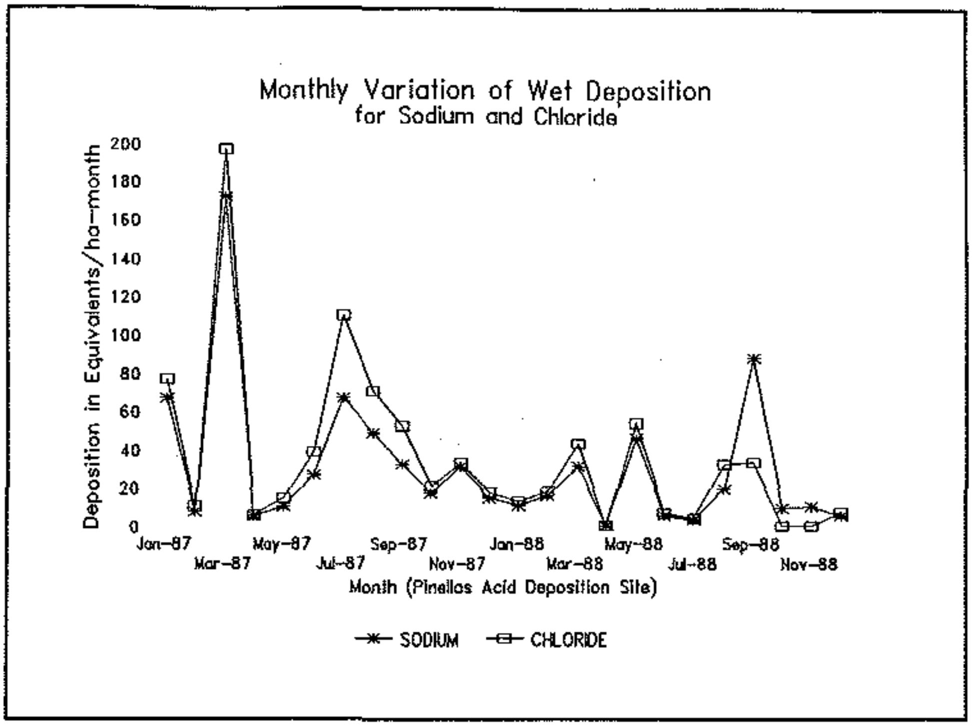

Figure 4. Monthly variation of wet deposition: sodium and chloride.

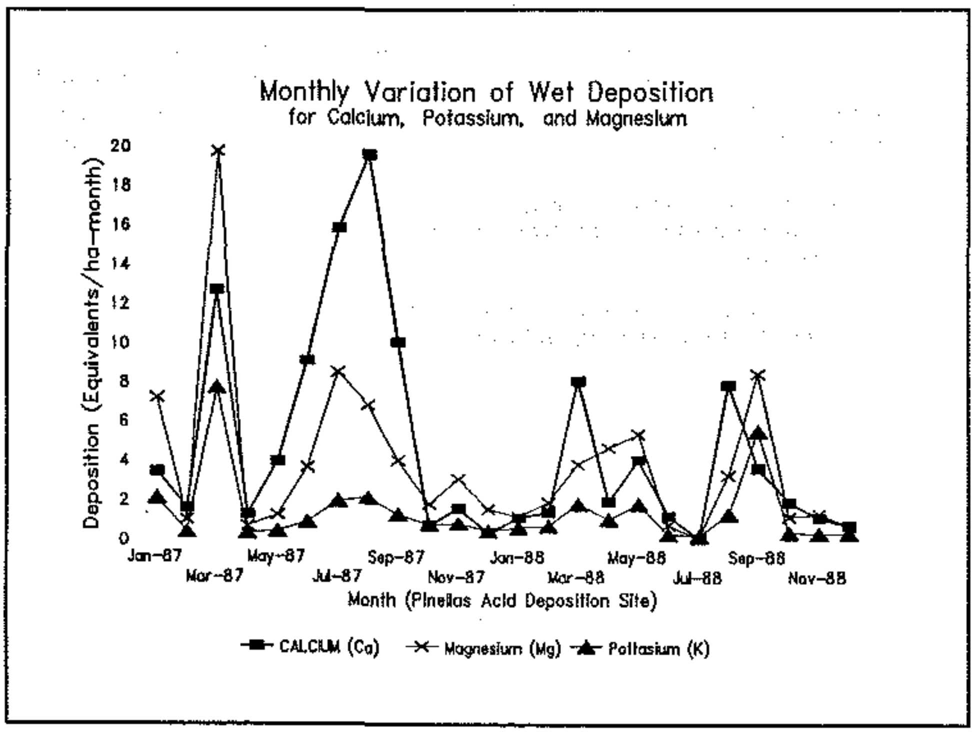

Figure 5. Monthly variation of wet deposition: calcium, potassium, and magnesium.

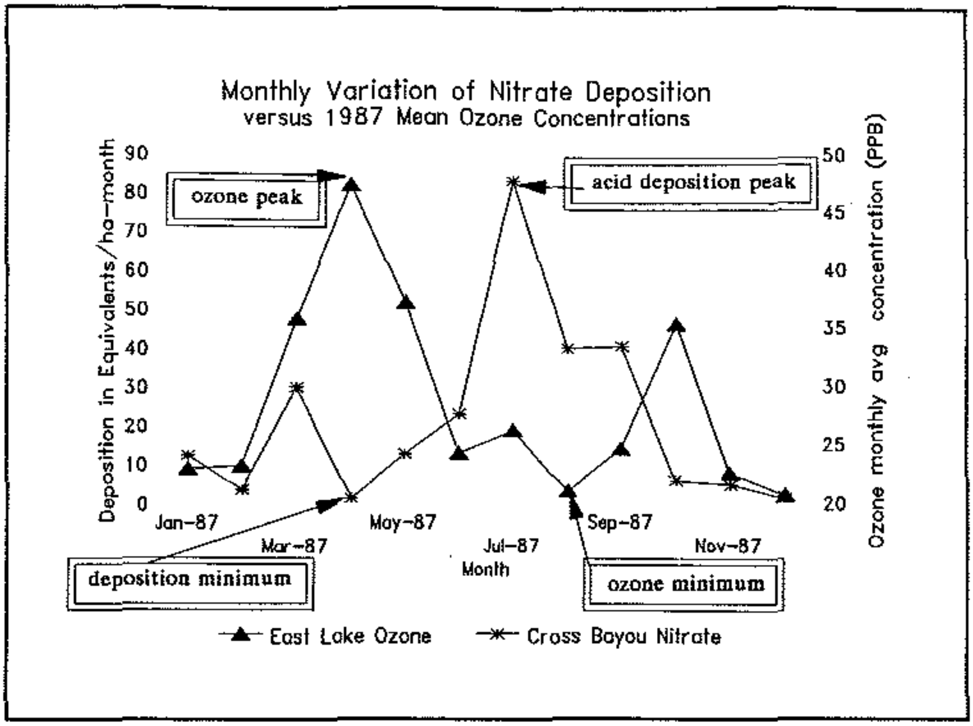

Figure 6. Monthly variation of nitrate deposition versus 1987 mean ozone concentration.

nitrogen dioxide reacts to form ozone. Dry deposition would therefore be a much greater portion of total deposition during the spring and fall.

Nitrogen dioxide is therefore both an important ozone precursor and an important acid rain precursor. During the night, ozone reacts with nitric oxide to form nitrogen dioxide, while during the daylight hours, ozone reacts with sunlight and NO to produce ozone. Estimates of dry deposition are highly uncertain, although it is believed that dry deposition is of the same order of magnitude as wet deposition.

NOTE: This report was edited and presented by Robert Roman. It is based on the original Acid Deposition Study as published in Pinellas County's 1987/88 Air Quality Annual Report, Section IV: Air Monitoring, Part 4.6: Acid Deposition.

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SURFACE WATER QUALITY MONITORING BY THE ENVIRONMENTAL PROTECTION COMMISSION OF HILLSBOROUGH COUNTY

R. N. Boler
R. C. Malloy
E. M. Lesnett

INTRODUCTION

The Environmental Protection Commission (EPC) of Hillsborough County was established through state legislation, the Environmental Protection Commission Act (1969), to serve as the regulatory agency for environmental issues in Hillsborough County. A provision of the act mandates that the EPC staff regularly report the status of air and water quality of Hillsborough County to the Environmental Protection Commissioners.

The Surface Water Quality Monitoring program was one of the first programs established at the EPC. Hillsborough County needed to establish the baseline condition of Tampa Bay and its tributaries for the purpose of determining the degree of pollution in these systems, as well as to characterize the constituents of pollution. Further, the hypothesis was that if point sources of pollution were eliminated or reduced, the effect would be reflected in ambient water quality.

MATERIALS AND METHODS

The Environmental Protection Commission routinely collects water quality information from several stations in Hillsborough County or Tampa Bay each week. We have 54 stations in Tampa Bay as presented in Figure 1. It takes three sampling efforts (performed on consecutive Wednesdays) to monitor all 54 stations. On the fourth week of each month, we sample the larger surface water systems in Hillsborough County. The Tributary Sampling Network has 40 stations as presented in Figure 2. This effort requires one sampling team on Tuesday and two sampling teams on Wednesday to monitor all 40 stations.

Samples of surface water are analyzed for 46 different parameters including metered parameters which are measured in the field. For field measurements, we have used Hydrolab equipment since 1975 and currently use the Hydrolab Surveyor II. The remaining parameters are "bottle" parameters and samples are analyzed in EPC's laboratory.

Methodology and quality control are based on Standard Methods, 17th Edition (1989; American Public Health Association, Washington, D.C.) or Methods for Chemical Analysis of Water and Wastes (1983; Environmental Protection Agency, Cincinnati, Ohio). Generally, quality control of the results—precision and accuracy—is quite good; the error for most analyses is less than 5%. The EPC laboratory is a DER/HRS Certified Environmental Laboratory.

The results of the Surface Water Quality Monitoring program are reported in the biannual EPC report, Surface Water Quality. The report fulfills the mandate of the Act. These reports are also provided to other government entities, public libraries, and the scientific and academic communities. The report is available to the general public for the cost of the printing. The most current report is for 1988 and 1989.

RESULTS AND DISCUSSION

Tampa Bay

Water Clarity

In an estuary such as Tampa Bay, the intensity of light which prevails in the water column is critical to much of the flora and fauna in the ecosystem (Steidinger and Gardiner 1985). The light climate of a body of water is dependent on the extinction of light with depth which, in turn, is controlled by two factors: the

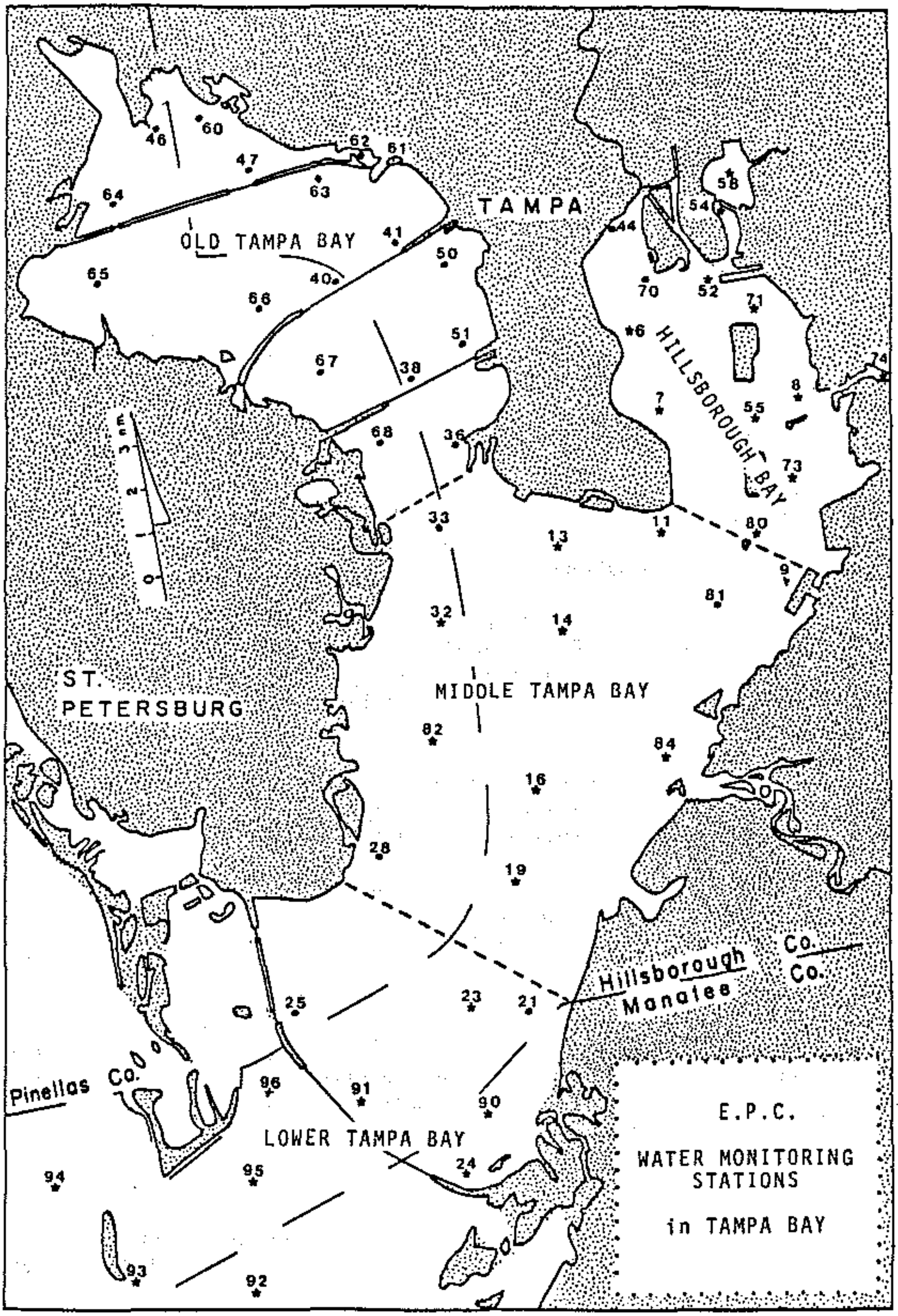

Figure 1. EPC water monitoring stations in Tampa Bay.

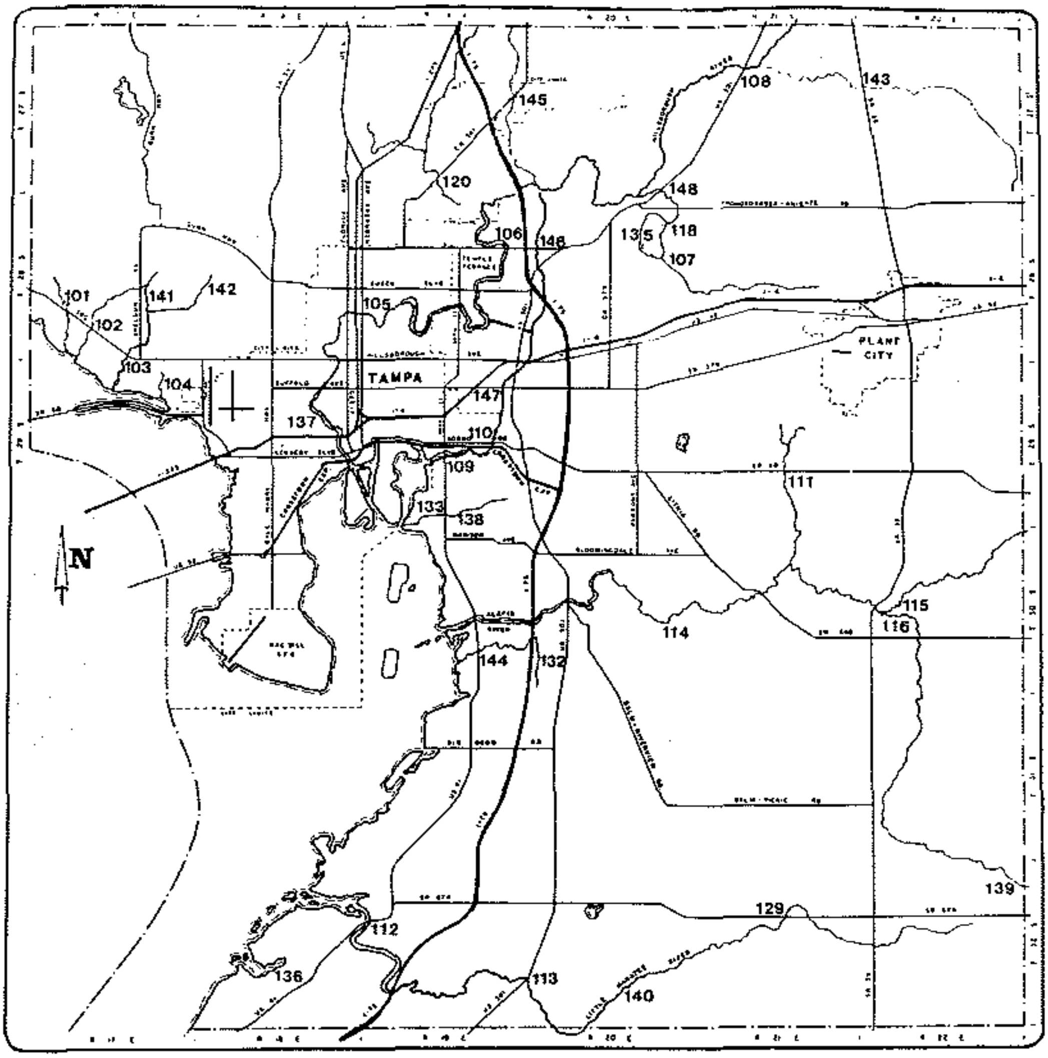

Figure 2. Freshwater monitoring stations, Hillsborough County, Florida.

absorption of radiation by water itself or by substances dissolved in water measured as "color" and the scattering of radiation by suspended matter measured as "turbidity" (Jerlov 1976). A Secchi disk is used to determine the vertical penetration of light.

An indication of the light climate of a body of water can be acquired by measuring turbidity, color, and light penetration. A comparison of these parameters throughout the waters of Tampa Bay can provide information concerning not only the relative degree of water clarity, but also the location of point and nonpoint sources of water pollution.

The waters of Tampa Bay were monitored monthly for turbidity, color and effective light penetration. Water samples were collected from mid-depth and analyzed in the laboratory for the determination of turbidity and color. Effective light penetration was measured in the field utilizing a 20 cm diameter Secchi disc.

Turbidity. Turbidity in water is the optical property of a sample which causes light to be scattered. Turbidity in water may be caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter, plankton or other microscopic organisms (Standard Methods 1989). Excessive turbidity in a body of water decreases the light intensity as it penetrates the water column resulting in a decreased compensation point of photosynthesis with a concomitant reduction of flora

(Estevez 1987). The injurious effect of turbidity may also result in the deposition of sediment on the surface of benthic flora and fauna (Stern and Stickle 1978, Wright 1978).

During 1988, turbidity annual averages ranged from 3 to 10 NTU; in 1989, the annual average turbidity range increased 5 to 13 NTU. In 1988, annual average turbidity of 7 NTU or greater were restricted to small areas in Hillsborough Bay (HB) and Old Tampa Bay (OTB); in 1989, all of Hillsborough Bay and portions of Old Tampa Bay and Middle Tampa Bay (MTB), as well as coastal areas of Lower Tampa Bay (LTB), had annual turbidity averages of 7 NTU or greater.

Figure 3 provides a historical perspective of turbidity in four major subdivisions of Tampa Bay (Lewis and Whitman 1985) by presenting the annual average turbidity values from 1974 through 1985. The graph shows considerable variability from year to year with no clear trend. Usually, Hillsborough Bay has had the highest turbidity values as compared to the three other areas of the Tampa Bay. Hillsborough Bay had high levels of turbidity in 1978 and 1979; concurrently, that area of Tampa Bay was being dredged as part of the Tampa Harbor Deepening Project. Turbidity values in Hillsborough Bay dramatically declined in 1980 to the lowest average measured, only to be followed in 1981 by a dramatic increase to the highest average measured at that time. The cause of the extreme variation in turbidity measurements for these two years is not known; quality control data was good. Meteorological conditions (wind and rain) may be a factor. In 1982 the turbidity average for Hillsborough Bay increased again and then decreased in 1983. Old Tampa Bay and Middle Tampa Bay had declining turbidity averages in 1982 and 1983. Turbidity values fluctuated only slightly in the other major subsections of Tampa Bay during 1984 and 1985, while increased turbidity was measured in Hillsborough Bay. However, 1983 was a year of unusually low turbidity in Hillsborough Bay; therefore, the increase noted during 1984 and 1985 may represent normal fluctuations rather than a trend towards increasing turbidity in Hillsborough Bay.

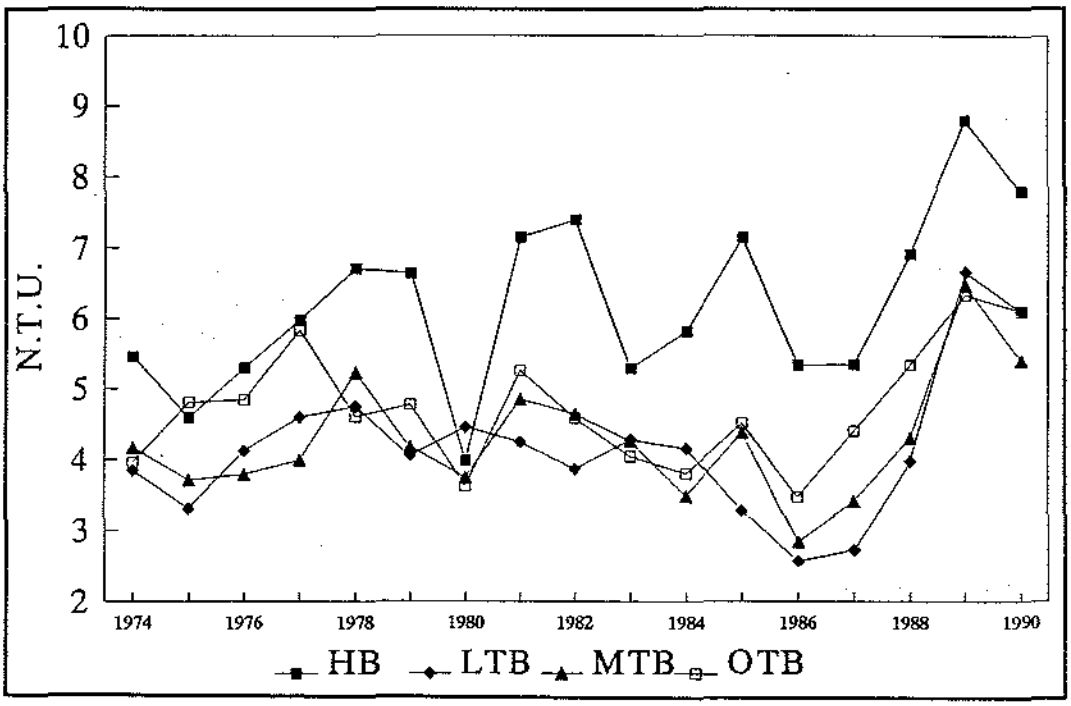

Figure 3. Tampa Bay: turbidity, 1974-1990 annual means by area.

In 1986, turbidity decreased to the lowest level for the period of record in all areas of the bay except for Hillsborough Bay, which also showed a marked reduction in turbidity from 1985. In 1987, the turbidity level in Hillsborough Bay remained low and essentially unchanged from 1986. The three other areas of the bay showed moderate turbidity increases in 1987 relative to 1986.

In 1988 and 1989 turbidity values continued to increase. For Hillsborough Bay and Tampa Bay values were at the highest average level in 1989 for the period of record. Although the 1990 annual averages for turbidity of the major subdivisions of Tampa Bay were lower than 1989, the averages remain higher than those of the mid-1980s.

The variable nature of the turbidity values from year to year is the result of several factors such as dredging (the Tampa Harbor Deepening Project), the occurrence of algae blooms (particularly in Hillsborough Bay), and runoff. Resuspended sediment and particles caused by wind driven waves in the shallower areas and prop wash by the large ships in the deeper portions of Tampa Bay are also contributing factors.

Effective Light Penetration (Secchi). In 1988, among stations deep enough to accurately determine annual average effective light penetration (Secchi), readings ranged from 32" in Hillsborough Bay to 141" in Lower Tampa Bay near the Skyway Bridge. All stations in McKay Bay and Hillsborough Bay had annual averages that were less than 70". Several stations in Old Tampa Bay also had annual averages less than 70". Light penetration generally improved toward the mouth of Tampa Bay averaging greater than 90" at most stations in Middle and Lower Tampa Bay. The best single light penetration measurement taken during 1988 was 240" at station 93 in lower Tampa Bay, near Egmont Key.

In 1989, annual averages for effective light penetration ranged from 38" in Hillsborough Bay to 133" in Lower Tampa Bay near the Skyway Bridge. All stations in McKay Bay and much of Hillsborough Bay averaged less than 50". The western section of Old Tampa Bay, including the Largo Inlet and Cooper's Bayou, also averaged less than 50" in 1989. Light penetration generally improved toward the mouth of Tampa Bay, averaging 110" or more. The best light penetration measurement taken during 1989 was 276" taken at station 23 in Lower Tampa Bay.

Figure 4 depicts trends for effective light penetration in Tampa Bay by comparing the annual averages of four areas of the bay from 1974 through 1989. The graph shows that over the years Hillsborough Bay has consistently had the poorest light penetration. All areas of the bay had decreasing effective light penetration from 1974 to 1979. The effective light penetration trend began improving in 1980 for all areas of the bay. Hillsborough Bay has had improving light penetration for each year since 1980 until 1985 when a slight decrease was measured. Light penetration continued to increase through 1988 in Hillsborough Bay. Lower Tampa Bay has had the greatest rate of improvement for light penetration, with significant increases occurring in 1984, 1985, and 1986. Light penetration values in 1988 were quite similar to 1987 levels in Lower Tampa Bay; however, a decrease was observed in 1989. Light penetration showed little change in Old Tampa Bay during 1988 and decreased slightly in 1989. Middle Tampa Bay showed a large increase for light penetration in 1986; the following years a decline in light penetration has occurred, although the value for Middle Tampa Bay in 1987 was higher than most other years. In 1988 and 1989 the trend indicates a slight decrease in water clarity in all areas of the bay relative to the mid-1980s. Overall effective light penetration has increased during the period of record.

Bacteria

Ambient water samples are collected each month from mid-depth and analyzed for total and fecal coliform. The purpose of bacteriological analyses is to determine suitability of the water for recreational purposes, to monitor the impact of domestic and industrial waste effluent discharges, to help determine stormwater impacts, to identify the sources of bacterial pollutants, and to evaluate the effectiveness of the pollution abatement program.

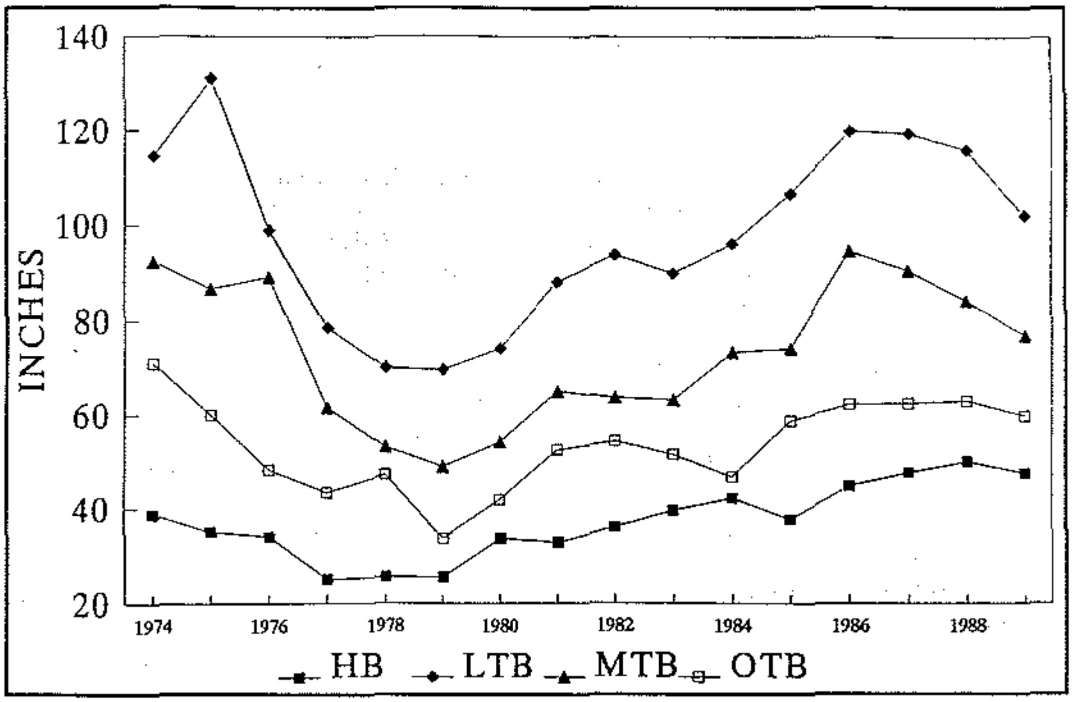

Figure 4. Tampa Bay: Secchi, 1974-1989 annual means by area.

Coliforms are widely distributed in nature and occur not only in human feces but in other media, such as sewage, surface waters, soils, and vegetation. They enter the natural waters directly through fecal discharge or via stormwater runoff, flooding, or inadequate sewage treatment. The presence of high numbers of coliform bacteria is deemed to be indicative of the presence of potentially harmful pathogenic micro-organisms. Coliforms tend to be more persistent in the aquatic environment; their survival rate depends on a variety of environmental factors. As a group, coliforms are considered harmless and often helpful to the digestion and vitamin synthesis in the body. However, some coliforms, such as *Escherichia coli* strains, are known to cause enteritis, while others may combine with fecal streptococcus strains to cause mild genito-urinary tract infections (Standard Methods 1989).

Fecal coliforms are a subgroup of the total coliform group. Their presence in water specifically indicates fecal waste contamination by warmblooded animals. These organisms occur relatively infrequently except in association with fecal pollution. Survival of the fecal coliform group is shorter in environmental waters than for the coliform group as a whole. It follows, then, that high densities of fecal coliforms are indicative of relatively recent fecal pollution. Fecal coliforms generally do not multiply outside the intestines of warmblooded animals. The major species in the fecal coliform group is *Escherichia coli*, and represents the possible presence of enteric pathogens.

The 54 bay stations and 35 tributary stations in the Water Quality Monitoring Network were analyzed for total and fecal coliforms. Selected stations were also routinely analyzed for fecal streptococcus. Water samples were collected from mid-depth and analyzed for total and fecal coliform utilizing the membrane filter method.

The annual averages for total and fecal coliforms were calculated for each station. During 1988, four bay stations had annual averages greater than 100 total coliform colonies per 100 ml of water. These same four stations also had fecal coliform concentrations greater than 100 colonies per 100 ml. The stations with elevated annual averages were #2 (mouth of the Hillsborough River), #74 (mouth of the Alafia River), #60 (north of Courtney Campbell Causeway), and #62 (Courtney Campbell Causeway). In 1989, only two stations, #2 and #74, averaged greater than 100 total coliform colonies and again these same two stations had fecal coliform concentrations greater than 100 colonies per 100 ml.

The trend graph for total coliform bacteria, Figure 5, shows the average total coliform level for the four largest subdivisions of Tampa Bay from 1974 to 1989. During the 16 years presented in the graph the trend has been a dramatic reduction in total coliform. The most significant reduction occurred in Hillsborough Bay in 1980.

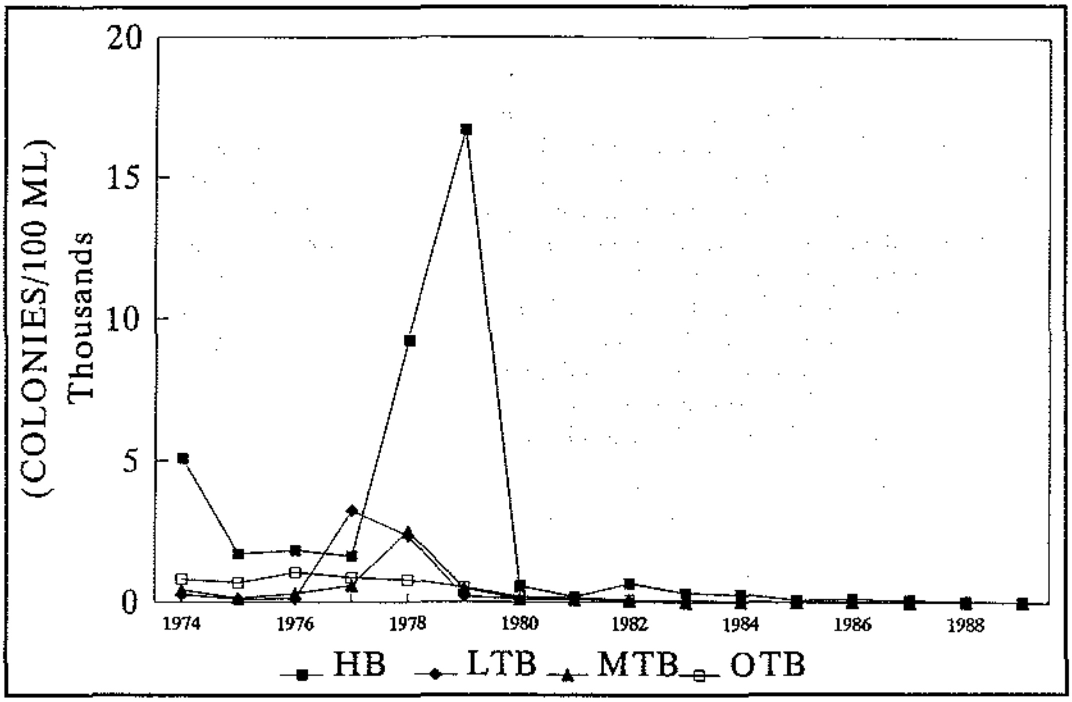

Figure 5. Tampa Bay: total coliform, 1974-1989 annual averages by area.

Chlorophyll

Chlorophyll analysis is useful as an indicator of the general ecology of a body of water because chlorophyll is an indirect measure of the quantity of planktonic algae present. Plankton algae are usually microscopic and often single-celled organisms that live suspended in the water column. The life cycles of these organisms can respond quickly to environmental conditions. In this way, chlorophyll can be used as an indicator of short and long term phenomena such as nutrient enrichment. Although planktonic algae are the basis of the food web, they can also be directly or indirectly responsible for fish kills, odors, discoloration of waters, and the reduction of water clarity.

Chlorophyll is not an absolute indicator of planktonic biomass since some species do not contain chlorophyll and when chloroplasts are present, they vary in number, size and pigment content per cell. Light, nutrients and other factors also influence the quantity of chlorophyll per cell so that their horizontal and vertical distribution in a body of water becomes important. Despite these variables and limitations, chlorophyll determinations are a useful indicator of phytoplankton population (Standard Methods 1989).

The amounts of chlorophyll *a*, *b*, *c* and total chlorophyll have been measured since 1972. Water samples are collected from mid-depth and analyzed using the trichromatic method, (Standard Methods 1989).

In 1988, annual average chlorophyll *a* concentration ranged from 1.8 μg/l near Egmont Key at the mouth of Tampa Bay to 19.1 μg/l in McKay Bay. In 1989, the highest annual average chlorophyll *a* concentration was 28.9 μg/l at station 8 in Hillsborough Bay near the mouth of the Alafia River; the lowest average chlorophyll *a* concentration was 3.1 μg/l inside Egmont Key at the mouth of Tampa Bay.

During 1988 and 1989, chlorophyll *a* concentrations throughout the bay remained at levels significantly lower than the early 1980s. In 1988 and 1989, most of Tampa Bay averaged less than 10 μg/l of chlorophyll *a*. The highest concentrations of chlorophyll *a* were in upper Hillsborough Bay and in the Largo Inlet area of Old Tampa Bay.

Figure 6 depicts yearly trends in chlorophyll *a* concentrations in four areas of Tampa Bay by comparing annual average chlorophyll *a* from 1974 through 1990. The graph shows that during the period of record, Hillsborough Bay has consistently had the highest chlorophyll *a* concentrations. This condition correlates with the numerous algae blooms observed in Hillsborough Bay. Old Tampa Bay and Middle Tampa Bay have not experienced algae bloom problems and the graph shows the chlorophyll *a* levels in these areas were consistently lower than Hillsborough Bay during the 1970s and early 1980s. Since 1982, the chlorophyll *a* concentration in Hillsborough Bay has declined. During recent years, the annual average for chlorophyll *a* in Hillsborough Bay has been much closer to the levels measured in Middle Tampa Bay and Old Tampa Bay. Lower Tampa Bay receives good flushing by the Gulf of Mexico and consequently has the lowest chlorophyll *a* concentration in the bay. Linear regression analysis indicates that chlorophyll *a* concentrations have declined in all areas of the bay, most dramatically in Hillsborough Bay.

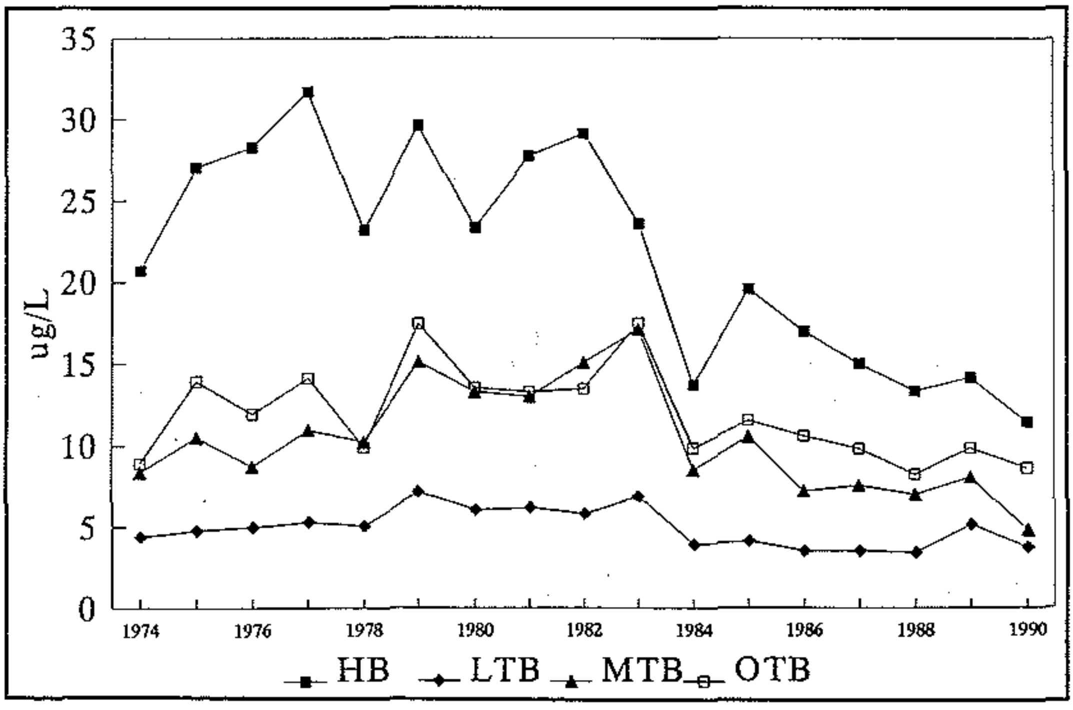

Figure 6. Tampa Bay: chlorophyll a, 1974-1990 annual means.

Yearly averages for chlorophyll *a* tend to relate to rainfall amounts. High rainfall amounts in 1979 and 1983 resulted in correspondingly higher chlorophyll concentrations. Similarly, lower chlorophyll concentrations were recorded in the years with lower rainfall amounts. However, the pattern is not absolute; other variables are involved. Normal rainfall was measured in 1988, while 1989 was a below-average rainfall year. However, chlorophyll *a* concentrations for all areas of the bay were greater in 1989 than 1988. The rainfall amount was well below normal in 1990 and correspondingly a decrease in chlorophyll *a* was measured in each of the four major subdivision of Tampa Bay.

General Water Quality Index

It is generally agreed among the scientific community that the primary water quality issue for Tampa Bay is eutrophication (high nutrient loading) resulting in increased algae growth, reduced light penetration and an unstable, often very low, oxygen environment (Lewis and Estevez 1988). The water quality index was primarily developed with this issue in mind.

It is important to bear in mind that the water quality index used here is not intended to be an absolute measure of conditions in Tampa Bay, but rather, simply as an index for quick assessment of water quality. Each parameter must be considered by itself to actually assess its role and influence in the bay's water quality.

The method used to generate the water quality index utilizes fixed scales for the parameters considered, allowing the comparison of data from one year to the next, hence, the development of a general water quality trend for Tampa Bay and its various subunits (Dunnette 1979). The results are expressed as water quality index (WQI) points. The scale represents discrete values in a relative relationship. The greater the WQI, the better the water quality and conversely, a lower WQI represents poorer conditions.

The index is an aggregate value of several parameters, combined in such a manner that the parameter's relative environmental significance is a factor in the final WQI value. The parameters incorporated into this index are dissolved oxygen, chlorophyll *a*, total coliform, biochemical oxygen demand, total phosphorus, total Kjeldahl nitrogen, and effective light penetration. For each parameter a scale of "good to bad" has been devised and subindex points are assigned. Each subindex value is multiplied by the parameter's relative environmental significance and combined with the other subindex values to produce the final WQI which will be in the range of 1-100 points. A score of 100 points represents the highest water quality possible.

In 1988, annual WQI values ranged from 52.7 points at the mouth of the Alafia River to 92.8 points in Lower Tampa Bay near Egmont Key. The lowest monthly WQI value was 41.3 points at station 74 in the Alafia River near the Highway 41 bridge; the highest monthly WQI value was 96.2 points at station 93 in Lower Tampa Bay.

In 1989, WQI values at most stations were quite similar to the 1988 values. The highest annual water quality index value was 92.5 points at station 93 in Lower Tampa Bay. Again, the lowest annual WQI value, 53.5 points, was at station 74 at Highway 41, near the mouth of the Alafia River. The lowest monthly WQI was 31.0 points at station 74. The highest monthly WQI was 99.5 points at station 93 in Lower Tampa Bay near Egmont Key.

Generally, the higher water quality index values are found in Lower and Middle Tampa Bay. Lowest water quality values are in Hillsborough Bay near the mouth of the Hillsborough and Alafia Rivers, and in the vicinity of the harbor including East Bay, McKay Bay and Seddon Channel. The index also indicated lower water quality at the station in Old Tampa Bay near the Baycrest/Dana Shores area, north of the Courtney Campbell Causeway.

A major attribute of this type of index is that it allows for comparing water quality from year to year. The lack of total Kjeldahl nitrogen data prior to 1980 restricts the time interval to which the water quality index can be applied. The trend graph, Figure 7, shows that since 1981 water quality has improved in each of the four major subdivisions of Tampa Bay.

Although Hillsborough Bay has the poorest water quality in the bay, the WQI derived for this subdivision has consistently increased for the period of record. While WQIs derived for Hillsborough Bay were virtually identical in 1988 and 1989, (71.3 points), over the 9-year period from 1981 through 1989, the WQI for Hillsborough Bay has increased by 16 points. The 1988 and 1989 WQIs for Hillsborough Bay represent a 3 point increase over the 1987 WQI.

The improvement in Hillsborough Bay is reflected by a 9 point increase in the WQI for Middle Tampa Bay. Old Tampa Bay and Lower Tampa Bay have each registered approximately a 7 point increase during the interval.

During 1987, slightly lower WQI values were derived for Lower, Middle, and Old Tampa Bay. The slight decline in water quality might be attributed to the increased rainfall of 1987, or may reflect a fluctuation within the normal range of values for these areas of the bay.

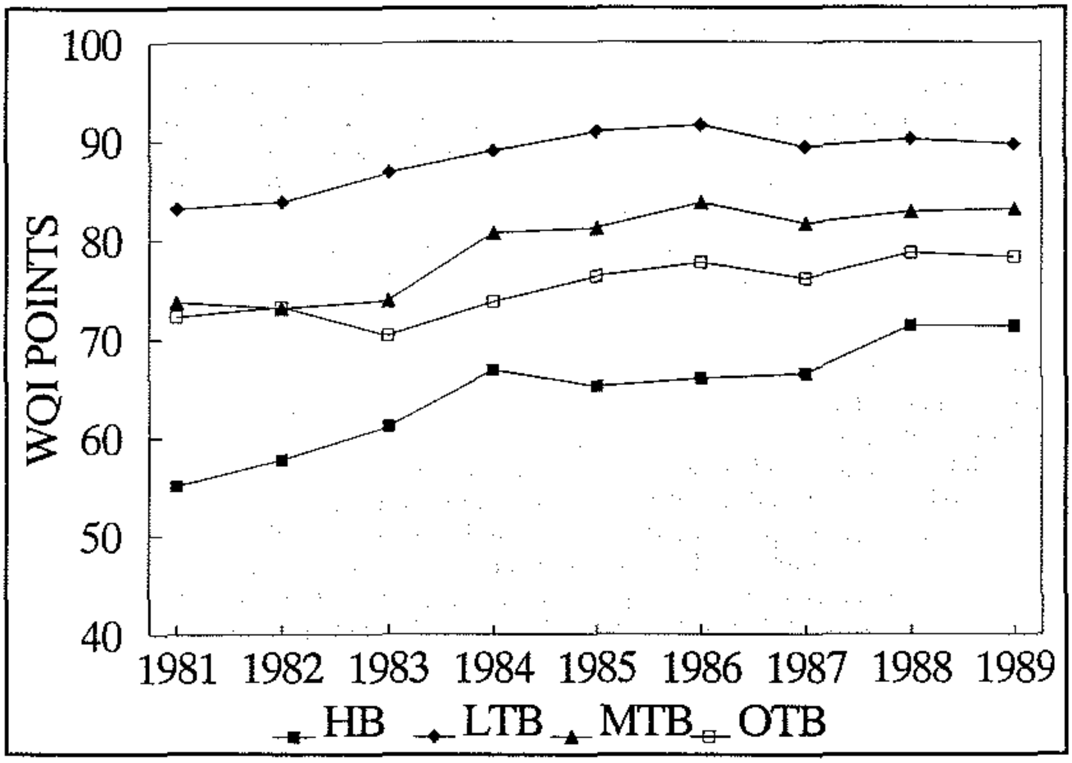

Figure 7. Tampa Bay: general water quality, 1974-1989 annual values by area.

Coastal Streams of Northwest Hillsborough County:
Double Branch Creek, Channel A, Rocky Creek, Sweetwater Creek

These are four small coastal tributaries to Old Tampa Bay. The sampling stations are relatively short distances from the open water of Old Tampa Bay. Hence, all of these stations have brackish water; the data indicates that in recent years, 1988 through 1990, salinity has increased at all stations (Boler 1990).

Double Branch Creek is located in western Hillsborough County, near the county line. Station 101 is monitored from the Hillsborough Avenue bridge. The station is just downstream from the confluence of the two branches. Until recently the headwaters of this stream have drained improved pasture and undeveloped land. This area is currently being developed for residential use. The watershed has a relatively high water table.

Channel A (Station 102) is monitored from the Hillsborough Avenue bridge. This system was channelized in the late 1960s and early 1970s as part of a grand scheme of drainage systems that was planned for Town 'n' Country and northwest Hillsborough County. A flow control structure, maintained and operated by the Southwest Florida Water Management District, serves as a salinity barrier. Station 102 is located about a half mile downstream of the structure and approximately two miles from the open water of Old Tampa Bay. The water tends to have the most consistent salinity range of these four streams. Upstream of the flow control structure, Hillsborough County operates the River Oaks Advanced Waste Treatment (AWT) facility, which discharges 10 million gallons per day of AWT effluent. Channel A will be receiving AWT effluent from two more large regional wastewater treatment facilities that will soon be on line.

Station 103 represents EPC's monitoring of lower Rocky Creek. This station is located at Hillsborough Avenue in the Baycrest area. EPC has another station farther upstream at Waters Avenue. At Station 103, the stream is relatively broad and shallow. It is the least saline of the four streams. This stream also has a flow control structure or salinity barrier located about 1.5 miles upstream of Station 103. The headwaters of Rocky Creek drain the area generally located between Dale Mabry Highway and Gunn Highway. Hillsborough County operates a regional AWT facility—Dale Mabry North—that currently discharges through a series of retention ponds in Carrollwood Village into Brushy Creek and ultimately into Rocky Creek. The County is currently cross-connecting this facility with the River Oaks AWT facility and the effluent will be redirected to Channel A.

Sweetwater Creek, station 104, is monitored at Memorial Boulevard. Downstream of this station is the Dana Shores subdivision. In this area, the creek has been channelized and encased in vertical concrete seawalls. The hardened shoreline ends just upstream of Memorial Boulevard. Sweetwater Creek receives about 0.5 million gallons per day of effluent from the Florida Cities Water Utilities Wastewater Treatment Plant.

Total Coliform

Total coliform, as indicated by annual averages (Figure 8a), has declined in all streams, especially in Sweetwater Creek. From 1977 through 1980, Sweetwater Creek had annual averages greater than 20,000 colonies per 100 ml of water. The maximum annual average of record occurred in 1980, which was 45,000 colonies per 100 ml. The 1990 annual average for Sweetwater Creek is 3050 colonies per 100 ml. Over the period of record, Rocky Creek and Double Branch Creek have exhibited very similar patterns. Despite improving water quality, with respect to bacteria, only Channel A has had annual averages that meet the safe swimming standards.

Effective Light Penetration (Secchi)

All of these streams exhibit a definite trend toward improving water clarity (Figure 8b). As with bacteria, the greatest improvement has occurred in Sweetwater Creek. In 1977, Sweetwater Creek had an annual average of 16" for the Secchi depth; the 1990 annual average was 48".

The fairly low Secchi values for Double Branch Creek are related to tannins, which give the stream its characteristic "black water". The tannins come from the numerous cypress domes in the drainage basin and floodplain of the creek.

Chlorophyll a

Channel A has consistently had the highest chlorophyll *a* values and has exhibited only moderate variability (Figure 8c). Sweetwater Creek has shown high variability;

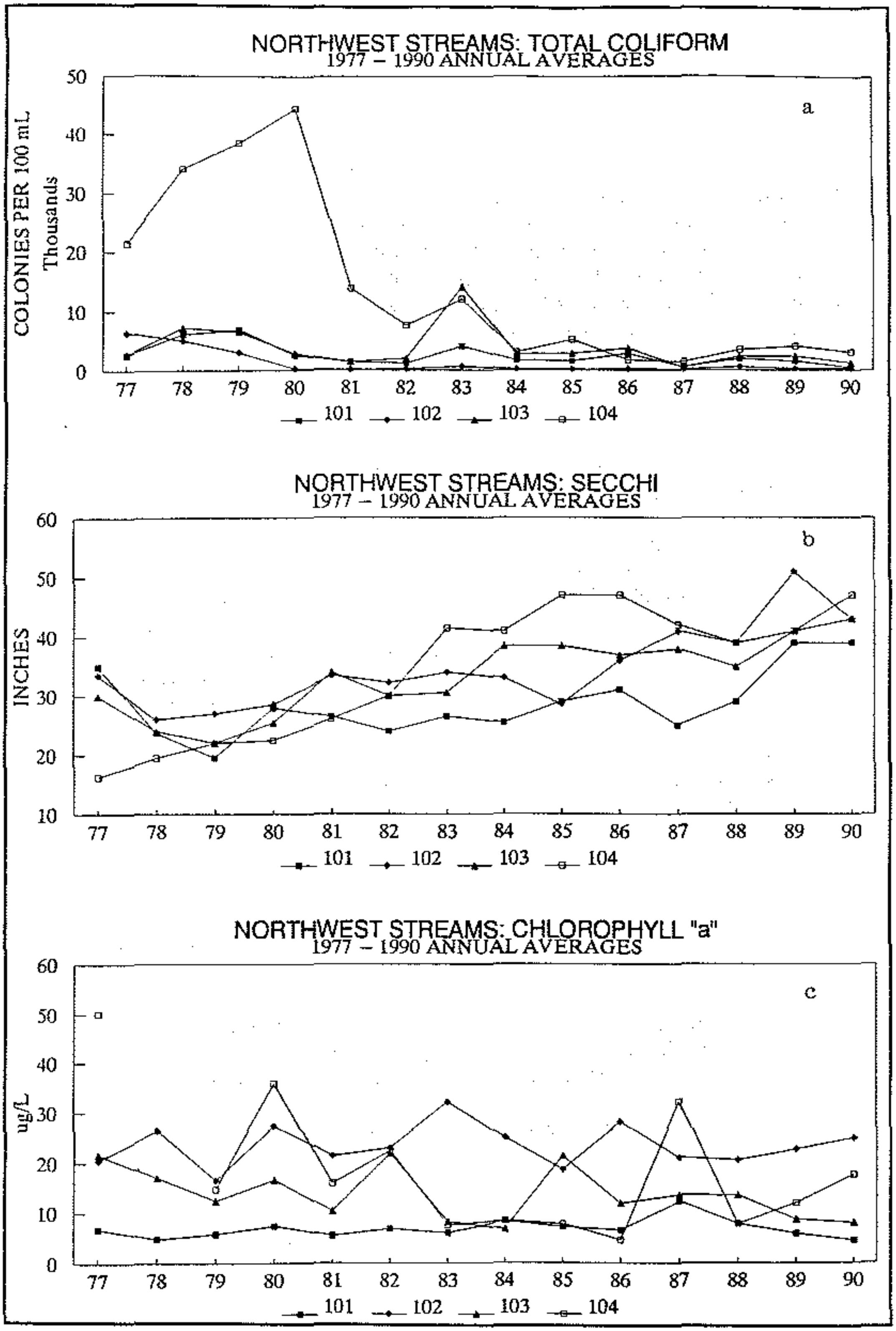

Figure 8. Northwest streams: a) total coliform; b) Secchi; c) chlorophyll a, 1977-1990 annual averages.

in 1987 the annual average was 37 μg/l. Double Branch Creek has had the lowest and most consistent annual average chlorophyll of these streams, probably as a consequence of low light penetration, the dark colored water, and the consistent flow in the creek.

Hillsborough River

The Hillsborough River provides the largest flow of freshwater to Tampa Bay. This is a river with a "split personality", caused by the dam located near Rowlett Park in north Tampa. Originally built to generate electricity, the dam now provides the drinking water reservoir for the City of Tampa. The water quality issues above the dam are quite different from those downstream of the dam. The lower Hillsborough suffers impacts associated with urbanization such as stormwater runoff and reduced flushing caused by the diversion of water for potable uses. The upper Hillsborough River drainage basin is largely undeveloped or used as rangeland.

The annual averages of various paramenters for four stations located on the Hillsborough River are presented graphically in Figures 9-12. Stations below the dam are #137 at Columbus Avenue and #105 at 22nd Street near Rowlett Park; above the dam, the stations are #106 at Fowler Avenue Bridge and #108 at Highway 301 at Hillsborough River State Park. The parameters presented are biochemical oxygen demand, effective light penetration (Secchi), total coliform, and total nitrogen.

Biochemical Oxygen Demand

Generally, the upper Hillsborough has lower biochemical oxygen demand (BOD) than the lower Hillsborough River (Figure 9). Station 106 at Fowler Avenue has lower values and a more consistent level of BOD, without large year-to-year fluctuations that are exhibited at the other stations. High variability is exhibited at the Columbus Avenue station and at station 108 in the upper Hillsborough River near the State Park.

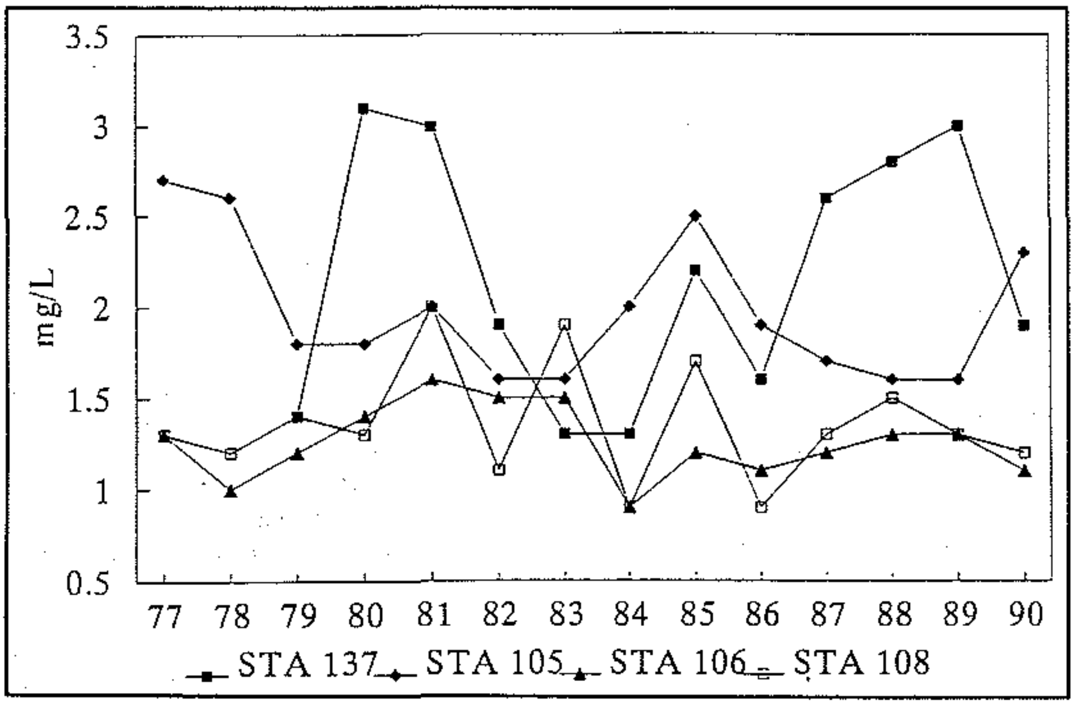

Figure 9. Hillsborough River: biochemical oxygen demand, 1977-1990 averages.

Station 137 showed a steady increase in BOD from 1986 through 1989, then a sudden decrease in 1990. During the same period, at station 105 near Rowlett Park the reciprocal pattern occurred; BOD decreased from 1985 through 1989, then a large increase occurred in 1990. High values at the Columbus Avenue station in 1980 and 1981 reflect problems with sewage collection systems for the City of Tampa.

Effective Light Penetration (Secchi)

Water clarity throughout the Hillsborough River has improved from 1982-83 to present as indicated by increasing annual average Secchi values (Figure 10). Station 105, at Rowlett Park, has consistently had the best Secchi values. As a consequence of the heavy rainfall that occurred in 1979, all stations had reduced annual average Secchi values.

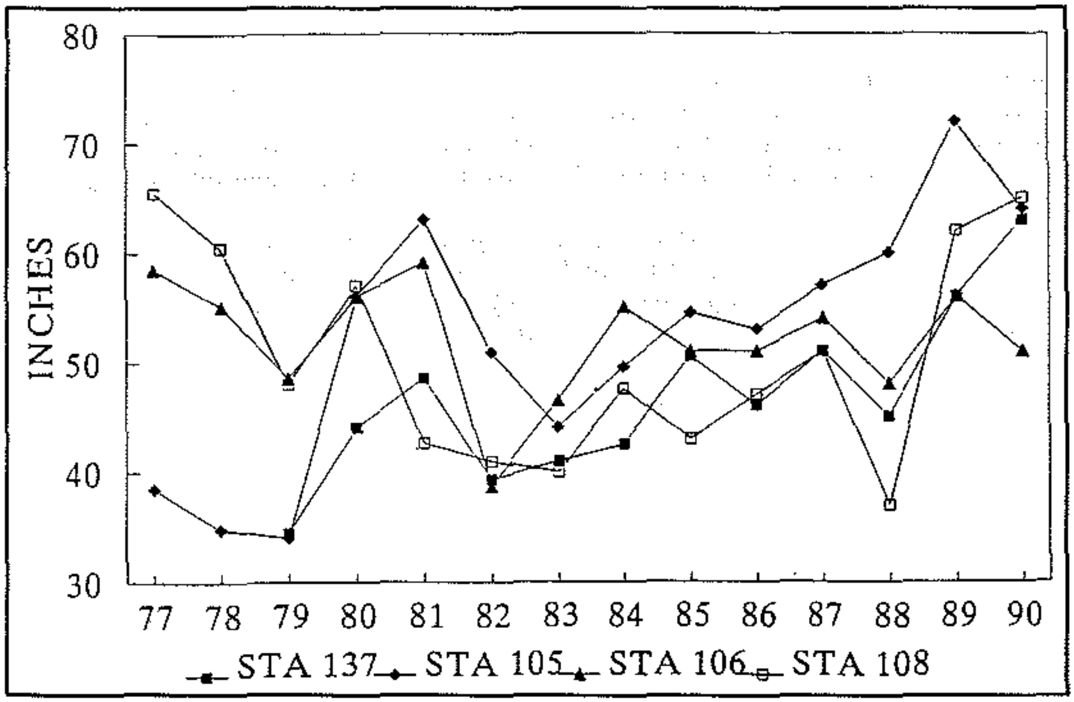

Figure 10. Hillsborough River: Secchi, 1977-1990 annual averages.

Total Coliform

For the period of record, all stations have shown a reduction in total coliform (Figure 11). Since 1980, the Hillsborough River at Fowler Avenue has had annual averages within the safe swimming standards. All stations had low annual averages for total coliform in 1990, most probably the consequence of the low rainfall.

The annual average at Columbus Avenue in 1979 was greater than 230,000 colonies per 100 ml of water. High values in 1981 are attributable to a failed sewage collection lift station which resulted in a large discharge of raw sewage to the Hillsborough River.

In the mid-1970s, a swimming pool was built at Hillsborough River State Park and the swimming area in the river was closed due to the high coliform values measured in the river. The total coliform concentrations at Station 108 have declined and annual averages are often within the state standards for swimming. However, individual total coliform samples, especially those during the summer months, are usually 4-5 times greater than the swimming standard.

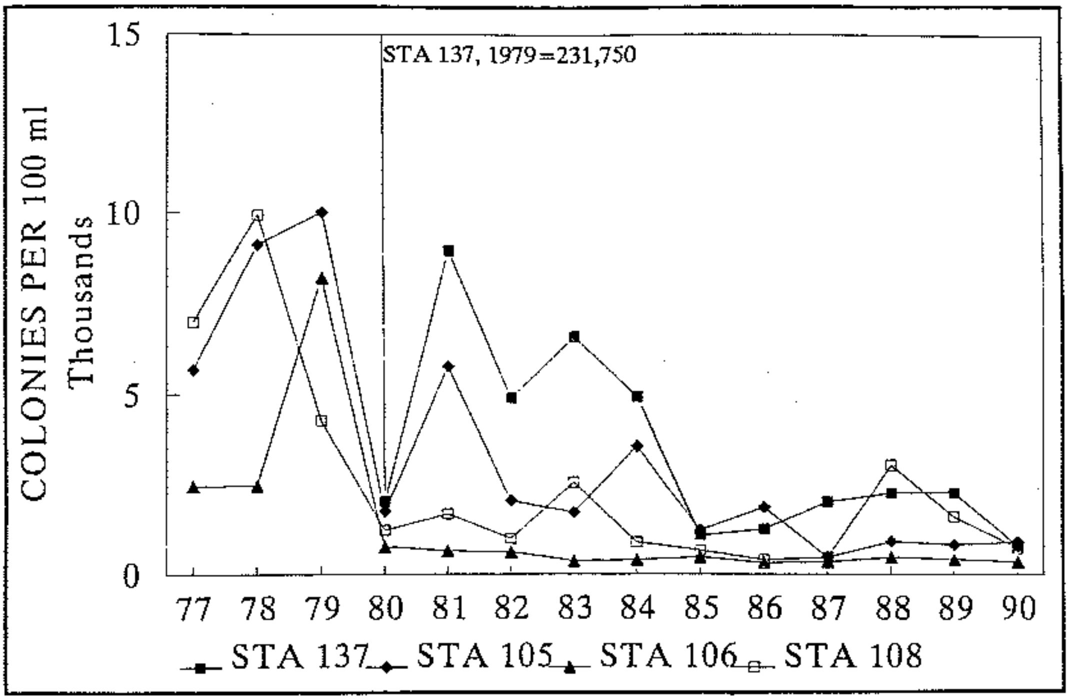

Figure 11. Hillsborough River: total coliform, 1977-1990 annual averages.

Total Nitrogen

Stations 137, 105,and 106, exhibit very similar annual averages values for total nitrogen (Figure 12). These values are typical of most Florida streams. However, the annual averages for station 108, near the Hillsborough River State Park, are appreciably higher; these values are higher than 80% of Florida streams. The annual averages for this station exhibit a remarkable sawtooth pattern—up one year, down the next year—which corresponds closely with the pattern of annual averages for BOD at the same location.

Lake Thonotosassa

The largest lake in Hillsborough County, Lake Thonotosassa has a surface area of 819 acres. It is one of the few large lakes in the County with public access; accordingly it receives a great deal of use, especially for fishing and water skiing. Lake Thonotosassa has been designated as a Surface Water Improvement and Management (SWIM) priority water body. Plans are in place to implement improvement strategies and projects.

Almost all of Lake Thonotosassa water enters by way of Baker Creek, which provides drainage from the south (North Brandon, Seffner, Mango) and receives Pemberton Creek which drains the area to the east of the lake (Plant City, Knights). There are two major point sources of pollution—effluent from Plant City STP and Treasure Isle, Inc. (Florida Snoman), a seafood processing and packing facility. Non-point source pollution includes agricultural runoff from poultry and dairy farms as well as pastures and orange groves.

Lake Thonotosassa is eutrophic (Cowell et al. 1975, Carlson 1977, Dawes et al. 1987, Hand et al. 1988) and is notorious for the massive fish kill that occurred in 1969. The lake still suffers periodic fish kills as a result of a more or less permanent blue-green algae bloom.

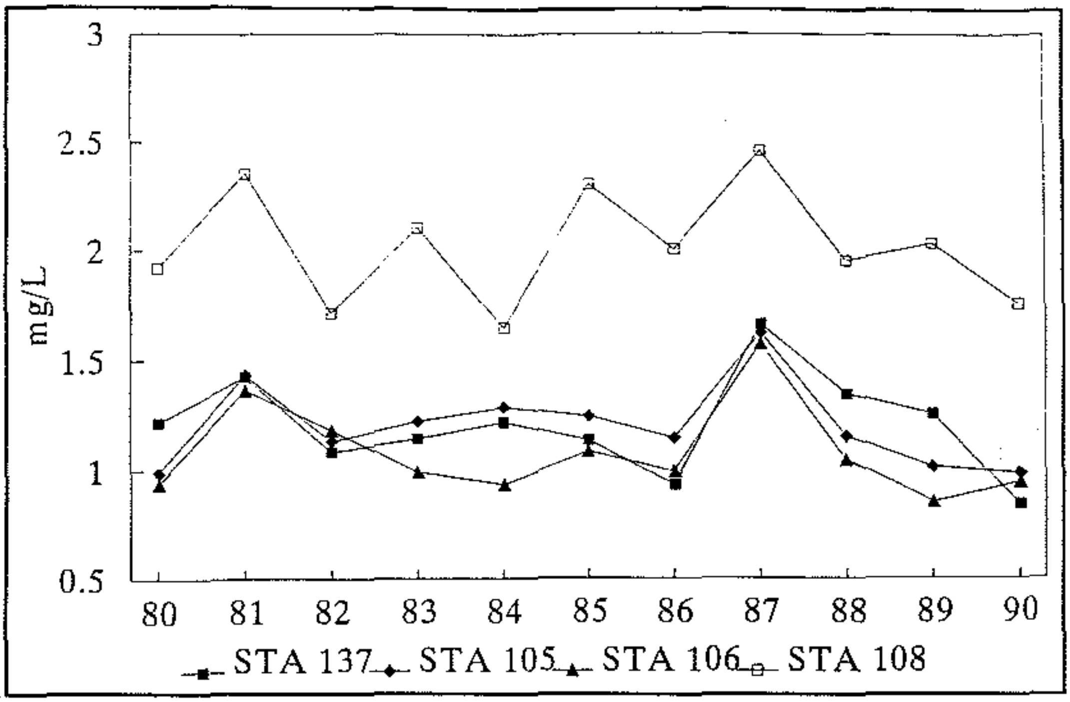

Figure 12. Hillsborough River: total nitrogen, 1980-1990 annual averages.

Nutrients

Nitrogen has generally averaged about 2.0 mg/l during the period of record (Figure 13a). The higher annual averages correlate with the activities of the two major point source contributors. Phosphorus has averaged about 0.5 mg/l during most of the record. In recent years the annual average for total phosphorus in the lake has been increasing. Water quality data from Baker Creek, just upstream from the lake, has also shown a definite increase in total phosphorus. These values are in the 80th percentile for all Florida lakes (Friedeman and Hand 1989).

Chlorophyll a

The high level of nutrients in Lake Thonotosassa supports an abundant population of phytoplankton. The annual averages indicate that chlorophyll *a* is increasing in the lake (Figure 13b). Floating blue-green algal masses were often observed during the 1990 sampling activities.

In 1986 the annual average chlorophyll *a* for the center of the Lake was 76.1 µg/l. At the mouth of Flint Creek, just upstream of the control structure, where water is exported from the lake, the 1986 annual average was 90.6 µg/l. Chlorophyll *a* values greater than 67 µg/l represent the 90th percentile for Florida lakes (Friedeman and Hand 1989).

There are a variety of ways to generate a trophic state index; they are based on the ratio or assessment of nitrogen, phosphorus, Secchi and chlorophyll levels (Carlson 1977; Cowell et al. 1975, Dawes et al. 1987, Hand et al. 1988). Regardless of the actual index used, Lake Thonotosassa is identified as eutrophic.

Dissolved Oxygen

Values are exactly as one would expect of a hypereutrophic lake—very high dissolved oxygen (DO) at the surface, and very low dissolved oxygen at the bottom (Figure 13c). Surface oxygen values represent a supersaturated condition and annual averages have consistently been greater than 10 mg/l, with individual readings as high

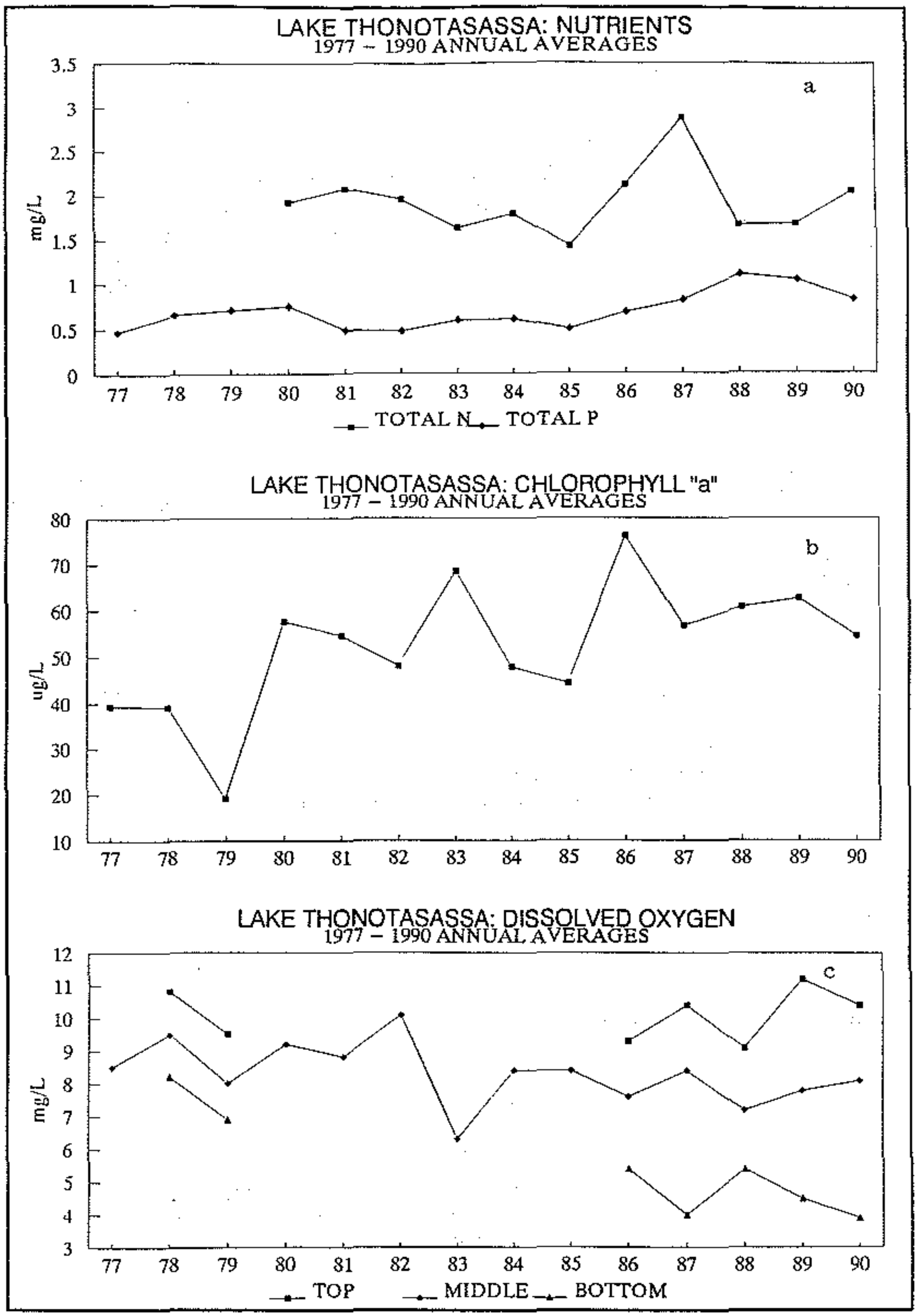

Figure 13. Lake Thonotosassa: a) nutrients; b) chlorophyll a; c) dissolved oxygen, 1977-1990 annual averages.

as 14 mg/l. During the summer months dissolved oxygen is usually less than 1.0 mg/l at the lower depths, usually 10.5′ to 11.0′ below the surface (2.0′ to 2.5′ above bottom); an anoxic zone exists for much of the summer. The sediments in the central part of the lake are made up of a dark, highly organic muck, 2′ to 3′ thick. This layer undoubtedly exerts a sizable oxygen demand.

In recent years, fish kills in the lake have occurred primarily in the juvenile shad population, hence the ratio of biomass to individuals is relatively low. These fish are plankton feeders and form large schools; they are especially sensitive to low dissolved oxygen. The high respiration rate of the blue-green algae population, coupled with a low rate of photosynthesis that can be caused by several days of overcast skies with low light, is usually sufficient to depress oxygen levels and cause fish kills.

Palm River

The Palm River was one of the four natural rivers in Hillsborough County. In the 1960s, a grand scheme for flood control—the consequence of Hurricane Donna—was begun. It included a massive channelization of the Palm River and Six-Mile Creek; the system now bears little resemblance to a small coastal river. Less than a half mile north of Highway 60, a flow control structure/salinity barrier has been constructed. The aquatic system upstream of this structure is now called the Tampa Bypass Canal. The Tampa Bypass Canal continues northerly and intersects with the Hillsborough River near the point where Interstate 75 crosses the river. Here, another control structure has been built to divert water from the Hillsborough River when deemed necessary. Designed and contracted by the Army Corp of Engineers, it was turned over to the Southwest Florida Water Management District to be maintained and operated; the system has been seldom used.

Currently, we monitor at two stations in the brackish water and at two stations upstream of the control structure in the Tampa Bypass Canal. The data for selected parameters at station 110 is presented. Station 110 is located in the Palm River at Highway 60, just downstream of the flow control structure. Water depth is nominally 15′ depending on tidal conditions; little net flushing occurs.

Chlorophyll a

The annual averages for chlorophyll *a* are relatively high, typically about 30 µg/l, as indicated in Figure 14. In 1990, the annual average was 33.2 µg/l.

Since 1986, annual averages of chlorophyll *a* have fluctuated widely, reflecting an extremely dynamic phytoplankton community. In 1986, the annual average was 55.4 µg/l; in 1988 the annual average was 48.6 µg/l. In these years, significant populations of *Schizothrix calcicola* were identified.

In 1989, an apparent "crash" of the phytoplankton population occurred, as evidenced by an annual average for chlorophyll *a* of 5.7 µg/l. The most identified planktonic species was *Euglena elasticans*.

Effective Light Penetration (Secchi)

Annual averages for Secchi indicate a trend toward improving water clarity (Figure 14). In the late 1970s, the annual averages for the Secchi depth at this station in Palm River was about 24"; the 1990 value was 44.0".

Dissolved Oxygen

Dissolved oxygen levels are generally disparate vertically in the water column, as is often the case in poorly flushed systems with large or dynamic phytoplankton populations (Steidinger 1985). During the period of record, dissolved oxygen at mid-depth in the Palm River has failed to meet state standards for Class III waters (Figure 15).

Surface oxygen is highly variable. Typically, measurements are made in mid-afternoon at this station. Individual DO readings often exceed 10 mg/l.

Almost invariably, an anoxic condition exists in the lower part of the water column. As indicated by the graph, the mid-depth also shows low dissolved oxygen. It is common to measure bottom DO as less than 1.0 mg/l.

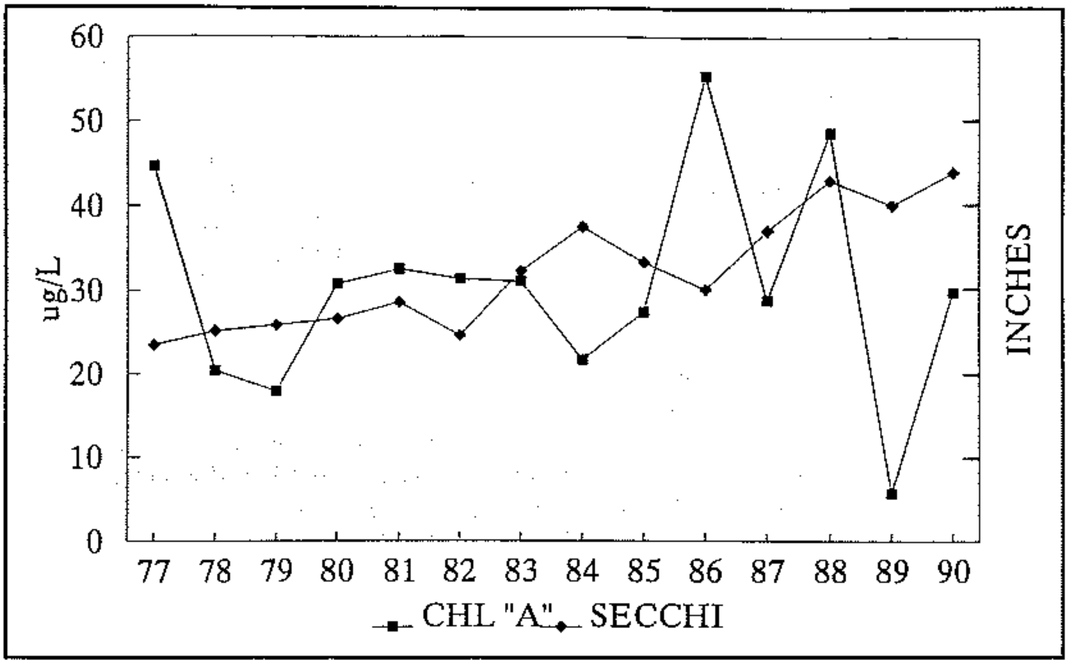

Figure 14. Palm River: chlorophyll a and Secchi, 1977-1990 annual averages.

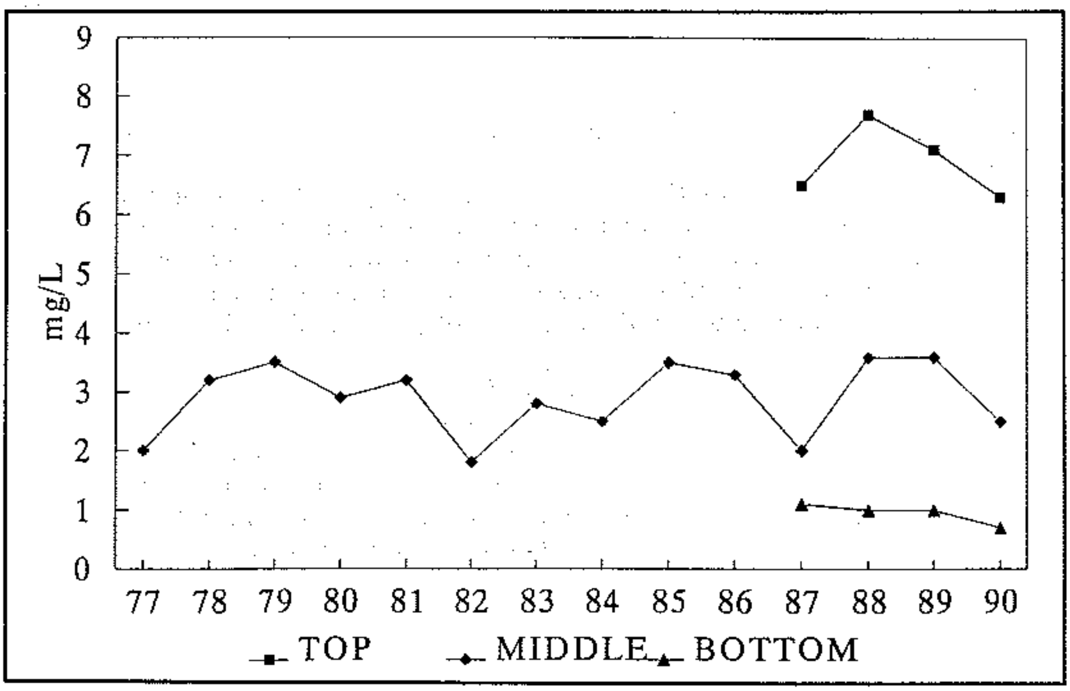

Figure 15. Palm River: dissolved oxygen, 1977-1990 annual averages.

Delaney Creek

Delaney Creek has been the "red-headed step-child" of Tampa Bay's tributaries. In its lower reaches, the creek continues to receive permitted industrial effluents and industrial stormwater runoff. The mouth of Delaney Creek receives a hot water discharge from TECO's Gannon facility. In addition, phosphate fertilizer loading terminals are located at and near the mouth of Delaney Creek. These facilities have been identified as a source of intense nutrient loading to Tampa Bay. Historically, a secondary lead smelting facility was located at Highway 41, adjacent to Delaney Creek. Operation of this facility impacted the creek with battery acid wastes and metals—lead, cadmium, and arsenic.

Slightly upstream from Highway 41, Delaney Creek continues to be the receiving water for the permitted industrial discharge from Nitram, Inc., a nitrogen fertilizer manufacturer. Over the years, the permitted discharge from this source has been reduced by two orders of magnitude. However, Nitram, Inc. continues to be permitted to discharge total nitrogen at a concentration of 7.0 mg/l and a rate of 50 lbs/day as monthly averages.

In the upper reaches, the creek has been channelized for drainage and flood control. Historically, the land has been used for rangeland and dairy farms. In addition, Black Gold, a commercial operation which stockpiled and composted cow manure for packaging and sale as fertilizer, was located adjacent to the creek. Poor management procedures and heavy rain events often resulted in this material being washed into the creek. This facility is no longer in operation.

Currently, the upper reaches of the Creek are under intense development; land use will be residential and for a regional shopping mall. In fact, the creek has again been rerouted and will be incorporated into the stormwater management system of the mall.

Nitrogen

In 1980, EPC began using a Technicon Autoanalyzer for nutrient analysis. Prior to 1980, analysis for nitrogen was done by wet chemistry methods; these methods allow for a large degree of analytical error and quality assurance is poor. Nitrogen data prior to 1980 are of dubious accuracy and are probably low by as much as one order of magnitude.

The 1980 value, which quality assurance data indicate are quite accurate, was 113.0 mg/l (Figure 16a). The 1990 annual average was 2.3 mg/l. This dramatic change is primarily attributed to improved pollution control practices at Nitram, Inc. The reduction in concentration also reflects a large reduction in loading rate. However, to meet the concentration limits of their current DER industrial permit, Nitram, Inc. dilutes its industrial effluent with freshwater. The elevated annual average in 1987 is attributed to a single event; a storage tank holding ammonium nitrate ruptured and an undetermined amount of product entered Delaney Creek.

Turbidity

The annual average for turbidity showed a sharp increase in 1983, up to 34 NTU; while values have declined since then, they remain elevated (Figure 16b). The 1990 annual average was 22 NTU. Historically, elevated turbidity was attributed to runoff from Black Cow and the dairy operations. More recently, turbidity has occurred as a consequence of land development, including the building of I-75.

Total Coliform

During the period of record, high coliform levels, both total and fecal, have been recorded in Delaney Creek. The 1976 annual average for total coliform was 299,000 colonies per 100 ml; the 1990 annual average for total coliform was 5,570 colonies per 100 ml (Figure 16c). While greatly reduced from earlier years, the more recent annual averages still represent high coliform pollution. The creek still drains a dairy pasture and is regularly visited by the livestock.

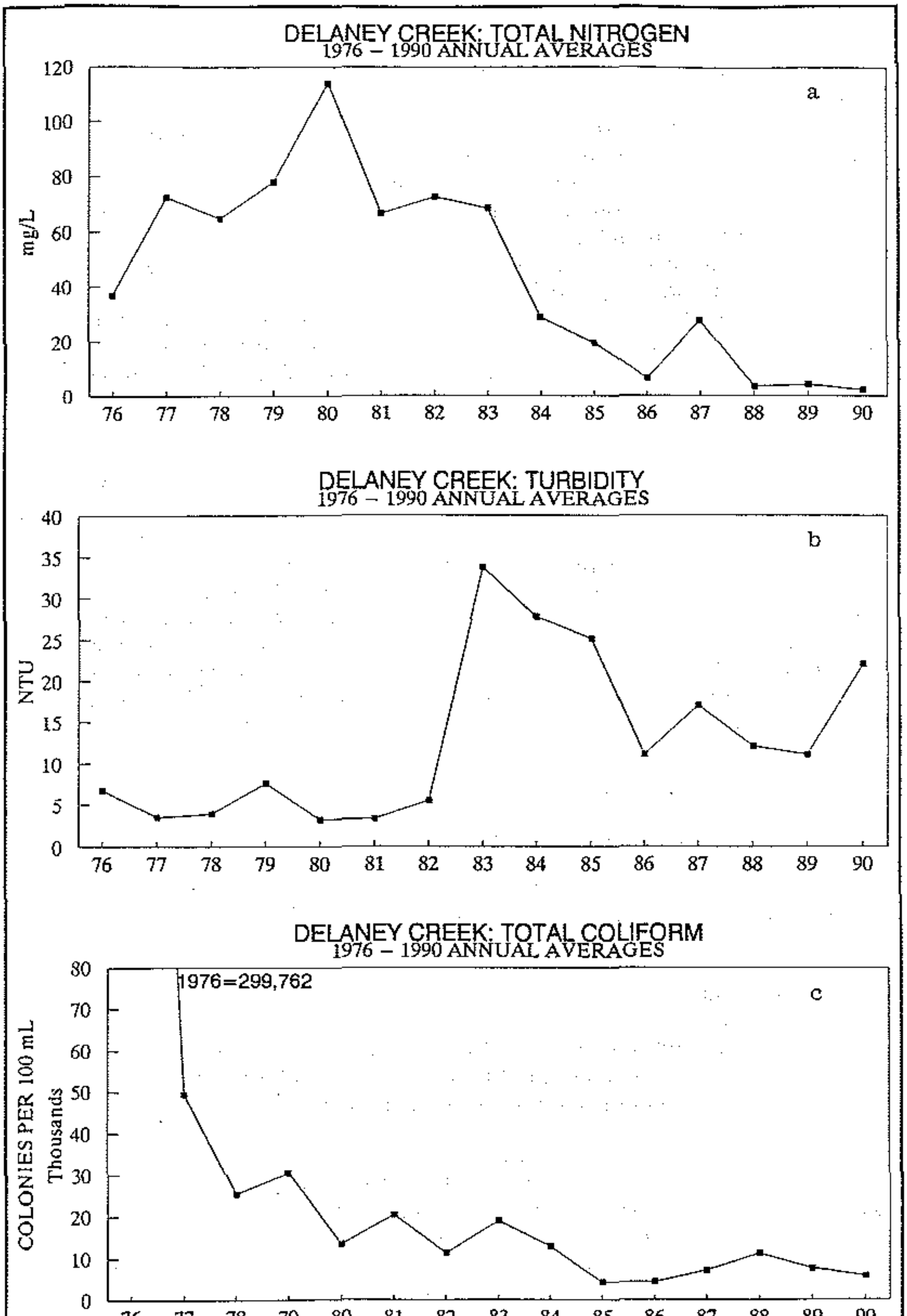

Figure 16. Delaney Creek: a) total nitrogen; b) turbidity; c) total coliform, 1976-1990 annual averages.

Alafia River

The headwaters of the Alafia River have suffered impacts from the phosphate industry since the early 1900s. The Alafia River has long been regarded as the most polluted of the major tributaries to Tampa Bay and though this distinction is probably true, it is more "stinging" than the river deserves.

The Alafia drains approximately 430 square miles in Hillsborough and Polk Counties. In eastern Hillsborough County, the Alafia River splits into two streams of relatively equal size, the North Prong and the South Prong. In the drainage basin of the South Prong, only mining and beneficiation occurs; in the basin of the North Prong, chemical/fertilizer manufacturing and processing occur. The Alafia has several smaller branches throughout its course, including Turkey Creek which has had poor water quality through the period of record (Boler 1990).

Data for the following stations on the Alafia River are presented in this paper: station 74 at Highway 41; station 114 at Bell Shoals Road; station 115 in the North Prong; and station 116 in the South Prong just upstream of their confluence. In addition to the stations listed here, EPC has a station on Turkey Creek at Highway 60 and a station well upstream on the South Prong, just inside the Hillsborough County line.

Phosphorus

Throughout the period of record, the North Prong has had appreciably more total phosphorus than the South Prong, in the range of five to six times greater (Figure 17a). In both 1988 and 1989, the annual average for total phosphorus in the North Prong was greater than 5 mg/l. The elevated values for total phosphorus measured at Bell Shoals station mirrors the influence of the North Prong's contribution to the system. At Highway 41, the concentrations for total phosphorus are approximately the same as those measured in the South Prong. If the concentration of total phosphorus in the North Prong could be reduced to a level similar to the South Prong, the net loading of total phosphorus to Hillsborough Bay would be reduced by more than 0.5 million pounds per year.

Biochemical Oxygen Demand

The freshwater stations have annual average BOD of 1.0 to 1.5 mg/l (Figure 17b). These values are typical of Florida streams. BOD has apparently declined in the mid-reaches of the river through late 1970s. Although the lower Alafia River has shown a slight increase in BOD since 1980, the annual average BOD has been about 3.0 mg/l at Highway 41. This value is typical for Florida estuarine water.

Total Coliform

Beginning about 1980 and continuing to present, a large decline in total coliform has been observed (Figure 17c). Annual averages for all stations range from 1000 to 1500 colonies per 100 ml. Prior to 1980, annual averages for total coliform were generally about 5000 colonies per 100 ml. In 1978 and 1979, the annual averages exceeded 10,000 colonies per 100 ml at some stations.

Little Manatee River

The Little Manatee River is the smallest of the four major tributaries to Tampa Bay and the least impacted. There are two small residential communities in the drainage basin but land use is primarily agricultural. The Department of Environmental Regulation has classified the Little Manatee River as an Outstanding Florida Water (OFW) from Highway 674 downstream to Tampa Bay. This designation affords the highest environmental protection to the river and prohibits activities in the drainage basin that would degrade water quality.

EPC'S Surface Water Quality Monitoring program has four stations in the Little Manatee River. The stations are #112 at Highway 41, #113 at Highway 301, #140 at

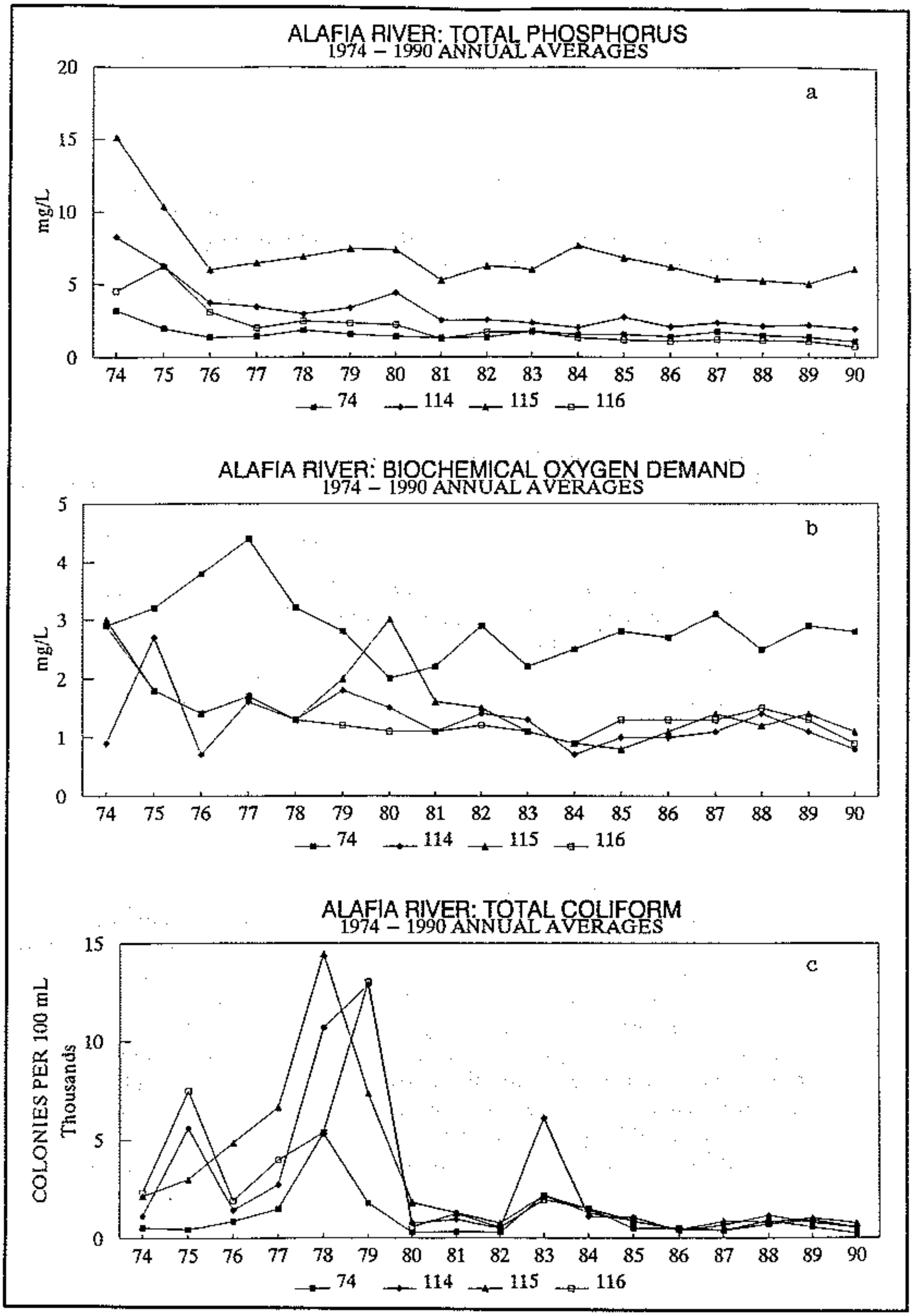

Figure 17. Alafia River: a) total phosphorus; b) biochemical oxygen demand; c) total coliform, 1974-1990 annual averages.

State Road 579, and #129 at Highway 674. No data are presented here; this tributary is discussed in detail elsewhere in this volume (Flannery et al., Peebles et al., Vargo et al.).

CONCLUSIONS

The data for water clarity parameters in Tampa Bay indicate a general north to south trend toward decreasing color, decreasing turbidity and increasing light penetration. The combined effect of these parameters indicate a general north to south trend toward increased water clarity and more favorable light climate. Over the entire period of record, water clarity has improved; however, in the past three years, the data indicates a moderate decline in water clarity. It is unclear if these data represent the normal variability of water clarity or if they represent the beginning of a trend of declining water clarity. Although the range of data for the tributaries is more variable, water clarity has improved in the tributaries.

During the 1970s, the high bacterial contamination that existed in Tampa Bay was largely attributed to inadequate or poorly operated sewage treatment plants discharging (point source pollution) into the area's coastal creeks. When these sewage treatment plants were taken off line or upgraded to AWT quality, a noticeable improvement in water quality, especially with respect to bacterial contamination, was observed. The reduced coliform bacteria population measured in the bay appears to have become established as the ambient condition.

The tributaries have shown a large reduction in bacteria during the period of record, but for the most part, the bacterial water quality has not changed much in the past several years. The tributaries are primarily affected by stormwater runoff resulting from rainfall (nonpoint source pollution), which is very difficult to predict or control, resulting in bacterial loading as well as other types of pollution.

Dissolved oxygen in many of the tributaries continues to fail to meet state standards. This is especially true at the lower levels of the water column in systems that are nutrient enriched or receive limited flushing.

During the period of record, chlorophyll *a* concentrations have declined and this has resulted in observable improvement in water quality. The greatest reduction in chlorophyll *a* occurred in Hillsborough Bay subsequent to the City of Tampa upgrading the Hookers Point sewage treatment plant to AWT standards.

The water quality in the tributaries remains a function of land use and the effectiveness of systems for pollution control and stormwater management. During the period of record of the Surface Water Quality Monitoring program, measurements confirm improved water quality in many of the major surface water systems including Tampa Bay. During the same period, regulatory efforts have been most focused primarily at point sources of pollution. Ambient surface water quality can be improved by upgrading treatment or eliminating point sources of pollution. Efforts to abate pollution caused by stormwater have been initiated, but remain limited in scope and application. With greater implementation and sophistication of stormwater management, additional improvement in water quality will probably be observed.

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STABLE CARBON AND OXYGEN ISOTOPE VARIATIONS IN WATERS OF THE TAMPA BAY ESTUARY

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ABSTRACT

The relationships between salinity and the $^{18}O/^{16}O$ (δ ^{18}O in ppt versus SMOW) in the water and the $^{13}C/^{12}C$ (δ ^{13}C in ppt versus PDB) in the dissolved inorganic carbon are being studied. For surface water δ ^{18}O is linearly related to salinity. At 0 ppt salinity the extrapolated δ ^{18}O is -2.2, reflecting the composition of precipitation in the Tampa Bay area. At high salinities of about 35 ppt, δ is about +1.6 ppt, reflecting the composition of open Gulf of Mexico surface waters. δ ^{13}C and salinity also show a linear relationship. At 0 ppt salinity, the extrapolated δ ^{13}C value is about -10 ppt which is somewhat higher than would be expected for dissolved inorganic carbon (DIC) resulting from the weathering of limestone (δ~0) with organic derived CO_2 [δ~-26]. This may be explained by isotopic exchange with atmospheric CO_2. At salinities approaching 35 ppt, δ ^{13}C values are about -2 ppt, again reflecting that of open Gulf waters and/or isotopic equilibration with atmospheric CO_2. These parameters are being used to get estimates for the exchange of water types in Tampa Bay and a better understanding of the recharge of deep aquifers in the Tampa Bay region.

INTRODUCTION

Over the past forty years the stable isotope compositions of carbon and oxygen in naturally occurring materials have been used to gain a better understanding of natural processes such as photosynthesis, petroleum formation, and the hydrological cycle. Relatively few stable isotope studies have been conducted in Florida and especially in the Tampa Bay area. This preliminary report on the δ ^{13}C of dissolved inorganic carbon (DIC) and δ ^{18}O of water as a function of salinity in the Tampa Bay estuary is intended to be the basis of more detailed subsequent studies designed to better understand the various sources and anthropogenic effects of carbon on Tampa Bay waters and information on the pathway of water during transport from the surface to underground aquifers. (δ ^{13}C and δ ^{18}O values in this paper are given in terms of the per mil deviations from the conventional PDB and SMOW standards, respectively.)

A simple representation of the processes which control carbon isotope compositions is given in Figure 1. It is based on the classical weathering reaction,

$$CaCO_3 + CO_2 + H_2O \dashrightarrow 2HCO_3^- + Ca^{++}.$$

$CaCO_3$ with a δ ^{13}C $\approx$0 reacts with organic derived CO_2 with δ~-26 (average composition of C_3 land plants) to produce HCO_3^- with a δ of ~-13 (one carbon from each reactant). The CO_2 may exchange with atmospheric CO_2 with a δ~-8 and shift the bicarbonate towards its equilibrium value of zero or it may exchange with the organic derived CO_2 and shift toward -18, the equilibrium value when gaseous CO_2 is -26. Generally the shift is towards the former rather than the latter. It should be noted that in this simple model δ ^{13}C of HCO_3^- may have a range of 18 ppt.

The δ ^{18}O composition of fresh water is controlled by the fractionation of oxygen isotopes during evaporation and condensation. This is nicely explained by the Raleigh distillation model given in Figure 2. At 25°C the δ ^{18}O of water vapor is about -9 ppt. The first condensate in equilibrium with the vapor has a δ = 0; if this condensate is removed before re-evaporation and/or isotope exchange can occur, the remaining vapor becomes depleted in ^{18}O. Subsequent condensate is also somewhat depleted in ^{18}O. The net result of these processes is that precipitation is increasingly depleted in ^{18}O in going polewards, with arctic and antarctic precipation becoming as light as -40 ppt. Florida precipation is close to the tropical source of water vapor and shows only a slight depletion with a composition of about -3 ppt vs SMOW.

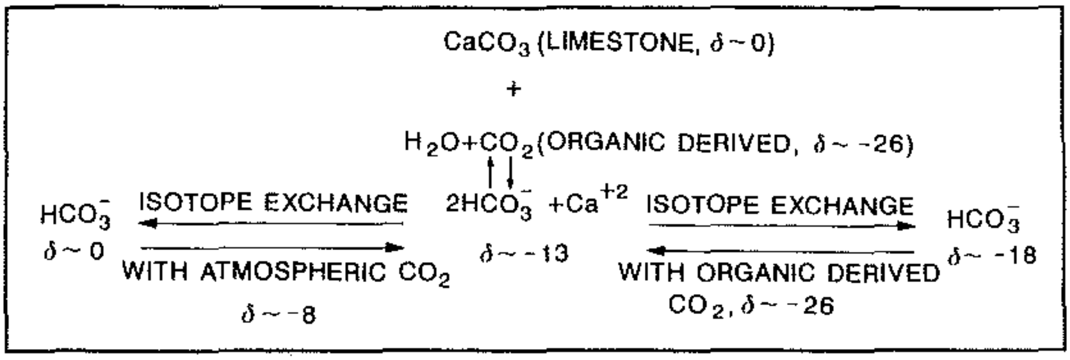

Figure 1. Model to explain variations in $\delta\ ^{13}C$ of dissolved inorganic carbon.

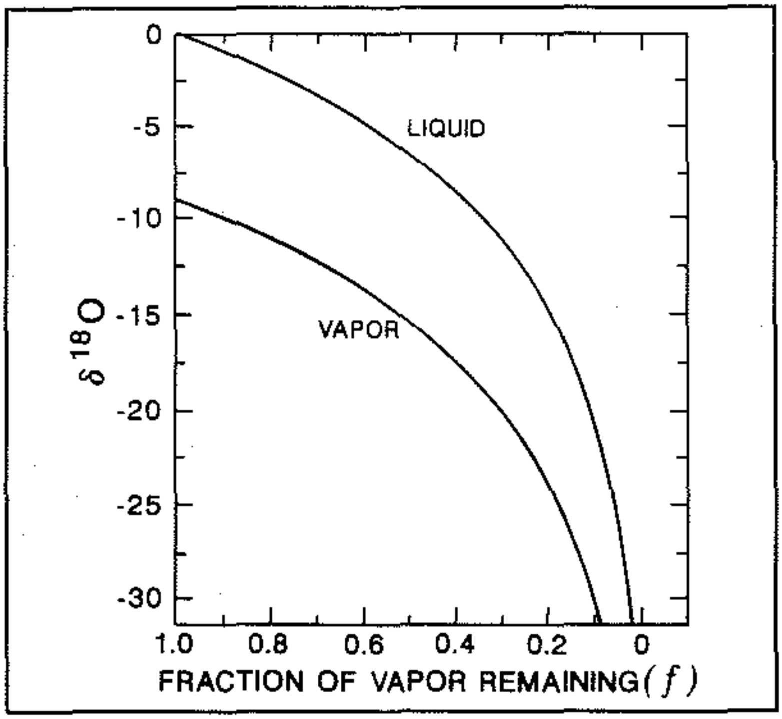

Figure 2. The Raleigh model for fractionation of oxygen isotopes during condensation of gaseous water at 25°C.

METHODS

Sampling Locations, Collection and Storage

Samples were collected in 500 ml glass screw cap jars. The jars were completely filled with the water sample to eliminate the possibility of exchange with atmospheric CO_2 in the air in the jar. Sampling locations are given in Table 1 and Figure 3. All numbered locations were taken from shore on March 19, 1990 and were immediately refrigerated and kept in the dark until their analysis over the next month.

Analytical Procedure

Salinities were determined by titrating water samples with silver nitrate using the modified Grasshoff (1983) method. Endpoints were detected by the change of precipitate color from white to light pink using sodium fluorescein indicator. Briefly, one ml of sample was titrated with a $AgNO_3 \approx [0.05\ M]$ solution which had been standardized against a NaCl solution with a salinity of 35.00 ppt. $\delta\ ^{13}C$ values were

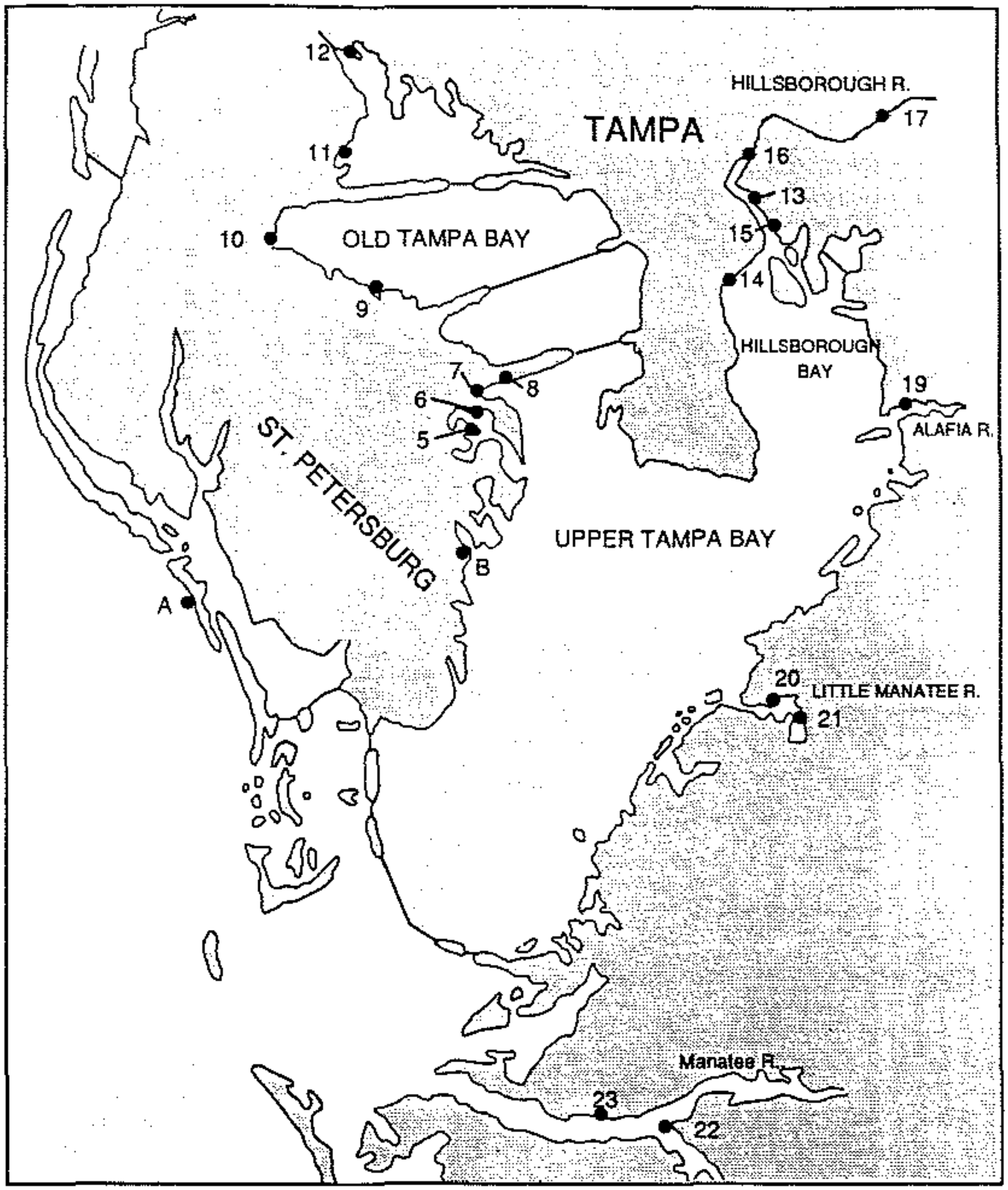

Figure 3. Sampling locations around Tampa Bay.

obtained for dissolved inorganic carbon by reacting 60 ml water samples with about 5 ml 85% H_3PO_4 in a partially evacuated side armed reaction vessel. The evolved CO_2 was collected at liquid N_2 temperature after passing through an isopropanol LN_2 slush bath (T=-80°C) to remove water vapor. $\delta\,^{18}O$ was determined by equilibrating a 25 ml aliquot of cylinder CO_2 with 25 ml of the water sample in 60 ml plastic syringes for one hour on a commercial paint shaker. The molar ratio of gas to water was 1 to 1200. The equilibrated CO_2 was collected and processed as above for carbon and measured relative to a laboratory SMOW standard.

In order to get an estimate of the rate of exchange of atmospheric CO_2 with dissolved inorganic carbon (DIC), the following experiment was set up on the roof of the Marine Science building at the University of South Florida in St. Petersburg, located at about the middle of the western coastline of Tampa Bay; this location should have approximately the same temperatures and wind velocities as the open bay.

11.4 liters of distilled water, poisoned with sodium azide to inhibit biological activity and having a HCO_3^- concentration of 2.33 mM, about that of sea water, was added to a round pan (34 cm X 13 cm) and placed under a platform to stop direct sunlight from hitting the water. The platform was placed about 10 cm above the surface of the water to allow the wind to freely flow across the water. 60 ml of the water were withdrawn periodically and analyzed.

Table 1. Sample locations in the Tampa Bay area.

SAMPLE NO.	DESCRIPTIVE LOCATIONS
5	North St. Petersburg, near Riviera Bay; Turner Creek near 4th St. N/79th Ave.
6	North St. Petersburg, near Riviera Bay; Weedon Park
7	Near Gandy Bridge; Snug Harbor, north of Riviera Bay
8	Near Gandy Bridge, north of Snug Harbor
9	Bayou Canal; near Roosevelt Blvd., St. Pete/Clearwater Airport and 49th Street
10	Allen Creek; near U.S. 19, north of Roosevelt Blvd.
11	Alligator Lake/Shore Boulevard, Safety Harbor
12	Safety Harbor, near Oldsmar/S.R. 580
13	Hillsborough River, near I-75
14	Hillsborough Bay, near Bayshore Boulevard
15	Hillsborough River, close to Crosstown Expressway
16	Hillsborough River, near Buffalo Avenue
17	Hillsborough River, 40th Street/Sligh Avenue
18	Alafia River, Riverview; 5 miles from Tampa Bay
19	Alafia River, close to I-75; one mile from Tampa Bay
20	Little Manatee River, close to U.S. 41; 2.5 miles from Tampa Bay
21	Little Manatee River, near I-75; 6 miles from Tampa Bay
22	Manatee River, 8 miles from Tampa Bay
23	Manatee River, 5.5 miles from Tampa Bay
B-2	Big Bayou, collected on February 6, 1991
B	Big Bayou, collected on December 6, 1990
A	Gulf of Mexico/Treasure Island, collected on December 9, 1990
A-2	Gulf of Mexico/Treasure Island, collected on February 7, 1991

RESULTS AND DISCUSSION

Because a linear relationship was expected between the two isotope parameters and salinity, demonstrating a simple mixing between two end members, each isotope parameter was plotted relative to salinity. Figure 4 shows the data for $\delta\ ^{13}C$ and salinity. Linear regression analysis gives the equation y = -10.41 + 0.240 X (r = 0.812). At salinity = 0, the intercept value for $\delta\ ^{13}C$ is -10.4 ppt. This is heavier than the value that would be obtained by the weathering reaction given above for organic derived CO_2 reacting with marine carbonate. This additional shift may be due either to exchange with atmospheric CO_2 or interaction with carbonate minerals and groundwater. Generally, samples with values falling below the regression line have probably exchanged with organic derived CO_2, those falling above with atmospheric CO_2. Extrapolation of the trend to 35 ppt salinity gives a δ value of about -2 ppt, a value close to that expected for equilibration with atmospheric CO_2.

Figure 5 shows the relationship between $\delta\ ^{18}O$ and salinity. The zero intercept of this linear regression (y = -2.220 + 0.108X, r = 0.917) is -2.20 ppt. For thirteen samples of rainwater collected between November 6, 1990 and February 14, 1991 on the roof of the Marine Science building at USF in St. Petersburg, $\delta\ ^{18}O$ values ranged from -0.38 to -5.50 with a mean value of -2.11, which almost exactly matches the extrapolated value given above. The value calculated from the linear regression equation for a salinity of 35 ppt is +1.58. This value is about 1 ppt higher than expected and is presumably related to the loss of oxygen-16 rich water vapor from surface water during evaporation.

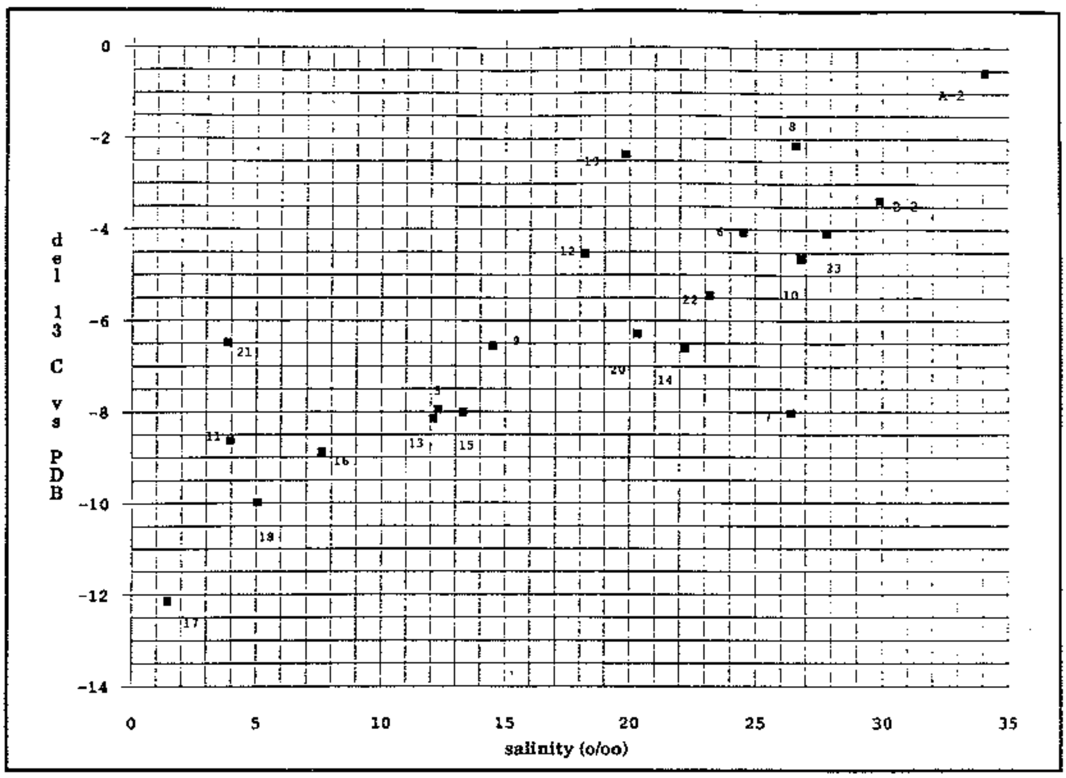

Figure 4. $\delta\ ^{13}C_{PDB}$ for dissolved inorganic carbon versus salinity in ppt. Numbers indicate sampling locations on Figure 3 and Table 1.

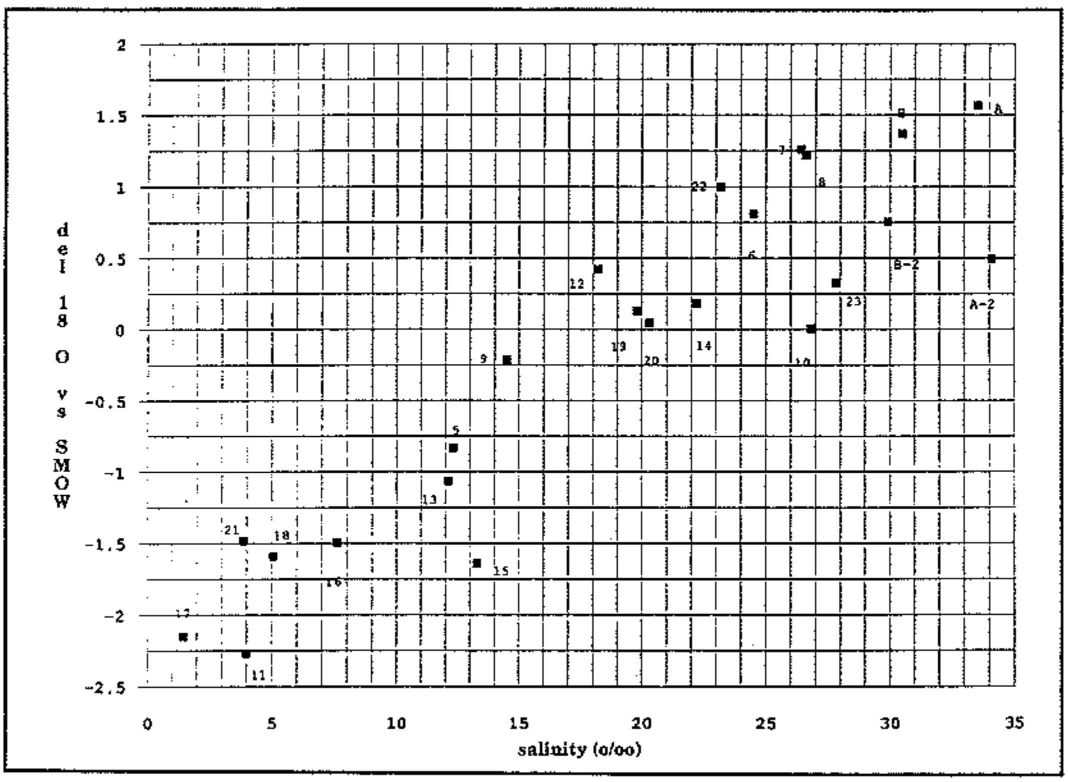

Figure 5. $\delta\ ^{18}O_{SMOW}$ versus salinity in ppt. Numbers indicate sampling locations on Figure 3 and Table 1.

The water supplies of the cities of St. Petersburg, Safety Harbor, Clearwater, Orlando and Tampa are all derived from the Floridan aquifer. $\delta\, ^{18}O$ values are -1.7, -2.0, -2.6, -2.0 and -2.8, respectively, with a mean value of -2.2 which again corresponds to the mean value for rainfall during the year. However, a range of about 5 ppt in the $\delta\, ^{18}O$ of rainfall has already been seen to date. Continued monitoring of the amounts and isotopic composition of rainfall during the coming year should help determine the reasons for these observations. Also needing confirmation is an inverse relationship between the amount and $\delta\, ^{18}O$ of rainfall.

The data given in Figure 6 show a marked change in ^{13}C with time in the direction for isotopic equilibration with atmospheric CO_2. For a freshwater mass with a δ of -13, the data suggest that it will take only a day or two to change to -10, the intercept for the trend shown in Figure 4. Thus, it appears that isotopic exchange is as important as water mass mixing in changing the isotope signature of waters being brought into the bay by runoff.

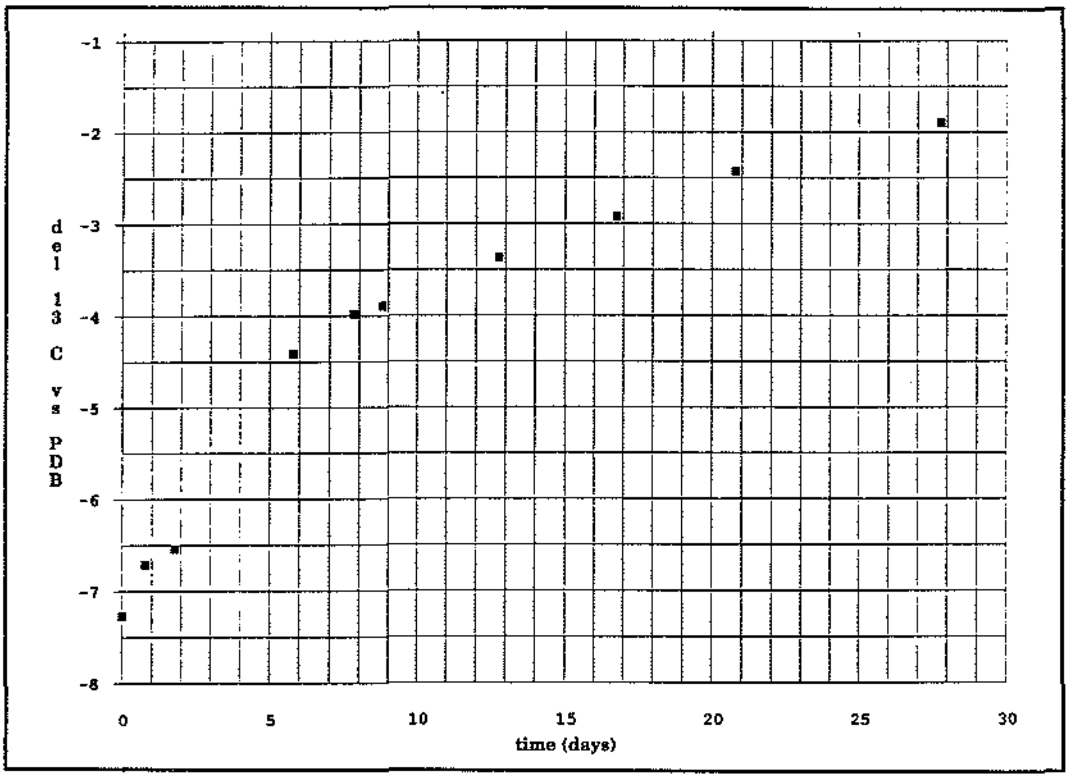

Figure 6. $\delta\, ^{13}C_{PDB}$ versus time in days for exchange experiment.

Each new study generally provides several leads that could be followed subsequently. This one has been no exception. Questions remain about the $\delta\, ^{13}C$ of biogenic CO_2 and its rate of exchange with DIC, the exact source and the $\delta\, ^{13}C$ of the nonbiogenic CO_2, the temporal changes of ^{18}O in rainfall, and the apparent inverse relationship between the amount of rainfall and its $\delta\, ^{18}O$. This study has shown once again that stable isotopes can provide a new understanding and provoke new questions about the biogeochemical environment around us.

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DISCHARGE MEASUREMENT TECHNIQUES FOR NUTRIENT LOAD COMPUTATIONS IN TIDALLY DOMINATED RIVERS

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ABSTRACT

Methods to determine seasonal and annual nonpoint source nutrient loads by measurements at the mouth of the tidally dominated Alafia River are currently being developed by the U.S. Geological Survey in cooperation with the Surface Water Improvement and Management department of the Southwest Florida Water Management District. Methods are being developed to 1) measure flood and ebb tidal discharge continuously, and 2) determine average constituent concentrations during selected flood and ebb tidal events in order to compute both upstream and downstream constituent loads. Tidal discharge measurement techniques (item 1) is the subject of this paper. The need for accurate flow measurements is a requirement for load computations and estimates. Tributary tidal influence prevents the use of standard discharge rating techniques and requires special measuring techniques and instrumentation.

Discharge is defined as the product of cross-sectional area and average water velocity in the cross section. Techniques to determine continuous discharge in the tidal Alafia River include the development of stage-area and index velocity-mean velocity relations and the measurement of an index velocity at a point in the stream using an electromagnetic flow meter. Unit (15-minute) index velocity and stage data, along with respective relations, provide a means for computing continuous discharge for load computations.

The success of the Alafia River experiment is attributed to the reconnaissance efforts that provided information for locating and operating an index velocity point. Index velocity proved to have high correlation with measured mean velocities.

INTRODUCTION

Nutrient enrichment in estuaries and coastal areas generally is accepted as a potential problem that contributes to the dedgradation of water quality in these areas. Excessive nutrients can result in blooms of phytoplankton and macroalgae, which can restrict the growth of submerged plants such as seagrasses through shading effects. About 80% of the seagrasses in Tampa Bay have been lost between about 1940 and 1981 (Lewis et al. 1985). These losses were attributed to progressive eutrophication and reduction in light penetration due to increased concentrations of micro- and macroalgae.

Water quality in Tampa Bay has been monitored for nearly 20 years by the Hillsborough County Environmental Protection Commission (Boler 1988). A water quality index has been formulated by the Environmental Protection Commission to allow comparison of water quality in the bay with previous years. The index is computed from concentrations of dissolved oxygen, chlorophyll *a*, total coliform bacteria, total phosphorus, total organic nitrogen plus ammonia, biochemical oxygen demand, and effective light penetration. The index has shown that water quality in the bay is poorest in Hillsborough Bay, with the lowest index values often found near the mouth of the Alafia River (Boler 1989).

The Tampa Bay Regional Planning Council (1990) indicated that eutrophication in Tampa Bay caused by nutrient overenrichment is a priority issue that needs to be addressed. In response to this need, the Surface Water Improvement and Management (SWIM) department of the Southwest Florida Water Management District is coordinating several studies that will provide information needed to determine the nutrient budget of Tampa Bay. Components of the budget are nutrient imports to the bay from point sources, tributaries, direct runoff from coastal areas, groundwater contributions, direct rainfall, release from the sediments and exports from the bay by way of losses to the Gulf of Mexico, adsorption to the sediments, removal by fisheries, and losses to ground water.

Flow and nutrient concentration data are available at stations on many of the major tributaries to Tampa Bay. These gaging stations, however, are upstream of the tidal part of the rivers. Total flows and nutrient loads to the bay can be extrapolated from data at upstream sites, but this technique is not precise (Richards 1989). In the Tampa Bay basin, the areas surrounding the tidal parts of inflowing rivers often are highly urbanized or industrialized. Additional nutrient loads to this part of the river would be unaccounted for using extrapolation techniques to compute total loads. Accurate load estimates for a tributary require accurate flow data (Richards 1989), and in tidal rivers, this component of load computations is the most difficult to measure. The U.S. Geological Survey, in cooperation with SWIM, is developing techniques that will be used to measure nutrient loads near the mouth of the Alafia River, a tributary to Hillsborough Bay. Once defined, these techniques could be used at other tributaries to measure total nutrient loads. Methods are being developed to 1) measure flood and ebb tidal discharge continuously, and 2) determine average constituent concentration during selected flood and ebb tidal events in order to compute constituent loads. The purpose of this paper is to describe discharge measurement techniques used for the Alafia River at Gibsonton, Florida (Fig. 1), and to give information on methods of developing procedures for continuous discharge computations.

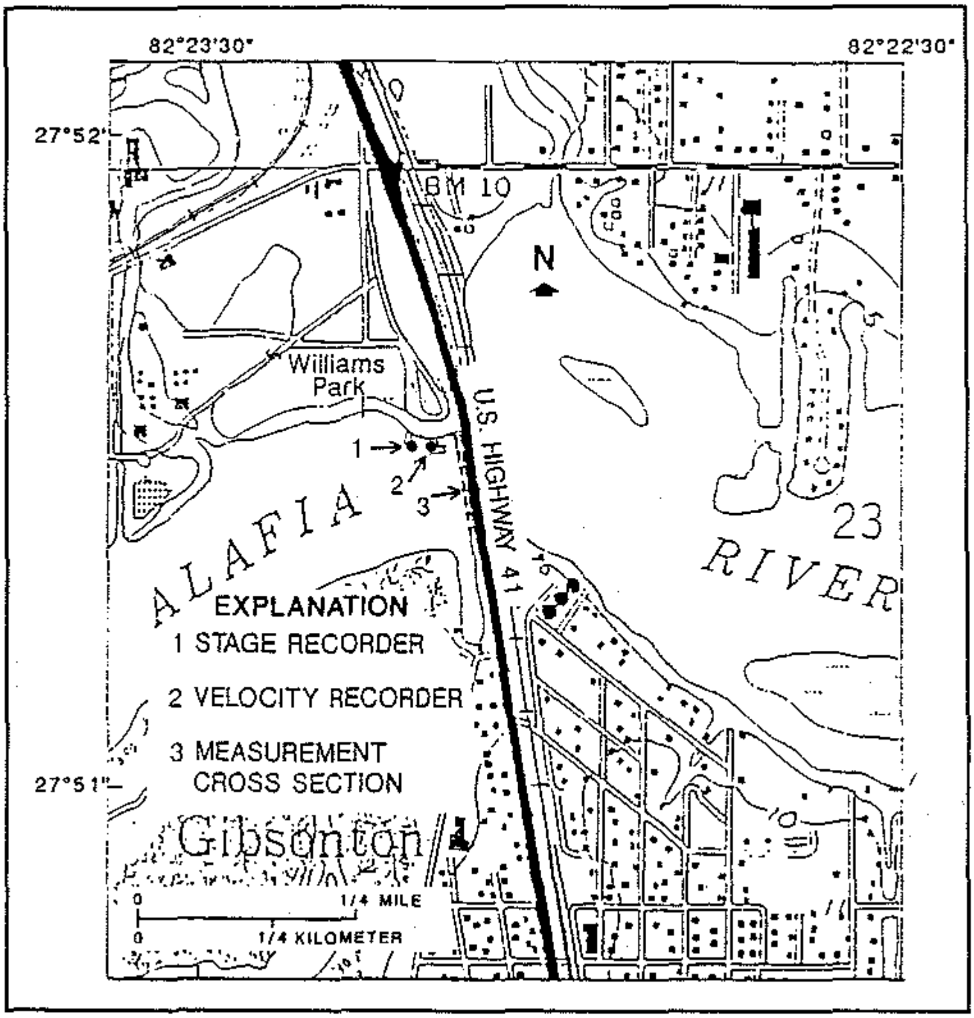

Figure 1. Alafia River study site, location of instruments, and cross section.

DISCHARGE MEASUREMENTS AND RATINGS

Discharge is defined as the product of cross-sectional area and average water velocity in the cross section. The vertical axis Price AA current meter is the standard meter used by the U.S. Geological Survey to measure velocity (Fig. 2). The principle of operation is based on the proportionality between the velocity of the water and the resulting angular velocity of the meter rotor. By placing the meter at a point in a stream and counting the number of revolutions of the rotor during a measured interval of time, the velocity of the water at that point can be determined. To determine water velocity from revolution rate of the meter, it is necessary to apply a rating or equation.

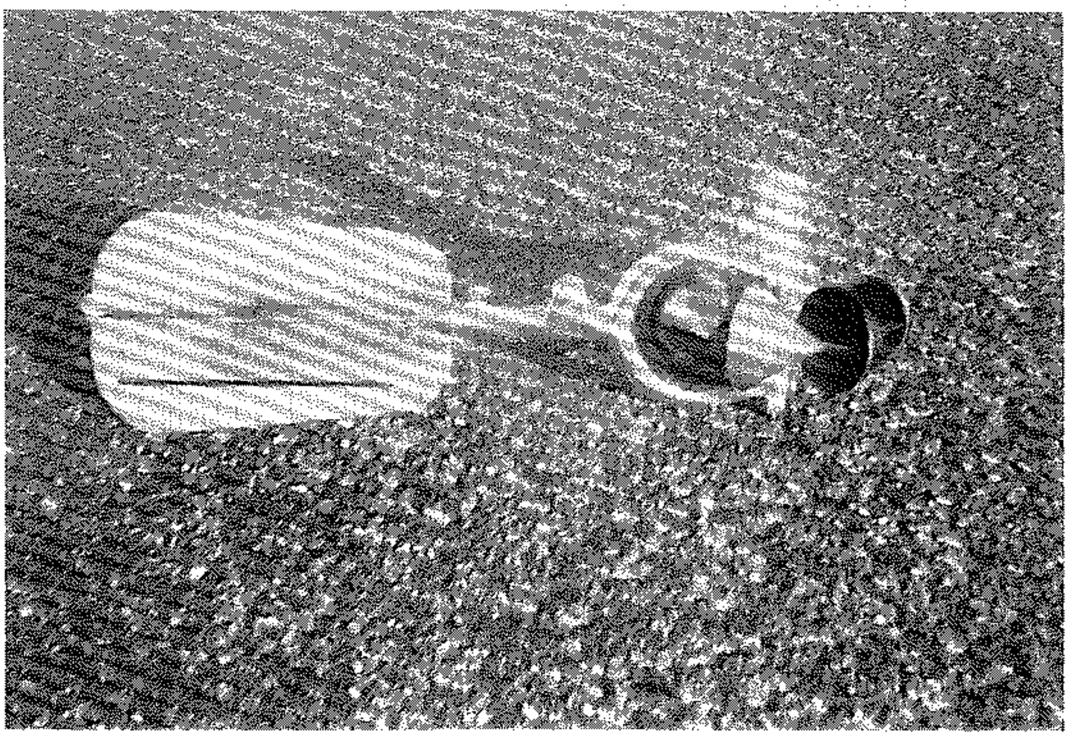

Figure 2. Price current meter.

To measure discharge at a cross section, stream depths, subsection widths, and velocities are measured at 20 to 25 or more points in the cross section. In the event that flow is not normal to the section, horizontal angle coefficients are observed and recorded for width corrections. The discharge is then computed by summing the products of the partial areas of the stream cross section and their respective average velocities. The equation

$$Q=\sum(a\ v)$$

represents the computation where Q is total discharge, a is an individual partial cross-section area, and v is the corresponding mean velocity of the flow normal to the partial area (Buchanan and Somers 1969).

The conversion of a record of stage to record of discharge is made by the use of a stage-discharge relation (rating). The physical element or combination of elements in the stream channel that controls the relation between stage and discharge is known as a control. The control may be simple or compound; natural, such as a sandbar, rock outcrop, or channel constriction; or it may be manmade, such as a weir, flume, or dam. A simple discharge rating (Fig. 3) that relates stage to discharge can be developed for many streams by observing or recording the stage of the pool immediately upstream from the control and periodically measuring the total discharge. Measurements need to be made over the range of stage expected to occur. Measurements are then plotted on rectangular or log-log graph paper to define a rating. The control is the stabilizing factor in the relation between stage and discharge. If control conditions remain stable, the rating will be stable and rating definition is simplified. Figure 4 illustrates the stage-control relation and the effect of a shifting sandbar control that is subject to change with time.

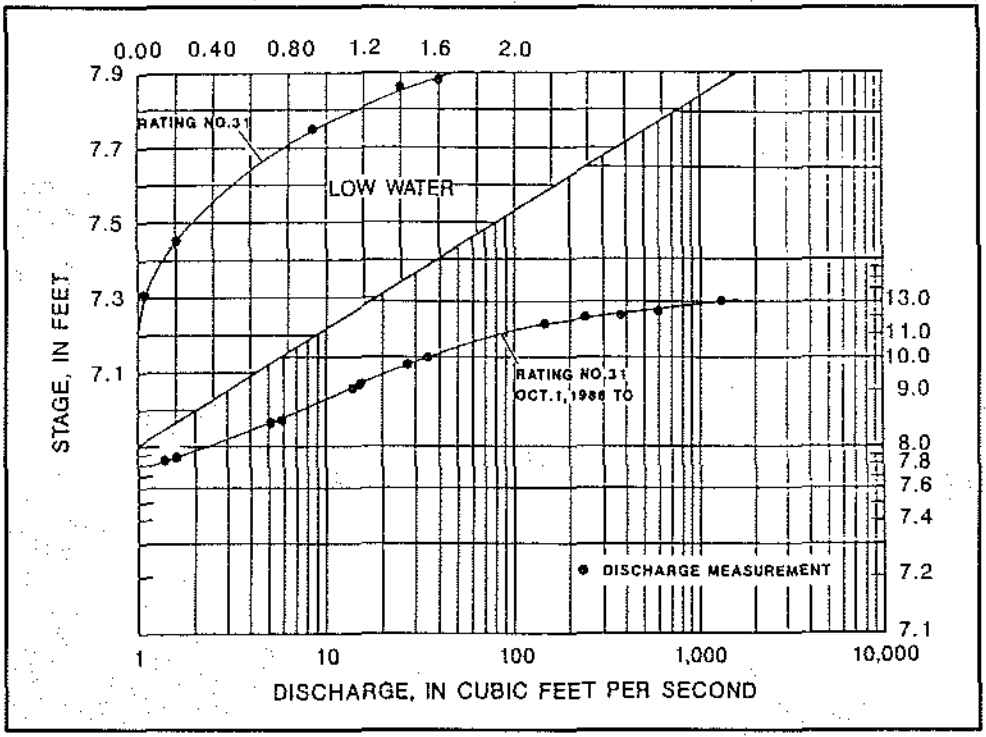

Figure 3. Simple stage-discharge rating.

A shifting control may be caused by scour or filling, lodging of debris, growing or dying vegetation, or backwater from a tributary, as well as other changing conditions. Minor shifting control conditions are adjusted for routinely by defining the shift from the base rating with additional discharge measurements. A new rating may be defined by discharge measurements, or mathematical means may be used for applying temporary shift adjustments.

At any given discharge, the effect on the stage at the gaging station that is attributable to the operative control element(s) is known as backwater. As long as the control elements are unvarying, the backwater for a given discharge is unvarying, and the discharge is a function of the stage only; the slope of the water surface for steady flow at that stage also is unvarying. If some of the control elements are variable for any given discharge, the stage at the station and the slope are also variable.

TIDAL DISCHARGE MEASUREMENTS AND RATINGS

At gaging stations on tide-affected streams, the tide is considered a variable control element. Determination of continuous discharge in tidal rivers, therefore, requires an accurate definition of both stage and velocity as continuous functions of time. Cross-sectional area is a well-defined function of tidal stage that can be determined by fathometric and planimetric methods. With this relation, continuously recorded tidal stage can be transformed into a continuous history of cross-sectional area fluctuations. In many field situations, a similar relation can be established between average water velocity in the cross section and a representative index velocity at some fixed location. With this relation, continuously recorded index velocity can be transformed into a continuous history of cross-sectional average water velocity fluctuations. The accuracy of continuous discharge computed in this way is dependent on the accuracy of recorded field measurements and the accuracy of stage-area and index velocity-average velocity relations.

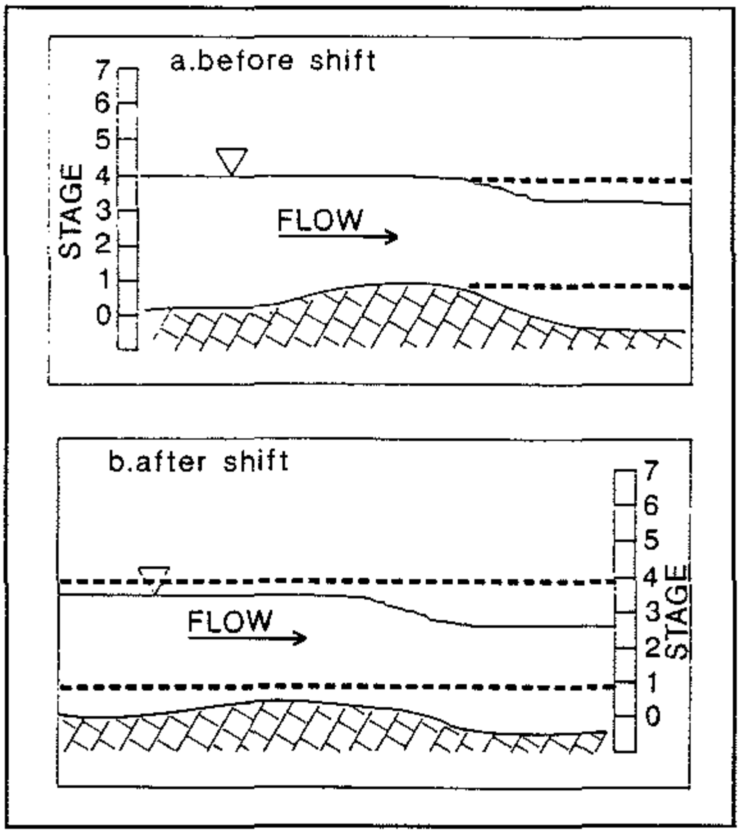

Figure 4. Effect of a shifting sandbar control on river stage.

One of the difficulties in making velocity observations in tidal streams is that the flow can reverse direction during a measurement. During periods of high freshwater runoff, stratification may occur so that near-surface velocities remain outgoing during flood tides while the bottom velocities are incoming. Meters used for tidal measurements need to be capable of indicating direction as well as velocity. The Price meter does not have this capability but can be equipped with an electronic compass for indicating direction. An acoustic or electromagnetic meter with integral compass also may be used.

Because flow is constantly changing in a tidal stream, measurements must be made in minimal time to minimize rate-of-change errors. Normal horizontal and vertical velocity distribution is demonstrated in Figures 5 and 6. Vertical distribution of velocity on a tidal stream may appear similar to the diagrams in Figure 7 at unique times in a tidal cycle.

Reconnaissance on the Alafia River included making visual inspections of likely sites, making preliminary cross-section profiles, and observing vertical velocity distribution to determine a probable location for the initial index-velocity measuring point. Generally, a satisfactory rating can be obtained for tidal streams when an index velocity point in or near the measurement cross section can be found that correlates well with the measured mean velocity. Figure 8 shows the vertical velocity distribution at three subsections in the Alafia River cross-section, and Figure 9 shows a comparison of those three verticals with the recorded index velocity for a 26-hour synoptic water quality sampling period in September 1990.

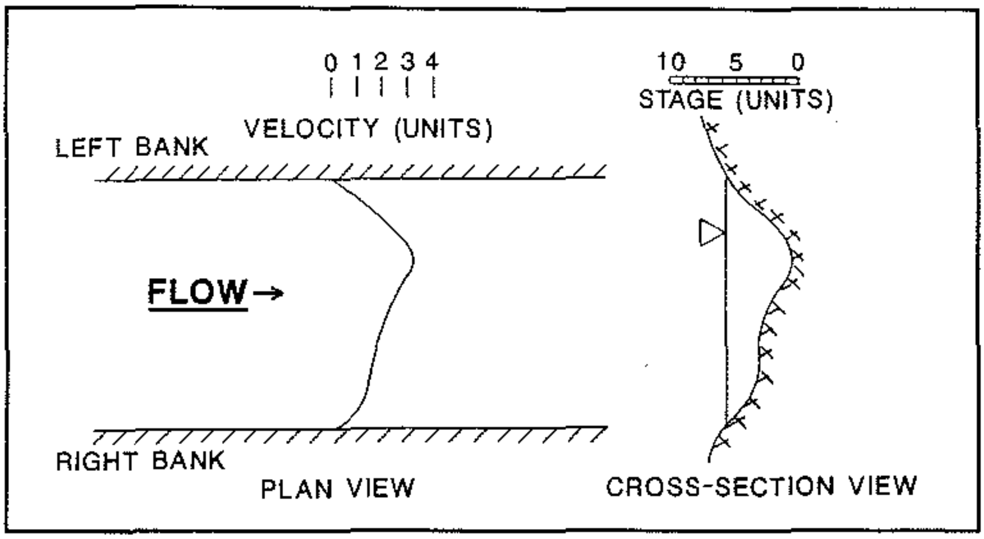

Figure 5. Normal horizontal velocity distribution in a stream.

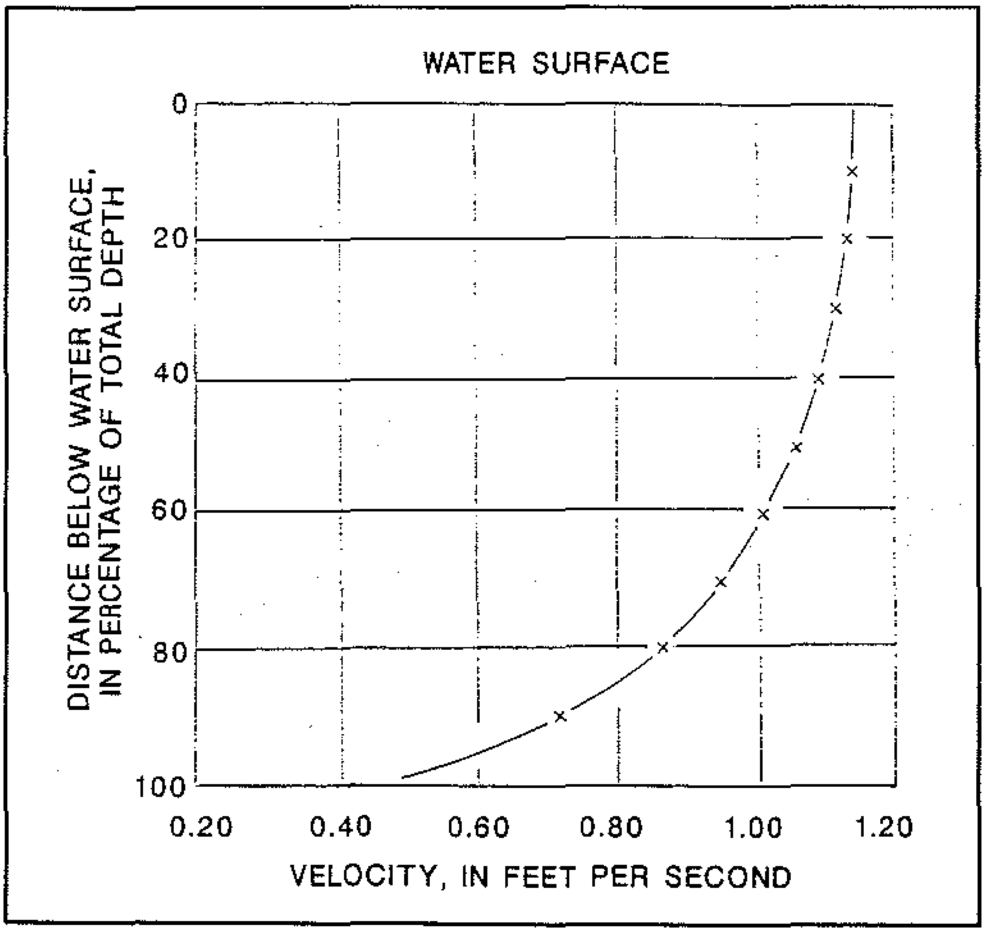

Figure 6. Normal vertical velocity distribution in a stream.

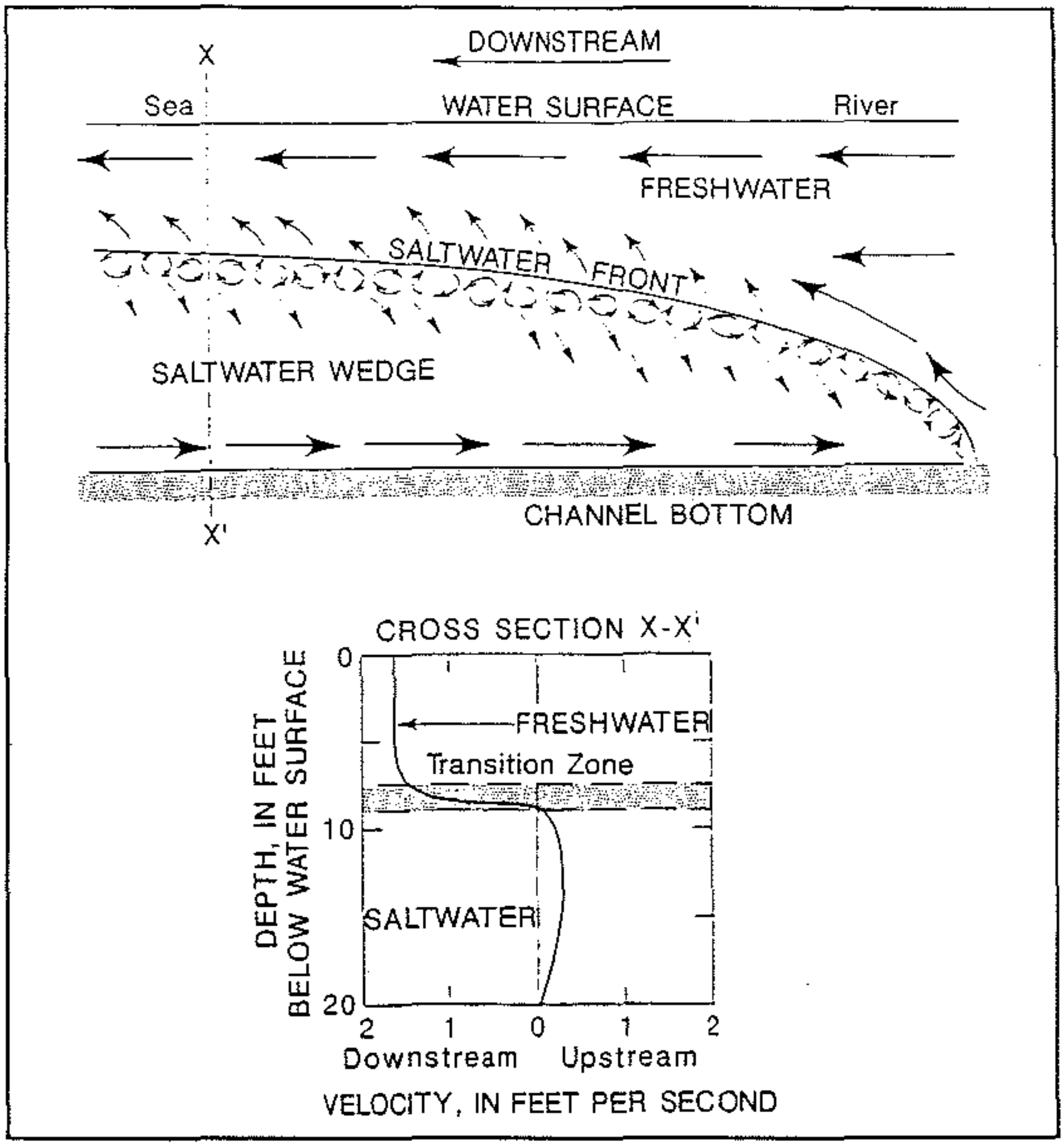

Figure 7. Velocity profiles showing variability of vertical distribution possible for some sites (modified from Giese et al. 1985, fig. 1.6).

A summary of discharge measurement data used to develop the index point-mean velocity and stage-area relations (Fig. 10) is given in Table 1. These relations are used to calculate discharge from index velocity and stage data. Discharge is calculated by entering the index velocity-mean velocity relation with the time-weighted index velocity to obtain the mean velocity, then entering the stage-area relation with the time-weighted stage to obtain the area. The area is then multiplied by the mean velocity to obtain the total discharge for the given time interval. Possible seasonal variations and physical changes require additional discharge measurements to verify relation stability.

A bidirectional electromagnetic flow meter (EFM) at the selected index point (Fig. 1) measures index velocity at 15-minute intervals. The velocity data are stored by an electronic data logger (EDL). Stage data are recorded by an analog-to-digital recorder (ADR) at the same time interval. Eastern Standard Time is used year round to facilitate using the data base for modeling.

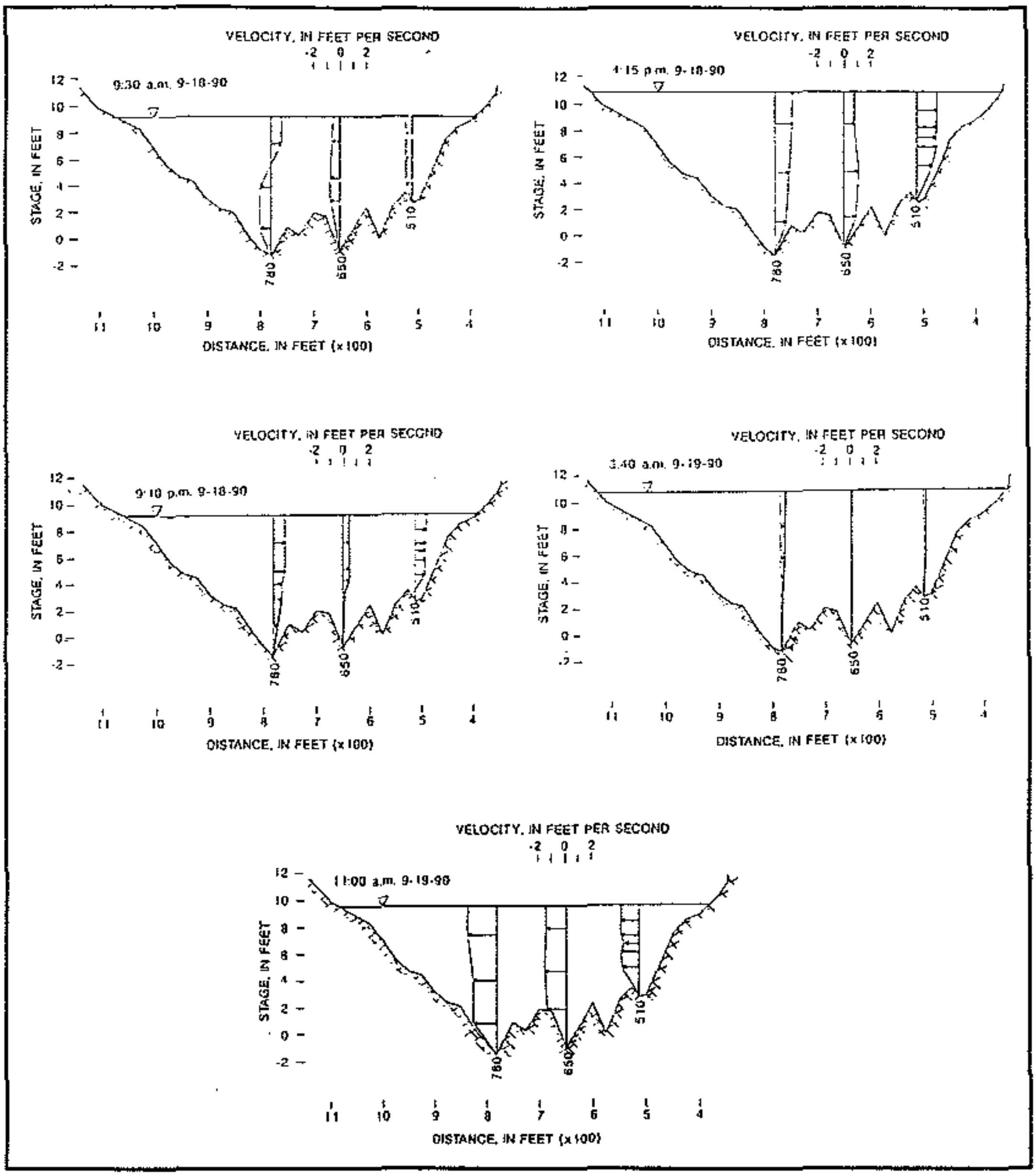

Figure 8. Selected velocity profiles at three subsections of the Alafia River measurement cross section.

An ultrasonic velocity meter (UVM) will be installed at a subsection of the bridge cross section as part of this experiment. In this application, the UVM provides an index velocity in a selected path across part of the channel instead of only at a point as provided by the EFM. The UVM measures the velocity of flowing water by means of an ultrasonic signal that moves faster downstream than upstream. Meters of this type are useful in determining discharge at streamflow sites where the relation between discharge and stage varies with time because of variable backwater conditions.

The UVM is a nonmechanical, nonintrusive device that is capable of measuring lower velocities than can be measured with a current meter. It can provide a continuous and reliable record of water velocities over a wide range of conditions, but several constraints apply:

1. Accuracy is reduced and performance is degraded if the acoustic path is not a straight line. The path can be bent by reflection if it is too close to a stream

boundary or by refraction if it passes through density gradients resulting from variations in water temperature, suspended sediment concentrations, or salinity. Reflection from stream boundaries can cause signal cancellation if boundaries are too close to the signal path.

2. Signal strength is attenuated by particles or bubbles that absorb, spread, or scatter sound. The concentration of particles or bubbles that can be tolerated is a function of the path length and frequency of the acoustic signal.
3. Changes in streamline orientation can affect system accuracy if the variability is random.
4. Errors relating to signal resolution are much larger for a single detection scheme than for multiple detection schemes (Laenen 1985).

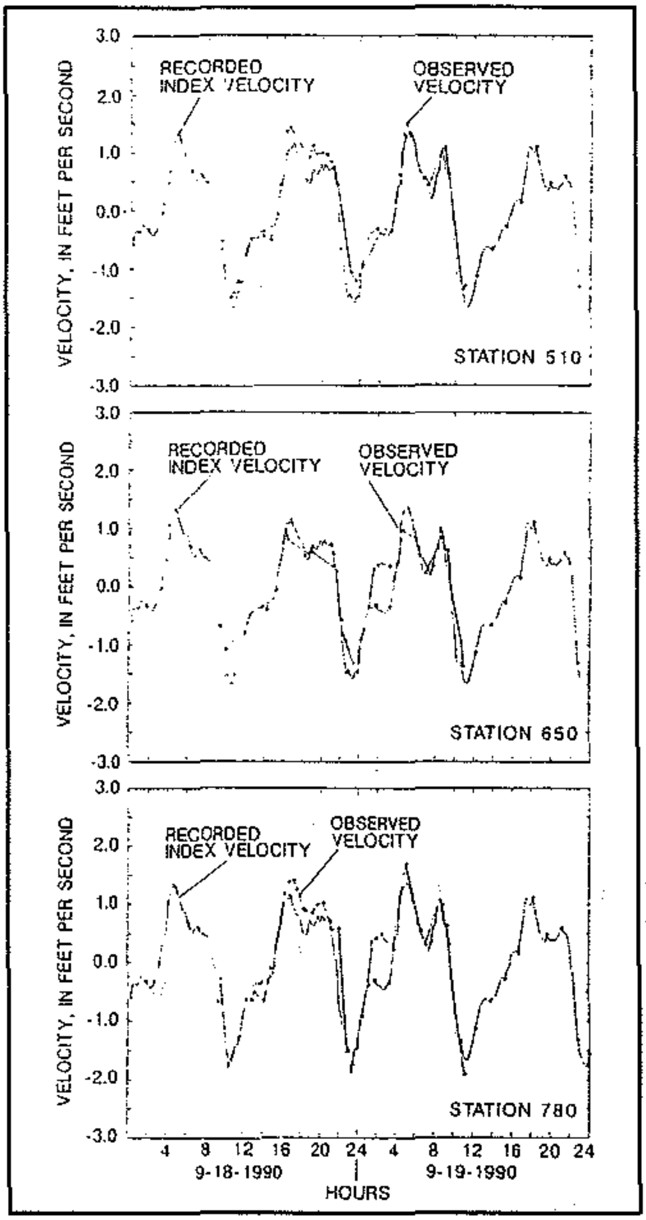

Figure 9. Mean velocities and recorded index velocities at three subsections.

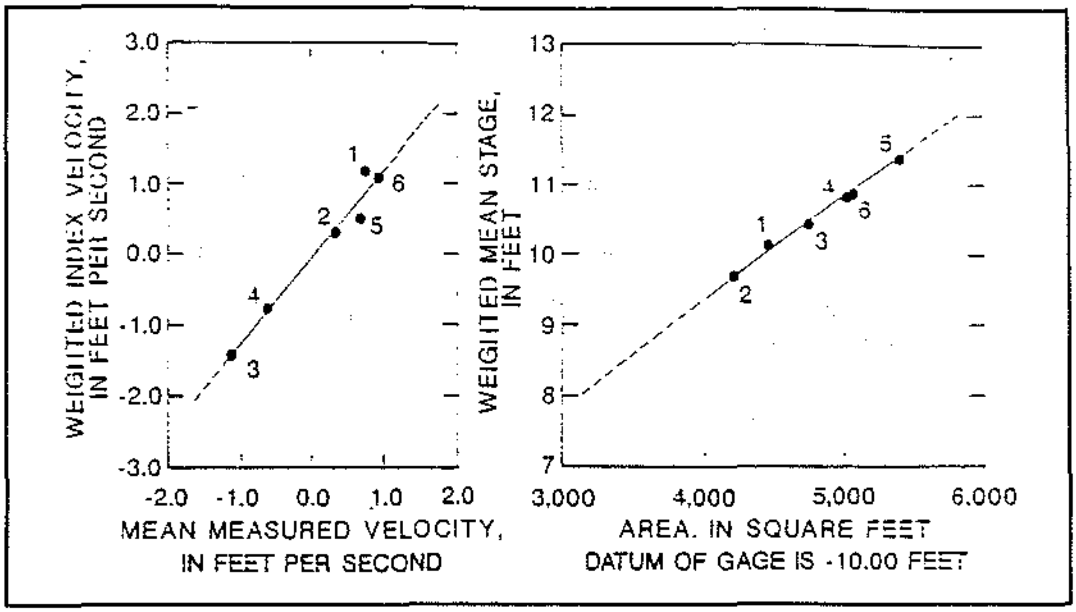

Figure 10. Index velocity-mean velocity and stage-area relations for the Alafia River.

Table 1. Discharge measurement summary data for the Alafia River at Gibsonton.

MEASUREMENT NUMBER	DATE	WEIGHTED MEAN STAGE (ft)	AREA (ft^2)	WEIGHTED INDEX VELOCITY (ft/s)	MEAN MEASURED VELOCITY (ft/s)	DISCHARGE (ft^3/s)
1	8/28/90	10.13	4,450	1.17	0.74	3,270
2	8/28/90	9.67	4,200	.30	.33	1,370
3	10/2/90	10.44	4,740	-1.44	-1.13	-5,370
4	10/2/90	10.84	5,020	-.79	-.63	-3,160
5	10/2/90	11.39	5,390	.48	.66	3,540
6	10/2/90	10.84	5,060	1.07	.92	4,640

The UVM, although more costly and complicated than the EFM, generally requires less maintenance for continuous operation. Figure 11 shows typical UVM components; Figure 12 illustrates the line velocity path of an acoustic pulse; Figure 13 shows voltage representation of transmit and receive pulses.

Specific conductance and temperature will be monitored at points near the bottom and near the surface in the subsection where the UVM is located. These properties will be useful in analyzing the effects of stratification on the operation of the UVM and will provide data needed in verification of the location of the freshwater-saltwater interface.

SUMMARY

Accurate flow measurements are needed to make load computations and estimates. When standard discharge rating techniques can be applied, the computations are simplified. However, tributary tidal influence in streams such as the Alafia River presents unique and difficult measuring conditions that require special measuring techniques and instrumentation.

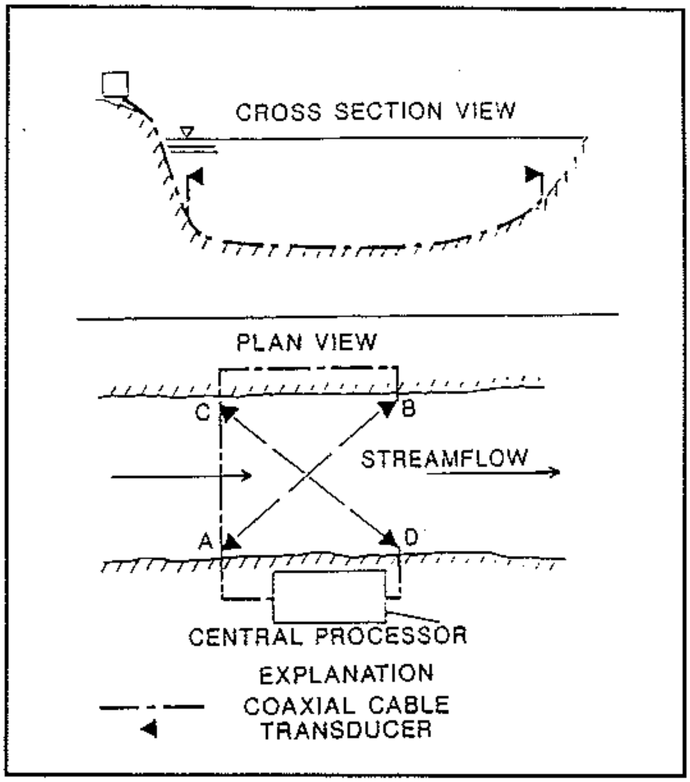

Figure 11. Typical location plan for single level cross path UVM components.

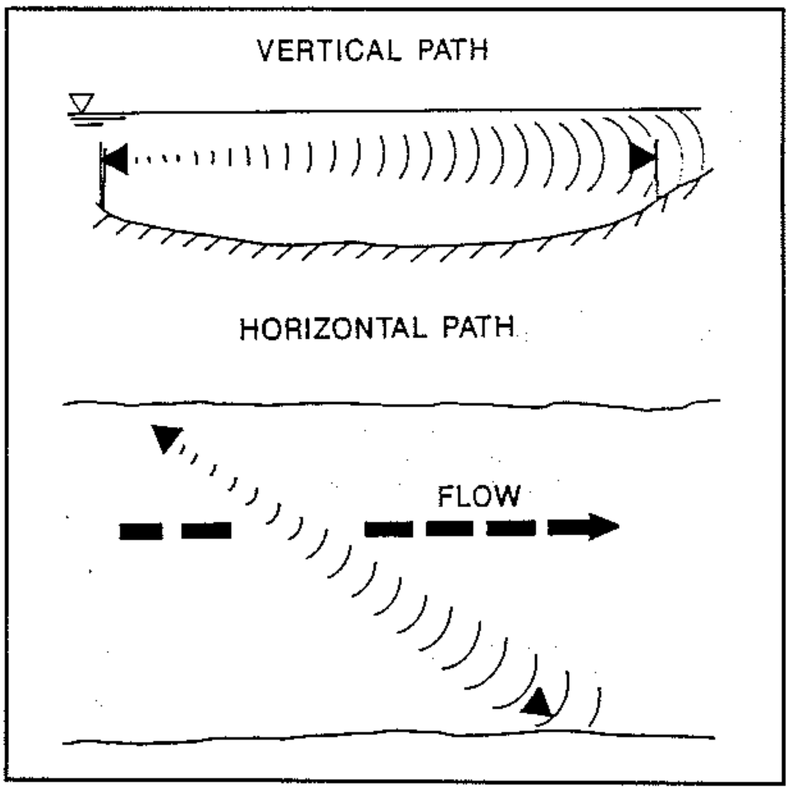

Figure 12. Acoustic pulse line-velocity path (modified from Laenen 1985).

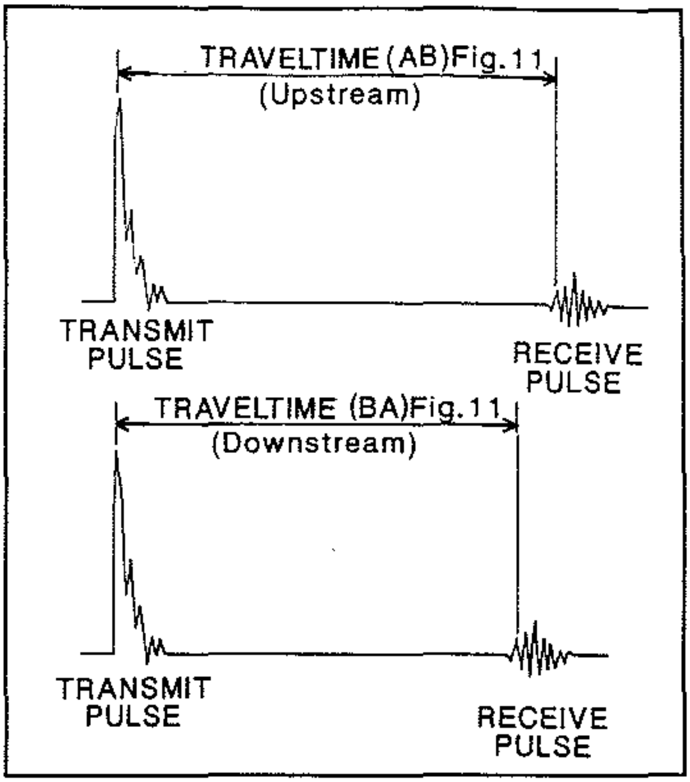

Figure 13. Voltage representation of UVM transmit and receive pulses at upstream and downstream transducers (from Laenen 1985).

In the Alafia River, index velocities are measured at a point in the river using an electromagnetic flow meter, and these velocities are used in conjunction with stage data and index velocity-mean velocity and stage-area relations to compute discharge. The success of this measurement technique is attributed to the reconnaissance efforts that provided information for locating and operating an index velocity point. The index point proved to have high correlation with measured mean velocities. Unit (15-minute) velocity and stage data, along with respective ratings, provide a means for computing continuous discharge for load computations. The method provided here may be used for other tidally influenced tributaries, but reconnaissance and discharge measurements will be required for each site to establish viability.

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LONG-TERM TRENDS OF NITROGEN LOADING, WATER QUALITY AND BIOLOGICAL INDICATORS IN HILLSBOROUGH BAY, FLORIDA

J. O. R. Johansson

INTRODUCTION

At the time of the first BASIS meeting in 1982, water quality conditions in Hillsborough Bay were very degraded and the bay had been in this state for many decades. Few improvements had been seen by 1982, despite that three years earlier one major point source of nutrients to the bay—the City of Tampa's wastewater plant at Hookers Point—had converted its process from primary to state of the art advanced wastewater treatment. The cost of this conversion was close to $100 million.

Within a year after the Hookers Point conversion in 1979, total coliform counts in Hillsborough Bay were reduced dramatically. However, it was a surprise and of concern to some of those working with the bay that no apparent improvement of other important water quality parameters and biological indicators, such as dissolved oxygen and chlorophyll, had occurred several years after the conversion. Further, no reduction of the dominant late summer to early winter blue-green phytoplankton community had been noted. It was not until 1984 that chlorophyll concentrations were reduced substantially, coincidental with a large decrease in planktonic blue-green algae. Dissolved oxygen in bottom waters of central Hillsborough Bay during the summer also improved at this time. Another concurrent sign of the recovery of Hillsborough Bay and areas close to Hillsborough Bay was the limited return of seagrasses to the shallow tidal and subtidal bars at the perimeter of the bay (Avery, this volume; Johansson and Lewis, in press; Lewis et al., this volume).

It is now evident that substantial improvements of several water quality parameters and biological indicators have occurred in Hillsborough Bay and other subsections of Tampa Bay since the mid-1980s. Although it is impossible to definitely demonstrate the cause of the recovery, a general understanding of the Tampa Bay ecosystem, coupled with comparative information from other estuaries, strongly suggests that the documented improvements have resulted from a large reduction of nitrogen loading from external sources. Nitrogen loading has not only been reduced from domestic wastewater sources, but also from industrial sources—specifically from the large and economically important central Florida fertilizer industry.

This report addresses general background information on Hillsborough Bay water quality, compares long-term nitrogen loading trends to water quality indicators, and recommends management options for improving bay conditions. First, the study area and its water quality history during the last several decades are described. The condition of Hillsborough Bay in the late 1960s was reported by the Federal Water Pollution Control Administration (FWPCA 1969). This was the first, and is to date, the most comprehensive eutrophication management study conducted in Tampa Bay; results and recommendations from the study are referenced extensively in this report. Second, long-term trends of nitrogen loading to Hillsborough Bay are discussed and compared to long-term trends of water quality and phytoplankton parameters. Specifically, nitrogen loading from external sources and ambient chlorophyll concentrations measured by the FWPCA are compared to the current Hillsborough Bay loadings and chlorophyll concentrations. In addition to the FWPCA (1969) report, sources of information used are from the City of Tampa Bay Study Group (COT), the Hillsborough County Environmental Protection Commission (HCEPC), the U.S. Geological Survey (USGS), the Fish and Wildlife Service (FWS), the Tampa Port Authority (TPA), the Southwest Florida Water Management District (SWFWMD), the Tampa Bay Regional Planning Council (TBRPC), and the Florida Department of Environmental Regulation (FDER). Finally, the report addresses water quality management needs, specifically the need to develop tools to help protect and enhance the natural resources found in Tampa Bay. A simple eutrophication model which

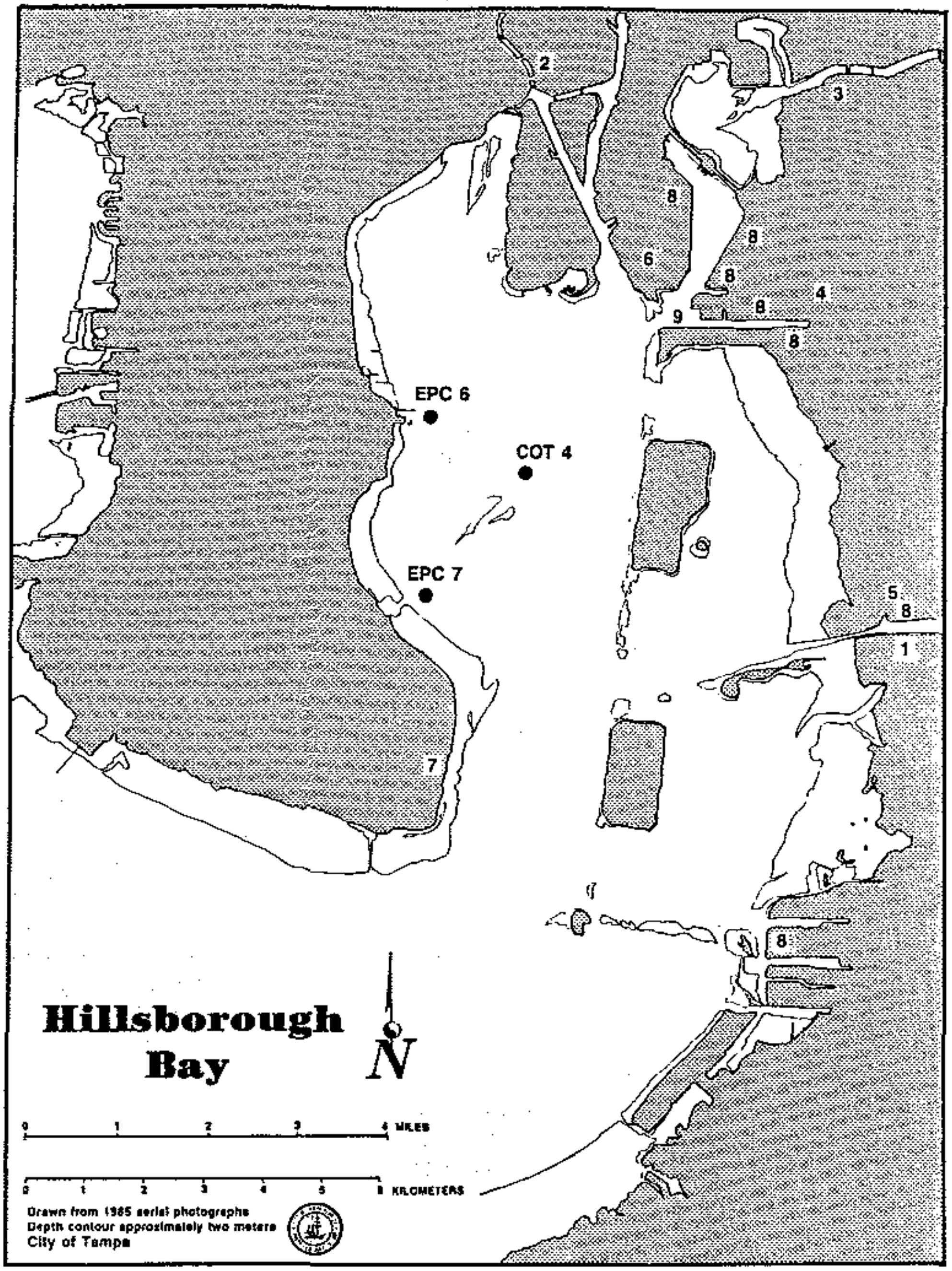

Figure 1. Hillsborough Bay, Florida.

1. Alafia River
2. Hillsborough River and downtown Tampa
3. Palm River/Tampa Bypass Canal
4. Nitram, Inc. and Delaney Creek
5. Cargill Fertilizer, Inc.
6. Hookers Point Wastewater Plant
7. MacDill AFB Wastewater Plant
8. Fertilizer shiploading terminals
9. Sutton Channel in East Bay

may link external nitrogen loading to valuable resources such as seagrasses and other benthic communities is discussed.

THE STUDY AREA

Tampa Bay is a shallow subtropical estuary located on the Gulf of Mexico coast of central Florida. It is one of the largest estuaries in the southeastern United States with an open water surface area of 1030 km^2 and with a watershed area of 5700 km^2. Population growth of the Tampa Bay region is one of the fastest in the United States. Approximately 1.7 million people now live within 80 km of the bay (TBRPC 1989). Hillsborough Bay is the eastern uppermost section of the Tampa Bay system with an open water area of 105 km2 (Figure 1). Although this is only 10% of the Tampa Bay surface area, three of Tampa Bay's five major rivers empty into Hillsborough Bay and the bay receives approximately 60% of the total surface freshwater flow to Tampa Bay (Goodwin 1987). Generally, Hillsborough Bay is the head of the Tampa Bay estuarine system, the area where freshwater and seawater mix, and it should not be surprising by this fact alone, that Hillsborough Bay historically had the "poorest" water quality of the Tampa Bay subsections. However, human impacts in the drainage basin have certainly been the major cause of eutrophication and degraded water quality.

The City of Tampa, which borders Hillsborough Bay to the north and the west, discharges stormwater to Hillsborough River and to the bay directly. Tampa also operates the largest domestic wastewater treatment plant in the area and currently discharges approximately 60 MGD of highly treated wastewater into the upper portion of the bay. Agricultural lands, extensive phosphate mines and many large fertilizer processing plants are located within the drainage area of the Alafia River to the east. In addition, several fertilizer facilities, such as processing plants, storage facilities and shiploading terminals are located near the eastern shores of the bay. The bay serves as a major shipping port of fertilizer products. In 1988 some 20 million short tons of fertilizer material were shipped from Hillsborough Bay (TPA, unpublished), which comprises approximately 80% of the United States production of phosphatic fertilizer and 50% of the production of nitrogen-containing fertilizer (Bureau of the Census 1988).

PAST WATER QUALITY CONDITIONS

Almost 40 years ago, Tampa Bay was described as grossly polluted due to discharges of poorly treated domestic wastewater and industrial waste from phosphate mines, citrus canneries and other industrial sources (Galtsoff 1954). However, water quality problems specific to Hillsborough Bay may have been present as early as 1928 when occasional noxious odors along the western shore of Hillsborough Bay were noted (FWPCA 1969). The odor was associated with abundant growth of macroalgae and poor water quality caused by discharges of untreated domestic and industrial waste. Odors continued sporadically until the City of Tampa completed the Hookers Point primary wastewater treatment plant in 1951. With the start-up of the primary plant the odors apparently subsided temporarily. However, odors from large amounts of macroalgae decomposing on beaches and next to seawalls became severe during the early 1960s; as a result, citizens living close to Hillsborough Bay complained to the authorities about the noxious odors. Also during this period, the water in the bay was not suitable for body contact due to high bacteria content. Signs were posted at several popular beaches to warn swimmers of the contaminated water.

The Federal Water Pollution Control Administration Study

In 1965, the City of Tampa and the Florida State Board of Health requested technical assistance from the FWPCA to help identify the causes of the poor water quality and the noxious odors in Hillsborough Bay and to recommend solutions to the problems. FWPCA conducted an extensive study of Hillsborough Bay water quality problems in 1967 and 1968 (FWPCA 1969). The FWPCA study confirmed the earlier observations of highly deteriorated conditions in Hillsborough Bay. Indicators of the poor water quality included high turbidity, high fecal coliform counts, anoxic bottom waters and large amounts of drift macroalgae in the shallows.

The study identified point source discharges with high nutrient and organic content as the underlying cause of the odor and degenerated water quality in Hillsborough Bay. Specific sources identified were the Alafia River and the fertilizer industry in its basin, the City of Tampa's wastewater plant at Hookers Point, the U.S. Phosphoric Products Company (now Cargill Fertilizer, Inc.) and the Nitram Chemical Company (now Nitram, Inc.). After an extensive monitoring program of these sources, it was estimated that the Alafia River and the chemical companies supplied 63% of the total nitrogen and 94% of the total phosphorus entering the bay. The Hookers Point facility discharged 32% of the total nitrogen and less than 5% of total phosphorus. However, this facility was the major contributor of organic material to the bay, supplying more than 85% of all carbonaceous material from point sources. Further, the study established that nitrogen was the growth-limiting nutrient in Hillsborough Bay and that any reduction in available nitrogen could be expected to produce a corresponding reduction in plant growth. Table 1 lists total nitrogen loadings from all sources identified and measured by FWPCA (1969) and one additional source, losses from shiploading terminals, which are discussed below.

Table 1. Total nitrogen loadings from major external sources to Hillsborough Bay during two time periods, 1967-68 and 1987-90.

SOURCES	TN (METRIC TONS/YR) 1967-68	1987-90	PERCENT CHANGE
Alafia River + fertilizer industry	1170	430	-63
Hillsborough River	160	280	75
MacDill AFB Wastewater Plant	20	0	-100
Nitram, Inc. + Delaney Creek	870	60	-93
Palm River/Tampa Bypass Canal	50	390	680
Hookers Point Wastewater Plant	1210	240	-80
Cargill Fertilizer, Inc.	350	20	-94
Fertilizer shiploading terminals	140	770	450
TOTAL	3970	2190	-45

The study recommended several short-term measures to improve conditions in Hillsborough Bay. In addition, an extensive long-term water quality management plan was outlined to restore and protect the bay. This plan recommended a 90% reduction of nitrogen loading to the bay from the sources studied to reduce phytoplankton and macroalgae growth. Further, to improve the dissolved oxygen conditions in the bay, it was recommended that the Hookers Point facility remove 90% or more of the carbonaceous material discharged. The study concluded that the degraded conditions in Hillsborough Bay developed over many years and, likewise, efforts to restore the bay would take time. However, it was also suggested that the implementation of the management plan, combined with the natural self-purification process of the estuary, may eventually restore Hillsborough Bay to a healthy aquatic environment.

City of Tampa Wastewater Discharges

The FWPCA (1969) management plan recommended that the City of Tampa upgrade its Hookers Point wastewater treatment plant from primary to secondary treatment, to greatly reduce the discharges of nitrogen and organic material to Hillsborough Bay. The City of Tampa initiated plans to construct an upgraded facility in 1970. The decision to upgrade was based on the recommendations of the FWPCA report and by public outcry in response to the poor conditions in Hillsborough Bay (Tampa Tribune 1969). However, in 1972, before plans for the secondary upgrade had been completed, the Florida legislature passed a law which required all domestic wastewater dischargers to tidal waters of west central Florida to provide advanced wastewater treatment (AWT). AWT was defined as 5 mg/l BOD_5, 5 mg/l total suspended solids, 3 mg/l total nitrogen and 1 mg/l total phosphorus. Directed by this law, the City of Tampa upgraded the Hookers Point facility from primary to AWT with a 60 MGD capacity. Nitrogen removal has been maintained at AWT levels since 1979. The AWT phosphorus requirement has been waived by the state because of evidence indicating that nitrogen is the limiting nutrient for algal growth in Hillsborough Bay and other sections of Tampa Bay (FWPCA 1969, COT 1983, FDER 1983).

Loadings of total nitrogen and carbonaceous material to Hillsborough Bay from the Hookers Point facility were reduced substantially when the plant converted from primary to advanced treatment. Current nitrogen loadings have been reduced by 80% compared to the loadings measured by the FWPCA study (Table 1), despite the fact that the discharge flow from the plant has nearly doubled since 1967-68.

Fertilizer Industry and Alafia River Impacts

The second major source of nutrients identified by the FWPCA (1969) management plan was the Alafia River and the fertilizer industry. The report specifically referenced three sources—Nitram, Cargill, and the Alafia River and the fertilizer companies located in its upper basin.

During the late 1800s, rich phosphate deposits were discovered east of Hillsborough Bay and in 1908 the first large vessels were used for transport of phosphate rock from the Tampa Bay area (Tiffany and Wilkinson 1989). Prior to the 1960s, fertilizer production and export consisted mostly of phosphate rock. Later, the production and export of processed fertilizer containing nitrogen became increasingly important. In 1990, approximately 10 million short tons of ammonium-phosphate product were exported from the Port of Tampa in Hillsborough Bay (TPA, unpublished). This large nitrogen processing industry in Tampa Bay is unique among estuaries.

The FWPCA (1969) study estimated that 63% of the point and nonpoint nitrogen sources entering the bay was derived from the combined contribution of Nitram, Cargill, and the Alafia River and the fertilizer companies located in its upper basin. Current nitrogen loading from the two large nitrogen processing industries, Nitram and Cargill, has been reduced by more than 90% since 1967-68 (Table 1), apparently through improved regulation of the industry and better production practices (Estevez and Upchurch 1985). Similarly, nitrogen loadings from the Alafia River have also been reduced, but to a smaller extent. However, it is unclear what fraction of the Alafia River loadings are contributed by the fertilizer industry. Other sources, such as runoff from agricultural lands and urban areas, must also be important nitrogen sources to the river. The Alafia River, which supplied slightly less nitrogen to Hillsborough Bay than the Hookers Point facility in 1967-68, is now the largest of the nitrogen sources originally identified and measured by FWPCA (1969).

In addition, the Hillsborough River and the Palm River/Tampa Bypass Canal (TBC) system show loading increases between 1967-68 and 1987-90 (Table 1), which may be a result of increased development in the basins. However, a major portion of the increase shown for the TBC system was caused by an unusually large discharge in

September 1988 following a large rain event. Excluding this event would result in an average nitrogen loading from this system of approximately 160 metric tons/year.

Although nitrogen loading from the fertilizer industry sources identified and measured by FWPCA (1969) has been reduced, it should be recognized that the study did not account for nonpoint losses of nitrogen-containing fertilizer from storage facilities and shiploading terminals located near or next to Hillsborough Bay. This loss is mainly in the form of surface runoff and dust. There are no quantitative measurements of these losses. The potential loading to the bay has been estimated from the amount of ammonium-phosphate product shipped from the Port of Tampa (TPA, unpublished). Abu-Hilal (1985) lists estimates of fertilizer product losses, ranging from 0.05% to 1%, from transportation and shiploading at the Port of Aquaba in the Gulf of Jordan. The most conservative estimate, 0.05% loss, has been used in this report to calculate nitrogen losses from the Hillsborough Bay storage facilities and shiploading terminals.

Port of Tampa shipping statistics suggest that nitrogen lost from storage facilities and shiploading terminals was a minor component of nitrogen loading to Hillsborough Bay during the period of the FWPCA study (Table 1). However, based on the amounts currently shipped, the loss of material may now be one of the largest sources of external nitrogen to Hillsborough Bay. In addition, water column measurements of dissolved ammonia in the port area of Hillsborough Bay (Figure 2) often show high concentrations of nitrogen near these facilities in comparison to central Hillsborough Bay locations (COT, unpublished). The concentration peaks in the port area generally occur during, or immediately following, rain events. These field measurements suggest that losses from the loading facilities may be a relatively large nitrogen source to Hillsborough Bay. Furthermore, future loadings from these facilities may become increasingly important, because the amount of nitrogen containing fertilizer shipped from the Port of Tampa is increasing rapidly (TPA, unpublished; Figure 3).

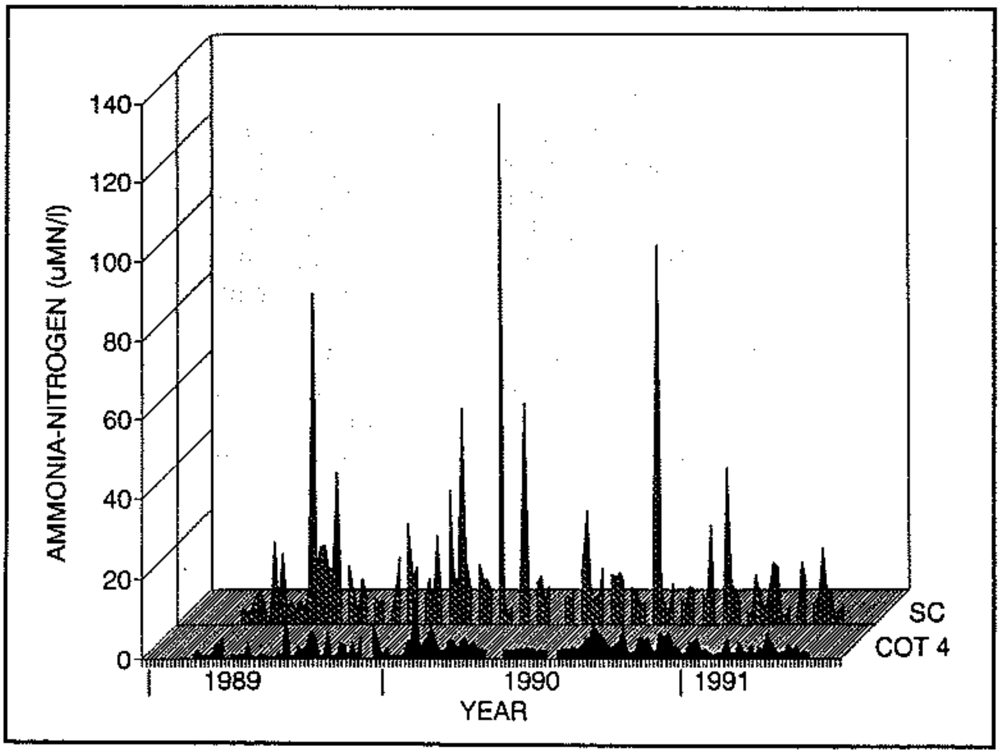

Figure 2. Surface ammonia-nitrogen concentrations in Sutton Channel (SC) and central Hillsborough Bay (COT 4), 1989-1991.

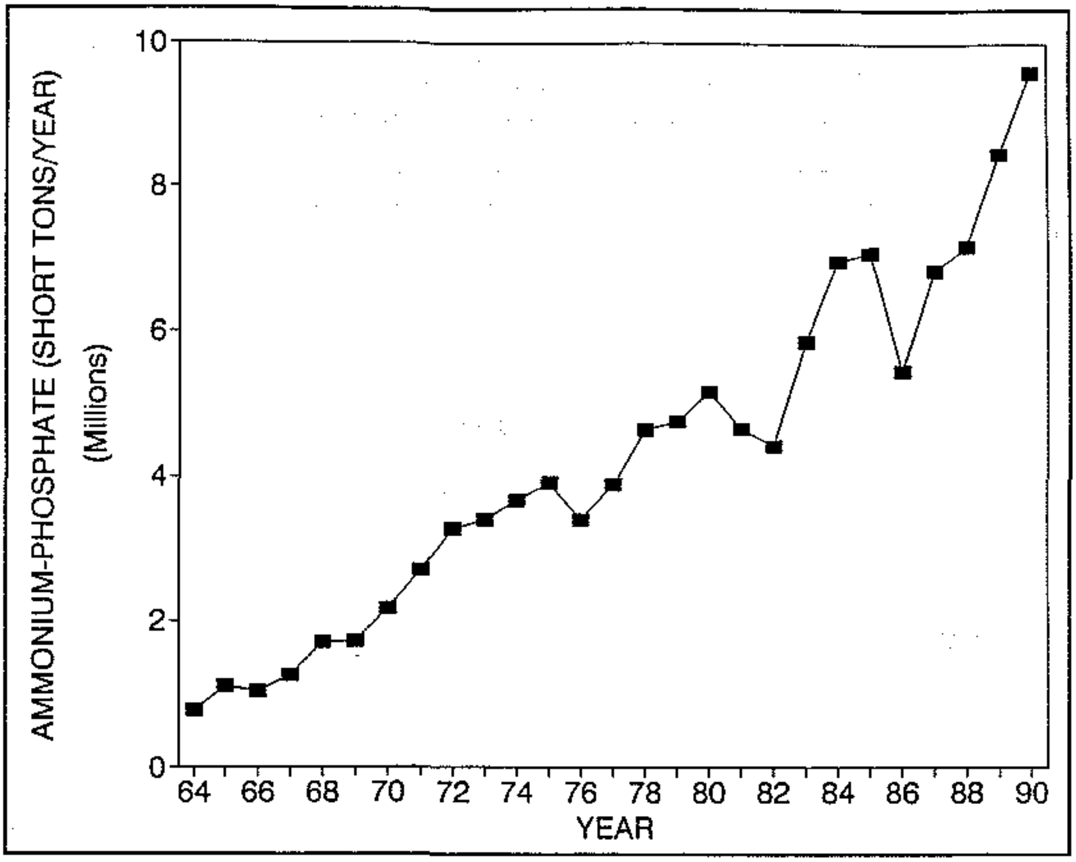

Figure 3. Outbound ammonium-phosphate fertilizer from the Port of Tampa, Hillsborough Bay, 1964-1990.

LONG-TERM TREND OF EXTERNAL NITROGEN LOADING

The comparison of total nitrogen loading measured by FWPCA (1969) for the period 1967-68 and current loadings for the period 1987-90 indicate that there has been a 64% reduction in loading from the sources identified in the FWPCA study. If the estimated losses from the shiploading terminals are included in this comparison, then the reduction is decreased to 45%. The comparison clearly establishes that there has been a substantial reduction of nitrogen loading from these external sources to Hillsborough Bay during the last two decades. However, the nitrogen loading record must be examined in greater detail to determine, as accurately as possible, when the large changes occurred. This detail is needed to establish a meaningful relationship between loading and bay conditions. Annual nitrogen loading rates have been calculated for the largest sources identified in the FWPCA report (the Alafia River, the fertilizer industry and Hookers Point) and the estimated loading from shiploading terminals (Figure 4). Of course, these are not the only external sources of nitrogen to Hillsborough Bay. Atmospheric loadings, most stormwater loadings, and loadings from groundwater, septic waste and several tributaries have not been included in the calculations. However, the included sources may be the most important ones and also the sources that have shown the greatest change over the period of study. Kelly and Harwell (1990) suggest that it may be more relevant to determine the response of a system from a relative change over time than from an absolute understanding of the system.

Information describing the sources used for loading calculations and the procedures used to deal with missing data are detailed in the Appendix. It should be emphasized that loadings for the fertilizer industry are very approximate for the period 1969-80. Figure 4 indicates that nitrogen loading remained relatively high and stable until 1979, when a substantial reduction began. Both the upgrade of Hookers Point and changes in fertilizer industry practices apparently caused the large nitrogen reduction. Loadings have remained relatively low since 1981.

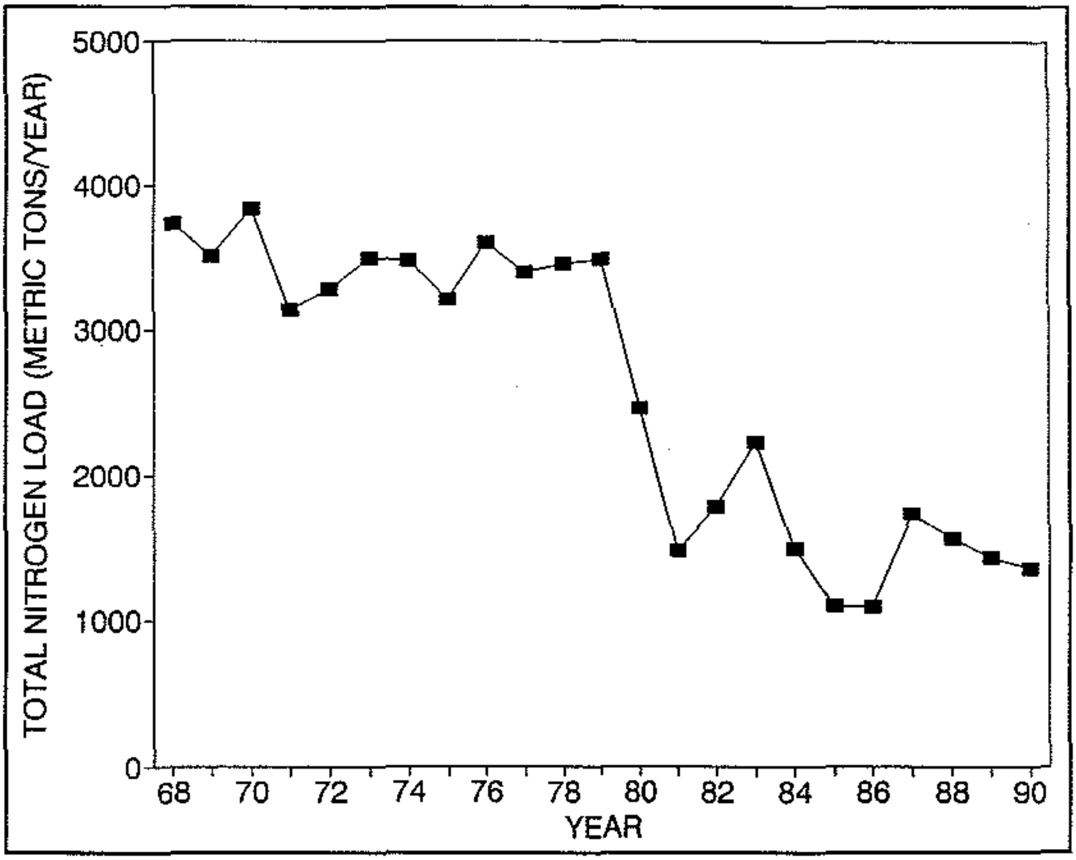

Figure 4. Total nitrogen loading to Hillsborough Bay from major external sources, 1968-1990.

Phytoplankton Biomass and Blue-Green Algae Abundance

With the recent reduction of nitrogen loading to Hillsborough Bay, reductions in phytoplankton biomass and changes in phytoplankton composition could be expected. Several reports discussing nitrogen loading to Tampa Bay have suggested that a direct relationship exists between nitrogen availability and growth of phytoplankton and macroalgae (FWPCA 1969; Spaulding et al. 1989; Johansson and Lewis, in press). Further, this relationship has been demonstrated, particularly for phytoplankton, in many estuaries world wide (Boynton et al. 1982). Chlorophyll *a* concentration is an estimate of phytoplankton biomass, but it is also an important indicator of estuarine eutrophication and has been linked to seagrass survival (Cambridge et al. 1986, Pearce 1991). The long-term Tampa Bay record shows a substantial chlorophyll reduction, particularly in Hillsborough Bay, since the mid-1980s (Figure 5). Sources of the long-term chlorophyll record are identified in the Appendix. Hillsborough Bay annual average concentrations have decreased from approximately 30 µg/l during the period prior to 1984 to the current level of less than 15 µg/l. The chlorophyll decrease is similar to the reductions in nitrogen loading discussed above. Although the large loading reduction occurred just prior to 1980, ambient chlorophyll concentrations did not decrease substantially before 1984. Three years may have been necessary for the bay's internal processes to equilibrate to the new level of nitrogen loading after several decades of excessive loadings from Hookers Point and the fertilizer industry. However, with smaller reductions of nitrogen loading anticipated from future management actions, the time lag may be shorter. Recent information has shown that several estuaries retain nitrogen poorly and may export most of the nitrogen they receive (Nixon 1987; Nowicki and Oviatt 1990; Boynton et al., in press).

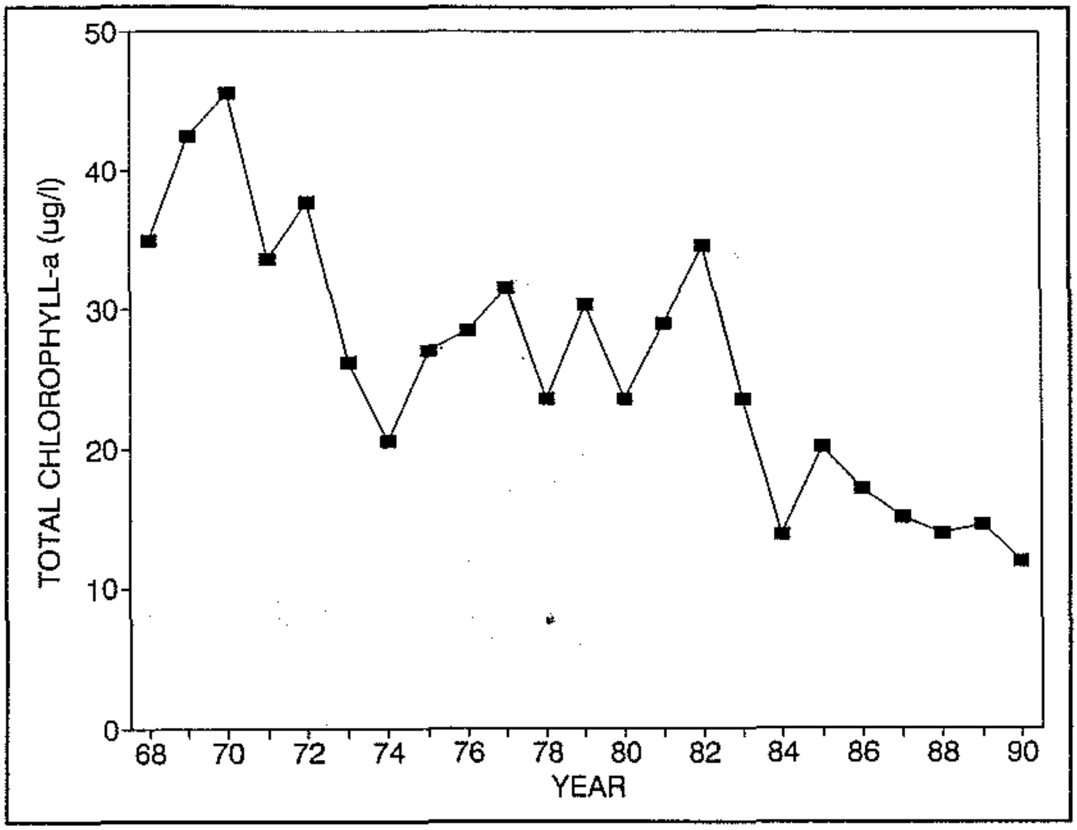

Figure 5. Total chlorophyll a concentrations in Hillsborough Bay, 1968-1990.

The substantial decrease of chlorophyll in Hillsborough Bay correlates with a large reduction of a planktonic filamentous blue-green alga (*Schizothrix calcicola sensu* Drouet), which prior to 1984 dominated the phytoplankton population from late summer to early winter (Johansson et al. 1985; COT, unpublished; Figure 6). This alga has been present in much reduced concentrations since 1984. There is no information to support that this blue-green alga is able to fix atmospheric nitrogen. Nutrient bioassay experiments with natural phytoplankton communities dominated by *S. calcicola*, from both Hillsborough Bay and Old Tampa Bay, clearly demonstrated the community to be strongly nitrogen limited (COT 1983). Therefore, growth of this blue-green alga is apparently limited by available water column nitrogen, and it is not surprising that its biomass has been reduced as nitrogen loadings have decreased. Many blue-green algae are considered nuisance species and are often indicators of poor water quality (Pearl 1987). The reduction of blue-green algae biomass agrees with other indicators suggesting decreased eutrophication in Hillsborough Bay.

Further, the decrease in blue-green algae biomass during late summer to early winter may be a key factor of the recent recovery of Hillsborough Bay. For example, the blue-green reduction should have caused less organic matter (blue-green algae filaments) to settle to the bottom, and sediment oxygen demand should have been lowered (see below). Similarly, there should have been less water column respiration. These changes should have improved water column and bottom oxygen conditions

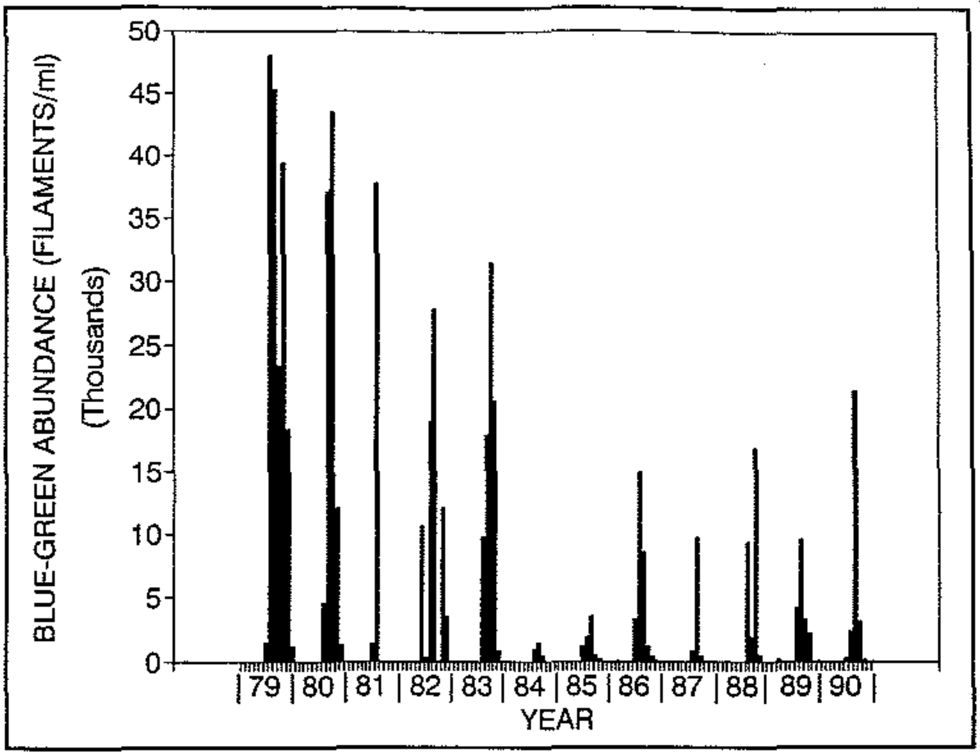

Figure 6. Monthly concentrations of a filamentous blue-green alga (Schizothrix calcicola sensu Drouet) in surface waters of central Hillsborough Bay (COT 4), 1979-1990.

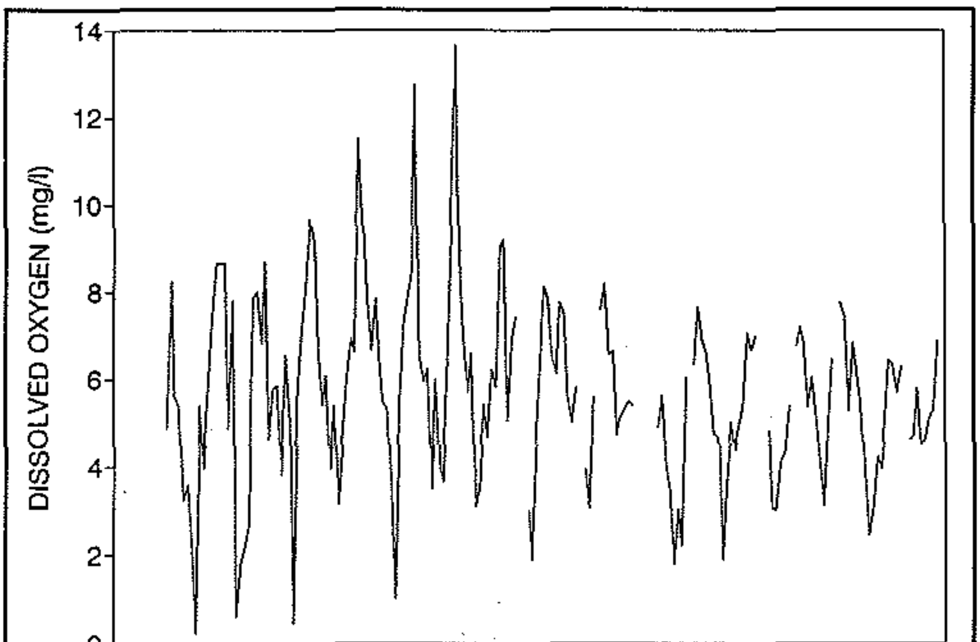

Figure 7. Monthly averages of near-bottom dissolved oxygen concentrations in Hillsborough Bay (EPC 6 and 7), 1974-1990.

during the critical summer period. Evidence that these changes have occurred concurrent with the reduction in blue-green algae abundance is apparent in the long-term near-bottom oxygen record for two stations located in the muddy section of Hillsborough Bay (HCEPC, unpublished; Figure 7). The annual amplitude of the near-bottom dissolved oxygen curve has narrowed considerably compared to the period of high blue-green algae abundance. In addition, hypoxia events have also become less frequent.

Phytoplankton biomass is an important factor limiting water column light penetration in phytoplankton-dominated estuaries such as Hillsborough Bay. Further, the dense concentrations of blue-green algae found in the bay prior to 1984 may have additionally suppressed light penetration. Kirk (1977) found that blue-green algae reduce light to a greater degree than other phytoplankton types. These findings may lend support to the improved Secchi depth readings in Hillsborough Bay after the blue-green algae biomass was reduced (Boler 1990; HCEPC, unpublished; Figure 8). Sufficient water column light penetration is essential for the survival of submerged seagrasses.

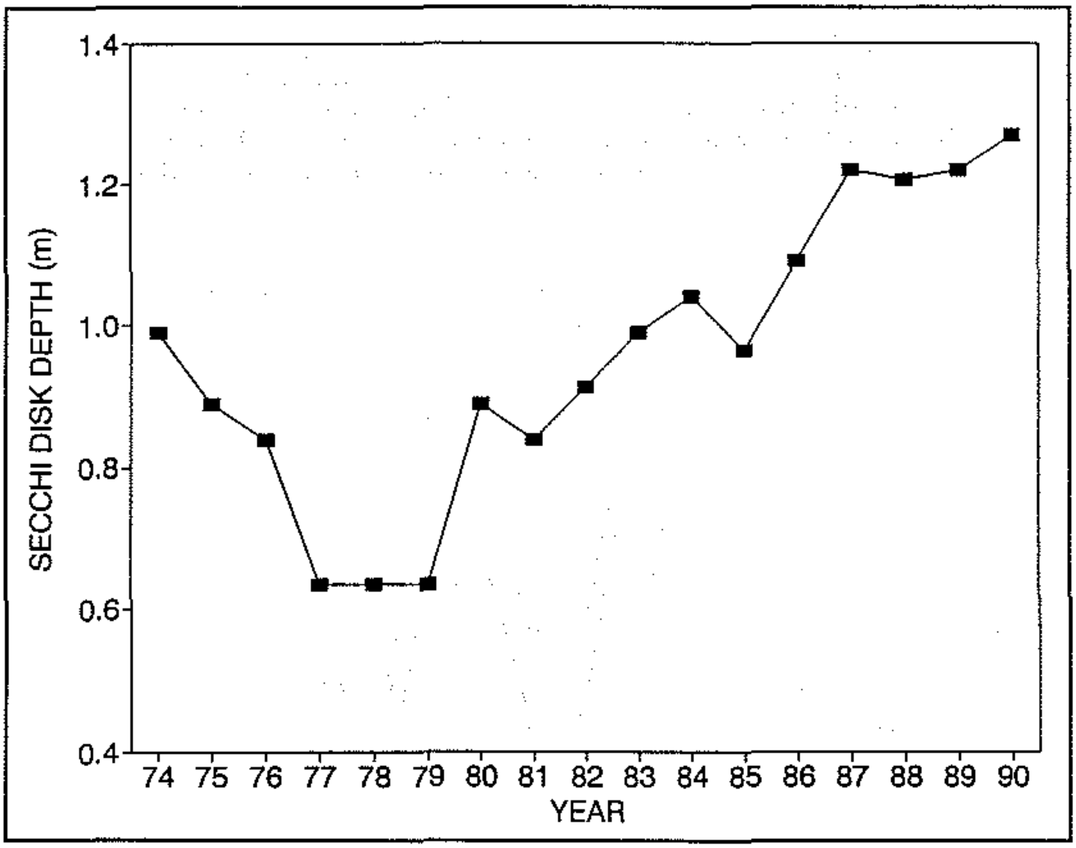

Figure 8. Secchi disk depth in Hillsborough Bay, 1974-1990.

Seagrass Recovery

Hillsborough Bay, and Tampa Bay as a whole, have had serious losses of seagrass. Historic records show that the areal coverage of Tampa Bay seagrasses has decreased dramatically during the last 100 years. In 1982, approximately 20% of the originally estimated seagrass coverage still remained (Lewis et al. 1985). Most seagrasses in Hillsborough Bay were lost between 1950 and 1980. However, modest seagrass recolonization was observed in Hillsborough Bay and other sections of Tampa Bay in 1984 and 1985 following the decrease in chlorophyll concentrations. Seagrass cover continues to increase in these areas. More detailed discussions of this issue are given by Avery (this volume), Johansson and Lewis (in press), and Lewis et al. (this volume).

Rainfall and Chlorophyll Concentration

Nutrient loading from runoff caused by rainfall has been suggested as an important driving force influencing Hillsborough Bay water quality (Lewis and Estevez 1988; Lewis et al., this volume). It is suggested that lower than average rainfall in the Tampa Bay area during the last three to five years may be responsible for the improvements in water quality and the recolonization of seagrasses in Hillsborough Bay and other areas of Tampa Bay. It is often difficult to separate ecosystem responses caused by natural variability from responses caused by management actions (National Research Council 1990). However, a general evaluation of the importance of rainfall on long-term water quality conditions in Hillsborough Bay is attempted here. Figure 9 shows the 1975-90 annual rainfall record at Tampa International Airport (TIA) (NOAA 1991), and at 27 locations in the Hillsborough and Alafia River basins that are monitored by SWFWMD (SWFWMD, unpublished). During the period 1975-90, annual rainfall at TIA has been consistently lower than the average rainfall over the basins. The result of this comparison suggests that many rainfall measuring sites must be used to estimate rainfall affecting Hillsborough Bay. Average rainfall during the recent period of low chlorophyll levels (1984-90) was approximately 6% lower than the long-term record (1975-90). It is unlikely that this small reduction in rainfall could have exclusively caused the substantial reduction in chlorophyll.

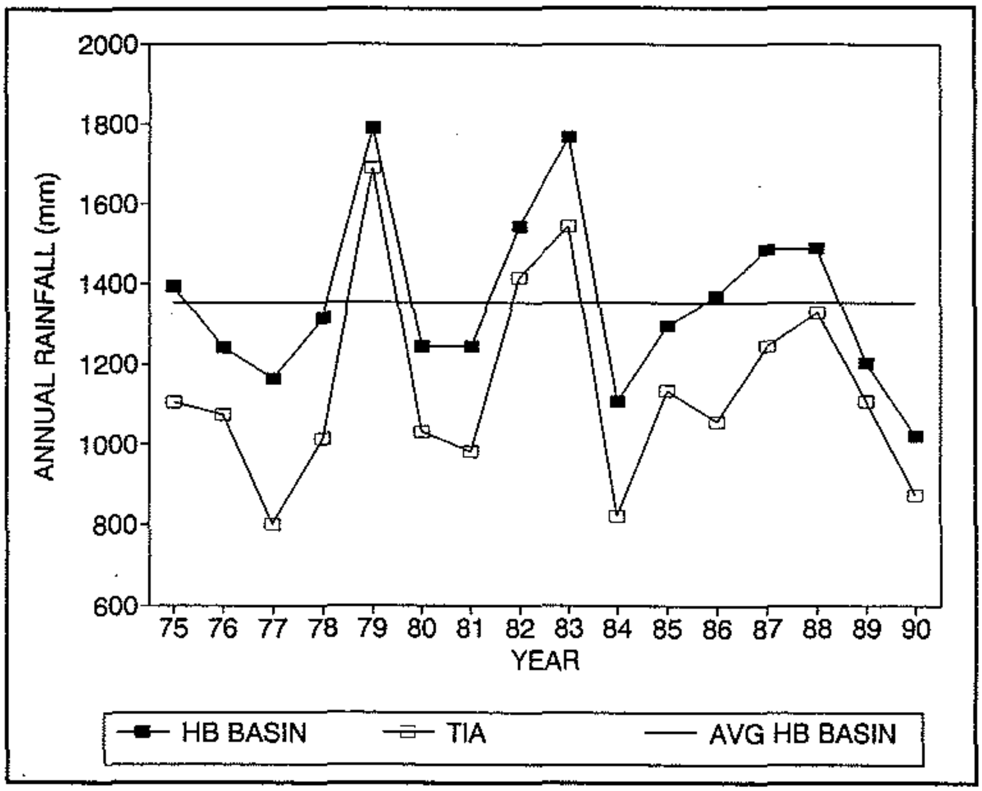

Figure 9. Annual rainfall at Tampa International Airport and at 27 rainfall measuring sites in the Hillsborough Bay basin, 1975-1990.

The relationship between rainfall over the Hillsborough Bay drainage area and ambient chlorophyll concentrations for the period 1975-90 is plotted in Figure 10. The lack of a relationship is encouraging because it implies that management actions taken during the last decade or two, aimed to decrease point-source nitrogen loading to the bay, have apparently been effective in reducing eutrophication.

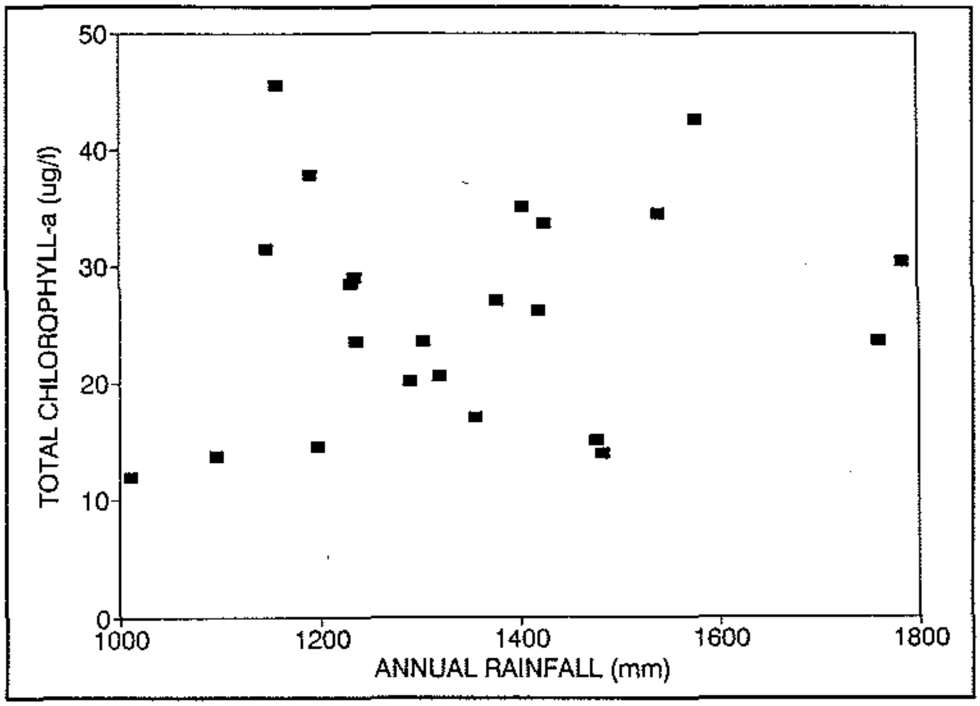

Figure 10. Relationship between annual rainfall over the Hillsborough Bay basin and Hillsborough Bay total chlorophyll a concentrations, 1968-1990.

NITROGEN LOADING AND CHLOROPHYLL CONCENTRATION

The long-term trend of nitrogen loading to Hillsborough Bay from the largest sources identified by the FWPCA in 1969 (the Alafia River, the fertilizer industry, and Hookers Point) and the estimated loading from the shiploading terminals have been plotted against the long-term Hillsborough Bay chlorophyll record (Figure 11). The linear relationship shown is statistically significant ($P>0.01$), but the regression coefficient ($R^2=0.49$) is weak. It is interesting to note that if a three-year time lag (see above) is assumed between nitrogen loading and the response in chlorophyll, then a much stronger regression coefficient is found ($R^2=0.76$) (Figure 12). In either case, the relationship suggests that over the period analyzed, each 150 metric tons/year reduction in nitrogen loading from major external sources has corresponded to a 1 µg/l reduction of ambient chlorophyll. This relationship describes a simple eutrophication model. With additional work to refine the relationship, it could be used by Tampa Bay managers to evaluate eutrophication abatement strategies.

The model must be used with care for predictions of future Tampa Bay chlorophyll concentrations, pending a better understanding of the chlorophyll/nitrogen loading relationship. It can not be assumed that the long-term relationship will remain linear as future nitrogen loading reductions are implemented. Several natural estuarine eutrophication control processes may become increasingly important with additional nitrogen reductions. FWPCA (1969) referred to these controls as processes of self-purification and suggested that these, combined with management actions, may eventually restore Hillsborough Bay to a healthy aquatic environment. Consequently, predictions of future chlorophyll concentrations from

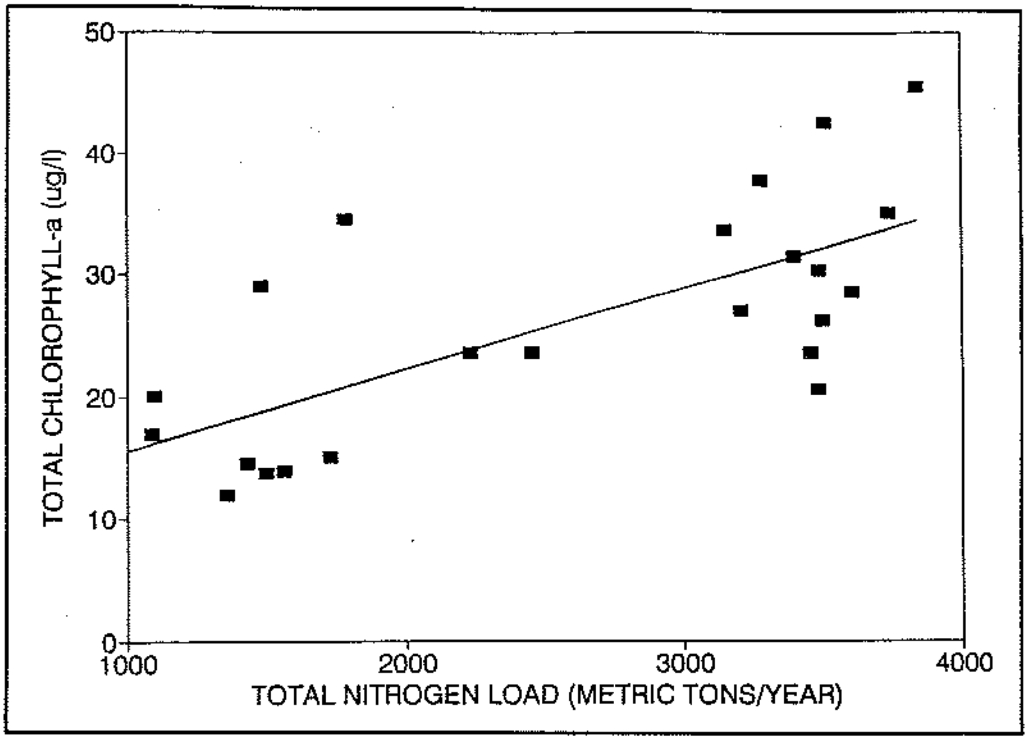

Figure 11. Relationship between total nitrogen loading to Hillsborough Bay from major external sources and Hillsborough Bay total chlorophyll a concentrations, 1968-1990.

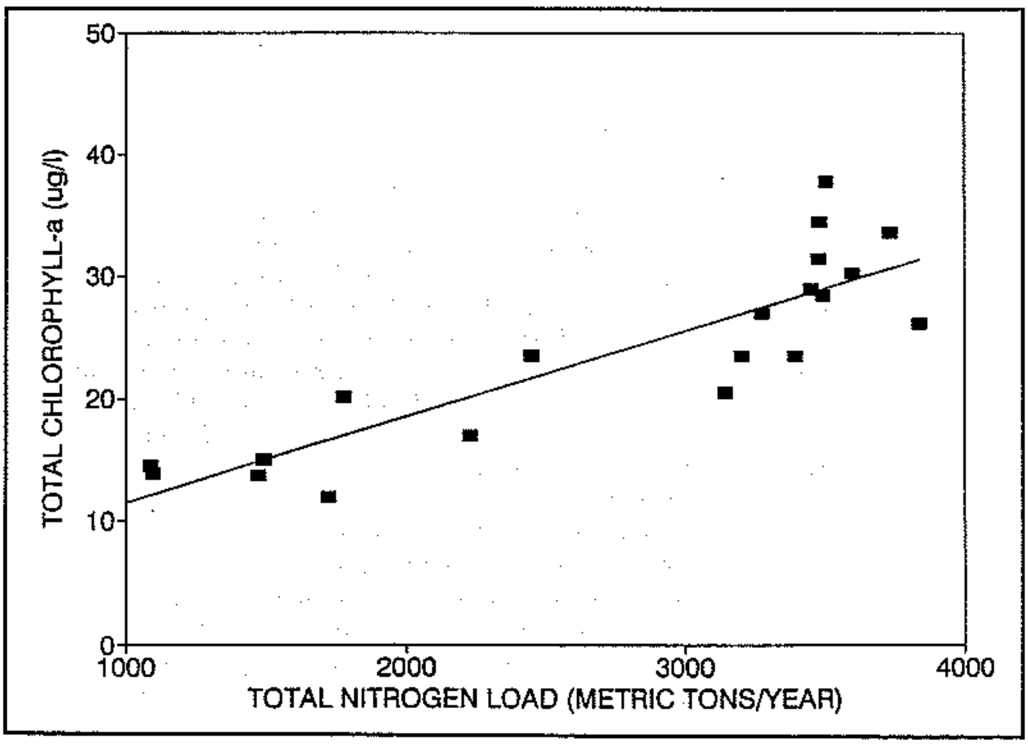

Figure 12. Relationship between total nitrogen loading to Hillsborough Bay from major external sources (1968-1987) and Hillsborough Bay total chlorophyll a concentrations (1971-1990). A three-year time lag has been applied to the chlorophyll concentrations in relation to the nitrogen loadings.

the long-term relationship without accounting for the natural eutrophication control processes may result in overestimated chlorophyll levels. Therefore, it is important to identify and evaluate the natural processes which could have large impacts on the development and the ultimate results of eutrophication management strategies. Three of these processes are addressed below. These may be some of the most important ones; however, there may be other important processes not addressed here.

First, hypoxia of bottom waters during the summer, specifically in Hillsborough Bay, which has the largest area of muddy bottom of the Tampa Bay system (Johansson and Squires 1987; USGS, unpublished), has been an annual phenomenon (Santos and Simon 1980a and 1980b). Although large areas in the deeper sections of the bay still experience hypoxia, it is now evident that both the area covered by and the duration of poor summer oxygen conditions have been reduced (see above and Figure 7). The improvement may be related to the substantial reduction of blue-green algae which occurred in 1984 (see above and Figure 6).

With the recent increase of oxic conditions in time and space it can be assumed that denitrification in the surface sediments has become increasingly important (Kemp et al. 1990; Koop et al. 1990). The loss of nitrogen by denitrification is an important natural eutrophication control process in estuaries, and may account for as much as half of the terrestrial input (Seitzinger 1988). Denitrification losses must therefore be included in Tampa Bay eutrophication strategies to accurately project results of management actions and to avoid costly overprotection. Field measurements and/or extensive comparisons with other estuaries should be conducted to estimate current and future denitrification rates.

Second, the potential of benthic filter feeding communities to reduce phytoplankton biomass and chlorophyll concentrations may increase from present levels as bottom oxygen conditions improve and areas of suitable habitat increase in Tampa Bay. Benthic macroinvertebrate filter feeding has been shown to act as a natural eutrophication control in many shallow estuaries (Officer et al. 1982, Hily 1991). Extremely clear water and low chlorophyll concentrations have been noted concurrent with dense concentrations of a solitary tunicate that has occasionally been present during the winter since 1987 in shallow areas of Hillsborough Bay (Pinson 1991). Also, survival of the benthic filter feeding amphipod *Ampelisca* appears to have improved recently with better bottom oxygen conditions (COT, unpublished). Santos and Simon (1980a and 1980b) attributed large scale die-offs of *Ampelisca* and other benthic animals to annual recurring hypoxia events of bottom waters in Hillsborough Bay during the late 1970s. A comprehensive benthic inventory study and a long-term monitoring program should be initiated. Further, the benthic habitats found in the large muddy areas in Hillsborough Bay should receive protection from damage caused by activities such as shrimp trawling and bait purse-seining. Protection of these habitats would also reduce sediment resuspension (USGS, unpublished).

Third, seagrasses may become important storage of nutrients, and as such, act as natural eutrophication control processes. It has been shown in Chesapeake Bay that seagrasses assimilate nitrogen primarily during spring and summer, and thus effectively reduce the amount of nitrogen available to the phytoplankton during the most active phytoplankton growing period (Kemp et al. 1984). Seagrass mortality and nitrogen release usually occurs during late fall and early winter when the nitrogen demand by the phytoplankton is relatively small. Kemp et al. (1983) estimated that the submerged vascular plant community that existed in Chesapeake Bay in 1960, before large vegetation losses occurred, could have acted as a seasonal sink for 7% of the nitrogen input from external sources. Therefore, the restoration of Tampa Bay seagrass meadows may not only increase physical habitat, particle trapping and food resources, but may also accelerate the recovery from eutrophication.

It is important to estimate and include the natural control processes in predictions of future chlorophyll concentrations. Consequently, before these processes are better understood, use of the nitrogen loading/chlorophyll model is limited to conservative estimates of future chlorophyll concentrations in Hillsborough Bay. With these shortcomings in mind, two examples are given below to illustrate the potential use of the model as a management tool.

First, the loss of nitrogen from the fertilizer loading terminals in Hillsborough Bay has been estimated at approximately 770 metric tons/yr (see above). If this estimate is accurate and the loss was eliminated, then the ambient chlorophyll concentrations in Hillsborough Bay should be reduced from the current 15 µg/l to a conservatively estimated concentration of near 10 µg/l. Actions are now underway to reduce this source and a study is planned to evaluate its current impact on water quality.

Second, if current external loadings to Hillsborough Bay from the sources discussed in Figure 4 were reduced by more than 1000 metric tons/year, a level of 5 µg/l or less of chlorophyll would be reached. This chlorophyll concentration has been suggested as the required level for Tampa Bay seagrass survival and propagation by TBRPC (1989). Improved handling of fertilizer at the shiploading terminals will probably account for a significant fraction of the needed reductions. However, the 1000 metric tons/yr reduction may be a difficult goal to reach in the near-term. The large external nitrogen sources to Hillsborough Bay that were identified several decades ago have already been reduced substantially. Several remaining potentially large sources, all inadequately evaluated, include losses from shiploading terminals, stormwater runoff from urban and agricultural lands, and loadings from the atmosphere, groundwater and septic waste. Assuming that the shiploading terminal losses will be corrected, then it may become difficult to implement additional large scale nitrogen reductions. However, it is encouraging that the projection above does not include the potential increase in future nitrogen losses from natural eutrophication control processes and may, as a result, be overly pessimistic.

These examples have illustrated the potential of the nitrogen loading/chlorophyll model to predict future Tampa Bay conditions and responses to management actions. Additional work to refine the relationship include improved loading estimates and increased knowledge of natural control processes. Further, the relationship needs to be linked to important natural resources, such as seagrasses and soft bottom communities, to help protect these and other valuable resources. A model based on the nitrogen loading/chlorophyll relationship is currently used in an Australian coastal embayment to manage and protect seagrasses (Pearce 1991). In Chesapeake Bay, a similar model is proposed to maintain adequate bottom oxygen conditions and protect benthic communities (Boynton et al., in press).

CONCLUSION

Several important water quality and biological indicators have recently improved in Hillsborough Bay in an apparent response to a substantial reduction in nitrogen loading to the bay from many important external sources. The reduction may have been as large as 50% and is related to actions aimed at reducing nutrient loadings to Tampa Bay, specifically from wastewater plants and the fertilizer industry. There is little evidence that the recent lower than average rainfall has been a significant factor of the improvement. Seagrasses have apparently responded to the improved water quality by colonizing shallow areas in Hillsborough Bay and other sections of Tampa Bay. The return of seagrass meadows is in an important sign of bay recovery.

In this report, a first attempt has been made to relate the long-term nitrogen loading to Hillsborough Bay from external sources to water quality conditions in the bay. A simple eutrophication model based on the nitrogen loading/chlorophyll relationship is presented. However, much work is still needed to refine the relationship. Specifically, the major external nitrogen sources and the natural eutrophication control processes should be better quantified. Atmospheric loadings, most stormwater loadings, and loadings from groundwater, septic waste and several tributaries have not been included in the current calculations due to lack of adequate information. However, the sources which have been addressed are some of the most important ones and also the ones which probably have shown the greatest change over the period of study. It is important that the eutrophication model is based on a long-term record spanning several decades to allow for separation of natural and manmade effects, and also to reduce the potential for costly overprotective actions. The model should be used in combination with a comprehensive monitoring program of loading sources, water quality, biological indicators and important natural control processes. Further, the nitrogen loading/chlorophyll model should be linked to valuable natural resources, such as seagrasses and soft bottom communities, to help protect these and other important resources in Tampa Bay.

ACKNOWLEDGEMENTS

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APPENDIX

The source of all nitrogen loadings for the period 1967-68 (Table 1) and the year 1968 (Figure 5), except shiploading losses, are from FWPCA (1969). Shiploading losses have been estimated as 0.05% of the amount of ammonium-phosphate product shipped from the Port of Tampa (TPA, unpublished).

Loadings from rivers and creeks for the period 1969-90 have been calculated from the sources listed below and at the locations described by Johansson and Lewis (in press). However, the Alafia River lacks concentration information for the period 1969-1973; therefore, concentrations for 1969-73 were calculated from 1969-73 flows and a regression relationship between flows and concentrations for the period 1973-79. Further, Delaney Creek lacks flow information for the period 1969-84 and concentration measurements for the period 1969-80. Therefore, 1980-84 loadings were calculated from a regression relationship between Delaney Creek and Bullfrog Creek flows for the period 1985-89. Delaney Creek loadings for the period 1969-79 were estimated to be equal to 1968 Nitram loadings.

River and creek flows are from USGS (1976, 1977, 1978, 1979, 1980a, 1980b, 1982, 1983, 1985, 1986a, 1986b, 1987, 1988, 1989, 1990), USGS (unpublished) and SWFWMD (unpublished). Concentrations are from Wilkins (1980, 1981, 1982), Cardinale and Boler (1984), Boler (1986, 1988, 1990) and HCEPC (unpublished). Additional Alafia River concentrations are from USGS flow references.

Cargill Fertilizer, Inc. supplied point-source loadings for the period 1981-90. Loadings for the period 1969-80 were estimated to be equal to 1968 loadings.

Hookers Point Wastewater Treatment Plant loadings for the period 1975-90 are from plant operation reports. Loadings for the period 1969-74 have been estimated from a linear relationship between 1968 and 1975 measurements.

McDill AFB Wastewater Treatment Plant has had no direct discharge to the bay during the last decade.

Chlorophyll concentrations are from FWPCA (1969), Saloman and Taylor (1972), Saloman (1973, 1974), Collins and Finucane (1974), Saloman and Collins (1974), Shaw and Wilkins (1975, 1976, 1977, 1978), Wilkins (1979, 1980, 1981, 1982), Cardinale and Boler (1984), Boler (1986, 1988, 1990), and HCEPC (unpublished).

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STATUS OF NATURALLY OCCURRING AND INTRODUCED *HALODULE WRIGHTII* IN HILLSBOROUGH BAY

W. M. Avery

ABSTRACT

In 1986, the City of Tampa Bay Study Group (BSG) started a seagrass program to complement other ongoing research assessing the environmental status of Hillsborough Bay. The initial survey in 1986 located 137 patches of naturally occurring Halodule wrightii (Ascherson). The areal coverage of these patches was nearly 2000 m^2. A second survey in 1989 found about 400 patches with areal coverage totaling 5000 m^2. In 1986, eight patches were selected as study sites. Total areal coverage of the study sites increased from 150 m^2 in 1986 to 1175 m^2 in 1990. In 1987, the BSG transplanted H. wrightii to eight locations in Hillsborough Bay. About 10.7 m^2 of donor material were transplanted as sod blocks to seven areas and 2.3 m^2 of material were used to plant bare root units in the eighth area. In 1990, three years after planting, transplant areal coverage was estimated at 825 m^2. Many intertidal and shallow subtidal areas in Hillsborough Bay are being recolonized by H. wrightii, apparently in response to recent improvements in water quality. As a result of increased water clarity, sufficient light may be available to allow seagrass recolonization to occur in shallow areas of Hillsborough Bay. If Hillsborough Bay water quality continues to improve, H. wrightii should recolonize most areas which historically had seagrass coverage.

INTRODUCTION

Seagrass meadows are an important constituent of the Tampa Bay ecosystem. They are among the most productive environments on earth (McRoy and McMillan 1977) and provide food, shelter and a nursery for many fish and invertebrates (Phillips 1960, Livingston 1984). Seagrass can significantly contribute to the organic carbon budget (Kemp et al. 1984) and are used indirectly in detrital food chains (Thayer et al. 1975). Established seagrass beds can improve water quality by reducing water velocity through the leaf canopy, which may enhance particulate settling rates (Ginsburg and Lowenstam 1958), and by decreasing the potential for erosion and resuspension of benthic sediments (Kemp et al. 1984).

Environmental degradation related to urbanization around Tampa Bay has resulted in an 81% reduction of historical seagrass coverage in the past century (Lewis et al. 1985). Lewis and Phillips (1980) reported a 79.6% loss of seagrass coverage in Hillsborough County from 1876 to 1980, with significant losses occurring in the past thirty years.

In 1960, Phillips (1962) surveyed seagrass coverage in Tampa Bay. In western Hillsborough Bay, between Gadsden Point and Ballast Point, extremely sparse coverage of *Diplanthera wrightii* (*Halodule wrightii*) was noted and *Ruppia maritima* was the only species observed north of Ballast Point. In eastern Hillsborough Bay, *R. maritima* was found near Delaney Creek, with sparse coverage observed south of the Alafia River. Phillips found *H. wrightii*, *R. maritima* and *Syringodium filiforme* in the Big Bend area, which is just north of Apollo Beach. Two decades later, Lewis et al. (1985) reported Hillsborough Bay supported only ephemeral *R. maritima* beds.

Hillsborough Bay has been severely impacted by urbanization. Dredge and fill operations have increased turbidity and removed substrate which may provide a suitable habitat for seagrass (Lewis 1977). Also, nutrient inputs from municipal and industrial sources caused increases in phytoplankton and macroalgae biomass, which reduce light available to seagrass beds. In the late 1960s, the Federal Water Pollution Control Administration (1969) implicated the City of Tampa Hookers Point Wastewater Treatment Plant as a major point source polluter in Hillsborough Bay.

In the past two decades, measures have been taken to alleviate impacts of municipal and industrial discharge to Hillsborough Bay. The City of Tampa upgraded the Hookers Point facility to advanced wastewater treatment in 1979, which resulted in the removal of over 90% of BOD, suspended solids, and nitrogen. Also, nutrient loadings to freshwater systems which drain into eastern Hillsborough Bay have been reduced due to increased regulation of the fertilizer industry (Estevez and Upchurch 1985; Johansson and Lewis, in press).

Reduction in nutrient loadings to Hillsborough Bay has resulted in substantial improvement in water quality since the mid-1980s. Water quality information collected by the City of Tampa Bay Study Group (City of Tampa 1988) and the Hillsborough County Environmental Protection Commission (Boler 1990) show a decrease of phytoplankton biomass concurrent with greater water clarity. Also, the Tampa Bay Regional Planning Council (1989) reviewed information on chlorophyll *a* and noted that chlorophyll *a* concentrations, after a period of elevation from 1969-1983, have returned to pre-1969 levels.

Aerial photographs from 1983-1986 provided evidence of minor seagrass renewal in Hillsborough Bay. This evidence prompted the City of Tampa Bay Study Group (BSG) to initiate a program to investigate the response of seagrass to improvements in water quality. Documentation of seagrass coverage in Hillsborough Bay began in April 1986 with a thorough groundtruthing effort in which each patch of *H. wrightii* was measured for areal coverage and mapped. A second groundtruthing effort was completed in October 1989. In addition, study sites have been established to follow seasonal trends of *H. wrightii*. In June 1986, the BSG and Mangrove Systems, Inc. (MSI) groundtruthed an area of eastern Middle Tampa Bay for seagrass. The groundtruth data was used to produce maps documenting re-establishment of *H. wrightii* between 1983 and 1988 using aerial photographs.

In 1987, the BSG, in cooperation with the Florida Department of Natural Resources and National Marine Fisheries Service Tampa Bay Experimental Seagrass Planting Effort, transplanted *H. wrightii* into Hillsborough Bay (City of Tampa 1991). This effort was designed to locate areas of Hillsborough Bay suitable for seagrass transplanting, to establish a source of vegetative material, and to determine if artificially introduced seagrass could generate functional seagrass communities.

STUDY SITES

Bay Study Group — Mangrove Systems, Inc.

In June 1986, the BSG and MSI sampled six transects, oriented perpendicular to the shoreline, in the intertidal-subtidal zone in eastern Middle Tampa Bay (Mangrove Systems, Inc. 1986, City of Tampa 1988). Two transects were previously examined by Lewis and Phillips (1980). The species composition and percent cover of seagrass and drift algae were estimated at 80 m intervals along each transect. Data from the groundtruth effort and color aerial photographs (scale 1"=500') were used to compare seagrass coverage in eastern Middle Tampa Bay between 1983 and 1986. Subsequently, the City of Tampa contracted MSI to estimate seagrass coverage in an area delineated by a 3 x 1 km rectangle located approximately 350m from shore utilizing vertical aerial photographs from 1983-1986 and 1988 (Figure 1). This area, with little macroalgae cover and only one seagrass species, *H. wrightii*, was selected to minimize interpretive errors.

Natural Seagrass

The City of Tampa (1988) selected eight patches of *H. wrightii* in Hillsborough Bay, representing a variety of geographic locations and substrate characteristics, for detailed study (Figure 2). A square grid (Figure 3) was set up to encompass each *H. wrightii* patch and the boundaries of each patch were measured in relation to the grid at 0.5 m intervals.

Areal coverage, short shoot density, blade length, salinity, surface water temperature, and depth were recorded in spring, summer, and fall surveys. In addition, subjective observations on epiphytic cover and condition of the seagrass were noted. The boundary of a patch was plotted on paper and the areal coverage calculated using a planimeter.

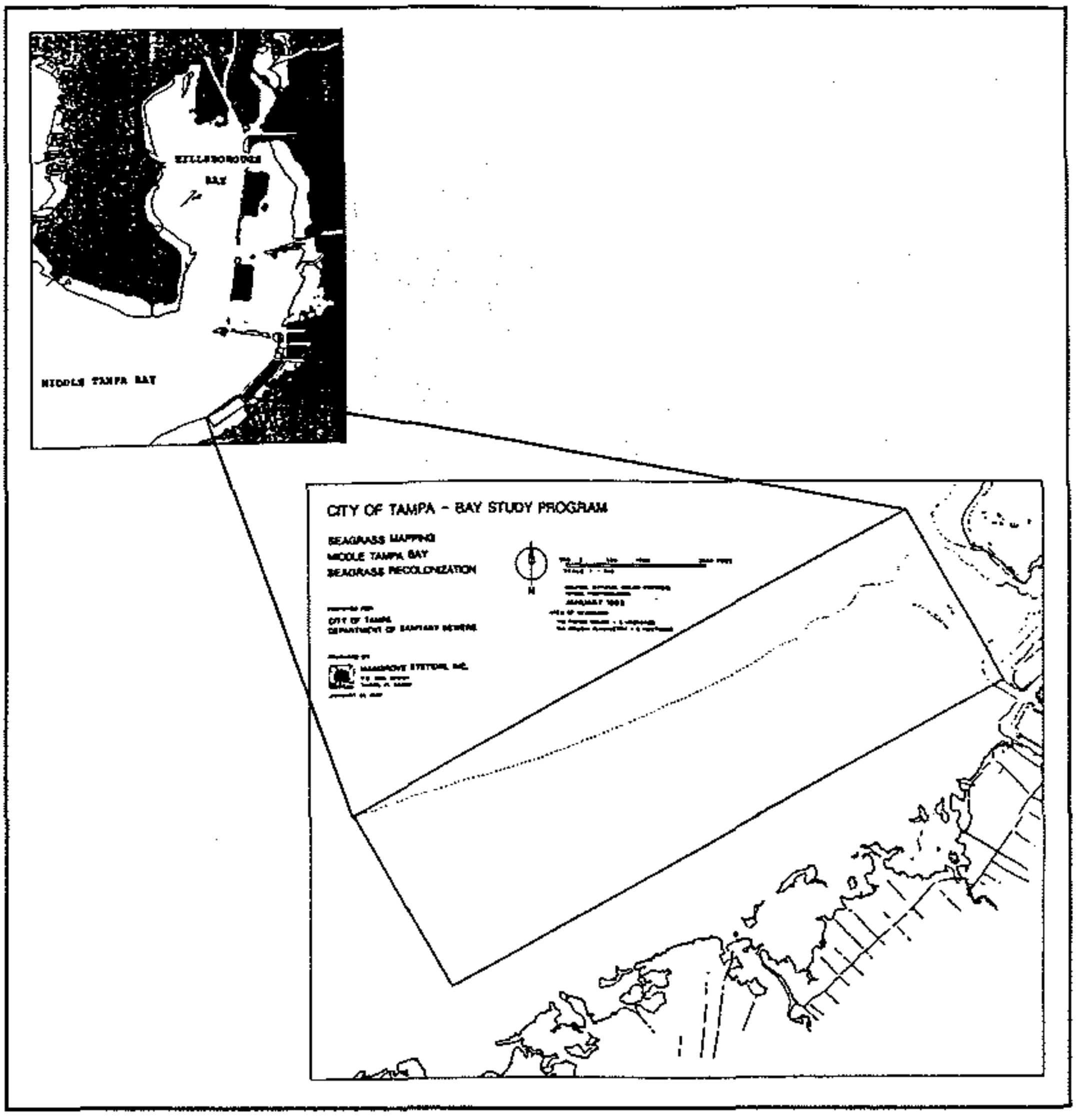

Figure 1. Halodule wrightii study site in eastern Middle Tampa Bay.

Transplanted Seagrass

Halodule wrightii sod blocks and bare root units were used in the 1987 transplanting effort. Source material was obtained from beds to be impacted from the widening of the Courtney Campbell Causeway traversing Old Tampa Bay. Approximately 350 sod blocks were planted in seven areas around Hillsborough Bay (Figure 4). An average sod block measured 14 x 23 x 15 cm and contained 170 short shoots and 23 apical meristems. In the eighth area (Figure 4), 861 bare root units were planted in a 10 x 20 m plot using methods described by Fonseca et al. (1987). An average bare root unit contained an average of 15 short shoots and 3 apical meristems.

Each transplant area was visited in the spring, summer and fall. Areal coverage, short shoot density, blade length, epiphytic cover, salinity, surface water temperature, and depth were recorded. The major and minor axis of each sod block was measured and the areal coverage estimated using the formula for an ellipse. In the first four surveys, 10% of the bare root units were randomly selected for an estimate of areal coverage. Areal coverage of each selected unit was estimated using the formula for an ellipse. Total areal coverage was estimated by multiplying the average bare root unit areal coverage times the number of surviving units. However, after the fourth survey, the bare root units began to coalesce and the areal coverage was determined using the grid method as in the natural seagrass study sites.

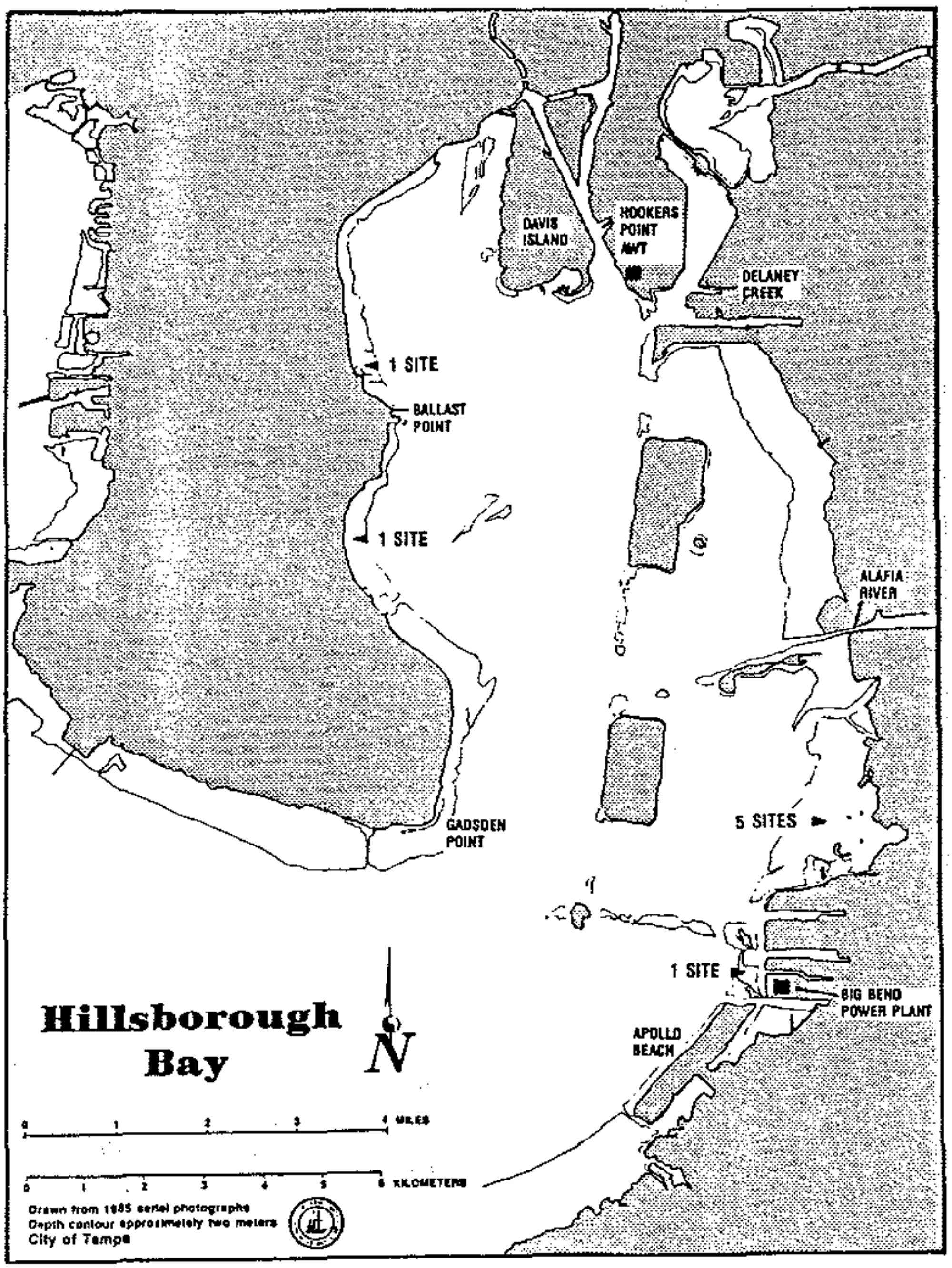

Figure 2. Halodule wrightii study sites in Hillsborough Bay.

Aerial Surveys

Seagrass surveys of Hillsborough Bay and adjacent areas have been conducted using on-site groundtruthing and aerial photography. Monthly low altitude surveys by helicopter and annual high altitude surveys by fixed-wing aircraft are used for oblique and vertical photography, respectively.

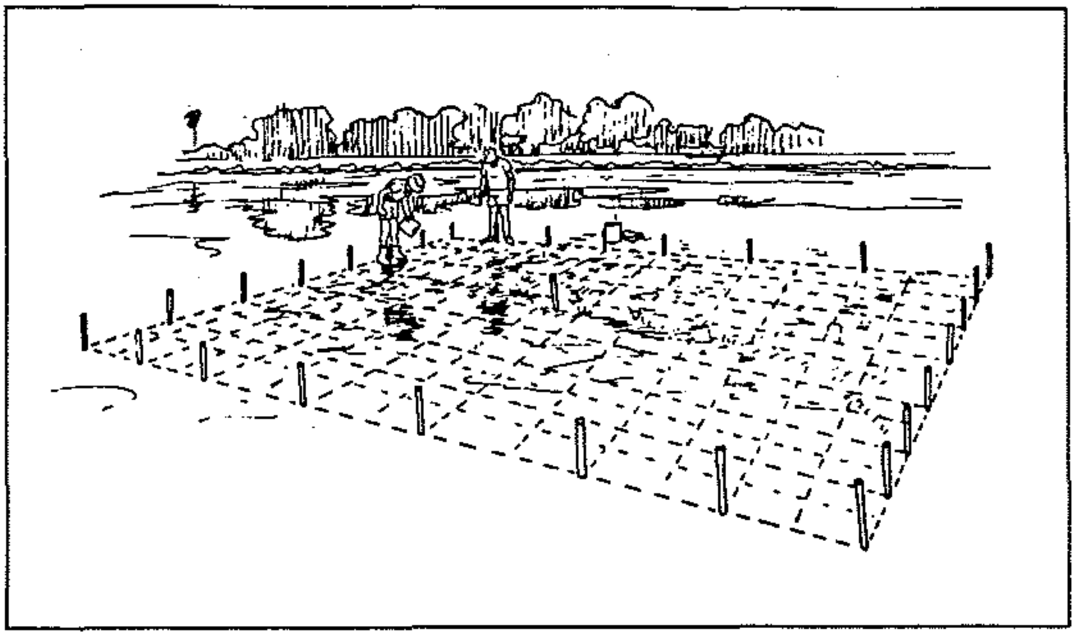

Figure 3. Grid system of a Halodule wrightii study site with PVC pipes at 1 m intervals. Dashed lines represent measuring tape placement for measurement of patch dimensions.

RESULTS AND DISCUSSION

Middle Tampa Bay Survey

In the six transects sampled in eastern Middle Tampa Bay, *Halodule wrightii* was the dominant species observed (Mangrove Systems, Inc. 1986). *Thalassia testudinum* was the next most frequently observed species and areas of *Ruppia maritima* were observed in the shallow inshore areas at each transect. MSI concluded there was greater seagrass coverage in the southern transects in 1986 compared to 1983. Further, inshore stations at each transect had greater seagrass coverage in 1986.

Recent seagrass recolonization has been documented in the 3 km^2 study area mapped by MSI. MSI reported no *H. wrightii* in the study area in the 1983 or 1984 aerial photographs. The 1985 photograph indicated seagrass renewal in the study area and areal coverage was determined at 6.4 ha. Subsequent photographs from 1986 and 1988 showed about 13 ha and 60 ha of *H. wrightii*, respectively (Figure 5).

Hillsborough Bay 1986 and 1990 Surveys

The BSG has completed two thorough groundtruth efforts to document *Halodule wrightii* coverage in Hillsborough Bay. The initial effort in 1986 located 137 patches of *H. wrightii* with total areal coverage of nearly 2000 m^2. In the second survey conducted three years later (October 1989), the BSG located 394 patches of *H. wrightii*, an increase of 190%, and the total areal coverage had increased by 140% to 4700 m^2. After reviewing photographs from monthly Hillsborough Bay overflights and evaluating study site information, the BSG estimated *H. wrightii* coverage to be 8000 m^2 in October 1990.

Seagrass recolonization patterns may reflect spatial differences in Hillsborough Bay water quality. Recolonization of shallow tidal flats in western Hillsborough Bay has occurred at the same elevation as seagrass coverage observed in 1986 and there has been no indication of recolonization in deeper areas. In contrast, recolonization in southeastern Hillsborough Bay has occurred at the same elevation as pre-existing beds and in areas 25-50 cm deeper than seagrass coverage observed in 1986. Recolonization trends in southeastern Hillsborough Bay may reflect better water quality in this portion of the bay.

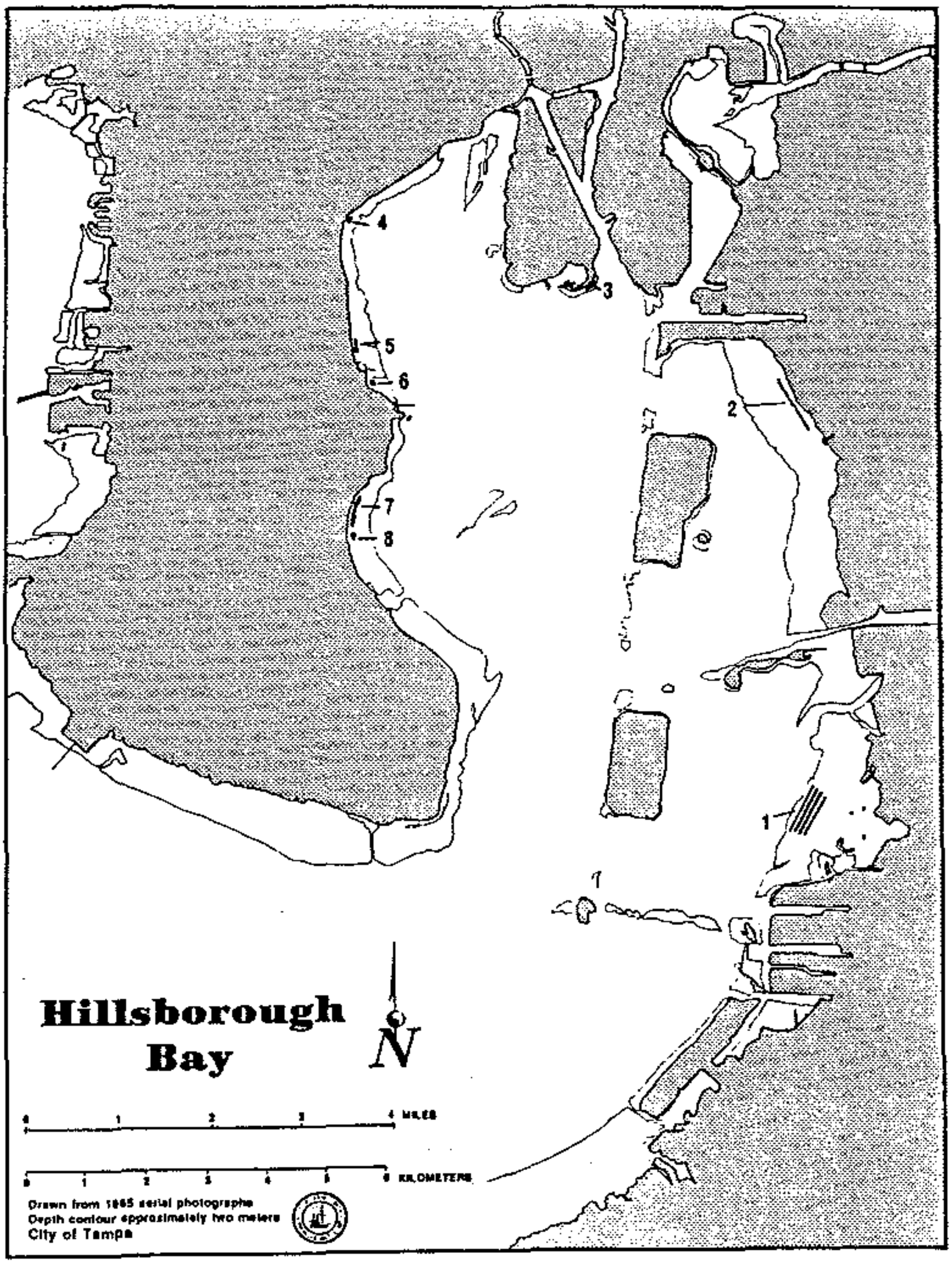

Figure 4. Halodule wrightii test planting sites.

Hillsborough Bay Study Sites

Total areal coverage for the study sites of natural *Halodule wrightii* was 147 m^2 in 1986 and had increased to 1178 m^2 in 1990 (Figure 6). Total areal coverage calculated in 1990 has included coalition of coverage at three study sites with adjacent patches of *H. wrightii* not previously included in the calculations.

The study sites were originally selected to estimate *H. wrightii* growth rates in Hillsborough Bay. However, the information was also used to estimate 1989 *H. wrightii* areal coverage in Hillsborough Bay for comparison with the areal coverage determined from the 1989 groundtruthing effort. Estimates of areal coverage using study site information were 40% higher than areal coverage determined by the groundtruth effort. Therefore, extrapolations made from study site information cannot be used to accurately estimate total *H. wrightii* coverage. Frequent surveys using aerial photography and on-site groundtruthing are imperative for accurate determination of seagrass coverage.

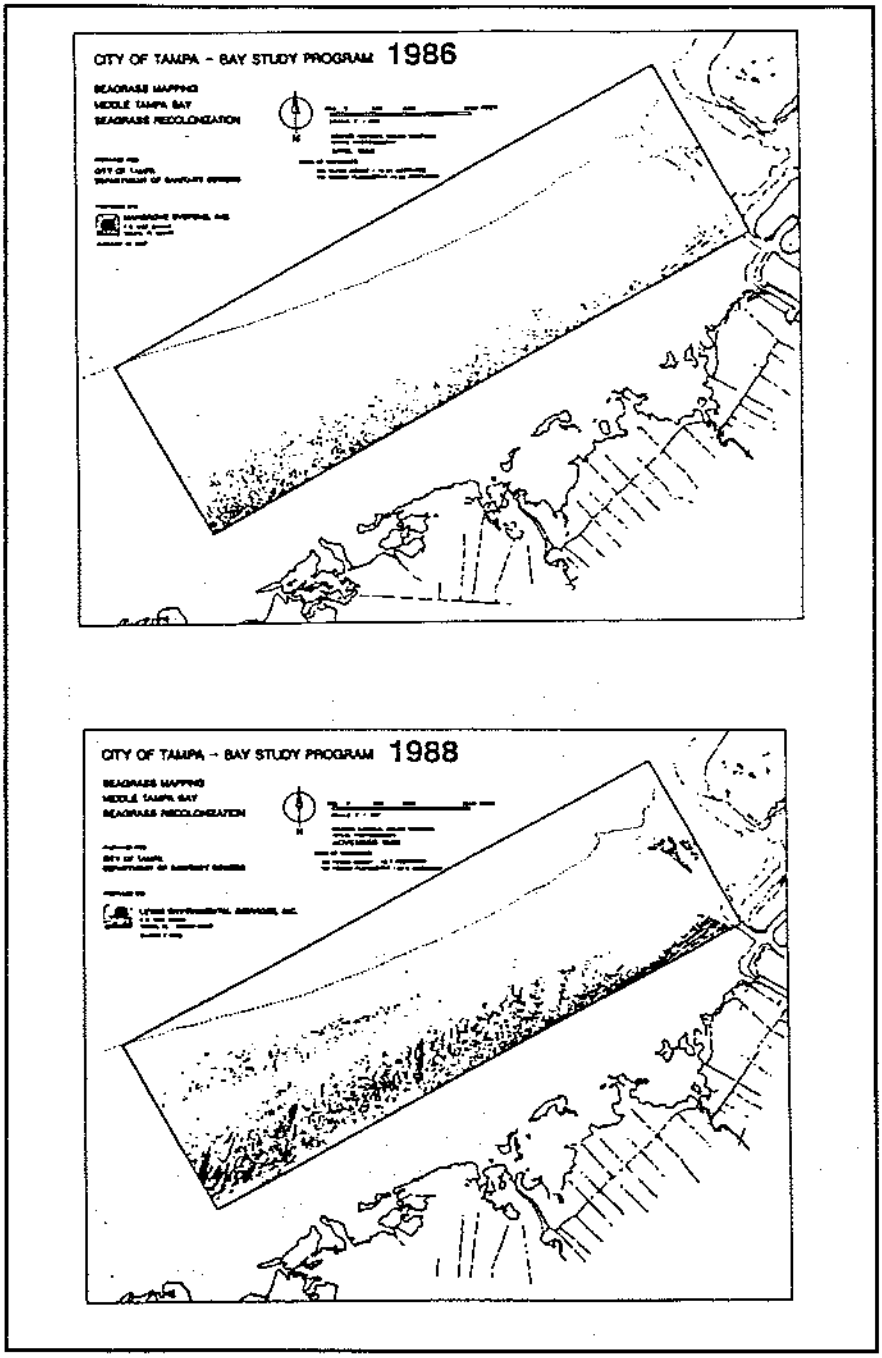

Figure 5. Halodule wrightii coverage in eastern Middle Tampa Bay in 1986 and 1988.

Natural Recolonization

Halodule wrightii coverage appears to be increasing rapidly in several areas of Hillsborough Bay. It is uncertain how revegetation of areas barren of seagrass is initiated as there has been no documentation of *H. wrightii* seed production in

Hillsborough Bay. However, bioturbation of seagrass, probably by the stingray, *Dasyatis sabina*, is a frequent occurrence and is one method to initiate rhizome dispersal. Also, *H. wrightii* may be uprooted by natural events (erosion by waves or tides) or by anthropogenic impacts (ship-generated waves, propeller cuts, dredge and fill). The polychaete, *Diopatra cupraea*, has been observed to add seagrass fragments to its habitat. These fragments may subsequently root and provide vegetative material for colonization.

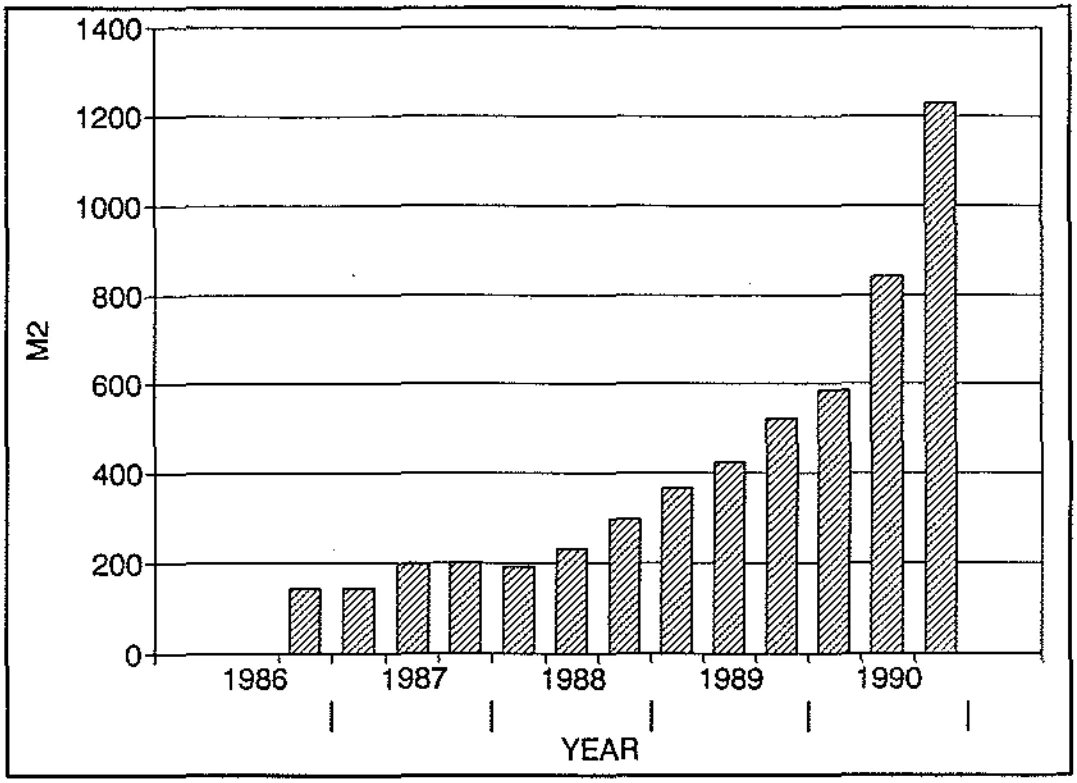

Figure 6. Total areal coverage for the Halodule wrightii study sites in Hillsborough Bay.

Transplants

In October 1990, three years after the initial planting of *Halodule wrightii* sod blocks and bare root units, transplants persisted in five of eight test areas. The transplanted material has expanded from an initial coverage of 13 m^2 in 1987 to over 800 m^2 in 1990 (Figure 7). Of the 350 sod blocks initially planted, about 40 have persisted. Areal coverage of the sod block planting in 1990 was about 525 m^2. An estimated 35% of the 861 bare root units survived nearly one year after planting. However, subsequent coalition of the bare root units made additional survival estimates impossible. Areal coverage of the bare root planting in 1990 was about 290 m^2.

In southeastern Hillsborough Bay, one *H. wrightii* sod block transect was planted at a depth 75 cm deeper than a similar transect 250 m closer to shore. Generally, *H. wrightii* short shoots in shallower areas reach maximum density by the summer and begin to decrease in the fall. However, short shoot densities in the deeper transect do not follow a seasonal pattern, with the exception of winter senescence. Also, areal expansion in the deeper transect is erratic and does not follow the trend of regular seasonal growth seen in the shallow transplants. The lack of seasonality in short shoot density and areal expansion may indicate that water quality is not yet sufficient to allow recolonization to occur in deeper areas which historically had seagrass coverage.

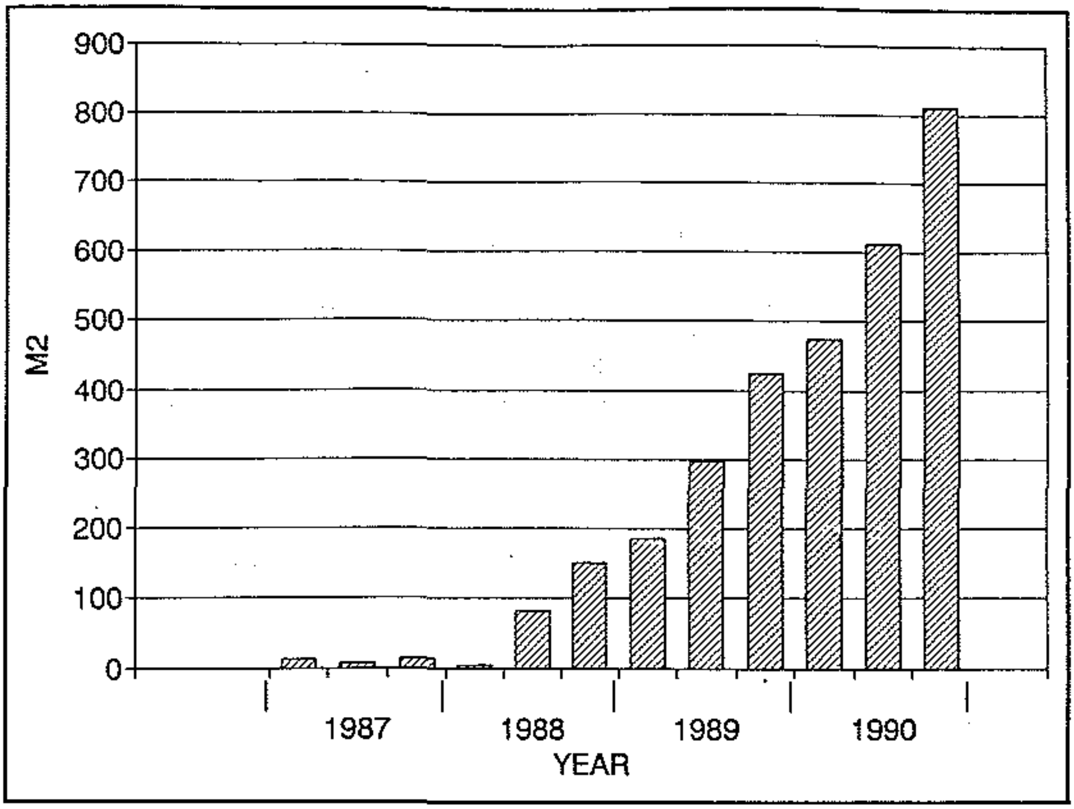

Figure 7. Areal coverage of transplanted Halodule wrightii in Hillsborough Bay.

Results from the transplant effort have been encouraging. Many sites suitable for seagrass transplanting have been identified and vegetative material has been provided to areas where little or no natural *H. wrightii* existed in 1987. Both methods have produced seagrass patches which have similar short shoot densities (5000/m^2) and maximum average blade length (30-35 cm) as the donor site. Meyer et al. (1990) concluded that *H. wrightii* transplanted into Tampa Bay in 1987 attained many functional characteristics of the natural reference beds within three years.

Recent Impacts on Seagrasses

Light availability for seagrass may be attenuated through shading by epiphytic or unattached algae, or by decreased water clarity (Cambridge et al. 1986). Thick mats of macroalgae, mostly *Ulva lactuca*, apparently killed naturally occurring and transplanted *H. wrightii* in two areas of Hillsborough Bay in late 1987 and early 1988. Also, an increase in phytoplankton biomass can reduce water clarity and apparently is the limiting factor allowing recolonization to occur in deeper areas which historically had seagrass. The appearance of macroalgae mats and occasional phytoplankton blooms may reflect the nutrient loading still occurring in Hillsborough Bay (Johansson and Lewis, in press).

Resuspension of sediments into the water column may exacerbate light attenuation in the water column. Tides, wind, ship channel maintainence dredging, ship traffic, commercial seafood harvest, and stormwater runoff promote resuspension and reduce light needed for seagrass persistence and growth.

Waves generated by maritime traffic may affect seagrass distribution. Two transplant areas may be considered high energy zones and about 20% of the sod blocks planted in these areas were probabaly lost to erosion.

Lack of awareness by commercial and recreational boaters may cause additional losses of seagrass. Propeller cuts in natural and transplanted *Halodule wrightii* beds in Hillsborough Bay have been seen. Boaters may be unaware of where seagrasses occur or they may not consider the impacts boats may have on seagrass beds.

Future Considerations

As Hillsborough Bay water quality continues to improve, *Halodule wrightii* should continue to colonize most shallow areas which historically had seagrass meadows. Therefore, large-scale *H. wrightii* transplant efforts in Hillsborough Bay may not be necessary. However, transplanting of *Syringodium filiforme* and *Thalassia testudinum*, the species next in colonizing succession, should be attempted in selected areas of Hillsborough Bay. Limited transplantings of these species would determine their ability to grow in Hillsborough Bay, and introduced material may provide a vegetative source for recolonization.

Activities which impede seagrass recolonization must be evaluated and arbitrated in favor of a healthier estuary. Continued identification and reduction of nutrient loadings to Tampa Bay is imperative. Also, activities which promote resuspension of sediments into the water column need to be controlled and minimized. Finally, commercial and recreational boaters must be educated on the importance of seagrass meadows, the effect that boating activities may have on seagrass, and efforts to revitalize and protect seagrass as a resource.

CONCLUSION

After several decades of declining seagrass coverage in Hillsborough Bay, limited *Halodule wrightii* recolonization is occurring concurrently with improving water quality. Monitoring changes in the seagrass community may be a useful tool to determine the health of Tampa Bay.

A standardized seagrass monitoring program should be established immediately in all sections of Tampa Bay. Annual photographic surveys from aircraft would provide documentation of the extent of Tampa Bay seagrass meadows. Further, transects should be established throughout Tampa Bay to follow the response of seagrass to changes in water quality.

Transplant efforts have been successful. Areas of Hillsborough Bay which are now able to support seagrass have been identified and a source of vegetative material has been established in several locations to enhance recolonization. Also, transplanted *H. wrightii* in Hillsborough Bay apparently provides a habitat similar to natural reference beds.

Large-scale *Halodule wrightii* transplant efforts may not be necessary due to the ability of the seagrass to rapidly cover a suitable site. Vegetative material established by small scale plantings in areas lacking seagrass may provide sufficient source material to promote recolonization. However, small-scale test plantings of *Syringodium filiforme* and *Thalassia testudinum* into selected areas of Hillsborough Bay should be considered in the future.

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RECENT AREAL EXPANSION OF SEAGRASS MEADOWS IN TAMPA BAY, FLORIDA: REAL BAY IMPROVEMENT OR DROUGHT-INDUCED?

R. R. Lewis III
K. D. Haddad
J. O. R. Johansson

INTRODUCTION

Lewis et al. (1985) summarized the information available on seagrass meadows in Tampa Bay at the first Bay Area Scientific Information Symposium in 1982. They reported that their best estimate of seagrass meadow coverage at that time (c. 1981) for the estuary was 5,750 ha (14,203 acres). Comparing this coverage with aerial photography dating back to 1938 and maps back to 1848, they estimated historical seagrass cover to have been 30,970 ha (76,496 acres). These data are compared with recent efforts by other researchers to determine similar trends in seagrass cover. The c. 1981 mapping data have been re-examined for this analysis and updated through 1988 to determine if the seagrass recovery process observed and reported by Johansson and Lewis (in press) has occurred baywide.

METHODS

Using the Florida Department of Natural Resources Marine Resources Geographic Information System (MRGIS), 1988 true color vertical aerial photography at 1:24,000 scale (Southwest Florida Water Management District [SWFWMD], Surface Water Improvement and Management [SWIM] Program) was computer digitized and interpreted. This effort was similar to previous efforts for c. 1950 and 1982 photography (Haddad 1989). The digitized data are presented as baywide maps (Figures 1-3).

RESULTS

Table 1 summarizes the seagrass areal cover for the three time periods (1950, 1982, 1988) by portion of the bay. All areas except Old Tampa Bay showed increases between 1982 and 1988. This may be an interpreting error within the SWFWMD - SWIM seagrass maps. This is being reinterpreted to check the potential error.

We feel comfortable, however, in stating that there has been a minimum of 919 ha (2,271 acres) of new seagrass meadows added to the Tampa Bay System during the 1982-1988 period. Our preliminary review of the 1990 SWIM photography indicates that this increase may be continuing. The Middle Tampa Bay area offshore of Wolf Branch that has been monitored by Johansson and Lewis (in press) is shown in Figure 4. An additional increase beyond that apparent in the 1988 photography is evident.

Table 1. Seagrass coverage in Tampa Bay: 1950, 1982, 1988 (hectares).

	1950	1982	1988
Old Tampa Bay	4,393	2,405	2,119
Hillsborough Bay	1,110	0	25
Middle Tampa Bay	3,844	1,636	2,287
Lower Tampa Bay	2,471	2,030	2,272
Terra Ceia Bay	297	304	399
Manatee River	51	53	99
Boca Ciega Bay	4,282	2,335	2,482
TOTAL	16,448	8,764	9,683

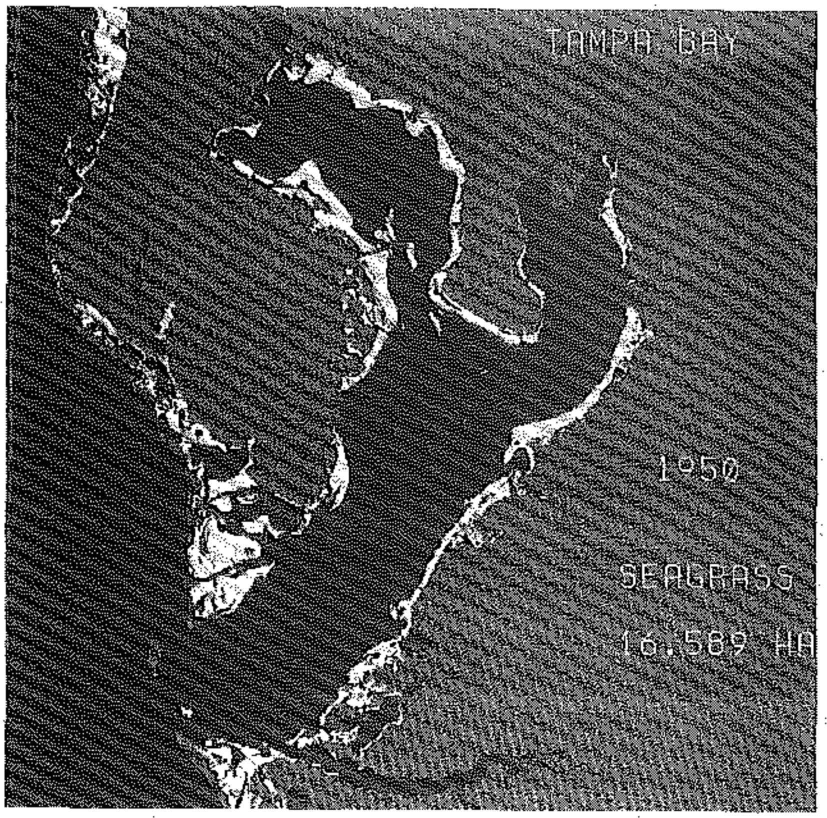

Figure 1. Seagrass coverage in Tampa Bay, 1950.

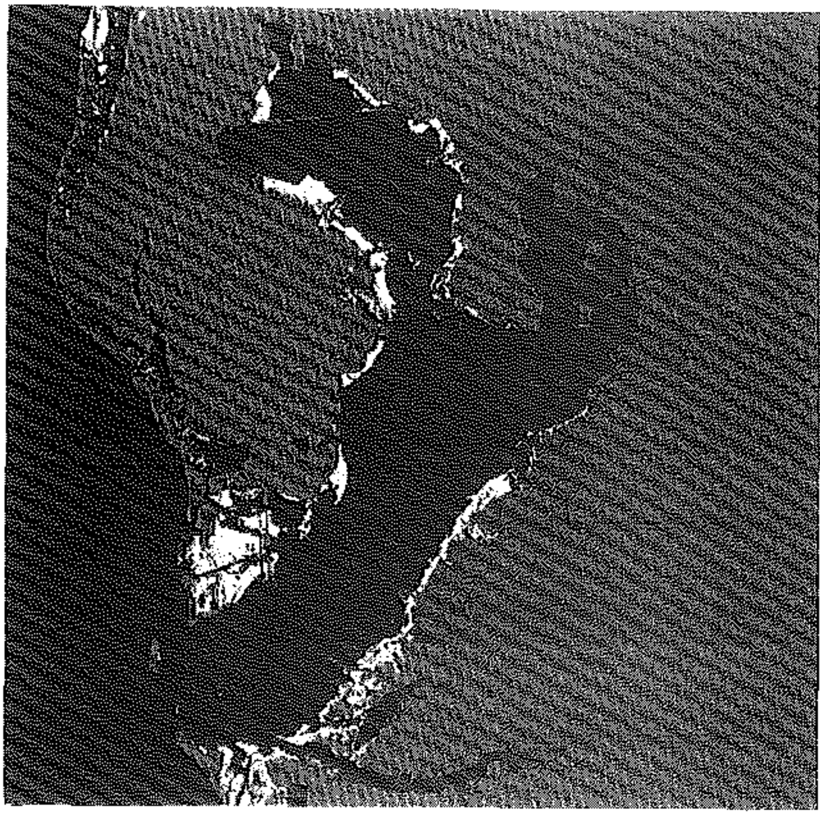

Figure 2. Seagrass coverage in Tampa Bay, 1982.

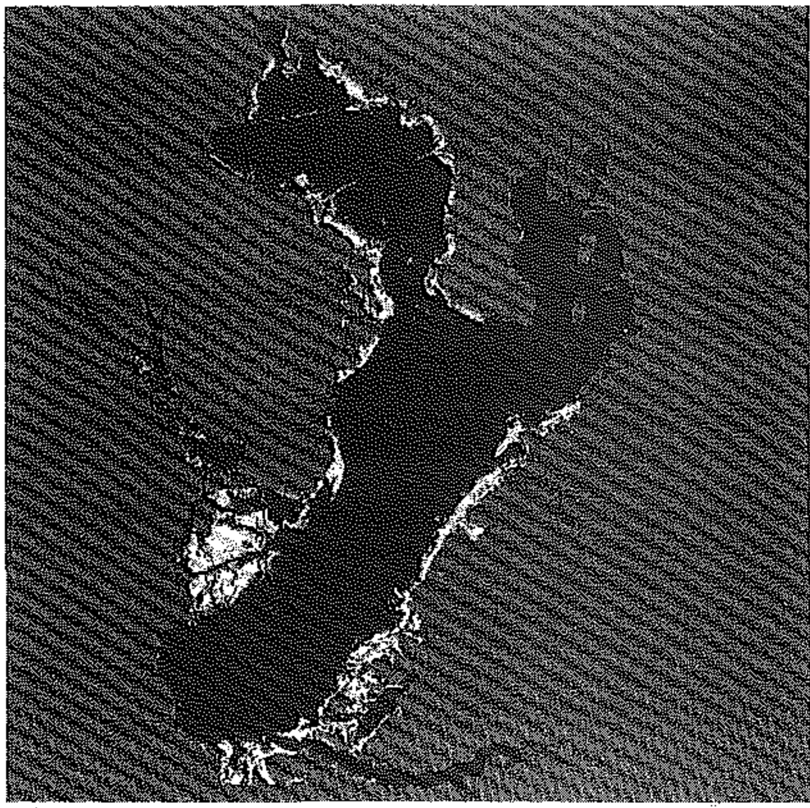

Figure 3. Seagrass coverage in Tampa Bay, 1988.

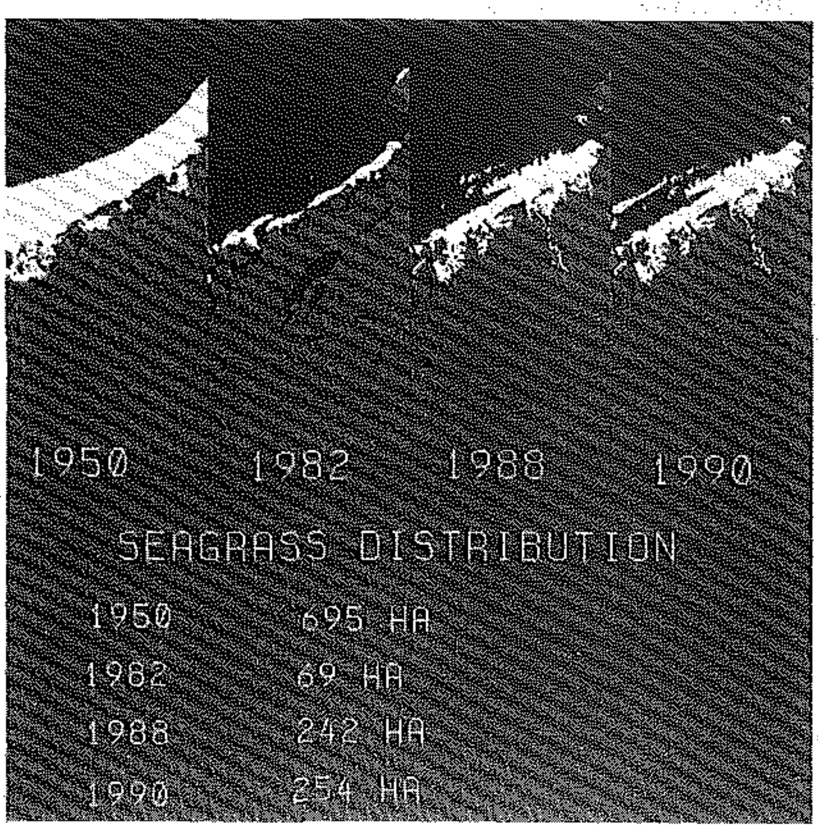

Figure 4. Seagrass recovery in Middle Tampa Bay, offshore of Wolf Branch.

DISCUSSION

Johansson and Lewis (in press) have documented improvements in water quality apparently associated with concurrent improvements to sewage treatment, particularly at the City of Tampa's Hookers Point Sewage Treatment Plant. These improvements are at least partially responsible for the significant decreases in chlorophyll *a* and increases in water clarity (Johansson, this volume) documented in Hillsborough Bay and Middle Tampa Bay.

At the same time however, a multi-year drought has significantly reduced watershed drainage into the bay. Kenworthy et al. (1988) report that tannin-stained "brownish-yellow colored water" produced as a result of a hurricane close to Hobe Sound significantly attenuated photosynthetically active radiation reaching seagrass in the sound. This effect lasted for several months. This possible impact, as well as additional nutrient inputs from a saturated watershed, have the potential to reverse the water quality improvements to date.

We recommend, at a minimum, continued detailed seagrass mapping every two years, preferably every year, in order to accurately document seagrass areal cover trends during normal rainfall years.

A comparison of our results with previous estimates of seagrass coverage in Tampa Bay is presented in Table 2.

Table 2. Tampa Bay seagrass trends (hectares).

YEAR	HECTARES	YEAR	HECTARES	PERCENT CHANGE	NO. OF YEARS	REFERENCE
1876	30,970	1982	5,750	-81	106	Lewis et al. 1985
1957	24,031	1982	12,648	-47	25	TBRPC 1986
1950	16,325	1982	9,120	-44	32	Kunneke and Palik 1984
1940	11,405	1983	5,566	-51	43	Palmer and McClelland 1988
1950	16,448	1982	8,764	-47	32	this paper

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COMPARISON OF BENTHIC MACROINFAUNA AMONG NATURAL AND PLANTED *SPARTINA ALTERNIFLORA* (GRAMINEAE) AND *HALODULE WRIGHTII* (POTAMOGETONACEA) FROM TAMPA BAY

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M. R. Milligan
J. R. Leverone
S. Mahadevan

INTRODUCTION

Planting of intertidal (saltmarsh) and subtidal (seagrass) vegetation has become popular in recent years largely due to the mitigation value for offsetting developmental impacts. Such plantings have been implemented with the intention of creating or restoring marine and estuarine habitat that are of considerable importance or "value" to the shallow water ecosystems. Implicit in this approach is the concept that creation of such habitat results in increased habitat diversity and enhanced production of marine resources, such as commercial and recreational fisheries, as well as the noncommercial fauna such as invertebrates and wading birds.

The long-term success of "created" habitat is very poorly documented, and recent investigations of mitigated habitat by the Florida Department of Environmental Regulation have indicated that the success of such projects is dismally low. Scientific data quantifying the habitat value of restoration sites are severely lacking.

A marine habitat research and restoration project was initiated by Mote Marine Laboratory under contract to the Florida Department of Natural Resources in July of 1986. The project was designed to obtain measurable physical, chemical and biological data of known importance to proper ecological functioning, and compare these parameters between planted and natural habitats. The objectives of the study were to determine experimentally if planted saltmarsh and seagrass communities assume the same ecological functions as their natural counterparts. Project components included water quality, sediment chemistry, and plant, macrofaunal, meiofaunal, and fisheries monitoring. This paper presents the results of the macrofaunal monitoring.

Benthic epifaunal and infaunal invertebrates are important components of the aquatic food chain both as adults and as larval plankton. They are abundant in fisheries nursery areas typically associated with aquatic vegetation such as seagrasses and marshes. The decline in estuarine aquatic vegetation and marsh areas has been indicated as a factor in the decline in abundance of west Florida fisheries stocks. Benthic infauna were therefore chosen as a monitoring component to serve as one of the indicators of successful establishment of marsh and seagrass plantings.

STUDY SITES

Three sites were selected for habitat restoration and subsequent monitoring, two sites in Pinellas County and one site in Manatee County. In Pinellas County, an unvegetated portion of Lassing Park (St. Petersburg) was planted with *Halodule wrightii* in June 1987, and *Spartina alterniflora* was planted at Pinellas Point in June-July 1986, and replanted in the spring of 1987. In Manatee County, an area south of Port Manatee, known as the Hendry or Redfish Creek site, was planted with *Spartina alterniflora* in June of 1987.

METHODS AND MATERIALS

Benthic fauna are known to show distinct faunal stratification between upper and lower marsh zones caused by differing periods of immersion (Subrahmanyam et al. 1976, Subrahmanyam and Coultas 1980). Therefore, two locations were sampled at the Pinellas Point planted and control sites: 1) upper intertidal one-half of the planted area; and 2) the lower intertidal one-half of the planted area. The natural control site was also sampled in this manner. Three stations were sampled at the Pinellas Point site: a bare "control" (PBC), a vegetated "control" (PVC), and planted *Spartina* (PS). Two stations were sampled at the Hendry Delta site, one a bare "control" site and a second planted with *Spartina*. Three stations were sampled at Lassing Park: a bare "control", a *Halodule* vegetated "control", and a *Halodule* planted plot. Preplanting sampling events were conducted at each site to establish baseline conditions.

Infaunal samples were collected using a 7.6 cm (3 in) diameter x 15 cm length, PVC core providing a surface area of 45.6 cm^2. Twelve randomly located replicate samples were collected from each area for each sampling event. Each sample was washed through a 0.5 mm mesh box sieve to remove silt and fine sand. Sieved samples were preserved with a 10% formalin solution buffered with seawater and containing rose bengal stain to facilitate sorting. Ten of the twelve replicate infaunal samples collected at each site were subsequently analyzed for benthic fauna. All organisms collected within each sample were identified and enumerated to the lowest practical taxonomic level (genus and species for most organisms).

Estimates of infaunal community parameters were calculated from the enumerated and identified fauna. Data were also analyzed using community analysis techniques that estimate the levels of similarity (or difference) between faunal assemblages. Tabulated and calculated parameters included: faunal density (number of organisms/m^2); species richness (number of taxa for each station); species diversity, Shannon's H' index using log base 10 (Shannon and Weaver 1963); equitability or evenness of distribution, Pielou's index (Pielou 1966); and faunal similarity, utilizing the Bray-Curtis Index (Bray and Curtis 1957, Field and McFarlane 1968). Hierarchical cluster analysis was conducted utilizing the Bray-Curtis Index and group average sorting (BioStat II Software, Pimentel and Smith 1986).

RESULTS

Successional trends for each site are presented below. Due to space limitations, details of species abundances and composition are not presented.

Pinellas Point *Spartina alterniflora* Monitoring

Table 1 lists the community parameters for each station by sampling date. A total of 221 taxa were collected from the three Pinellas Point stations over the course of the monitoring program. The lower vegetated control (PVC-Lower) station exhibited the greatest number of taxa (158) over all sampling events, followed by the upper vegetated control station (PVC-Upper, 135 taxa) and the lower planted station (PS-Lower, 103 taxa). The upper planted station (PS-Upper) and the bare control site had the lowest cumulative numbers of taxa (99 and 96 taxa, respectively).

Species richness ranged from a low of 13 taxa for the lower marsh planted site (PS-Lower) in August 1986 to a high of 55 taxa for the January 1988 sampling of the lower vegetated control station (PVC-Lower). The trends in species numbers for each station for all sampling events are illustrated in Figure 1. With the exception of one sampling event (March 1989), the number of species found within the vegetated control station (both upper and lower) was greater than the number of species found within the planted site. There were two occasions when the bare control station (PBC) exhibited a greater number of taxa than either of the vegetated controls. Conversely, the species numbers exhibited very little difference for comparisons between the planted site and bare control. The bare control station had a greater number of taxa than either the upper or lower planted stations for eight of the thirteen sampling events. Prior to April 1988, the number of taxa collected at the vegetated control sites was distinctly greater than the number collected at the planted site. For the July and November 1988 collections, the number of taxa recovered from the control site dropped to approximately the number found at the planted site. By March 1989, the number of taxa were very similar among the upper planted, lower control and bare control stations, while the lower planted and the upper control were similar to one another, but not to the other stations.

Figure 2 illustrates the differences in species richness among the three plots, for species lumped according to major taxonomic groups. The numbers of arthropod species (principally crustaceans) showed the greatest differences among stations, for August 1986 through April 1988. After April 1988 the plots exhibited a convergence in species numbers, then a slight divergence for the last sampling event. Molluscs showed the least differentiation among plots and lacked consistent patterns. There were large differences in the number of annelid species among plots at the beginning of the study, but species numbers became more similar during later sampling events.

Table 1. Benthic faunal parameters for each Pinellas Point sampling station and date.

SAMPLING DATE		NUMBER TAXA	NUMBER INDIVIDUALS	INDIVIDUALS PER M^2	SHANNON	PIELOU
Bare Control Station						
1986	AUG	15	159	3487	2.09	.77
	SEP	15	403	8838	1.37	.51
	NOV	23	1352	29649	1.37	.44
1987	JAN	25	1183	25943	1.61	.50
	MAR	22	612	13421	1.94	.63
	APR	26	897	19671	2.02	.62
	MAY	31	1223	26820	1.70	.49
	JUL	21	484	10614	1.65	.54
	SEP	23	395	8662	1.79	.57
1988	JAN	34	834	18289	1.99	.56
	APR	31	563	12346	1.72	.50
	JUL	34	796	17456	2.29	.65
	NOV	30	1472	32281	1.75	.51
1989	MAR	21	357	7829	1.46	.48
Planted Lower Marsh Station						
1986	AUG	13	290	6360	1.60	.62
	SEP	18	407	8925	1.52	.53
1987	JAN	18	604	13246	1.76	.61
	MAR	20	471	10329	2.01	.67
	APR	26	496	10877	1.98	.61
	MAY	29	971	21294	1.39	.41
	JUL	21	193	4232	2.30	.76
	SEP	20	262	5746	1.95	.65
1988	JAN	31	507	11118	2.14	.62
	APR	33	182	3991	2.86	.82
	JUL	22	199	4364	1.66	.54
	NOV	27	676	14825	1.91	.58
1988	MAR	34	333	7303	1.94	.55
Planted Upper Marsh Station						
1986	AUG	18	179	3925	1.82	.63
	SEP	15	211	4627	1.71	.63
1987	JAN	17	327	7171	1.86	.66
	MAR	20	364	7982	2.00	.67
	APR	20	413	9057	2.22	.74
	MAY	26	665	14583	1.64	.50
	JUL	22	274	6009	2.42	.78
	SEP	16	160	3509	2.12	.77
1988	JAN	28	491	10768	1.95	.59
	APR	21	176	3860	2.26	.74
	JUL	20	221	4846	1.71	.57
	NOV	29	622	13640	2.21	.66
1989	MAR	23	295	6469	1.04	.33

(continued)

Table 1 continued.

SAMPLING DATE		NUMBER TAXA	NUMBER INDIVIDUALS	INDIVIDUALS PER M^2	SHANNON	PIELOU
Vegetated Control Station - Lower Marsh						
1986	AUG	35	249	5461	2.49	.70
	SEP	26	300	6579	2.25	.69
	NOV	40	672	14737	2.25	.61
1987	JAN	45	1237	27127	2.39	.63
	MAR	41	1244	27281	2.22	.60
	APR	41	1298	28465	2.11	.57
	MAY	50	2312	50702	2.14	.55
	JUL	46	2218	48640	1.95	.51
	SEP	32	1058	23202	2.17	.62
1988	JAN	55	2297	50373	1.75	.44
	APR	50	3695	81031	1.59	.41
	JUL	24	1690	37061	1.06	.33
	NOV	30	1139	24978	1.87	.55
1989	MAR	25	1120	24561	1.02	.32
Vegetated Control Station - Upper Marsh						
1986	AUG	28	531	11645	1.49	.45
	SEP	31	238	5219	2.52	.73
	NOV	28	566	12412	2.03	.61
1987	JAN	38	871	19101	2.18	.60
	MAR	33	1599	35066	1.84	.53
	APR	35	1576	34561	1.97	.55
	MAY	45	1924	42193	2.11	.56
	JUL	39	1000	21930	2.34	.64
	SEP	32	858	18816	1.77	.51
1988	JAN	49	2580	56579	1.60	.41
	APR	40	2732	59912	1.56	.42
	JUL	32	2526	55395	1.63	.47
	NOV	26	1219	26732	1.20	.37
1989	MAR	35	1198	26272	1.28	.36

Faunal density ranged from a low of 3,487 organisms/m^2 at the bare control station (PBC, August 1986) to a high of 81,031 organisms/m^2 at the lower vegetated control station (PVC-Lower, April 1988). Temporal trends in faunal density for each station are illustrated in Figure 1. With only a few exceptions, the vegetated control exhibited the greatest faunal densities. The planted site exhibited the lowest faunal densities for all sampling events with the exception of August 1986, when the bare control had the lowest faunal density. There were no long-term increases in faunal density evident at the planted station during the study period.

Trends in faunal density for the major taxonomic groups (Polychaeta, Mollusca and Arthropoda) are shown in Figure 3. No trends were discernable with regard to site. During spring 1987, mollusc and arthropod densities increased substantially at the vegetative control station, while only slight increases in the densities of these groups were observed at the bare or planted stations during the same period. Similarly, from September 1987 to November 1988, a pronounced increase in the numbers of annelids occurred only within the vegetated control site and not at the bare or planted site.

The vegetated control site exhibited the greatest numbers of taxa. Many taxa listed for this site were "rare" or the result of a single individual occurring during a single sampling episode. There were 72 taxa found within the vegetated control site that were not recovered from either the planted or bare control sites. On the other hand, there were only eight taxa unique to the bare control site, and 24 taxa found only at the planted site. The remaining 104 taxa occurred at all sites but in differing densities.

The oligochaete species complex *Tubificidae* spp., consisting of at least five species, exhibited the greatest numbers of individuals for all Pinellas Point plots. The oligochaete complex, *Enchytraeidae* spp., was the third most abundant taxon, represented by at least two distinct species. At the species level the most abundant taxon was the polychaete *Laeonereis culveri*, followed by *Hargeria rapax* (tanaid) and *Capitella capitata* (polychaete). These five taxa accounted for over 70% of all individuals collected from Pinellas Point.

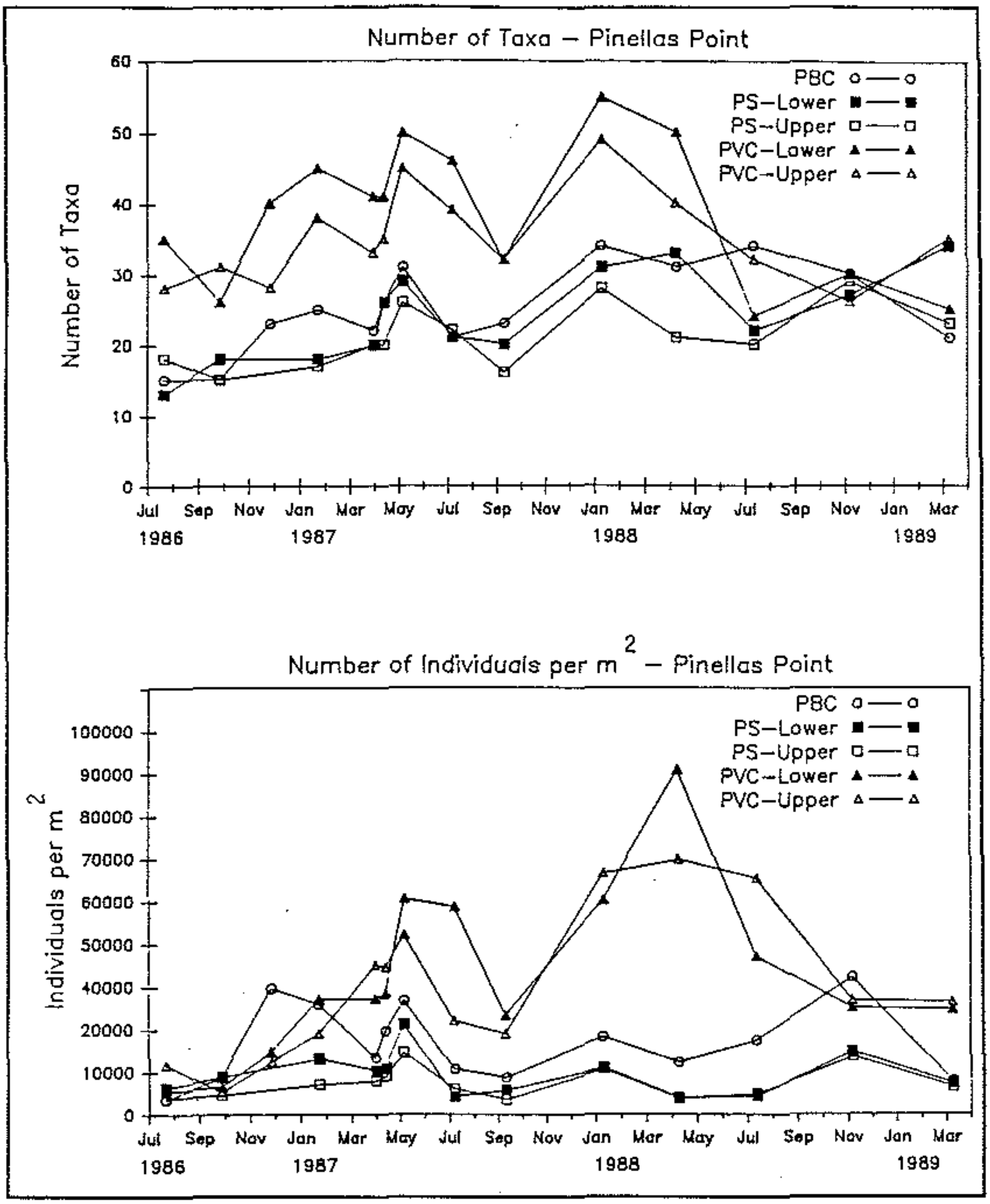

Figure 1. Number of taxa and individuals per m^2 for each Pinellas Point sampling station and date.

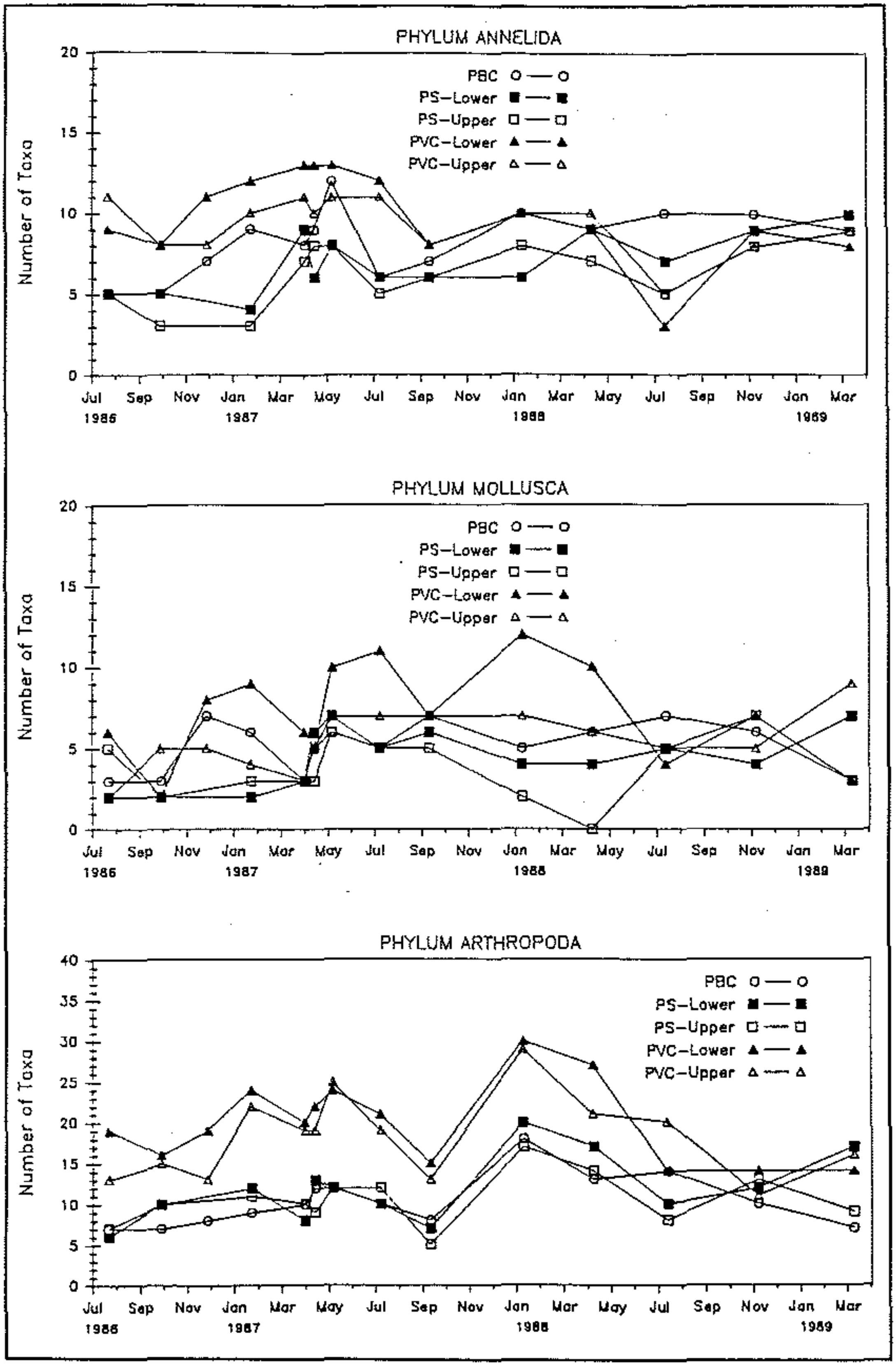

Figure 2. Number of taxa in major faunal groups for each Pinellas Point benthic sampling station and date.

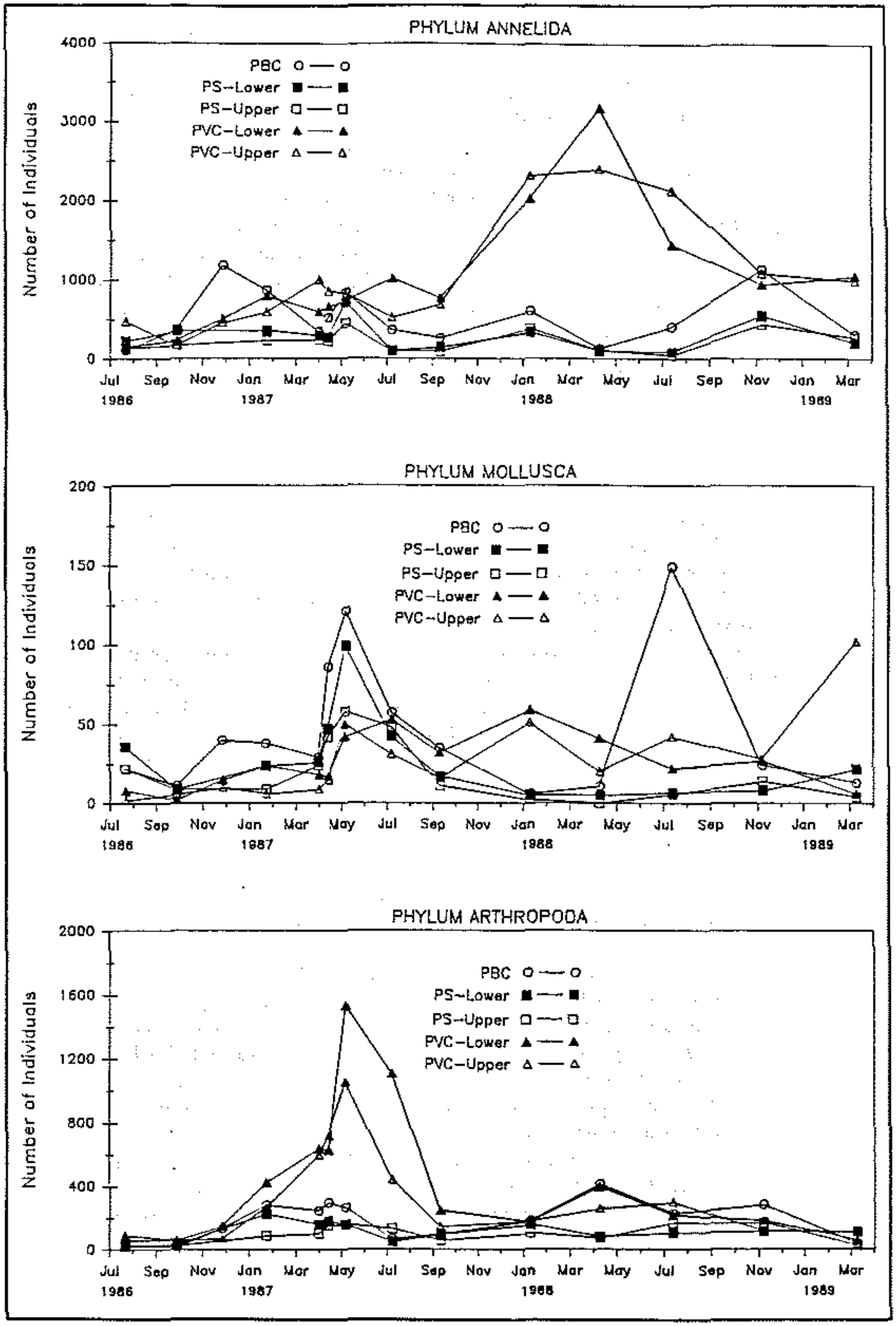

Figure 3. Number of individuals per m^2 in major faunal groups for each Pinellas Point benthic sampling station and date.

Tubificidae spp. were extremely abundant at the vegetated control stations. They were less abundant at the planted site, and even less so at the bare control site. *Enchytraeidae* spp. were found almost exclusively at the vegetated control site. Species that were found predominantly at the vegetated control site included *Hargeria rapax*, *Uca* sp. (decapod, juvenile specimens), *Hemiptera* sp., *Assiminea succinea*, *Gammarus mucronatus*, *Cyathura polita*, *Athenaria* sp., *Balanus* spp., and *Guekensia demissa*. *Laeonereis culveri* was more than twice as abundant at the bare control site than at the other two sites, where its abundance was similar. Additional species which were most abundant at the bare control site were *Almyracuma* sp. A, the bivalves *Parastarte triquetra* and *Tagelus plebius*, and the polychaetes *Aricidea philbinae*, *Eteone heteropoda* and *Leitoscoloplos robustus*. Species exhibiting higher numbers at the bare site were usually common at the planted site. *Capitella capitata* was less abundant at the planted site than at either the bare or vegetated control sites. Other organisms exhibiting a similar pattern of distribution included all species of *Corophium* and Cytherideidae, *Actinaria* sp., *Leitoscoloplos robustus* and *L. foliosus*.

Faunal Similarity

Faunal similarity analysis was performed on data for all station sampling event combinations (2,278 comparisons). All stations showed strong seasonal differences in faunal similarity based on the low to very low similarity indices. The planted site (PSL and PSU) exhibited the strongest similarities to the bare control (PBC) from August 1986 through May 1987, after which time the faunal similarity between these sites decreased. The planted site did not show a marked difference in fauna between upper and lower marsh stations.

The planted site showed very little similarity to the vegetated control (PVL and PVU) for the duration of the study. Of the 728 comparisons between the planted and the vegetated control sites there were only two combinations (0.27%) with a high similarity (PSL and PSU November 1988 vs. PVU November 1986). There were 36 pairs (4.9%) of moderate similarity between the two sites. Thirty of the moderate combinations occurred during September 1986, November 1986 and January 1987. The remaining combinations (690) between the planted and vegetative control sites had low to very low similarity index values. The bare control site illustrated the same pattern of no similarity to the vegetated control site. Overall, the planted site exhibited the greatest level of similarity to itself, between upper and lower marsh comparisons and for temporal comparisons. Of the 325 planted site versus planted site comparisons, 12 were highly similar (3.7%), 45 moderately similar (13.8%), and the remaining 268 comparisons low or very low similarity (82.5%). The bare control and vegetated control also exhibited the highest levels of similarity when compared to themselves for temporal events or for upper and lower marsh comparisons.

Cluster analysis (Figure 4) illustrates the low level of faunal similarity between sampling sites. The highest similarity connections were for within site comparisons over time, or between upper and lower marsh within the same site. The closest between-station connections were for the vegetated control stations (PVC upper and lower), while the planted stations and bare control exhibited affinities only at lower levels of similarity. For 1986 through the first half of 1988, the greatest clustering affinities exhibited by the planted site were with itself (between sampling dates and between upper and lower marsh) and with the bare site. From November 1988 to March 1989, the planted site began to cluster with the vegetated control site.

Hendry/Redfish Creek *Spartina alterniflora* Monitoring

Ten sampling events were conducted at the Hendry/Redfish Creek revegetation site from June 1987 through March 1989. The June 1987 event represents the pre-planting baseline; all other events were post-planting.

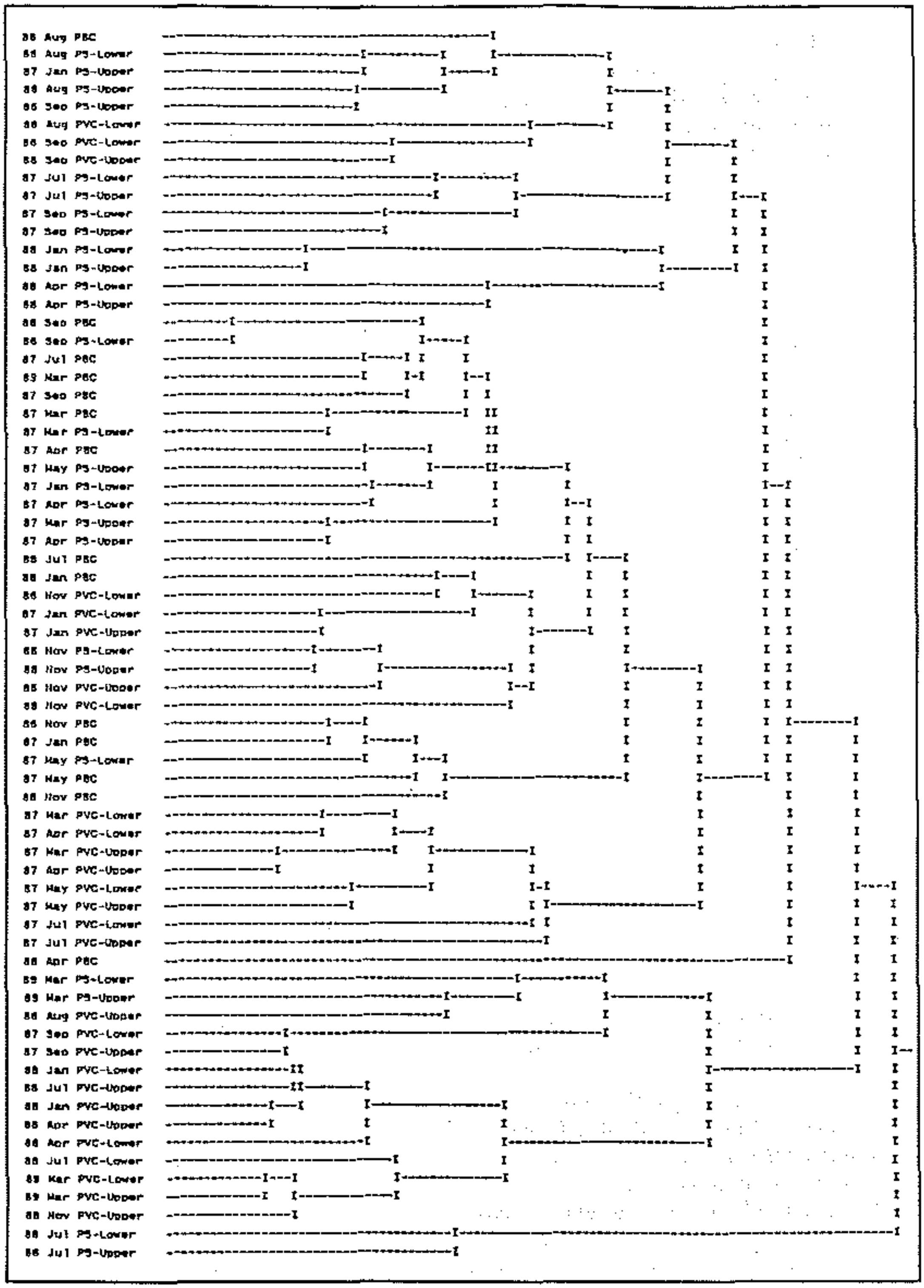

Figure 4. Cluster analysis dendrogram for Pinellas Point benthic sampling stations and dates.

Table 2 lists the community parameters for each station by sampling date. A total of 87 taxa were collected at the Hendry site. Forty-nine taxa were collected from the bare control plot, while 72 taxa were collected from the planted plot. Species counts ranged from a low of only one taxon collected from the bare plot in July 1988 to a high of 31 taxa at the planted plot in August of 1987. For most sampling dates, the planted site exhibited greater numbers of taxa than the bare site, with an average of 16.8 taxa (SD=7.9) and 8.5 taxa (SD=5.1) for the planted and bare sites, respectively. Seasonal variation in species numbers for both plots was pronounced. Species numbers at the bare site ranged from one to 18 taxa, while the planted site had a minimum of nine and a maximum of 31 taxa. Figure 5 illustrates the variation in species numbers through time.

Table 2. Benthic faunal parameters for each Hendry Site sampling station and date.

SAMPLING DATE		NUMBER TAXA	NUMBER INDIVIDUALS	INDIVIDUALS PER M^2	SHANNON	PIELOU
Bare Control Station						
1987	JUN	18	52	1140	2.43	.84
	JUL	9	26	570	1.72	.78
	AUG	13	57	1250	1.73	.68
	OCT	13	31	680	2.33	.91
	DEC	6	8	175	1.67	.93
1988	FEB	8	11	241	1.97	.95
	APR	3	3	66	1.10	1.00
	JUL	1	2	44	.00	N/A
	NOV	8	22	482	1.52	.73
1989	MAR	6	11	241	1.64	.92
Planted Station						
1987	JUN	14	83	1820	1.86	.70
	JUL	19	129	2829	2.31	.79
	AUG	31	532	11666	1.58	.46
	OCT	30	406	8903	2.22	.65
	DEC	18	68	1491	2.23	.77
1988	FEB	9	19	417	1.66	.76
	APR	13	45	987	2.15	.84
	JUL	9	53	1162	1.54	.70
	NOV	12	258	5657	.98	.39
1989	MAR	13	322	7061	.95	.37

Of the 87 taxa found at this site, 34 were common to both bare and planted plots; 38 were found only within the planted plot, and 15 were found only within the bare plot. Three species (the polychaetes *Capitella capitata* and *Laeonereis culveri*, and the fiddler crab, *Uca* sp.) accounted for 70% of the organisms collected at both plots. Taxa common to both plots, such as the dominant polychaetes *Laeonereis culveri* and *Capitella capitata* and the fiddler crab *Uca* sp. (juvenile), were usually much more abundant within the planted plot. Two of the most abundant species found only within the planted plot—*Spirorbis spirillum* (Polychaeta) and *Balanus improvisus* (Crustacea)—are epiphytic and were associated with *Spartina* stalks. Other taxa exclusive to the planted plot (such as the tanaid *Hargeria rapax* and the isopod *Cyathura polita*) were not as abundant but occurred more frequently. All of the taxa unique to the bare site were rare occurrences of one or two individuals.

Taxa are lumped by phyla for bare and planted plots in Figure 6. For both the annelids and the molluscs there was a large drop in species numbers from August 1987 to June 1988. Variation in the number of annelid and mollusc taxa between planted and bare site decreased from 1988 through to 1989. The arthropods exhibited a sharp decline in numbers of taxa from August 1987 to June 1988. The planted site, however, exhibited more stability in the number of arthropod taxa.

Faunal densities ranged from 44 organisms/m^2 at the bare station (July 1988) to 11,666 organisms/m^2 at the planted station (August 1987). The planted station exhibited greater densities than the bare station for all sampling events including the pre-planting baseline collections. Figure 5 illustrates the variation in faunal densities through time for both plots. There was strong seasonal variability in faunal densities at the planted plot, and to a lesser degree at the bare plot. The planted site exhibited much greater variation than did the bare site. By late 1988 (November) and March of 1989 faunal densities had returned to 1987 levels for the planted plot, but remained very low at the bare site.

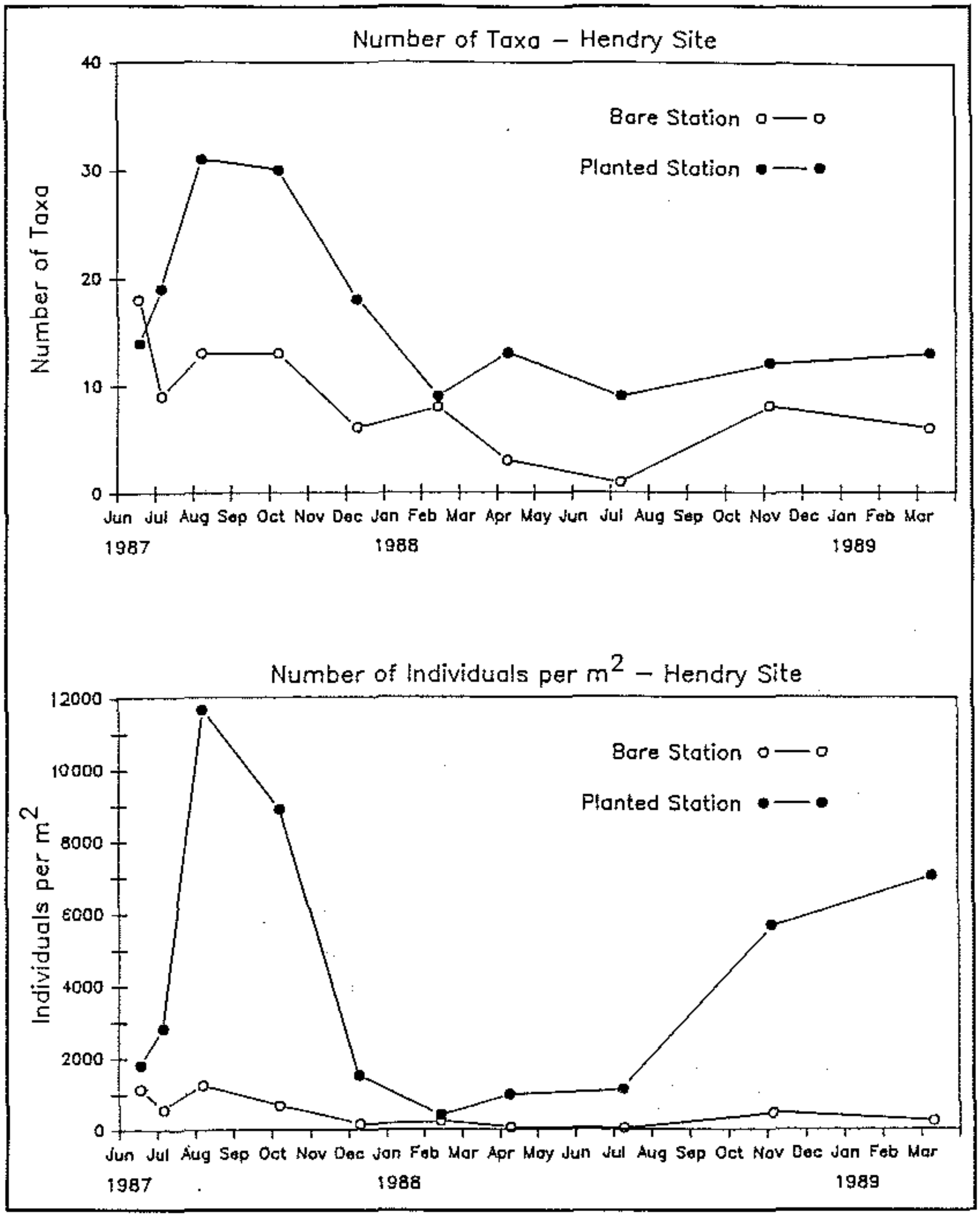

Figure 5. Number of taxa and individuals per m^2 for each Hendry Site benthic sampling station and date.

Figure 7 illustrates trends in faunal densities by phyla. All three phyla exhibited large decrease in numbers between 1987 and 1988. The annelids and crustaceans returned to previous levels by 1989 while the molluscs remained at very low levels. The arthropods (primarily crustaceans) recovered most rapidly from the decline in total numbers.

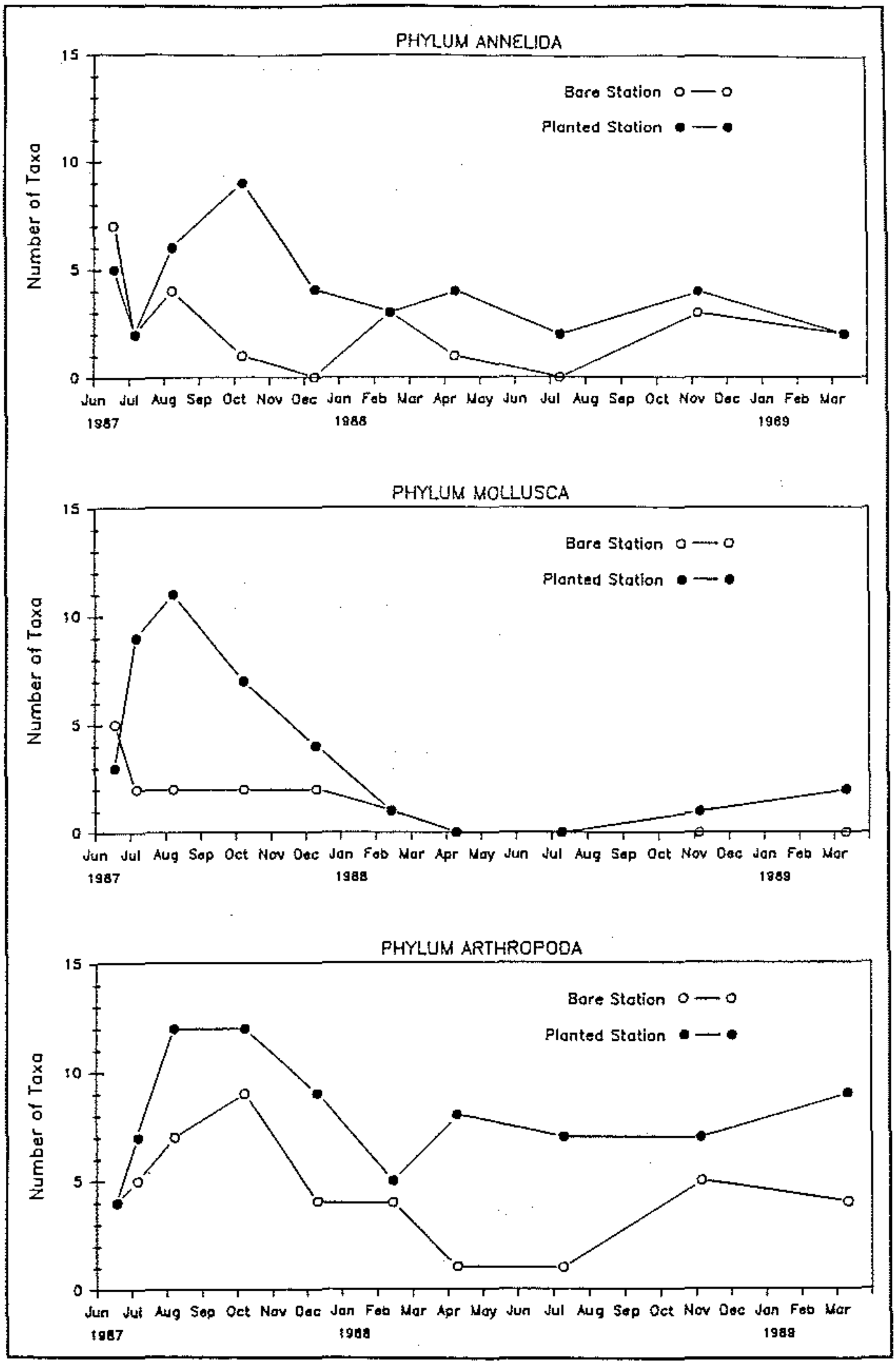

Figure 6. Number of taxa in major faunal groups for each Hendry Site benthic sampling station and date.

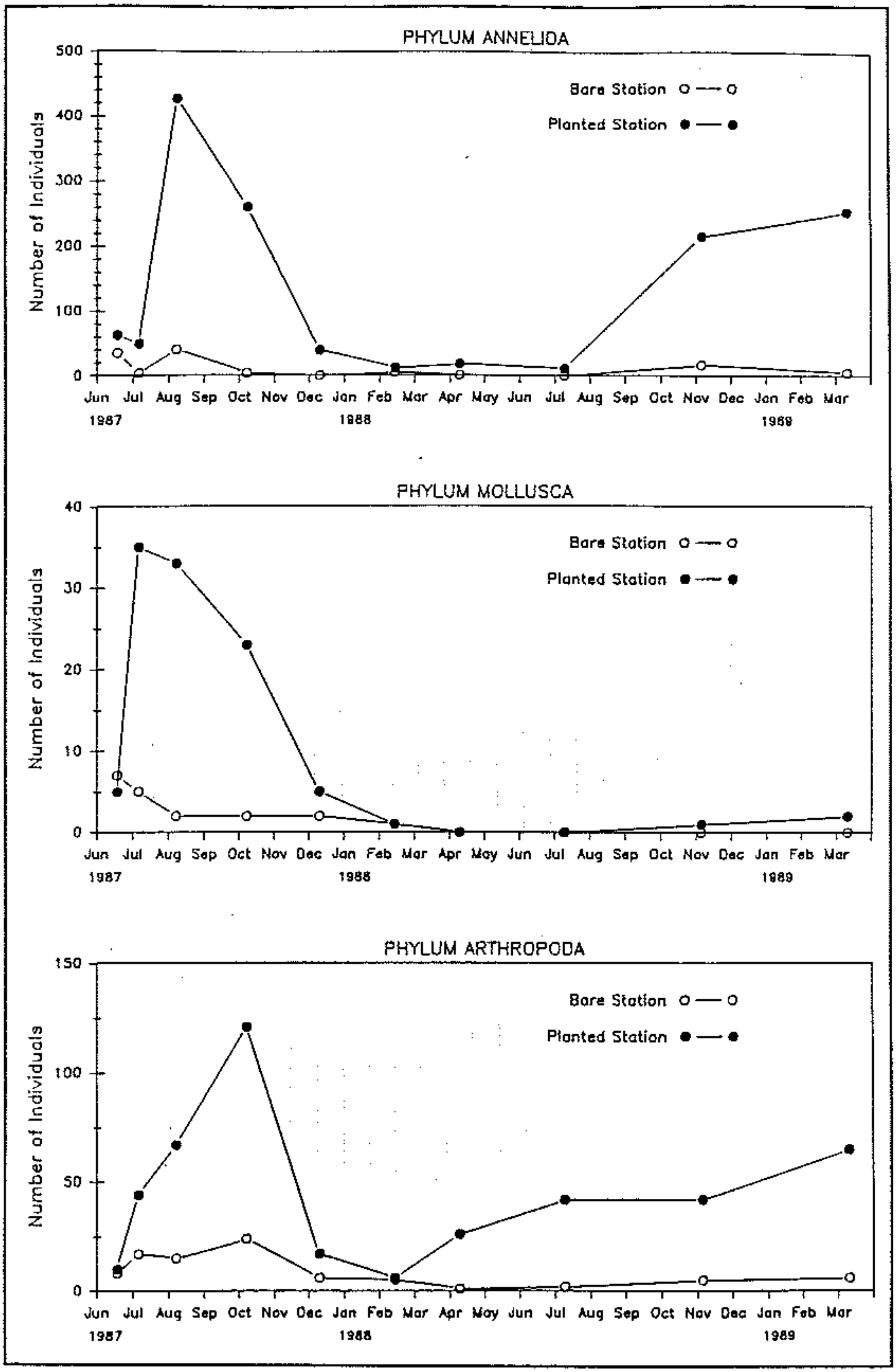

Figure 7. Number of individuals per m^2 in major faunal groups for each Hendry Site benthic sampling station and date.

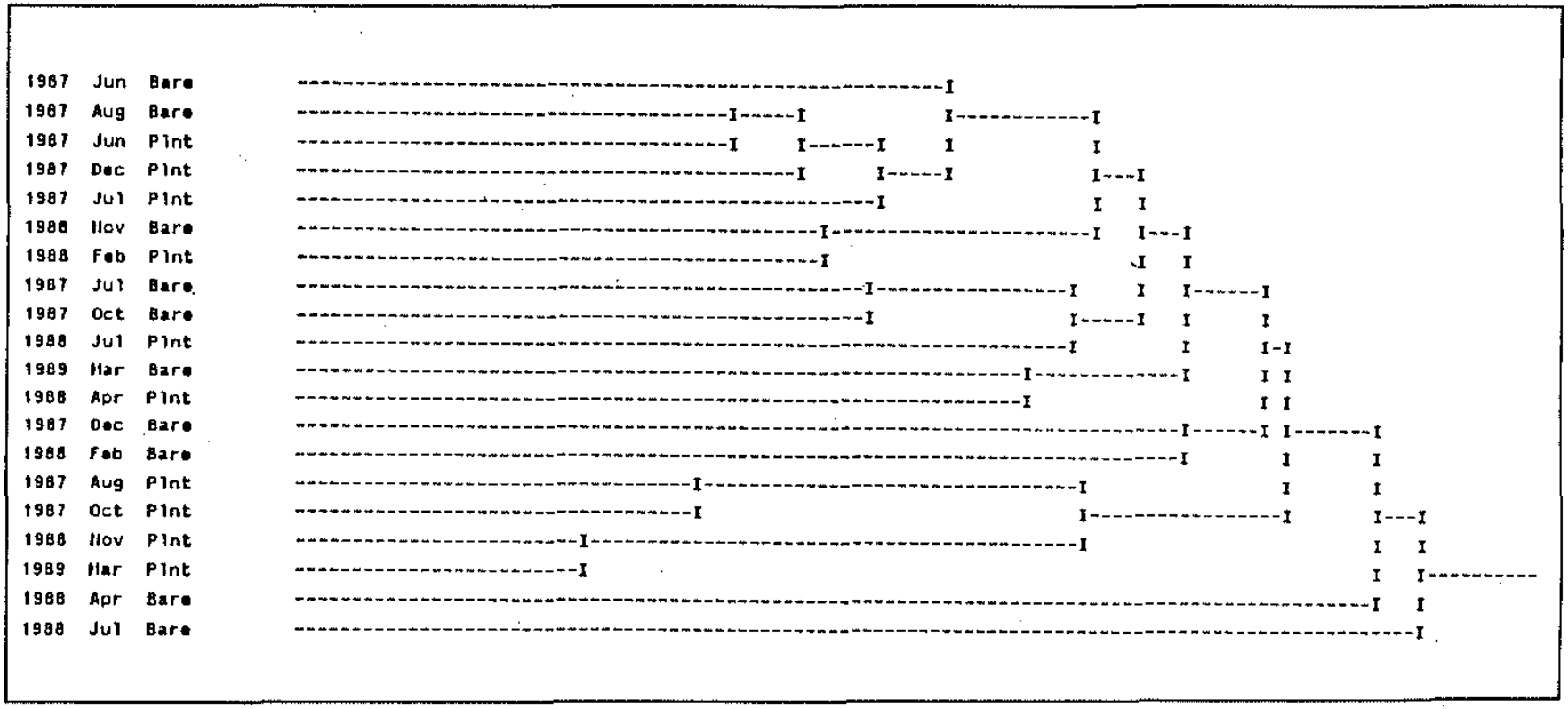

Figure 8. Cluster analysis dendrogram for Hendry Site benthic sampling stations and dates.

Faunal similarity analysis for all station/date combinations revealed that for 190 station pairs there was only one combination of high similarity, five combinations of moderate similarity, 31 low similarity combinations, and 153 very low similarity combinations. The one high similarity value was for the planted station between November 1988 and March 1989. For the moderate similarity combinations three were for bare/planted comparisons, and two for planted/planted comparisons. There were no high or moderate similarities between bare versus bare comparisons. Cluster analysis (Figure 8) illustrates the lack of distinct station (or treatment) separation for the duration of the monitoring.

Lassing Park *Halodule wrightii* Monitoring

A total of 309 taxa were recovered from Lassing Park. The number of taxa ranged from 46 taxa at the vegetated control station (October 1987) to 106 taxa from the plug planted station (July 1988) (Table 3). The vegetated control station exhibited the greatest number of taxa for eight of the ten sampling events. There was an average of 73 taxa (SD=15.7) at the vegetated control station for all sampling events. The *Halodule* plug planted site exhibited the next overall highest number of taxa with an average of 65.2 taxa (SD=16.7) collected per sampling event. An average of 60.0 taxa (SD=7.8) were collected from the bare control.

A total of 216 taxa was collected from the vegetated control site during the study. Seventy-three taxa (33.8% of vegetated control total) were found exclusively at this site. A total of 196 taxa was collected from the plug station, with 30 unique taxa. The bare station exhibited 173 total taxa, and also had 30 taxa not found at either of the other sites.

The number of infaunal taxa collected from each station throughout the study are illustrated in Figure 9. The number of taxa collected at the planted site closely paralleled the number collected at the bare control.

Figure 10 displays temporal changes in the distribution of species lumped by phyla. All three sites exhibited similar trends in species richness of annelids throughout the study. Molluscs also showed similar trends in species richness for the three sites, although the control station had greater numbers of taxa (except for one sampling event) from February 1988 to March 1989. The arthropods showed the most distinct differences in numbers of taxa between sites. The control site contained consistently greater numbers of arthropod taxa than the bare and planted sites. With one exception (July 1988), the bare and planted sites had similar numbers of arthropods.

Many of the species common to all sites exhibited a preference for either the control or bare/planted sites. No major differences in species composition were observed between the bare and planted station. The gastropod *Diastoma varium* (which feeds on epiphytic growth present on *Halodule*) was much more abundant at the control site than the bare or planted sites. Other taxa that were most abundant at the control station were *Cymadusa compta* (amphipod), and the polychaetes *Aricidea philbinae*, *Prionospio heterobranchia*, *Kinbergonuphis simoni*, *Aricidea taylori*, and *Polydora ligni*. Also common were *Mitrella lunata* (gastropod), *Erichsonella attenuata* (isopod), and *Neopanope texana* (decapod).

Species which occurred more commonly at the bare/plug stations were *Axiothella mucosa* (polychaete), *Ampelisca holmesi* (amphipod), *Acanthohaustorius* sp. A (amphipod), *Mysella planulata* (bivalve), *Paraonis fulgens* (polychaete), *Oxyurostylis smithi* (cumacean), *Brania wellfleetensis* (polychaete), and numerous other taxa at lower densities.

Faunal densities ranged from 10,439 organisms/m^2 at the plug station (December 1987) to 100,833 organisms/m^2 at the control station (June 1987). The control station exhibited the greatest faunal densities for all sampling periods and showed an average density of 52,219 organisms/m^2 (SD=25,991). The bare station had the lowest densities for seven of ten sampling events and an overall average density of 20,289 organisms/m^2 (SD=10,108). Faunal densities at the plug station were similar to those of the bare station, with an average of 23,136 organisms/m^2 (SD=10,212). Pronounced seasonal variations in numbers of organisms were evident. The lowest densities occurred in October and December of 1987 and February of 1988 (Figure 9). The bare control and plug planted site showed similar patterns in faunal density. The vegetated control site showed different trends in faunal density from the bare and plug sites for all sampling except November 1988.

Table 3. Benthic faunal parameters for each Lassing Park sampling station and date.

SAMPLING DATE		NUMBER TAXA	NUMBER INDIVIDUALS	INDIVIDUALS PER M^2	SHANNON	PIELOU
Bare Control Station						
1987	JUN	71	743	16294	3.20	.75
	JUL	66	1047	22961	3.02	.72
	AUG	65	1002	21974	2.69	.65
	OCT	59	578	12675	3.24	.80
	DEC	51	479	10504	3.28	.83
1988	FEB	48	506	11096	3.12	.81
	APR	70	1087	23838	2.96	.70
	JUL	55	828	18158	2.87	.72
	NOV	58	2077	45548	2.08	.51
1989	MAR	57	905	19846	2.67	.66
Vegetated Control Station						
1987	JUN	94	4598	100833	2.81	.62
	JUL	77	3765	82566	1.48	.34
	AUG	65	2232	48947	1.15	.28
	OCT	46	1695	37171	1.13	.30
	DEC	63	1156	25351	2.46	.59
1988	FEB	71	829	18180	2.80	.66
	APR	83	2370	51974	2.63	.59
	JUL	71	2552	55965	2.45	.58
	NOV	67	1480	32456	2.71	.65
1989	MAR	100	3135	68750	3.04	.66
Planted (plug) Station						
1987	JUN	71	895	19627	3.29	.77
	JUL	72	1112	24386	2.98	.70
	AUG	61	882	19342	3.01	.73
	OCT	63	783	17171	3.34	.81
	DEC	53	476	10439	3.36	.85
1988	FEB	49	583	12785	3.11	.80
	APR	71	1428	31316	3.02	.71
	JUL	106	1835	40241	3.48	.75
	NOV	54	1733	38004	1.94	.49
1989	MAR	52	823	18048	2.57	.65

Figure 11 illustrates the temporal trends in faunal densities of organisms arranged by phyla. The numbers of polychaetes were greatest at the control station for seven of ten events (70%). The plug station had greater numbers of polychaetes than the bare site for seven of ten events. The number of molluscs were similar for all sampling events between the bare and plug sites. Molluscs were very abundant at the control site from July 1987 to February 1988, at which time the number dropped sharply to levels similar to the bare station. The number of arthropods was similar between sites, except for June 1987, November 1988 and March 1989.

Of the 435 station/date comparisons of the faunal similarity analysis, there were five high similarity pairs (1.1%), 20 moderate similarity pairs (4.6%), 124 low similarity pairs (28.5%), and 286 pairs (65.7%) of very low similarity. There were no high or moderate similarities (and only one low similarity) between comparisons of the vegetated control site with either the bare or plug sites. In contrast, comparisons between the bare and plug sites exhibited numerous high and moderate faunal similarities, including comparisons between sampling dates.

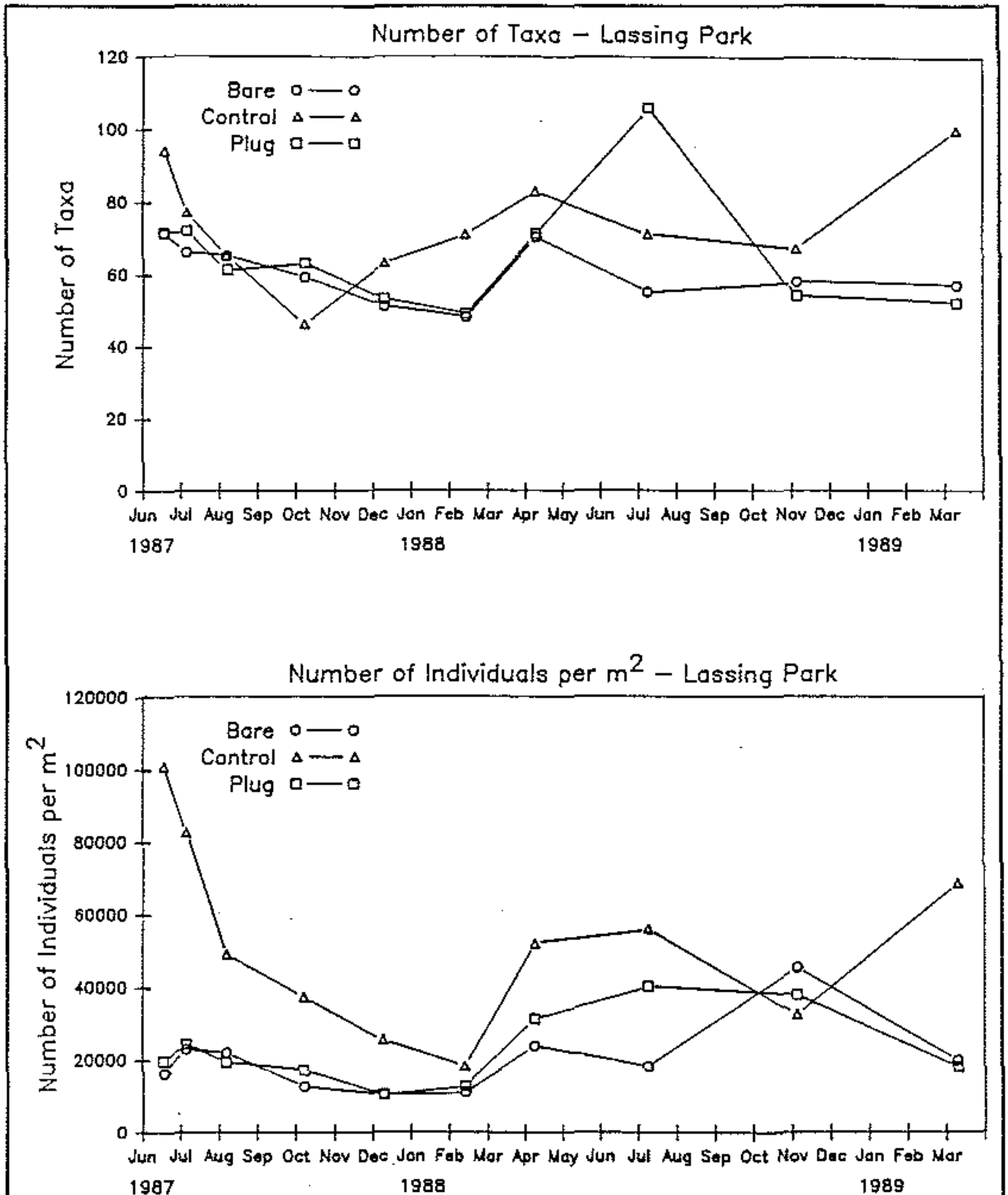

Figure 9. Number of taxa and individuals per m^2 for each Lassing Park benthic sampling station and date.

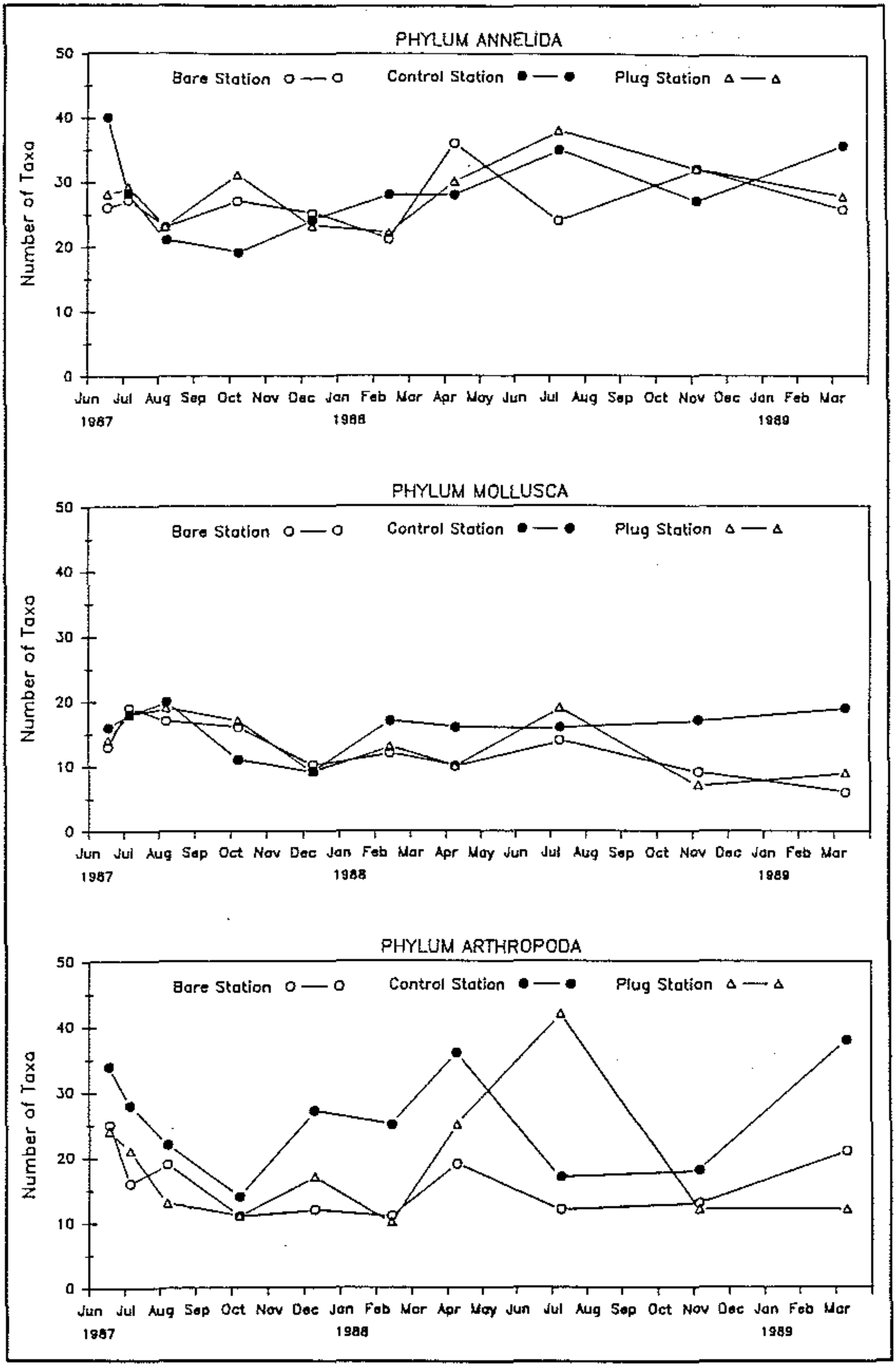

Figure 10. Number of taxa in major faunal groups for each Lassing Park benthic sampling station and date.

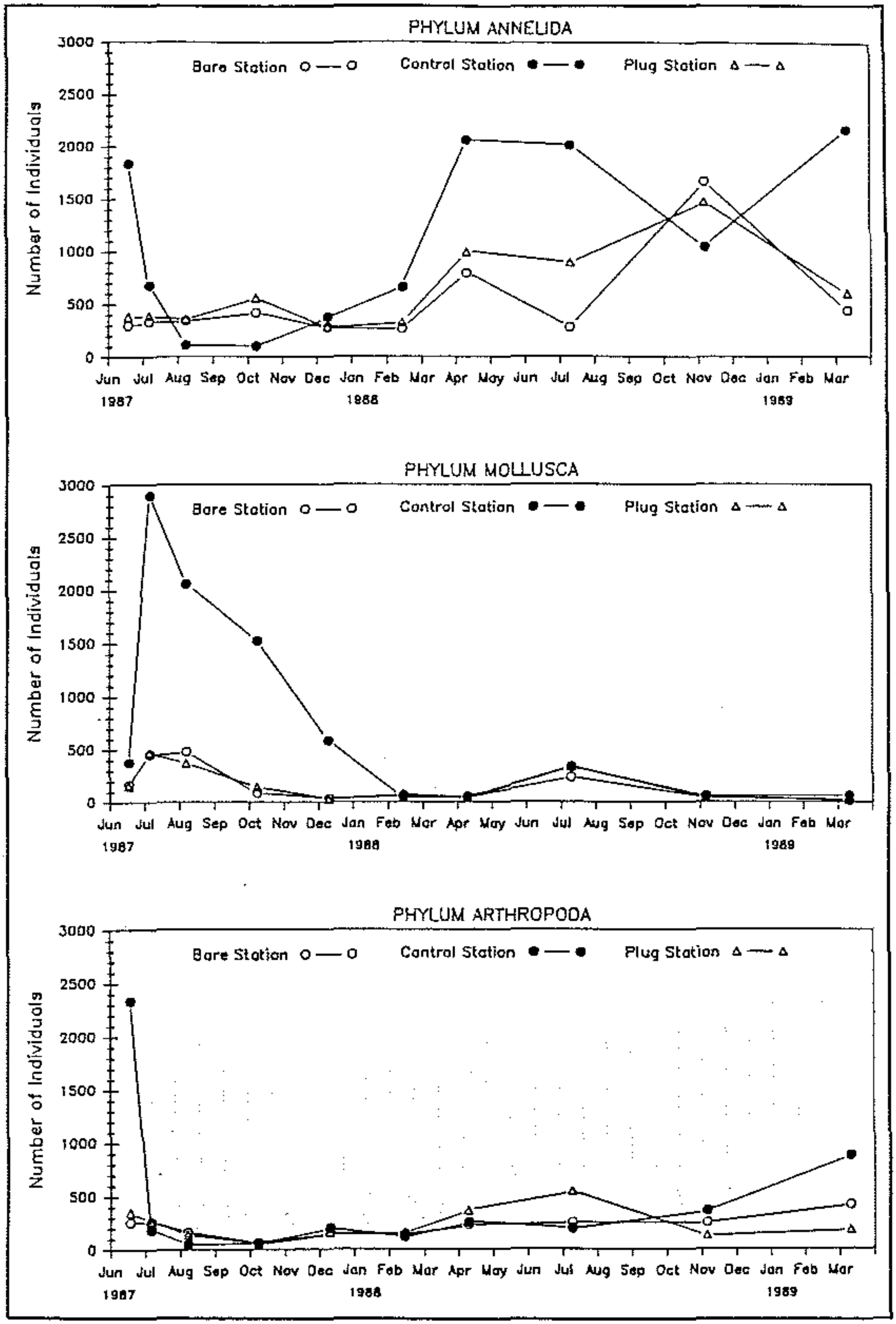

Figure 11. Number of individuals per m^2 in major faunal groups for each Lassing Park benthic sampling station and date.

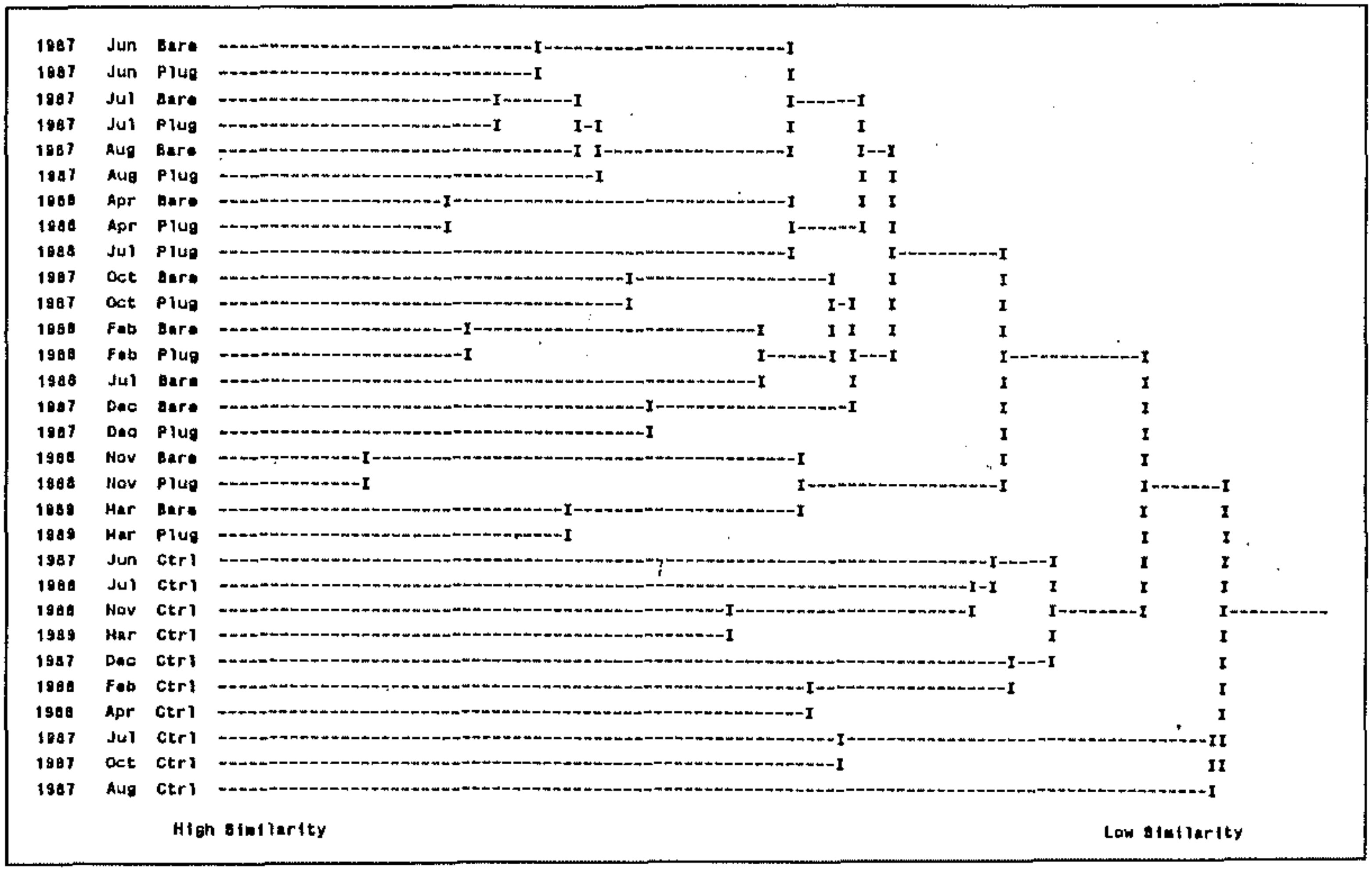

Figure 12. Cluster analysis dendrogram for Lassing Park benthic sampling stations and dates.

Figure 12 illustrates site groupings based on cluster analysis. The cluster diagram illustrates the dissimilarity between the control site and the other two sites. All of the control samples are grouped together at the bottom of the figure. The highest levels of similarity were found between the bare and plug stations for common sampling dates. The sites were less similar when compared between sampling dates.

DISCUSSION

By July 1988 it was apparent that the two saltmarsh plantings—Pinellas Point and Hendry/Redfish Creek—had taken root and were increasing in area of cover and density. In this respect the plantings will probably be successful in the short term, barring any catastrophic defoliations. While it also appears that the *Halodule* plantings of Lassing Park have successfully rooted, it was not immediately obvious that they would become successfully established, due to winter die off and only one year of follow-up monitoring data.

Pinellas Point

This site received two plantings; the first, in August 1986, exhibited a large die-off and was therefore replanted in April 1987. Rapid proliferation subsequently occurred at this site, with the plot nearing total coverage by July 1988.Distinctspecies preferences for the vegetated control were observed. The oligochaete complex, *Enchytraeidae* spp., consisted largely of a species living within the inner layers of *Spartina* stalks. Most other taxa exhibiting a preference for the control site appeared to be species exhibiting a clinging or crawling mode of foraging.

Similarity measurements indicate that the control marsh remained quite distinct from the bare control and the planted plot. This observation is also borne out by comparisons of the faunal parameters of the three sites. The vegetated control plot had far more species, greater diversity values, and two to four times more biomass (data not presented) than the other sites. Most of the organisms at the bare and planted sites were burrowing forms able to penetrate the root-free, soft sediments. Many of the organisms inhabiting the vegetated control plot are able to utilize the *Spartina* blades for food or attachment, or are well suited to penetrate and live among the sediment-root complex. The density of the *Spartina* at the vegetated control plot made it difficult to observe surface sediment features and fauna. However, there were large numbers of *Littorina irrorata*, an epifaunal grazing gastropod associated with *Spartina*, observed at the control plot. Very few *Littorina* were observed within the planted plot, indicating that perhaps a minimal density of *Spartina* is necessary for colonization by *Littorina*.

If the *Spartina* at this location continues to grow and spread, it is anticipated that the planted site will become more similar to the vegetated control. The close proximity of a naturally established marsh should enable the recruitment of a similar fauna. Presumably, the infaunal community structure is regulated by both surface coverage and subsurface sediment structure. In this case, the planted marsh may take several additional years to form a complete subsurface root structure that will physically and chemically alter the sediment characteristics.

Hendry/Redfish Creek

The sediments of the Hendry/Redfish Creek site are the result of a impoundment spill and are not a natural grain size distribution. The sediments exhibited a low nutrient level and a hard, smooth, compacted surface of fine sand generally of uniform size. Surface sediments had a low porosity with little bioturbation. A thick clay layer approximately 25 cm below the surface further complicates the sediment structure. Thus, the probability of this type of sediment supporting long-term *Spartina* growth and propagation was unknown. As of November 1990, the plantings were growing and propagating.

The Hendry/Redfish Creek revegetation site was the least productive of all the study sites in terms of benthic macrofauna. This site contained the fewest species, lowest faunal densities, and fewest epifaunal features of any site. Prior to planting, the only evidence of benthic infauna was the presence of *Uca* burrows visible at low tide. This plot was planted in an area with no nearby natural saltmarshes although there were extensive mangrove fringes. The lack of a suitable vegetated control plot prevented comparison of faunal composition and community parameters between planted and natural saltmarsh. Very little faunal similarity was displayed between the bare and planted plots at the Hendry site. This may be due, in part, to the low numbers of organisms collected during the study. Both plots were almost totally devoid of benthic fauna from February through July 1988.

The experimental plots at the Hendry site were established in the upper intertidal zone where they were subjected to extended aerial exposure. Unintentionally, the bare plot was situated very slightly higher in the intertidal zone than the planted plot. This resulted in the bare plot being uncovered sooner and remaining dry slightly longer than the planted plot. The three dominant taxa of the bare plot (*Capitella capitata, Laeonereis culveri*, and *Uca* sp.) were found in greater abundance at the planted site. This faunal distribution may have largely been governed by tidal exposure.

After one year of monitoring, indications were that the planted site was becoming more diverse than the bare control and supporting greater numbers of individuals. The recruitment rate of a marsh faunal community is expected to be much slower at this site than at the Pinellas Point location, due to lack of a nearby natural marsh and the foreign nature of the substratum. As the *Spartina* grows and spreads, it can be expected to alter the surface sediments by accumulating a detrital organic layer, and aerating or loosening the compacted sediments by penetration of roots and rhizomes.

Lassing Park

The benthic fauna of Lassing Park (the only seagrass site) was less definitive in trends than the saltmarsh sites. The site exhibited the greatest number of species, greatest faunal densities, and highest diversity values of all of the study sites. All three plots supported large numbers of taxa throughout the study. There were pronounced differences between the vegetated control and the experimental plots (bare and planted). There was not any definite differentiation between the bare and planted plots, indicating that any *Halodule* growth that occurred was not sufficient to alter the macrofaunal community composition.

There were no apparent differences in species composition between the bare and planted plots, but the vegetated control site contained many species not found at the other two sites. The gastropod *Diastoma varium*, which feeds on epiphytes growing on *Halodule* blades, was very abundant due to the dense cover of seagrasses and was therefore dominant at the control station. Fauna which were more abundant at the plug/bare plots were burrowing forms. The species more abundant at the control site, mostly deposit and filter feeders, were found associated with the sediment surface.

Faunal similarity analysis revealed no similarity between the vegetated control site and either the bare or plug sites. The bare and plug sites, in contrast, exhibited numerous high and moderate faunal similarities between them, including comparisons between sampling dates. The fewer high similarity pairs between sampling dates is due to seasonal variations in faunal composition and abundance.

The differences in relative density of *Halodule* in the planted and vegetated control sites was quite pronounced throughout the study. It is likely that significant alteration of the fauna from a bare substratum community to a vegetated substratum community will require much greater *Halodule* growth over the course of several years. These findings indicate that the benthic faunal community of the Lassing Park planted plot remained more closely associated with the bare control community for the duration of the study. All plots, however, supported a rich and diverse fauna. As the *Halodule* plugs grow and spread, and the root structure develops, the faunal composition of the planted area should become similar to the control area. It is apparent that this will take longer than the time during which this study was conducted.

ACKNOWLEDGEMENTS

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ASPECTS OF SEAGRASS RESTORATION IN TAMPA BAY

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ABSTRACT

This study, supported by the Florida Department of Natural Resources, the National Marine Fisheries Service, the University of South Florida and NOAA's Coastal Ocean Program, was conducted to determine if artificially propagated seagrass meadows provide habitat functions similar to those they are intended to replace as mitigation. We monitored the rate of seagrass growth, and shrimp, fish and crab numerical abundance and species composition in transplanted *Halodule wrightii* and *Syringodium filiforme* beds in Tampa Bay over a 2.8-year period. We also examined the recovery of *H. wrightii* and *S. filiforme* donor beds, which included excavations of up to 0.25 m^2, over a one year period. Transplanted shoot density of both *H. wrightii* and *S. filiforme* was predicted to reach an asymptote after 3.38 years. Shrimp and fish abundance in the transplanted *H. wrightii* beds became equal to natural beds after 1.2 years while crab abundance was still not equivalent after 2.8 years. *Syringodium filiforme* transplants followed similar trends. Faunal species composition in transplanted beds was still not similar to their natural counterparts after 2.8 years. *Halodule wrightii* and *S. filiforme* donor bed excavations recovered to equal or greater shoot densities within one year as compared to controls. Improvements in water quality in Tampa Bay, and especially Hillsborough Bay, as evidenced by concomitant studies, indicate that large-scale restoration of seagrass beds could provide a significant fishery resource enhancement with rapid recovery of the beds used for donor stock. The positive results of this study, however, do not support the substitution of created seagrass beds for existing beds as mitigation.

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EVALUATION OF LONG-TERM STUDIES OF THE BENTHIC COMMUNITY IN THE VICINITY OF BIG BEND, TAMPA BAY

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J. S. Sprinkel
M. R. Milligan
S. Mahadevan

INTRODUCTION

Analysis of benthic infauna is a key element of many environmental monitoring programs. Due to the relative immobility of the constituent organisms and their varied sensitivity to physiological stresses, the benthic community is generally considered to be the most important faunal system in assessing environmental stress (Dills and Rogers 1972). In addition, the relative longevity of benthic organisms makes them valuable indicators of past and present water quality (Mackenthun 1966, McKee 1966, Cairns and Dickson 1971). As a result, countless investigations have been performed worldwide to monitor changes in benthic infaunal communities due to natural and anthropogenic influences.

Studies of the benthic faunal communities of Tampa Bay have been summarized by Taylor (1973), Simon (1974), and Simon and Mahadevan (1985). General conclusions regarding these communities include the following observations (Lewis and Estevez 1988):

- The estuary supports "an extremely abundant and diverse assemblage of bottom organisms, except in Hillsborough Bay..." (Taylor 1973);
- Seasonal fluctuations in the abundance and diversity of these organisms are pronounced;
- Opportunistic and "pollution indicator" species are abundant;
- Sediment type appears to be a controlling factor in determining infaunal distribution in the bay; and
- A general increase in species richness and decrease in total population abundance are evident on a north-to-south gradient in the bay.

While information is available on the spatial distribution of macrobenthic communities from Tampa Bay, including patterns associated with environmental gradients, little long-term data exist with which to evaluate the normal dynamics of these communities over extended time periods. Knowledge of the nature and causes of natural fluctuations is critical in assessing the effects of man's activities on estuarine communities. From 1976 to 1986, a series of studies was conducted on the benthic infaunal communities of the Big Bend region of Tampa Bay. Collectively, these studies provide the opportunity to investigate the long-term changes in faunal composition of a shallow subtidal benthic community within the Tampa Bay estuary.

The purpose of this evaluation is to: 1) describe the biotic and abiotic conditions within the benthic community of the Big Bend area; 2) identify within-year and between-year fluctuations in benthic community parameters; 3) identify temporal patterns in the population dynamics of the dominant species and determine the degree to which they shape overall community structure; and 4) compare these findings with those from other benthic communities within Tampa Bay.

MATERIALS AND METHODS — DATA ANALYSIS

Four separate studies (Table 1) were conducted to evaluate changes in benthic community structure due to various operational phases of Tampa Electric Company's Big Bend Steam Electric Generating Station (Mahadevan et al. 1977, 1980; Mahadevan and Culter 1985; Leverone and Mahadevan, 1986). Collectively, these studies provide the opportunity to analyze long-term changes in benthic faunal composition of the Big Bend area of Tampa Bay.

Table 1. Benthic studies conducted at Big Bend, Tampa Bay, between 1976 and 1986.

STUDY	DURATION	STATIONS	FREQUENCY
1	Feb 1976 - Feb 1977	22	Quarterly (every six weeks)
2	May 1979 - Dec 1979	11	Every six weeks
3	Aug 1981 - Feb 1984	5	Bimonthly
4	Apr 1984 - Feb 1986	15	Bimonthly

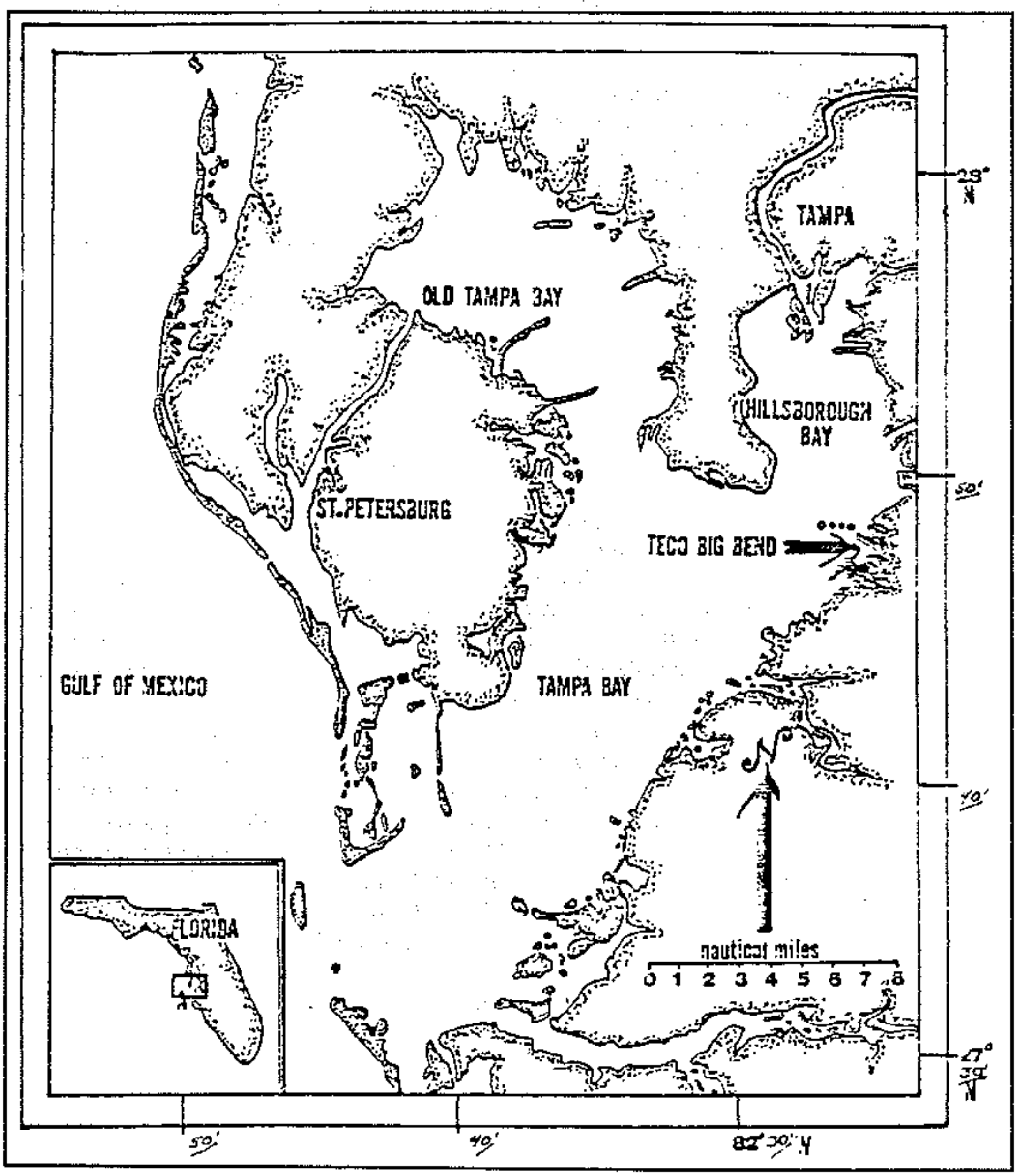

Figure 1. Map of Tampa Bay showing the location of the Big Bend area.

Description of Study Area

Big Bend (Figure 1) is located on the eastern shore of Tampa Bay (latitude 27°47'30"N, longitude 82°23'27"W), just above the line of demarcation between Middle Tampa Bay and Hillsborough Bay (Lewis and Whitman 1985). Benthic habitats in the area are devoid of vegetation. Sandy and muddy bottoms are prevalent with sandy-type habitats dominating nearshore areas (Mahadevan et al. 1977).

Station Selection

From a total of 22 stations, five were initially selected based on their high frequency of sampling over the entire ten year period (Figure 2). Preliminary analyses were conducted to determine the degree of faunal similarity between these stations for the same time period. An association matrix was generated for all station-date combinations and the Bray-Curtis distance quantitative coefficient employed to generate similarity matrices (Bray and Curtis 1957). Using the group-average clustering method, a high degree of similarity was found between stations 5 and 6 as well as between stations 11 and 12, while station 8 was highly dissimilar to these four stations. Station 8 was closest in proximity to the point of discharge from the power plant, and was shown to undergo slight changes in faunal composition as a result of the thermal plume during the colder months of the year (Leverone and Mahadevan 1986). As a result, station 8 was dropped from the long-term analysis. Stations 5 and 6 were located on a thermal transect while stations 11 and 12 were located on a control transect. These four stations were shown to be essentially unaffected by the thermal effluent from the power plant (Mahadevan et al. 1977). These stations were divided into two spatially distinct groupings (designated north and south stations) and each grouping analyzed separately for temporal trends in faunal composition.

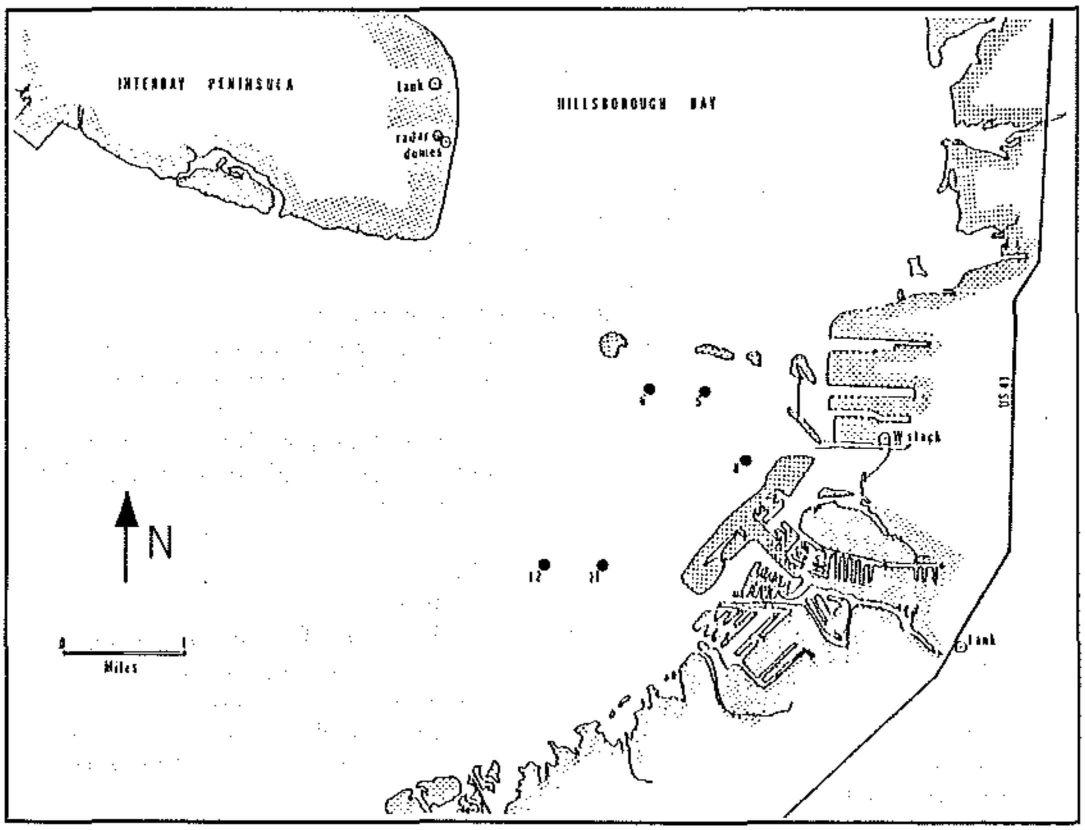

Figure 2. Station locations.

Sampling Frequency

Stations 5 and 11 were sampled every six weeks from February 1976 through February 1977, while stations 6 and 12 were sampled quarterly. During 1979, samples were collected approximately once every six weeks commencing in May and ending in December. Two separate collections were made in August 1979 to correspond with various power plant operations. Beginning in August 1981, all stations were sampled bimonthly until the studies were concluded in February 1986.

Sampling Procedures

Surface and bottom measurements were obtained for temperature, dissolved oxygen, salinity and turbidity. Temperature and dissolved oxygen measurements were made with a YSI Model 57 DO meter. Salinity measurements were made with a Beckman RS2-3 Inductive SCT meter. Surface and bottom water samples were collected with a 5-liter Nisken sampler for laboratory analysis of turbidity.

Faunal samples were collected with a petite Ponar grab, which samples an area of 0.0225 m^2 and penetrates approximately 10 cm in muddy substrates (slightly less in sandy substrates). Six replicates were collected and analyzed from each station. An additional sample was collected for sediment granulometry and percent organic content.

Faunal samples were washed and sieved on a 0.5 mm mesh sieve. A 10% $MgCl_2$ solution was used as a narcotizing agent. Samples were fixed in a 10% formalin/rose bengal solution and transferred to 70% isopropyl alcohol after 48 hours for final preservation. Organisms were separated from the sediments, identified and counted.

Data Analysis

Data were compiled from individual technical reports and collated. Species identifications were checked for synonymies and name changes before data entry. Nematodes and copepods were excluded from analysis. The following faunal analyses were performed:

- Species composition
- Abundance and percent composition of dominant species
- Faunal density (number of individuals/m^2)
- Species richness (number of species/station)
- Species diversity (H', Shannon and Weaver 1963)
- Equitability (J', Pielou 1966)

The coefficient of variation was employed as a measure of the persistence of the dominant populations over time (Sanders 1978). Together with the percent occurrence for each dominant population, a two-dimensional plot showing the relationship among dominant taxa was generated.

A comparison was made between this study and other quantitative benthic studies conducted in Tampa Bay to determine if a north-south gradient in species richness and faunal abundance exists within the Tampa Bay system.

RESULTS

Abiotic Parameters

Mean bottom temperature and salinity for all stations for each sampling date are presented in Figure 3. No appreciable difference in either temperature or salinity was observed among stations for any given sampling event. Temperature ranged from 14°C (February 1977) to 32°C (August 1981) and followed a typical seasonal pattern. Salinity ranged from 15 ppt (September 1979) to 32 ppt (February 1985), with values ranging between 25-28 ppt throughout most of the study.

Sediment mean grain size and percent silt/clay are presented as yearly means for all stations in Figure 4. Mean grain size was approximately 3 phi units and remained consistent from year to year. Yearly silt/clay values were highly variable and showed no long-term pattern. Sediments from the Big Bend area can be characterized as fine to medium sands with a moderate silt/clay content.

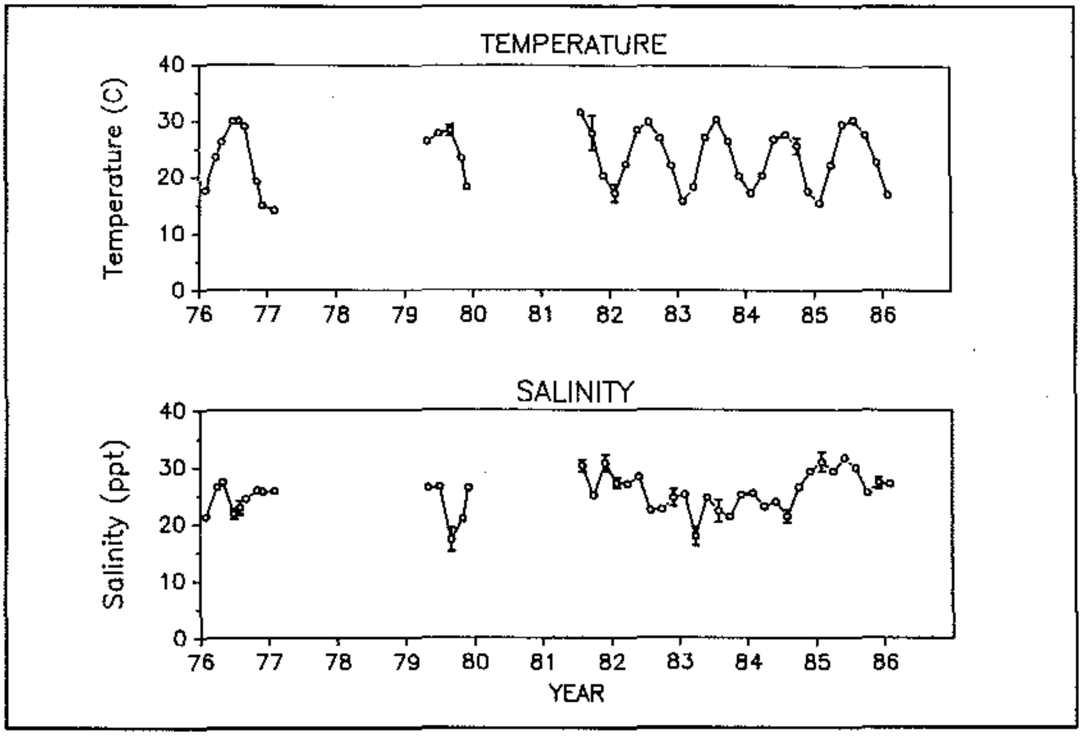

Figure 3. Mean bottom temperature (°C) and salinity (ppt) for all stations for each sampling period, 1976-1986.

Biotic Parameters

Figure 5 shows mean number of taxa and mean number of individuals (all stations-years combined) for each sampling month. This information addresses within-year or "seasonal" variability in faunal composition. The mean number of taxa was highest during winter and spring and lowest during late summer and fall. The mean number of individuals was highest during spring and early summer and lowest during late summer and fall.

The average number of taxa for north and south stations for each sampling date are presented in Figure 6. The number of taxa was lowest during the summer and fall of 1979, 1982 and 1983. Seasonal fluctuations in number of taxa were more pronounced at the north stations, where fewer taxa were present during the summer and fall of 1979, 1982 and 1983 than at the south stations. Since 1981, there has been a steady increase in the number of taxa at both the north and south stations in the Big Bend area.

The average number of individuals for north and south stations for each sampling date are presented in Figure 7. The average number of individuals was lowest at both sites during the fall 1979 followed by fall 1983 and fall 1982. Unusually high numbers of individuals were present in the spring and early summer 1983, followed immediately by a large decline in late summer and fall.

Average values for Pielou's index, a measure of the evenness with which individuals are distributed among species, are shown for north and south stations in Figure 8. Two large drops in the Pielou's index occurred at the north stations during the summers of 1982 and 1983, indicating a faunal dominance by one or a few organisms. Other years showed similar but less drastic reductions in Pielou's index during the summer and fall.

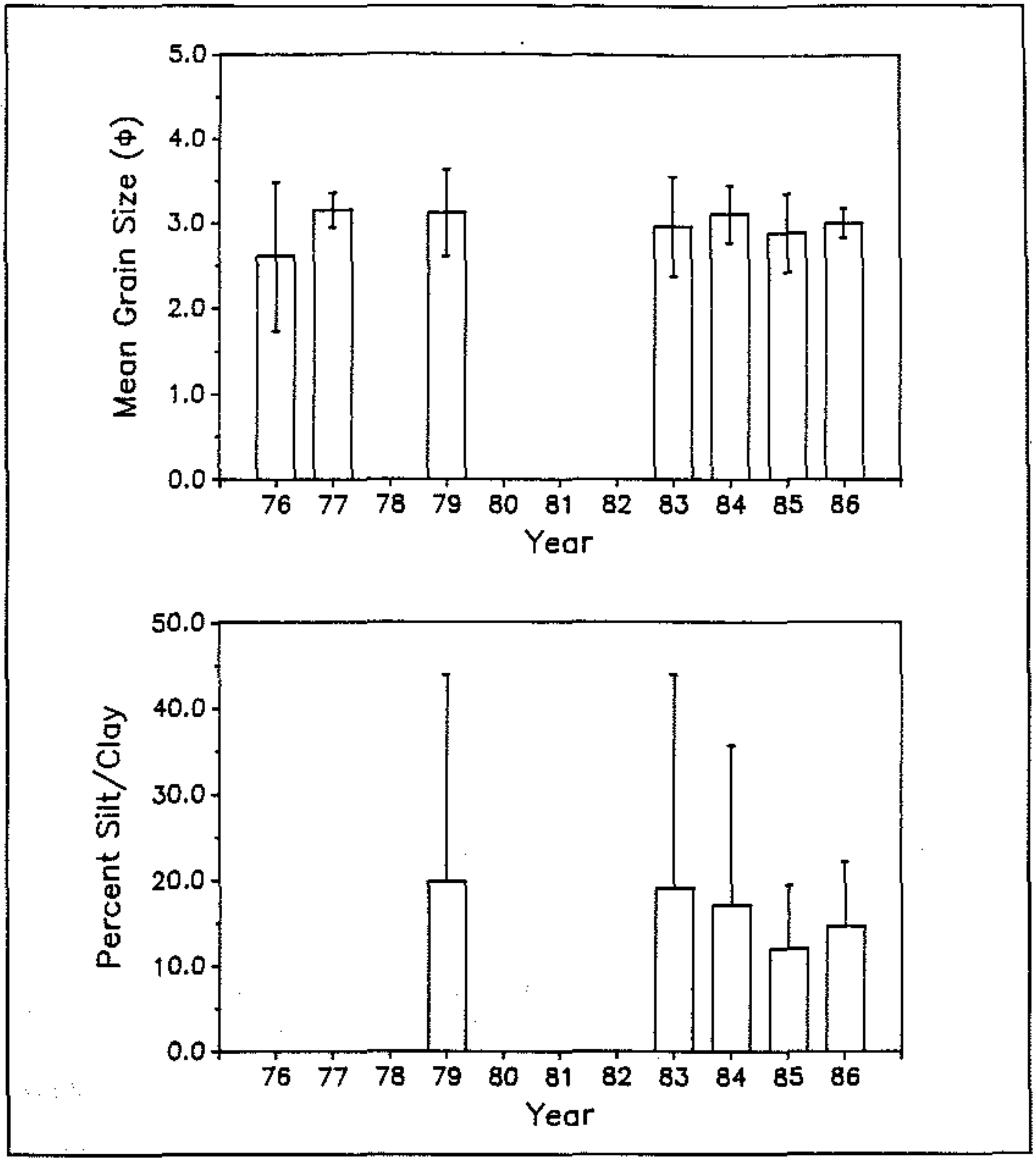

Figure 4. Sediment mean grain size and percent silt/clay for all stations for each year, 1976-1986.

Figure 9 summarizes the mean number of taxa and mean number of individuals (all stations-dates combined) for each year of the study. Mean number of taxa was lowest in 1979. Since 1979, there has been a steady increase in the mean number of taxa at the study site. The mean number of individuals was also lowest in 1979 and highest in 1983. No trends in the mean number of individuals were evident during the course of the study.

Dominant Taxa Analysis

Figure 10 is a plot of the coefficient of variation (CV) against the number of occurrences for each of the 25 dominant taxa from the study. Both terms are a measure of the "persistence" of a species over time, with the CV reflecting the variation in species population numbers. This figure presents a spatial portrayal of the different reproductive strategies employed by the various dominant species. Most of the dominant taxa exhibited a moderate coefficient of variation and a moderate to high number of occurrences. Several species have been highlighted to show the various extremes in reproductive strategy employed by the infauna of the Big Bend area. These reproductive strategies and the corresponding population dynamics of the highlighted species are described below.

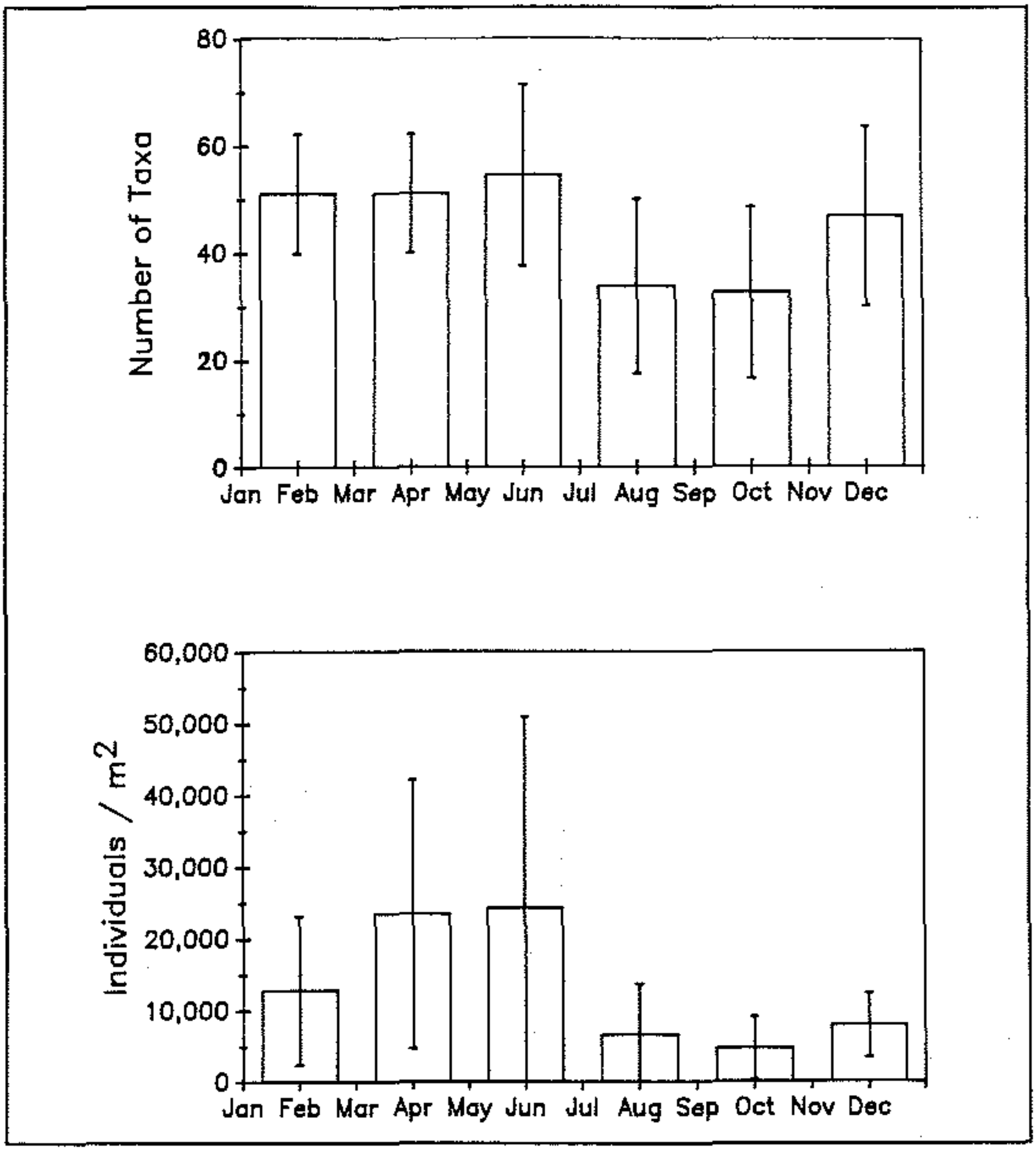

Figure 5. Mean number of taxa and mean number of individuals (all stations-years combined) for each sampling month, February-December.

Cumella sp. A (cumacean crustacean) exemplifies those species with a low number of occurrences and a high CV. These species are frequently absent from the study area, but occasionally experience large "population explosions" and greatly affect overall community structure. *Paraprionospio pinnata* (polychaete), on the other extreme, exhibited a high number of occurrences and a low CV, indicative of persistent species with a regular reproductive cycle. The majority of dominant species fell into a middle grouping characterized by moderately high numbers of occurrences and a low to moderate CV.

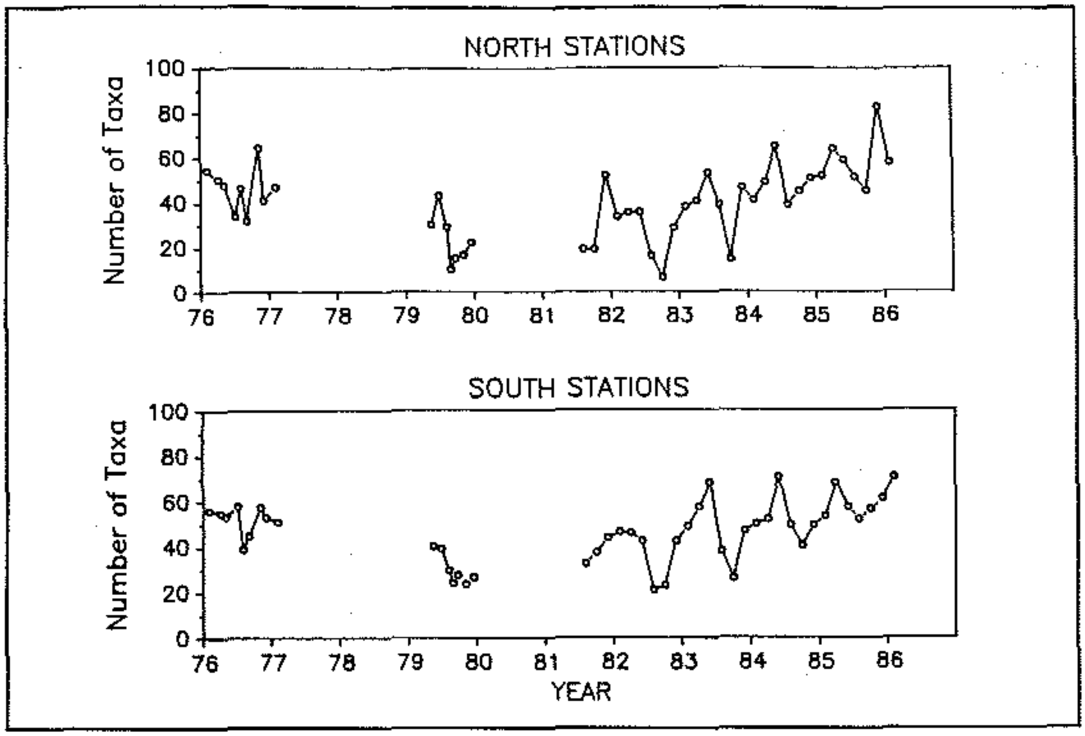

Figure 6. Average number of taxa for north and south stations for each sampling period, 1976-1986.

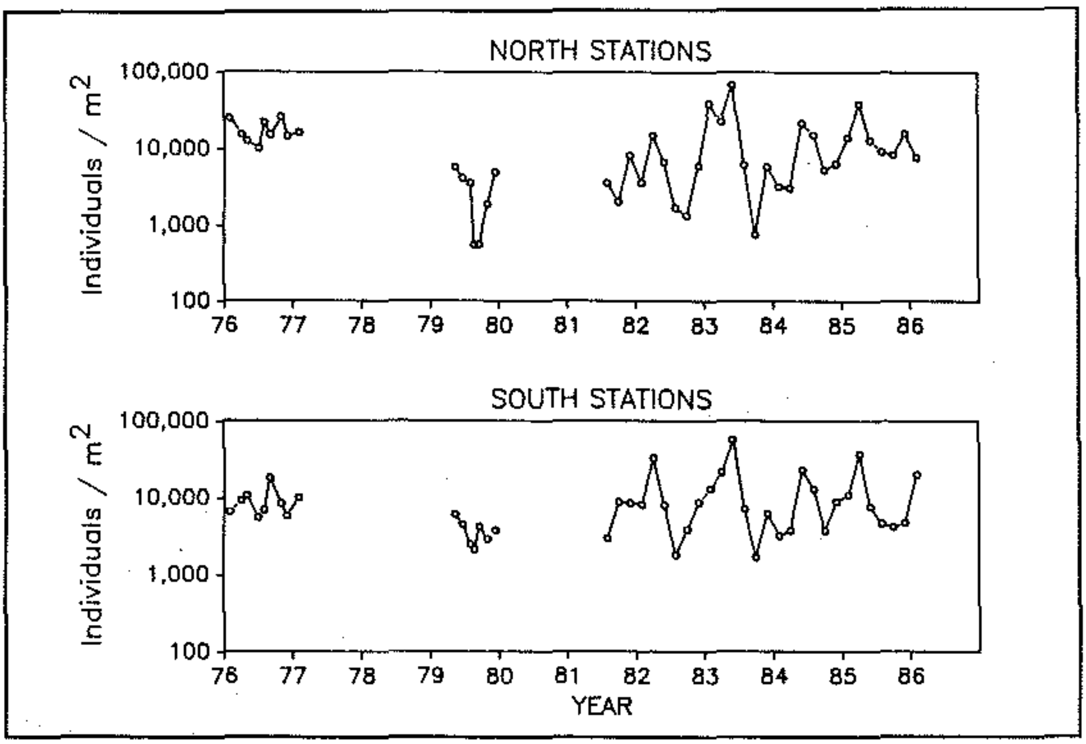

Figure 7. Average number of individuals for north and south stations for each sampling period, 1976-1986.

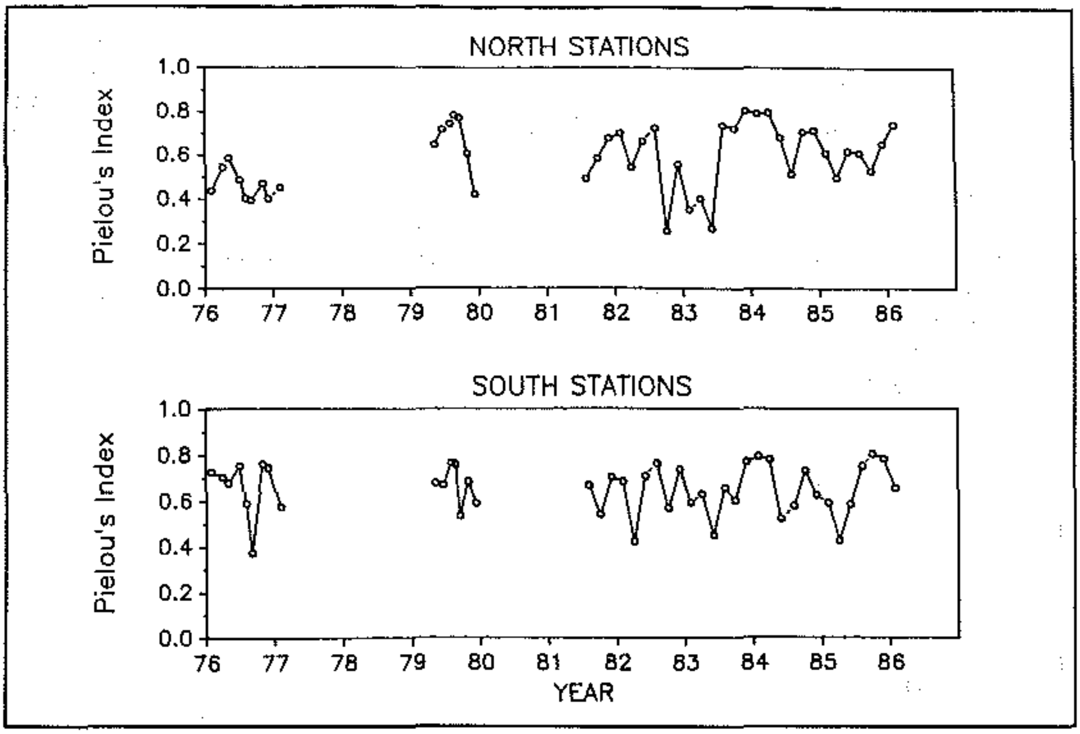

Figure 8. Average values for Pielou's index for north and south stations for each sampling period, 1976-1986.

Temporal trends in population dynamics of the five highlighted species are shown in Figures 11-15. *Cumella* sp. A (Figure 11) exhibited a large population increase during the first half of 1983, after which the species essentially disappeared from the study area. *Mulinea lateralis* (bivalve mollusc) also underwent a huge increase in numbers during the same period (Figure 12), but remained an integral part of the infauna during the rest of the study. Large population increases of the bivalve, *Tellina versicolor*, on the other hand, occurred during 1985 and 1986 (Figure 13). Finally, *Pinnixa pearsi* (decapod crustacean) and *Paraprionospio pinnata*, which represent fauna with a low CV and high number of occurrences, exhibited regular annual patterns in reproduction (Figures 14 and 15).

Comparisons of average species richness and faunal densities reported for subtidal benthic studies from Tampa Bay are presented in Table 2. Locations in Hillsborough Bay typically exhibited the lowest species richness, while regions of Lower Tampa Bay supported the highest number of species. Reported faunal densities varied throughout the bay system, but were generally within the range of 10-20,000 individuals/m^2. One notable exception to this pattern was the presence of 73,000 individuals/m^2 in Hillsborough Bay between 1975-1978.

DISCUSSION

The collected studies from Big Bend, Tampa Bay provide the opportunity to investigate both seasonal and long-term patterns in benthic community structure. The simultaneous collection of water column and sediment physical data allow for the potential to relate changes in faunal composition to physicochemical factors or possible environmental perturbations.

Most estuarine soft-bottom benthic communities appear to exhibit substantial seasonal variability in faunal composition (Boesch et al. 1976). The faunal community from Big Bend was no exception, experiencing distinct seasonal cycles in abundance and number of taxa throughout the study. Each year, faunal density and diversity were highest from late winter to early summer, followed by sharp reductions from late summer through fall. Similar seasonal patterns have been reported for other estuaries, including Apalachicola Bay (Mahoney and Livingston 1982) and Chesapeake Bay (Boesch et al. 1976). These seasonal cycles are typically driven by complex interactions between physical forces, such as temperature and salinity, and the more subtle biological factors which affect reproduction, recruitment and survival. The persistent regularity in the seasonality of the Big Bend benthic fauna probably reflects stable community dynamics associated with healthy, unperturbed environments. Additionally, the number of taxa found at Big Bend increased steadily from 1981 to 1986, after a low in 1979. While it is difficult to assess the nature or cause of this increase, it should be noted that increases in the number of taxa at Big Bend coincides with improvements in water quality in Hillsborough Bay (HCPEC 1987, City of Tampa 1988), located just to the north of Big Bend.

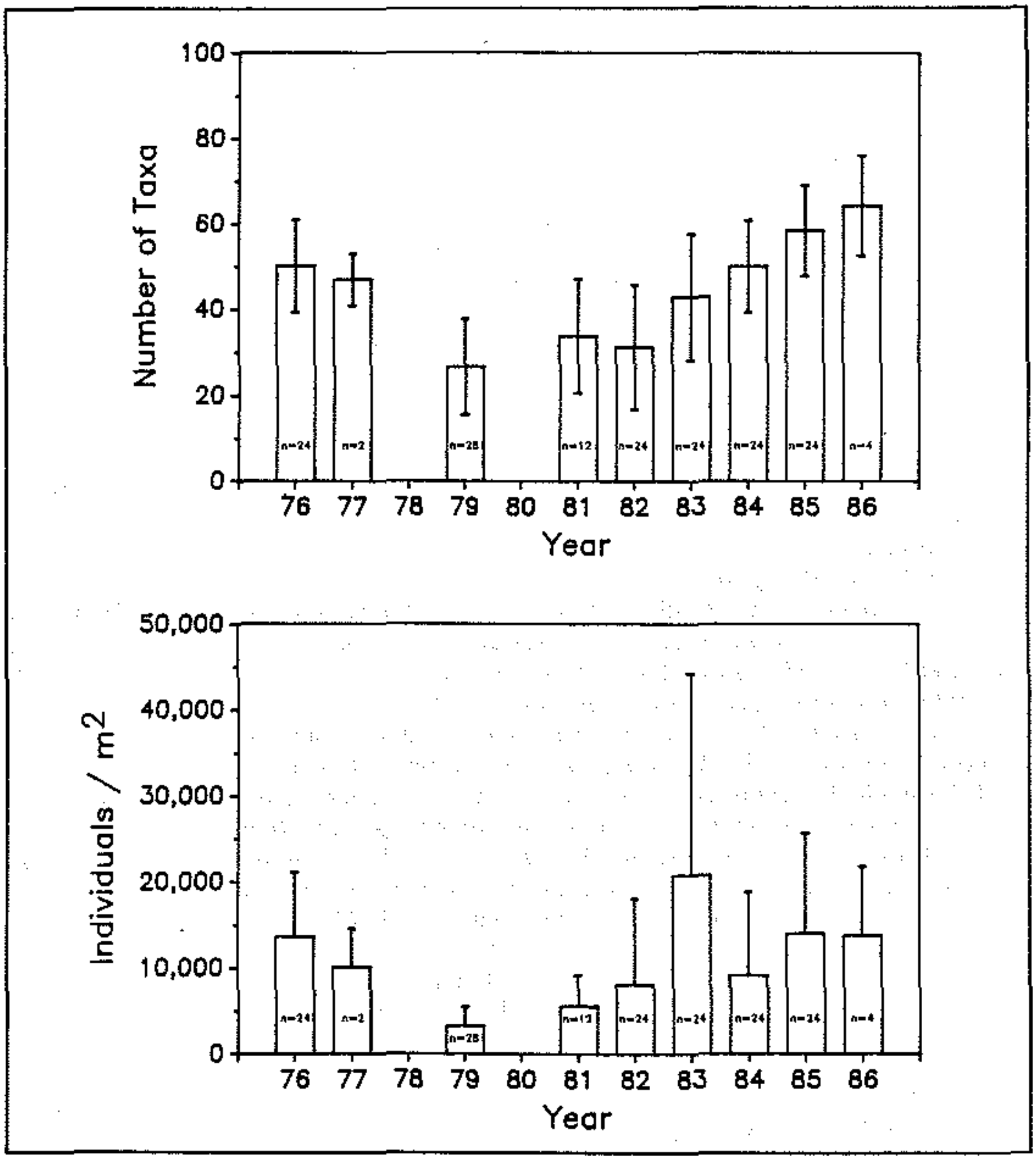

Figure 9. Mean number of taxa and mean number of individuals (all station-dates combined) for each year of the study, 1976-1986.

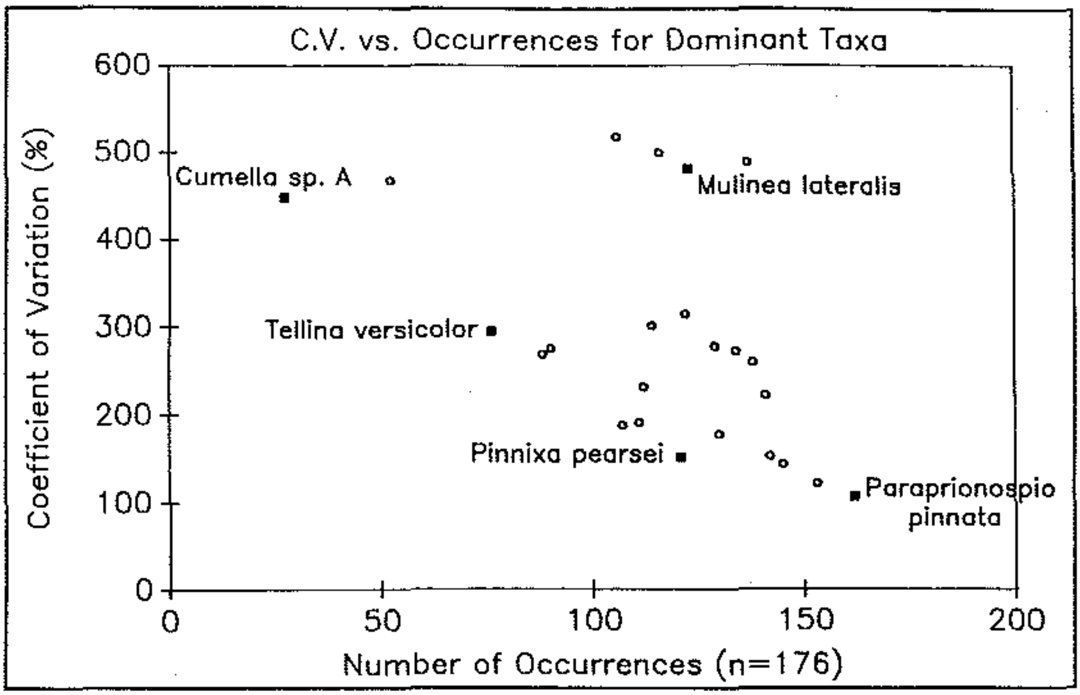

Figure 10. Coefficient of variation (%) versus number of occurrences for the 25 dominant taxa from the study area; ■ - highlighted species; O - remaining taxa.

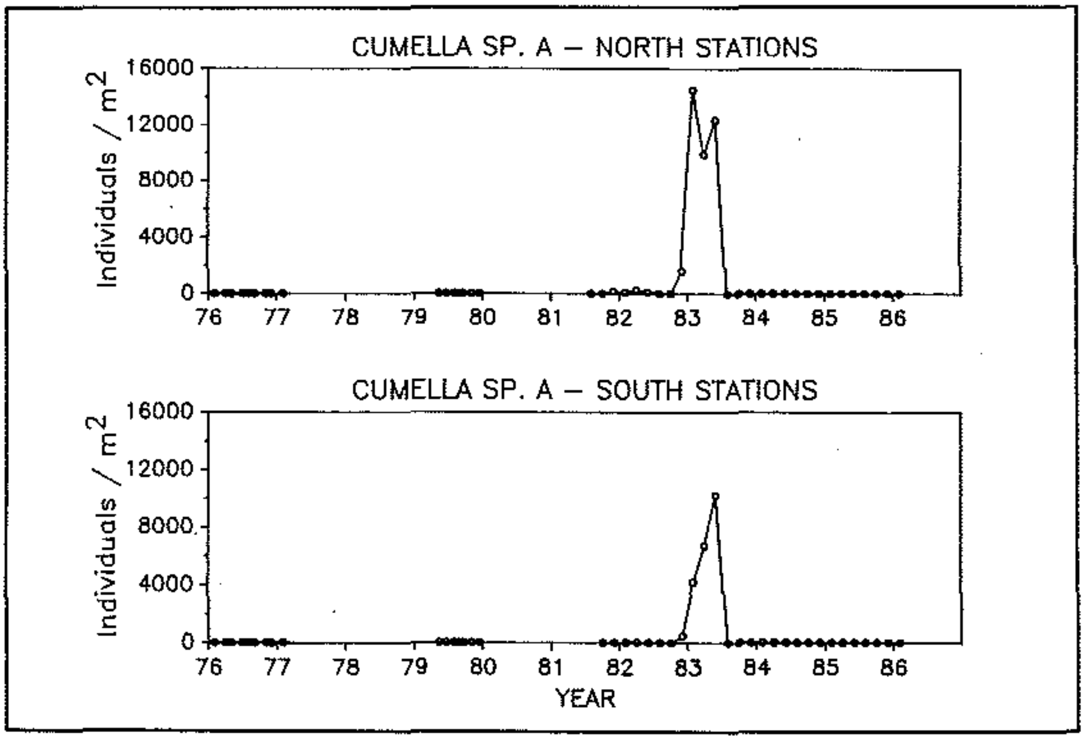

Figure 11. Average abundance of Cumella sp. A for north and south stations for each sampling period, 1976-1986.

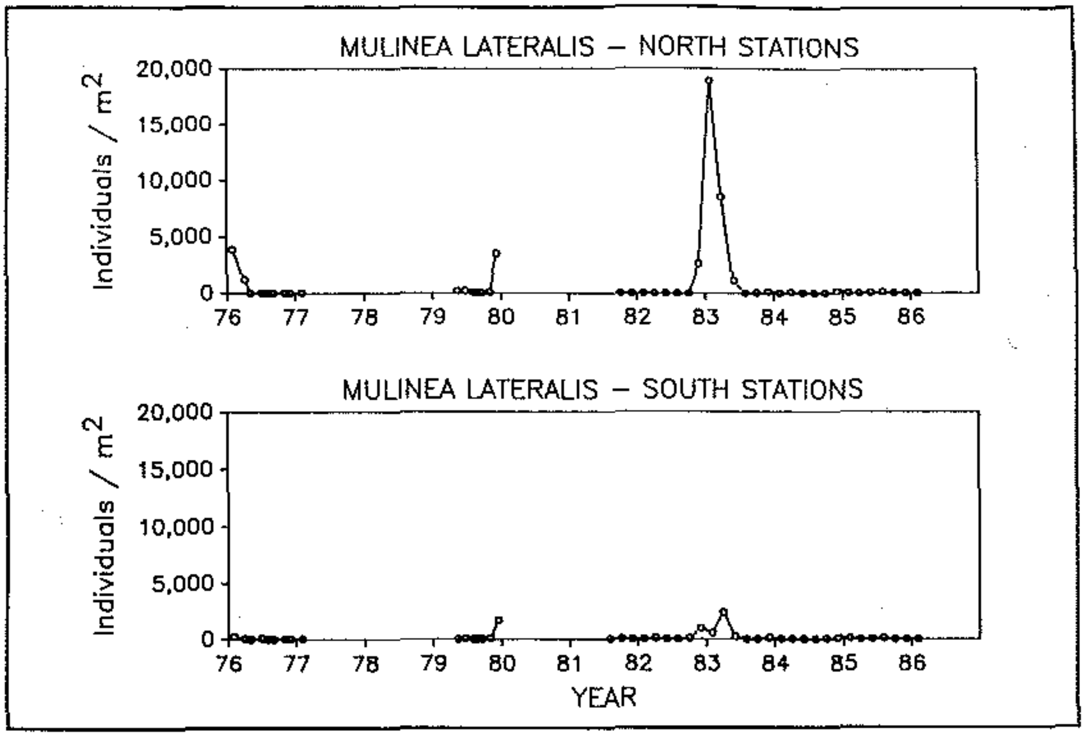

Figure 12. Average abundance of Mulinea lateralis for north and south stations for each sampling period, 1976-1986.

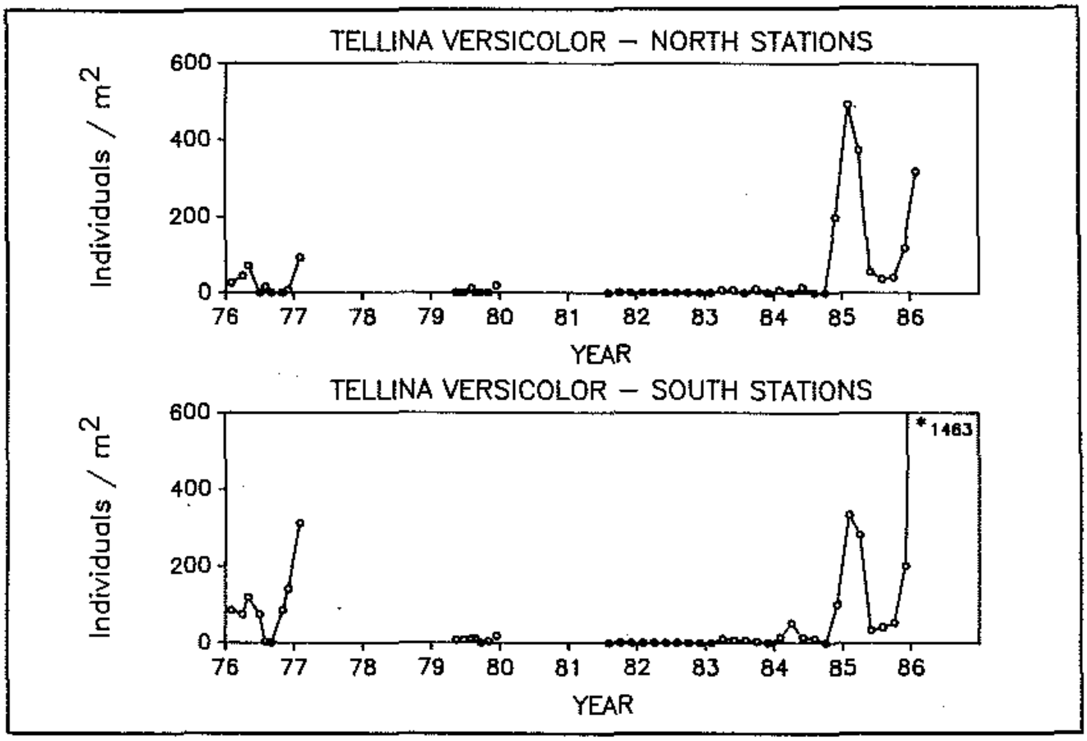

Figure 13. Average abundance of Tellina versicolor for north and south stations for each sampling period, 1976-1986.

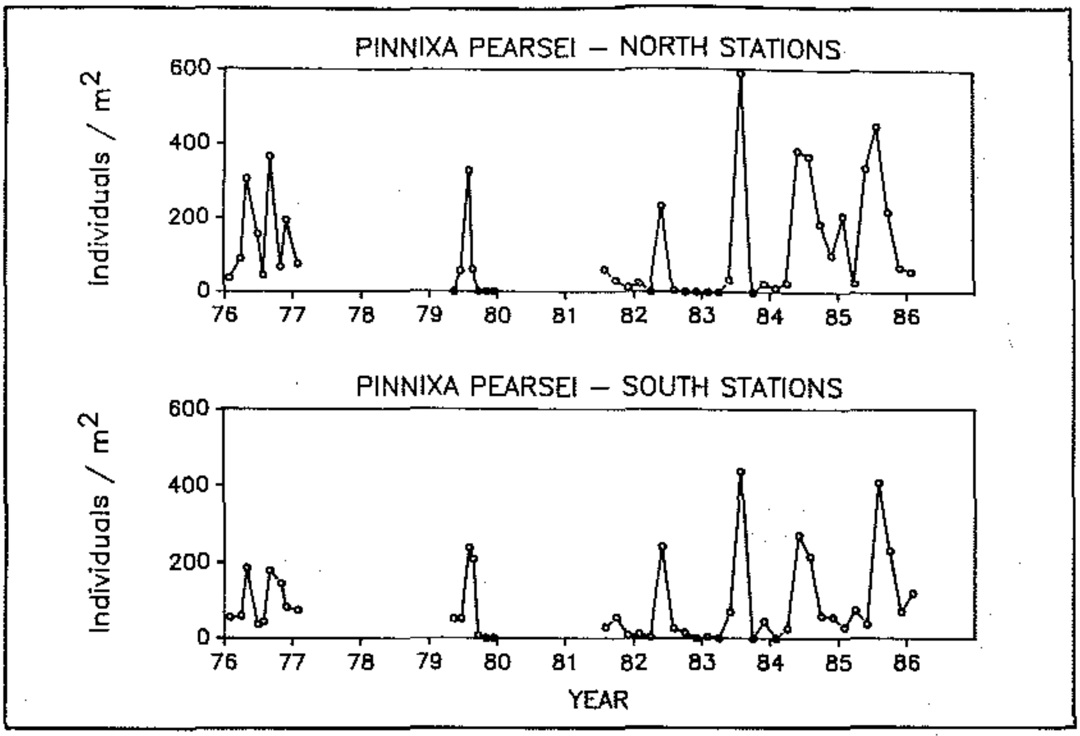

Figure 14. Average abundance of Pinnixa pearsi for north and south stations for each sampling period, 1976-1986.

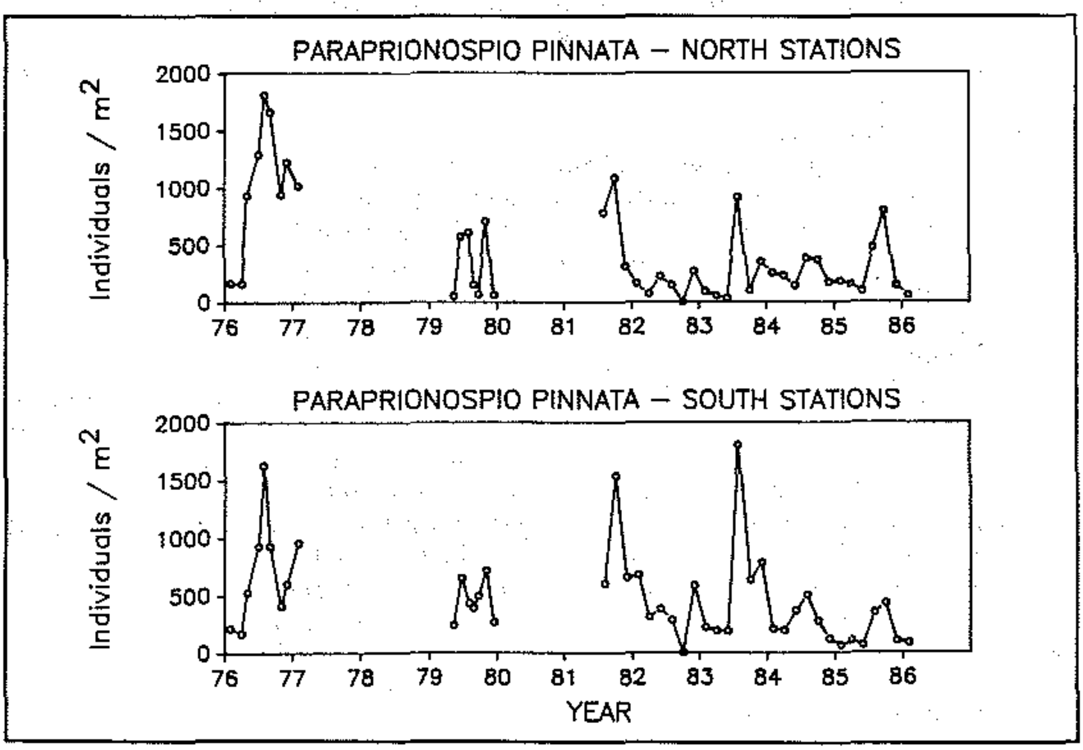

Figure 15. Average abundance of Paraprionospio pinnata for north and south stations for each sampling period, 1976-1986.

Table 2. Comparisons of average species richness (number of species/station) and faunal densities (individuals/m^2) for subtidal benthos in Tampa Bay, Florida.

DATE	LOCALITY	RICHNESS	DENSITY	SOURCE
1975-1978	Hillsborough Bay	14	73,000	Santos and Simon 1980
1975	Gardinier	10	12,000	Upchurch et al. 1976
1975	Bullfrog Creek	21	8,865	LETCO 1975
1974-1976	Gadsden Point Cut	51	15,000	Simon, Doyle and Conner 1976
1971-1973	Old Tampa Bay (Courtney Campbell Causeway)	66	(7,000)	Simon and Dauer 1977
1987-1989	Lassing Park (unvegetated)	60	20,289	MML, unpublished
1976-1986	Apollo Beach (Big Bend)			
	a) 1976	49	13,602	Mahadevan et al. 1977
	b) 1979	30	5,489	Mahadevan et al. 1980
	c) 1981-1984	42	14,629	Mahadevan and Culter 1984
	d) 1984-1986	60	15,391	Leverone and Mahadevan 1986
1975-1976	Beacon Key			
	a) Sandy Substrate	99	10,400	Mahadevan 1976
	b) Channel	46	3,949	Mahadevan 1976
1982	Piney Point	75	16,736	MML, unpublished

Modified from Upchurch et al. 1976
Updated from Mahadevan 1977

Occasionally, large deviations from normal cycles are observed in benthic faunal composition. These anomalies are generally caused by ephemeral irruptions of certain species, which greatly affect overall community structure (Boesch et al. 1976). In the present study, several species experienced huge, sporadic oscillations in abundance which accounted for large fluctuations in the "amplitude" of the seasonal faunal cycles. Most notable were the bivalve mollusc, *Mulinia lateralis*, and the cumacean, *Cumella* sp. A, which were responsible for the high faunal densities in June 1983. Populations of these two species were practically nonexistent before and after this episode. *Mulinia* is well known for "explosions" in population densities (Rhoads 1974, Levington and Bambach 1970). *Cumella* sp. A is a highly motile, surface feeding crustacean. While the causes of the population explosions are unclear, unseasonably low salinities (16 ppt) were recorded during the previous sampling effort (April 1983). Although several species exhibited reproductive patterns similar to *Mulinia*, many others, including the pea crab, *Pinnixa pearsi* and the polychaete, *Paraprionospio pinnata*, showed a very clear annual mode of reproduction.

Certain species of benthic infauna, most notably the polychaetes *Capitella capitata*, *Polydora cornuta* and *Streblospio benedicti*, have opportunistic life histories which enable them to colonize disturbed habitats quickly. Initial response to disturbed conditions, the ability to proliferate rapidly, large population size, early maturation and high mortality are all features of opportunistic species (Grassle and Grassle 1974). These species were frequently abundant in Hillsborough Bay during the mid-1970s (Santos and Simon 1980). These organisms were only found in low numbers throughout the studies at Big Bend and never constituted a dominant portion of the benthic community. Based on these criteria, the low levels of "indicator organisms" suggest a healthy benthic environment in the vicinity of Big Bend.

Findings from the collected studies at Big Bend (as well as other unpublished studies by Mote Marine Laboratory) support the concept of an increase in species richness along a north-south gradient in Tampa Bay. Several studies conducted in Tampa Bay during the 1970s have shown Hillsborough Bay to contain relatively few benthic infaunal species. Regions of Middle Tampa Bay (including Big Bend) average 50-60 benthic species per survey, while upwards of 75 different species have been reported from Lower Tampa Bay. However, a decrease in faunal density along the same gradient was not substantiated by either the Big Bend results or other Mote

Marine Laboratory benthic studies. Faunal densities throughout Tampa Bay typically ranged from 10-20,000 individuals/m^2. Two deviations from this range involved a study by Santos and Simon (1980), who reported 73,000 individuals/m^2 from Hillsborough Bay, and another by Mahadevan (1976) where less than 4,000 individuals/m^2 were reported from the shipping channel in Lower Tampa Bay. These two studies were conducted in severely impacted or altered habitats which were not indicative of the natural conditions of the surrounding bay bottom. Even under natural conditions, large fluctuations in benthic faunal densities are quite common, which hinder the ability to make accurate predictions or substantive generalizations. More complete spatial and temporal data on Tampa Bay benthos are needed to verify the existence of a gradient in faunal abundance within the estuary.

Changes in biomass and numbers of individuals along a sediment gradient have been found in other major estuaries, including the Newport River estuary, a shallow system in North Carolina (Chester et al. 1983). The increase in species richness from north to south in Tampa Bay may also be driven by a similar sediment gradient. The upper reaches of Tampa Bay, particularly Hillsborough Bay, contain anaerobic fine particulate sediments, while Lower Tampa Bay has predominantly aerobic sediments consisting of sand and shell. While both sediment types appear to support large numbers of individuals, fewer species appear able to tolerate the conditions found in Hillsborough Bay and similar areas of Upper Tampa Bay.

Unvegetated subtidal bottoms are a major component of Tampa Bay, comprising 92,334 ha, or 74% of the estuary (Haddad 1989). While recent research efforts in Tampa Bay have focused on other, more visible habitats, the huge expanse of unvegetated bay bottom cannot be disregarded or considered by resource managers as a single homogeneous habitat. Our current knowledge of the biological resources and functional habitats for the vast majority of the subtidal areas of Tampa Bay is practically nonexistent. Suggestions for alleviating this inadequacy include redirecting research support to regionally representative studies of long-term variations in natural and altered communities in preference to the temporally inadequate, facility-specific studies performed to date. More attention should be placed on the equilibrium species in a community rather than on opportunistic "pollution indicators" which can also sporadically exploit pristine habitats. Only through such long-term studies can we gain the necessary insight into dynamic processes required to interpret site-specific surveys. A better understanding of the nature and causes of natural fluctuations in species populations and community structure will help in the development of natural resource plans geared ultimately towards the proper management and protection of the Tampa Bay estuarine system.

SUMMARY

1. Benthic communities from Big Bend exhibited seasonal patterns in faunal abundance and diversity similar to most other regions of Tampa Bay during the ten-year study period (1976-1986).
2. Faunal densities were lowest in 1979 and highest in 1983.
3. Species richness was lowest in 1979 and gradually increased from 1981-1986.
4. The lack of dominance by "indicator organisms" suggests a lack of serious environmental stress on the Big Bend faunal communities.
5. The concept of a north to south gradient in species richness, but not in faunal abundance, was supported by findings from the current study.
6. More complete areal and temporal coverage of the benthic communities will be necessary if effective resource management of the Tampa Bay estuary is to be realized.

ACKNOWLEDGEMENT

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NURSERY HABITATS OF IMPORTANT EARLY-JUVENILE FISHES IN THE MANATEE RIVER ESTUARY SYSTEM OF TAMPA BAY

R. E. Edwards

ABSTRACT

Shoreline and shallow water habitats of the middle and upper portions of the Manatee River estuary system (MRES) were studied with regard to habitat characteristics and utilization by early-juvenile (EJ) stages of important fishes. A habitat classification system based on shoreline morphology, intertidal morphology, and intertidal vegetation was developed and used to characterize MRES habitats. More than 200 stations covering representative examples of important (areal extent and/or frequency of occurrence) habitats were sampled during late summer/early fall and again during winter to determine EJ habitat utilization patterns. The MRES was found to be an important nursery for snook (Centropomus undecimalis), spotted seatrout (Cynoscion nebulosus), sand seatrout (C. arenarius), striped mullet (Mugil cephalus) and red drum (Sciaenops ocellatus). Early-juvenile snook were collected only from a few small, special and uncommon habitat categories and appeared almost never to utilize the most extensive or most common categories; the latter habitats were utilized by seatrout. Like snook, EJ striped mullet were found to utilize special habitats almost exclusively. Early-juvenile red drum also utilized special habitats most heavily but were found also to utilize many of the extensive and common habitats. Salinity regime also was an important aspect of EJ habitat relationships. Snook primarily utilized low salinity (<7 ppt) environments, while striped mullet and seatrout utilized environments with salinities above 5 ppt. Red drum were collected over a wide salinity range (0-21 ppt) but were most abundant at the middle to upper part of this range. The study results indicate that for fully effective protection, management, improvement or creation of fishery habitat in Tampa Bay and other estuaries, approaches that are more detailed and "fine-grained" than those traditionally taken are needed. The MRES and similar estuaries should be viewed as a mosaic of stationary nursery habitats over which dynamic habitat parameters, like salinity, are superimposed to determine productivity and recruitment of fishes. Because the MRES is one of Tampa Bay's most important nurseries for valuable fishes, careful management and protection are warranted.

INTRODUCTION

The Manatee River Estuary System

The Manatee River estuary system (MRES) includes the Manatee River and its estuarine tributary, the Braden River (Fig. 1). The Manatee River Estuary extends from Tampa Bay upstream approximately to the Lake Manatee Reservoir impoundment, which is about 28 km to the east of the river's entrance into Tampa Bay at Emerson Point. Its major tributary, the Braden River, is also impounded, with its estuarine portion extending approximately 8.6 km upstream from its confluence with the Manatee River, approximately 11.2 km from Tampa Bay. The annual discharge of the Manatee River has been estimated at 6.87×10^{10} gal/yr (2.60 x 108 m^3/yr), ranking it third among Tampa Bay rivers, behind the Hillsborough and Alafia Rivers (Dooris and Dooris 1985). The flow of the Braden River has not been measured, but based upon total drainage basin area for the two rivers (Estevez et al., this volume), total annual discharge of the MRES is probably second only to that of the Hillsborough River.

Important features of the Manatee and Braden Rivers are that along much of their reaches they are wide, shallow and relatively unchannelized. This results in broad estuarine mixing zones which include large areas with diverse geomorphology and vegetational habitats. This situation contrasts with the two Tampa Bay rivers with larger flow, the Hillsborough and Alafia, which are relatively more narrow, more channelized, and have smaller mixing zones (compressed salinity gradients) and smaller areas of estuarine habitat. Lewis and Whitman (1985) estimated that the Manatee River subdivision of Tampa Bay included 1,530 ha of emergent wetlands and was surpassed only by the Old Tampa Bay and Middle Tampa Bay subdivisions with 1,870 and 1,700 ha, respectively. Lewis and Whitman (1985) did not include the Braden River and the upper 17.7 km of the Manatee River estuary, which, if included, would certainly result in the MRES containing more emergent wetlands than

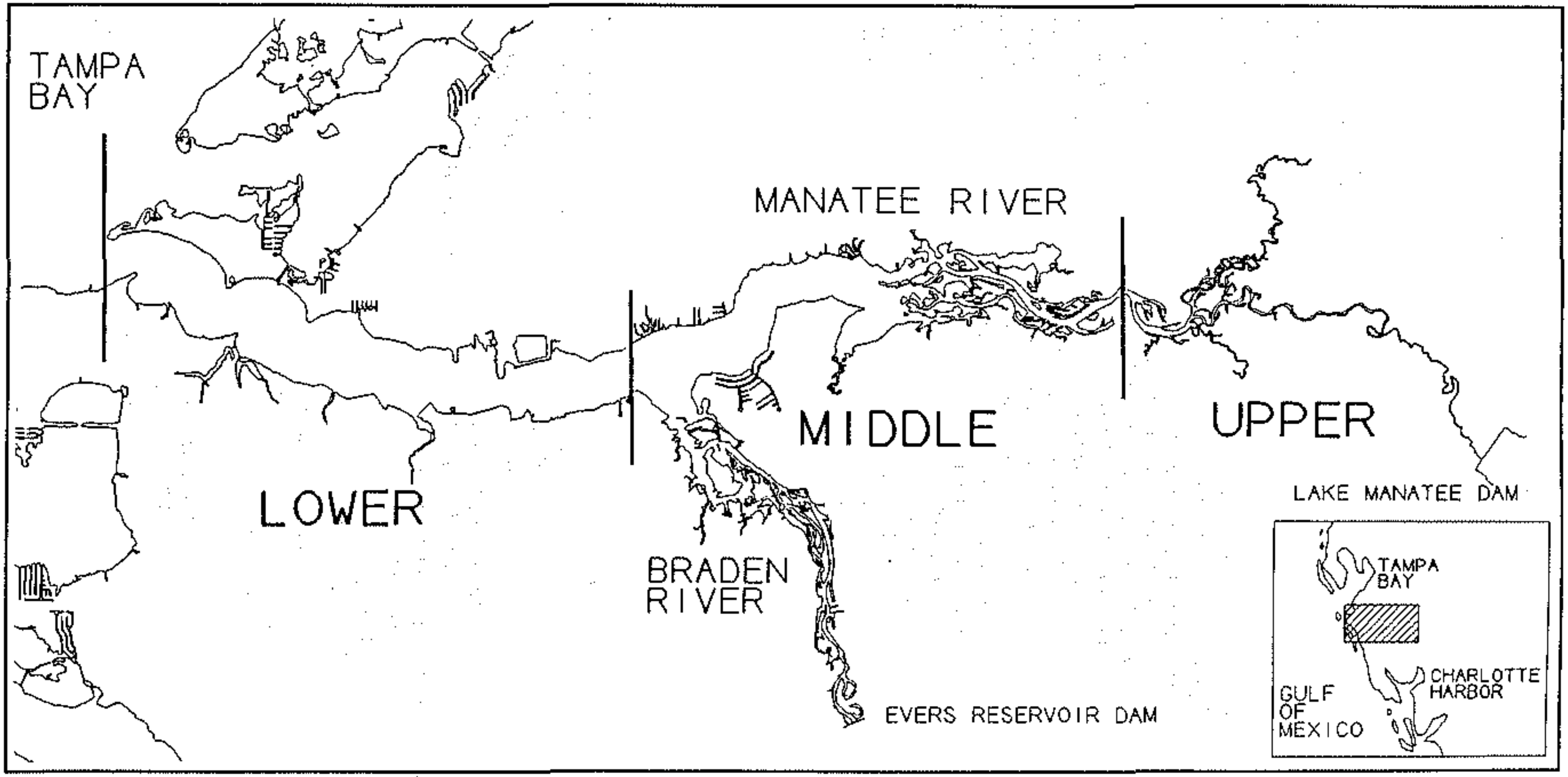

Figure 1. Manatee River Estuary System.

any other subdivision of Tampa Bay. Even as calculated by Lewis and Whitman (1985), the Manatee River had an areal ratio of wetlands to open water of 0.47, which is far greater than the ratios for other subdivisions which, with the exception of adjoining Terra Ceia (ratio = 0.30), ranged only from 0.03 to 0.10. Beyond these tabulated estimates and a few water quality and hydrological studies, there have been very few ecological studies or surveys of the MRES. A study performed during 1982-1984 for the Manatee County Utilities Department (MCUD and CDM 1984) included water quality, hydrology, salinity modeling, vegetation surveys, and a benthic (infauna and sediments) survey. A cursory survey of the Manatee and Braden Rivers (Murdoch 1957) is the only report on MRES fish and fisheries.

The MRES can be divided into lower, middle and upper reaches (Fig. 1). The lower portion includes the section from the Manatee River mouth to the confluence of the Braden and Manatee rivers at Ayres Point (about 11.8 km along the main axis of the river) upstream. The middle MRES extends from Ayres Point to Fort Hamer (11.2 km) on the Manatee and includes all of the tidal Braden River (8.6 km). The upper MRES includes the remainder of the tidal Manatee River to the Lake Manatee dam, as well as several important tributaries including Gamble Creek and Mill Creek. The straight-line distance of the river from its mouth to the Lake Manatee Dam is about 28 km. Distances along the river, which becomes very serpentine in the upper reach, are much greater.

Most of the lower MRES is highly altered. With the exception of a short (2 km) length of mangrove-fringed shoreline on the northern side of the river immediately upstream from its mouth at Emerson Point, little natural shoreline exists in the lower MRES. The lower MRES is bordered by the City of Bradenton (southern shore) and City of Palmetto (northern shore). The City of Bradenton's sewage treatment plant and an industrial point source discharge into the MRES upstream of downtown Bradenton, at a point about 2 km downstream from the Braden River.

The middle and upper portions of the MRES contain extensive areas of natural, physically unaltered estuarine habitat. In some places, the Manatee River approaches 2 km in width, while the Braden River approaches 1.5 km. These wide reaches include extensive areas of saltmarsh islands. Almost all of the MRES's intertidal wetlands are in the middle and upper reaches.

Salinity in the middle and upper MRES typically ranges from mixohaline (up to about 30 ppt) to freshwater conditions. The system experiences large seasonal salinity transitions, which in some areas may exceed 25 to 30 ppt. Salinity changes are probably amplified by the existence of the dams and reservoirs on both the Manatee and Braden Rivers.

Morphologically, the middle and upper MRES is very complex and ranges from narrow riverine channels with firm, clean, sandy bottoms and steep banks, to broad estuarine shallows with soft, organic-rich, muddy sediments and without well defined banks. The system includes countless irregularly shaped islands, meandering marsh creeks, and interconnected channels. The system is fed by numerous tributaries, ranging from rivulets that drain immediately adjacent uplands to major tidal tributaries with watersheds extending tens of kilometers from the rivers.

Much of the this part of the system is natural and relatively unaltered. However, substantial areas that are highly altered and/or surrounded by residential development or intensive agriculture are present in the middle MRES. Land use in the immediate area is in a dynamic state of transition. Several very large residential developments bordering the estuary or in the watershed are under construction or in final stages of planning.

The shoreline and marsh vegetation in the middle and upper MRES ranges from freshwater species and communities to classical estuarine saltmarshes. Saltmarshes range from well developed mangroves typical of tropical and subtropical regions to marshes vegetated by species such as *Spartina alterniflora* and *Juncus roemerianus*, more typical of temperate regions. The MRES is located at or near botanical/zoological climatological boundaries and zoogeographic ranges. The system exists in a state of dynamic succession that occurs in response to episodic climatic events (e.g., freezes, droughts and tropical storms).

Complexity also is great within major habitats. Almost every habitat has its own set of unique conditions in terms of geomorphic configurations, elevations, sediments, and vegetation. Even monospecific marshes (e.g., *Juncus* marshes) include a diversity of subhabitats and geomorphic conditions, with conditions changing rapidly over distances as small as a meter or so.

Fishes of the MRES range from freshwater species such as large mouth bass (*Micropterus salmoides*) and shiners (*Notropus* sp.), estuarine species, like red drum (*Sciaenops ocellatus*) and spot (*Leostomus xanthurus*), to occasional marine species, like cobia (*Rachycentron canadum*) and Spanish mackerel (*Scomberomorus maculatus*). Fishes range from species like tarpon (*Megalops atlanticus*) that are normally found in tropical regions to species like menhadens (*Brevoortia* sp.) that are more typical of temperate regions.

The Manatee River Estuary System as Fish Nursery Habitat

Because of its broad salinity gradient and large area of wetlands, the Manatee River estuary system can be assumed to be extremely important as a nursery for estuarine fishes, but previously it had not been assessed in this regard. Comp's (1985) review of the literature on fishes of Tampa Bay was unable to find any reports of ichthyological studies or collections in the Manatee River, whereas all other areas of Tampa Bay had been sampled and studied to some extent. Perhaps the only ichthyofaunal study of the MRES was the cursory 1957 survey by the Florida Board of Conservation (Murdoch 1957) that concluded that the area was an important nursery for striped mullet, red drum, snook and other fishes, and which stated, "The areas provided by rivers, bays and adjacent lowlands are undoubtedly important nursery grounds for most of the fish found in this region."

For Tampa Bay in general, and for the Manatee River estuary system specifically, there is a serious need to protect and manage important estuarine nursery habitats. However, nursery habitats are not well understood, known, or identified. Comp's (1985) review included the following recommendations (p. 413):

> It is recommended therefore, that an indirect approach be taken toward monitoring fish stability and/or production within the Bay. Such an approach will involve locating, then monitoring, the community structure (and perhaps, relative abundance) within the major nurseries in Tampa Bay. Information on seasonal use of several nurseries in the Bay is provided in this report; however, to understand best the extent of utilization the location of <u>all</u> nurseries should be identified. Once the locations of the major nurseries have been established, steps can be taken to ensure that these areas are preserved since, as shown in previous reports, a loss of critical estuarine habitat can result in a loss of fishery resources.

In this light, a study of the estuarine nursery habitat relationships of several important fish species was conducted in the middle and upper MRES. The purpose of the study was twofold. First, it was aimed at providing basic information about juvenile fish habitat relationships in this and other estuarine systems ("the estuarine nursery habitat problem"—see below). Second, it was designed to provide information and an inventory that could be used to conserve and manage critical fisheries habitat in this large and diverse estuarine system that faces potential anthropogenic alterations such as diversion of freshwater inflows and physical alterations due to development along the MRES and in its watershed.

The Estuarine Nursery Habitat Problem

It is now generally accepted that many recreationally and commercially important fishery species are estuarine-dependent (Gunter 1957) in as much as estuaries are essential to all or part of their life cycles. It is also recognized that for many species, estuaries are most important as nurseries for juveniles (Sykes and Finucane 1966), and fisheries ecologists know that certain general types of habitat, such as saltmarshes and seagrass meadows provide nursery habitat for many important species (Lewis et al. 1985).

Habitat requirements of estuarine fishes are closely tied to life history patterns. Many important estuarine fishes have a life history starting with spawning in open coastal waters, followed by movement of planktonic larval stages to very shallow estuarine habitats as larvae approach metamorphosis at an age of about three to four weeks. In order for these newly metamorphosed juveniles to survive, they must find certain special nursery habitats; they almost never survive or are found elsewhere. Special early-juvenile habitat is utilized for several months until the fish attain a size of around 100 mm SL, at which point they begin to move to other, usually deeper habitats (Gilmore et al. 1983). For such species, the entire recruitment or year-class strength potentially can be determined by availability of these special early-juvenile habitats (Edwards 1989).

For this reason, resource management for Tampa Bay and many other areas of Florida must focus on protecting remaining nursery habitats (as opposed to protecting estuarine systems generally). If sufficient nursery habitat is not maintained, a biological bottleneck will exist, and other improvement, enhancement, or management will not be effective in maintaining fishery resources. Increasing water clarity, reducing nutrient loading, elevating dissolved oxygen levels, and creating additional adult habitat (e.g., seagrass beds, reefs, etc.) will not enhance or even sustain a fishery if there are not enough young fish being produced and recruited to take advantage of the improved subadult and adult conditions and habitats. Therefore, for species with special nursery requirements, nursery habitat identification, characterization, protection, and in some cases enhancement, should have high priority in improvement and management programs.

There is another aspect to habitat protection that is not always understood and appreciated to the extent that its importance warrants. This aspect is the fact that it is not sufficient that proper estuarine structural habitat be physically available and abundant; it is also necessary that conditions within the habitat be suitable for survival and growth. Freshwater inflow and resultant salinity regime are primary factors that often determine if the structural habitat is suitable. Browder and Moore (1981) developed this idea into a conceptual model (Fig. 2A) in which production (recruitment) occurs in an area which is the intersection of stationary (structural) habitat and dynamic habitat (often salinity regime). Another way of conceptualizing this idea in a more concrete manner is to consider parts of the estuary as stationary or structural habitat over which a salinity gradient is superimposed (Fig. 2B). Only the portion of stationary habitat that is within suitable salinity ranges is highly productive in terms of recruitment. Another feature of this concept is that a relatively large area of stationary habitat is generally required to ensure that sufficient areas of productive habitat are available due to intersection of stationary and dynamic habitat. For this reason larger estuarine systems are probably extremely valuable as areas of consistently productive nursery habitat. Furthermore, as pointed out by Estevez et al. (this volume), the configuration of most river estuaries is such that the area and volume of stationary habitat decreases geometrically upstream.

Traditionally, the common approach toward natural resources management and fisheries protection has been to seek to preserve, conserve, protect, and, in some cases, to restore, create, or enhance general types of habitat like saltmarshes and mangroves. What has not been so widely appreciated is the fact that these general habitat types themselves are not uniformly valuable as nurseries. Instead, the specific nursery habitat for early-life stages of many species may be largely restricted to certain subhabitats and structural components of these general habitat types. In the Tampa Bay region and in many other areas of Florida, where large areas of estuarine nursery habitat have been destroyed or altered, it is essential that a thorough understanding of these special subhabitats and structural components and their relationship to important fishery species be fully understood so that the remaining (existing, restored or created) habitat can be optimized with regard to its management and productivity.

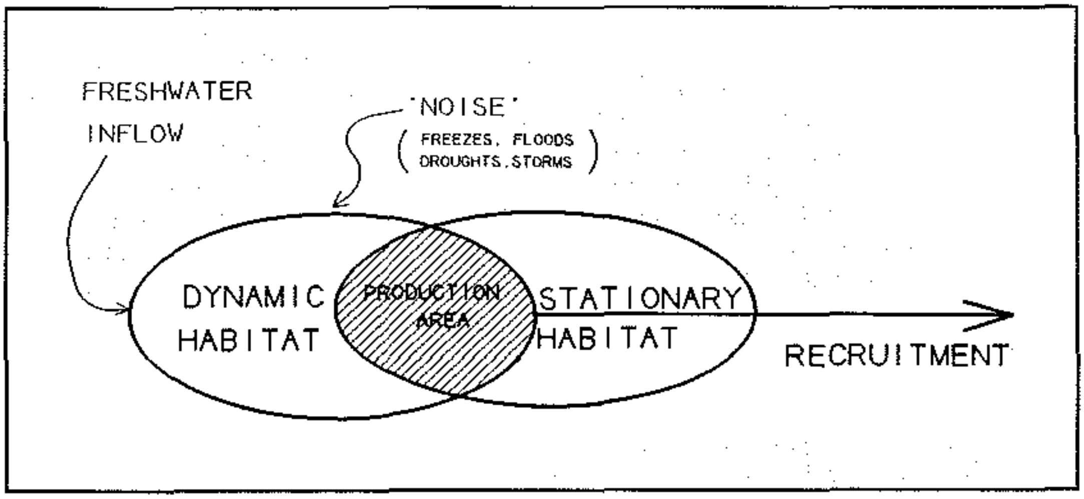

Figure 2A. Diagrammatic areal representations of stationary and dynamic habitat (adapted from Browder and Moore 1981). The distinction between representations A and B is discussed in the text.

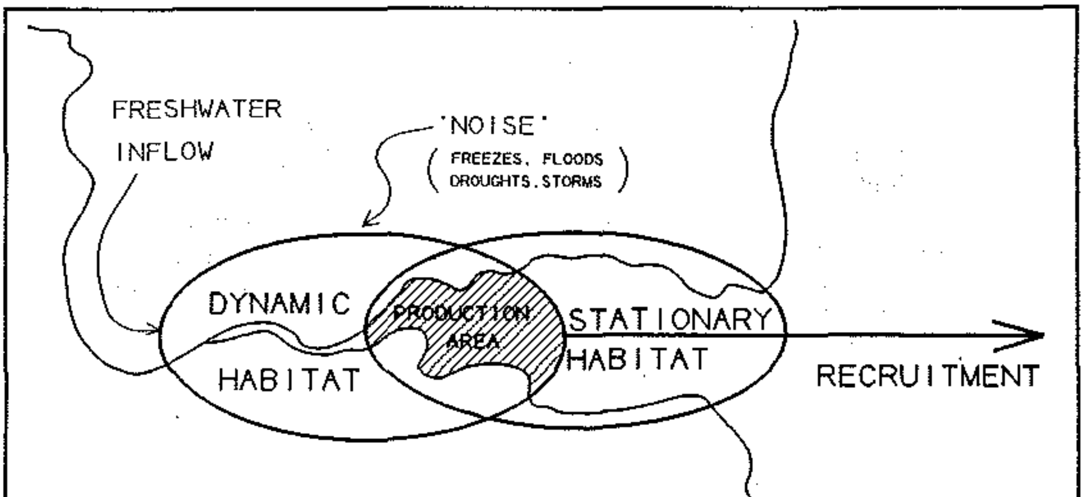

Figure 2B. Diagrammatic areal representations of stationary and dynamic habitat (adapted from Browder and Moore 1981). The distinction between representations A and B is discussed in the text.

General Project Description

The project described here focused on identifying the nursery habitat relationships of three commercially or recreationally valuable fishes: snook (*Centropomus undecimalis*), red drum (*Sciaenops ocellatus*) and striped mullet (*Mugil cephalus*). All of these species are important in the MRES, and the MRES is important to Tampa Bay as a nursery for these and other species.

The project had three phases: 1) habitat classification and mapping; 2) fall 1989 sampling; and 3) winter sampling. In the first phase, a habitat classification system was developed and used to map the middle and upper MRES with respect to habitat categories of the system. The fall sampling phase was designed to sample habitats (as defined and mapped in the first phase) during the period of maximum abundance of early-juvenile snook in nursery habitats. Similarly, the winter sampling phase was designed to sample MRES habitats during the period of maximum abundance of early-juvenile red drum and striped mullet in nursery habitats. Complete details of the project design and results are available in a final project report to the Southwest Florida Water Management District's (SWFWMD) Tampa Bay Surface Water Improvement and Management (SWIM) Program (Edwards 1990).

METHODS

Study Area

The study area consisted of the middle and upper sections of the MRES. Additionally, the uppermost 1.7 km of the lower section of the MRES was included because there is some mangrove-fringed shoreline along the northern shore that potentially could be nursery habitat.

Habitat Classification, Survey and Mapping

A habitat classification system was designed to categorize and classify MRES habitats that might be utilized as nurseries by recreationally or commercially important juvenile fishes. The system was designed to be meaningful with respect to distribution and ecology of juvenile fishes that primarily utilize shoreline and shallow habitats, while at the same time be practical relative to implementation and application to field studies.

The system was based on general geomorphic, intertidal morphological, and intertidal vegetational descriptors. It provided a trinomial classification that could be applied to all shorelines and shallow waters in the MRES. The system is summarized below. Details of the system are provided in Edwards (1990).

Geomorphic descriptors (Fig. 3) included:

A—Altered Shorelines. This categorization was applied to any unnatural habitats, including seawalls, rip-rapped shoreline, dredged canals, etc.

B—Bights. This categorization was applied to indentations in linear shorelines. An indentation was classified as a bight if its opening was generally at least one-half the width of its major axis. Bights were further classified with respect to size.

C—Tidal Creeks. Tidal creeks were subcategorized as C1 rivulets (less than 1 m wide), C2 small creeks (generally less than 2 m wide), and C3 large creeks (wider than 2 m).

E—Embayments. Shorelines were described as embayments if the connection to open waters was restricted compared to the overall size (major axis). Embayments were subcategorized as E1, small embayments less than 5-m wide, or E2, large embayments.

L—Linear Shorelines. This category was used to denote relatively straight or smoothly curving shorelines. This is the dominant geomorphic category, in terms of areal extent, in the MRES.

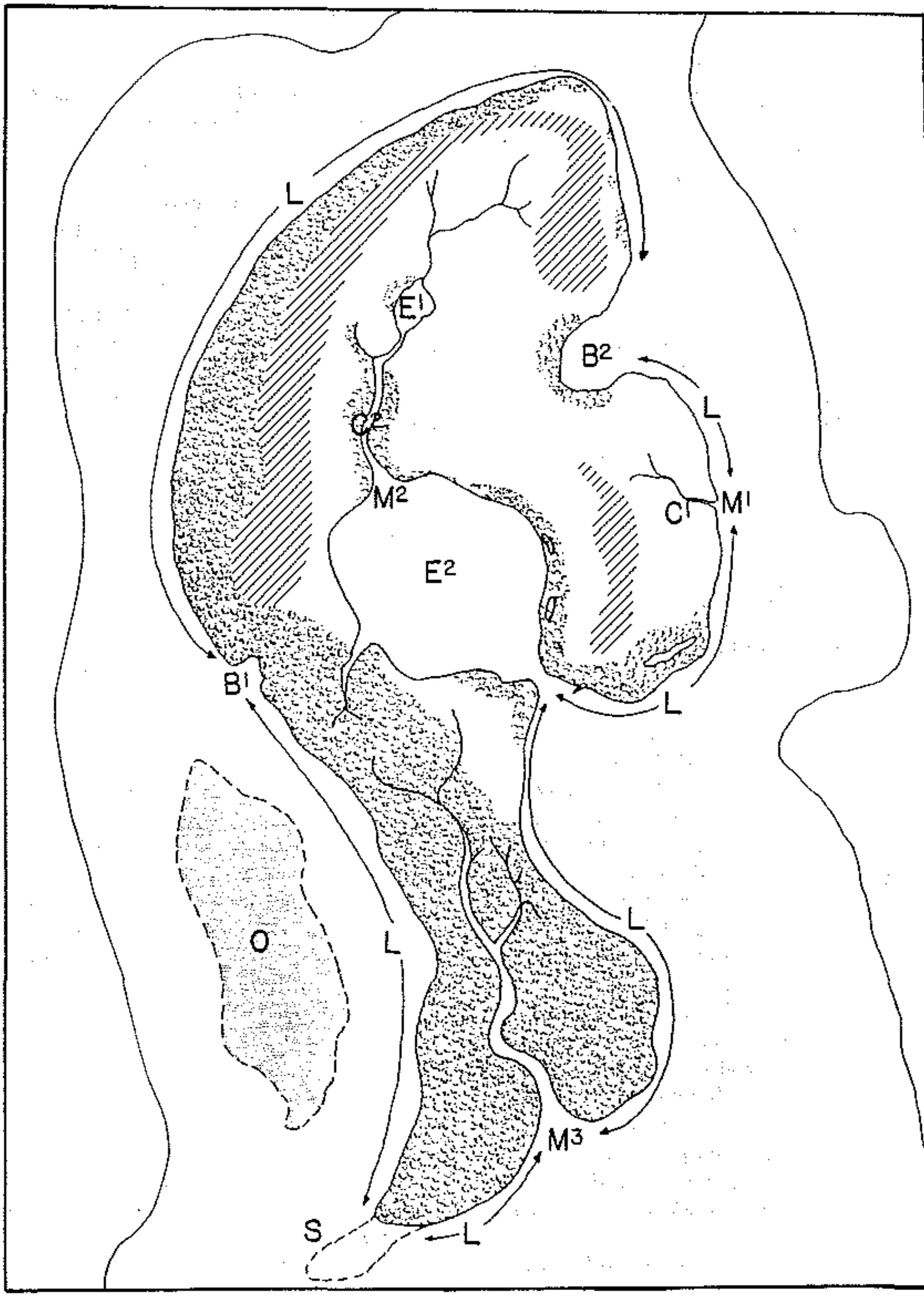

Figure 3. Schematic diagram of a "typical" marsh island in the MRES showing geomorphic categories used in the classification system. Symbols are explained in the text.

M—Creek Mouths. Most creeks widen at their confluence with their receiving water body. Such mouths were denoted as M1, M2, or M3, corresponding to their respective creek size.

O—Open-Water Shoals. Shallow (less than 0.5 m on MLW) shoals in open water were included because their depth range, being comparable to shoreline habitats, suggests the possibility of their being utilized as early-juvenile habitats.

S—Spit Shoals. Shoals, usually in the form of sandy spits accreting at the downstream terminus of an island or a peninsula, are common components of the system.

Intertidal morphological descriptors included:

1—Upland Shorelines. Upland shorelines are characterized by having limited intertidal areas that interface directly with uplands (or non-intertidal flood plains). Such shorelines normally have no significant intertidal vegetation.

2—Upland Shorelines with Patchily Distributed Marsh Vegetation. This category pertains to cases in which the intertidal zone includes patches of vegetation ranging from a few to up to around 10 m in width (alongshore dimension). Vegetation does not form a continuous fringe or a marsh of extensive depth (less than about 5 m deep shoreward).

3—Upland Shorelines with Continuous Marsh Fringe. This category includes all shorelines with a continuous marsh fringe (>10 m width alongshore, <5 m in depth shoreward).

4—Fringed Solid Marsh. Areas of extensive (>5 m deep shoreward) intertidal marsh are usually either solid (a dominant species of vegetation with or without a significant intermix of other species) or consist of a narrow fringe of one species nearest open water interfacing an extensive zone of marsh dominated by another species. The former case is designated as 5, Solid Marsh (see below), and the latter case is designated as a fringed solid marsh. Many fringed solid marshes in the MRES may reflect successional states of marsh vegetational communities.

5—Solid Marsh. This category includes all marshes deeper than 5 m that do not have a distinct band or fringe of plants different from the main portion of the marsh.

Shorelines and marshes were categorized according to dominant vegetation. The following species were present in sufficient abundance or dominance to merit separate descriptors:

Common Name	Scientific Name
Needlerush	*Juncus roemerianus*
Red Mangrove	*Rhizophora mangle*
Black Mangrove	*Avicennia germinans*
White Mangrove	*Laguncularia racemosa*
Saltmarsh Cordgrass	*Spartina alterniflora*
Smooth Cordgrass	*Spartina bakeri*
Cattails	*Typha* sp.
Brazilian Pepper	*Schinus terebinthifolius*
Leather Fern	*Acrostichum* sp.

The system was used to classify and map habitats onto FDOT aerial blueprints (Edwards 1990) during a field survey (7/12/89-9/5/89) of the entire study area and to establish and classify sampling sites.

Habitat Sampling

Juvenile fish sampling stations were selected and distributed with the intent of sampling the important (areal extent and/or frequency of occurrence) habitat types in the middle and upper MRES. A total of 207 sampling stations were distributed throughout the study area, but extended upriver only as far as the Rye Road bridge because no marine fishes were collected in periodic roving samples in the upper one-third of the upper MRES (above Rye Road).

Each station was sampled with a 4.6-m, 9.2-m, 30.5-m, or 61.0-m long seine. All seines were 1.8 m deep and constructed of 0.3-cm mesh knotless nylon netting. The 30.5-m and 61.0-m seines had a 1.8-m square bag sewn into the middle of the seine. The largest seine that could be effectively deployed at the station was used. All juveniles of commercially or recreationally important fish species were enumerated and measured (SL) in the field. Other species collected were subjectively classified as present, common or abundant, and so recorded. To the extent possible, fish were released alive at the collection site. Environmental data (salinity, temperature, dissolved oxygen concentration, sediment type, tidal stage) were also collected at each station.

In order to assess habitat utilization by early juveniles of the three target species (snook, red drum and striped mullet), two different sampling periods were required. Half of the field sampling effort (203 stations) was allocated to sampling the MRES habitats during the fall (9/22/89-11/2/89), when EJ snook and EJs of other summer spawners utilize estuarine nurseries. The other half was allocated to sampling (204 stations) during the late winter (1/8/90-2/8/90), when EJ red drum, striped mullet and juveniles of other fall/winter spawners utilize nursery habitat.

RESULTS AND DISCUSSION

Fall Sampling Period

Recreationally or commercially valued species collected (as early juveniles) during this period were: snook, *Centropomus undecimalis* (43 individuals, 19 stations), spotted seatrout, *Cynoscion nebulosus* (221 individuals, 53 stations), sand seatrout, *Cynoscion arenarius* (326 individuals, 34 stations), and sheepshead, *Archosargus probatocephalus* (3 individuals, 3 stations). A total of 27 larger (>100 mm) juvenile snook were collected at 20 stations. A total of 41 juvenile white mullet (*Mugil curema*) were collected. Detailed data for all stations have been tabulated in Edwards (1990).

Snook

EJ snook were collected only in or near the middle reach of the MRES. EJ snook were collected in the Manatee River from about 6.2 km downstream of Fort Hamer (junction of middle and upper MRES) up to a bayou off the main river just above Fort Hamer. They were collected in the Braden River from around 3.0 km upstream from its mouth to about 0.7 km from the Evers Reservoir. Salinity at the stations where EJ snook were collected ranged from 0 to 11 ppt (Fig. 4), with 70% collected at 0 ppt and only two collected at stations with salinity greater than 6 ppt. However, the 0 ppt stations were all close to areas of salinity; EJ snook were not collected in the purely freshwater reaches of the MRES.

All EJ snook were collected from habitats associated with creeks. They were collected from tidal creeks, creek mouths, shoreline habitats immediately adjacent to creek mouths, and from two stations with linear shoreline bordered by cattails (*Typha* sp.). Snook collected at the stations with *Typha* may represent associations with creeks or freshwater inflow. No distinct relationships between EJ snook distribution and shoreline morphological or vegetational descriptors of the trinomial system were detected within the limited sampling of the many classification combinations. The distribution of EJ snook in the fall of 1989 probably was affected by extremely low salinity conditions in the MRES arising from sudden freshwater flows from the Lake Evers and Lake Manatee as these reservoirs, which were at extremely low levels prior to onset of the wet season, became filled to capacity and began to overflow as flood gates were opened (Lake Manatee) in late August. Almost all of the upper reach of the Manatee River and upper third of the Braden River were fresh (<0.5 ppt) during the study period.

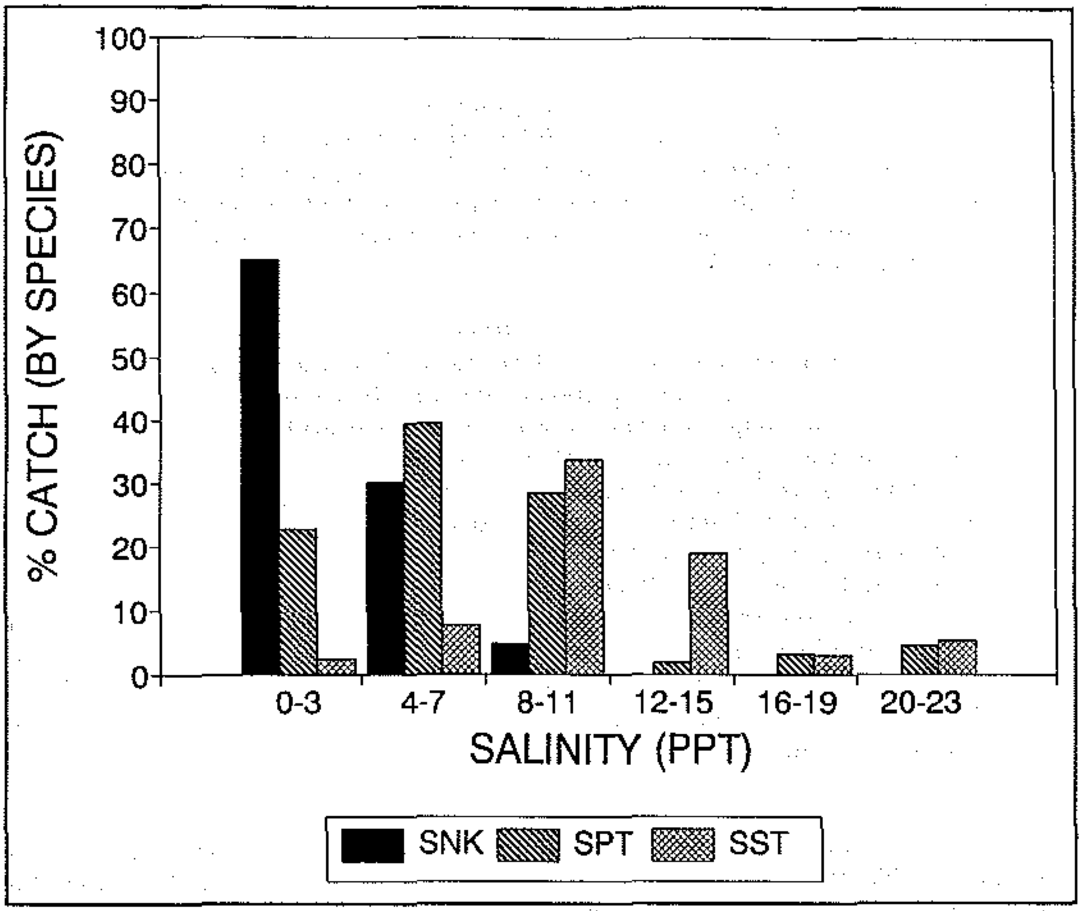

Figure 4. Salinity at stations where early-juvenile snook (SNK), spotted seatrout (SPT), and sand seatrout (SST) were collected during the fall sampling period.

Spotted and Sand Seatrout

Although originally not target species, large numbers (221) of spotted seatrout and sand seatrout (326) were collected throughout the middle MRES. Early-juvenile spotted seatrout were collected at 53 stations and at salinities ranging from 0 to 22 ppt. In the Braden River, EJ spotted seatrout were concentrated (with the exception of one station and two individuals) in the lower half of the tidal river. EJ sand seatrout were collected at 34 MRES stations and at salinities ranging from 0 to 22 ppt. Compared to EJ snook, EJ spotted seatrout and sand seatrout were collected at stations with higher salinities (Fig. 4). More than 95% of the spotted seatrout were collected in salinities greater than 3 ppt, and over 95% of the EJ sand seatrout were collected in salinities greater than 7 ppt. As for snook, the unusual low salinity conditions during the study period probably influenced seatrout distributions.

Both spotted seatrout and sand seatrout were collected from linear shorelines primarily, with 62% and 83%, respectively, coming from habitats classified as having the L (linear) geomorphic descriptor. Spotted seatrout were also frequently (26%) collected from medium creek mouths (M2), whereas sand seatrout were only infrequently (4%) collected from creek mouths. Spotted seatrout and sand seatrout were only infrequently collected (3% and 4%) from the creeks proper.

Niche partitioning or separation between the two seatrout species was indicated by the fact that only 4% (12/326) of the sand seatrout were collected at stations where more than three spotted seatrout were collected. Similarly, only 12% (26/221) of the spotted seatrout were collected at stations where more than three sand seatrout were collected. The partitioning did not appear to be a function of habitat classification, although it is possible that the partitioning was based on parameters not considered in the classification system.

Winter Sampling Period

A total of 338 EJ red drum and 716 EJ striped mullet were collected during the period. With the exception of six early-juvenile snook, one early-juvenile spotted seatrout and one early-juvenile sand seatrout, no other juveniles of commercially or recreationally important species were collected. During the period, salinity at the stations ranged from 0 to 26 ppt.

Red Drum

EJ red drum were collected at 43 stations throughout the middle MRES and from the upper MRES as far as 5.5 km upstream along the river into the upper reach (about 4.5 km downstream along the river from the Rye Road bridge). Salinity at stations where red drum were collected (Fig. 5) ranged from 0 to 21 ppt. Lengths, dates of collection, and growth estimates (Peters and McMichael 1987) indicated that juvenile red drum were recruited into the MRES from late October through January, and continued sampling might have detected even later recruitment.

Most EJ red drum were collected in habitats other than linear marsh shorelines, with only 13% coming from such (L) stations. However, they were collected at 26% of the linear shoreline stations which accounted for 21% of all stations. Overall, the results indicate that although EJ red drum, like snook, may be more abundant in specialized habitats, they are also distributed at lower concentrations throughout most of the shoreline habitats in the MRES.

Striped Mullet

A total of 716 EJ striped mullet were collected at 28 stations throughout the middle MRES. With the exception of three stations in a bayou 0.7 km above Fort Hamer, EJ striped mullet were not collected in the upper MRES. Only 16 mullet from four stations were collected in the Braden River (67 total stations). EJ striped mullet were also not abundant in the previous collections in the Braden River (Edwards 1987). EJ striped mullet were collected at stations with salinity as high as 21 ppt but were not collected from stations with salinity less than 5 ppt, probably reflecting the fact that their capacity to osmoregulate and thus penetrate into low salinity areas does not develop until they attain a size of around 40 mm SL (Nordlie et al. 1982). Juvenile mullet collected in the MRES ranged from 20 to 40 mm SL, with over 95% ranging from 20 to 30 mm SL (most were 25-30 mm). Although no accurate growth estimates are available for striped mullet juveniles and postlarvae, based on estimated growth rates of 0.6-0.8 mm SL/d typical for estuarine fishes, it is likely that most of the mullet were spawned in December and were recruited to the MRES starting in early January.

Striped mullet and red drum exhibited a high degree of habitat partitioning or separation. Although the red drum and mullet were similar in size, making red drum predation on mullet at this stage unlikely, mullet were not collected in abundance at stations with numerous red drum, and vice-versa. At stations where more than one mullet was collected (total of 708 mullet), only 13 red drum were collected. Similarly, at stations where five or more red drum were collected (total of 305 red drum) only one mullet was caught. This habitat separation was not directly related to salinity because both species were most abundant at intermediate salinities (Fig. 5), being substantially and significantly (Chi-square, $p < 0.01$) more numerous in collections at stations with salinities ranging from 16 to 20 ppt. Slightly over half (53%) of the red drum and 83% of the EJ mullet were collected over this salinity range, despite the fact that only 25% of the stations fell within this range.

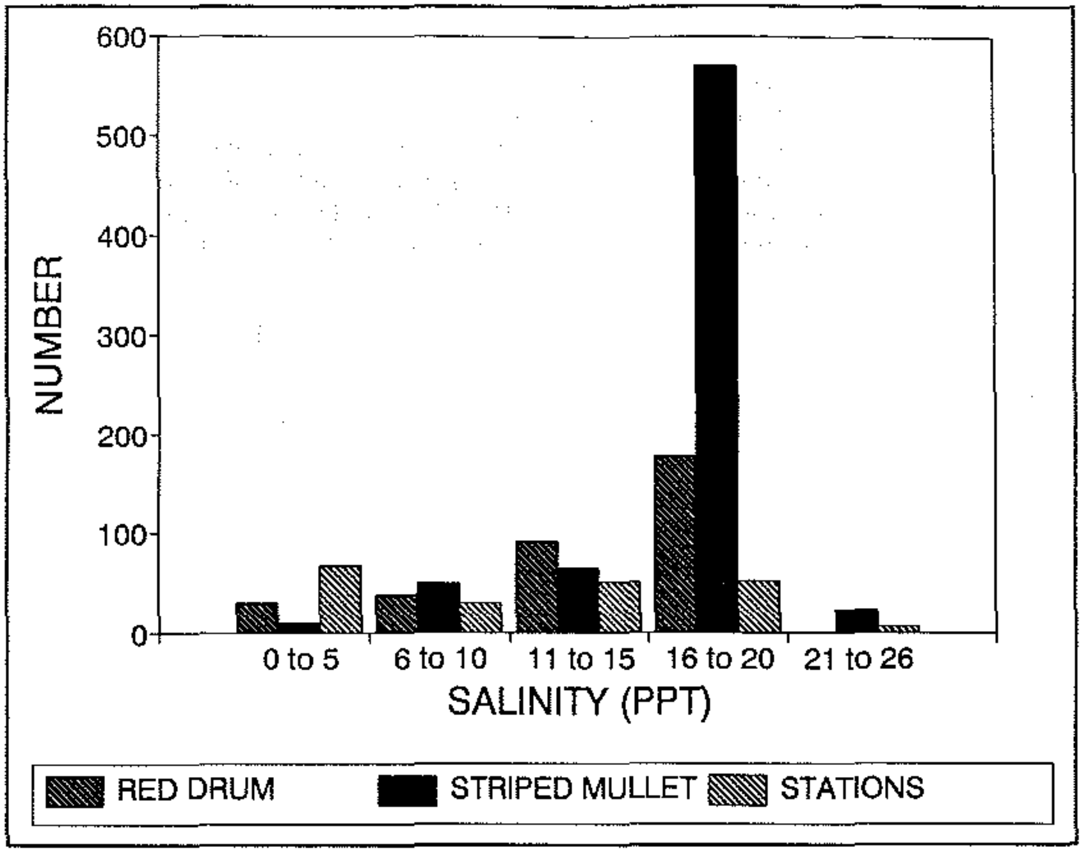

Figure 5. Salinity at stations where early-juvenile red drum and striped mullet were collected during the winter sampling period.

Only 4% of the mullet were caught at stations along linear marsh or mangrove shorelines. Overall, most mullet were collected at stations in or closely associated with tidal creeks, creek mouths and other specialized habitats. Kilby (1948) noted that small pools in marshes along the northern Florida Gulf coast were primary juvenile mullet habitat. The results of the present study indicate that a similar situation occurs in the MRES, with small creeks, creek mouths and other specialized habitats being particularly important as striped mullet nursery habitat.

CONCLUSIONS

Certain specific types of habitats in the MRES (and other estuarine systems) are the most important early-juvenile nurseries for snook, red drum, striped mullet and other important species. These nursery habitats often are not the most common or most extensive habitats, but instead consist of relatively uncommon and small structural habitats. This is particularly true with regard to early-juvenile snook and striped mullet, both of which utilize a very limited suite of habitats. Red drum and seatrouts similarly utilize specialized habitats most intensively but also utilize common and extensive habitats.

These habitat relationships provide a concept of estuarine nurseries in which stationary nursery habitat is viewed not in terms of general areas of environments of the estuary. Instead, estuarine systems must be viewed as a mosaic of small, irregularly distributed stationary habitats that occur within a general area of the estuary and within general types of environments. The potential productivity of the general area of the estuary is a function of the density of these stationary habitats. Different species may utilize different stationary habitats and thus have a different stationary habitat mosaic.

The actual productivity of the estuary depends not only on the stationary habitat mosaic, but also on the conditions in the estuary. Conditions suitable for survival and growth of a species can be conceptualized as its dynamic habitat (Browder and Moore 1981). Again, as for stationary habitat, different species often have different dynamic habitats. The productivity of an estuary largely depends on the density of stationary habitat within the dynamic habitat. This model is shown in Figure 6 which is presented as a refinement of the Browder and Moore (1981) model.

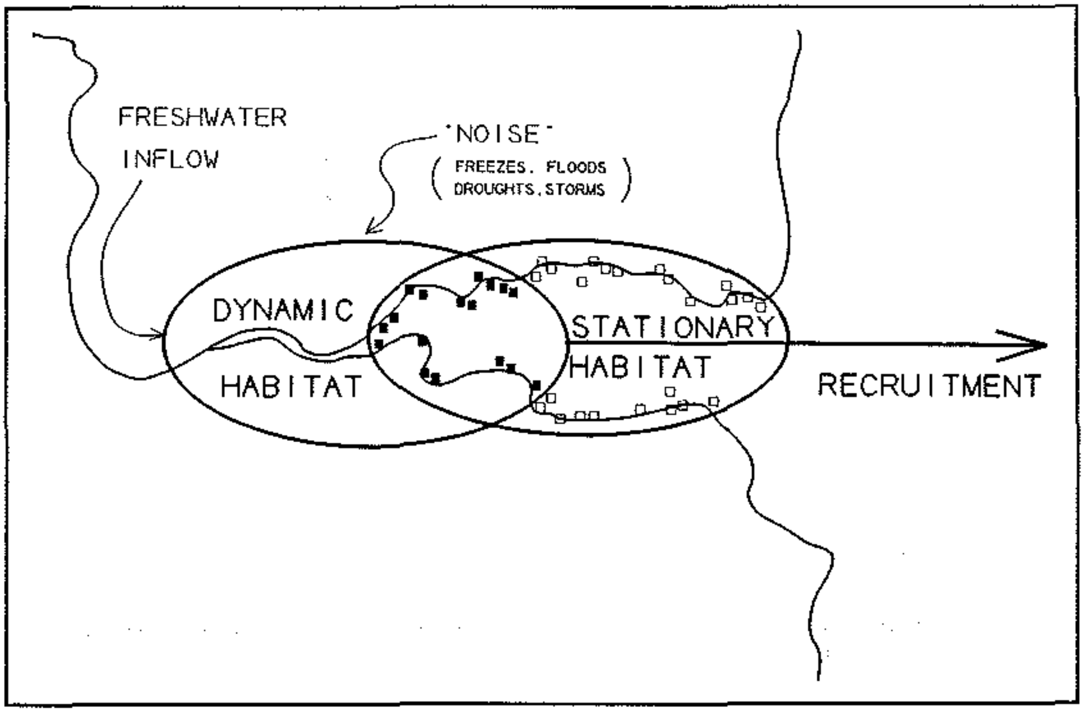

Figure 6. Diagrammatic habitat-mosaic representation of stationary and dynamic habitat. Open boxes represent stationary habitats that are not occupied, because they are outside the dynamic habitat. Filled boxes represent occupied, productive habitats.

For systems like Tampa Bay, where estuarine nursery habitat has dwindled to critical levels, optimal resource management must involve understanding and identification of stationary habitat mosaics as well as understanding of dynamic habitats. Both types of habitats must be conserved and managed if Tampa Bay fisheries productivity is to be sustained. The Manatee River estuary, because of its large area of natural environments that can provide stationary nursery habitats for many species, is one of the most important components of Tampa Bay. Not only should these stationary habitats be further understood, identified, preserved and protected, but also the dynamic habitats (particularly salinity) of important species must be carefully considered in efforts to protect and manage the Manatee River estuary system.

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A REVIEW OF THE FUNCTIONAL VALUE OF NATURAL AND CREATED WETLAND HABITATS IN THE TAMPA BAY AREA

R. L. Whitman, Jr.

ABSTRACT

Declines in areal cover of Tampa Bay wetlands have been well documented, while efforts to restore these losses have not. Monitoring of mitigation projects is driven by a regulatory process, the focus of which is site-specific and on the establishment of the vegetative component. More recently, however, superficial attention has been paid to habitat function, with "no net loss" of function policies being developed as a regulatory construct applied as a measure of success for mitigation efforts in a variety of habitats, principally wetlands. Comparatively few analytical investigations of habitat function have been accomplished in Tampa Bay, and a comprehensive study has yet to be initiated. A review and discussion of existing research, especially comparative studies of faunal use and fisheries community structure in natural and created wetlands (principally *Spartina alterniflora* marshes), provides essential baseline information.

Fishery utilization of natural and created saltmarshes has been studied as part of the Southwest Florida Water Management District's Surface Water Improvement and Management (SWIM) Program. Results of that study will be available pending District acceptance of the final report.

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FLORIDA'S MARINE FISHERIES-INDEPENDENT MONITORING PROGRAM

R. H. McMichael, Jr.

INTRODUCTION

Florida's marine fisheries-independent monitoring program is a long-term study designed to monitor relative abundances of juvenile (pre-fishery size) fishes. This program was developed because of the need to be able to detect fluctuations in fish stocks quickly and accurately.

Proper management of Florida's marine fisheries resources requires information from a number of sources. The majority of this information can be classified into two categories, fisheries-dependent and fisheries-independent data.

Fisheries-dependent information is obtained directly from the fishery itself. The traditional method of monitoring changes in fish stocks has been to use catch-per-unit-effort data gathered from studies of commercial and recreational fisheries. Analysis of these data can provide information on the status of adult fish stocks. However, there are problems with using data from these sources. Changes in vessels, gears, or methods of operation can make effort data difficult to interpret (Ulltang 1977). Closed seasons, changes in size or bag limits, or fluctuations in market values can bias catch data and make analysis difficult.

Fisheries-independent information is collected through statistically valid sampling methods independent of the commercial fisheries and the commercial or recreational fishermen. A fisheries-independent monitoring program targeting populations of fish that have not been subjected to the recreational or commercial fisheries can provide a relatively unbiased estimate of trends in fish stocks. Prompted by shifts in juvenile abundance, modifications to harvesting regulations can be implemented before the fish have reached a size at which they would be vulnerable to the fishery.

Both short- and long-term research programs are used to gather information for fisheries-dependent and fisheries-independent databases. Short-term research programs focus on specific questions or problems. Long-term research programs provide information about trends in fisheries or fished populations that can be used to assess the impact of fisheries management regulations, fishing practices, and environmental changes. Long-term data have proven extremely valuable in documenting ecosystem changes, in differentiating natural changes from those caused by man, and in generating and analyzing testable hypotheses (Wolfe et al. 1987). In addition to their use in management decision-making and in basic scientific inquiry, long-term databases are helpful in generating new ideas and establishing new hypotheses (Coull 1985). After establishing natural variation in fish populations, a long-term monitoring program could be used to identify changes in stock size that are due to fishing restrictions, large-scale weather events, manmade influences, or other factors.

The state's Department of Natural Resources Florida Marine Research Institute (FMRI) began formulating a fisheries-independent program in 1985 with funding provided by a grant from the U.S. Fish and Wildlife Service Federal Aid Program for Sport Fish Restoration. In 1988, additional funds became available from special state appropriations. The program is now partially supported by funds from the sale of saltwater fishing licenses. Initiated in Tampa Bay (1989) and expanded to Charlotte Harbor and Indian River (1990), the monitoring program will eventually cover all major coastal areas of Florida.

METHODS

Tampa Bay is sampled using stratified-random sampling in the spring and fall; each sampling season lasts twelve weeks. These seasons coincide with periods of peak young-of-the-year recruitment into the bay. In addition to the spring and fall stratified-random sampling seasons, fixed stations in a number of habitats throughout Tampa Bay are sampled monthly.

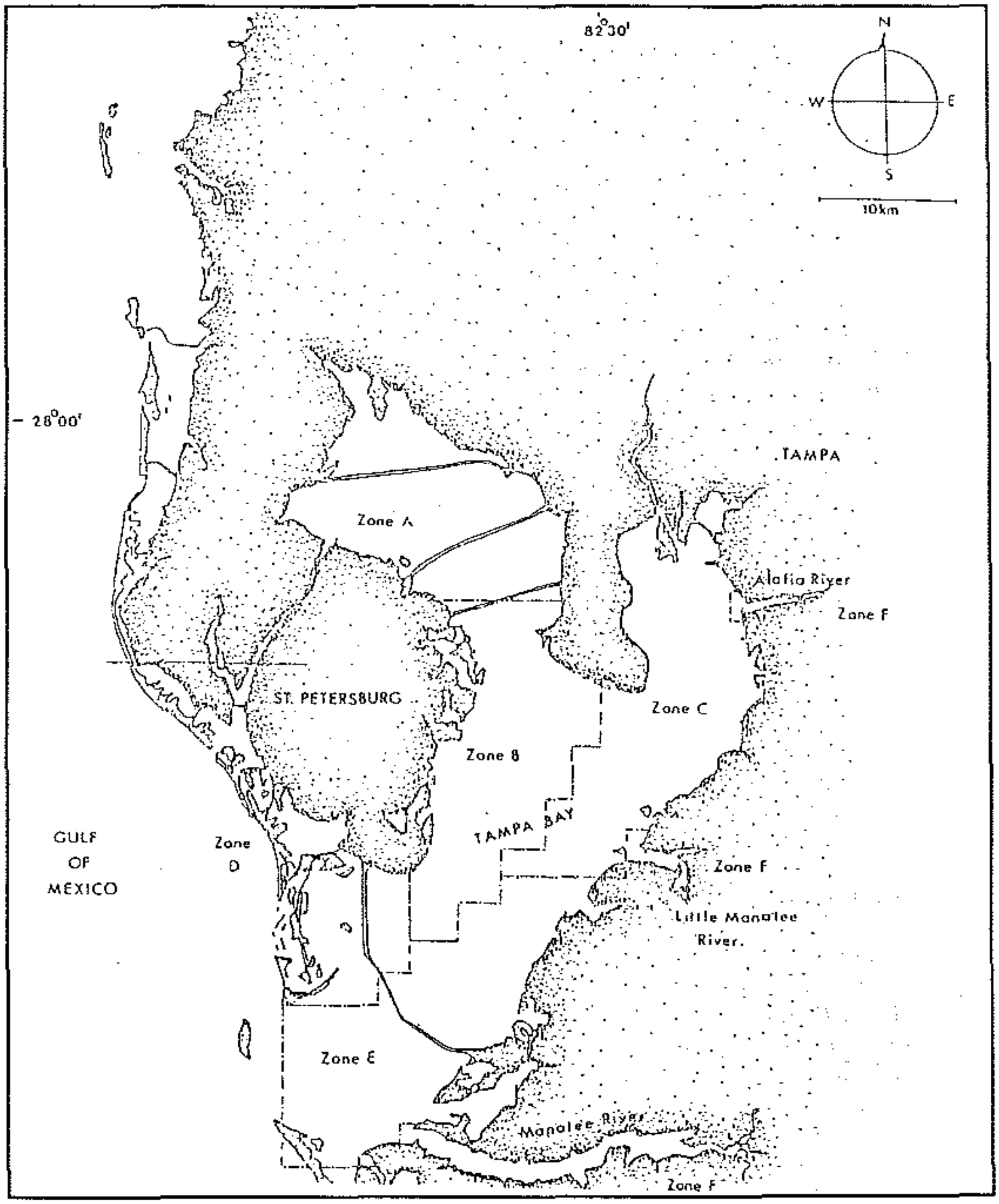

Figure 1. Tampa Bay, Florida, showing sampling area separated by zone for the marine fisheries-independent monitoring program.

Stratification has several advantages when compared to purely random sampling. The precision of abundance indices estimated from a given number of samples is increased by identifying areas that are as homogeneous as possible, dividing the areas into strata, and allocating sampling effort between strata according to an optimum sampling scheme (Cochran 1963, Saville 1977, Ulltang 1977). Random sampling ensures no bias in station selection. The principal spatial strata used in Tampa Bay were depth and habitat.

Advantages of site-specific (fixed station) sampling include reduction of spatial variability (temporal changes will be clearer at the selected sites) and detection of recruitment outside the stratified-random sampling periods. Extrapolation of results beyond those sites must be done cautiously.

Gears and their deployment must be standardized in order to compare data collected from different habitats, seasons, and times of day. Gears must also be efficient, quantifiable, and logistically manageable. Seines, trawls, gillnets, and dropnets were selected as the primary gears in the monitoring program. These gears are adequate for sampling most of the habitats encountered in Florida's estuarine systems, and they are relatively efficient at collecting small juvenile fish (Perret and Caillouet 1974, Hamley 1975, Kushlan 1981, Ross et al. 1987, Sogard et al. 1989).

Gear-testing was initiated for the four primary gears to determine the efficiency of each in the monitoring program and to refine deployment techniques. Experimentation on additional gears continues in an effort to improve our ability to sample habitats and sizes of fishes not efficiently sampled by the four primary gears. The gear-testing process continues to refine and redefine the methods used to sample juvenile fish.

In order to produce statistically valid estimates of abundance, the variability within sampling methods was reduced by standardizing the sampling protocol (gear design and deployment) throughout the Tampa Bay estuarine sampling area. A procedure manual was developed to instruct all staff on proper use of all gears and methods.

TAMPA BAY

For purposes of this program, Tampa Bay is defined as any water within the bay north of 27°30'N, including Old Tampa Bay, Hillsborough Bay, and the northern half of Anna Maria Island. Rivers emptying into Tampa Bay (the Alafia, Little Manatee, and Manatee) are sampled until the freshwater-saltwater interface is reached.

Tampa Bay is divided into six zones (A-F), based primarily on geographic and logistical criteria (Fig. 1). Each zone is sampled twice during a given monitoring season, once during the day and once at night. The order in which the zones are sampled is randomly generated. Zones are further divided into 1'-latitude x 1'-longitude (approximately one square nautical mile) grids. Characteristics including depth, habitat type, and potential sampling methods are recorded for each grid. A total of 465 grids were identified for Tampa Bay and entered into a computerized database.

Actual sampling location is determined by randomly selecting a grid within the selected zone. A 10 x 10 matrix is placed over the grid to divide the grid into 100 microgrids, each with its own corresponding number from the matrix. Sampling locations are selected by computer-generated random numbers. If a microgrid cannot be sampled based on criteria defined in the procedure manual, an alternative location is selected by moving in a counterclockwise spiral over the grid until a suitable sampling location is found. If suitable sampling points cannot be found within a given grid, the process is repeated in the next counterclockwise grid. This process ensures that sampling sites are randomly selected. A sampling day is broken into four periods: dawn, day, dusk, and night. Dawn and dusk are defined as the period from one hour before to one hour after sunrise and sunset, respectively. All time periods are sampled with a variety of gears.

Four basic gear types are used over different bottom types and depths. A 22-m (3.2-mm mesh) bag seine is used over mud, sand, mud/sand and seagrass bottom types in waters less than 1.5 m deep. Two types of 22-m bag seines are used, one with a center bag and the other with the bag at one end of the seine (terminal-bag seine). Three methods of deploying and retrieving the seines are used depending upon the area being sampled. Three seine hauls are made at each seine site. The area covered by each seine haul is standardized for each method of deployment. A 6.1-m otter trawl (38-mm mesh) with a 3.2-mm liner is used over unvegetated areas in water deeper than 1.5 m. Three tows are made at each trawl site. Trawl tow time (10 min for bay areas and 5 min for river areas) and boat speed are kept constant for each replicate. Distance covered for each tow is calculated using LORAN. Tow speed is standardized to about 1.5 knots. Dropnets (1 m^2, 3.2-mm mesh) are used in seagrass and algae habitats in water less than 1.0 m deep and only during daylight hours.

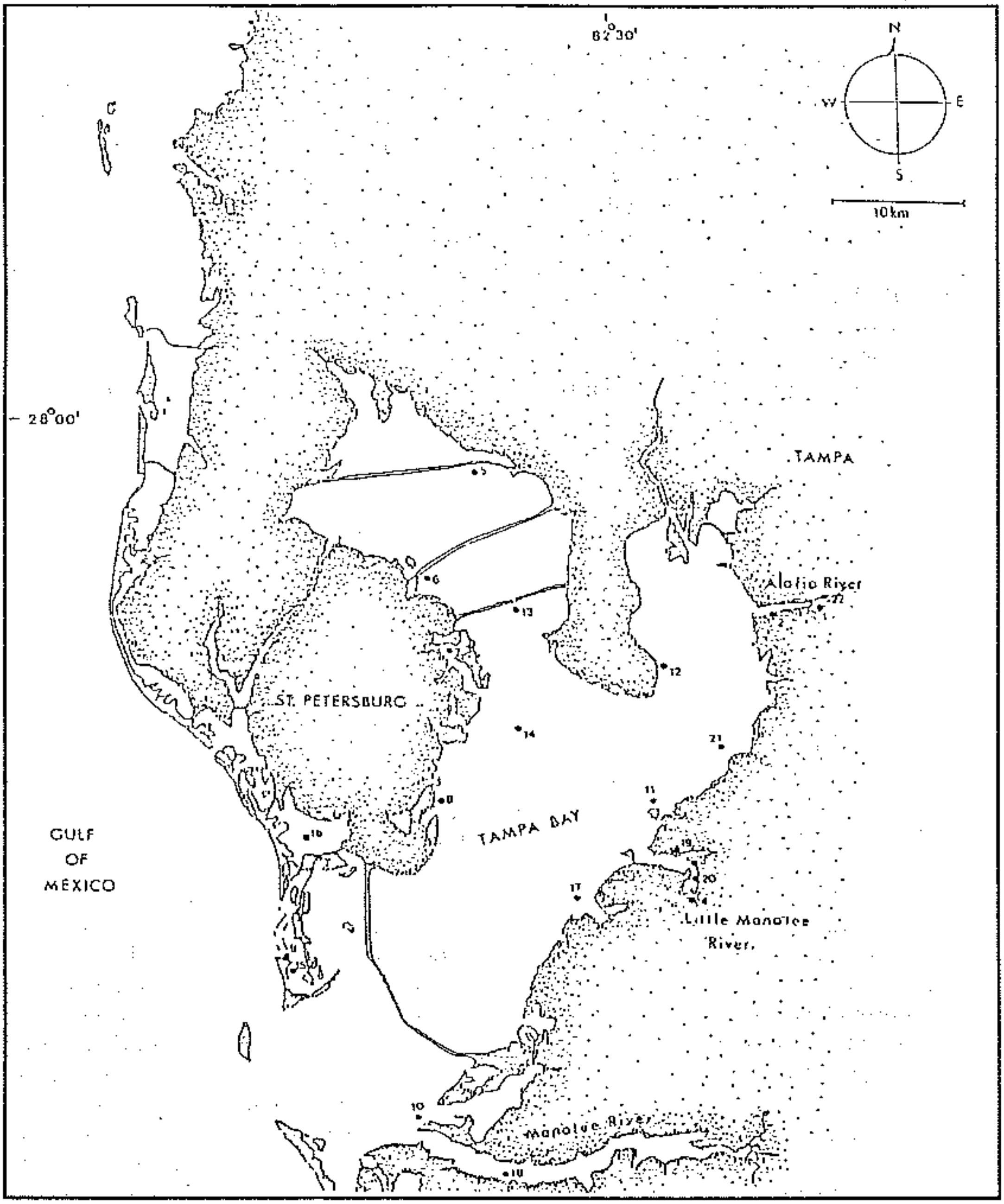

Figure 2. Tampa Bay, Florida, showing fixed sampling stations for the marine fisheries-independent monitoring program.

Three dropnets are suspended and simultaneously deployed from a boom that extends from the stern of a boat. Five drops (fifteen, 1 m^2 dropnets) are made within each of two grids. Fish are removed from the dropnets by sweeping an internal seine through the net a minimum of ten times. If fish are collected on either of the last two sweeps, four additional sweeps are made and sweeps continue until two consecutive sweeps contain no fish. Dropnets are not used in riverine areas, which lack seagrass habitat. Experimental gillnets consist of four 45.0 m panels, each of which has a different mesh size (75 mm, 100 mm, 125 mm, 150 mm stretched monofilament). Gillnets are set with the small-mesh end placed on the shore and the net deployed perpendicular to shore in water less than 2.0 m deep. Three gillnets are set within each of two grids during night sampling trips, and a single gillnet is set during dawn sampling.

Fixed stations within Tampa Bay and riverine habitats are sampled by seining and trawling (Fig. 2). In addition to fixing the station locations, the time of day and sampling procedures for all collections are kept consistent from month to month. A minimum of three replicate seine hauls are made at each fixed sampling station with a 22 m terminal-bag seine. Additional seine hauls are made at several of the stations to increase data resolution.

Fixed seining stations were implemented in March 1989. There are nine fixed trawling stations, six distributed throughout Tampa Bay and three in riverine habitat. Three replicate trawl tows are made at each station following standard trawling procedures. Sampling at these stations was initiated in January 1990.

Large numbers of fish are often collected in any given sample. In order to complete the required number of replicates on any given sampling trip, a method to quickly and accurately subsample large catches was developed. When choosing subsampling techniques, trade-offs must often be made between the costs involved (time and money) and the objectives of the project (Van Guelpen et al. 1982). Splitters are devices used to subsample collections that are too large to be effectively enumerated in the field in a timely manner. The two-way splitter is currently being used by the fisheries-independent monitoring program. Results of testing indicate that this design is consistently more accurate than the other splitters tested.

Physical parameters measured at all sampling stations include water temperature, salinity, dissolved oxygen, pH, depth, time of day, cloud cover, wind direction and speed, bottom type, bottom vegetation, and LORAN coordinates.

Florida's fisheries-independent monitoring program is designed to be multi-specific, with data analyzed for all species collected. The abundance of each species collected during a sampling event is recorded. This multi-species approach allows the estuarine system to be examined as a whole and allows the determination of inter-specific relationships. With this holistic approach, it should be possible to differentiate species-specific effects on abundance from system-wide effects. In addition, species other than those of primary interest may serve as indicators of the potential year-class strength of the species of primary interest. These "indicator" species could help identify chronic degradation of estuarine systems or predict the future of fish populations of primary interest. The multi-species approach also enables us to characterize juvenile habitats within the estuary and to determine primary habitats.

The monitoring program in Tampa Bay currently makes over 2,300 collections per year (Table 1). The policy of the program is to collect, work-up, and release all fish alive. However, representative specimens and unknown species are brought back to the laboratory for confirmation and identification. The program has collected just under 2 million fish during the past two years of monitoring (Table 2). Over 100 species have been identified from these collections.

Data from this program can be used not only as a management tool to monitor the effects of regulatory changes but also as a predictive tool, using young-of-the-year class strength to estimate future year class strength. These data can also be used to define several aspects (growth rates, recruitment patterns, and habitat preferences) of the life history of juvenile fishes and the interactions among species and their environment.

Table 1. Summary of effort by gear for stratified random sampling (SRS) and fixed stations for 1989 and 1990.

GEAR	SRS Number of hauls		FIXED Number of hauls	
	1989	1990	1989	1990
Seines				
Boat set	48	93	365	374
Offshore (center)	100	0	117	0
Offshore (terminal)	102	198	75	262
Walking beach set	157	159	67	90
Trawls	372	390	0	421
Gillnets	89	88	0	0
Dropnets	300	300	0	0
TOTAL	1,168	1,228	774	1,130

Table 2. Summary of catch by gear for stratified random sampling (SRS) and fixed stations for 1989 and 1990.

GEAR	SRS Number of hauls		FIXED Number of hauls	
	1989	1990	1989	1990
Seines				
Boat set	14,122	147,387	707,796	79,116
Offshore (center)	32,656	0	100,230	0
Offshore (terminal)	23,378	46,402	178,983	13,437
Walking beach set	118,990	137,586	117,483	9,808
Trawls	119,721	70,553	0	33,006
Gillnets	2,624	2,681	0	0
Dropnets	2,697	1,647	0	0
TOTAL	314,188	406,256	1,104,492	135,367

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AN ECOLOGICAL OVERVIEW OF TAMPA BAY'S TIDAL RIVERS

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ABSTRACT

Although a relatively large amount of fresh water reaches Tampa Bay as organized drainage of surface water, most of the waters of low salinity (<15 ppt) occur only in the tidal reaches of major rivers. Very low salinity waters (below 5-8 ppt) are critical for larval and early juvenile stages of many invertebrate and finfish species of ecological or economic importance. Very low salinity water occurs along the bay's eastern shore in tidal river reaches with similar channel geometries, soils, and wetland plant communities, although these patterns have been distrupted by channel improvements, dams and diversions of water, and shoreline development. In terms of length, basin area and reported discharge, the rivers exhibit a north-south gradient in which the Hillsborough is the largest river, and the Braden the smallest. The Hillsborough also has the highest rate of permitted withdrawal (2.7 m^3/sec), although the Manatee has a larger percentage of flow withdrawn for use (33.3%), followed by the Hillsborough (15.1%) and Braden (10.0%). Tidal effects gradually diminish in upstream direction and the length, area, and volume of the tidal reaches have been variously defined. A new method of defining tidal reach on the basis of soils is introduced. A transition from alluvial to tidal soils depicted in first-edition maps of the region tends to be distinct in the Myakka, Braden, Little Manatee, and Alafia Rivers, and Double Branch Creek. Familiarity with salinity structure of the tidal Myakka River suggested that the area of soil transition corresponded with very low salinity, which was found to be the general case for other rivers. Historical soil data may be useful indicators of the natural salinity structure of rivers. Such data suggest that the "tidal" Manatee is 28.2 km (17.5 miles) long, which is almost the combined lengths of the "tidal" Little Manatee, Alafia, and Palm Rivers, and more if the tidal length of the Braden River is added. Florida Game and Fresh Water Fish Commission data from a LANDSAT habitat mapping project were evaluated for each tidal river. A total of 3,347 ha of wetlands was tabulated for major rivers, of which 1,397 ha, or 42%, were mangrove forests and coastal salt marshes. Highest wetland density (44.1%) occurs in the Braden River. About one-third of the Little Manatee River is tidal wetland, and one-fourth to one-fifth of the Alafia River is wetland. Despite having the largest total salt marsh and mangrove area (686 ha), the Manatee River's wetland density is comparatively low because of 3,167 ha of open water. Nearly half of the bay area's tidal river wetland occurs in the Manatee River. The Manatee and Braden Rivers comprise nearly two-thirds of all tidal river wetlands in the bay area. The Manatee/Braden wetland system constitutes 9.5% to 13.7% of the range in total bay area wetlands reported in previous studies. Because one-fourth of the bay's total tidal river wetland resides in the Little Manatee River, the southern three rivers constitute 90% of all river wetland compared to only 10% in the northern three rivers. Overall, the area of wetlands and open water in major rivers is approximately 8% of the wetland plus open water area of Tampa Bay. The volume of mesohaline and oligohaline waters is considerably less than the volume of the bay because tidal river volume decreases logarithmically with upstream distance. Volumetric trends are similar in the Myakka, Little Manatee and Hillsborough Rivers, compared to the Manatee River, and these differences may explain salinity and habitat differences among tidal rivers. Bay management efforts may have underestimated the relative importance of the Manatee and Braden Rivers, and improved management (especially of regulated flows and low salinity wetlands) is recommended for all rivers.

INTRODUCTION

Tampa Bay is an estuary by virtue of the freshwater that flows into it, and most inflow is presumed to be from the organized drainage of surface water runoff provided by its rivers and larger creeks. Given a surface area of 1,031 km^2 (Lewis and Whitman 1985), 123.7 cm of direct rainfall during an average year (Wooten 1985) accounts for approximately 1.28×10^9 m^3 of freshwater. Groundwater inflow of freshwater directly to the bay is unknown (Culbreth et al. 1985) but is probably more than direct rainfall and less than river flow.

Previous estimates set the freshwater contribution of gaged and ungaged streams near 1.8×10^9 m^3/yr (Flannery 1989), or approximately 51% of the bay's mean-tide volume (Ross et al. 1984). On an annual basis, the combined inflow of rain, groundwater and stream flow would theoretically result in a baywide salinity of about half that in the Gulf of Mexico, or 15.0 ppt. In reality, salinity in open bay water is usually greater than 15.0 ppt; salinity varies with tide and season, and strong salinity gradients exist over the length and width of the bay (Boler 1990).

Virtually all of the low salinity (less than 15.0 ppt) areas in the bay occur in the tidal reaches of the larger tributaries. Such areas may be called estuarine rivers or tidal river estuaries, to distinguish them from the open water, higher salinity areas of the bay to which they are connected. Tidal river estuaries are the interface between the bay and its watershed, and a critical contributor to estuarine productivity.

The importance of estuaries for the maintenance of fish diversity and fisheries production has been shown in Florida by Comp and Seaman (1985), in other Gulf states by Rounsefell (1975), in Mexico by Yanez-Arancibia (1985), and throughout the world by many others (Yanez-Arancibia 1985, Welcomme 1985, Rozengurt and Hedgpeth 1989). A common theme in these reviews is the importance of wetland areas and low salinity waters in maintaining fisheries. Dovel (1981) developed the idea that anadromous fish have a "critical area" corresponding to a tidal river area with salinities below 10 ppt, and that recruitment depends on the effect of tides and freshwater inflow on the size and location of this zone. Browder and Moore (1981) defined an estuary's productive area as the overlap in its "dynamic" and "stationary" habitats. Examples in tidal river estuaries of these habitats are salinity regime (dynamic habitat) and wetlands and shallow water areas (stationary habitat).

As part of NOAA's Estuarine Living Marine Resources (ELMR) project, the National Ocean Service (NOS) recently reviewed the distribution and abundance of fishes and invertebrates in eastern Gulf of Mexico estuaries, and demonstrated the importance of mixing (0.5 to 25 ppt) and tidal freshwater areas in the life histories of 36 species selected for commercial, recreational, or ecological value, or as indicators of environmental stress (Williams et al. 1990). In a corollary ELMR study, NOS evaluated the salinity ranges of fishes and invertebrates in the mid-Atlantic region. A new salinity classification system was proposed and compared to the Venice System (Bulger et al. 1990). Detailed statistical analysis resulted in the recognition of five salinity zones used by fishes (freshwater to 4 ppt, 2 to 15 ppt, 11 to 19 ppt, 15 to 28 ppt, and 23 ppt to marine salinity). Similar work is underway for other coastal areas, which may be expected to show the importance to other species of the moderate to low salinity areas that occur in tidal river estuaries, including the tributaries of Tampa Bay.

The purposes of this paper are to describe some of the structural features of tidal rivers, discuss the location and size of river areas with low salinity (<15 ppt), underscore their importance to maintenance of bay productivity and usefulness, and suggest future research and management directions.

TIDAL RIVER ESTUARIES OF TAMPA BAY

All of Tampa Bay's tidal rivers are situated along the bay's eastern shoreline in Hillsborough and Manatee Counties. All but the Braden, a tributary of the Manatee, open directly into the bay. The Tampa Bypass Canal occupies the place of the Palm River, also called Sixmile Creek. Constructed to relieve flooding in the Hillsborough River floodplain, the canal's flow is comprised of runoff from the Palm River basin, contributions from the Hillsborough River, and significant additions from upper formations of the Floridan Aquifer, which was breached during canal construction (Knutilla and Corral 1984). Discharge from the canal is regulated by a number of structures, and only 7.1 km of unregulated waterway occur between McKay Bay and the most downstream gate (Motz 1975). Little natural shoreline remains in the tidal reach of the canal, which was dredged from Structure 160 to the bay to accommodate flood discharges. Because of these extreme alterations and the small amount of tidal stream remaining in unaltered condition, our review concentrates on the four remaining rivers that flow to the bay, and the Braden River.

In terms of length, basin area and reported discharge, the rivers exhibit a north-south gradient in which the Hillsborough is the largest river and the Braden the smallest (Table 1). The Hillsborough also has the highest rate of permitted withdrawal (2.7 m^3/sec), although the Manatee has a larger percentage of flow withdrawn for use (33.3%), followed by the Hillsborough (15.1%) and Braden (10.0%). As discussed below, discharge and flow-reduction estimates summarized in Table 1 are affected by a number of variables.

Table 1. Summary statistics for rivers on Tampa Bay.

	LENGTH (km)	BASIN AREA (km^2)	MEAN FLOW (m^3/sec)	WITHDRAWALS (1988) (m^3/sec)	MAXIMUM DRY SEASON SALT (0.5 ppt) PENETRATION (river km)
Hillsborough	88	1684	17.9	2.7	...
Alafia	80	1062	11.5	0.2	16.7
Little Manatee	63	570	4.9	0.3	18.0
Manatee	58	725	4.5	1.5	35.4
Braden	37	212	1.9(1)	0.2	dam

(1) estimated flow
Source: Estevez et al. 1991.

Linear Aspects

The present length of the tidal reach of the Braden River (9.1 km) is unambiguous because the City of Bradenton's reservoir and spillway were constructed in tidal waters in 1939. In other rivers, tidal effects gradually diminish in upstream direction, and the lengths of their tidal reaches have not been directly determined. Any method to define the tidal reach is arbitrary, but if methods are applied uniformly between rivers, patterns of similarity and difference can be described. A useful marker would be the location in each river where sea level first intercepts the river bed, but reliable data for this attribute could not be found.

According to known salt penetration data, the Manatee River has the longest tidal reach (Table 1). Another marker that can be used to measure tidal river length exists in the first editions of soil maps produced by the Soil Conservation Service. Along each tributary to the bay, bank sediments were classified as Alluvial Land (Ac), Tidal Marsh (Tb), or Tidal Swamp (Tc). Other upland and wetland soils removed from the river corridor had other designations. Alluvium is material of mixed origin deposited by river flow, usually from fine sand to fine sandy clay. Tidal marsh and tidal swamp soils occupy level areas affected by tides and they contain variable amounts of organic matter. Marsh soils support tidal herbaceous wetlands whereas tidal swamp soils are dominated by mangroves (Soil Conservation Service 1958). These designations were modified in subsequent editions of soil maps.

The transition from alluvial to tidal soils depicted in first edition maps of the region tend to be distinct in the Myakka, Braden, Little Manatee, and Alafia Rivers, and Double Branch Creek. The transition is illustrated for the Little Manatee River in Figure 1, in which dark areas are alluvial soils and light areas are tidal marsh soils. In the Manatee the transition occurs along a river reach near the mouth of Gamble Creek. In the Palm River both soil types were patchy and intermixed with upland soils. Soil patterns were obscured by urbanization along the Hillsborough River but alluvial soils were mapped along Lowry Park. More recent soil maps of the Anclote River suggest an historical transition but development along the transitional point required that a reach of probable transition be used.

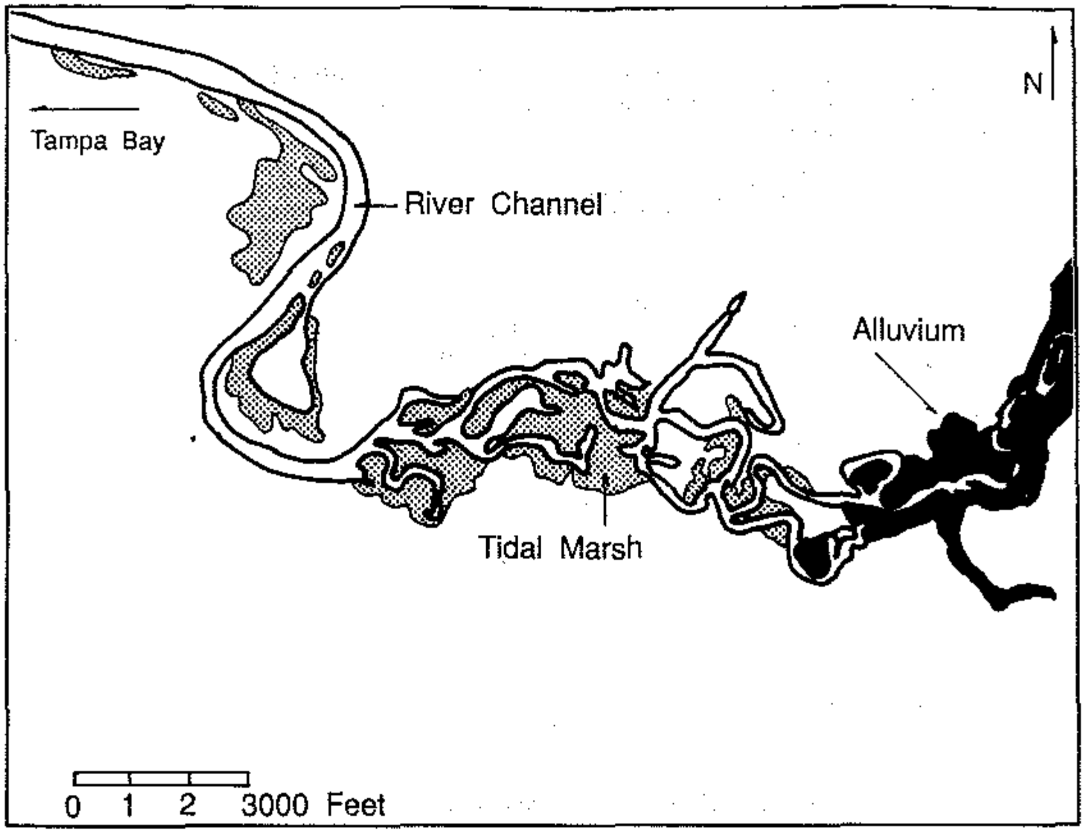

Figure 1. Transition from alluvial soils (dark areas) to tidal marsh soils (shaded areas) along the banks of the Little Manatee River in Hillsborough County, Florida (adapted from SCS 1958).

Familiarity with salinity structure of the tidal Myakka River suggested that the area of soil transition corresponded with very low salinity. With the assistance of Sarasota County and the Southwest Florida Water Management District, a composite salinity profile was made for the area of soil type transition in each river (Table 2). Assuming that surface salinity affects wetlands and soil type more than bottom salinity, it is noteworthy that salinities at soil transitions in the Myakka and Little Manatee Rivers were comparable (1.4 ppt), with similar variation and range. On the one hand, differences in sample size and river hydrology set limits to the usefulness of the comparison. On the other hand, it is interesting that soil transition salinities increased as flow alteration in listed rivers increased.

If it can be assumed that long-term tidal action and salinity affect soil types then historical soil data may be useful indicators of the natural salinity structure of rivers. However, changes in rainfall, basin hydrology, river bathymetry, and sea level would have to be taken into account. It would be very interesting to compare the location of soil transitions in a river to the location where sea level intercepts the river bed.

The length of river between its mouth and soil transition increases in a north to south direction along the eastern shore of Tampa Bay (Table 3). In most cases the rivers empty into Tampa Bay. The "tidal" Manatee is 28.2 km (17.5 miles) long, which is almost the combined lengths of the "tidal" Little Manatee, Alafia and Palm Rivers, and more if the tidal length of its tributary, the Braden River, is added. The distance from soil transitions to Egmont Key probably double between the Braden and Hillsborough Rivers, and this difference may have affected the utilization of low salinity rivers by early life stages of Gulf species, before major changes to the bay, rivers, and basins.

Table 2. Salinity data in parts per thousand (ppt) for selected west coastal rivers, near transitions between alluvial and tidal soil types.

RIVER	(N)	MEAN	SD	MAXIMUM	SOURCE
A. High tide surface salinity, near soil transitions:					
Anclote	26	2.13	3.24	10.94	SWFWMD
Alafia	26	2.22	nd	12.14	SWFWMD
Little Manatee	36	1.41	2.05	8.18	SWFWMD
Manatee	57*	4.77	4.83	nd	(1)
Myakka	16	1.42	3.38	11.10	(2)
B. High tide bottom salinity, near soil transitions:					
Anclote	26	2.82	4.34	13.19	SWFWMD
Alafia	26	6.75	nd	18.55	SWFWMD
Little Manatee	36	1.59	2.28	8.18	SWFWMD
Manatee	57*	5.97	5.33	nd	(1)
Myakka	16	1.56	3.48	11.10	(2)

*mixed tides
nd - not determined
(1) CDM and Manatee County Utilities Department, 1984.
(2) S. Lowrey, Sarasota County Ecological Monitoring Division.

Table 3. Linear features of tidal rivers flowing into Tampa Bay.

	Distance (km) from alluvial soils to:		
RIVER	RIVER MOUTH	TAMPA BAY	GULF OF MEXICO
Braden	11.3	18.2	33.3
Manatee		28.2	37.7
Little Manatee		16.3	46.5
Alafia		9.8	56.5
Palm		3.1	58.7
Hillsborough		nd	nd

nd - not determined.

Surface Area Aspects

Throughout the Gulf of Mexico, the area of wetlands in an estuary is related to that system's stock of shrimp and fishes, and commercial landings of fishery species (Gulf of Mexico Program 1991). Wetland productivity is also related to secondary productivity, and both are intimate functions of freshwater inflow (Deegan et al. 1986). Although data on the productivity of wetlands in Tampa Bay are scant (Estevez and Mosura 1985), recent mapping efforts make it possible to evaluate wetland area within and between rivers, compared to all of Tampa Bay.

Past estimates set the area of salt marsh and mangrove forest in Tampa Bay at 6,513 ha (16,098 acres) (Reyer et al. 1988) to 9,462 ha (23,385 acres) (Haddad 1989), with other estimates (McNulty et al. 1972, Lewis and Whitman 1985, and the U.S. Fish and Wildlife Service's National Wetland Inventory) within this range. Estimates vary because of differing methods, materials, and map boundaries. None has separated the wetland area of tidal rivers from the wetland area of open bay shorelines.

The Florida Game and Fresh Water Fish Commission provided data on river wetlands from their LANDSAT habitat mapping project. A cooperative project with the Florida Departments of Natural Resources and Transportation, this digital map set identifies nine upland and eight wetland plant communities, plus four disturbed community types. Data were tabulated for each map unit within polygons covering each tidal river. Polygons were defined to include all mangrove forests and salt and fresh water marshes in a river, based upon the authors' experiences. Polygons extended inland to include forested wetlands in the river corridor (excluded from analysis), and upland to include mangroves and marshes in tributaries (included).

A total of 3,347 ha (8,272 acres) of wetlands was tabulated for major rivers, of which 1,397 ha (3,453 acres), or 42%, were mangrove forests and coastal salt marshes (Table 4). Other wetland types, in order of descending total area, were hardwood swamps, fresh water marshes and wet prairies, and cypress swamps. Some "tidal fresh water marsh" included wetlands not associated with the river, and others were probably mapped as "coastal salt marsh". As a result, our discussion is confined to salt marsh and mangrove habitat types. The reported absence of mangroves in the Braden River is an artifact of mapping scale (Judy Elert, Florida Game and Fresh Water Fish Commission, personal communication). The area of mangroves and salt marshes in rivers cannot presently be compared to the area of these wetlands in Tampa Bay, determined by the same methods, but 1,397 ha (3,453 acres) constitute 14.8% to 21.4% of total marsh and mangrove area reported in earlier studies. Nearly all oligohaline wetlands are presumed to occur only within the riverine systems tributary to Tampa Bay (NOAA Strategic Assessments Branch 1987).

Table 4. Area, in hectares, of selected wetland types and open water in tidal rivers of Tampa Bay. Data provided by Florida Game and Fresh Water Fish Commission.

RIVER	SALT MARSH	FRESH MARSH	MANGROVE	TOTAL WETLAND	OPEN WATER
Hillborough	4.5	12.1	0	38.4	127.9
Palm	7.3	3.2	0	15.4	127.4
Alafia	80.1	135.9	47.7	688.2	420.0
Little Manatee	226.2	293.3	136.8	1,003.8	696.3
Manatee	627.5	155.8	58.7	1,269.2	3,167.2
Braden	208.4	67.5	0	331.8	264.6
TOTAL	1,154.0	667.9	243.2	3,346.8	4,803.4

Figures 2 and 3 illustrate within-river and between-river wetland abundances. In Figure 2 the area of wetland is calculated as a percentage of wetland plus open water in each river. The amount of open water upstream of tidal conditions, and on uplands, was regarded as negligible in each river polygon. Highest wetland density (44.1%) occurs in the Braden River. About one-third of the Little Manatee River is in mangrove and salt marsh, and one-fourth to one-fifth of the Alafia River is a wetland plant community. Despite having the largest total salt marsh and mangrove area (686 ha) the Manatee River's wetland density is comparatively low because of 3,167 ha of open water (not counting the reservoir at Lake Manatee).

Between-river wetland comparisons are made in Figure 3. Nearly half of the bay area's tidal river wetland occurs in the Manatee River. If the Braden River is added, the Manatee and its major tributary comprise nearly two-thirds of all tidal river wetlands in the bay area. The Manatee/Braden wetland system constitutes 9.5% to 13.7% of the range in total bay area wetlands reported above. Most (93%) of the wetland mapped in these two rivers is salt marsh, and the exact amount of fresh water marsh that is tidal in character is not known. Because one-fourth of the bay's total tidal river wetland resides in the Little Manatee River, the southern three rivers constitute 90% of all river wetland compared to only 10% in the northern three rivers.

Volumetric Aspects

The area of wetlands and open water in major rivers is approximately 8% of the wetland plus open water area of Tampa Bay (Table 4; Lewis and Whitman 1985). The volume of mesohaline and oligohaline waters is considerably less because tidal river volume decreases logarithmically with upstream distance from a river's mouth. Within

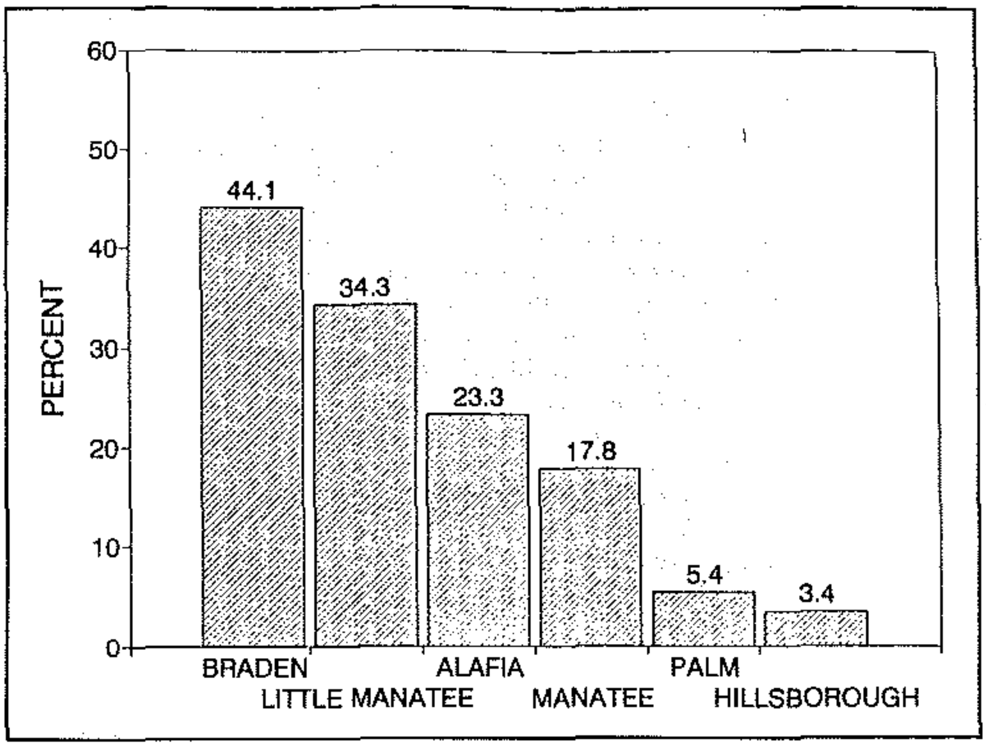

Figure 2. Within-river comparison of coastal salt marsh and mangrove forest area, expressed as percentages of wetland plus open water in each river (adapted from data provided by Florida Game and Fresh Water Fish Commission).

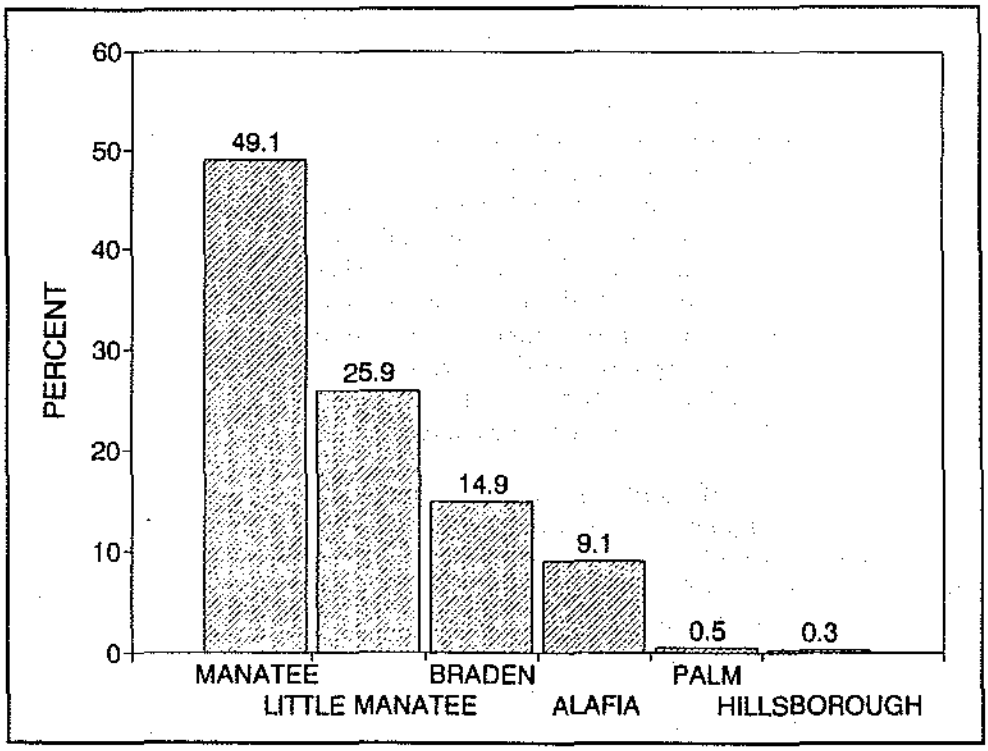

Figure 3. Between-river comparison of coastal salt marsh and mangrove forest area, expressed as percentages of total wetland area in all rivers combined (adapted from data provided by Florida Game and Fresh Water Fish Commission).

such reaches, zones of maximum mixing of fresh and salt water are characterized by high turbidity due to phytoplankton productivity as well as flocculation of colloidal materials. In zones where flocculation and water color are sufficiently dilute, rapid phytoplankton growth and biomass accumulation may be a consequence of the mixture of river waters limited by phosphorus or nitrogen, and bay water limited by nitrogen (McPherson et al. 1990; Garber and Boynton, this volume).

The intensity of mixing zone blooms may also be a consequence of the concentrating effect of upward entrainment in subtidal riverine currents. The presence of residual up-river bottom currents in the tidal Manatee River is discussed by Galperin et al. (this volume). Plankton blooms are important food sources for many larval and juvenile fishes as well as filter-feeding adults such as menhaden. Blooms also regulate oxygenation of tidal river waters and thereby affect water quality and associated regulatory programs.

Data on the volume or cross-sectional area of tidal rivers were collected from reports and unpublished sources. Myakka data were taken from Siler et al. (1990). Manatee data were extracted from CDM and Manatee County (1984). Little Manatee data were provided by Michael S. Flannery, Southwest Florida Water Management District. Hillsborough River data were found in Ross and Jerkins (1980). All data were converted to cubic foot volumes in sections at known river miles. Myakka, Manatee and Little Manatee volumes are for average tides. Volumes in the Hillsborough River are for mean low water.

On a semi-logarithmic plot, volume decreases monotonically in the tidal Myakka River (Figure 4). This pattern is the result of river width (including wetlands) decreasing over orders of magnitude, compared to river depth decreasing by a maximum of about 75%. Near river mile 25, the river becomes an incised lotic system and volume becomes constant. Volume per mile of the Manatee River is much different than that in the Myakka River. Because the Manatee is uniformly wide and deep from the bay to about river mile 15 (km 24), volume changes comparatively little. Upstream of that point, the river simultaneously narrows and the area of shallow subtidal and intertidal bottom increases. These changes result in rapid volume reduction upstream of Redfish Point.

The tidal Hillsborough and Little Manatee Rivers are similar in general volume trend. Volume decreases as a function of river mile similar to the Myakka River trend. The Little Manatee is constricted near river mile 3.0 (km 4.8) but not greatly so, compared to the Myakka. The Hillsborough River's volume decreases stepwise, probably as a combined result of bank shape and extensive channel dredging during the past several decades. Data for the Alafia River are not shown. Streambed elevations in the Alafia are generally between 3 to 5 m below NGVD from the bay to a point about 13 km (8 miles) upstream of U.S. Highway 41, then elevations rise to near sea level over the length of another two river miles (Giovannelli 1981). River width decreases from 450 m near the bay to less than 100 m near U.S. Highway 301, meaning that Alafia River volumes may exhibit a biphasic trend like that of the Manatee.

The significance of rapidly decreasing volume in tidal rivers is that the effective habitat space of oligohaline plankton and nekton is many times smaller than the available habitat of higher salinity reaches of the river. River geometry controls the effect of fresh water inflow on salinity structure. Because river geometry is non-linear the effect of inflow on salinity in these transitional areas also is nonlinear; small inflow changes over critical ranges can cause large salinity changes, resulting in a dislocation of favorable physical habitat and favorable salinities (see Browder, this volume). Abrupt changes in the rate of river volume change per unit of river distance, such as seen in the Manatee River, have the potential of further amplifying the impacts of alterations to inflows or river geometry.

It is important to note that tidal fresh water reaches are contiguous with upstream lotic waters in rivers lacking structural barriers. Depending on the life history of individual species, effective habitat size may be significantly extended by access to nontidal river reaches. Utilization of inland river reaches by marine and estuarine animals is common on the Florida peninsula (Odum 1953). Champeau (1990), for example, found that 3.4% of electrofished samples near Ft. Meade, on the Peace River, was comprised of snook, *Centropomis undecimalis*. Ft. Meade is approximately 130 km (80 miles) upstream from the mouth of the Peace River and snook were common throughout (Champeau 1990). Dams on the Hillsborough, Palm, Manatee and Braden Rivers prevent snook and animals with similar range from reaching upstream waters, in proportion to the length of each river isolated from tidal water.

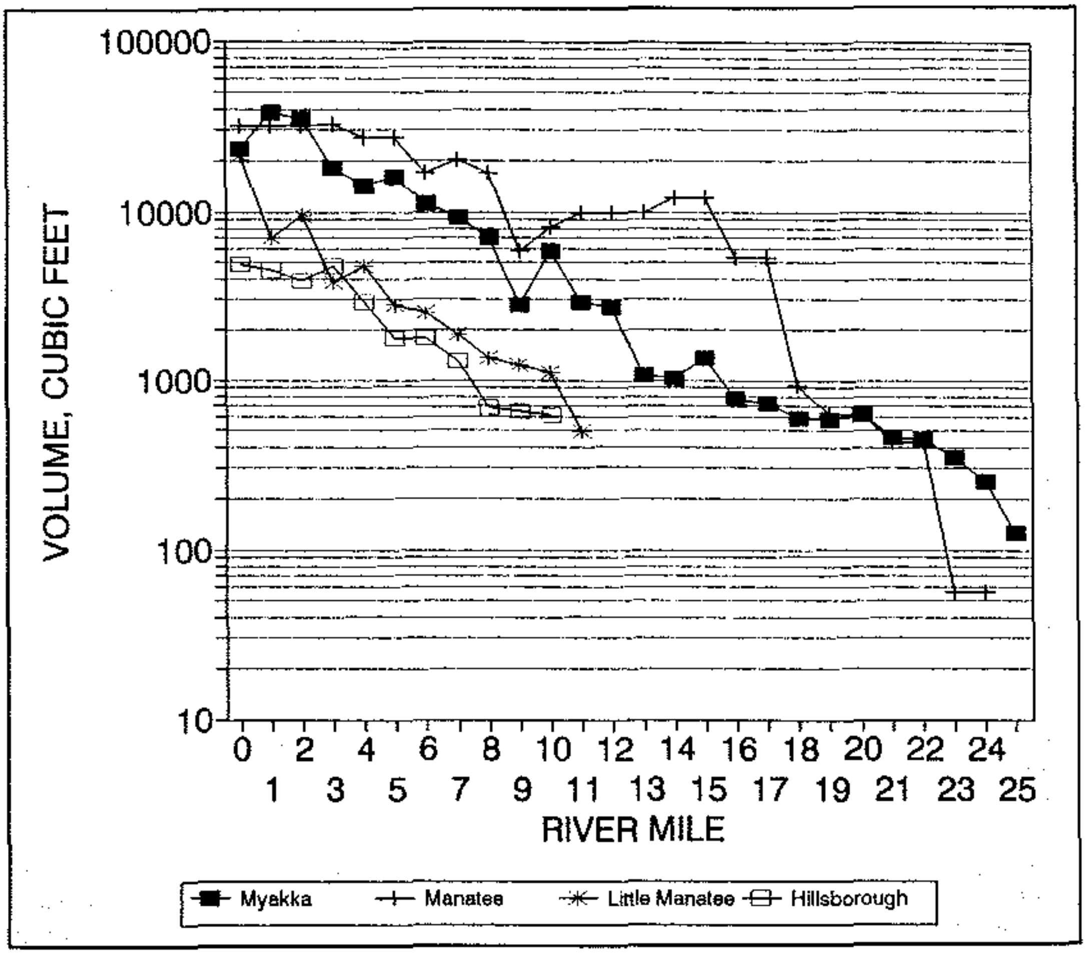

Figure 4. Volume, in cubic feet, in relation to river-miles on the (1) Myakka, (2) Manatee, (3) Little Manatee and (4) Hillsborough Rivers. See text for description of sources and data reduction methods. One cubic foot = 0.02832 cubic meter; one mile = 1.609 km.

DISCUSSION

Reviews of monitoring data produced by the Hillsborough County Environmental Protection Commission and the NOAA Strategic Assessment Branch's estuarine data atlas indicate that most permanent low salinity habitat in Tampa Bay is located within tidal rivers flowing into the bay. The size and river-specific locations of these habitats are not known well, and the same may be said for their ecological role specific to primary and secondary productivity for the bay area. Moreover, structural and functional features of low salinity areas are affected by tides, winds, normal variations in fresh water inflows, and extreme events such as droughts, tropical storms, and freezes (Estevez 1989, McPherson and Hammett 1991.) but the significance of these effects is also unknown.

Taken as a whole, there are approximately 80 kilometers (50 miles) of "tidal" river environments connected to the bay. The Manatee River contains the longest single tidal reach. It also contains almost half of the total area of tidal river wetland, or two-thirds when combined with its major tributary, the Braden River. The Braden River, in turn, contains the highest density of wetlands in the bay area. The two rivers probably have more mangrove forest than presently reported in the Game and Fish Commission data base. The amount of "coastal salt marsh" in low salinity, or of "fresh water marsh" that is actually tidal and fresh water in character, is unknown.

The Manatee River contains the largest volume of tidal water and may exhibit residual upstream movement of bottom waters during periods of net discharge to Tampa Bay. Such reverse flow is a critical factor in the dispersal of eggs and larvae into upriver nursery areas, and reverse flows of bottom water may also occur in the Alafia River because of its depth. Robison (1985) examined the role of bottom currents and larval movement in the retention of young sciaenids and other fishes in open bay waters, and opined that similar processes extend into rivers. Utilization of the Manatee River by early juvenile fishes is reported by Edwards (this volume), and ongoing, fishery-independent stock assessments conducted by the Florida Marine Research Institute will add to knowledge of this function of other low salinity habitats around the bay.

The Manatee and Braden River system constitutes a significant part of the oligohaline wetland resources of Tampa Bay. Efforts to preserve its structural integrity deserve to continue, by avoiding dredging and filling projects along shorelines, in wetlands, and in shallows. Efforts to understand and improve the system's functional integrity—in the sense proposed by Browder and Moore (1981)—are also needed, and should begin with the system's hydrology (Estevez et al. 1991). As noted previously, small increments of inflow have the potential to alter salinity significantly, and such changes may be all that are necessary to register oligohaline waters with large wetland areas.

It is not clear just how much water enters Tampa Bay via its tributaries. A number of estimates are available (Flannery 1989), including a recent basin-wide assessment made for the Southwest Florida Water Management District (Dames & Moore, Inc. 1990). These estimates actually describe inflows of mostly surface water runoff into rivers, but not necessarily the discharge of rivers to the bay. In some cases, past estimates did not account for the contribution of springs, such as Sulfur Springs in the Hillsborough River system. In every case, the impoundment and diversion effects of reservoirs have not been considered. Needed are: estimates of fresh water inflow to separate river reaches (lotic, tidal fresh, etc.); the cumulative effects of augmentations, diversions, and impoundments; and finally, the net outflows of rivers to the bay. Ongoing work by the U.S. Geological Survey holds much promise for measuring the latter feature directly at river mouths, and this work should be expanded to all bay tributaries.

A better understanding of river hydrology will improve our understanding of circulation, water quality, and ecology in Tampa Bay as a whole, as well as in specific rivers. One research goal should be an ability to state the extent to which modern day river flows depart from their historic ranges. Rozengurt et al. (1987) argue that flow alterations in excess of natural variability will damage estuarine resources, and this view was shared by consensus of a 1991 national symposium on coastal fish habitat conservation (Safina 1991). We believe that the Hillsborough and Palm River flows may already have been altered beyond their natural ranges, that flows in the Alafia and Little Manatee Rivers have not, and that additional data are needed in the two southern rivers.

Wetlands and open waters of rivers constitute less than 10% of the area of wetlands and open water throughout Tampa Bay, but the river systems play a unique role in the life cycles of numerous marine and estuarine species of economic or ecological value. The remarkable but very rare habitat type of tidal fresh water marsh (Odum et al. 1984) occurs in the region only in rivers. Before their extirpation, sturgeon were common in the Hillsborough River, and manatees still make regular use of low salinity reaches in all of the rivers around the bay.

These qualities commend the restoration of tidal river environments. In northern rivers there is a need for habitat creation and inflow optimization, whereas habitat is abundant in southern rivers where inflow optimization holds the greatest promise. Restoration programs should be based upon process-oriented research, such as the Little Manatee River and Basin Study, described by Flannery et al. (this volume). Although the science of inflow optimization for estuaries still is young, productive theory and successful methods have emerged for other Florida systems (Browder et al. 1990) that we believe are appropriate for the rivers of Tampa Bay.

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DISTRIBUTION AND ABUNDANCE OF BOTTLENOSE DOLPHINS (*TURSIOPS TRUNCATUS*) IN TAMPA BAY

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ABSTRACT

In Tampa Bay, aerial surveys were conducted at least monthly to assess abundance and distribution of bottlenose dolphin (Tursiops truncatus). The flights focused on waters within about one kilometer of the entire shoreline of the bay. Between November 1987 and December 1990, dolphins were sighted 4,390 times during 51 one-day surveys (mean count per survey = 86 dolphins). The counts ranged from 22 to 232, with counts greater than 100 occurring in every season and nearly every month. Calves represented only 3.7% of the dolphins sighted in the bay. Average density for the survey area was 0.15 dolphins/km^2. Most of the high-use areas were located around the mouth of the bay.

INTRODUCTION

The bottlenose dolphin (*Tursiops truncatus*) has become the focus of considerable interest and controversy for a variety of reasons. High levels of dolphin mortality have been noted along the mid-Atlantic and northern Gulf of Mexico coastlines in recent years; dolphins are being used in various captive settings, such as "swim-with-the-dolphin" and military programs; dolphins are seen as a potential indicator of ecosystem health; their intelligence and behavior invite study; and recently, some feed-the-dolphin programs have involved wild dolphins. Fundamental questions concerning wild dolphins remain, even though many recent studies have concentrated on bottlenose dolphins in the southeastern United States. Research has involved at least four primary topics: ecology, behavior, and status of local, inshore groups of dolphins; abundance and distribution of offshore animals; nature and extent of dolphin mortality; and stock discreteness.

Unquestionably, the best known group of dolphins, studied since 1970, inhabits Sarasota Bay (Scott et al. 1990), but groups residing in other coastal and estuarine areas have also received attention (see reviews by Shane et al. 1986, Leatherwood and Reeves 1990). As a result, considerable information is available regarding abundance and distribution of *Tursiops* in inshore waters. In addition, Scott and Hansen (1989) described offshore surveys in the Gulf of Mexico that resulted in an estimate of 35,000-45,000 bottlenose dolphins in Gulf waters less than 183 m deep. More recently, Mullin et al. (1991) surveyed the waters of the upper continental shelf of the north central Gulf of Mexico. They sighted at least 15 different species of cetaceans. Bottlenose dolphins were the third most commonly sighted species (39 herd sightings), following Risso's dolphins, *Grampus griseus* (61 sightings), and sperm whales, *Physeter catodon* (43 sightings). Dolphin population densities ranged from 0.17 dolphins/km^2 in 1990 to 0.095 individuals/km^2 in 1989 (Mullin et al. 1991).

Mortality of bottlenose dolphins in the southeastern United States has also been studied. Odell's (1991) summary of dolphin strandings in the southeastern U.S. indicated that between 1978 and 1987, 531 *Tursiops* were recovered. More recently, bottlenose dolphin die-offs have caused the mortality rate to rise sharply. In 1987-1988, over 740 dolphins were recovered along the Atlantic coast; brevetoxin from red tide may be the primary cause of death (Geraci 1989). In early 1990, 274 dolphins were recovered from the northern Gulf of Mexico, and an additional pulse of 13 dolphins was recovered at Galveston, Texas, later that year (Marine Mammal Commission 1991). The cause(s) of the deaths in the Gulf has not been wholly determined.

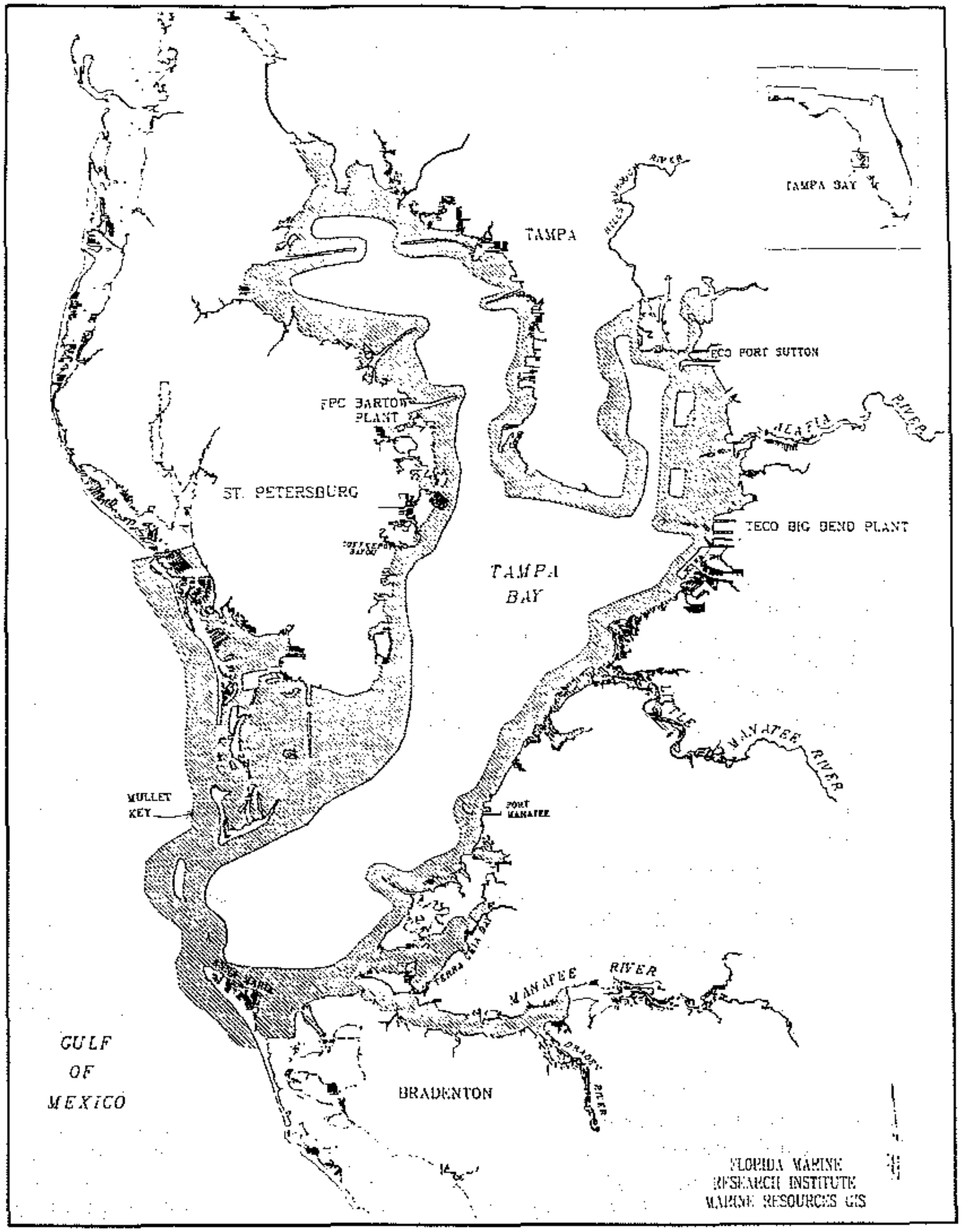

Figure 1. Study area in Tampa Bay surveyed for bottlenose dolphins and manatees.

The other primary area of investigation involves stock discreteness of dolphins in the southeastern United States. Duffield and Wells (1987, cited in Scott and Hansen 1989) electrophoretically examined blood proteins of dolphins from Florida's Gulf coast and found greater similarity between dolphins from Tampa Bay and those from Charlotte Harbor-Pine Island Sound to the south than between either of these dolphin groups and dolphins from Sarasota Bay, which is between the other two localities. Duffield and Wells (1987) suggested, however, that the group of dolphins residing in Sarasota Bay was not reproductively isolated from neighboring dolphin groups.

Another question needing clarification is the extent to which offshore and inshore stocks of *Tursiops* are reproductively isolated.

Research has focused on *Tursiops* in the southeastern U.S. because of intrinsic interest in the behavior and ecology of the species as well as for pragmatic population management reasons. For decades, undetermined numbers of bottlenose dolphins have been captured in southeastern U.S. waters for scientific research and public display. Since the passage of the Marine Mammal Protection Act in 1972, over 500 dolphins have been permanently removed from these waters for these purposes. Until recently, the National Marine Fisheries Service had established quotas for such live-capture of dolphins based on the "2% rule," under which the assumption was made that dolphin productivity was sufficiently high that up to 2% of any area's estimated population could be removed annually without detriment.

Validity of the 2% rule has been questioned, especially in light of reported high levels of incidental take of *Tursiops* in the southeastern United States (Reynolds 1986) and incomplete knowledge of dolphin stocks and population dynamics. At present, there is a moratorium on collection of dolphins in the southeastern U.S., pending resolution of uncertainties regarding the status of dolphins and the effects of live-capture operations on local dolphin populations.

Research on dolphins in Tampa Bay has been relatively limited compared to that in many other areas of the southeast, although Tampa Bay has been a site for dolphin collection. Scott et al. (1990) extended their photoidentification studies from their primary study site in Sarasota Bay to include adjacent waters of southern Tampa Bay. Weigle (1990) provided the most comprehensive view of Tampa Bay dolphins by conducting surveys by boat in Lower Tampa Bay between April and October of 1983 and 1984. He found that: 1) dolphin population density was higher in summer and early fall than in spring; 2) dolphins in Tampa Bay mixed with identified animals from the Sarasota Bay population; and 3) about 9.7% of the dolphins in Tampa Bay were calves. He provided evidence suggesting that the resident dolphin population in the bay was supplemented by transients and that "an apparently open population of dolphins used the study area." Other extant data for bottlenose dolphins in Tampa Bay include results of carcass salvage operations maintained by the Southeastern United States Marine Mammal Stranding Network.

To address some of the deficiencies in the database, regular aerial surveys of dolphins occupying inshore areas of the bay were initiated in 1987. This aerial survey database provides information useful for understanding and managing bottlenose dolphins in Tampa Bay.

METHODS

Aerial surveys of manatees and dolphins in Tampa Bay were conducted twice monthly from November 1987 through February 1989 and once per month thereafter. No flight was made in November 1989 or November 1990. Data through December 1990 are reported here. Each survey involved two Cessna 172 aircraft flying simultaneously, one on each side of the bay. Flights were made at an altitude of 150 m and an air speed of approximately 80-85 knots. J. Reynolds or P. Houhoulis was primary observer in the aircraft that surveyed the western half of Tampa Bay; B. Weigle, E. Beeler, or B. Ackerman was primary observer in the aircraft that covered the eastern half.

The aerial surveys concentrated on nearshore areas of the bay from the shoreline to about 1.0 km offshore (Figure 1). This area was calculated to contain 568.5 km^2 of water surface area. Approximately 440 km^2 in the middle of the bay were not surveyed because the flights were designed to maximize manatee counts (Reynolds et al. 1991) by concentrating on shallower waters where manatees and their primary food source, seagrasses, are located. Flight paths were parallel to the shoreline, periodically circling to provide observers with adequate time to spot dolphins and manatees. When dolphins or manatees were observed or suspected to be present, additional circles were made for as long as necessary to obtain an accurate count. Data recorded for each group included total number of dolphins present; number of calves present (defined as dolphins less than half the length of a closely associated animal); the animals' behavior, including feeding, resting, or direction of travel; and their precise location.

Sightings of dolphins were recorded on photocopies of NOAA navigation charts (1:40,000 scale). Other data including time of day, air temperature, water clarity, and sea-surface conditions were also recorded on the maps. Following each flight, data were entered into a Geographic Information System (GIS) at the Florida Marine Research Institute (Florida Department of Natural Resources). Observations were categorized into one of 21 geographic zones of the bay.

Statistical tests of counts between seasonal time periods were made using analysis of variance (ANOVA) procedures, using Duncan's multiple range test for multiple comparison of means (SAS 1985). Dolphin density was calculated for each zone, by season and for all surveys, by normalization of the counts using the number of aerial surveys and the area of the zone. The seasons were defined as follows: winter—December through February; spring—March through May; summer—June through August; fall—September through November.

RESULTS

Fifty-one aerial surveys were made from November 1987 through December 1990 (Table 1). A total of 4,390 *Tursiops* was spotted during the surveys (mean=86; SE=6.2; range 22-232). Counts varied considerably from month to month (Table 1, Figure 2); more than 100 dolphins were sighted during individual surveys at least once in every month except June. Seasonal mean counts of dolphins were as follows: spring, 77; summer, 75; fall, 102; and winter, 91. These means were not statistically different (ANOVA, p=0.45).

The size of groups ranged from 1 to 54 and averaged 3.2 dolphins (SE=0.09) for the 1,381 groups sighted. Seasonally, groups were largest in the fall (mean=3.42, SE=0.20) and decreased through winter (mean=3.36, SE=0.19), spring (mean=3.17, SE=0.18), and summer (mean=2.70, SE=0.13). Groups in fall were significantly larger than groups in summer (ANOVA, p=0.03). Groups of ten or more dolphins (n=69) were spotted throughout the survey area, but groups of more than 20 (n=6) occurred only during the fall and winter seasons in the lower bay.

Calves represented between 0% and 9.8% of the dolphins sighted during individual surveys of Tampa Bay (Table 1). Calf presence in the bay was highly variable and ranged from zero to 12 individuals observed during a single survey. Overall, calves represented 3.7% of all dolphins observed. Seasonally, the percentage of calves was highest in summer (4.7%), followed by winter (3.8%), fall (3.6%), and spring (2.4%); these results were not statistically different (ANOVA, p=0.14).

Density over the entire study area was 0.15 dolphins/km^2. Dolphins were observed in virtually all parts of the bay (Figure 3). Waters at the northern mouth of the bay were the most heavily used. Along the south and west shores of Mullet Key (Fort DeSoto Park), density levels of 0.54 and 0.49 dolphins/km^2 occurred, respectively. At the southern mouth of the bay, around Anna Maria Island and Passage Key, densities ranged from 0.22/km^2 to 0.29/km^2. The waters from the south end of the Skyway Bridge north to Apollo Beach also had dolphin densities greater than 0.20 dolphins/km^2. Additional areas with densities exceeding the bay-wide mean included Egmont Key (0.18), Terra Ceia Bay (0.19), St. Petersburg from the Skyway Bridge to Bayboro Harbor (0.16), Bayboro Harbor to the Gandy Bridge (0.20), and the east end of the Gandy Bridge to Gadsden Point (0.20). Two areas had minimal dolphin sightings; none were sighted in the Braden River in Manatee County, and only three were seen in the Little Manatee River.

Trends in seasonal dolphin densities by zone were not substantially different from those in overall densities. On the south shore of Mullet Key, dolphin density exceeded 0.50 in every season. In summer and fall, both Passage Key and the Port Manatee areas had densities above 0.30. In fall, Anna Maria Sound had the highest density observed (0.81) for any zone. The Gulf area west of Anna Maria Island also had its highest level (0.34) in fall. Around Egmont Key, density peaked in the winter (0.33) and was much lower during the remaining seasons.

Table 1. Results of dolphin aerial surveys in Tampa Bay, Florida, from November 1987 to December 1990.

DATE	WEATHER	SEASON	GROUPS	ADULTS	CALVES	TOTAL	% CALVES
13NOV87	Warm	Fall	33	105	3	108	2.77
28NOV87	Warm	Fall	27	136	6	142	4.22
18DEC87	Cold	Winter	45	220	12	232	5.17
31DEC87	Cold	Winter	30	95	4	99	4.04
18JAN88	Cold	Winter	34	112	3	115	2.60
29JAN88	Cold	Winter	21	67	2	69	2.89
15FEB88	Cold	Winter	13	28	0	28	0.00
29FEB88	Cold	Winter	45	151	2	153	1.30
14MAR88	Warm	Spring	11	22	0	22	0.00
25MAR88	Warm	Spring	34	123	2	125	1.60
06APR88	Warm	Spring	49	172	8	180	4.44
18APR88	Warm	Spring	7	32	0	32	0.00
05MAY88	Warm	Spring	11	26	1	27	3.70
17MAY88	Warm	Spring	43	153	2	155	1.29
07JUN88	Warm	Summer	31	96	3	99	3.03
20JUN88	Warm	Summer	29	72	2	74	2.70
12JUL88	Warm	Summer	39	134	4	138	2.89
22JUL88	Warm	Summer	15	42	0	42	0.00
04AUG88	Warm	Summer	37	98	5	103	4.85
23AUG88	Warm	Summer	36	103	4	107	3.73
19SEP88	Warm	Fall	33	126	5	131	3.81
30SEP88	Warm	Fall	30	87	3	90	3.33
26OCT88	Warm	Fall	40	85	1	86	1.16
16NOV88	Warm	Fall	29	87	1	88	1.13
09DEC88	Cold	Winter	34	113	7	120	5.83
20DEC88	Cold	Winter	27	99	6	105	5.71
11JAN89	Cold	Winter	16	65	1	66	1.51
26JAN89	Cold	Winter	29	56	2	58	3.44
11FEB89	Cold	Winter	21	60	5	65	7.69
25FEB89	Cold	Winter	19	44	2	46	4.34
28MAR89	Warm	Spring	23	66	2	68	2.94
26APR89	Warm	Spring	21	42	3	45	6.66
24MAY89	Warm	Spring	30	101	2	103	1.94
20JUN89	Warm	Summer	18	37	2	39	5.12
20JUL89	Warm	Summer	16	28	3	31	9.67
25AUG89	Warm	Summer	35	72	3	75	4.00
29SEP89	Warm	Fall	15	57	2	59	3.38
27OCT89	Warm	Fall	31	77	1	78	1.28
29DEC89	Cold	Winter	20	79	3	82	3.65
10JAN90	Cold	Winter	38	103	3	106	2.83
09FEB90	Cold	Winter	18	45	1	46	2.17
02MAR90	Warm	Spring	18	34	0	34	0.00
18APR90	Warm	Spring	32	102	3	105	2.85
11MAY90	Warm	Spring	13	29	1	30	3.33
22JUN90	Warm	Summer	21	52	4	56	7.14
26JUL90	Warm	Summer	34	93	3	96	3.13
08AUG90	Warm	Summer	20	37	4	41	9.76
21SEP90	Warm	Fall	34	120	6	126	4.76
29OCT90	Warm	Fall	27	101	11	112	9.82
03DEC90	Cold	Winter	13	33	2	35	5.71
17DEC90	Cold	Winter	36	111	7	118	5.93

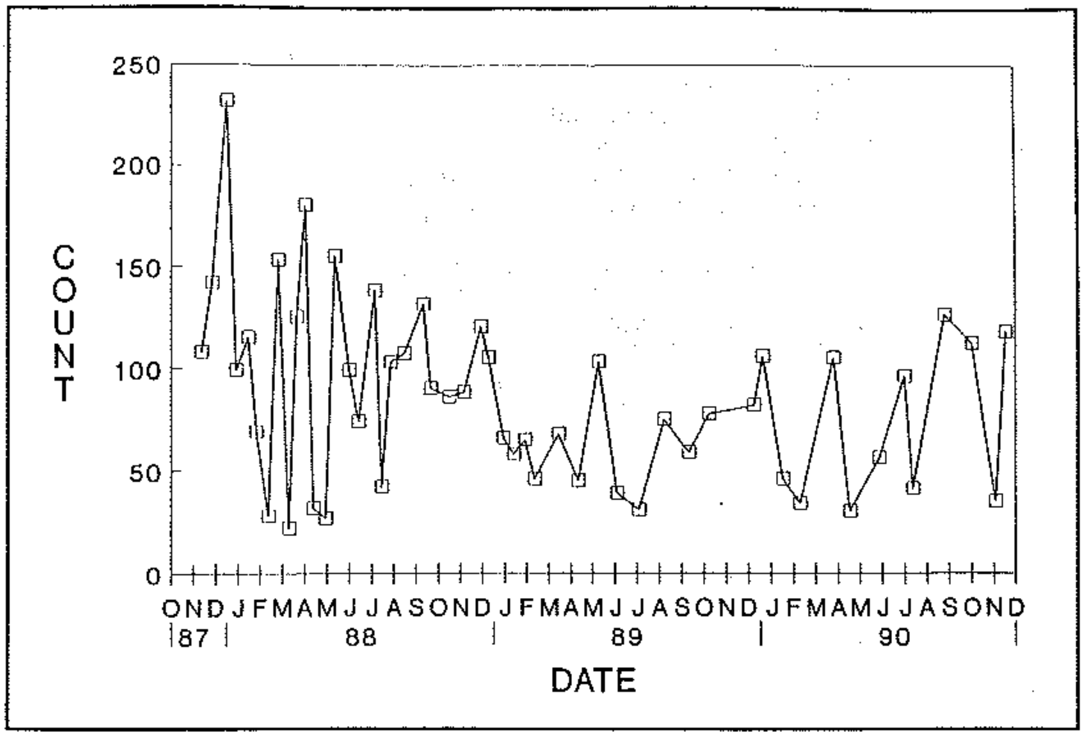

Figure 2. Counts of dolphins observed during 51 aerial surveys of Tampa Bay from November 1987 to December 1990.

DISCUSSION

Abundance and Distribution

Inshore waters of Tampa Bay provide an important habitat for bottlenose dolphins; as many as 232 have been sighted in a single survey. Wells et al. (1987) and Weigle (1990) have demonstrated that dolphins in Tampa Bay mix with those in adjoining Sarasota Bay, although the extent of mixing is unknown. Wells and Scott (1990) documented that the resident Sarasota dolphin community contained approximately 100 individuals during 1980-1987, so it is conceivable that, at times, the two bays contain over 300 *Tursiops*.

Even though hundreds of dolphins may occupy the Tampa Bay area at times, the resident community is probably much smaller. The exact size of the resident population is unknown, but the mean count per survey was 86 dolphins. Weigle (1990) did not provide an estimate of the size of the resident population, but using photoidentification of 246 dolphins, he concluded that many transient dolphins move in and out of Lower Tampa Bay. The transit of animals into and out of the bay almost certainly contributed to variability in counts. Other factors that were likely to have caused variability included weather conditions (although some very low counts occurred on days with excellent weather) and movement of dolphins into unsurveyed, middle bay areas.

Sizes of groups observed were similar to those determined by other aerial and boat surveys along the Gulf coast of Florida, as compiled by Leatherwood and Reeves (1982) and Wells et al. (1980). Average group size (3.2 dolphins) for Tampa Bay was low compared to other areas reviewed and was comparable to that determined by surveys of Everglades National Park (2.95) and the coastal pelagic area off Sarasota (2.87). Weigle (1990) reported 5.0 dolphins per group, whereas the mean group size was 4.84 in adjoining Sarasota Bay (Wells et al. 1980). Shane et al. (1986) noted that larger dolphin groups tend to be more common in deep water areas. Our data support that trend, as do Weigle's (1990); in both cases, groups of more than 20 dolphins occurred only near the mouth of Tampa Bay. We further note that the surveys we describe in this report covered shallow inshore waters where small groups might be expected (Shane et al. 1986).

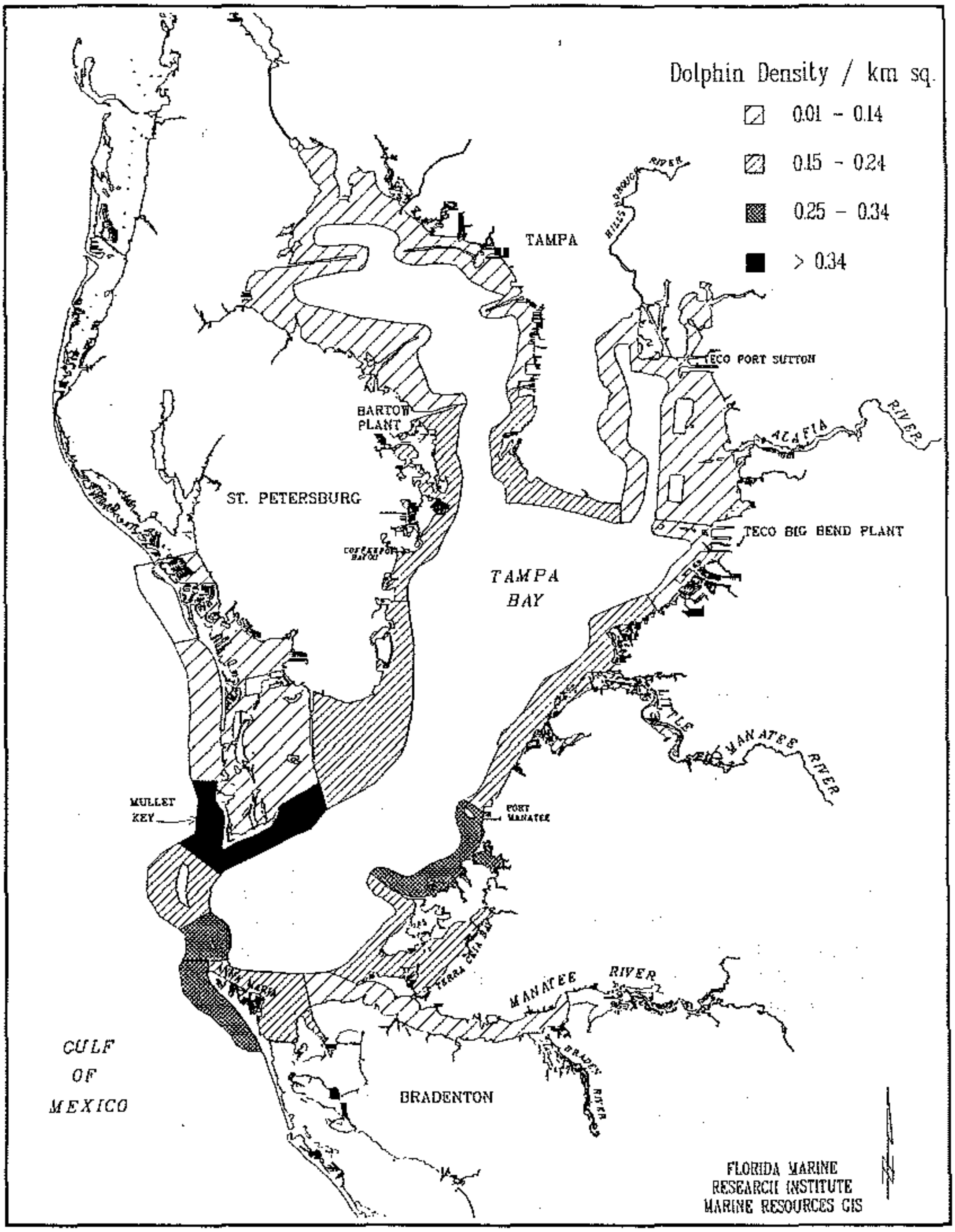

Figure 3. Dolphin density (dolphins/km^2) calculated for all surveys in each of 21 geographic zones.

Density of the dolphin population in Tampa Bay, as measured by our surveys, was 0.15/km^2 overall. Weigle (1990) reported that density in the lower portion of the bay varied from 0.06/km^2 in April to 0.38/km^2 in July, with a mean of 0.27/km^2. Densities from other estuarine locations in Florida (compiled by Shane et al. 1986) are generally higher than in Tampa Bay. Our results are comparable to seasonal surveys of Charlotte Harbor in October (0.17) and April (0.21) and are much lower than densities in Sarasota Bay (0.6-1.8) and the Indian River Lagoon (0.68-1.22). In Texas, densities determined from aerial surveys ranged from 0.314 to 1.025, whereas those determined from surveys conducted by boat were even higher (1.4-4.8) for small study areas.

The distribution of sightings was not surprising, because Weigle (1990) reported widespread dolphin distribution in the lower bay, with highest use around the bay mouth, especially along the south and west shores of Mullet Key, in Anna Maria Sound, and around Passage Key. Our surveys were much broader in extent, but we also found that these areas, along with the western shore of Anna Maria Island and the eastern bay shoreline from Apollo Beach to the Skyway Bridge, were the most highly used by dolphins. Hillsborough Bay (0.07 dolphins/km^2), Boca Ciega Bay (0.09/km^2), and Old Tampa Bay (0.10/km^2) had low levels of density.

Calves

Only 3.7% of the dolphins sighted were calves; this percentage is extremely low compared to that found in other studies. Wells and Scott (1990), for example, reported that up to 20% of the dolphins in Sarasota Bay were calves, and Weigle (1990) found that 9.7% of the dolphins he observed in Lower Tampa Bay in 1983 and 1984 were calves. Elsewhere in southeastern United States coastal waters, values ranged from 2.7% to 15.6% (Leatherwood and Reeves 1982). Some of the differences are attributable to how calves are defined or classified. In Sarasota Bay, many animals classified as calves are known to associate with their mothers for up to five years, yet at that age the calves may be much larger than half the mother's size, giving a higher calf percentage that is not directly comparable to the results of our aerial survey. Other studies in Florida have reported calf percentages well above the results of our surveys; numerous surveys of the Indian River and Banana River Lagoons have reported dolphin calf percentages ranging from 8.1% (Asper and Odell 1980) to 15.6% (Leatherwood and Show 1980), whereas Irvine et al. (1980) found 5.7% calves along Florida's Gulf coast. In the Mississippi Sound area, calves composed 7.7% to 12.4% of the population (Leatherwood et al. 1978). Shane (1977) found that calves averaged 7.6% during a 15-month survey around Aransas Pass, Texas, whereas Barham et al. (1980) reported 9.4% to 10.7% calves during aerial surveys from Aransas to Matagorda.

The reason for the low percentage of calves in our aerial surveys is unknown. Possibly, calves are easier to detect and recognize by boat than from the air, which would explain why Wells and Scott (1990), Weigle (1990), and Shane (1977) found a higher percentage of calves. It does not explain why other aerial surveys (e.g., Leatherwood and Show 1980, Irvine et al. 1980) also found calves to represent a higher percentage of the animals than we did.

Management Considerations

Management of bottlenose dolphins in the southeastern U.S. has received considerable attention because the live-capture industry removes animals for public display and scientific research. Effective management has been complicated by lack of data regarding:

- size of local dolphin stocks;
- stock discreteness;
- life history parameters;
- other types of "take" of dolphins besides live-capture for display or research; and
- human-caused mortality.

Our survey results suggest that over 230 dolphins may inhabit Tampa Bay at certain times but that the resident population is much smaller (probably less than 100).

The dolphins in the bay apparently produce few calves compared to other groups of dolphins surveyed.

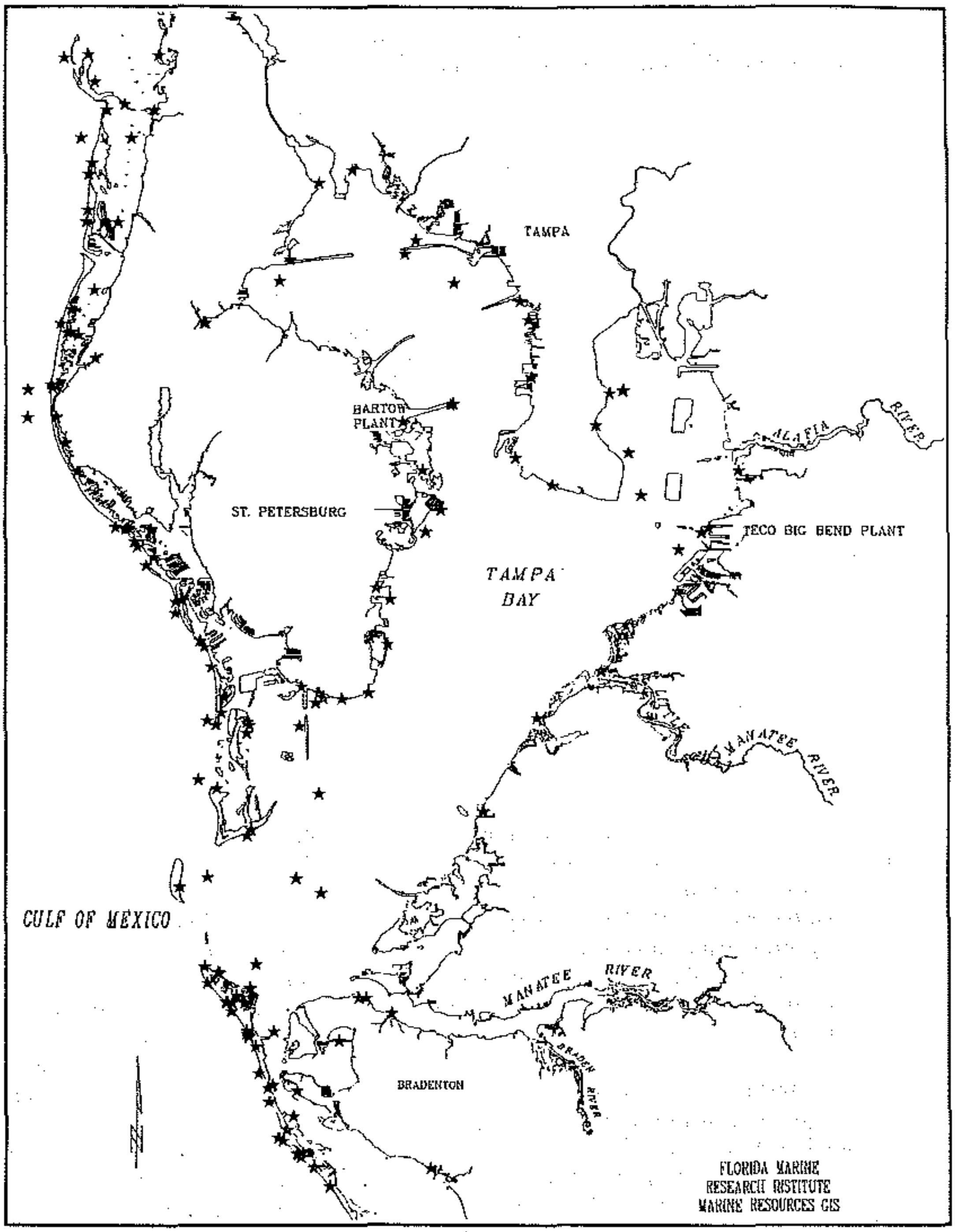

Figure 4. Locations where stranded bottlenose dolphins were recovered in the Tampa Bay area from 1980 to 1990 (data provided by Southeastern U.S. Marine Mammal Stranding Network).

To understand the status of a dolphin population, it is helpful to compare abundance and distribution data with mortality data (Southeastern U.S. Marine Mammal Stranding Network, unpublished data). From 1980 through 1990, the majority of reported strandings occurred along the Gulf beaches, especially near the mouth of Tampa Bay (Figure 4). Areas along the Gulf coast having the highest dolphin densities observed in this study (Figure 3) correspond with locations having high numbers of strandings (Figure 4). The number of stranded dolphins did not vary appreciably with season over the 1980-1990 time period (Figure 5); seasonal mean counts were not significantly different. Hillsborough County had the fewest reports of stranded dolphins, and Pinellas County had the most (Figures 5 and 6). Overall, the mortality and distribution data sets appear complementary.

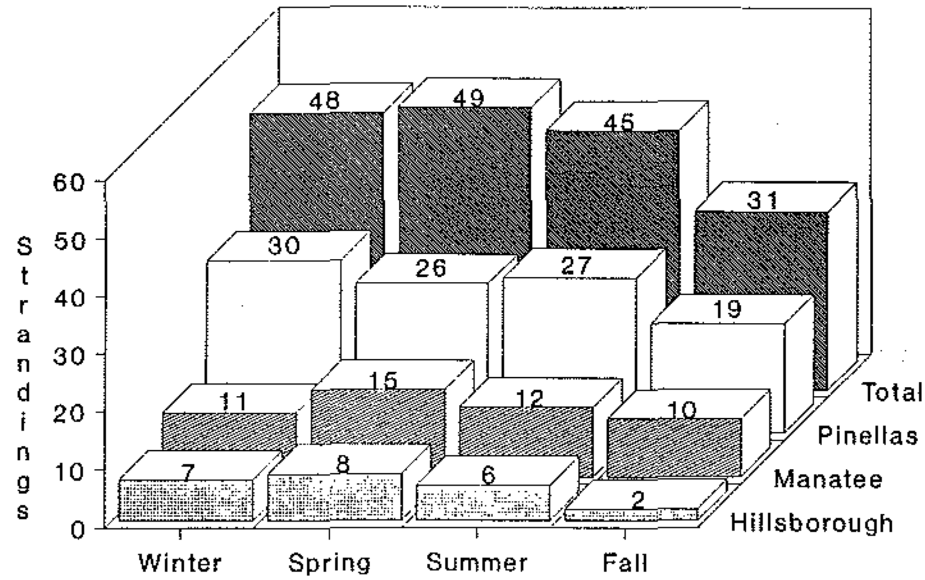

Figure 5. Seasonal strandings of bottlenose dolphins in the Tampa Bay area from 1980 to 1990 (data provided by Southeastern U.S. Marine Mammal Stranding Network).

A dramatic increase in the number of stranded dolphins has occurred since 1986 (Figure 6). Prior to 1986, the highest annual number of stranded dolphins reported was nine, whereas from 26 to 33 were reported annually between 1986 and 1990. Some of the increase is attributable to greatly expanded participation in the stranding network by biologists from Mote Marine Laboratory, Clearwater Marine Science Center, and the Florida Department of Natural Resources. Expanded participation alone probably does not account for the tripling of strandings because a mechanism for the public to report strandings through the Florida Marine Patrol has been in existence since the 1970s and has not substantially changed. Increased research is needed to determine factors that caused the apparent increase in mortality. Density of dolphin populations in Tampa Bay appears to be low compared to populations in the Indian River, Sarasota Bay, and other areas studied in the southeastern United States. The low frequency with which calves are observed, together with apparently rising dolphin mortality in the bay area, indicates that taking dolphins for any reason (e.g., harassment, live capture, incidental take by fishermen) should be minimized and that population monitoring should continue.

ACKNOWLEDGEMENTS

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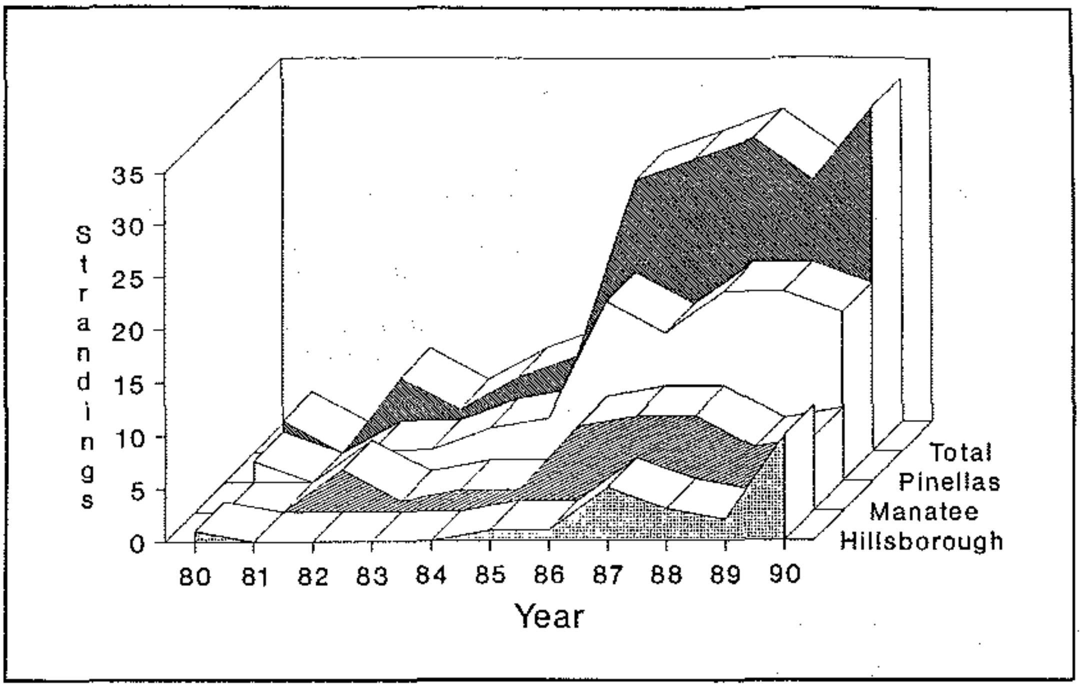

Figure 6. Yearly strandings of bottlenose dolphins in the Tampa Bay area from 1980 to 1990 (data provided by Southeastern U.S. Marine Mammal Stranding Network).

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ASSESSMENT AND MANAGEMENT OF MANATEES (*TRICHECHUS MANATUS*) IN TAMPA BAY

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ABSTRACT

Manatees in Tampa Bay have been studied in two primary ways. Since 1974, dead manatees have been recovered in Tampa Bay and elsewhere in Florida to determine cause and location of death, and to obtain specimens for anatomical research. Aerial surveys have periodically assessed manatee abundance and distribution in the bay since the late 1970s; most notably, since 1987 intensive and regular surveys have provided insight into manatee abundance, distribution, critical habitats, and seasonal or year-round high-use areas. Manatee mortality has risen from an average of 4.1 manatees in the decade from 1976-1985 to an average of 8.8 manatees per year in the period from 1986-1990. Human activities accounted for 8 manatee deaths between 1976 and 1985 but caused 11 manatee deaths between 1986 and 1990. The manatees in the bay are most abundant (up to 101 animals) and most aggregated in winter when they gather in warm-water discharges of power plants. The bay in winter contains 7% of the minimum observed population of 1465 manatees in the United States (Florida Department of Natural Resources [FDNR], unpublished data). Calves represent over 8% of the manatees observed during surveys of the bay. Manatees predictably frequent locations with critical resources—warm water in winter, fresh water, and abundant seagrass for food. Geographically-referenced data on manatee biology, together with data on habitat features and human activities, are incorporated into a Geographic Information System, a powerful computer system that allows easy visualization of locations in the bay where seasonal or year-round regulatory zones must be created to protect manatees directly, as well as critical habitat for manatees, and other important natural resources.

INTRODUCTION

Although the Florida manatee (*Trichechus manatus latirostris*) has been studied for several years in some areas of the state, studies in the Tampa Bay area have not been extensive. Aerial surveys conducted in the 1970s (Irvine and Campbell 1978, Irvine et al. 1981) indicated that manatees in Tampa Bay used warm-water effluents from power-generating stations as refugia from cold winter weather. Patton (1980) focused on manatee use of areas near power plants in aerial and boat surveys conducted in 1979 and early 1980; he documented over 50 manatees using those areas in winter. Subsequently, in a series of annual reports to Florida Power & Light Company, Reynolds (see, for example, Reynolds, 1990) provided some aerial counts of manatees using power plant discharge zones during winter from 1982-1990. Weigle (1983) did boat surveys of manatees using discharge zones in winter 1982-1983 at Gardinier Phosphate Company's plant (now Cargill Fertilizer Company) on the Alafia River and at Tampa Electric Company's (TECO) Big Bend power plant. Weigle et al. (1988) gave results of these surveys and stressed that a long-term database was needed "for managers to make well-informed decisions to protect the 60-80 manatees that utilize Tampa Bay habitats".

The lack of data on Tampa Bay manatees is only one reason for quickly assessing the population there. Human population growth in the Tampa Bay area occurred at an annual rate of 3% between 1980 and 1984 (Tampa Bay Regional Planning Council 1986). Rapid population growth in Florida coupled with inadequate plans to address effects of that growth (Reynolds and Gluckman, 1988) could easily lead to diminution of natural resources, including manatees, in the bay area. Lewis (1986) estimated that dredge-and-fill operations have eradicated 81% of Tampa Bay's seagrass communities (a primary food source for manatees) as well as 44% of the mangroves and tidal marshes. Knowledge of manatee distribution and abundance will permit managers to create appropriate regulatory zones to safeguard the animals and their critical habitat.

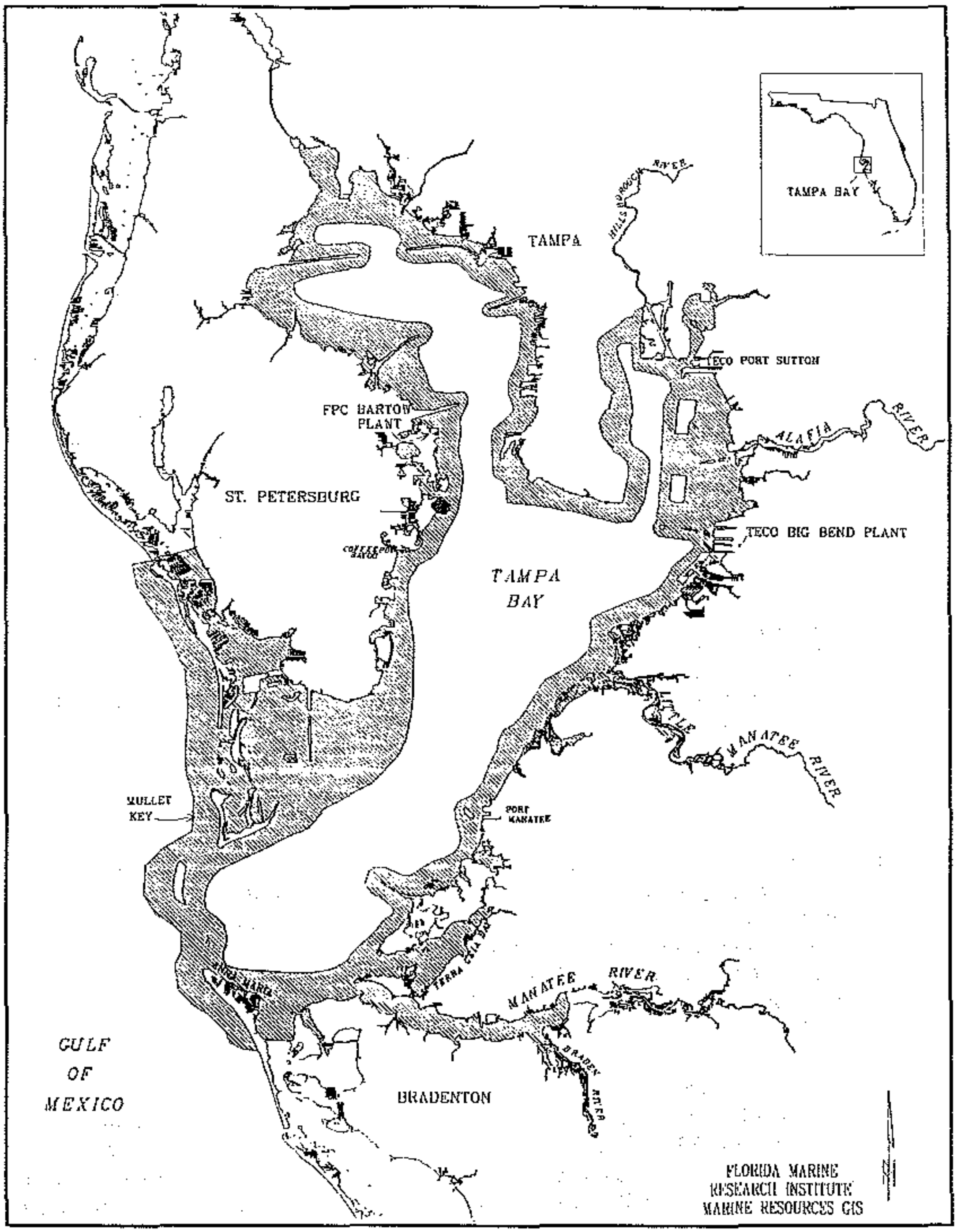

Figure 1. Map of areas covered during manatee aerial surveys in Tampa Bay, November 1987 to December 1990. Map also indicates locations of warm-water discharges.

To underscore the need for prompt action, one should note that the increase in human population size and human activities in Tampa Bay has apparently already influenced manatee mortality. From 1976 to 1985, 41 dead manatees were verified in the bay area (Beeler and O'Shea 1988), an average of 4 animals a year. Eight of the 41 (20%) died due to collisions with watercraft. Since 1986, the number of deaths has increased, with significant numbers dying of human-related causes (Florida Department of Natural Resources, unpubl. data), as described in this paper.

Our study was designed to assess manatee distribution, abundance, and high-use habitats in Tampa Bay. A combination of regular aerial surveys and intensive shore-based surveys at power plants in winter provided data that increased our knowledge of manatees in Tampa Bay, and allowed us to develop site-specific management recommendations to protect manatees and manatee habitat.

METHODS

Mortality

Since 1974, dead manatees have been recovered throughout Florida to determine cause and location of death and to obtain specimens for many kinds of research. An intensive carcass recovery program yielded 1737 manatee carcasses in Florida from 1974 through 1990. This is believed to represent a high proportion of all deaths, at least since salvage efforts intensified in 1976. Carcass recovery was coordinated by FDNR in 1985-90 (FDNR, unpublished data) and U.S. Fish and Wildlife Service in 1974-85 (O'Shea et al. 1985). The University of Miami also participated in 1974-80. Probable cause of death was determined when possible using thorough field and laboratory necropsies. Unfortunately, the advanced state of decomposition of many specimens sometimes precluded detailed examination. Cause of death could usually be determined based on gross examination of external wounds from boat propellers, flood gates, nets, etc., or internal evidence such as broken ribs, hemorrhage, depletion of fat stores, and other lesions. Cause of death was classified into six major categories, including "undetermined".

Aerial Surveys

Aerial surveys of manatees and dolphins in Tampa Bay have been flown since November 1987 and are continuing at present. Surveys were initially twice per month, but beginning in 1989 only one survey per month was flown between March and November. Data are reported here through December 1990. Each survey involved two Cessna 172 aircraft flying simultaneously, one covering each side of the bay (Figure 1). Each flight took about four hours per aircraft. Flights were made at an altitude of 150 meters (500') and an air speed of approximately 80-85 knots (150-160 km/hr, 90-100 mph). Reynolds or Houhoulis was primary observer in the aircraft that surveyed the western half of Tampa Bay; Weigle, Beeler, or Ackerman was primary observer in the aircraft that covered the eastern half. Results from dolphin surveys are presented by Weigle et al. (this volume).

The aerial surveys concentrated on nearshore areas of the bay (from the shoreline to about 1.0 km offshore (Figure 1). The aircraft proceeded along the shoreline by a series of circles designed to provide observers with adequate observation time to spot manatees. When manatees were spotted or suspected to be present, additional circles were made for as long as it took to obtain an accurate count. The most intensive circling occurred at the power plants during winter cold weather, when the manatees predictably sought refuge in the warm-water discharge zones.

Data were recorded when manatees were spotted, as in other aerial surveys of manatees (see, for example, Irvine 1982, Reynolds and Wilcox 1986). These data included total number of manatees present, number of calves present (defined as manatees less than half the length of a closely associated adult), the animals' behavior, including feeding, resting, or direction of travel, and their precise location. Photographs were taken to verify counts of groups of manatees. Observations were categorized into one of 21 geographic zones of the bay.

Sightings of manatees were recorded on photocopies of NOAA navigation charts (1:40,000 scale). Other data including time of day, air temperature, water clarity, and water surface conditions were also recorded on the maps. Following each survey flight, the data were entered into the FDNR Marine Resources Geographic Information System (MRGIS). The MRGIS uses pcArc/Info software (Environmental Systems Research Institute, Inc., Redlands, Calif.) and digitized shoreline base maps taken from U. S. Geological Survey quadrangles and National Oceanic and Atmospheric Administration navigation charts.

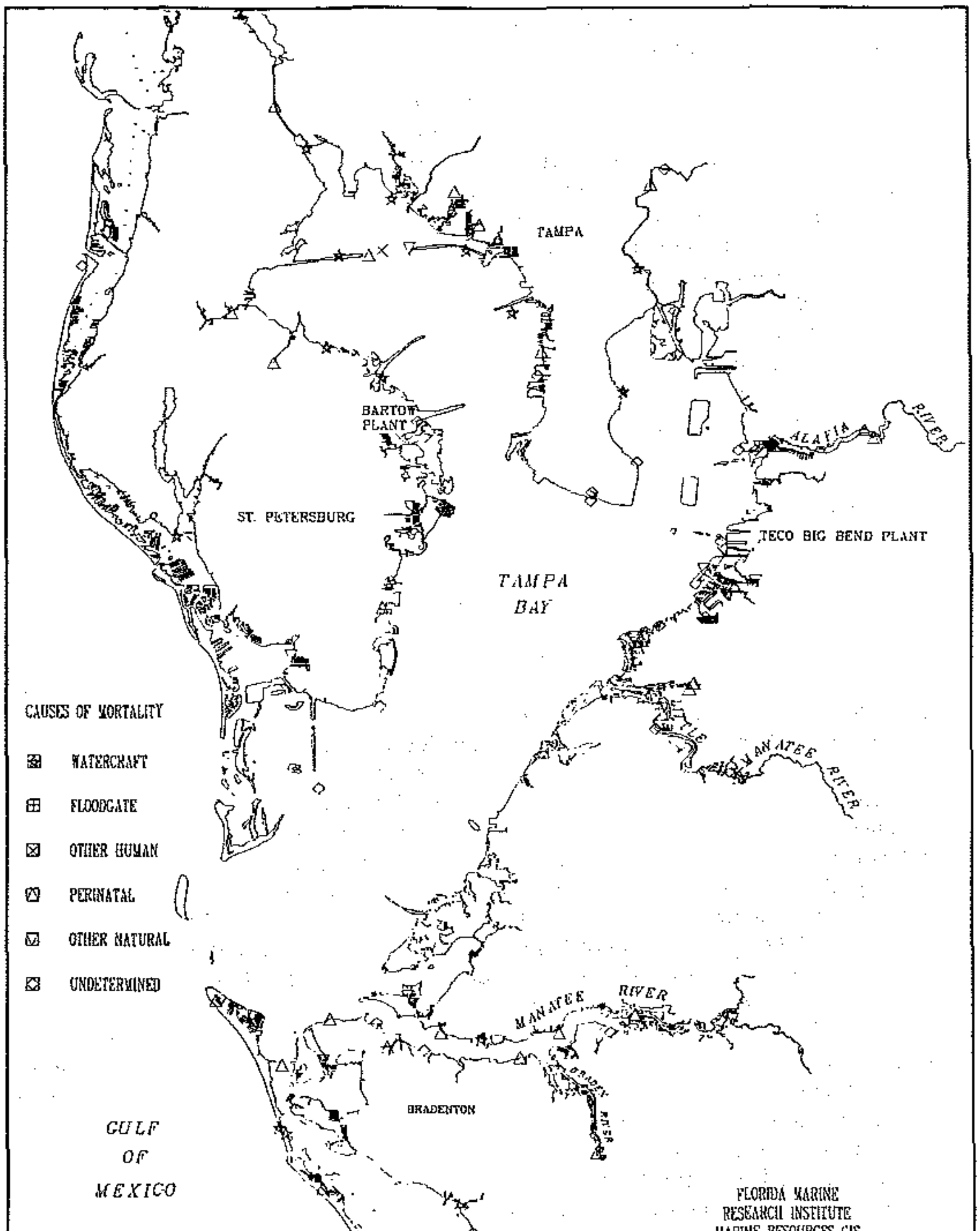

Figure 2. Map of manatee mortalities (n=41) in Hillsborough, Manatee, and Pinellas counties, 1976 to 1990. Symbols indicate six causes of death.

The database of manatee aerial survey sightings was combined using the GIS with other databases, including locations of recovered manatee carcasses, seagrass distribution and density, and locations of warm-water discharges, marinas, boat ramps, and freshwater sources. Combining these "layers" of data permitted easy identification of areas commonly used by manatees, locations of critical resources and habitats, and sites where human activities could be especially detrimental to manatees or to their critical resources.

Statistical tests of counts between time periods were made using analysis of variance procedures, including Duncan's multiple range test for multiple comparison of means (Proc GLM, SAS 1985).

RESULTS AND DISCUSSION

Mortality

From 1976 to 1985, 41 dead manatees were verified in the Tampa Bay area (Hillsborough, Manatee, Pinellas Counties; Beeler and O'Shea, 1988), an average of 4.1 animals a year (Table 1, Figure 2). Eight of the 41 (20%) died due to collisions with watercraft. From 1986 to 1990, 44 dead manatees were recovered in the bay area (an average of 8.8 animals per year), with 7 (16%) dying from watercraft collisions. These deaths represent 5.0% of the statewide total mortality of 1701 from 1976 through 1990. Tampa Bay watercraft deaths accounted for 24.8% of the statewide total during that period.

Between 1986 and 1990, four (9%) of the 44 deaths in Tampa Bay were from human activities other than boating, whereas in 1976-1985, no deaths in the bay area were attributed to any other human activities. Together, human activities resulted in eight manatee deaths between 1976 and 1985 (0.8/yr, 20% of total), but caused 11 manatee deaths between 1986 and 1990 (2.2/yr, 25% of total).

Aerial Counts

Aerial surveys of manatees were conducted from November 1987 to the present. Combined flight time for the two aircraft averaged about 7 hours per survey. Counts were analyzed through December 1990 for this report. A total of 2579 individual manatee sightings was made during 51 survey flights (mean=50.6) (Table 2, Figure 3). These sightings comprised 976 groups of manatees. The highest count (adults plus calves) was 101, while the lowest count was 15 manatees. Highest counts each year occurred between December and February, with lowest counts occurred between June and October.

Record high counts of 104 and 109 have subsequently occurred in January and February 1991, but are not included here. The count of 104, part of a statewide manatee survey on 17 and 18 February 1991 (FDNR, unpubl. data), represented 7.1% of the statewide count of 1465.

Counts were divided into two seasons, "cold" (December through February) and "warm" (March through November) months. These seasons were chosen to reflect the annual pattern of manatee movements in Tampa Bay. Manatees aggregated at warm-water sites from December through February (and to a lesser extent in adjacent months), then dispersed widely. Counts were significantly higher ($p=0.017$, $r^2=0.111$) in the cold season ($n=17$ flights, mean=60.1 manatees, range 28-101) than in the warm season ($n=34$, mean=45.8, range 15-81) (Table 3).

Counts were highly variable from flight to flight, due at least in part to varying weather conditions (Figure 3, Table 2). Low counts in summer may have reflected seasonal differences in visibility rather than being caused by emigration of manatees from the survey area (Table 4). Manatees become less easy to spot when they disperse widely in scattered groups throughout Tampa Bay, sometimes into areas with reduced water clarity. Search effort was also likely lower in areas away from the warm-water sites and other intensively used areas. While previous studies documented some movement by manatees to and from distant study areas on the west coast of Florida between winter and summer (Lefebvre and Frohlich 1986, Weigle et al. 1988), this may not be the general pattern. There is at present no strong evidence to indicate that large numbers of animals leave the bay in summer. Occasionally, high counts in summer even exceed the lowest winter counts (Table 2). Radiotelemetry studies began

Table 1. Manatee mortality by cause of death and year, for Tampa Bay area (Hillsborough, Manatee, Pinellas Counties), 1976-1990 (see text for sources of data).

	YEAR														
CAUSE OF DEATH	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	TOTAL
Watercraft collision			2		1		1		1	3	2		1	3	1	15
Flood gate/canal lock											2					2
Other human-related													1	1		2
Perinatal	1		2	2		1	1	1	2	2	2	4	4	3	5	30
Other natural						1		1	1	1		1	1	2	3	11
Undetermined	1	3	3	1	1	2	2	2		2	3				5	25
TOTAL	2	3	7	3	2	4	4	4	4	8	9	5	7	9	14	85

Description of cause of death categories:

Watercraft collision: Manatees hit by boats, barges, or any other type of watercraft. Death may result from propeller wounds, impact, crushing, or a combination of the above.

Flood gate/canal lock: Manatees killed by crushing or asphyxiation in flood gates and canal locks.

Other human-related: Manatee deaths caused by vandalism, poaching, entrapment in pipes and culverts, complications due to entanglement in ropes, lines, and nets, or ingestion of fishing gear or debris.

Perinatal: Manatees up to 150 cm in total length which were not determined to have died due to any human-related causes.

Other natural: Manatee deaths resulting from infectious and non-infectious diseases, birth complications, natural accidents, and natural catastrophes (such as cold stress and red tide poisoning). Manatees which die as a result of exposure to prolonged cold weather are usually emaciated and in a general state of malnutrition.

Undetermined: Manatee deaths in which the cause of death could not be determined. Rarely, deaths were reported and verified, but the carcass was not available for examination.

in February 1991 and will yield additional information on manatee movement patterns in Tampa Bay and into adjacent regions.

Total counts were inversely related to low ($p=0.003$, Figure 4) and high ($p=0.017$) daily air temperatures (measured at Tampa International Airport, U.S. National Climatic Data Center 1987-1990). Counts within the Big Bend zone were highly significantly correlated with daily low air temperature ($p=0.001$), indicating that this zone was most highly used in cold weather. Further comparisons of counts with water temperatures in the bay and at the TECO discharge, and with other environmental variables such as wind speed, cloud cover, and water clarity, are in progress.

Table 2. Results of aerial surveys of manatees in Tampa Bay, Florida, November 1987 through December 1990.

DATE	SEASON	QUARTER	GROUPS	ADULTS	CALVES	TOTAL	% CALVES
13NOV87	Warm	Fall	12	54	6	60	10.00
28NOV87	Warm	Fall	29	63	8	71	11.26
18DEC87	Cold	Winter	9	44	3	47	6.38
31DEC87	Cold	Winter	5	35	3	38	7.89
18JAN88	Cold	Winter	13	52	4	56	7.14
29JAN88	Cold	Winter	8	34	8	42	19.04
15FEB88	Cold	Winter	5	25	3	28	10.71
29FEB88	Cold	Winter	9	76	12	88	13.63
14MAR88	Warm	Spring	19	44	4	48	8.33
25MAR88	Warm	Spring	24	71	3	74	4.05
06APR88	Warm	Spring	28	60	6	66	9.09
18APR88	Warm	Spring	24	55	2	57	3.50
05MAY88	Warm	Spring	34	63	3	66	4.54
17MAY88	Warm	Spring	33	64	9	73	12.32
07JUN88	Warm	Summer	14	29	4	33	12.12
20JUN88	Warm	Summer	26	59	7	66	10.60
12JUL88	Warm	Summer	27	40	3	43	6.97
22JUL88	Warm	Summer	21	41	2	43	4.65
04AUG88	Warm	Summer	13	21	5	26	19.23
23AUG88	Warm	Summer	14	30	4	34	11.76
19SEP88	Warm	Fall	8	32	3	35	8.57
30SEP88	Warm	Fall	13	40	3	43	6.97
26OCT88	Warm	Fall	19	36	2	38	5.26
16NOV88	Warm	Fall	20	55	4	59	6.77
09DEC88	Cold	Winter	25	66	4	70	5.71
20DEC88	Cold	Winter	6	48	8	56	14.28
11JAN89	Cold	Winter	31	60	3	63	4.76
26JAN89	Cold	Winter	12	29	2	31	6.45
11FEB89	Cold	Winter	16	74	7	81	8.64
25FEB89	Cold	Winter	3	46	5	51	9.80
28MAR89	Warm	Spring	17	39	4	43	9.30
26APR89	Warm	Spring	10	24	2	26	7.69
24MAY89	Warm	Spring	20	44	2	46	4.34
20JUN89	Warm	Summer	11	16	1	17	5.88
20JUL89	Warm	Summer	12	16	1	17	5.88
25AUG89	Warm	Summer	14	24	4	28	14.28
29SEP89	Warm	Fall	10	26	4	30	13.33
27OCT89	Warm	Fall	21	27	4	31	12.90
29DEC89	Cold	Winter	28	84	5	89	5.61
10JAN90	Cold	Winter	29	63	6	69	8.69
09FEB90	Cold	Winter	30	65	6	71	8.45
02MAR90	Warm	Spring	32	58	5	63	7.93
18APR90	Warm	Spring	38	75	6	81	7.40
11MAY90	Warm	Spring	18	33	2	35	5.71
22JUN90	Warm	Summer	13	24	1	25	4.00
26JUL90	Warm	Summer	27	48	3	51	5.88
08AUG90	Warm	Summer	9	13	2	15	13.33
21SEP90	Warm	Fall	22	44	5	49	10.20
29OCT90	Warm	Fall	21	61	2	63	3.17
03DEC90	Cold	Winter	21	37	3	40	7.50
17DEC90	Cold	Winter	53	95	6	101	5.94

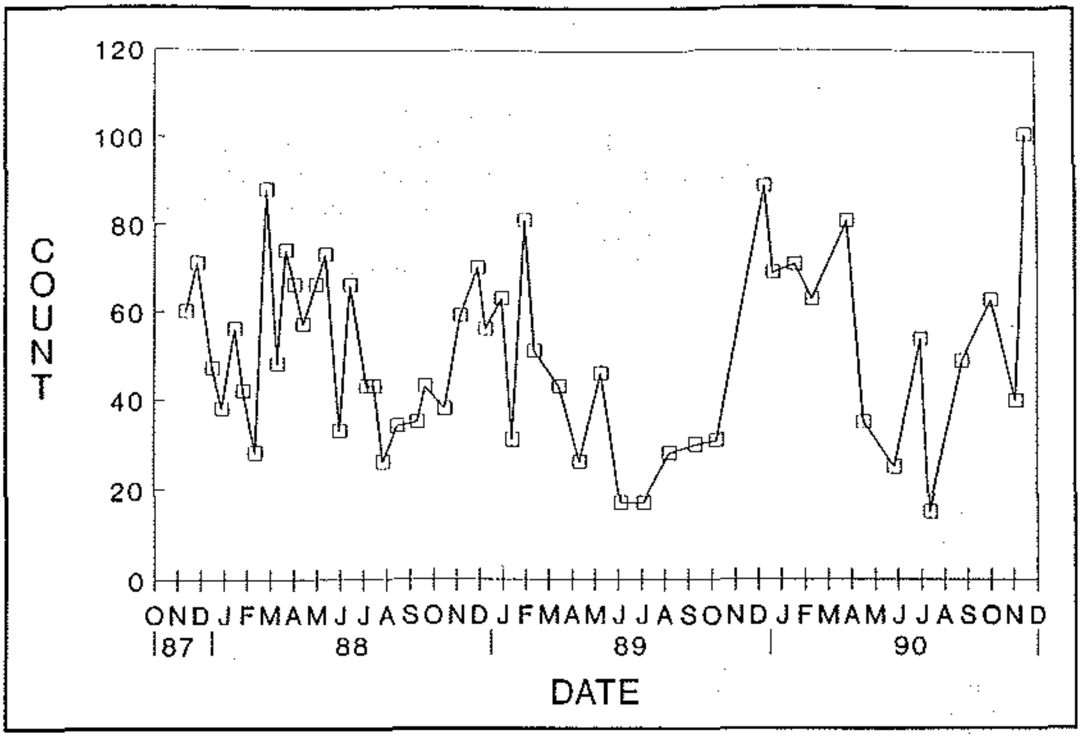

Figure 3. Counts of manatees during aerial survey counts (n=51) in Tampa Bay, November 1987 to December 1990.

Table 3. Results of aerial surveys of manatees, by seasons, in Tampa Bay, Florida, November 1987 through December 1990.

SEASON	N	MEAN	SE	MIN	MAX	% CALVES
Cold	17	60.1*	5.2	28	101	8.61
Warm	34	45.8	3.1	15	81	8.22
TOTAL	51	50.6	2.9	15	101	8.37

*Mean of cold season was significantly greater than warm season ($p=0.017$, $r^2=0.111$).

Table 4. Results of aerial surveys of manatees, by time periods, in Tampa Bay, Florida, November 1987 through December 1990.

SEASON	PERIOD	N	MEAN	SE	MIN	MAX	% CALVES
Warm	Nov 87	2	65.5	5.5	60	71	10.7
Cold	Dec 87 - Feb 88	6	49.8	13.7	28	88	11.0
Warm	Mar 88 - Nov 88	16	50.3	3.9	26	74	8.0
Cold	Dec 88 - Feb 89	6	58.7	8.5	31	81	8.2
Warm	Mar 89 - Nov 89	8	29.8	3.7	17	43	9.2
Cold	Dec 89 - Feb 90	3	76.3	6.4	69	89	7.4
Warm	Mar 90 - Nov 90	8	48.1	7.7	15	81	7.3
Cold	Dec 90	2	70.5	30.5	40	101	6.4
TOTAL		51	50.6	2.9	15	101	8.4

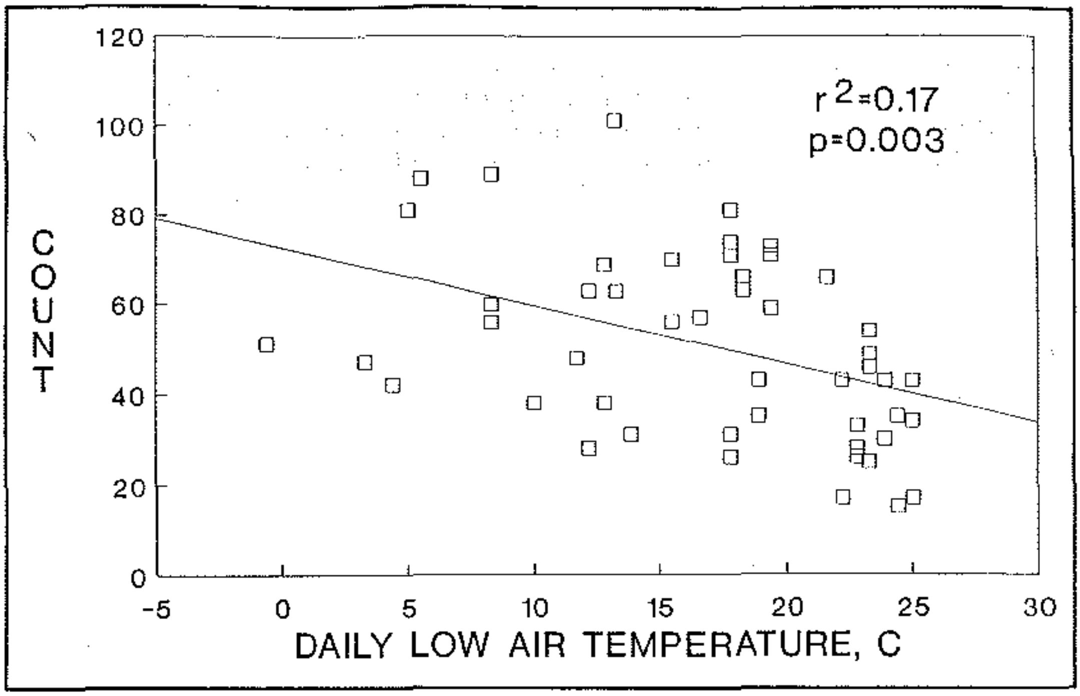

Figure 4. Counts of manatees during aerial survey counts (n=51) in Tampa Bay, November 1987 to December 1990, plotted against low air temperature (°C) at Tampa International Airport on the day of the survey (U. S. National Climatic Data Center 1987-1990).

Percent Calves

One to 12 calves were counted per survey (mean=4.2). The percent of calves seen per survey ranged from 3.5 to 19.2 (mean=8.4) (Table 2). High (>10%) percentages of calves were observed at least once in every month except March, April, and July. In August of each survey year, there was a noticeable increase in the percentage of manatees represented by calves, as compared to July.

Both the number of calves observed and the percent of calves were quite variable, but this was assumed to result from visibility biases as much as from actual changes in the number of calves present. Calves were defined as animals less than about half the length of the adult with which they were associated (Irvine 1982). This length is consistent with calves aged approximately up to six months. If the population is largely resident year-round and if breeding occurs year-round, it could be assumed that the number of calves does not actually change much from month to month. This suggests that visibility bias contributed to the observed differences in counts at least as much as actual changes in number of calves present.

It is interesting to note (Table 4) that the percentage of manatees that were calves appears to be dropping over time. A similar trend has been noted around Florida Power and Light Company power plants in eastern and southwestern Florida in the past four winters (Reynolds, unpublished data). This could be due to at least two factors: 1) the presence of fewer calves in the population, or 2) a change in the ability of observers to distinguish juveniles from calves. It would be very serious if there actually were lowered reproductive rates in some areas of the state, given the species' low population size and high mortality.

Distribution

In cold months, manatees were restricted by low water temperatures to the areas in the vicinity of three warm-water sources—the TECO Big Bend and Port Sutton power plants and Florida Power Corporation's (FPC) Bartow plant (Figure 5). On warm days, animals venture out to feed several kilometers from each site. The Port

Sutton and Bartow plants appear to be used early and late in winter, or during warm periods within winter when water temperatures are not extreme. The Big Bend plant is used most when water temperatures are low, likely because the large discharge canal maintains warmer water temperatures with less dilution by surrounding waters. Of the 21 defined zones in Tampa Bay, counts in the zones containing these three power plants included 83.7% of manatee sighted in the cold season.

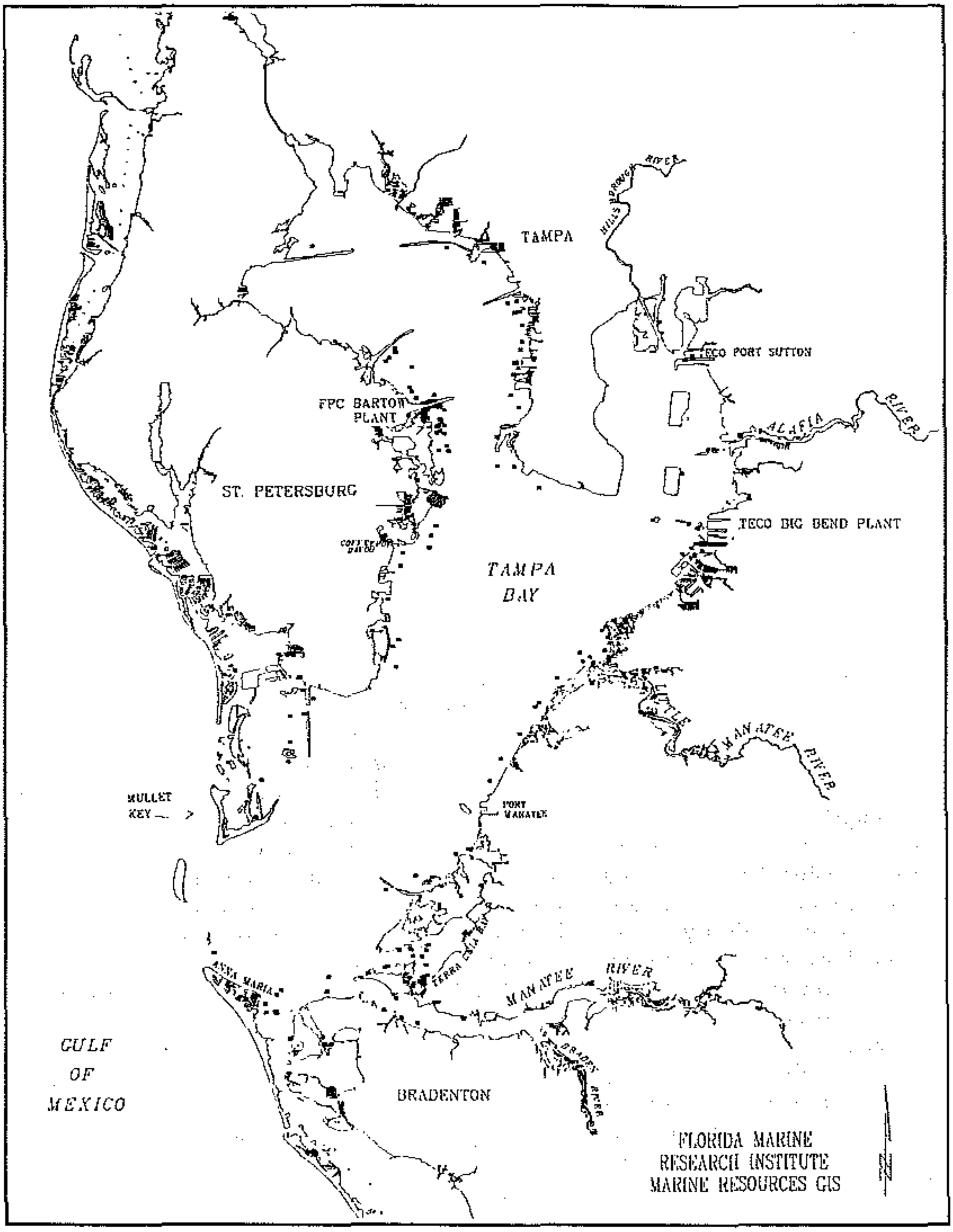

Figure 5. Map of manatee groups sighted during manatee aerial surveys (n=17) in the cold season (December through February) in Tampa Bay, November 1987 to December 1990. Note that in the discharge canals at Tampa Electric Company's Big Bend Power Plant and Florida Power Corporation's Bartow Power Plant, hundreds of groups of manatees in winter are plotted together.

In warm months, manatees were found in many areas around the bay and up tributary rivers (Figure 6). Highest counts occurred in the Old Tampa Bay, Big Bend, Terra Ceia Bay, North St. Petersburg, and Manatee River zones. Together, these zones comprised 77.5% of manatees sighted in the warm season. Areas from Apollo Beach to the Little Manatee River were most used in late winter and spring, since these offered seagrass beds near the warm-water refuge at the Big Bend plant. Manatees return to the plant when temperatures drop for a few days in late winter and spring. In summer, animals are distributed widely around the bay. Some animals leave the bay for areas to the north and south, while other animals arrive from the south (Lefebvre and Frohlich 1986, Weigle et al. 1988).

MANAGEMENT RECOMMENDATIONS

Human-related manatee mortality, primarily due to watercraft collisions, and the destruction of essential manatee habitat must be effectively managed in order to protect manatees in Tampa Bay. Geographic Information System mapping of manatee distribution and mortality data and seagrass density and distribution facilitates the making of regulatory recommendations for manatee and habitat protection (Reynolds and Haddad 1990).

In Tampa Bay, a 300-m wide (1000′) slow-speed (8-11 km/hr, 5-7 mph) shoreline buffer is recommended for the entire upper and lower bay along the shorelines of Pinellas, Hillsborough and Manatee counties (Figure 7). The western boundary in the Gulf of Mexico is an arc connecting the northern tip of Anna Maria Island with Pass-a-Grille Beach. The buffer zone also includes the inshore waters of southwest Manatee County and the inshore waters of Boca Ciega Bay, north of Pass-a-Grille Beach in Pinellas County. In areas of the bay with dense seagrasses and heavy manatee usage, the buffer zone should be widened to as much as approximately 1500 m (5000′). The proposed buffer zone will apply to all creeks, rivers, bays, and bayous connected to Tampa Bay. This buffer zone will cover approximately 70% of the manatee aerial survey sightings and 50% of the seagrass beds. Navigation channels that are heavily used by boaters and less used by manatees may be exempted from the slow-speed buffer zone, but a maximum speed limit of 40 km/hr (25 mph) is recommended for these channels.

Manatees predictably frequent locations with critical resources such as warm water in winter, fresh water, and abundant seagrass for food. Key areas for manatees around the bay which provide these critical resources include:

- Warm-water outfalls at FPC's Bartow power plant, TECO's Big Bend and Port Sutton power plants, and the Gardinier Phosphate Company plant (now Cargill Fertilizer Company)
- Coffeepot Bayou
- Hillsborough River
- Portions of the Little Manatee and Manatee Rivers
- Braden River
- Terra Ceia Bay
- Anna Maria Sound

In these essential habitat areas, site-specific protection measures are necessary to adequately protect manatees and their habitat while also addressing the recreational uses of these waterways.

The TECO Big Bend power plant in Hillsborough County is a major warm-water aggregation site, with a high count of 94 manatees observed during one winter aerial survey (Figure 8). A winter (November 15-March 31) idle and no-entry zone was implemented in the discharge canal in 1986. TECO implemented a year-round no-entry zone for the discharge canal in 1989, based on increasing use by manatees. In 1986, the company built a manatee observation platform along the south and east sides of the discharge canal.

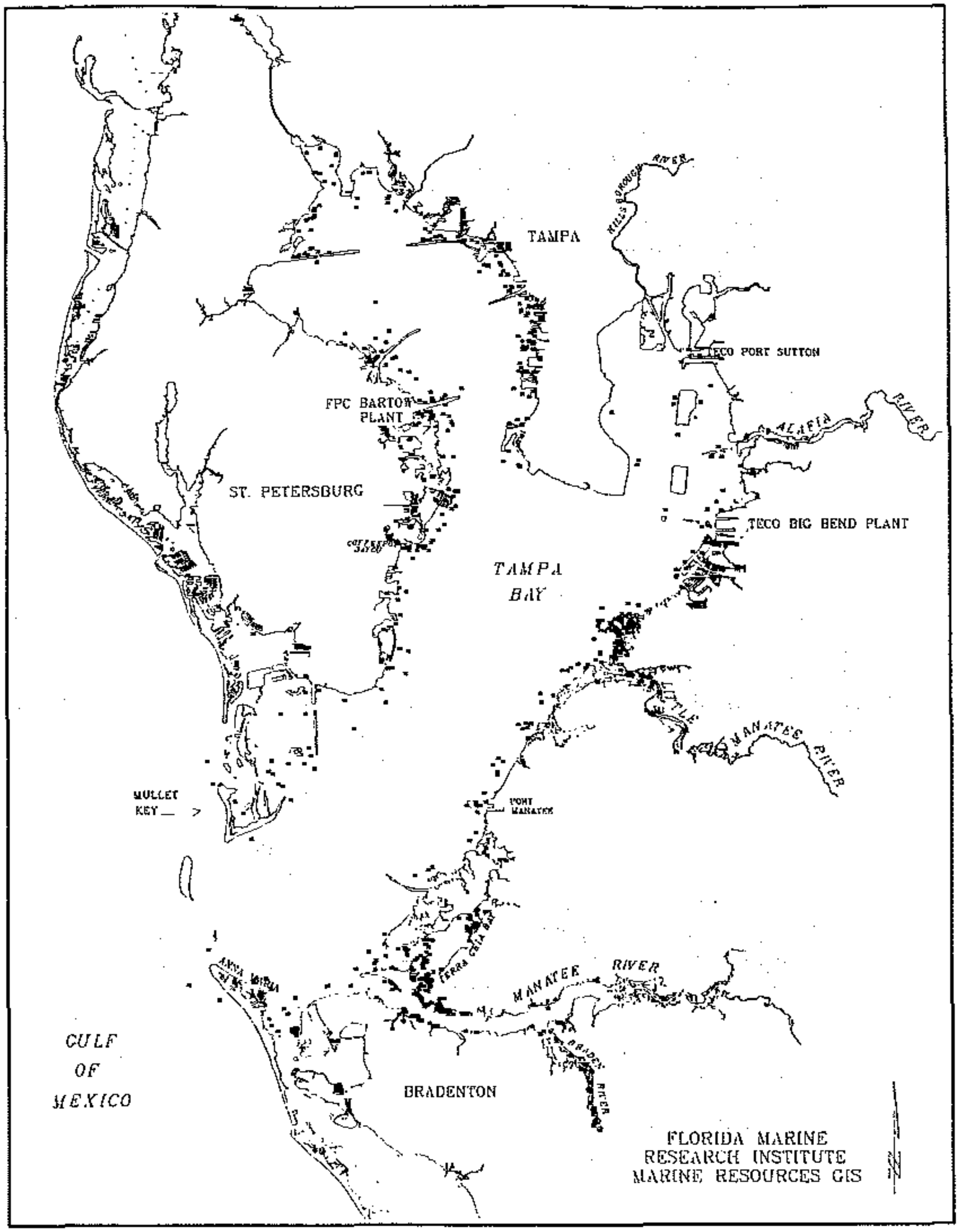

Figure 6. Map of manatee groups sighted during manatee aerial surveys (n=34) in the warm season (March through November) in Tampa Bay, November 1987 to December 1990.

A maximum of 50 manatees has been observed at the FPC Bartow power plant in Pinellas County during a winter aerial survey (Figure 9). A no-entry area which would exclude boats and people is recommended for the north-south channel leading to the plant's discharge canal and the surrounding grassbeds from November 15 to March 31. The east-west channel along the southwest shore of the Gandy Bridge causeway is heavily used by both boats and manatees and should be regulated as slow-speed from November 15 to March 31. During non-winter months, when fewer manatees are in the vicinity of the Bartow plant, the north-south channel and grassbeds should be regulated as slow-speed within the shoreline buffer zone and the east-west channel should have a maximum speed limit of 25 mph.

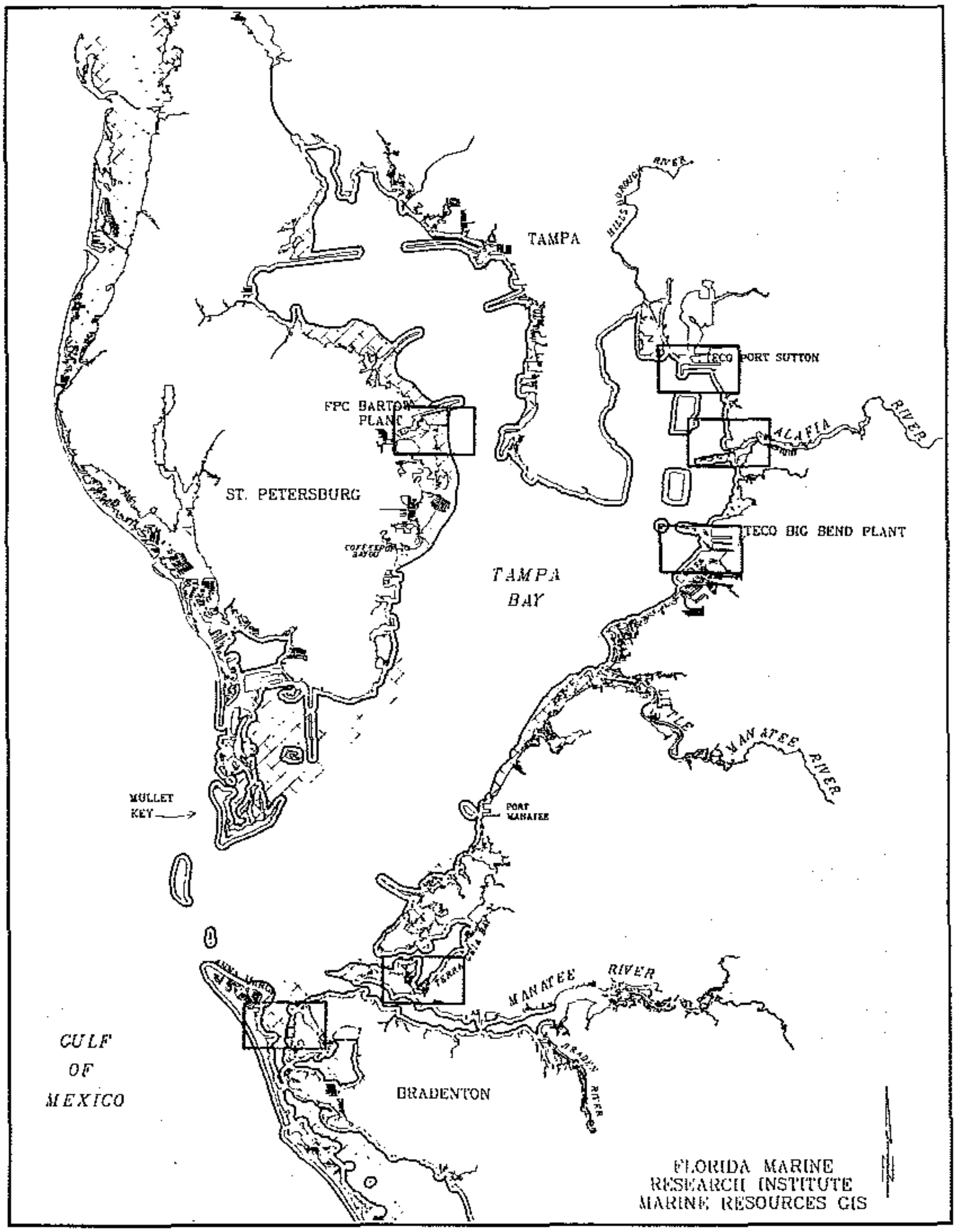

Figure 7. Map of recommended manatee protection zones with proposed 300-m wide slow-speed shoreline buffer zone in Tampa Bay. Map also shows areas with submerged aquatic vegetation. Six boxes indicate protection zones shown in greater detail in Figures 8-13.

The TECO Port Sutton power plant is a minor winter aggregation site for manatees in Upper Tampa Bay (Figure 10). A maximum of 10 manatees has been observed during a winter aerial survey. A no-entry zone is recommended for the small discharge canal at Port Sutton from November 15 to March 31. Access to the discharge canal will be allowed to riparian land owners. A year-round slow-speed zone is recommended for the entire Port Sutton canal, adjacent to the discharge canal.

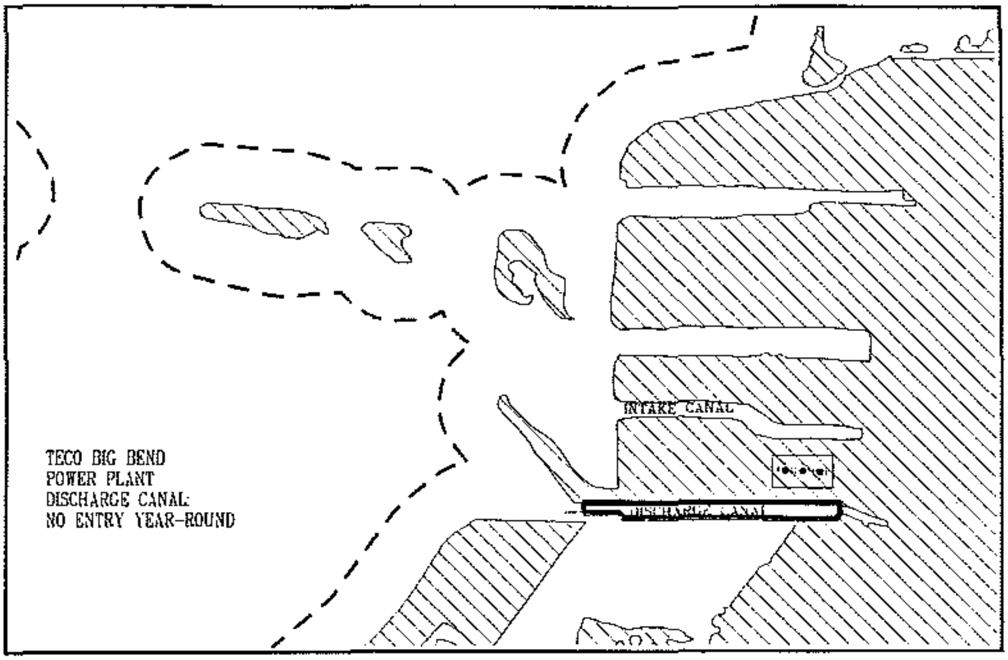

Figure 8. Map of recommended manatee protection zone (no-entry, year-round) at Tampa Electric Company's Big Bend Power Plant, Tampa Bay.

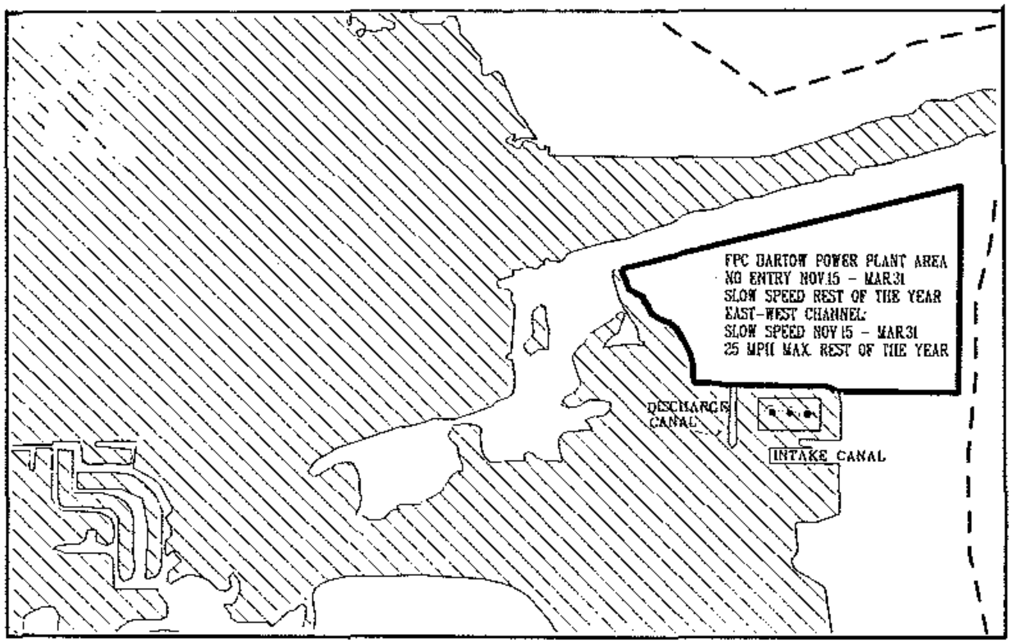

Figure 9. Map of recommended manatee protection zone near Florida Power Corporation's Bartow Power Plant, Tampa Bay (see text for proposed regulations).

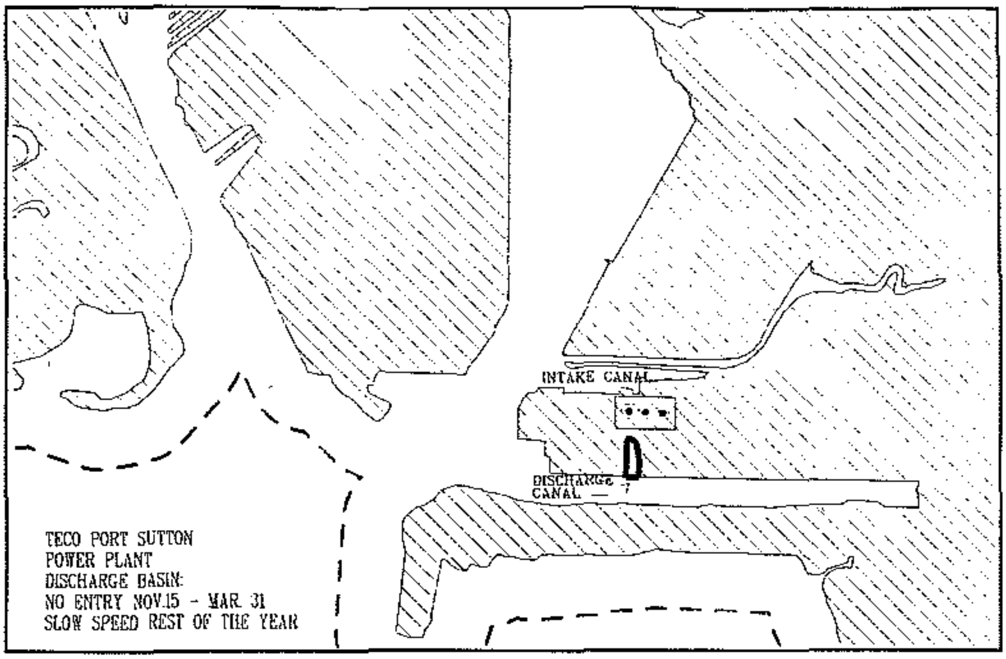

Figure 10. Map of recommended manatee protection zone (no-entry, Nov. 15 - Mar. 31) at Tampa Electric Company's Port Sutton Power Plant discharge basin, Tampa Bay.

The Gardinier Phosphate Company plant (now Cargill Fertilizer Company) located on the Alafia River was the major wintering area for manatees in Tampa Bay prior to 1986 (Figure 11). In 1985, a high count of 60 manatees was observed at the plant during one aerial survey, but use of this warm-water source decreased in 1986 with a reduction in the effluent flow. It is now a minor winter site. The Alafia River has been regulated as a speed zone since 1978, with a slow-speed channel leading from Tampa Bay to the river and idle-speed zones in the discharge basin and the Alafia River up to the Highway 41 bridge. FDNR plans to reduce the current speed restrictions to reflect the zone's decreased use by manatees. New recommendations include:

- The marked channel leading from the north-south shipping channel to channel markers 13 and 14 at the mouth of the Alafia River should have a maximum speed limit of 25 mph year-round.
- The Alafia River from markers 13 and 14 to the Highway 41 bridge and the plant discharge basin should be slow-speed in the winter (November 15-March 31).
- The Alafia River from markers 13 and 14 to the Highway 41 bridge should be slow-speed channel-exempt during the remainder of the year, with a maximum speed limit of 25 mph in the channel.

Manatees are frequently seen drinking at a freshwater discharge site in the western portion of Coffeepot Bayou in St. Petersburg. This portion of the bayou is currently regulated as an idle-speed zone. The rest of the bayou and the channel leading into the bayou should be a slow-speed zone year-round.

Sulphur Springs, a freshwater spring on the upper Hillsborough River, also attracts manatees, which are frequently observed traveling up and down the river. The entire Hillsborough River up to the dam (except for the existing idle-speed zone) should be slow-speed under the 300-meter shoreline buffer. A new boat ramp is proposed for the river, close to its mouth. By providing a boat-launching facility closer to boaters' final destinations, there should be less boat traffic down the river from the existing boat ramps at Lowry Park. A slow-speed zone in the Hillsborough

River should provide additional incentive to boaters to use the ramp closer to Hillsborough Bay.

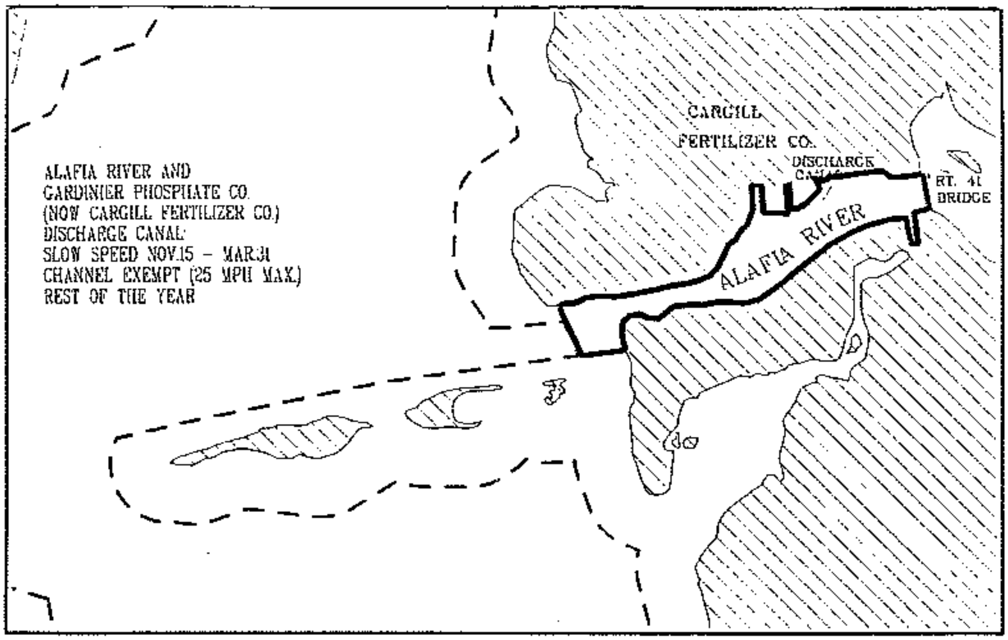

Figure 11. Map of recommended manatee protection zone (slow-speed, Nov. 15 - Mar. 31, channel-exempt, 25 mph maximum) in the Alafia River, Tampa Bay, near Gardinier Phosphate Company's (now Cargill Fertilizer Co.) plant (see text for proposed regulations).

The lower Little Manatee River has many manatee sightings and should be slow-speed year-round up to Hayes Bayou. Upstream of Hayes Bayou there are fewer sightings and this portion of the river is recommended for a maximum 25-mph speed limit year-round.

The shoreline buffer zone on the Manatee River is similarly recommended to end at the Interstate 75 Bridge. There is little manatee use but considerable waterskiing in the upper part of the river.

In the Braden River, it is recommended that a non-dredged, shallow-water channel be marked. The river should then be regulated as slow-speed, channel-exempt, with the channel having a maximum speed limit of 25 mph.

Manatees have been observed year-round at a sewage treatment discharge pipe in the southeast corner of Terra Ceia Bay, drinking from the pipe and feeding on the nearby grassbeds (Figure 12). An area-specific, year-round no-entry zone is recommended, which would provide protection for manatees at the pipe and at nearby seagrass beds without significantly impacting local boating use.

Similarly, in the southeast portion of Anna Maria Sound, west of Perico Island, an area-specific, year-round no-entry zone is recommended (Figure 13). There is a small area, approximately 6 m (20′) deep, where manatees are frequently observed. Grassbeds in the vicinity of the deeper water are heavily used by manatees and should be incorporated into the no-entry area.

The manatee speed zone recommendations presented in this paper will be passed on to the local governments concerned. During the 1990 legislative session, local governments gained the authority under the Manatee Sanctuary Act to implement manatee protection zones through local ordinances. The final proposals must be submitted to FDNR for approval and once they are approved, the local government can move forward with zone adoption.

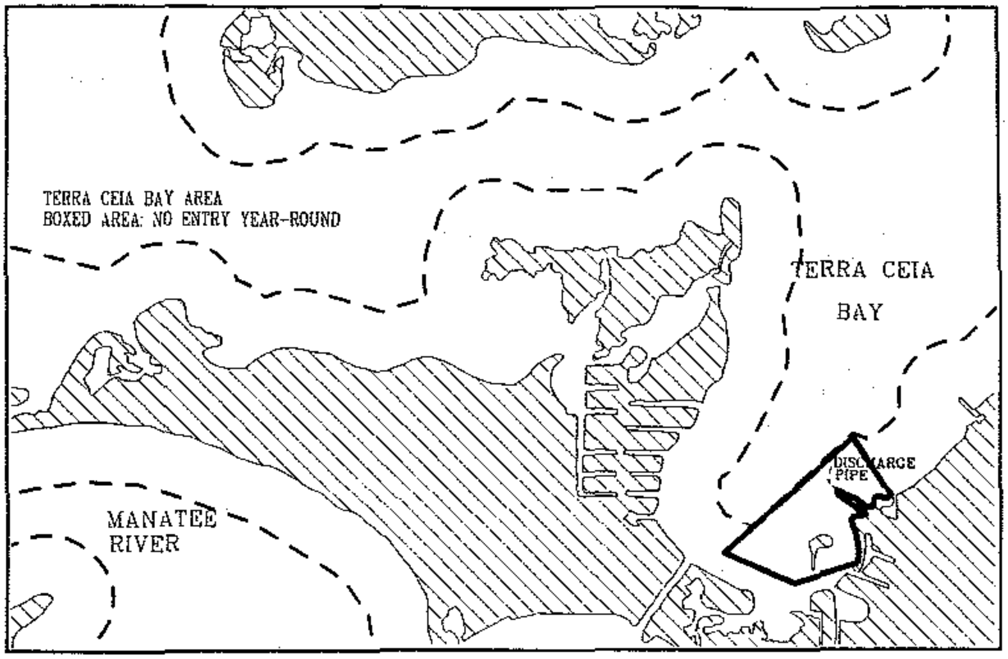

Figure 12. Map of recommended manatee protection zone (no-entry, year-round) in Terra Ceia Bay, Tampa Bay.

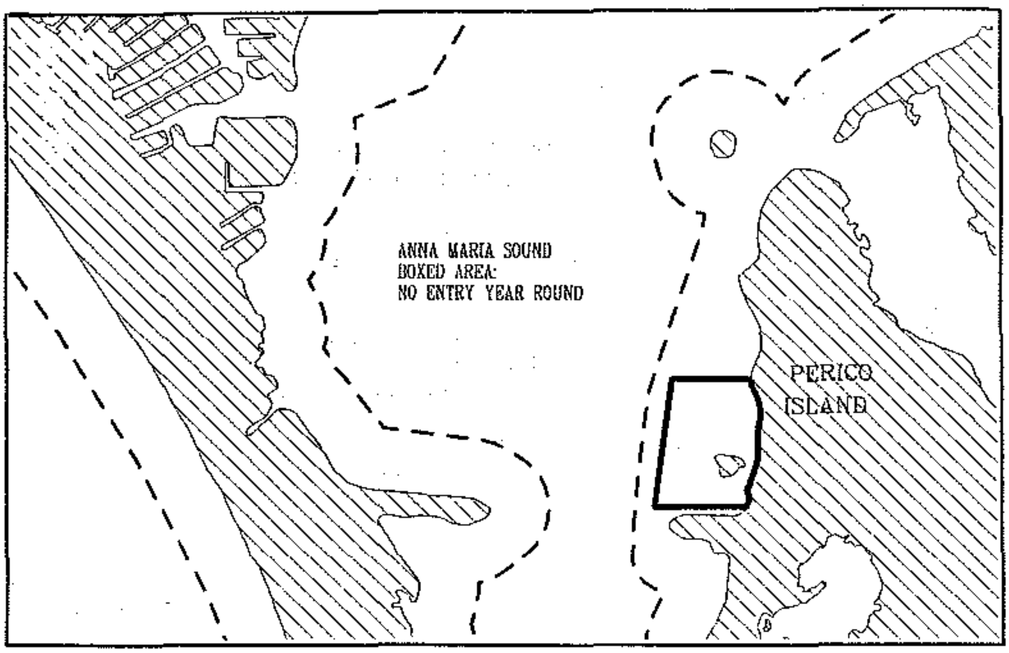

Figure 13. Map of recommended manatee protection zone (no-entry, year-round) near Perico Island in Anna Maria Sound.

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DIRECT ENUMERATION OF VIRUSES IN TAMPA BAY AND SURROUNDING WATERS

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S. C. Jiang
J. B. Rose

ABSTRACT

Determination of the abundance of viruses in surface waters is important as an indicator of water quality (i.e., coliphage abundance) and as a measure of specific health hazards (i.e., presence of hepatitis A virus, poliovirus, and others). The enumeration of viruses in surface waters has been performed in the past by cultivation on particular hosts. Although these methods yield information on particular types of viruses present, only the cultivatable viruses are enumerated. Recent evidence suggests that the numbers of viruses in aquatic environments are four to seven orders of magnitude greater than determined by cultivation on hosts. These viruses may play a significant role in aquatic ecosystems by controlling bacterioplankton and phytoplankton populations. We have developed a method for the concentration of viruses from surface waters by vortex flow filtration. This process had an overall efficiency of 69-77% as determined by concentration of T2 phage from sterile seawater. Viral preparations concentrated in this fashion could be accurately enumerated by transmission electron microscopy. During the summer of 1990, viral concentrations were determined in surface waters from the Bahamas, the southeastern Gulf of Mexico, and Tampa Bay using this technology. Viral concentrations ranged from 2.4×10^5/ml for the oligotrophic Gulf of Mexico surface waters to 3.4×10^7/ml for Bayboro Harbor in Tampa Bay, and were correlated with bacterial abundance. The methodology developed here for the concentration of viruses for direct enumeration may also be applicable to the detection and quantification of pathogenic viruses and other microbial pathogens from estuarine waters.

INTRODUCTION

The occurrence of viruses, and bacteriophages in particular, in the marine environment has been known for some time (Zobell 1946; Spencer 1955, 1960; Carlucci and Pramer 1960; Wiebe and Liston 1968; Hidaka 1971, 1977; Baross et al. 1978a, b; Moebus 1980). Accurate methods to enumerate total viruses, akin to methods for direct enumeration of bacteria (Francisco et al. 1973, Hobbie et al. 1977), did not exist prior to 1989 and estimates based on plaque assays on defined hosts implied that their occurrence was infrequent or sporadic. Semiquantitative observations by transmission electron microscopy (Johnson and Sieburth 1978, Annual Meeting of the American Society for Microbiology, Abst. N95; Sieburth 1979; Torrella and Morita 1978) suggested that viruses were abundant in the marine environment. Using ultracentrifugation to concentrate viruses from natural waters, Bergh et al. (1989) reported viral abundances in natural water as high as 2.5×10^8/ml, or 10^3 to 10^7 times more than had been reported based on plaque assay. These observations have since been corroborated by other investigators using other methods to concentrate viruses (Procter and Fuhrman 1990, Bratback et al. 1990, Borsheim et al. 1990, Suttle et al. 1990).

We have adapted vortex flow filtration (VFF) technology to the simultaneous concentration of viruses and free (soluble) DNA from the dissolved (<0.2 µm) fraction of freshwater and marine environments. Vortex flow filtration is a filtration technology based upon Taylor vortices (Taylor 1923). Taylor vortices are established in a vortex flow filtration device by rotation of a cylindrical filter inside a second cylinder.

In this report, we demonstrate the application of this technology to the concentration of viruses and dissolved DNA in marine and freshwater samples. Additionally, we report some preliminary findings on the detection of coliphage and animal viruses concentrated by VFF from marine sewerage outfalls.

MATERIALS AND METHODS

Field sampling sites. Freshwater samples were collected from the Medard Reservoir, Valrico, Fla. Estuarine surface water samples were taken from Tampa Bay at Bayboro Harbor, North Shore Park, and the Pier at St. Petersburg, Fla. Samples were taken in the southeastern Gulf of Mexico and the Dry Tortugas during a research cruise aboard the RV *Pelican* June 22-29, 1990. During a second research cruise aboard the RV *Cape Hatteras* (#CH-12-90), water samples were taken in the Atlantic Ocean near Miami, in Northwest Providence Channel, Bahamas, and near Mama Rhoda Rocks, Chub Cay, Bahamas.

Recovery of T2 Phage and Calf Thymus DNA from Artificial Seawater. T2 phage (final concentration ~10^8/ml) or calf thymus DNA (10 to 30 µg/l) was added to two or three liters of autoclaved, sterile filtered artificial seawater (ASWJP; Paul 1982). Phage titers were determined immediately after addition to seawater prior to VFF and after concentration by VFF. DNA content in concentrated samples was determined by the fluorometric Hoechst 33258 method (Paul and Meyers 1982).

VFF Concentration of Samples. A Benchmark rotary biofiltration unit (Membrex Inc., Garfield, N.J.) was used for VFF concentration of samples. The system was set up in the recirculation configuration (Fig. 1) using either a 200 cm^2 or 400 cm^2 filter. The 400 cm^2 filter allowed a greater sample filtration rate. Filtration was performed at 7 to 8 PSI for the 100 kd and 10 to 12 PSI for the 30 kd filters with a filter rotation speed of 2000 rpm (200 cm^2 filter) or 1500 rpm (400 cm^2 filter). The retentate was fixed with 2% glutaraldehyde and further concentrated for transmission electron microscopy (TEM) by ultracentrifugation for 90 min @ 70,000 x G.

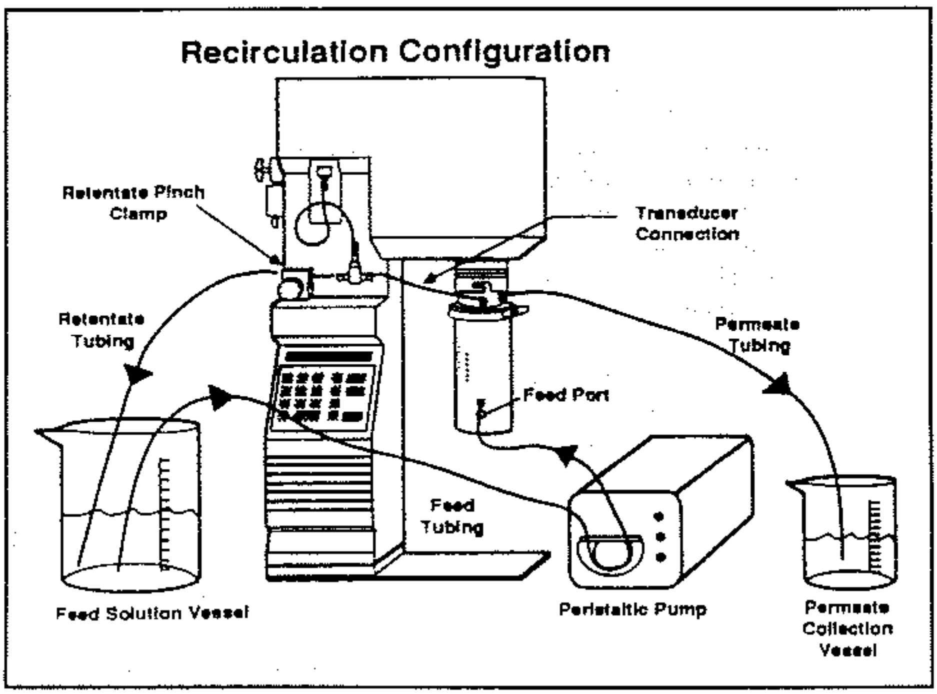

Figure 1. Benchmark vortex flow filtration device used to concentrate viruses and dissolved DNA from the marine environment. The sample is added to a feed solution vessel, and pumped by peristaltic pump through the feed port to the filter chamber. The filtrate (termed permeate) goes to waste, and the viruses retained by the filter (termed retentate) return to the feed solution vessel. This apparatus has been successfully employed to concentrate viruses from 3 to 1000 l to 25 ml. A larger industrial version is also available, capable of processing ~1000 liters.

Enumeration of Viruses — Transmission Electron Microscopy. VFF-concentrated samples were diluted with DI to decrease salt content and one µl was spotted onto a Formvar-coated copper grid and allowed to dry. The samples were stained with 2% uranyl sulfate (Polysciences, Warrington, Penn.), allowed to dry, and viewed with a Hitachi H500 TEM.

Coliphage and Animal Virus Studies from Marine Outfalls. Samples were taken from the northern Dade County outfall (306 l) and from Hookers Point (40 l) and concentrated to 50 ml by VFF. Volumes of 1.0, 0.1 and 0.01 ml were assayed for coliphage by the agar overlay method using *E. coli* or assayed for human enteroviruses using brilliant green monkey kidney continuous cell lines.

RESULTS

Efficiency of VFF

The results of efficiency studies using the Membrex Benchmark VFF device and artificial seawater appear in Table 1. The efficiency of virus concentration (two to three liters seawater to 15 ml) ranged from 68% to 81% (mean = 72.8 ± 5.7%), with no difference observed between the 30 and 100 kd filters. If viral enumeration was required only, then the 100 kd filter was used, which filtered at a flow rate approximately three times that of the 30 kd filter.

Evaluation of Viral Enumeration Techniques

The results of evaluation of three methods for viral enumeration appear in Table 2. In cell-free lysates, DAPI direct counts of T2 were approximately the same order of magnitude (within a quarter log unit) of the plaque titer. The TEM counts of T2 were generally closer to the plaque assays (δ % = 21.2 ± 3.65) than DAPI counts. Enumeration of viruses by DAPI counts in natural waters resulted in values considerably lower than those obtained by TEM. For all environmental samples when viruses were enumerated, counts were made by TEM.

The effect of 0.2 µm filtration on viral abundance was investigated using T2 phage in artificial seawater and in natural water samples (Table 3). The effect of filtration on T2 abundance was variable, decreasing plaque titers in filtered samples by 49.1 to >99% (mean decrease of 78.9%). The effect on natural phage populations was also variable, having either no effect or decreasing phage counts by ~90%. For all data, the average phage abundance was only 34% of the unfiltered samples.

Table 1. Comparison of filtration efficiency of the Membrex Benchmark system using sterile artificial seawater.

SAMPLE DATE	FILTER RETENTION CUTOFF (kd)	INITIAL TITER OR DNA CONC. (10^7/ml or µg/l)	FINAL TITER OR DNA CONC. (10^7/ml or µg/l)	EFFICIENCY (percent)
T2 Phage[1]				
3/7/90	100	10	8.1	81
7/24/90	100	11.7 ± 2.6	8.4 ± 3.6	72
7/12/90	30	20.8 ± 2.3	14.1 ± 6.6	68
7/24/90	30	11.7 ± 2.6	8.2 ± 2.4	70
Calf Thymus DNA[2]				
3/13/90	100	30	3.54	12
6/7/90	50	20	3.91	20
3/19/90	30	30	23.7 ± 1	79
6/7/90	30	20	15.9	80

[1]T2 phage recovery was from two or three liters autoclaved, sterile filtered seawater, and phage titer determined by plaque assay.
[2]Calf thymus DNA was added as two or three liters autoclaved, sterile filtered seawater, and the DNA content determined fluorometrically using Hoechst 33258 (Paul and Meyers 1982).

Table 2. Comparison of methods to enumerate phage particles (10^6 viruses/ml ± SD). Values in parentheses are percent plaque assay values.

EXPERIMENT OR SAMPLE	PLAQUE ASSAY	ENUMERATION BY: TEM	DAPI DC
A. T2 phage in cell-free lysates[1]			
Expt 1	41,000 ± 11,000	ND	50,400 ± 2100 (123)
Expt 2	29,000 ± 3,600	ND	18,000 ± 2100 (62.1)
Expt 3	35,000 ± 700	ND	22,000 ± 2200 (68.9)
B. T2 Phage in artificial seawater[2]			
Expt 4	71.7 ± 7.0	85.9 ± 9.9 (120)	29.2 ± 6.6 (40.7)
Expt 5	82 ± 24.2	67.0 ± 17 (81.7)	114.0 ± 19 (139)
Expt 6	84.2 ± 36.0	62.9 ± 55.6 (74.7)	117.0 ± 2.3 (139)
C. Natural Populations from the Gulf of Mexico[3]			
Mouth of Tampa Bay, sta. 1	ND	1.8 ± 0.34	0.18 ± 0.095
Gulf of Mexico, sta. 2	ND	0.28 ± 0.136	0.0154 ± 0.007
Gulf of Mexico, sta. 3	ND	0.26 ± 0.09	0.017 ± 0.004

[1]Counting and plaque assays performed directly in phage-host system medium without concentration.
[2]For experiments 4, 5, and 6, T2 phage was added to autoclaved, filter sterilized artificial seawater and the phage then concentrated by VFF.
[3]Samples were prefiltered through 0.2 μm filters prior to VFF, which accounts for the low viral titers.

Table 3. Effect of 0.2 μm filtration on recovery of viruses prior to VFF concentration. All virus abundances (10^6 viruses/ml) determined by TEM.

SAMPLE	UNFILTERED	0.2 μm FILTERED	PERCENT OF UNFILTERED
A. T2 Phage in Artificial Seawater			
Expt 1	963 ± 209	117 ± 26	12.1
Expt 2	81 ± 16	0.23 ± 0.1	0.28
Expt 3	141 ± 23	71.7 ± 7.1	50.9
B. Natural Phage Populations			
Mouth of Tampa Bay	17.4 ± 2.5	1.78 ± 0.34	10.2
Gulf of Mexico, sta. 2	0.24 ± 0.06	0.28 ± 0.14	117
Gulf of Mexico, sta. 3	0.44 ± 0.5	0.26 ± 0.09	59.1
Dry Tortugas	1.5 ± 0.1	0.14 ± 0.03	9.3
	0.19 ± 0.12[1]	12.7	

[1]Value determined for prefiltration with a 142 mm Durapore filter.

Table 4 shows the distribution of viral abundance in unfiltered samples concentrated by VFF taken from estuarine, coastal oceanic, and oligotrophic oceanic environments. The estuarine samples exceeded 10^7 viruses/ml, the one exception being the Pier sample (from Tampa Bay) that was taken in December. The coastal oceanic samples (all measured during summer) were in excess of 10^6 viruses/ml, while oligotrophic offshore oceanic stations (also sampled in summer) contained 2.4 to 4.5 x 10^5 virus particles/ml.

Figure 2 shows the beginning of a seasonal study of the distribution of chlorophyll *a*, bacterial counts, and viral abundance from the Pier in Tampa Bay. Bacterial abundances decreased from November to February, from nearly 4 x 10^6/ml to 1.8 x 10^6/ml. Although there was variability in the viral abundance data, viral counts appeared to increase as bacterial counts decreased, from 4 x 10^6 to over 6 x 10^6.

Table 4. Viral abundance in Tampa Bay, the eastern Gulf of Mexico, and the Bahamas Bank as determined by TEM direct counts on VFF-concentrated water samples.

SAMPLE	INITIAL VOLUME OF SAMPLE (liters)	VOLUME AFTER VFF CONCENTRATION (ml)	10^6 VIRUSES/ml (initial volume)
Bayboro Harbor, Tampa Bay	3	25	34 ± 14
Mouth of Tampa Bay, sta. 1	3	21.3	17.4 ± 2.5
Hookers Point, Tampa Bay	20	57.0	13.3 ± 5.5
St. Petersburg Pier, Tampa Bay	5	46.0	6.04 ± 1.49
Florida Bay	20	18.9	2.0 ± 0.1
Loggerhead Key, Dry Tortugas	15	8.4	1.5 ± 1.0
Joulter's Cay, Bahamas	10	50.0	2.3 ± 1.1
Gulf of Mexico, sta. 2	20	17.4	0.24 ± 0.06
Gulf of Mexico, sta. 3	30	16.0	0.44 ± 0.15
NW Providence Channel, Bahamas	25	36.4	0.42 ± 0.06

Figure 3 shows some of the phage observed in samples from various marine and freshwater environments. Although no systematic attempt was made to size phage in all samples counted, sizing of phage in photomicrographs indicated a head size range of 46.4 to 141 nm (mean 85.8 ± 21.1 nm; n=30). This result suggests that the use of T2 as a standard may be justified, because T2 has a head size of 80 to 110 nm (Friefelder 1987), slightly larger than the mean phage head size observed for field samples. However, we cannot discount the possibility that photographed phage were a biased subsample of the natural phage population, because large tailed phage were more likely to be photographed than small tailless forms.

In some of the samples taken for viral direct counts, bacterial abundance by direct counts was also measured. The relationship between log bacterial abundance and log viral abundance appears in Figure 4. The relationship between these two parameters resulted in a correlation coefficient of 0.86, indicating a significant correlation between bacterial and viral concentrations (0.002<P<0.00P; Zar 1974) for the subtropical environments sampled.

Coliphage and Human Enteroviruses

No viruses were isolated from the Tampa Bay outfall site. Viruses were isolated from the northern Miami outfall. Coliphage levels were 212 pfu per 100 l and animal viruses were 15 pfu/100 l. The animal viruses have been passaged but have not yet been identified.

DISCUSSION

VFF has been shown to be an efficient and rapid means to concentrate phage particles and dissolved DNA from seawater. The efficiency of harvesting T2 phage and calf thymus DNA was between 70% and 80%, in agreement with claims of the VFF manufacturer for biological materials in general. Although any of the pore-sized ultrafilters (100, 50, and 30 kd) could be used to efficiently harvest viruses, only the 30 kd filter collected DNA efficiently.

The decrease in viral abundance caused by 0.2 µm filtration is not surprising because collection of viruses on 0.2 µm filters has been used for some time by aquatic virologists (Gerba and Goyal 1982). Viruses are known to adsorb to particulate matter, and thereby would be collected on 0.2 µm filters. It seems that a greater percentage of viruses passed the filters in samples from oligotrophic waters, perhaps because of the smaller amount of particulate matter available for viral adsorption. If samples are 0.2 µm prefiltered to remove bacteria and other microorganisms for viral enumeration, underestimation of the total viral population may occur.

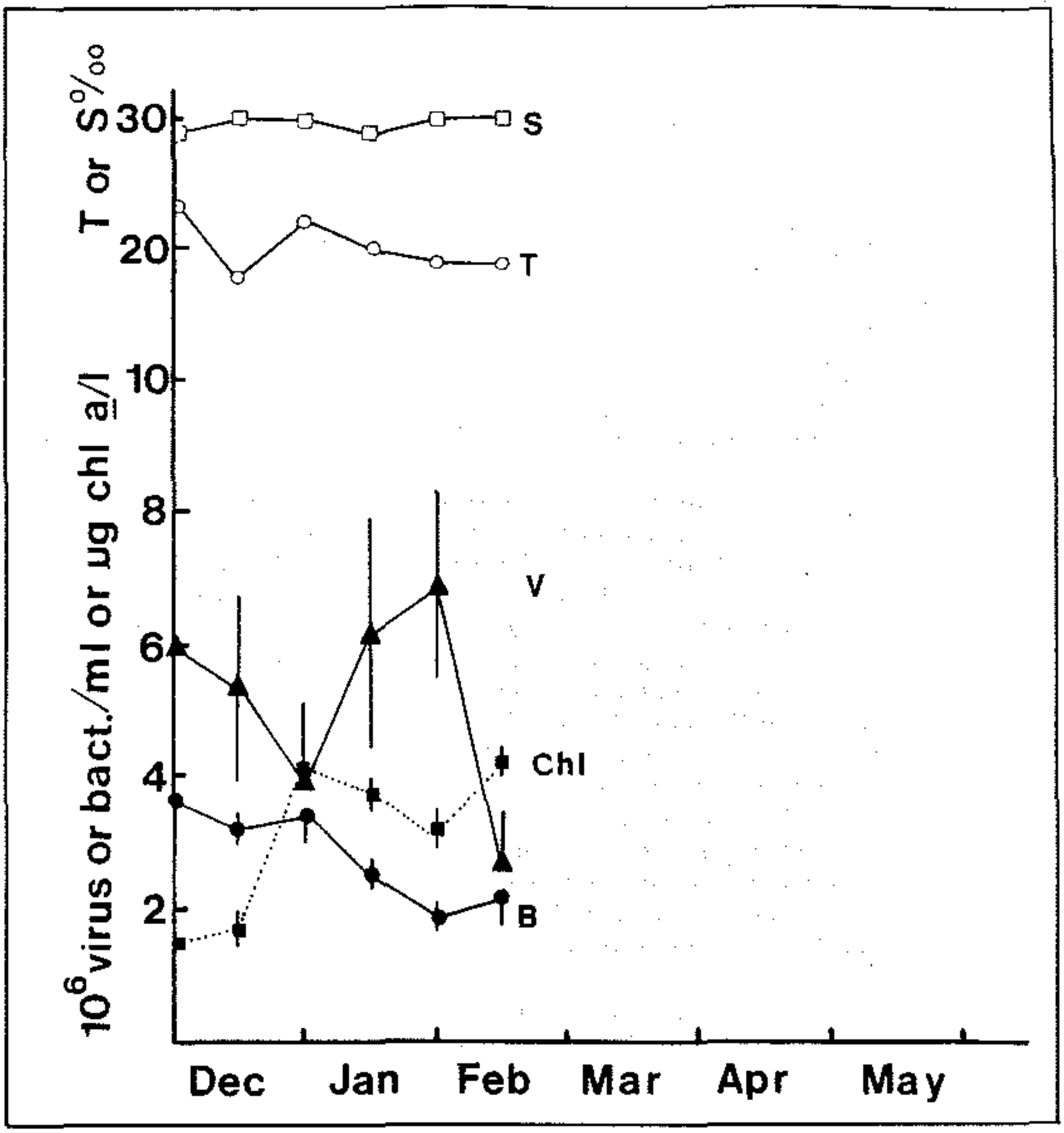

Figure 2. Preliminary findings of a seasonal study (Nov. 28, 1990 to Feb. 15, 1991) on the distribution of viruses (triangles), bacteria (filled circles), and phytoplankton (i.e., chlorophyll a, filled squares) in surface waters from Tampa Bay collected at the Pier in St. Petersburg, Fla. Also shown is salinity (open squares) and water temperature (open circles).

A significant linear relationship was found between phage and bacterial abundance. It may be argued that the log/log relationship only reflected differences between offshore and nearshore environments, and that any biological parameter will decrease as a function of distance from shore, and hence correlate. However, the occurrence of phage in any environment is contingent upon the presence of bacterial hosts. Our data suggest that viral abundance exceeds bacterial abundance by approximately one-half log unit when both are high, as in estuarine environments. In oligotrophic environments, bacterial abundance is fairly close to viral abundance (i.e., both at 2 to 4 x 10^5/ml). Borsheim (1990) found viral abundance to exceed bacterial abundance by approximately one order of magnitude for samples taken in a Norwegian fjord. Although viral abundances for our coastal samples are similar to theirs (i.e., 10^6 to 10^7/ml), their bacterial abundances were only 1 to 4 x 10^5, which are considerably lower than those found in this study. It is not known why bacterial abundances were so low in the coastal fjord environments sampled.

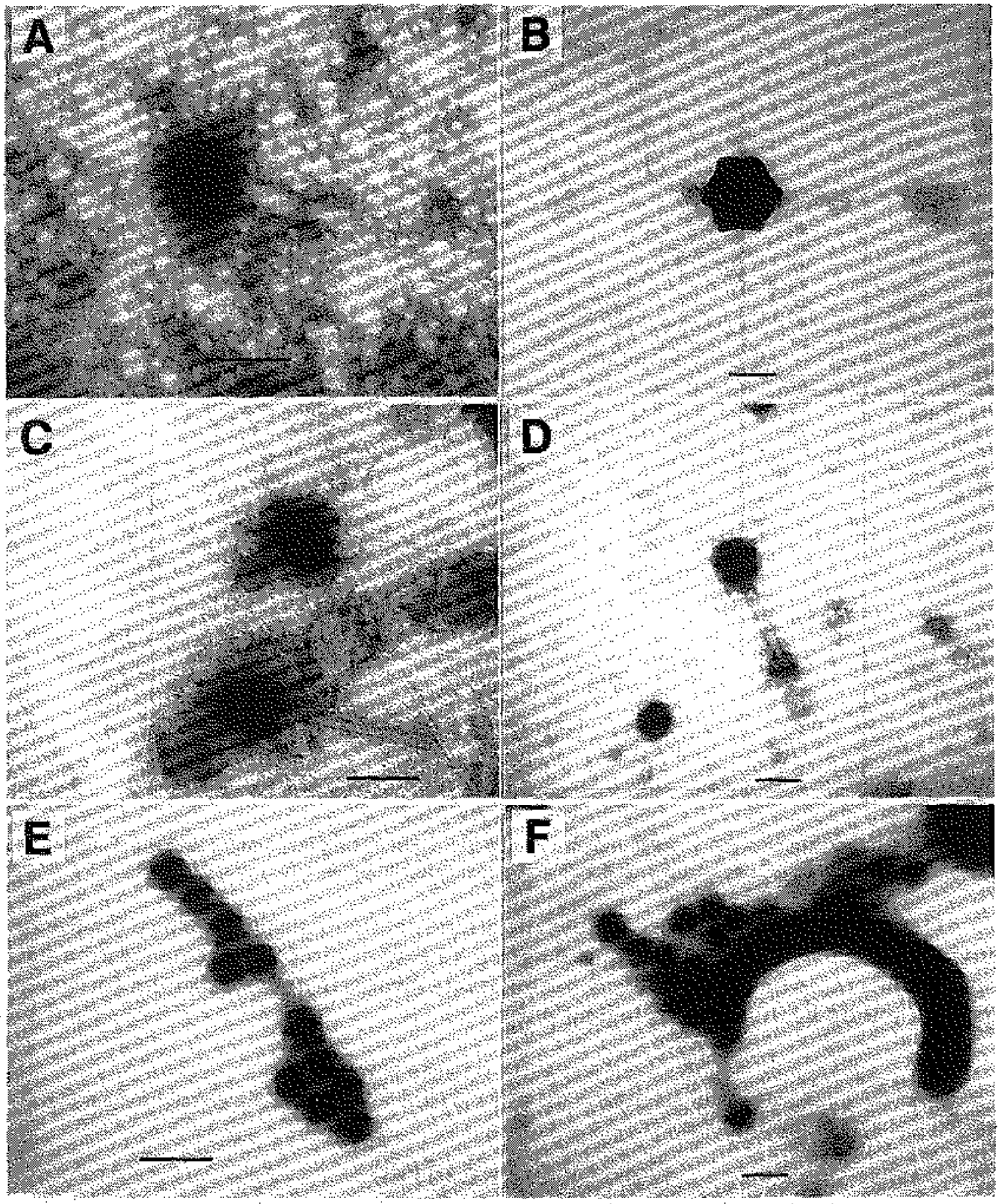

Figure 3. Electron photomicrographs of bacteriophage and virus-like particles concentrated by VFF from Tampa Bay and surrounding waters: A) tailed phage from the Medard Reservoir, Valrico, Fla.; B) large algal virus-like particle from a sample from the Dry Tortugas near Loggerhead Key; C) tailed phage from Bayboro Harbor, Tampa Bay; D) tailed phage from outside the mouth of Tampa Bay; E) virus-like particles taken from 1500 m depth in the Atlantic Ocean east of the Bahamas; F) virus-like particles (similar to those in E) on a bacterial cell surface from surface waters in the Dry Tortugas.

Enumeration of coliphage by plaque titer resulted in values nearly nine orders of magnitude below those obtained by direct viral counts. Obviously, not all phage observed would be expected to be coliphage. However, one might expect perhaps one in 10^3 to one in 10^6 to be a coliphage. This data underscores the difference between classical phage enumeration and direct viral enumeration. As yet, there is no practical method to directly enumerate animal viruses because of their low concentration.

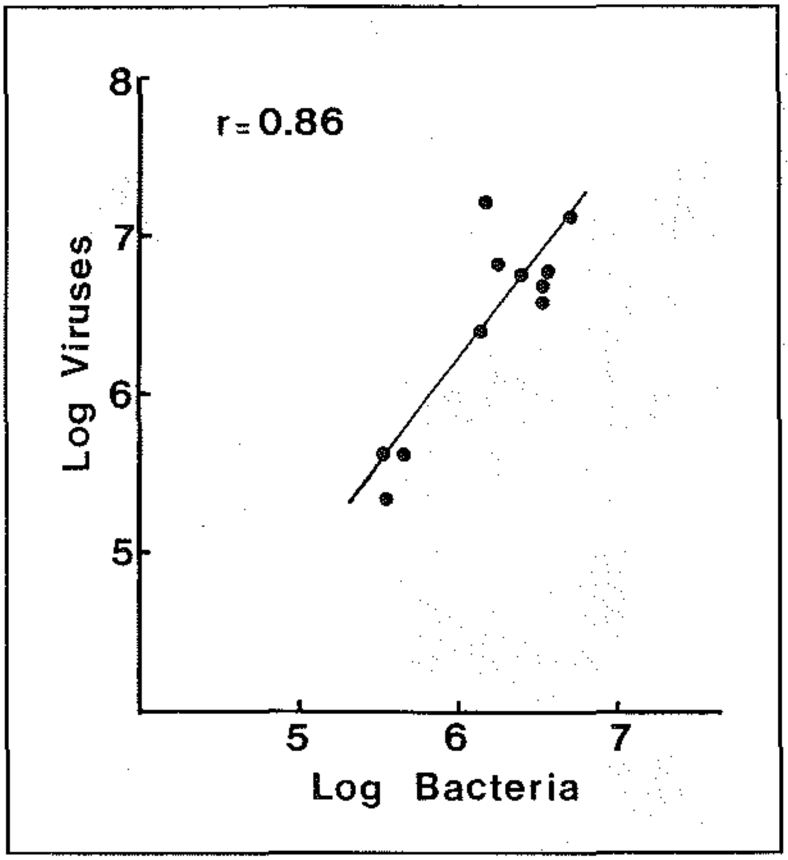

Figure 4. Relationship between virus abundance and bacterial abundance for samples taken in Tampa Bay and surrounding waters. The correlation coefficient appears in the upper left corner of the figure.

Our results show that vortex flow filtration is a promising technology for use in environmental viral concentration. Coupling VFF with direct viral enumeration has resulted in a rapid and efficient way to enumerate viruses in aquatic samples for water quality, public health, and ecological purposes.

ACKNOWLEDGEMENTS

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PHYTOPLANKTON PRODUCTION IN TAMPA BAY AND TWO TIDAL RIVERS, THE ALAFIA AND LITTLE MANATEE

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D. Howard
J. H. Paul

INTRODUCTION

Freshwater inflow from tributaries associated with estuarine ecosystems plays a dynamic role in the functioning of these systems. Delivery of fresh water is key to the control of circulation within the estuary and, with concomitant chemical and biological loadings, is associated with the overall productivity of an estuary.

Information on chemical/biological constituents of Tampa Bay tributaries has been summarized in several recent publications (Lewis and Estevez 1988, Flannery 1989, Estevez et al. 1991). This paper summarizes some of the data available on two tributaries of Tampa Bay, the Alafia River and the Little Manatee River (LMR). The Alafia, which drains an urbanized and industrialized watershed, is generally considered to be a heavily impacted tributary with poor water quality in lower sections. The Little Manatee, which has received designation as an Outstanding Florida Water, drains a watershed composed of agricultural and range land with a minimum of urban and industrial areas (Estevez et al. 1991).

METHODS

Methodology for the determination of primary production and chlorophyll *a* differed for the two studies used in this summary. Paul et al. (1989, in press) determined primary production in Alafia River samples with a 2-hr incubation period at approximately 50% of ambient light intensity at ambient temperature. Subsamples for carbon-14 uptake in the total and <1μm size fraction were removed at time 0, 1 and 2 hours to determine the linearity of uptake vs. time. The final sample, corrected for isotopic concentration and discrimination, was used to calculate carbon fixation. Primary production for the 1988-1989 LMR locations was determined in the laboratory with 3-hr incubations at ambient temperature and a constant irradiance of 300 $\mu E/m^2/s$ in a circulating water bath illuminated from below. Four locations were sampled at two week intervals: Tampa Bay, the 18, 12, and 0 ppt salinity zones. Carbon fixation was calculated after appropriate corrections using measured total inorganic carbon concentrations. In 1989-1990, LMR samples from the 12 ppt salinity zone and Tampa Bay were incubated in running sea water at seven light levels under ambient irradiance for 24 hours. Size fractionation was done after incubation by filtering a subsample onto 0.4 μm Nuclepore filters for the "Total" fraction, followed by filtration of the remaining sample through stacked 12 μm and 5 μm Nuclepore filters. Where necessary, size fractions were calculated by difference. Inorganic carbon concentration was determined on all initial samples.

Chlorophyll *a* in all 1988-1989 LMR samples was determined spectrophotometrically with acetone extracts by the Florida Department of Natural Resources Marine Research Institute. Both the Lorenzen (1967) and Jeffrey and Humphrey (1975) equations were used to calculate chlorophyll *a* and phaeopigments. The Lorenzen values were used to calculate the productivity index (PI: mgC/mgChl/hr) since they were corrected for chlorophyll degradation products.

Differences in the methods used to determine primary production in the two LMR studies, particularly the length of the incubation period, does not allow for a direct comparison of production for the two years. Short incubation times lead to a production value that is closer to gross production whereas respiration and excretion of fixed, labelled, carbon during the 24-hour incubation period yields a value that may be closer to net production (Eppley and Sharp 1975). Comparisons between the Alafia and 1988-1989 LMR data were made since the methodology and incubation period were similar.

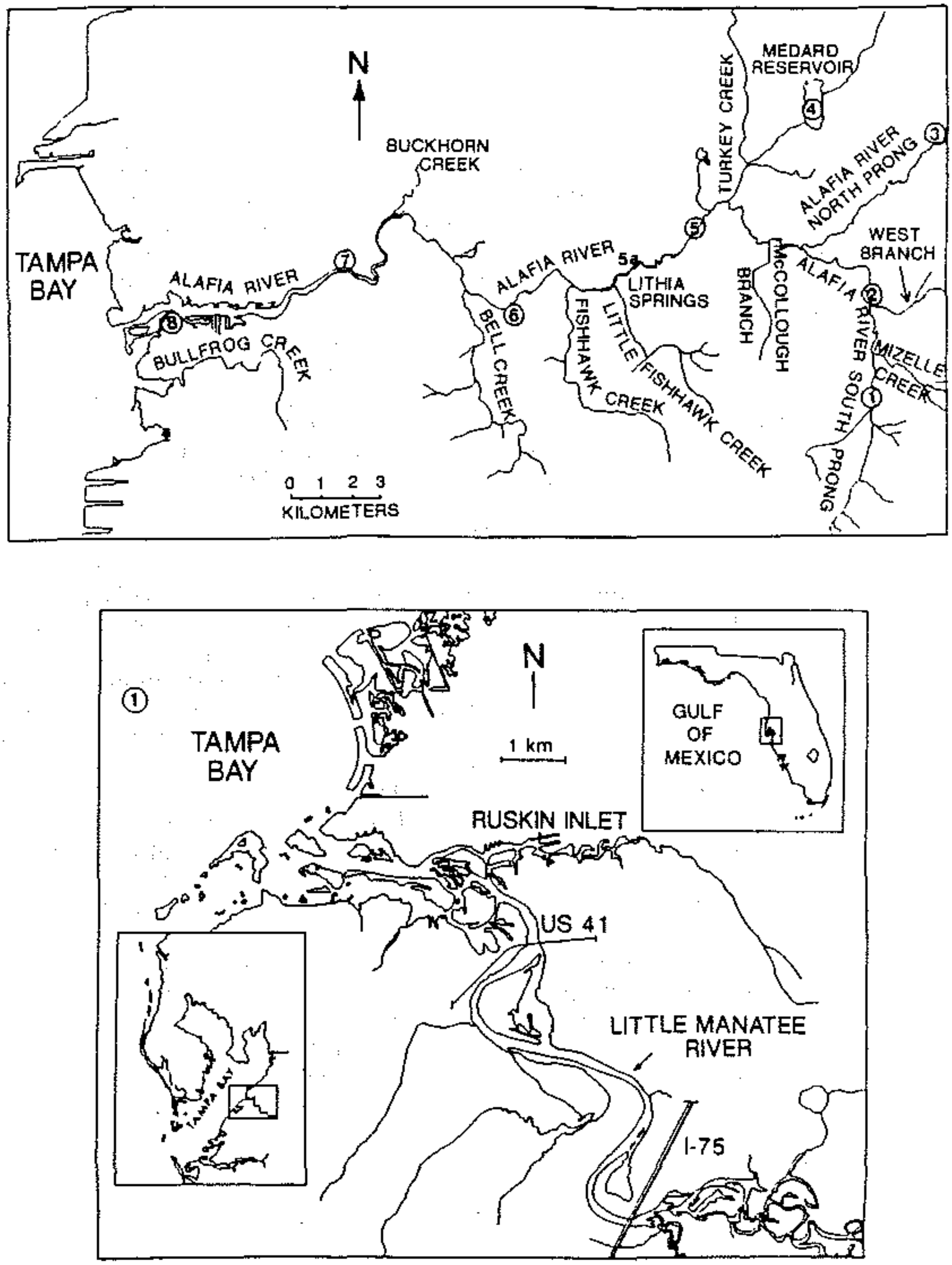


Figure 1. Locations of stations on the Alafia River (upper) and the Little Manatee River (lower). The Tampa Bay station located off the mouth of the Little Manatee River is designated as station 1.

Quarterly samples from the Alafia river were collected in 1987-1988 at eight locations (Fig. 1). Information from stations 2 and 4 was not used for this summary because station 2 had a limited data set and station 4, the Medard Reservoir, is highly eutrophied and is not representative of the river complex. Sampling locations for the LMR were not geographically fixed stations. Specific salinity zones were sampled twice monthly during 1988-1989 and monthly during 1989-1990. Salinity zone locations for the 1988 program are listed in Table 1. The location of the 12-ppt salinity zone for the 1989 study differed somewhat from the previous year on a month to month basis but the annual average of 2.93 miles from the mouth was comparable to the 1988 average of 2.25 miles. The Tampa Bay station was located approximately 1.24 miles northeast of the mouth of the river (Fig. 1). Data from Ruskin Inlet, a branch of the LMR, has not been used for the same reasons stated above for the Medard Reservoir.

Table 1. Location of Little Manatee River salinity zones during the 1988-1989 study by rivermiles. Rivermiles were measured as distances from the mouth of the river. Negative numbers indicate distance into Tampa Bay while positive numbers are distances from the mouth toward the head of the river.

			STATION		
DATE	TAMPA BAY	18 ppt	12 ppt	6 ppt	0 ppt
01/26/88	-1.24	-0.25	N.D.	N.D.	5.70
02/10		-0.36	N.D.	N.D.	6.10
02/24		0.44	1.95	3.40	6.50
03/09		0.00	0.83	3.00	4.65
03/22		-0.87	-0.21	1.53	4.15
04/06		0.00	2.55	6.00	7.20
04/20		1.30	3.60	6.25	8.45
05/04		1.85	3.70	6.15	8.35
05/18		2.55	6.10	7.23	10.23
06/01		3.70	5.65	8.30	10.46
06/15		4.80	6.60	8.60	10.45
06/29		5.10	6.16	9.60	10.63
07/14		3.50	5.19	8.34	9.85
07/28		1.40	3.50	5.30	7.19
08/10		0.00	0.34	1.15	4.24
08/30		-0.93	-1.20	0.00	3.40
09/08		-1.04	T.Bay	-0.93	0.00
09/22		T.Bay	1.53	4.10	6.25
10/11		T.Bay	-0.52	4.20	6.25
10/25		-0.22	1.00	2.72	7.10
11/07		-0.83	-0.97	1.40	4.55
11/21		-0.43	0.95	4.70	7.83
12/08		-0.83	0.80	3.80	7.19
12/20		0.00	1.51	4.65	7.19
01/11/89		0.00	2.70	4.44	7.60
01/24		T.Bay	-0.82	0.91	4.24
Average		0.90	2.25	4.37	6.76
1989-1990 Average			2.93		

RESULTS

River Characteristics

Flannery (1989) and Estevez et al. (1991) provide a summary of the streamflow and water quality characteristics for all the major rivers entering Tampa Bay. Both the Alafia and LMR exhibit similar seasonal trends in streamflow with maximum flow during July through September which corresponds to regional rainfall patterns. In addition, the Alafia has input from artesian springs; Lithia Springs (station A5) supplements baseflow and is the source of high nitrate input (Flannery 1989). Water quality in many sections of the Alafia is classified as fair to poor, largely due to the urbanization of the region and to extensive phosphate mining and processing industries located within its drainage basin (Estevez et al. 1991). Water quality in the LMR is considered good over the majority of the river.

Tidal influence in the Alafia reaches approximately 10 miles from the mouth and the depth of penetration of 0.5 ppt salinity during the dry season is approximately 10 miles (Estevez et al. 1991), which would include stations 7 and 8 (Fig. 1). The LMR is tidal 15 miles from the mouth with penetration of the 0.5 ppt salinity isopleth to approximately 11 miles during the dry season. This distance would encompass all of the salinity zones sampled in the LMR during both studies (Table 1).

River flow patterns for the LMR during the two year study had similar seasonal variations (Fig. 2). Relatively low constant flow rates characterized winter and spring followed by highly variable and short-lived periods of high flow during summer. Maximum flow was observed during September 1988 with a peak exceeding 9700 cfs on September 8. In contrast, the maximum flow rate in 1989 was approximately 1300 cfs on September 27 (Fig. 2).

Nutrient Availability

Concentrations of phosphate and nitrite+nitrate were present in excess throughout the Alafia River (Fig. 3). Phosphate input occurred above station 3 on the North Prong accompanied by high nitrate and nitrite concentrations. However, nitrate concentrations over 200 μg-at/l at Lithia Springs (station A5) far overshadowed station 3 inputs (Fig. 3).

The source of elevated nitrate and silicate concentrations in the LMR was above Wimauma. (The "Wimauma" station was located on the LMR at Highway 301.) Levels of both nutrients decreased rapidly toward the mouth (Fig. 4). Concentrations of ammonium and phosphate, which showed a high degree of seasonal variation, had relatively constant annual averages and spatial patterns. Although nitrate input was high, N/P atomic ratios were low with an order of magnitude variation from Tampa Bay to Wimauma (Table 2). Low N/P ratios are indicative of potential nitrogen limitation of primary production. Freshwater influx at or above Wimauma carried an elevated silica load with concentrations that exceed 250 μg-at/l and an annual average of 180 μg-at/l (Fig. 4). Such elevated silica concentrations resulted in low N/Si and P/Si ratios (Table 2), which suggests that silica should not be limiting for diatom growth if sufficient nitrogen and phosphorus are available (Doering et al. 1989).

Table 2. Ratios of dissolved inorganic nitrogen, phosphorus and silica (by atoms) based on the annual mean concentration measured at each location in the Little Manatee River.

LOCATION	N/P	N/Si	P/Si
Tampa Bay	0.38	0.14	0.38
18 ppt	0.90	0.13	0.14
12 ppt	1.23	0.13	0.11
6 ppt	1.66	0.14	0.08
0 ppt	3.58	0.21	0.06
Wimauma	4.05	0.26	0.07

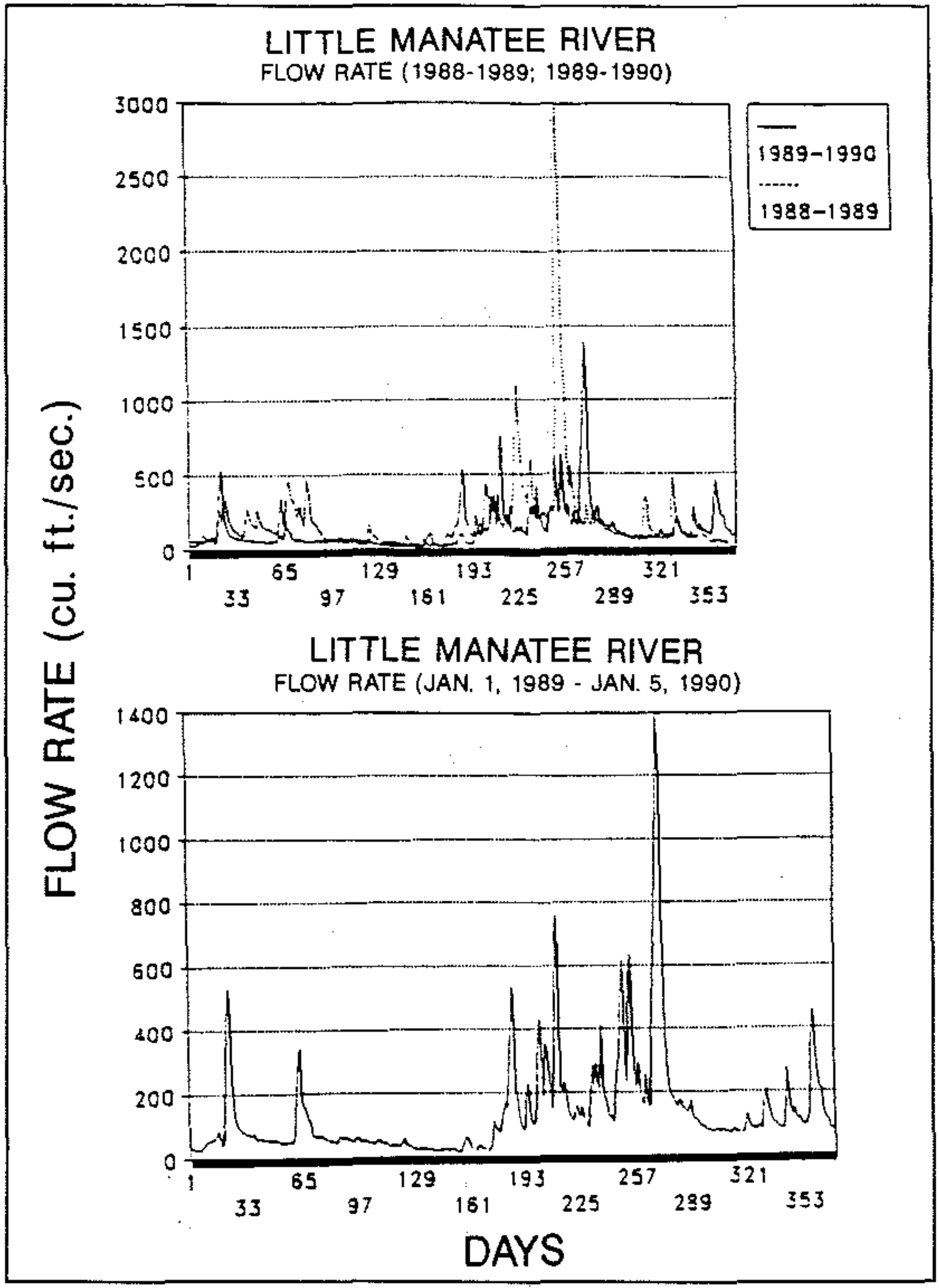


Figure 2. River flow (cfs) for the Little Manatee River measured at Wimauma. The scale in the upper figure was reduced for clarity; flow rates for the 1988-1989 study exceeded 9700 cfs.

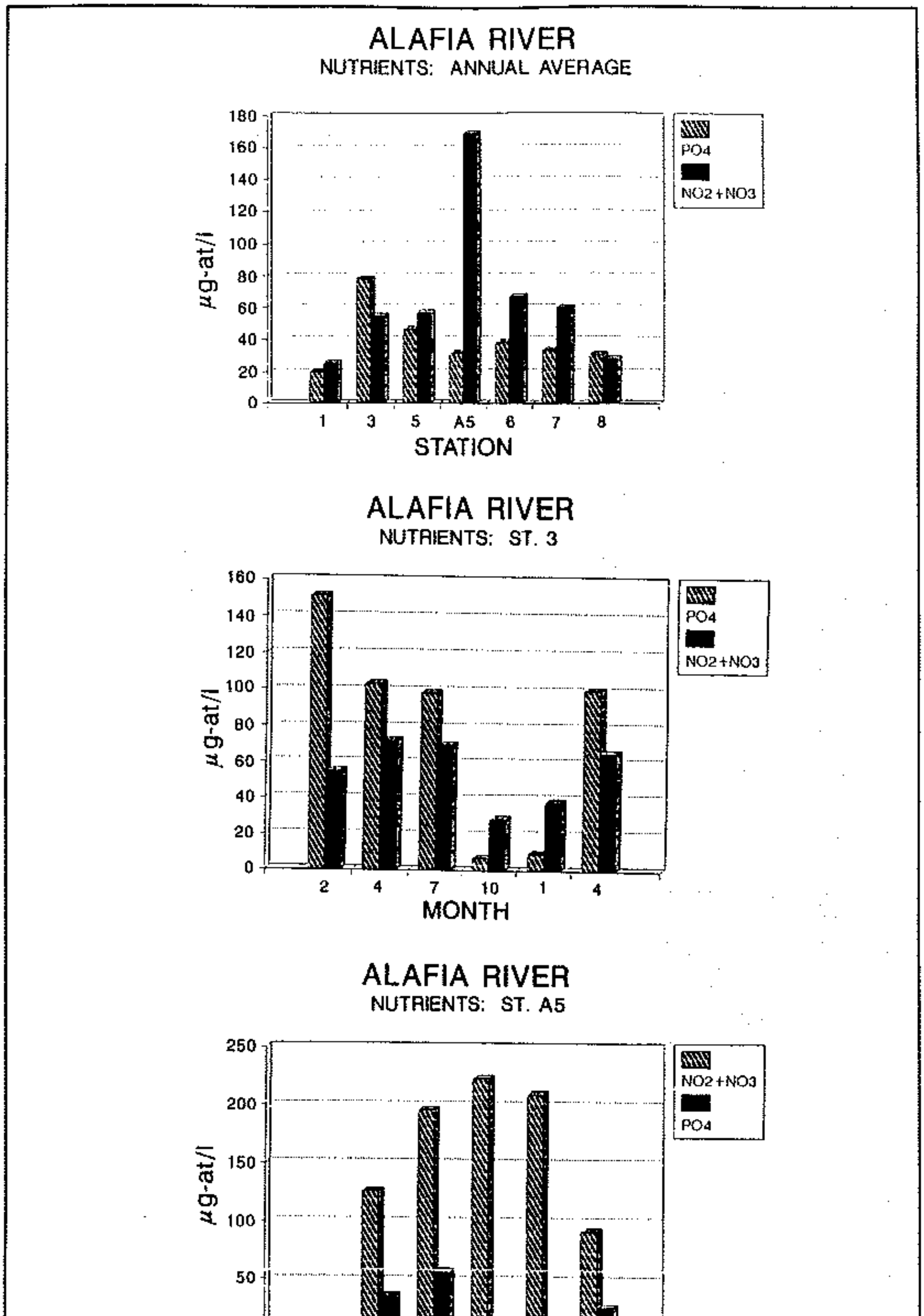
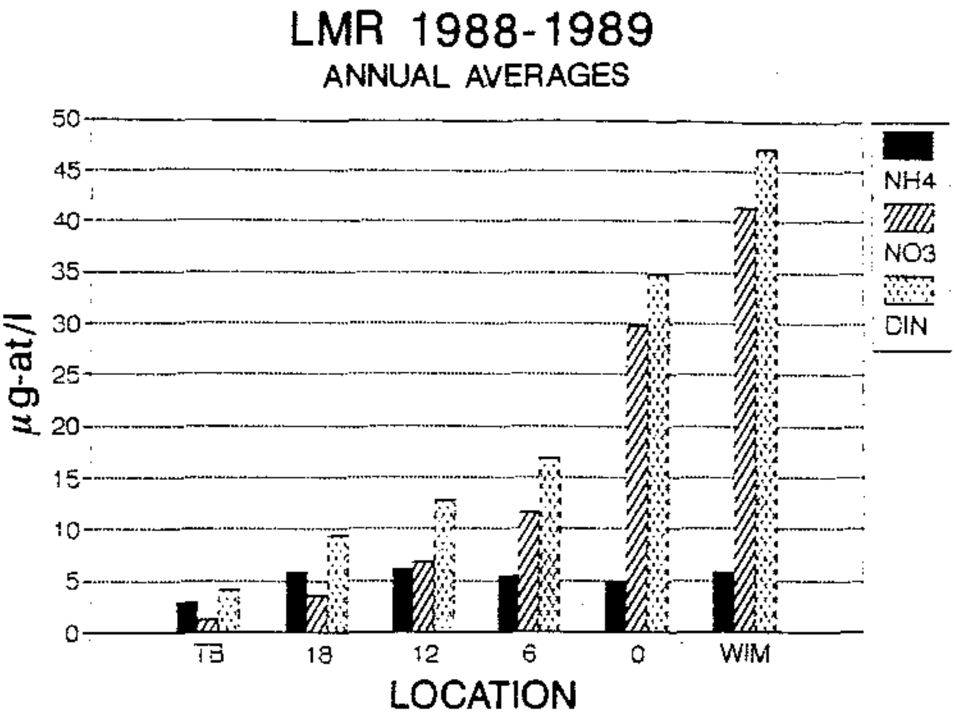


Figure 3. Concentrations (µg-at/l) of phosphate and nitrate + nitrite in the Alafia River as the annual average for each location and monthly values for stations 3 and A5 (Lithia Springs).



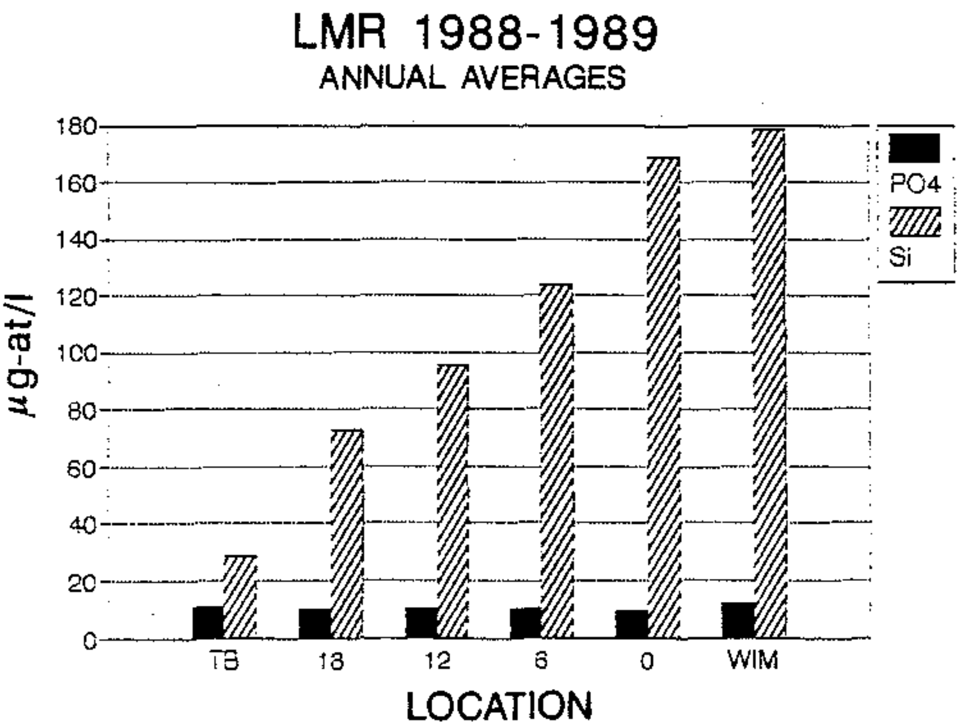


Figure 4. Annual average concentrations (µg-at/l) of nutrients for various locations on the Little Manatee River for the first year study (1988-1989).

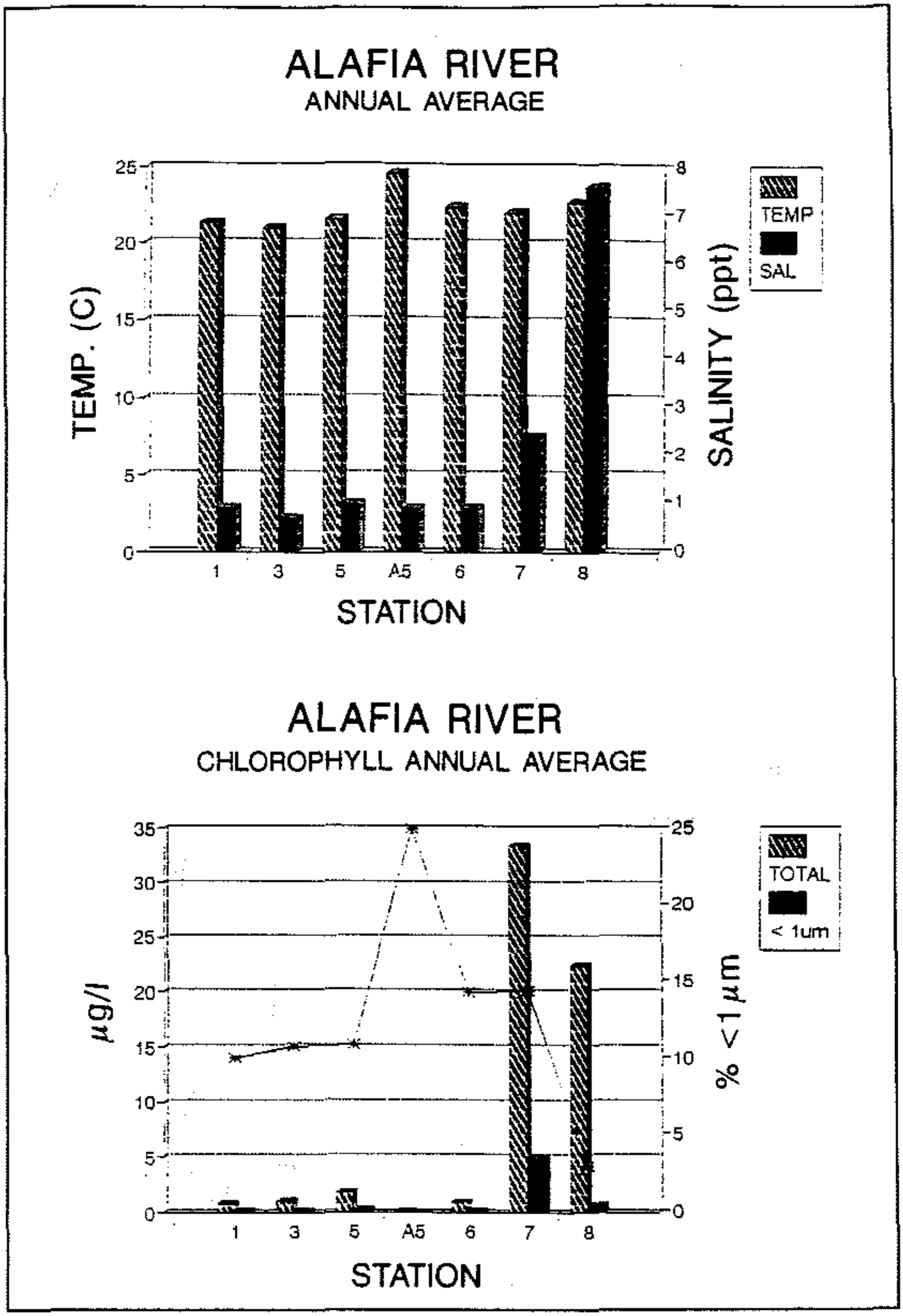


Figure 5. Average temperature, salinity and chlorophyll concentrations for stations along the Alafia River. Chlorophyll concentrations, as a percent of the total, are based on annual averages of the total and <1 µm size fraction (*), in lower panel.

Chlorophyll and Primary Production Patterns

Spatial trends in chlorophyll concentration and primary production in the Alafia river increased dramatically in that section of the river influenced by increasing salinity (Figs. 5 and 6). The annual average chlorophyll concentrations for the total size fraction did not exceed 0.7 µg/l for stations upstream of station 6 whereas the seasonal range at station 7 was 1.2 to 164 µg/l and 1.2 to 66 µg/l at station 8. The <1 µm size fraction contributed a significant proportion of the phytoplankton biomass at stations 1 to 7 with a range of 10% to 25% whereas the larger size fraction (>1 µm) represented 96% of the chlorophyll at the mouth (Fig. 5).

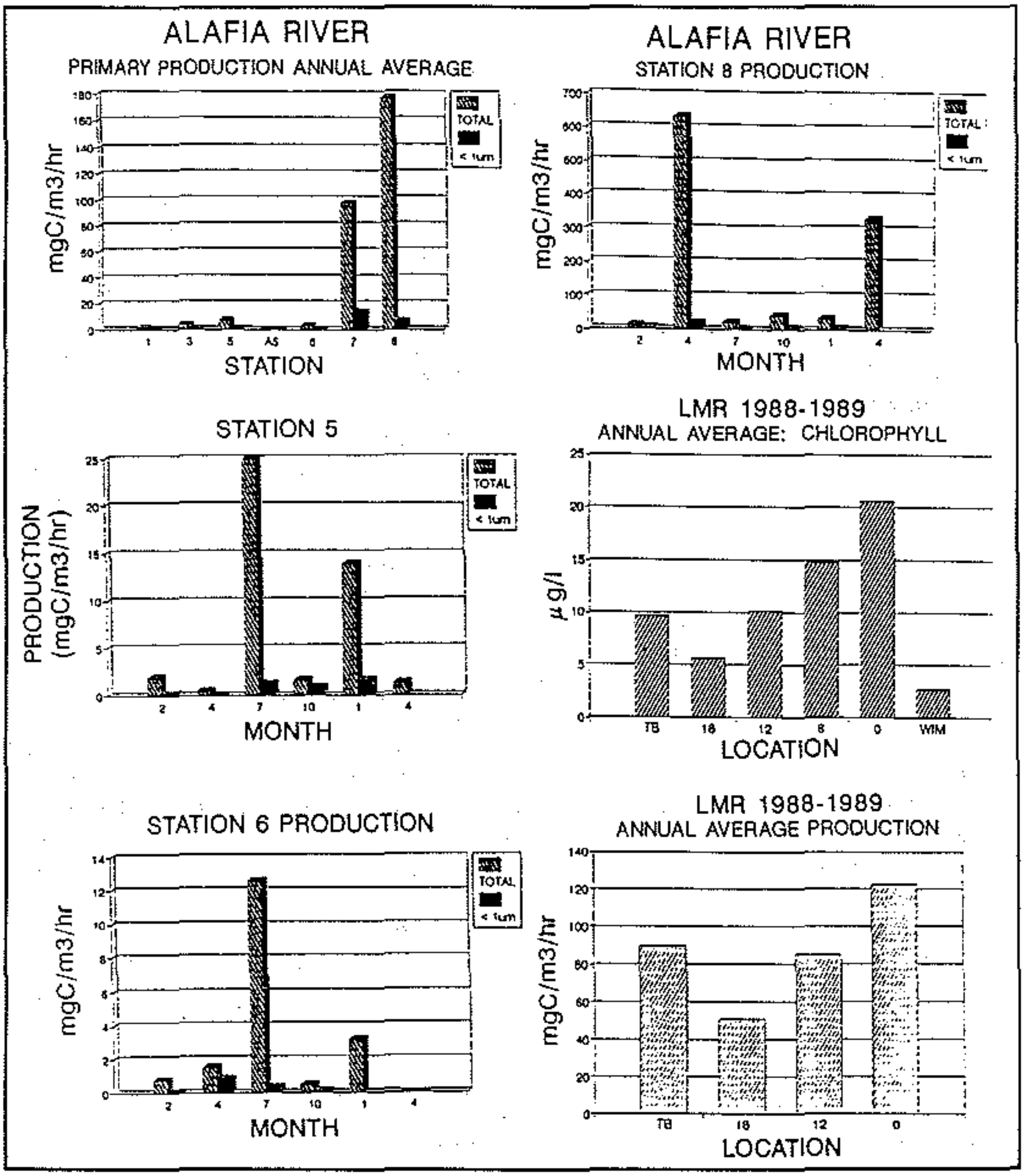


Figure 6. Production rates for the total and <1 µm size fraction averaged annually and as monthly values for selected stations along the Alafia River, and annual averages of chlorophyll concentration (µg/l) and potential production at locations along the Little Manatee River during the first LMR study.

Annual averages of primary production in the Alafia followed the same spatial trend as chlorophyll (Fig. 6). Production rates for locations upstream of station 6 ranged from 0.28 $mgC/m^3/hr$ at Lithia Springs (A5) to 7.4 $mgC/m^3/hr$ at station 5 and were consistent with the chlorophyll distribution. Maximum production rates occurred at the mouth with peaks in April of both years (Fig. 6). Rates of over 300 and 600 $mgC/m^3/hr$ corresponded to chlorophyll concentrations of 34 and 22 µg/l, respectively. Such elevated production rates skewed the annual average to 177 $mgC/m^3/hr$ for this location, although rates throughout the year were higher than all other locations upstream of station 6 (Fig. 6). All Alafia river stations upstream of station 6 had a similar seasonal pattern with a maximum in July with secondary peaks in April at stations 1 and 3 and January at station 5. Annually, the <1 µm fraction represented 8% to 23% of the total production at stations 1 to 7 and 3% at the mouth (Fig.7).

The spatial pattern of chlorophll and primary production in the Little Manatee River was the mirror image of that found in the Alafia, with maximal chlorophyll and production at the lowest salinity, decreasing toward the mouth (Fig. 6). The annual average chlorophyll concentration at the 0 ppt salinity zone was approximately 4-fold higher than at 18 ppt while the average production was 2.5-fold higher (Fig. 6).

An interesting feature of the spatial distribution of chorophyll in the LMR was the low chlorophyll levels at Wimauma. In 1988, the maximum concentration occurred in July (8 µg/l) with most other values less than 4 µg/l. Therefore, the upper reaches of the LMR, above the region of tidal influence and penetration of the 0.5 ppt isohaline, exhibited characteristics similar to the freshwater sections of the Alafia. Increased biomass and production in the LMR appeared to coincide with the region of the river influenced by saline penetration.

Seasonal patterns of production at the 18 and 12 ppt salinity zones in the LMR and Tampa Bay during the 1988-1989 season were highly variable (Fig. 8) but were generally higher from June through September with lower rates during winter. At 0 ppt, production varied on a semi-monthly to monthly frequency, increasing in the early spring and fall. All locations had a minimum in primary production in early September 1988 that coincided with a period of high river flow (see Fig. 2). Flows over 9700 cfs were recorded on September 8, 1988, which effectively washed out the standing crop of phytoplankton in the river (Vargo 1990). Dramatic increases in production occurred at all salinity zones within one to two sample periods, presumably as a result of increased nutrient input and/or restabilization of the water column.

During the 1989-1990 season, chlorophyll concentration and primary production in the LMR and Tampa Bay were assessed in several size fractions. Seasonal cycles of chlorophyll in the total size fraction at both locations were similar to year 1 patterns, although the monthly sampling regime during year 2 tended to dampen the observation of short-term periodicity. Generally biomass was elevated from June through August (Fig. 9) with lower concentrations in winter and fall. The annual cycle at the 12 ppt salinity zone corresponded to year 1 distributions. A distinctive feature of the seasonal distribution, however, is the pattern associated with various size fractions. In Tampa Bay and at 12 ppt, the >12 µm fraction represented most of the biomass during spring and summer while the <12 and <5 µm fractions were dominant in winter/spring (Fig. 9).

Daily water column integrated production in the bay and river displayed a bimodal seasonal pattern in 1989-1990 (Fig. 10). Elevated production rates occurred in March-April and August to October at both locations. The September sample date corresponded to the period of maximum river flow for this year (Fig. 2). Production in the bay was maximal on this date while the rate at the 12 ppt salinity zone was lower than the August peak. River flow was considerably lower during this year with a rate of about 1400 cfs on this date. This flow was apparently not strong enough to cause the wash out at the 12 ppt station noted in year 1, but appeared to supply sufficient nutrients to enhance production rates during this and preceding months.

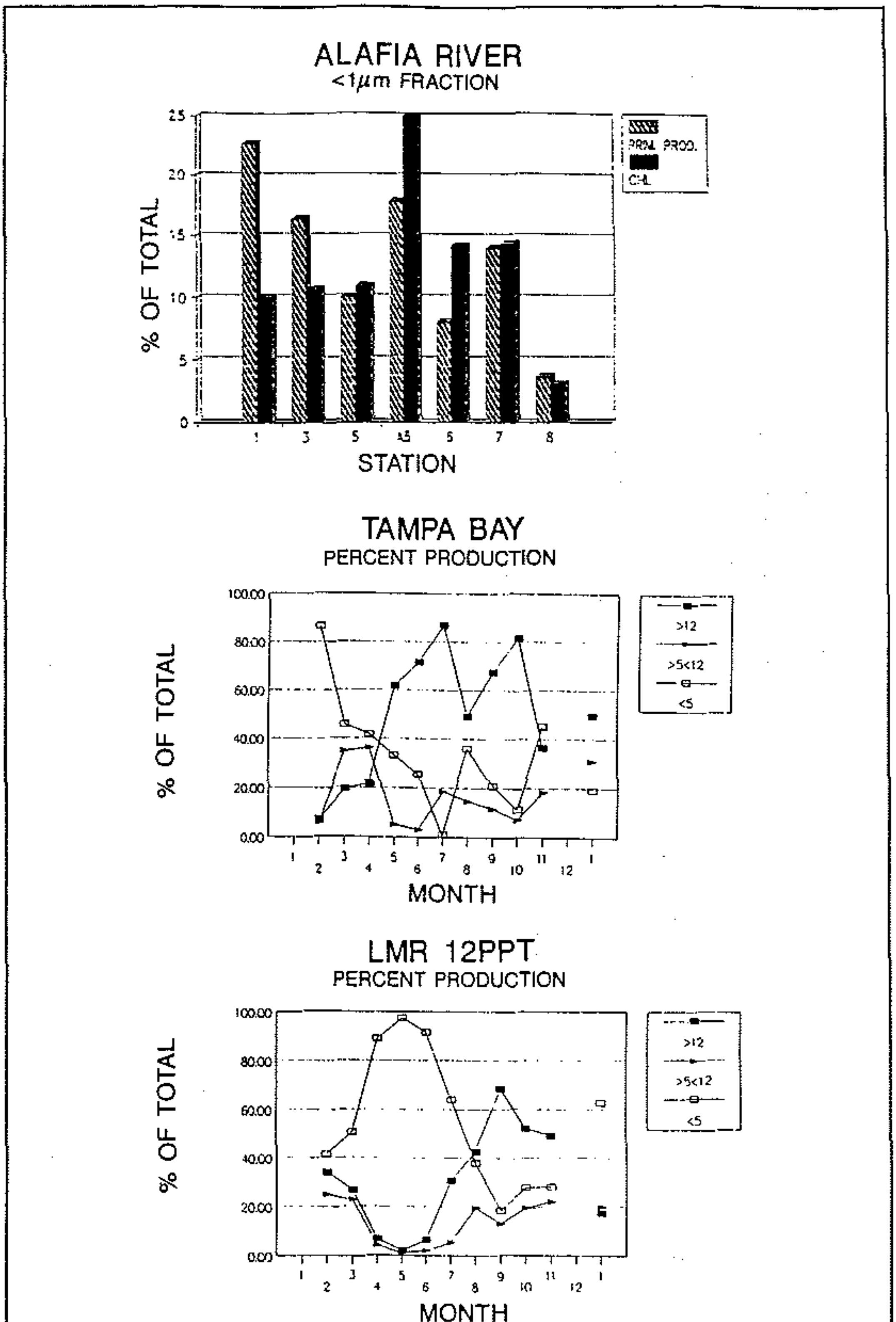


Figure 7. The contribution of the <1 μm size fraction to chlorophyll concentration and primary production in the Alafia River (upper), and the fraction of total production contributed by several size fractions in Tampa Bay and the Little Manatee River at the 12 ppt salinity zone during the second LMR study (1989-1990).

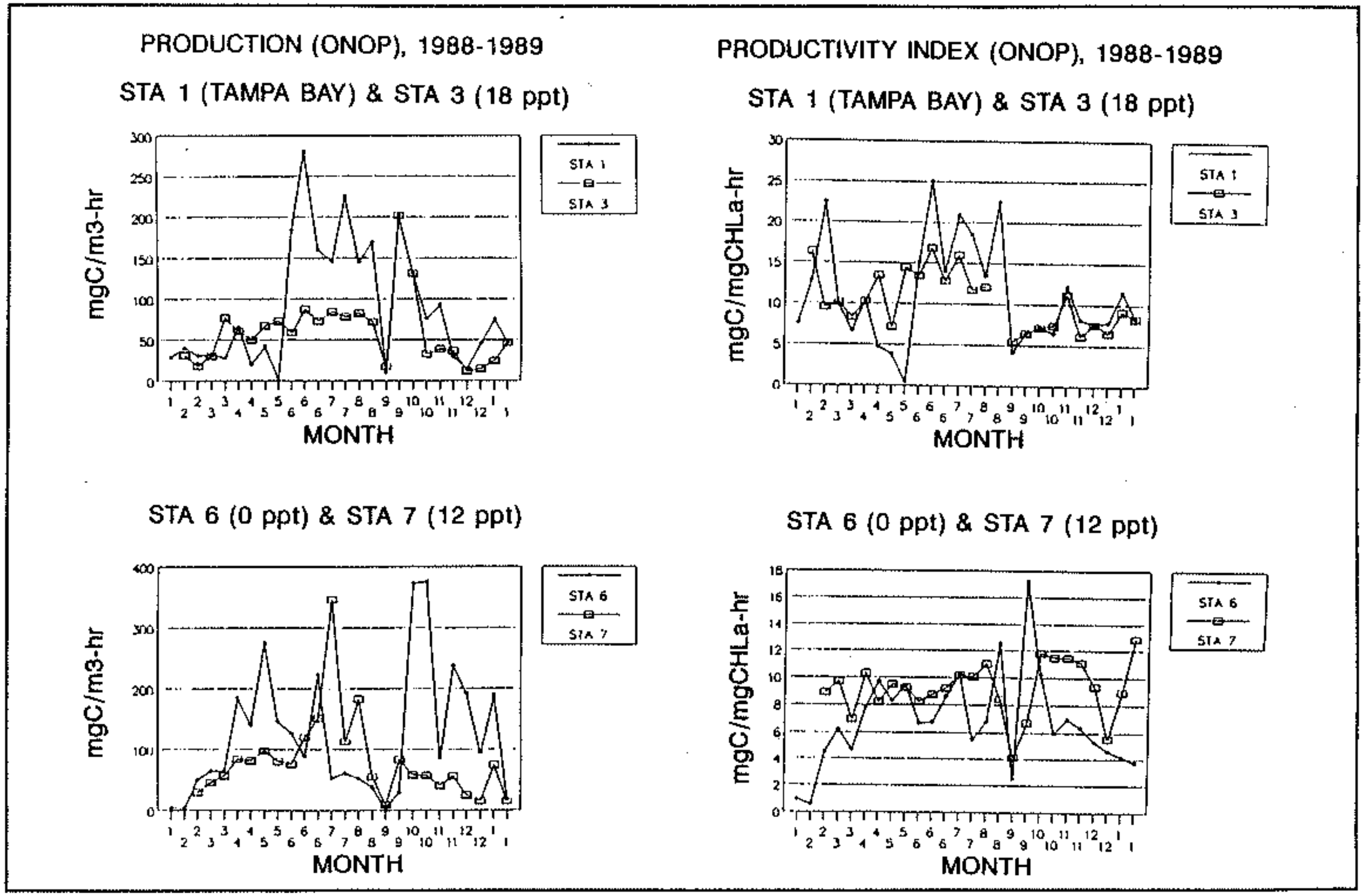


Figure 8. Seasonal variation in potential production ($mgC/m^3/hr$) and the productivity index (PI: mgC/mgChl/hr) in Tampa Bay and the Little Manatee River during the first year LMR study (1988-1989).

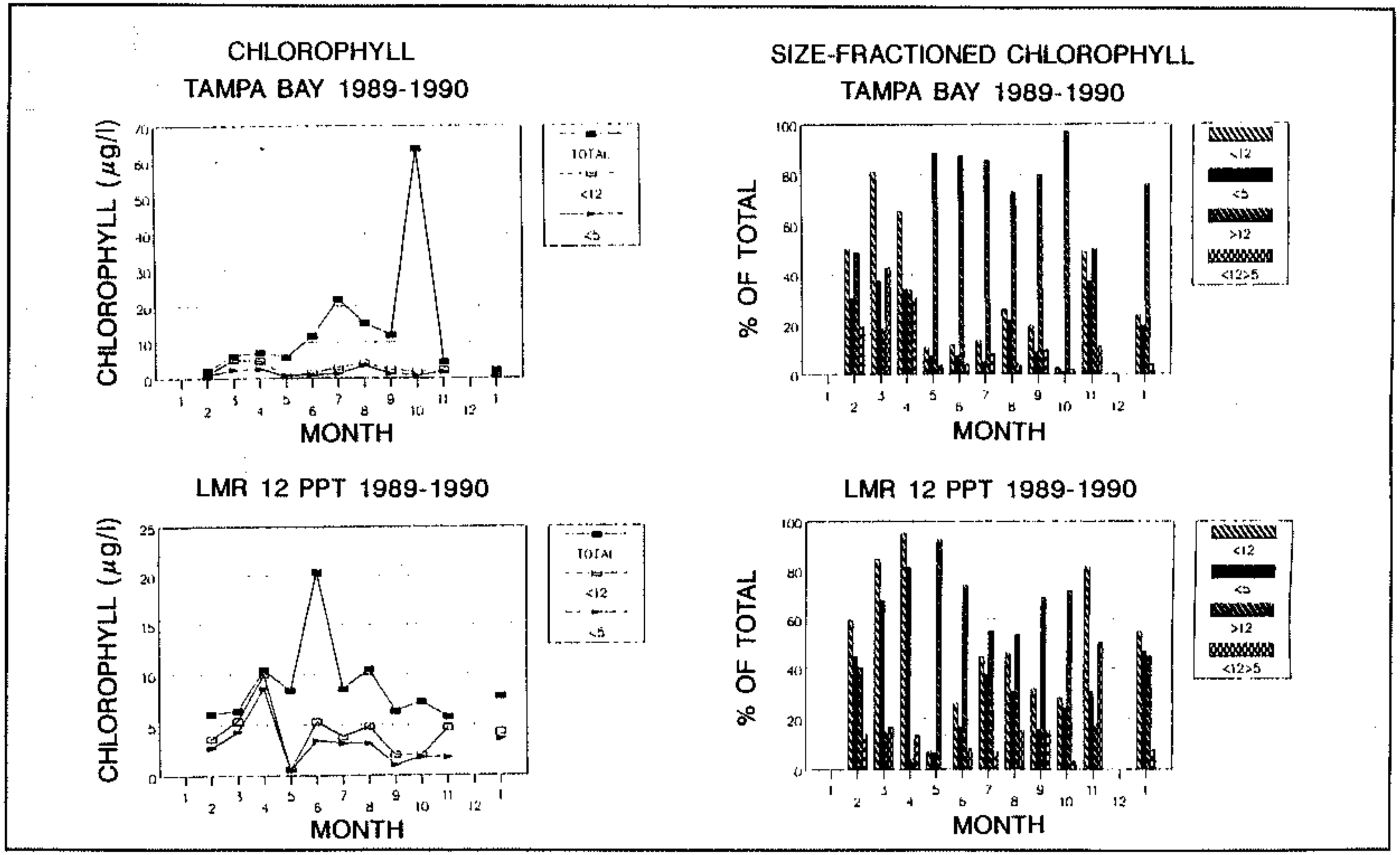


Figure 9. Seasonal variation in chlorophyll concentration (µg/l) in various size fractions from Tampa Bay and the 12 ppt salinity zone of the LMR (left panels), and as a fraction of the total chlorophyll concentration (right panels) during the second LMR study (1989-1990).

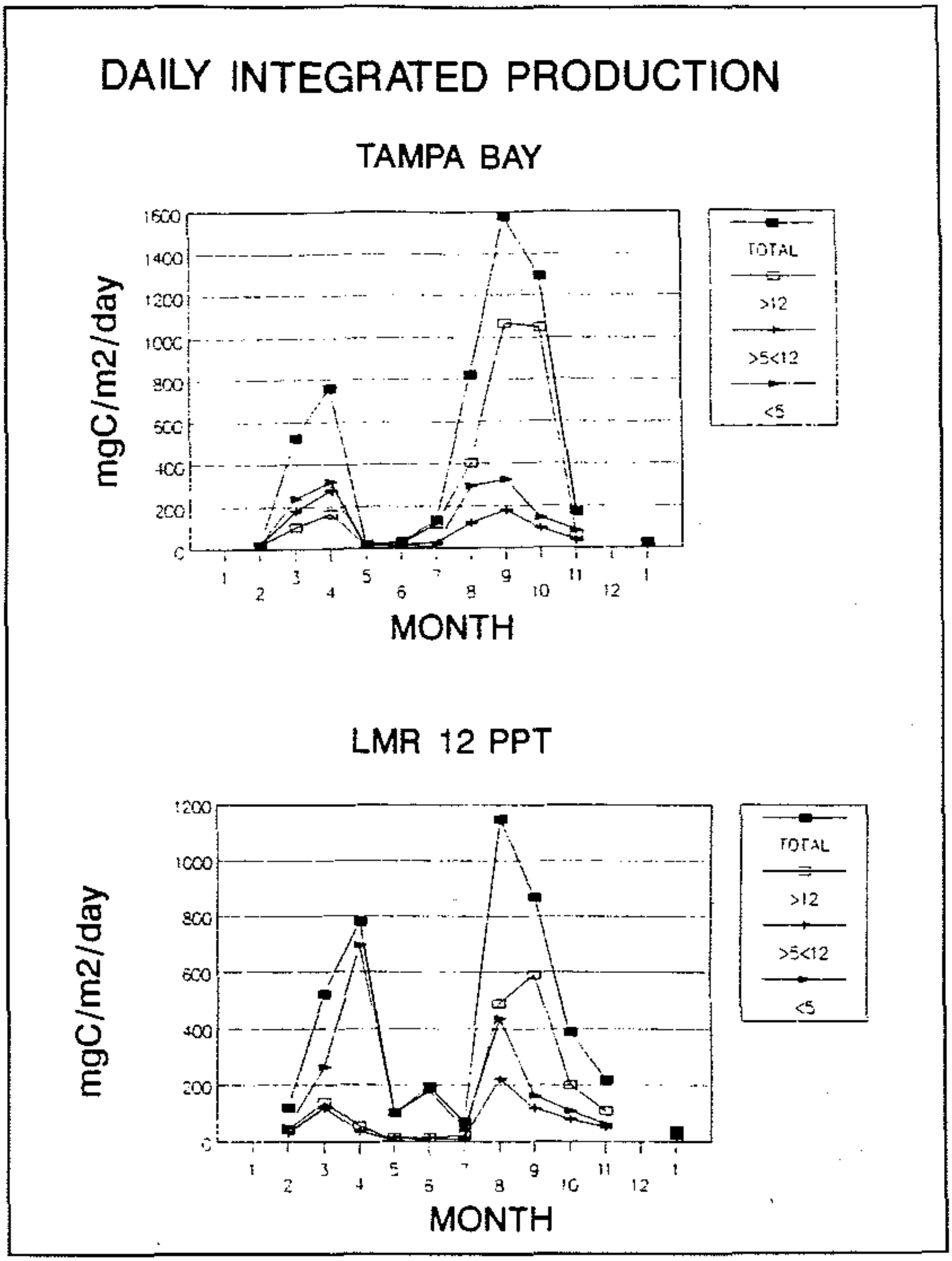


Figure 10. Seasonal distribution of integrated water column primary production (mgC/m^2/day) in various size fractions for Tampa Bay and the 12 ppt salinity zone of the Little Manatee River for the second LMR study (1989-1990).

Production in Tampa Bay was dominated by the >12 μm fraction for most of the year whereas there was a distinct seasonal partitioning of production between the <5 and >12 μm fractions in the river (Fig. 7). The seasonal partitioning between the two major size fractions in the river and bay corresponded to the fractionation in chlorophyll. Diatoms dominated the larger size fractions whereas unidentified microflagellates represented the bulk of the <12 and <5 μm fractions (Vargo 1991).

Potential Nutrient Limitation

The low dissolved inorganic nitrogen:phosphorus ratios that occur in Tampa Bay (Table 2, and Fanning and Bell 1985) and the LMR suggest potential nitrogen limitation of primary production. The potential for nutrient limitation was assessed as part of the 1988-1989 LMR study. Additions of nitrogen and phosphorus (as nitrate and ortho-phosphate) in varying combinations and ammonium enhanced dark carbon-14 uptake measurements were made on samples from Tampa Bay and three salinity zones in the LMR. The use of short-term photosynthesis measurements with nutrient additions as a measure of potential nutrient limitation was summarized by Elrifi and Turpin (1987) for nitrogen and by Lean and Pick (1981) for phosphorus in fresh waters. Nitrogen- and/or phosphorus-limited populations have reduced photosynthesis rates over the short-term as a result of competition for available carbon skeletons and directing available energy to nutrient uptake. Reduction in carbon-14 uptake was measured in the first tens of minutes to 2-3 hours after the addition of nitrate, nitrite or ammonium to nitrogen deficient cells and within the first 3 hours for phosphate addition to cultures and natural populations of freshwater phytoplankton. Enhancement of carbon-14 uptake in the dark upon the addition of ammonium was used as an indicator of nitrogen limitation in cultures and natural phytoplankton populations by Morris et al. (1971) and Yentsch et al. (1977). Elrifi and Turpin (1987) subsequently described a mechanism for enhanced uptake and demonstrated enhancement in the ratio of dark uptake with and without ammonium in cultures over a range of nitrogen limited growth. The ratio increased to approximately 3 in populations under severe nitrogen limitation while a ratio of 1 was indicative of nutrient-sufficient populations.

No consistent pattern of reduction or enhancement of carbon-14 uptake could be demonstrated with the addition of nitrate or phosphate alone or in combination to Tampa Bay or LMR samples based on seasonal responses of populations from all salinity zones and Tampa Bay (Vargo 1990) or the annual averages for each location (Fig. 11). Enhancement of dark carbon-14 uptake followed a similar pattern although annual averages did yield consistent ratios >1 for all locations in both years (Fig. 11). However, ratios of approximately 3 or greater occurred on only two occasions (February and October 1989). Thus, phytoplankton populations in the LMR and Tampa Bay can be considered nutrient sufficient to borderline nitrogen limited for short-term photosynthesis requirements.

Relationships with Chlorophyll

The photosynthetic index (PI), or assimilation number, is defined as the maximum rate of photosynthesis at light saturation normalized to the chlorophyll concentration (mgC/mgChl/hr). It is often used as an indication of the physiological status of phytoplankton populations especially when potential productivity is measured, i.e. photosynthesis rates determined with short incubation times (4-6 hours) under constant light and temperature conditions (Curl and Small 1965, Malone 1971, Eppley et al. 1973). Production rates determined in the Alafia river and the 1988-1989 LMR study met these requirements whereas production rates determined during the second year LMR study, which were incubated under *in situ* temperature and light conditions for 24 hours, did not.

Average PI indices for stations located within the zone of saline penetration (mouth, 7 and 8) of the Alafia river were within the range found for the 1988-1989 LMR study (Table 3). PI values for stations upstream of station 7 were approximately 3; the high indices at stations 5 and A5 were the result of a single elevated value which, if deleted, yields indices comparable to the remaining fresh water stations.

Generally, the PI index for the <1μm size fraction in the Alafia was greater than for the total size fraction.

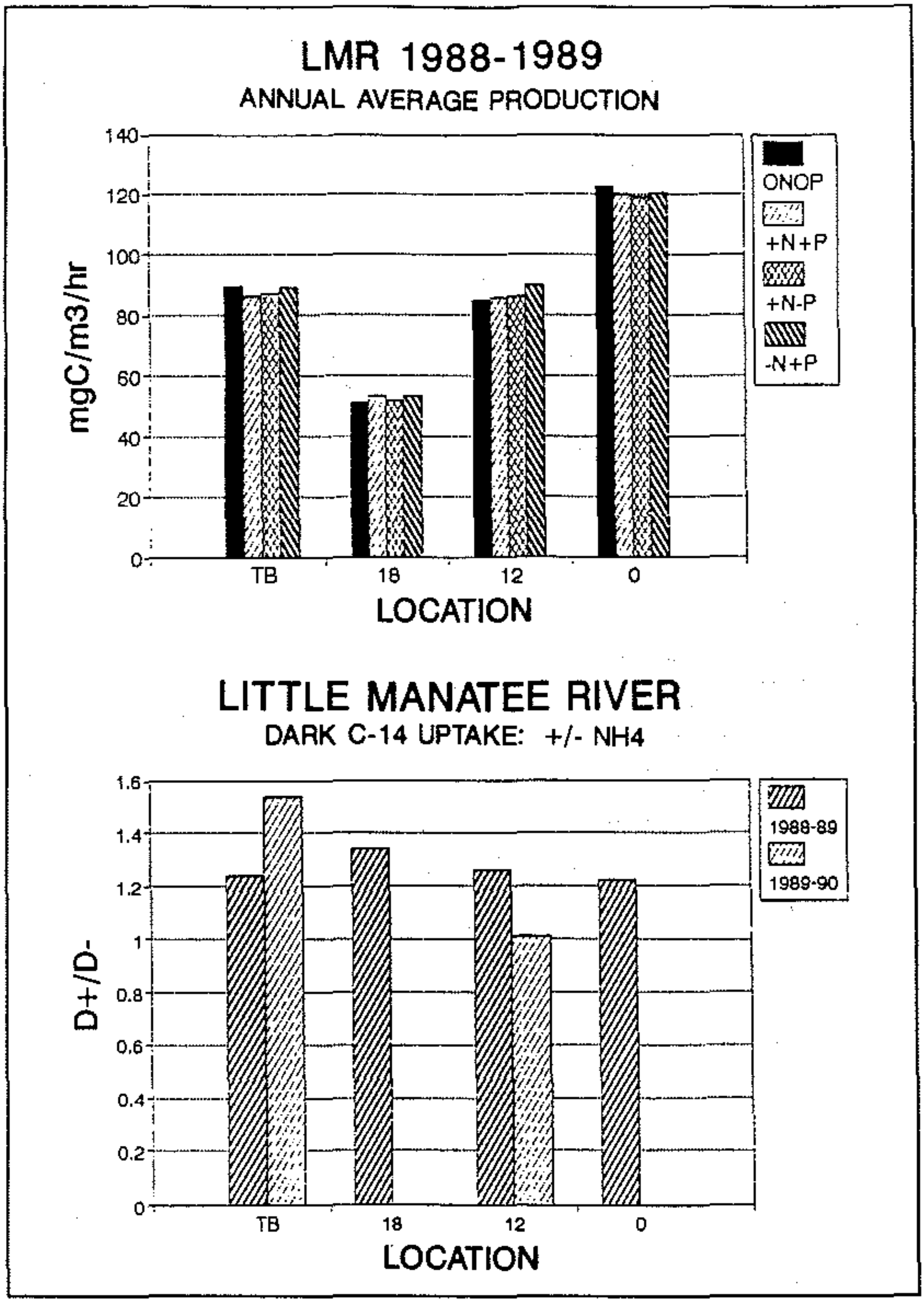


Figure 11. The effect of nitrate (N) and phosphate (P) added alone and in combination on potential primary production for four locations during the first LMR study (upper panel). Values are the annual averages for all combinations of N and P additions. Annually averaged values for the ratio of dark carbon-14 uptake during 3-hour incubations with (D+) and without (D-) the addition of 5 ug-at/l ammonium (lower panel).

The PI index for Tampa Bay during the 1988-1989 study displayed considerable seasonal variation with values that ranged from less than 1 to 25 but were generally greater than 5 (Fig. 8). Indices for the LMR locations generally ranged between 5 and 15 although several higher values were found at the 0 ppt salinity zone (Fig. 8). Annual averages for the bay and river were all greater than 8. There were no obvious trends between the PI values and salinity although the seasonal averages for LMR locations tended to decrease with decreasing salinity (Table 3).

Although PI values for the second LMR study were lower than the first year values, they were within the range reported for a wide variety of marine waters (Malone 1980). Lower PI values for the second LMR study may have resulted from differences in methodology as noted above. Therefore, the indices were not directly comparable with those calculated during the earlier study. Additional information on the PI indices for the second LMR study and their relationships with other factors is contained in Vargo (1991) and will not be reiterated here.

Table 3. Average photosynthetic index values (PI, mgC/mgChl/hr) for Tampa Bay, the Alafia and Little Manatee Rivers. Values in parentheses for station 5 and A5 of the Alafia River are averages computed with the single highest monthly PI removed.

		SIZE FRACTION			
LOCATION	TOTAL	>12 μm	>5<12 μm	<5 μm	<1 μm
Alafia					
Station 1	2.16				4.42
3	3.13				5.28
5	9.28 (3.3)				5.87
A5	8.32 (3.9)				9.93
6	2.73				4.95
7	8.33				2.71
8	9.08				14.68
Mouth	12.86				
Little Manatee, Year 1					
18	12.34				
12	11.41				
0	8.79				
Little Manatee, Year 2					
12	2.63	3.22	4.15	3.47	
Tampa Bay, Year 1	10.66				
Tampa Bay, Year 2	1.38	1.25	2.60	4.40	

In general, if phytoplankton populations are not nutrient limited, then production rates should be proportional to biomass. Positive linear relationships between production and biomass were obtained for Tampa Bay and LMR locations during the 1988-1989 study (Fig. 12) and for the annual averages of production and chlorophyll for the Alafia river and the LMR (Fig. 13). In the Alafia, linear regressions of productivity and chlorophyll for all locations except stations 5 and A5 had correlation coefficients greater than 0.6 while the annual averages for all river stations had a coefficient of 0.7. Correlation coefficients for Tampa Bay and the individual LMR locations (Fig. 12) ranged from 0.59 to 0.96 (12 ppt) while the annual average relationship (Fig. 13) was highly correlated ($r^2 = 0.94$). All relationships between production and biomass obtained for the Alafia river and LMR 1988-1989 studies were indicative of nutrient replete phytoplankton populations.

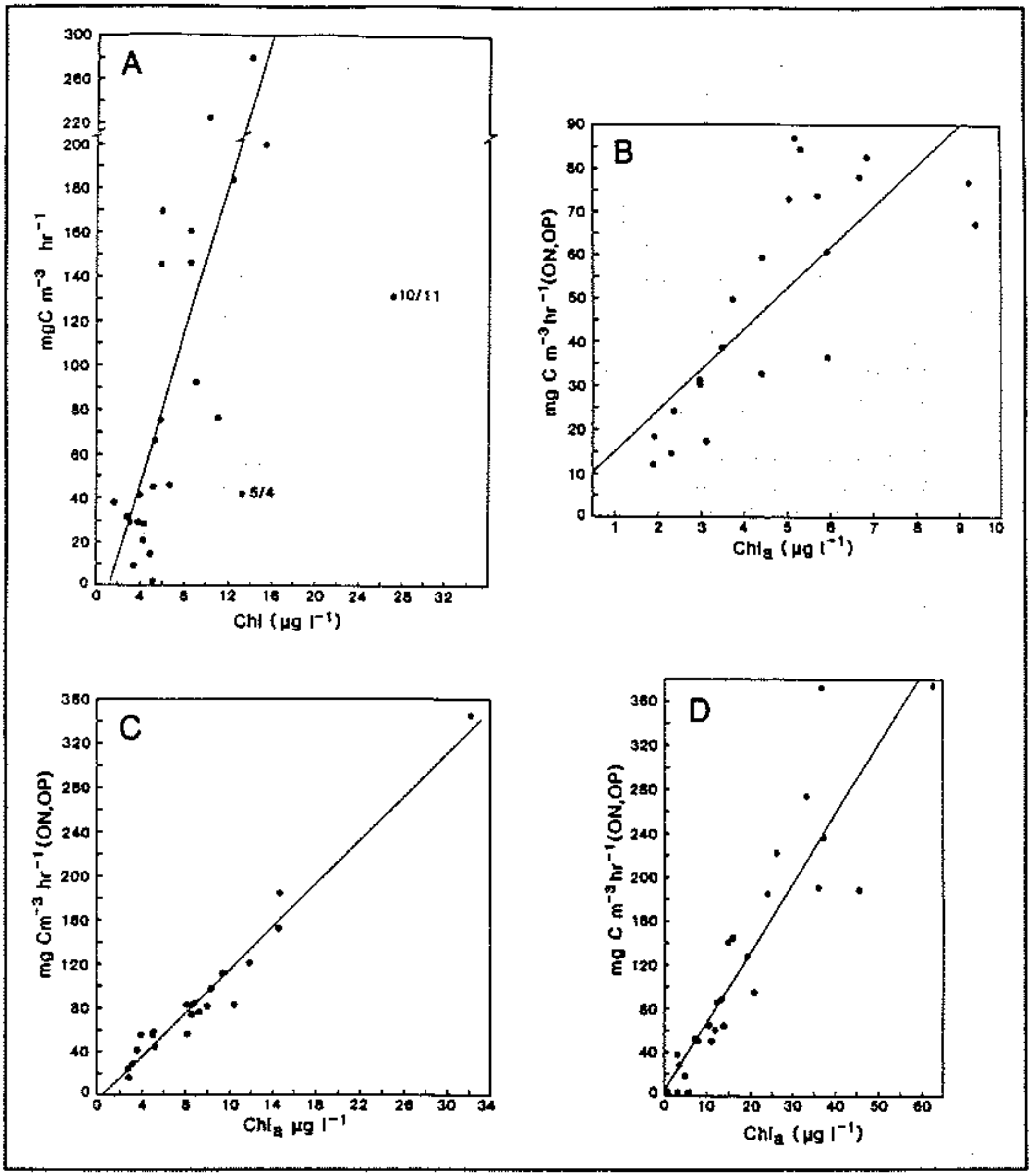


Figure 12. Relationships between potential primary production (mgC/m^3/hr) and chlorophyll concentration (µg/l) in samples without nitrate and phosphate additions for Tampa Bay (A), the 18 ppt salinity zone (B), the 12 ppt salinity zone (C), and the 0 ppt salinity zone (D) during the first LMR study (1988-1989). See text for regression coefficients.

Responses of Various Size Fractions

One method used to assess the dynamics of various components (groups or species) in the phytoplankton community is to determine the physiological responses of various cell size fractions. Although the physical partitioning of a phytoplankton community by screens or micropore filters does not correspond directly to the actual size of organisms, the general relationships between cell size and physiological response tends to follow established patterns (Malone 1980). Larger cells such as diatoms and large dinoflagellates are relatively easily separated with micropore filters although long chains of diatoms, which may have small diameters, can become incorporated into the "large" cell fraction. Since nutrient utilization rates can be related to cell size, the composition of and the competition between species in a community may be determined by nutrient availability. Turpin and Harrison (1979,1980; among others) have demonstrated that the magnitude and frequency of nutrient input can select for specific size classes of phytoplankton and act as regulators of competition between groups of phytoplankton. Therefore, information on the biomass, production rate, the physiological state, and the nutritional status of groups within the phytoplankton community is required for interpretation of potential interactions within the community, potential shifts in community structure and, in turn, relationships with higher trophic levels.

Limited information on size fractionated chlorophyll concentrations and primary production was available for the Alafia river from Paul et al. (in press). They were primarily concerned with microbial and dissolved DNA dynamics and consequently investigated the response of the <1 μm size fraction. This size fraction contributed 10% to 25% of the total chlorophyll at stations 1 to 7 whereas the larger fraction represented 96% of the chlorophyll at the mouth (Fig. 5). Annually, the <1 μm fraction represented 8% to 23% of the total primary production at stations 1 to 7 and approximately 3% at the mouth (Fig. 7). Generally, production in the <1 μm fraction contributed a greater proportion of the total at locations upstream of station A5 (Lithia Springs). The values used in Figure 7 were biased by the use of annual averages. There was a high degree of seasonal variability at each location. For example, the seasonal range in the contribution of the <1 μm fraction at station 8, which had the lowest annual average, was 3% to 65% for primary production and 2% to 100% for chlorophyll concentration. Highest values occurred in February. Production and chlorophyll in the <1 μm fraction represented 59% and 33% of the total, respectively, at station 5 and 43% and 16% at station 1. Therefore, in the upstream sections of the Alafia river the small size fraction represented a significant proportion of the biomass and productivity of the phytoplankton community and was seasonally important at the highly productive area near the mouth of the river.

The distribution of chlorophyll and primary production in four size fractions in Tampa Bay and the 12 ppt salinity zone of the LMR was examined during the 1989-1990 season. The annual cycle of chlorophyll in the <12 and <5 μm fractions corresponded to that of the total in both the bay and river (Fig. 9); however, the relative contribution of these size fractions varied seasonally and with location. The >12 μm fraction dominated the biomass from May to October in the bay and river whereas the <12 and <5 μm fractions never contributed more than 30% of the total during this period in Tampa Bay (Fig. 9). Smaller size fractions dominated the biomass during winter/spring in the bay and river and were a significant component of the river community during the May-October period (Fig. 9). Annual averages indicated that the >12 μm fraction, which represented diatom populations, contributed 82% of the total chlorophyll in Tampa Bay and 52% at 12 ppt in the river (Table 4). The <5 μm fraction, composed primarily of microflagellates and picoplankton, represented a greater proportion of the chlorophyll concentration in the river (35%) than in the bay (10%).

Annual cycles of primary production in several size categories followed the seasonal pattern for the total in both Tampa Bay and the LMR (Fig. 10). However, the proportion contributed by the >12 and <5 μm fractions varied seasonally and with location. Production in the bay was dominated by the >12 μm fraction for most of the year whereas there was a distinct seasonal partitioning of production between the <5 and >12 μm fractions in the river (Fig. 7). Although the >12 μm fraction represented a greater proportion of the biomass in the river from May through October, smaller size fractions were clearly physiologically dominant from February through July (Fig. 7). This dominance was reflected in the annually integrated production values for each location. The >12 μm fraction dominated in the bay, contributing 59% of the total, while partitioning between the >12 and <5 μm fractions in the river was essentially equivalent (Table 4). However, smaller components of the phytoplankton community clearly dominated production in the river since the sum of the <5 and >5<12 µm fractions represents 60% of the annual integrated total.

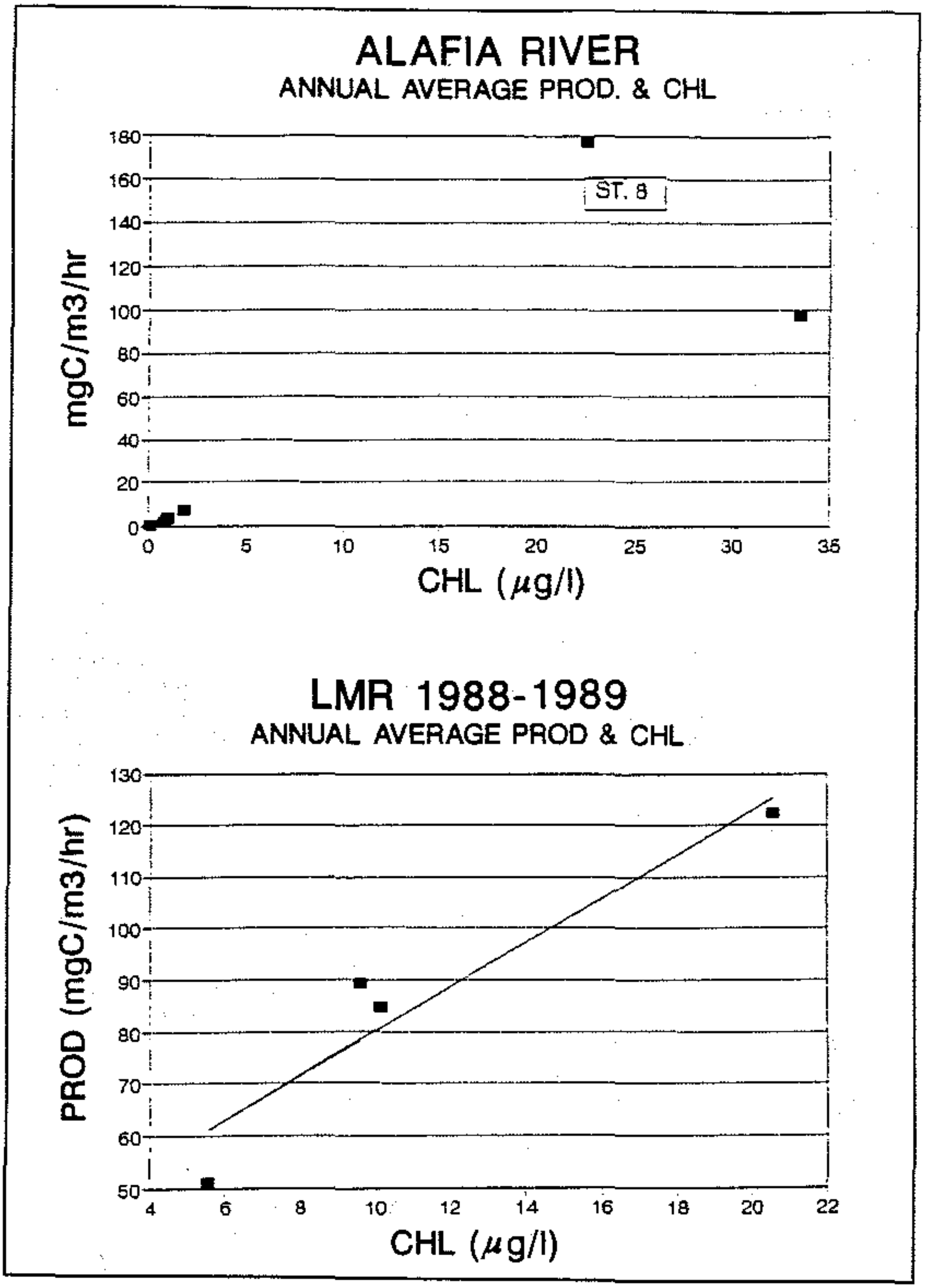


Figure 13. Relationships between annually averaged values of potential production and chlorophyll concentration for the Alafia River and the Little Manatee River. See text for regression coefficients.

Table 4. Annual integrated primary production and the average annual chlorophyll concentration for several size fractions in Tampa Bay and the Little Manatee River at the 12 ppt salinity zone during the 1989-1990 study.

	PRODUCTION (μgC/m²/yr):				CHLOROPHYLL (μgChl/l):			
	TOTAL	>12	>5<12	<5	TOTAL	>12	>5<12	<5 μm
Tampa Bay	174.6	103.1	27.4	44.3	13.98	11.49	1.06	1.43
Percent of total		59.0	15.7	25.3		82.2	7.6	10.2
Little Manatee	138.2	54.9	20.9	62.4	8.94	4.68	1.12	3.14
Percent of total		39.7	15.1	45.2		52.3	12.5	35.2

SUMMARY AND CONCLUSIONS

1. Elevated primary production rates in the Alafia River occurred within the region influenced by tidal movement and salt penetration. While station locations cannot accurately determine the extent of tidal mixing and saline influence, the salinities at stations 7 and 8 are indicative of bay-river interactions. In the LMR, low chlorophyll concentrations in the freshwater section of the river, coupled with elevated production at the 0 ppt salinity zone (which had an annual average salinity of 0.2 ppt) also suggests that physical mechanisms which operate in the region of salt and freshwater interaction contribute significantly to the maintenance of phytoplankton biomass and production. Indeed, Cloern et al. (1983) demonstrated a relationship between density-selective accumulation of diatom populations and estuarine circulation under specific freshwater flow regimes in a tribuatry of San Francisco Bay. Therefore, circulation patterns based on estuarine dynamics (freshwater/saltwater interactions) appear to play a major role in maintaining primary production in at least two tributaries of Tampa Bay.
2. The time scale of phytoplankton-associated events in Tampa Bay and the LMR, based on the 1988-1989 season, is on the order of weeks. Monthly sampling, as our second year LMR study suggests, may lead to a biased view of seasonal cycles.
3. Nutrient addition experiments performed during the 1988-1989 season in the LMR combined with PI values from the LMR and downstream stations of the Alafia river and the relationships between biomass and productivity in the LMR suggest that short-term phytoplankton production in the Alafia and LMR is not nutrient limited. Dark carbon-14 uptake experiments for both LMR studies further indicate nitrogen sufficient to borderline nitrogen limitation of short-term production in the LMR (Vargo, 1990, 1991). Although dissolved inorganic nitrogen to phosphate ratios in the LMR and Tampa Bay are indicative of potential nitrogen limitation (Table 2), nitrate and ammonium concentrations in both the Alafia and LMR are rarely undetectable. Therefore, river input and recycling mechanisms apparently are sufficient to meet photosynthetic requirements. However, nitrogen appears to be the major limiting nutrient for long term growth in the LMR and Tampa Bay. Linear relationships between ammonium additions and final yield in assays of natural populations from Tampa Bay and the 12 ppt salinity zone of the LMR indicate nitrogen was the only nutrient limiting growth (Rodriguez and Vargo 1991). Low nitrogen and phosphorus to silica ratios for the bay and the LMR (Table 2) suggest that diatom populations would dominate the phytoplankton community (Hecky and Kilham 1988, Doering et al. 1989). Indeed, the >12 μm size fraction (diatoms) dominated the final yields in all of the LMR and Tampa Bay nitrogen addition experiments. High silicate levels, at least in the LMR, combined with pulses of nitrogen from upstream inputs, may therefore govern the magnitude of the phytoplankton standing crop and the dominance by larger size fractions (i.e. diatoms) in Tampa Bay and its tributaries.

4. Seasonal shifts in the dominance of functional size groups in the phytoplankton community characterize Tampa Bay, the LMR and, to a lesser extent, the Alafia River. Particle size is related to food chain dynamics since zooplankton or microzooplankton selectively graze on specific size classes of phytoplankton (Cowles 1979, Poulet and Marsot 1980, Frost 1980). The preponderance of one size category over another may also determine the type of food web present (Cushing 1989). Dominance by nanoplankton (<20 μm) and ultraplankton (<5 μm) tend to increase the importance of the microbial food web (Azam et al. 1983, Cushing 1989) which includes bacteria and microzooplankton intermediaries. Larger size cells such as diatoms are major components in more traditional food chains, which, as Cushing (1989) and Legendre (1990) note, are related to the major fisheries of temperate regions of the world. However, significant contributions to biomass and production by the nano- and ultraplankton size fractions in the LMR indicate that they have a major role in the carbon flux and trophic dynamics of the river-bay ecosystem. Negligible sinking rates for the smaller size fractions (Takahashi and Bienfang 1983) imply that this component of the phytoplankton community will remain suspended in the water column for longer periods of time. Therefore, they will be available for utilization by water column herbivores and demersal or epibenthic predators and, based on their higher PI indices, may be responsible for a large proportion of the carbon flux in the LMR.
5. Alternately, it is clear that nitrogen additions to Tampa Bay and LMR populations will result in dramatically increased yields of diatom populations. What is the fate of carbon production by the larger size fractions? Diatom blooms of high magnitude imply growth rates greater than loss rates. When time lags between increases in diatom populations and herbivorous zooplankton or other grazers occur, the carbon represented by such blooms is not completely utilized in the water column. Rapid and, at times, complete sedimentation of diatom blooms to the bottom occurs (see Legendre 1990). If benthic communities are not capable of utilizing this influx of carbon, then microbial degradation processes can lead to anoxia. Diatoms are commonly considered to be desirable species because of their role in traditional food chains; they usually do not form noxious surface blooms; and, with at least one exception, they do not produce toxins (Officer and Ryther 1980, Ryther and Officer 1981, Hecky and Kilham 1988). However, carbon flux in excess of use can lead to environmental degradation no matter what the source of carbon. The proportions of nitrogen and silicate is critical to the maintenance of diatom populations and to the level of biomass (chlorophyll) in the bay-tributary complex. Both nutrients can be related to freshwater influx, with nitrogen input also related to a variety of external loading factors. Increased knowledge of the interplay between freshwater flows and nitrogen and silicate fluxes is critical for the maintenance of phytoplankton populations, particularly diatom populations in the tributary/estuary complex. However, the fate of elevated diatom populations must also be known in order to establish relationships with higher trophic levels of potential economic importance. For the present, however, nitrogen input must be regulated since it is the key factor in establishing levels of phytoplankton biomass in Tampa Bay and the Little Manatee River.

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FISH NURSERY UTILIZATION OF THE LITTLE MANATEE RIVER ESTUARY: RELATIONSHIPS TO PHYSICOCHEMICAL GRADIENTS AND THE DISTRIBUTION OF FOOD RESOURCES

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ABSTRACT

A two-year survey of ichthyoplankton, juvenile fishes, zooplankton, phytoplankton, water chemistry and freshwater inflows in the Little Manatee River estuary was used to describe distributions of these parameters with emphasis on relationships with freshwater discharge. Salinity zone volumes in the tidal river were found to have a curvilinear relationship with freshwater flow. The tidal portion of the river was heavily utilized by young estuarine-dependent fishes, including menhaden (Brevoortia spp.), bay anchovies (Anchoa mitchilli), snook (Centropomus undecimalis), red drum (Sciaenops ocellatus), sand seatrout (Cynoscion arenarius), spot (Leiostomus xanthurus), and striped mullet (Mugil cephalus). Migrations into the tidal river were evident in relationships between fish length and salinity at capture and also in age-specific plots of fine-scale spatial distribution. Most fish species migrated to and concentrated within the lower 16 km of the river during the postlarval or early juvenile stage, with spatial peaks in mean fish concentration coinciding with peaks in mean mysid, amphipod, and harpacticoid copepod abundance. Tampa Bay's plankton assemblage was dominated by calanoid and cyclopoid copepods, which invaded the lower river at times of low discharge, and appeared to be more susceptible to discharge-induced displacement downstream than did mysids, amphipods and harpacticoid copepods. Various nutrients and dissolved organic carbon were positively correlated with freshwater discharge, while chlorophyll a levels in the water column of the upper tidal river were negatively correlated with discharge. A recently initiated trophic study indicates that detritus deposition and benthic diatom production are important contributors to the base of the tidal river's food web, with mysids, amphipods, harpacticoid copepods, and juvenile anchovies functioning as trophic intermediates between these forms of organic carbon and young estuarine-dependent fishes.

INTRODUCTION

The utilization of low salinity nursery habitats in creeks and rivers has been observed for the early juvenile stages of many ecologically and economically important fishes (Wilkins and Lewis 1971, Gilmore et al. 1983, Weinstein 1983, Rogers et al. 1984, Rozas and Hackney 1984, Hastings et al. 1987, Peters and McMichael 1987). Fishes which exploit these geographically limited habitats appear to be among the most successful of coastal fishes (Miller et al. 1985). Furthermore, species which migrate offshore following occupation of low salinity habitats contribute either directly or indirectly to fisheries production outside the estuary (Deegan 1985). These observations have led local resource managers to suggest that the proper management of tidal creek and river habitats is critical for maintaining or improving fisheries associated with Tampa Bay (TBRPC 1986, Lewis and Estevez 1988). The development of good management strategies, however, has been hampered by a lack of data specific to these habitats. With the exception of some recent work (Edwards, this volume; Haddad et al. 1989a, 1989b, 1990, McMichael 1989), studies of Tampa Bay have not examined fish communities upstream of creek or river mouths.

A central component of the multidisciplinary Little Manatee River (LMR) project has been an investigation of fish utilization of the tidal portion of the river and the ecological linkage between the fish communities of the river and Tampa Bay. In this effort, ichthyoplankton and shoreline fish communities were sampled biweekly for two years along a 21 km transect between fresh water and the open, saline waters of Tampa Bay. Fish sampling was coordinated with monitoring programs for zooplankton, phytoplankton, water chemistry and freshwater inflows. This paper

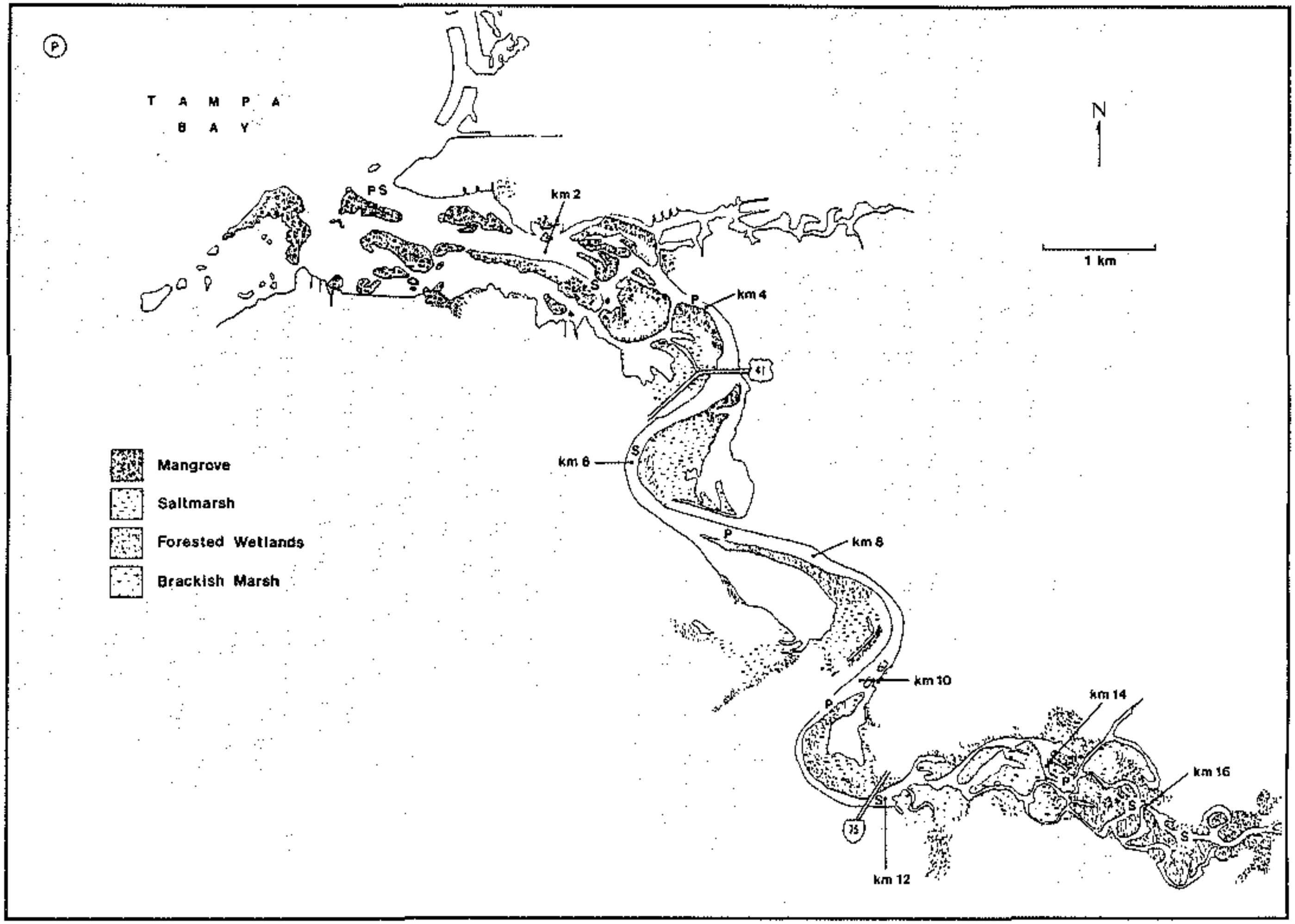

Figure 1. Estuarine portion of the Little Manatee River, indicating plankton (P) and seine (S) collection locations.

presents an overview of the fisheries-related findings of the project. For more detailed information, readers are encouraged to consult technical reports available from the Southwest Florida Water Management District (Peebles, in prep.; Rast and Hopkins 1991; SWFWMD and Dames & Moore, in prep.; Vargo 1991) or the Florida Marine Research Institute (Haddad et al. 1990).

The results presented in this paper are organized along two general themes. The first is a description of basic spatial and temporal patterns of fish utilization of habitats within the tidal river. Since the pre-recruit period begins at spawning, we have identified species whose spawning activity could potentially be impacted by watershed-related processes. For those fishes which concentrate in low salinity habitats at early stages, but were evidently spawned elsewhere, we have documented post-spawning immigrations of young fishes into the river.

The second objective of this paper is to investigate the influence of freshwater discharge on the quantity and quality of tidal river nursery habitat. McHugh (1967) has proposed that fishes with wide salinity tolerances use estuaries as nursery grounds in order to take advantage of the relatively low species diversity which typically occurs there; reduced diversity is reflected in both a reduced number of predatory species and a reduced number of species competing for abundant estuarine food resources. A second hypothesis holds that productive habitats such as estuaries promote rapid growth, which lowers predation pressure by reducing the time spent at smaller, more vulnerable sizes (Ware 1975, Morse 1989). These two hypotheses are correlative, and together they define the nursery in dynamic terms of salinity structure (=species composition) and food resource availability (=growth potential). In addressing our second objective, we examine the watershed's influences on salinity zone formation and the availability of food resources within the Little Manatee River estuary.

THE STUDY AREA

The Little Manatee River (LMR) drains approximately 576 km^2 of Hillsborough and Manatee Counties and flows into Middle Tampa Bay along its eastern shore. Streamflow in the river is characterized by low flows in the spring and fall and high flows during the summer wet season (June to September), during which roughly 60% of the yearly streamflow typically occurs. Water quality in the freshwater reaches of the river is characterized by high levels of color and dissolved nutrients and low levels of phytoplankton, as indicated by chlorophyll *a*. Additional information regarding the watershed and the freshwater characteristics of the river are presented elsewhere in this volume by Flannery et al.

The estuarine portion of the river is considered to be the lower 16-18 km of river channel (Fig. 1), since brackish waters (>1 ppt) do not typically extend upstream of 16-18 km during the dry season. Daily tidal amplitudes average 0.76 m at the mouth of the river. Downstream of kilometer 18, the Little Manatee River estuary has a surface area of about 5.6 km^2 and contains a water volume of about 6.8×10^6 m^3 at mean tide. In addition to these open water habitats, the estuary contains over 5.8 km^2 of associated mangrove, saltmarsh, brackish marsh and forested wetlands.

The tidal river can be divided into three zones based on the physical and vegetative characteristics of its shorelines (see Figure 1). Between the river's mouth and kilometer 4, the river channel is divided by numerous islands with mangroves (primarily red mangrove, *Rhizophora mangle*) dominating those shorelines which have not been developed. Oyster growth is moderate to extensive along the shoreline of the lower river, and seagrass beds (primarily *Halodule* and *Thalassia*) occur on the shallow (<1 m), sandy flats near the river's mouth. Farther upstream, between kilometers 4 and 12, the river is confined to one channel but three relatively large tidal embayments connect with the channel. Saltmarshes, dominated by the black rush (*Juncus roemerianus*), are associated with the interiors of each of these embayments.

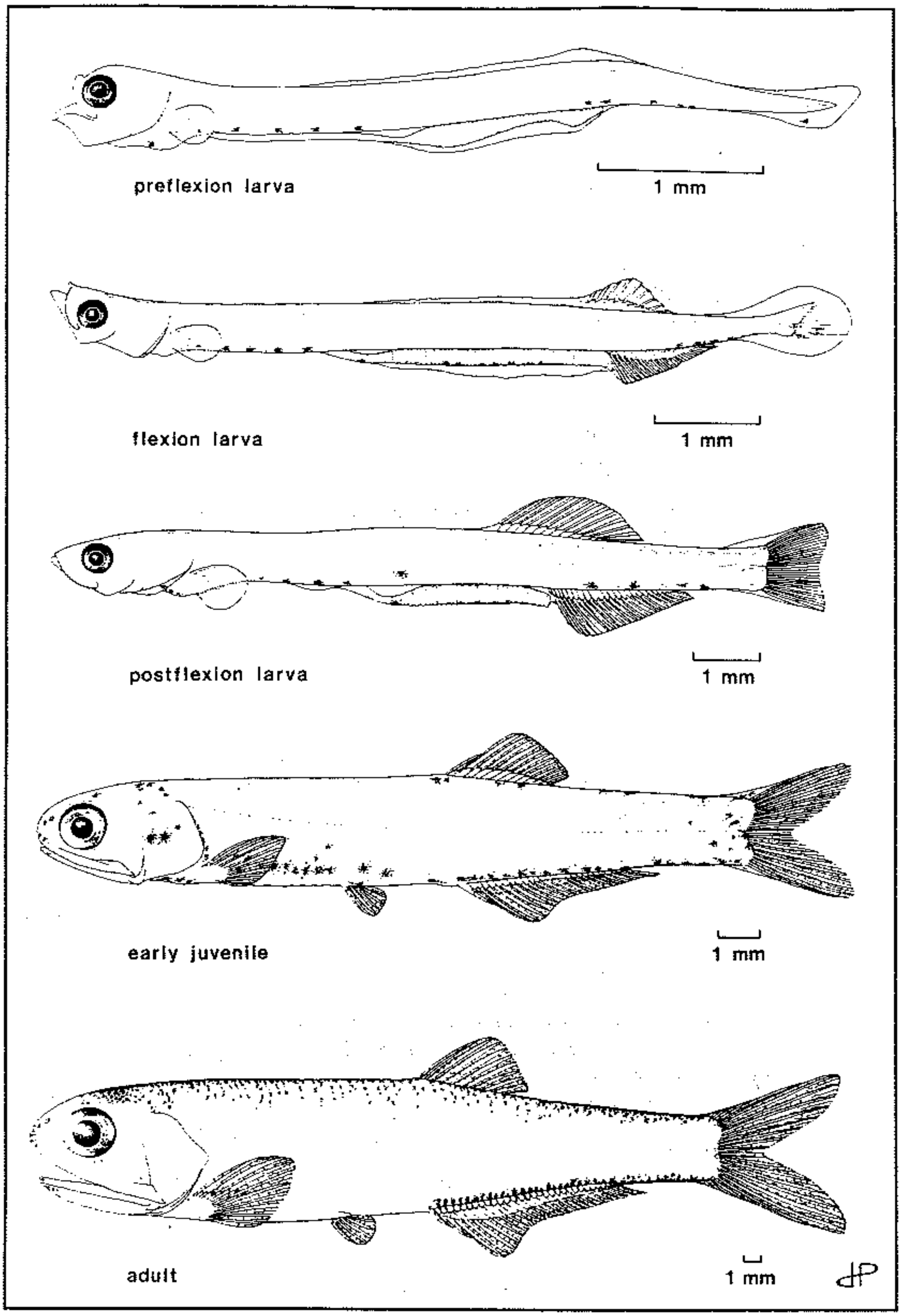

Figure 2. Developmental stages of bay anchovy (Anchoa mitchilli) collected from the LMR estuary and Tampa Bay, measuring 4.6, 7.0, 10.5, 16, and 33 mm SL.

In this 4-12 km reach, the river channel meanders within a well-defined corridor with high bluffs occurring alternately on erosional, outside banks of turns in the channel. Narrow bands of intertidal wetlands occur along the depositional, inside banks in this area. Between kilometers 12 and 16, the river again becomes braided with shorelines dominated by brackish wetlands (*Typha*, *Acrostichum*, *Cladium* and *Juncus*). Above kilometer 16, in the freshwater reaches, the river largely returns to one primary channel and freshwater aquatic vegetation (*Nuphar luteum*, *Hydrocotyle* spp.) becomes more common. Hardwood forests typically border the river upstream of kilometer 15.

METHODS

The collection of plankton, seine, and water chemistry samples were achieved through independent field efforts: plankton samples were collected by the USF Department of Marine Science; seine samples were collected by the Florida Marine Research Institute (FMRI), and water chemistry samples were collected by the Southwest Florida Water Management District (SWFWMD).

Ichthyoplankton and Macrozooplankton Collections

Ichthyoplankton/macrozooplankton collections were made at fixed locations along the longitudinal axis of the LMR estuary from January 1988 through January 1990. During 1988 and early 1989, 24 collections were made at two-week intervals at six locations along an 18 km transect between a very low salinity area of the estuary and the open waters of Tampa Bay (Fig. 1). Collections were continued at river kilometers -3.5, 0.0, 3.8 and 10.3 during the remainder of 1989 and in early 1990, bringing the total number of collection dates to 48 during the two-year period.

All collections were made at night on a flood tide. Sampling gear consisted of a 0.5 meter mouth, 505 µm mesh, conical (3:1) plankton net equipped with a nylon bridle, a flowmeter, and a 1 liter cod-end jar. A 9 kg (20 lb.) lead weight was positioned 15 cm below the bottom of the mouth ring. At each location, two three-step oblique tows (bottom-midwater-surface), one surface tow and one bottom tow were made (total of 960 samples). Fishing depth of the weighted net was controlled by adjusting the length of the tow line while keeping tachometer readings and line angle constant. The line was attached to a hand-operated winch located on the gunnel near the transom, and this caused a controlled "crabbing" by the outboard-powered 5 m boat, which in turn directed propeller turbulence away from the towed net. The net was towed at approximately 2 m/s for 5 min, resulting in a tow length of about 500 m and an average volume-filtered of about 73 m^3. The contents of the net were rinsed into the cod-end jar and premeasured preservative was added, bringing the concentration to 6-10% sodium borate-buffered formalin in saline. Before and after net deployment, salinity, temperature, and dissolved oxygen were determined electronically at surface, at bottom, and at one-meter intervals between surface and bottom. The electronic meters were periodically tested against standard solutions, titrations, and other instruments. The flowmeters were calibrated before and after the study period.

In the laboratory, the oblique-tow ichthyoplankton samples were rinsed with water and transferred to 70% ethanol in deionized water. Dissecting microscopes were used to separate fishes from invertebrates for later identification, measurement, and enumeration. The taxonomic nomenclature used here follows Robins et al. (1980). All fishes were classified according to developmental stage. The classifications were based primarily on the status of skeletal development in the caudal region of the young fishes (Fig. 2), specifically:

- preflexion larval stage—period between hatching and notochord flexion; tip of notochord is most distal osteological feature.
- flexion larval stage—period during notochord flexion; upturned notochord or urostyle is most distal osteological feature.

- postlarval stage (= postflexion stage)—period between completion of flexion and juvenile stage; hypural bones are most distal osteological feature.
- juvenile stage—period beginning with attainment of meristic characters and body shape comparable to adult fish and ending with sexual maturity.

For each net sample, an estimate of median standard length was made for each developmental stage of each fish taxon collected, using an ocular micrometer for specimens <10 mm standard length. This number was based on a maximum of 20 specimens from each stage of each taxon. Approximately 35,000 fish were measured.

Fishes caught by the plankton nets were counted without splitting the samples, except on a few occasions when anchovy numbers were very large. In these samples, a plankton splitter (Motoda 1959) was used to split the anchovies after all other fishes had been removed. The abundances of fish eggs and dominant macrozooplankters (mysids, amphipods, isopods, cumaceans, decapod larvae, etc.) were estimated after subsampling, if necessary, with the Motoda splitter. For each sample, abundances of up to 10 dominant invertebrate groups were estimated. As a convention, invertebrate taxa represented by fewer than 10 individuals after splitting were considered to be nondominants, and their abundance was recorded only as presence-absence data. The presence of large particulate organic matter in the sample was recorded either as recognizable plant structures (leaves and sticks) or vascular plant tissue of indeterminant structure.

Zooplankton Survey

Zooplankton sampling was conducted in direct conjunction with the ichthyoplankton/macrozooplankton sampling. A >28 μm sample was taken from each end of the plankton tow region, with each sample consisting of four casts with an 11-liter Niskin bottle. The depths of the bottle casts were varied so that sampled depth ranges were comparable to the depth ranges sampled by corresponding plankton net tows. The water samples from each set of four casts were collectively filtered through a 28 μm Nitex sieve. Plankters retained by the sieve were then rinsed into sample jars for preservation in 3-5% sodium borate-buffered formalin in saline.

In the laboratory, the samples were split using a Motoda splitter until an aliquot of roughly 1500 plankters was obtained, which was then placed in ruled petri dishes. A minimum of 100 specimens of each dominant taxon was counted. In cases where it was not necessary to count all individuals in the entire petri dish, individuals in two crossing diagonal grid transects were counted. Most holoplanktonic taxa were identified to species level, whereas meroplankton, tychoplankton, and hypoplankton were identified to major group.

Seine Survey

Seine samples were collected biweekly from six fixed locations ranging between the river's mouth and nearly permanent fresh water 16 km upstream (Fig. 1). Although these collections are continuing at the time of writing, data reported here are taken from the time period from January 1988 through December 1989. Three seine hauls were made at each station on each collection date in 1988. In 1989, three hauls were made at kilometers 0.0 and 11.8 and two hauls were made at kilometers 2.5, 5.8, 15.5 and 16.4. A total of 689 hauls were made over the two-year period, with a minimum total of 90 hauls per station. Seining was conducted during daylight hours and required 10-12 hours of field effort on each collection date.

A 23 m bag seine with 3.2 mm mesh was used for all collections. Haul direction was perpendicular to the shoreline at all locations. All fishes collected were sorted to species and counted. Standard length was recorded for a maximum subsample size of 20 (during 1988) or 40 (during 1989) specimens per species per seine haul. Salinity, water temperature, dissolved oxygen, pH and turbidity were recorded for each collection. Additional details regarding sampling methodology can be found in Haddad et al. (1989a, 1989b, and 1990).

Water Chemistry Survey

The methods and results presented in this paper are limited to general water chemistry, including salinity and chlorophyll *a*. Results of the phytoplankton survey, primary production and nutrient limitation analyses are discussed by Vargo et al. (this volume). Water chemistry sampling was conducted 37 times during the study, at biweekly intervals during the first year (1988) and monthly intervals during the second year (1989). Four water chemistry stations had moveable positions which were determined by the location of the 0.5, 6.0, 12.0, and 18.0 ppt surface isohalines. A fifth water chemistry station was located at a fixed location in Tampa Bay, near the bay ichthyoplankton sampling site (Fig. 1).

An 8-liter Van Dorn bottle was used to sample surface and bottom waters on flood tides during morning or early afternoon hours. Water samples were placed on ice and transported to the SWFWMD laboratory where analyses were performed according to EPA (1983), APHA (1983), and Perkin-Elmer (1987). Samples for chlorophyll *a* determination were stored in dark bottles placed in an insulated river-water bath for transport to the FMRI laboratory in St. Petersburg, where they were filtered that afternoon. Chlorophyll *a* concentrations were measured spectrophotometrically on acetone extracts according to the equations of Lorenzen (1967) and Jeffrey and Humphrey (1975). Results using the Jeffrey and Humphrey equations are presented here.

In addition to the regular water chemistry sampling, 52 trips were made on the river between 1985 and 1989 in which vertical profiles of salinity and other *in situ* parameters were measured electronically at a minimum of 13 fixed stations under slack high tide conditions.

Analyses

Abundances of fishes and invertebrates collected by the plankton net and Niskin bottles were described as volumetric density (number collected/volume) using volumes determined from flow meter readings and known Niskin bottle capacities. Abundances of fishes collected by seines were standardized by correcting for variation in the area typically sampled by the seine at different locations. Zooplankton counts from both ends of each plankton net tow region were averaged. Whenever analyses necessitated the combination of individual abundance measurements, an average value was calculated for all collection attempts, including those where the taxon concerned was not collected.

For better comparison with the plankton and seine data, water chemistry values presented in this report are grouped by river zone. These zones correspond to the following divisions of the river channel upstream of the river mouth: 0.0 to 1.8; 1.8 to 5.3; 5.3 to 8.7; 8.7 to 12.2; and greater than 12.2 km. For a given date, all water chemistry parameters measured within a zone were averaged to yield a single set of values for that zone. Because the locations of water chemistry stations were based on surface isohalines, there were no data for some of the zones on particular dates. In these cases, water chemistry values from locations immediately upstream and downstream of a zone were averaged to produce an estimated value. All statistics were then generated from a data set that contained one set of values for each river zone-date combination.

The Kruskal-Wallis one-way ANOVA was used to test the significance of spatial variation in certain variables. For the biological data, Kruskal-Wallis tests were conducted using positive values only (zero catches were excluded). In calculating mean salinity at capture for the various taxa, the mean water column salinity at the time of collection was weighted by the instantaneous abundance of the taxon concerned.

Spearman's rank correlation was used to identify migratory or advective processes within the study area. For each fish developmental stage, correlations between median standard length (plankton samples) or mean standard length (seine samples) and average water column salinity at the time of capture were examined as potential indicators of movement against or along the salinity gradient. Similarly, correlations between freshwater discharge and biological and chemical variables were examined as evidence for discharge-related changes in abundance or concentration. These correlations were performed using preceding three-day average flows and data from the upstream locations (8.7-16.4 km), downstream locations (0.0-5.3 km), and all sampling locations (0.0-16.4 km) within the riverine estuary.

In order to predict freshwater discharge's influence on surface isohalines in the middle of the estuarine conveying channel, $\log_{10}$-transformed preceding three-day average flows from the Cypress Creek and LMR near Wimauma gages were regressed against locations of the 0.5, 6, 12 and 18 ppt isohalines as determined from 52 salinity surveys. In most cases, the isohaline locations used in these regressions were estimated by interpolating between adjacent fixed-location stations. The average distance between sampled locations was 1.4 km.

The total water volume of the riverine estuary was estimated using 1"=1000' aerial photography combined with tide-corrected depth tracings. Using volumes contained within 41 delineated polygons, a plot of cumulative volume increase in the downstream direction was obtained for the region between brackish water's typical upstream limit (18 km) and the mouth of the river.

RESULTS AND DISCUSSION

Over 120,000 fishes representing 72 species were identified from the ichthyoplankton collections. Seine collections yielded approximately 600,000 fishes representing 98 species. In regard to species number, roughly 40% of the species had peak abundances within the river; the remaining species invaded the study area to various extents, but generally had their abundances centered outside the tidal portion of the river. Our discussion here is limited to those species which appeared to spawn within or near the study area or concentrate within the study area after being spawned elsewhere. Emphasis is on fishes which were dominant in the collections and/or fishes which are of economic value. For the species selected, the frequency of collection and total number of individuals collected are presented in Table 1.

Spawning Ground Proximity

Many coastal fishes are highly fecund and have planktonic eggs which become distributed widely after spawning. The offspring of certain species can be reliably identified during the egg stage, but most do not become identifiable until the early larval stages or later. In relatively warm inshore waters, the egg and preflexion larval stages tend to have durations on the order of days rather than weeks. Species-specific spawning ground locations fall more or less along a continuum in the inshore-offshore direction. For convenience in later discussions, however, this continuum will be separated into two sections, with species which spawn in the LMR estuary or Tampa Bay referred to as "inshore" spawners, and those which spawn in the Gulf of Mexico on the continental shelf or beyond referred to as "offshore" spawners.

In treating the LMR study area as a whole, Table 2 illustrates the most basic patterns of larval stage distribution. Fishes listed in the upper categories of Table 2 were most abundant as early-stage larvae, suggesting that spawning occurred inshore. Conversely, species listed near the bottom of Table 2 were not collected in the study area until later developmental stages, suggesting that their spawning grounds were positioned farther offshore. It is likely that abundances of species with relatively small preflexion stage larvae were under-represented in the samples as a result of extrusion through the meshes. In general, however, the patterns identified during the ichthyoplankton survey are in good agreement with previously reported larval distributions, such as those summarized by Johnson (1978) and Fahay (1983).

Table 1. Catch data and distributional statistics for selected fishes collected by plankton net (P) and seine (S): numbers of individuals caught (n) which are indicated by e were estimated using split samples; f is collection frequency, which is the sample size used in statistical tests; S_D is density-weighted mean salinity at capture; r_s is the sign and probability value from Spearman's rank correlation between median fish length and salinity at capture; location of A_{max} is location (km) with the highest mean fish abundance; and KW is the probability value for significant variation among location mean fish densities as calculated using the Kruskal-Wallis ANOVA.

TAXON	STAGE	GEAR TYPE	n	f	$\bar{S}_D$	r_s	LOCATION OF A_{max}	KW
Clupeidae								
Brevoortia spp. (menhaden)	flexion	P	8	7	18.8	NS	BAY	NS
	postflexion	P	2388	125	2.8	- p<0.001	7.1	p=0.009
	juvenile	S	15413	78	1.6	+ p<0.001	11.8	p=0.005
Engraulidae								
Anchoa spp. (anchovies)	preflexion	P	9169 e	131	24.4	NS	BAY	p<0.001
	flexion	P	11287 e	155	25.7	NS	BAY	p<0.001
Anchoa hepsetus (striped anchovy)	eggs	P	563 e	9	26.2		BAY	NS
	postflexion	P	798 e	31	30.0	- p=0.05	BAY	NS
	early juvenile	P	45	13	28.4	NS	BAY	NS
	juvenile/adult	S	283	10	5.2	NS	5.8	NS
Anchoa mitchilli (bay anchovy)	eggs	P	9863 e	39	25.8		BAY	p=0.02
	postflexion	P	7909 e	175	22.1	- p<0.001	BAY	p<0.001
	early juvenile	P	40760 e	377	7.2	NS	7.1	p<0.001
	juvenile/adult	S	279689	421	5.5	+ p<0.001	11.6	p<0.001
Gobiesocidae								
Gobiesox strumosus (skilletfish)	eggs	P	332 e	9	22.1		0.0	NS
	preflexion	P	1950	175	17.6	- p=0.03	0.0	p=0.02
	flexion	P	2095	113	15.7	+ p=0.05	3.8	p=0.04
	postflexion	P	787	84	11.8	- p=0.005	7.1	NS
	juvenile	P	69	25	12.9	NS	3.8	NS
	adult	S	43	24	15.2	NS	0.0	p=0.008
Atherinidae								
Menidia spp. (silversides)	eggs	P	2	1	0.0		7.1	NS
	preflexion	P	83	37	14.2	NS	0.0	NS
	flexion	P	59	28	18.6	NS	0.0	NS
	postflexion	P	18	16	21.7	- p=0.05	BAY	NS
	early juvenile	P	77	31	6.8	NS	10.3	NS
	juvenile/adult	S	85938	553	11.7	+ p<0.001	2.5	p<0.001
Gerreidae	preflexion	P	62	23	25.2	NS	BAY	NS
	flexion	P	50	23	26.1	NS	0.0	p=0.01
Diapterus plumieri (striped mojarra)	postflexion	P	122	33	19.8	- p<0.001	0.0	NS
	juvenile	S	1241	115	2.9	NS	8.8	p=0.02
Eucinostomus spp. (mojarras)	postflexion	P	39	30	18.5	NS	3.8	NS
	early juvenile	P	23	17	6.2	NS	7.1	NS
	juvenile/adult	S	19738	321	8.4	+ p<0.001	2.5	p<0.001
Sciaenidae								
Bairdiella chrysoura (silver perch)	preflexion	P	275	47	24.8	NS	BAY	NS
	flexion	P	629	82	23.5	- p<0.001	0.0	p=0.002
	postflexion	P	216	71	16.4	- p<0.001	0.0	NS
	early juvenile	P	51	26	9.7	NS	0.0	NS
	juvenile	S	2529	67	11.1	NS	0.0	NS
Cynoscion arenarius (sand seatrout)	preflexion	P	716	63	25.2	+ p=0.01	BAY	p=0.03
	flexion	P	647	89	24.0	- p=0.05	BAY	p=0.008
	postflexion	P	444	98	18.8	- p<0.001	BAY	p<0.001
	early juvenile	P	84	26	5.4	- p=0.003	7.1	NS
	juvenile	S	328	39	5.6	NS	5.8	NS
Cynoscion nebulosus (spotted seatrout)	preflexion	P	123	46	25.1	+ p=0.01	BAY	p=0.003
	flexion	P	173	71	22.4	- p<0.001	0.0	p=0.007
	postflexion	P	67	37	16.1	NS	0.0	NS
	juvenile	S	660	103	11.2	+ p=0.05	0.0	p=0.002
Leiostomus xanthurus (spot)	postflexion	P	86	31	7.0	- p=0.001	10.3	NS
	early juvenile	P	22	13	4.2	- p=0.02	7.1	NS
	juvenile	S	16289	223	10.2	+ p<0.001	2.5	p<0.001
Menticirrhus spp. (kingfishes)	preflexion	P	314	50	24.2	NS	BAY	NS
	flexion	P	238	58	25.0	- p=0.05	BAY	NS
	postflexion	P	96	42	21.8	NS	BAY	NS
	juvenile	S	157	50	10.4	- p=0.01	5.8	p=0.03

(continued)

Table 1 continued.

TAXON	STAGE	GEAR TYPE	n	f	$\bar{S}_0$	r_s	LOCATION OF A_{max}	KW
Sciaenops ocellatus (red drum)	flexion	P	15	6	23.8	NS	BAY	NS
	postflexion	P	34	10	22.3	- p=0.02	BAY	NS
	early juvenile	S	1151	125	5.5	- p=0.02	5.8	p<0.001
Mugilidae								
Mugil cephalus (striped mullet)	juvenile	S	2416	161	5.7	- p=0.01	11.8	p=0.004
Blenniidae	preflexion	P	1157	119	21.5	NS	0.0	p=0.009
Chasmodes saburrae (Florida blenny)	flexion	P	379	61	23.4	NS	0.0	p=0.005
	postflexion	P	163	57	22.1	NS	0.0	p=0.07
	juvenile/adult	S	104	23	12.4	NS	0.0	NS
Gobiidae	preflexion	P	5210	200	18.6	- p<0.001	0.0	p=0.001
	flexion	P	195	11	14.9	NS	3.8	NS
Gobiosoma spp. (gobies)	flexion	P	8052	143	18.3	- p<0.001	3.8	p<0.001
	postflexion	P	10586	191	14.8	NS	3.8	p=0.002
	juvenile	P	317	39	9.9	NS	14.2	NS
	juvenile/adult	S	8597	372	1.9	NS	15.5	p<0.001
Gobiosoma bosci (naked goby)	juvenile	P	101	48	4.7	+ p=0.02	7.1	NS
Gobiosoma robustum (code goby)	juvenile	P	145	24	8.0	NS	14.2	NS
Microgobius spp. (gobies)	flexion	P	3093	186	21.5	NS	0.0	p=0.002
	postflexion	P	5642	168	23.6	- p<0.001	BAY	p<0.001
Microgobius gulosus (clown goby)	early juvenile	P	141	58	11.3	- p=0.02	10.3	NS
	juvenile/adult	S	7217	350	2.4	+ p<0.001	15.5	p=0.008
Bathygobius soporator (frillfin goby)	preflexion	P	779	60	22.0	NS	0.0	NS
	flexion	P	334	56	21.6	NS	3.8	p=0.02
	postflexion	P	124	34	23.1	- p=0.05	0.0	NS
	juvenile/adult	S	73	24	4.8	NS	2.5	NS
Microdesmidae								
Microdesmis sp. (wormfish)	preflexion	P	307	44	22.6	NS	0.0	NS
	flexion	P	62	30	22.9	NS	0.0	NS
	postflexion	P	13	11	19.6	NS	0.0	NS
Soleidae								
Achirus lineatus (lined sole)	preflexion	P	49	24	24.7	NS	BAY	NS
	flexion	P	83	36	25.3	NS	BAY	NS
	postflexion	P	202	69	21.2	- p=0.03	BAY	p=0.005
	juvenile	P	30	19	6.0	NS	0.0	NS
	juvenile/adult	S	58	19	17.3	NS	0.0	NS
Trinectes maculatus (hogchoker)	preflexion	P	210	56	19.3	NS	0.0	NS
	flexion	P	185	65	16.8	- p<0.001	0.0	p=0.01
	postflexion	P	433	101	10.4	- p<0.001	3.8	NS
	juvenile	P	231	69	1.7	- p=0.04	10.3	NS
	juvenile/adult	S	21630	440	0.4	+ p<0.001	15.5	p<0.001
Unidentified	eggs	P	167840 e	132	26.2		BAY	p=0.05

Among fishes considered to be inshore spawners, those which spawn within the LMR estuary can be assumed to be the most likely to be impacted by changes in the watershed. In order to separate these species from other inshore spawners, spatial distributions were examined on a finer scale. Examples of fine-scale distributional patterns are presented in Figures 3 and 4. Table 1 summarizes fine-scale distributional data by identifying locations of maximum abundance and by indicating whether or not abundance varied significantly with location (Kruskal-Wallis ANOVA, $p<0.05$). In Table 1 and Figures 3 and 4, it can be seen that the earliest stages of some inshore spawners had their highest abundance in Tampa Bay, whereas the earliest stages of other inshore spawners had peak abundance within the tidal river. If it is assumed that the latter pattern occurred because these species spawned in closer proximity to the tidal river than did other inshore spawners, then fishes such as the skilletfish (*Gobiesox strumosus*), the Florida blenny (*Chasmodes saburrae*), gobies of the genus *Gobiosoma*, the frillfin goby (*Bathygobius soporator*), and the wormfish (*Microdesmis* sp.) spawned within or very close to the tidal river.

Table 2. Relative abundance of preflexion (PR), flexion (FL), and postflexion (PO) stage larvae of estuarine and estuarine-dependent fishes:
X = most abundant stage, as determined by number collected
x = stage collected, but not most abundant
\+ = stage included in higher resolution taxonomic category
\- = stage included in lower resolution taxonomic category

TAXONOMIC CATEGORY	STAGE PR	FL	PO
Bathygobius soporator (frillfin goby)	X	x	x
Microdesmis sp. (wormfish)	X	x	x
Cynoscion arenarius (sand seatrout)	X	x	x
Menticirrhus spp. (kingfishes)	X	x	x
Prionotus spp. (searobins)	X	x	x
Menidia spp. (silversides)	X	x	x
Blenniidae (blennies)	X	+	+
Chasmodes saburrae (Florida blenny)	-	x	x
Gobiesox strumosus (skilletfish)	x	X	x
Bairdiella chrysoura (silver perch)	x	X	x
Cynoscion nebulosus (spotted seatrout)	x	X	x
Anchoa spp. (anchovies)	x	X	+
Anchoa mitchilli (bay anchovy)	-	-	x
Anchoa hepsetus (striped anchovy)	-	-	x
Trinectes maculatus (hogchoker)	x	x	X
Achirus lineatus (lined sole)	x	x	X
Gerreidae (mojarras)	x	x	+
Eucinostomus spp. (mojarras)	-	-	x
Diapterus plumieri (striped mojarra)	-	-	X
Gobiidae (gobies, excl. Bathygobius)	x	+	+
Gobiosoma spp. (gobies)	-	x	X
Microgobius spp. (gobies)	-	x	X
Brevoortia spp. (menhaden)		x	X
Orthopristis chrysoptera (pigfish)		x	X
Sciaenops ocellatus (red drum)		x	X
Archosargus probatocephalus (sheepshead)		x	X
Micropogonias undulatus (Atlantic croaker)		x	X
Leiostomus xanthurus (spot)			X
Synodus foetens (inshore lizardfish)			X
Elops saurus (ladyfish)			X

Among species which do not widely broadcast their offspring, there were many which appeared to reproduce within or very near the tidal portion of the LMR. Killifishes (cyprinodontids), for example, have relatively low fecundities and hatch at relatively advanced stages of development. The collection of what appeared to be newly-hatched killifishes in the study area suggests that some killifishes, in particular the rainwater killifish (*Lucania parva*) and the Seminole killifish (*Fundulus seminolis*), spawned within the study area. Similarly, tilapia (*Tilapia* spp.) and Gulf toadfish (*Opsanus beta*) protect their young for a period of time after hatching, and therefore collection of small juveniles suggests that both spawned in the study area. Parturition by live-bearing mosquitofish (*Gambusia affinis*), sailfin mollies (*Poecilia latipinna*), Gulf pipefish (*Syngnathus scovelli*), and chain pipefish (*Syngnathus louisianae*) also appeared to occur within the study area. On one occasion, eggs of the tidewater silverside (*Menidia beryllina*) were collected from vegetation in fresh water. Because the genus *Menidia* could not be identified to species during the larval stages, it is likely that the data for this genus in Table 1 reflects a combination of the early life history patterns of *M. beryllina* and *M. peninsulae*, both of which occur in the study area.

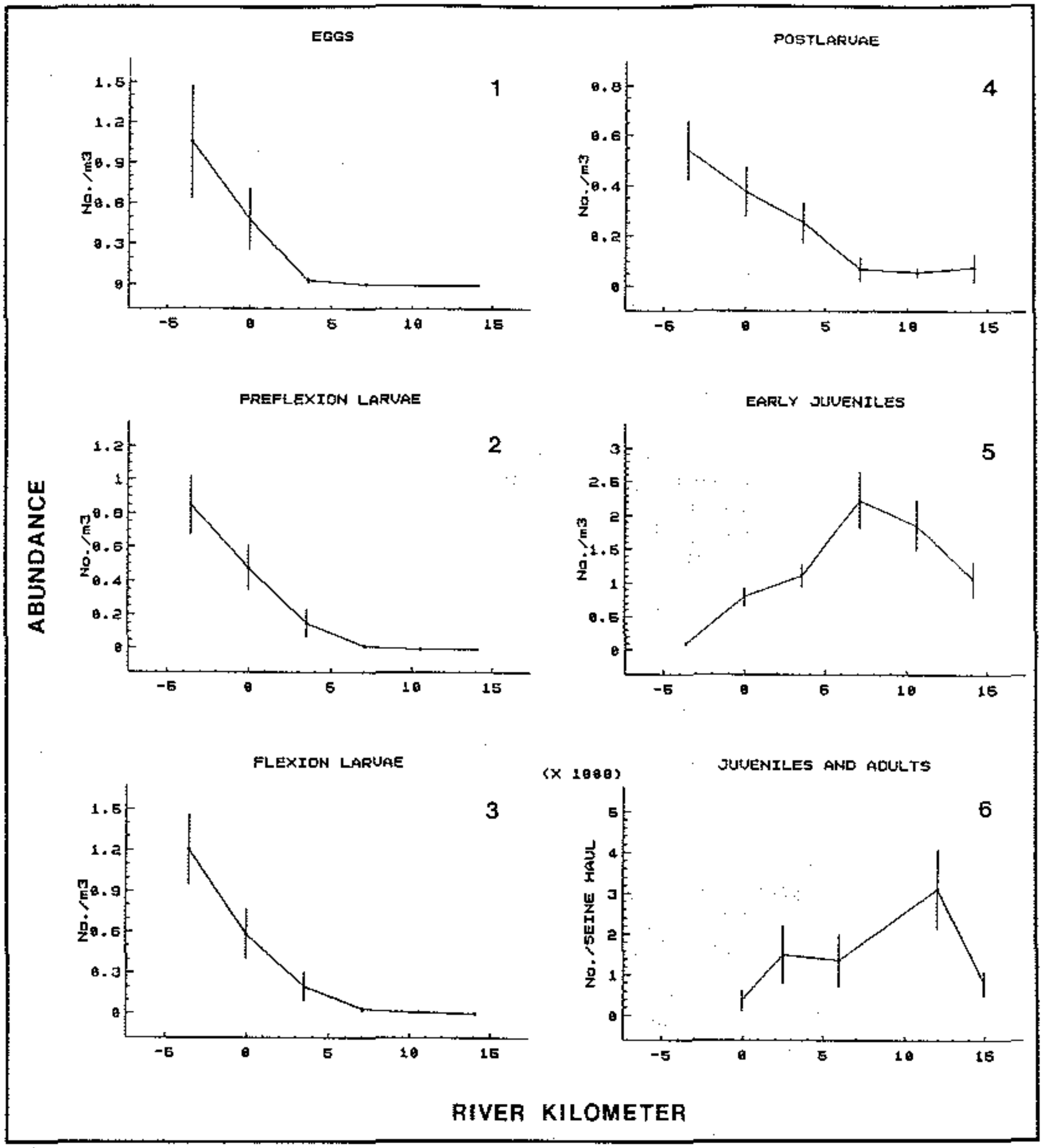

Figure 3. Mean abundances and associated standard errors for anchovy developmental stages collected from the LMR study area. Age increases in the numerical order indicated. Preflexion and flexion stages are predominantly composed of bay anchovies (Anchoa mitchilli), but also contain striped anchovies (A. hepsetus); all other stages are entirely composed of A. mitchilli.

Most of the fishes included above are diminutive, weakly motile, and/or cryptic. The earliest stages of the remaining fishes, including those of economic importance, were generally more abundant in Tampa Bay than in the riverine estuary, which suggests that their spawning activity was centered outside the study area. Some of these, such as the bay anchovy (*Anchoa mitchilli*), striped anchovy (*Anchoa hepsetus*), spotted seatrout (*Cynoscion nebulosus*), sand seatrout (*Cynoscion arenarius*), silver perch (*Bairdiella chrysoura*), and kingfishes (*Menticirrhus* spp.) appeared to spawn near, if not within, the study area, and should be considered to be inshore spawners along with the species included above. It is important to note that anadromous fishes such as striped bass (*Morone saxatilis*), shads (*Alosa* spp.) and sturgeons (*Acipenser* spp.) ascend rivers to spawn and, although not represented in the present survey, are to be expected in larger Florida rivers.

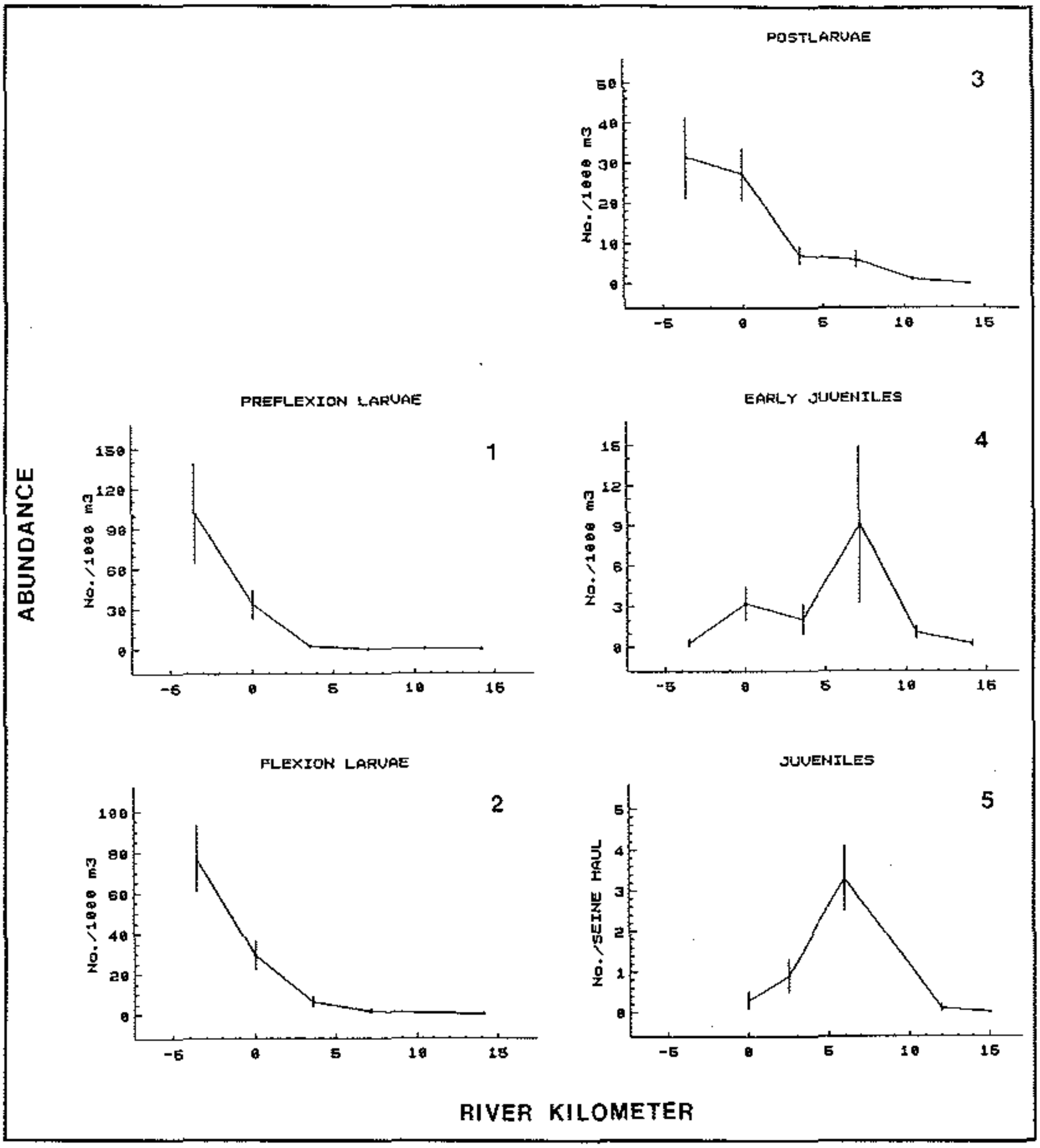

Figure 4. Mean abundances and associated standard errors for sand seatrout (Cynoscion arenarius) developmental stages collected from the LMR study area. Age increases in the numerical order indicated. The egg stage was not identified.

Inshore-spawning fishes tended to spawn most heavily during late spring and early summer and were generally collected over a longer seasonal period than were offshore spawners. Inshore spawners were largely responsible for the increase in ichthyoplankton diversity which occurred during late spring and early summer. Spawning seasons for the offshore spawners appeared to be not only shorter but more seasonally distinctive than those of the inshore spawners. Offshore-spawned fishes tended to arrive at the study area in distinct pulses, and one or more offshore-spawned species could be found in the study area at any time of year. In Figure 5, the occurrences of menhaden in winter, sand seatrout in spring and summer, and bay anchovies year-round provide examples of the distinctive seasonal patterns exhibited by young fishes in the estuary.

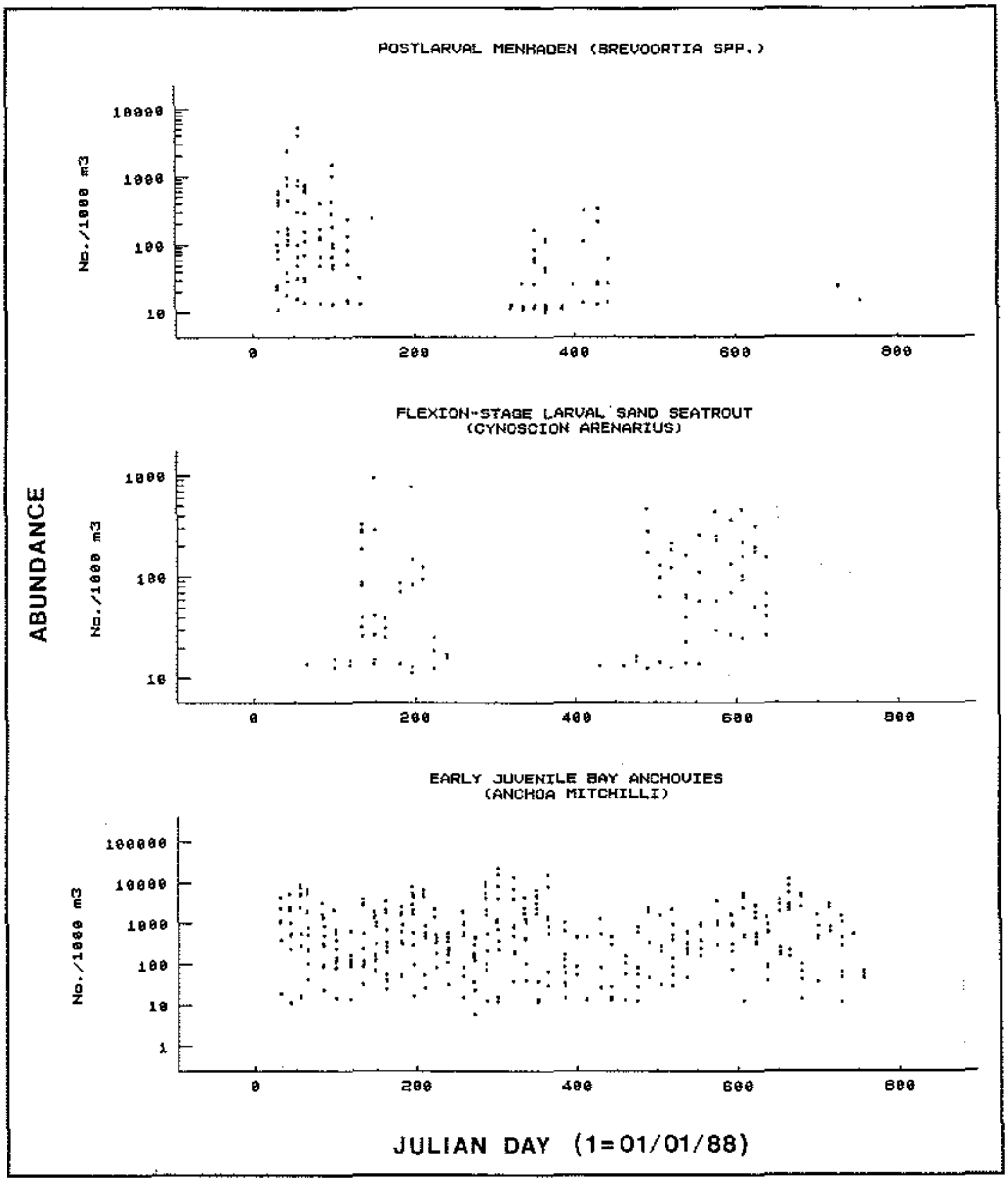

Figure 5. Examples of seasonal patterns observed for young estuarine-dependent fishes in the LMR estuary.

Post-Spawning Concentration Within the Tidal River

After appearance in the study area as larvae or juveniles, many species were observed to migrate upstream into low salinity habitats. The following three indicators, presented in Table 1, were used collectively in identifying fishes which depend on tidal river nursery habitats:

1. Within-stage negative correlation (r_s) between fish length and salinity at capture;

2. Decrease in average salinity at capture (S_D) with progression of developmental stage;
3. Upstream shift in the location of peak abundance (A_{max}) with progression of developmental stage.

Correlations (r_s) presented in Table 1 indicate that migration tended to be much stronger during the postlarval and early juvenile stages than during early larval stages. The sensitivity of this statistic is dependent on growth (or, more specifically, change in length) during migration against the salinity gradient, and therefore may not be sensitive to stages which are migrating rapidly. Examples of decreasing average salinities of capture (S_D) with progressing development are presented graphically in Figure 6. The stage of "peak ingression" is identified here as the first stage which had peak abundance (A_{max}) in the tidal river rather than in Tampa Bay. Peak ingressions by menhaden (*Brevoortia* spp.) and spot (*Leiostomus xanthurus*) occurred during the postlarval stage. Peak ingressions by bay anchovies (*Anchoa mitchilli*), snook (*Centropomus undecimalis*), sand seatrout (*Cynoscion arenarius*), red drum (*Sciaenops ocellatus*) and striped mullet (*Mugil cephalus*) appeared to first occur during the early juvenile stage. It is possible, however, that structure-oriented fish such as snook were present near the shoreline at smaller sizes than those collected by the seines (plankton tows were made in open areas of the channel).

As seen in Table 1, the early juveniles of concentrating species had peak abundances located well within the tidal river, generally between kilometers 4 and 16. The location of maximum abundance of some species shifted upstream or downstream in response to changing freshwater discharge rates. In cases where there was overlap in the size ranges collected by the plankton net and seines, the two independent gears produced the same general pattern (Figs. 3 and 4). Furthermore, the species found to concentrate in the LMR estuary have been shown to have similar affinities for low salinity habitats in other locations (Wilkins and Lewis 1971, Markle 1976, Chao and Musick 1977, Reis and Dean 1981, Mihursky et al. 1981, Gilmore et al. 1983, Weinstein 1983, Rogers et al. 1984, Rozas and Hackney 1984, Miller et al. 1985, Hastings et al. 1987, Peebles 1987, Peters and McMichael 1987).

For most estuarine-dependent fishes, occupation of low salinity habitats is followed several months later by gravitation of larger individuals toward higher salinities. Positive correlations between mean fish length and salinities measured during the seine survey indicate that several species, including menhaden, bay anchovies and spot, began their seaward return while still small enough to be collected regularly by seines.

Congregation in low salinity habitats as a part of early life history is not universal among estuarine-dependent fishes. Species such as the spotted seatrout (*Cynoscion nebulosus*), silver perch (*Bairdiella chrysoura*), and frillfin goby (*Bathygobius soporator*) were abundant as larvae and juveniles in the study area, but had their peak abundances located in moderate salinities nearer the mouth of the river, generally between kilometers 0 and 4.

Distribution of Salinity, Turbidity and Color

The effects of variation in freshwater discharge on salinity distribution in the riverine estuary are readily apparent. All of the regressions between the 0.5, 6, 12 and 18 ppt isohaline locations and preceding three-day average flow rates had slopes which were significantly different from zero ($p<0.05$), yet the influence of freshwater flows on isohaline location was stronger in the upper reaches of the estuary, where variation in flow explained 84% of the variation in the location of the 0.5 ppt isohaline. As expected, tidal and wind event influence on isohaline location became stronger downstream, and variation in freshwater flows explained only 41% of the variation in the location of the 18 ppt isohaline.

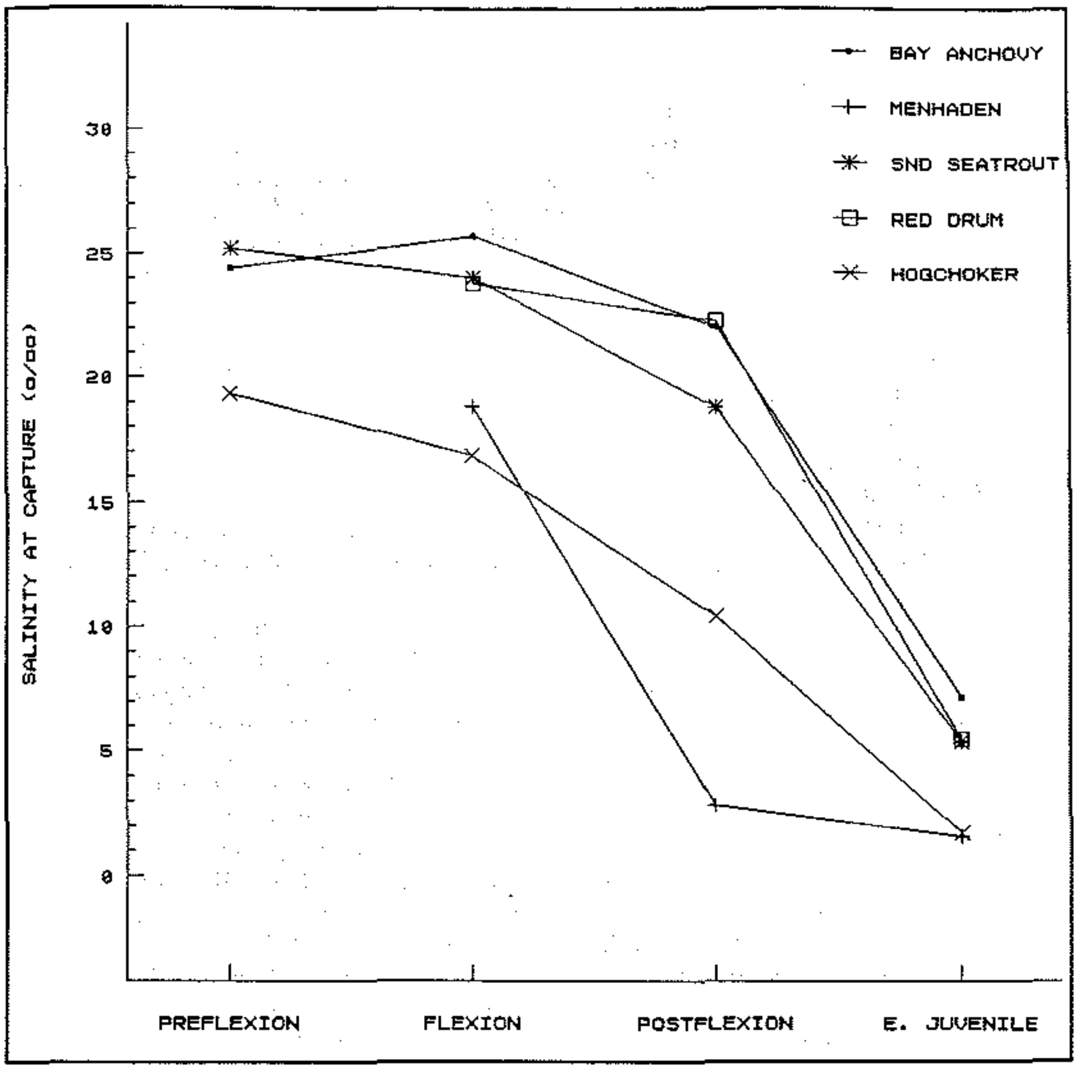

Figure 6. Examples of decrease in salinity at capture with progressing development.

In Figure 7, predicted isohaline locations at high slack tide are plotted against flows ranging from 0 to 14 m^3/sec. Also shown is the estimated volume of the estuary that occurs upstream of each isohaline at various levels of flow. The semi-logarithmic scaling of channel location relative to cumulative volume is due to the funnel shape of the tidal river; volume increases at a faster rate as the mouth of the river is approached. The volumes in Figure 7 are approximate since the isohaline locations were predicted using data from the middle of the main conveying channel, and surface isohalines are likely to be different in areas which convey less discharge. Nevertheless, the figure demonstrates the curvilinear relationship between freshwater discharge and salinity-zone volumes, particularly when flows are in the range of 0 to 4 m^3/sec. Over the past 52 years, recorded daily flows for the LMR near Wimauma have ranged between 0.2 and 398 m^3/sec, but during most years the range has been much smaller. The river flows at comparatively low rates most of the time; the median daily streamflow at the LMR near Wimauma gage is 1.6 m^3/sec (55.7 cfs), and flows have exceeded 11.2 m^3/sec only 10% of the time. Therefore, the salinity-flow relationships in the LMR estuary function within the far left, curvilinear area of Figure 7 most of the time. This has important implications for watershed management, since actions which cause even small reductions in flow rate are capable of causing large reductions in the area and volume of the low salinity habitats available for use by young, estuarine-dependent fishes.

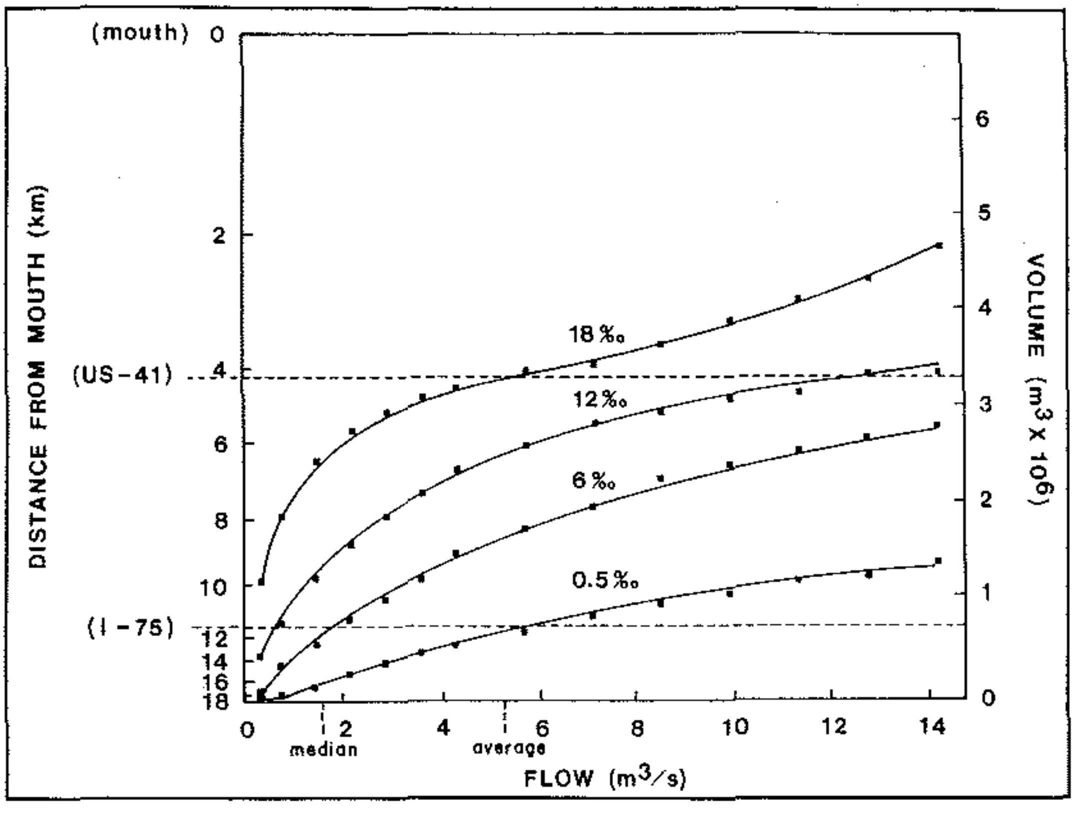

Figure 7. Response of isohaline locations and salinity zone volumes (at high slack tide) to freshwater flows into the LMR estuary.

Cyrus and Blaber (1987) have proposed that the high turbidity levels found in many estuaries reduce visibility, thereby providing protection from predation. Mean turbidity levels were relatively low (4.3 to 5.5 NTU) throughout the LMR estuary (Fig. 8) and there was little indication of a turbidity maximum along the salinity gradient. A distinct concentration gradient was observed for dissolved color, with highest values found in the upper reaches, particularly after periods of high streamflow. Conceivably, high color concentrations could reduce visibility and aid in predator avoidance. In general, however, peak fish abundances did not coincide with maximum levels of turbidity or color.

Distribution of Food Resources

All forms of organic carbon, both organismal and extra-organismal, were considered to be potential food resources utilizable by young fishes either directly or through trophic intermediates. Spatial trends in the concentrations of dissolved organic and particulate carbon and the abundance of phytoplankton (as indicated by chlorophyll *a*) and invertebrates were examined.

Dissolved and Particulate Carbon

Concentrations of dissolved organic carbon (DOC) were highest at the upper end of the tidal river (Fig. 8). Throughout the LMR estuary, DOC concentrations were roughly an order of magnitude higher than total particulate carbon concentrations. The ratio of dissolved to particulate carbon was slightly higher in the upstream areas of the estuary, reflecting the chemical characteristics of the freshwater inflows, and possibly the conversion of DOC to particulate carbon through biological uptake or precipitation processes in the estuary (Kennish 1986). Although the role of DOC as a direct food source for larval fishes has not been substantiated, DOC can be important in the establishment of detritally based benthic communities through microbial processing and transfer of fixed carbon and nutrients to trophic intermediates (Bowen 1984, Sibert and Naiman 1980, Kennish 1990).

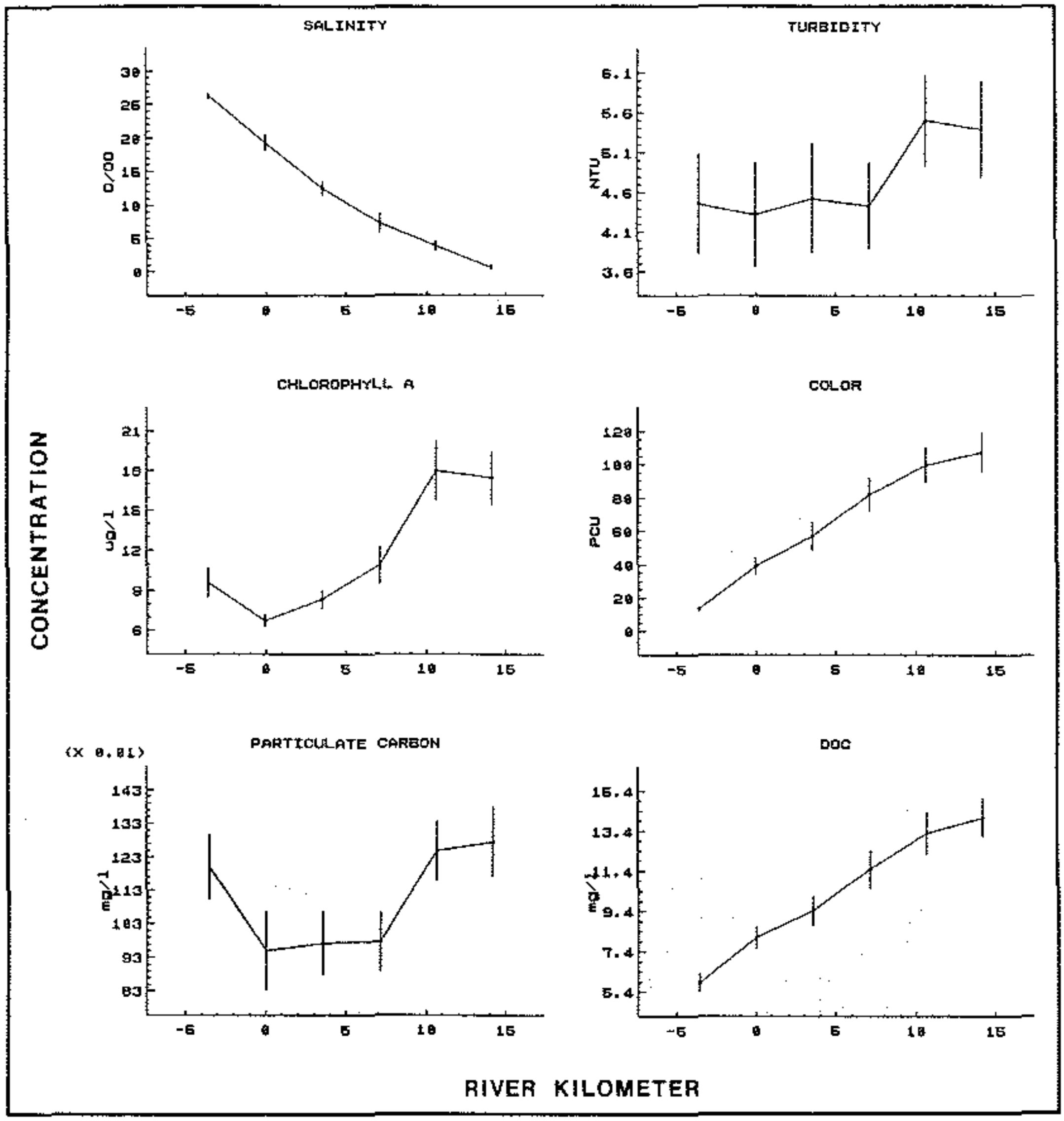

Figure 8. Mean concentrations and associated standard errors for water chemistry parameters measured in the LMR estuary.

Dissolved organic carbon concentrations were highly correlated with flow throughout the estuary (Table 3). This relationship was stronger in the upper estuary, where freshwater inflows are diluted less by bay water. The waters of the upper riverine estuary are similar to the freshwater region of the river in that they are highly colored, presumably due to the leaching of tannins and humic materials from plant detritus and soils in the basin. Concentrations of DOC and color were highly

Table 3. Spearman's rank correlation coefficients for preceding three-day average flow and the quantity of potential food resources within the tidal river. Sample sizes are in parentheses.

FOOD RESOURCE		DOWNSTREAM RANGE 0.0-5.3 km	ENTIRE RANGE 0.0-16.4 km	UPSTREAM RANGE 8.7-16.4 km
Chlorophyll <u>a</u>		-0.02 (35) NS	-0.52 (37) <0.001	-0.65 (37) <0.001
Dissolved organic carbon		0.65 (31) <0.001	0.78 (32) <0.001	0.81 (30) <0.001
Total particulate carbon		0.14 (35) NS	0.06 (36) NS	-0.13 (36) NS
Copepods:	Nauplii	-0.16 (96) NS	-0.42 (192) <0.001	-0.71 (72) <0.001
	<u>Oithona</u> <u>colcarva</u>	-0.46 (90) <0.001	-0.35 (131) <0.001	-0.61 (26) 0.002
	<u>Acartia</u> <u>tonsa</u>	-0.61 (89) <0.001	-0.54 (139) <0.001	-0.72 (35) <0.001
	<u>Parvocalanus</u> <u>crassirostris</u>	-0.13 (62) NS	-0.05 (70) NS	- (4) -
	Harpacticoids	-0.18 (96) NS	-0.26 (191) <0.001	-0.37 (71) 0.002
Polychaete larvae		-0.09 (96) NS	-0.29 (182) <0.001	-0.58 (62) <0.001
Bivalve larvae		-0.40 (75) <0.001	-0.42 (126) <0.001	-0.48 (35) 0.005
Decapods:	zoea larvae	-0.41 (103) <0.001	-0.42 (178) <0.001	-0.58 (51) <0.001
	mysis larvae	-0.56 (68) <0.001	-0.52 (106) <0.001	-0.56 (21) 0.01
Mysids		-0.01 (154) NS	-0.17 (308) 0.003	-0.38 (111) <0.001
Amphipods		-0.11 (121) NS	-0.10 (206) NS	-0.13 (72) NS
Cumaceans		-0.37 (108) <0.001	-0.36 (109) <0.001	- (1) -
Copepods (from plankton net)		-0.36 (22) NS	-0.57 (34) 0.001	-0.81 (10) 0.01

correlated with each other (r=0.75) in the riverine estuary. Various analyses of river systems have indicated that the chemical composition and nutritional quality of DOC in streams can vary with discharge rates and differ between headwater and lower river reaches (Vannote et al. 1980, Meyer 1986, Leff and Meyer 1991). Although the relative biological availability of DOC in the LMR is difficult to assess, the estuary receives very large quantities of these materials. At a flow level corresponding to the average streamflow at the LMR near Wimauma gage, approximately 2.3 metric tons of DOC enter the estuary each day. Precipitation and biological uptake of allochthonous DOC in the upper estuary is a process that could supply the low salinity nursery habitat with organic carbon originating from distant parts of the watershed.

In comparison with DOC, concentrations of total particulate carbon were not as strongly correlated with flow within the estuary (Table 3). One possible reason for this is that particulate carbon concentrations in the bay (mean=1.19 mg/l) were often higher than in the freshwater reaches (mean=0.85 mg/l), and appeared to cause particulate carbon concentrations in the estuary to be high during low flow periods. However, the analytical method used for measuring particulate carbon did not distinguish between organic and inorganic forms, so use of this parameter for measuring the distribution of particulate organic carbon in the estuary is limited. In the freshwater reaches, where it is believed that most of the particulate carbon is organic, particulate carbon concentrations are highly correlated with flow. Other observations, such as the prevalence of suspended and deposited vascular plant detritus in the upper reaches of the tidal estuary, indicate that organic production in the watershed contributes directly to the food resources of the estuarine fish nursery. Suspended large particulate organic matter in the form of vascular plant detritus was most frequently encountered in the plankton nets and seines at the upstream end of the estuary, where detrital deposits were observed to be locally extensive in backwater, depositional environments.

Phytoplankton

As discussed in a companion paper (Flannery et al., this volume), concentrations of the nutrients ortho-phosphorus and particulate nitrogen were positively correlated with flow in the freshwater reaches of the river. Although concentrations of dissolved inorganic nitrogen (NH_4+NO_3) and silica either showed no relation or were negatively correlated with flow, overall loading of these nutrients nevertheless increased with flow rate.

Concentrations of chlorophyll *a* were highest in the upper tidal river (Fig. 8). The upstream chlorophyll maximum averaged 18.1 mg/m^3, and was supported by relatively high rates of primary production (see Vargo et al., this volume). The high phytoplankton abundance in the oligohaline waters was evidently due to production within the estuary and not importation from fresh water, since chlorophyll concentrations in the freshwater reaches of the river were consistently low, averaging less than 3 mg/m^3.

A comparison of the distribution of chlorophyll *a* values in the estuary with corresponding levels of flow demonstrates interesting patterns with regard to zones of maximum algal biomass. Mean chlorophyll concentrations were highest in the upper estuary, yet instantaneous chlorophyll concentrations were negatively correlated with flow in this region of the river (Table 3). This relationship is probably caused by two different factors. First, phytoplankton blooms were observed to occur in the spring and fall when streamflow levels were decreasing. Evidently, nutrient loading to the upper estuary during low flows is sufficient to support high production in this zone. Second, a washout effect was observed for chlorophyll concentrations in the upper part of the estuary, where concentrations averaged 7.7 mg/m^3 at flows above 5 m^3/sec, compared to an average concentration of 23.1 mg/m^3 at lower flows. During high flows, phytoplankton washout in upper estuarine areas results from sharply reduced residence times in the upper tidal river. Nearer the mouth of the river, where discharge-related current velocities are diminished due to increasing cross-sectional area of the estuary, washout may not be apparent or may occur at progressively higher flow rates. Chlorophyll concentrations near the mouth of the river and other zones downstream of kilometer 5.3 showed no relationship with short-term (3-10 day) preceding average flow rates.

Invertebrates

Mean abundances of mysids, amphipods, harpacticoid copepods, isopods, and insect larvae were higher in the riverine estuary than in Tampa Bay (Table 4, Fig. 9), whereas polychaete larvae, cumaceans, decapod larvae, chaetognaths, *Lucifer faxoni*, ostracods, dominant types of calanoid and cyclopoid copepods and most cladocerans were more abundant in Tampa Bay and near the mouth of the river (Table 4, Fig. 10). With the exception of cumaceans and ostracods, the potential prey organisms collected from the water column in Tampa Bay could be characterized as planktonic, whereas potential prey organisms in the water column of the middle and upper tidal river could be considered to be vertically migrating or suspended members of the benthic community.

Abundances of planktonic Tampa Bay organisms typically decreased either linearly or exponentially with distance upstream, while mysids, amphipods, harpacticoid copepods and isopods had more irregular distributions, with peak abundances generally coinciding with the area of the river where young estuarine-dependent fishes concentrated. Part of the these organisms' irregular distribution may reflect associations with variable bottom types (Egglishaw 1964) or advective displacement.

The Tampa Bay plankton assemblage invaded the lower river during periods of low discharge, sometimes to the extent that abundances of some plankters were as high or higher in the lower river as in the bay. In Table 3, negative correlations indicate that increased freshwater discharge decreased the abundance of calanoid and cyclopoid copepods, polychaete larvae, bivalve larvae, decapod larvae, and cumaceans (chaetognaths and *Lucifer faxoni* were abundant in the bay, but were comparatively rare in the river). The negative relationships between the abundance of these zooplankters and flow were strongest in the upper estuarine reaches, where relatively small freshets reduced zooplankton numbers. Larger flow events were required to affect the zooplankton near the mouth of the river, where physical and chemical conditions were more stable.

Flow-induced reductions in abundance were less evident for amphipods, mysids and harpacticoid copepods, which exhibited the weakest negative correlations between flow and abundance in the upper and entire ranges of the tidal river (Table 3). Mysids were abundant over a wide range of salinities in the tidal river, and experimental work has indicated that growth and molting rate of estuarine mysids may not be affected by reduced salinities (Pezzack and Corey 1982). Under most flow conditions, amphipod abundance did not decrease with increasing freshwater flow rate. Although estuarine mysids, harpacticoid copepods, and amphipods are typically associated with benthic deposits, nighttime migrations into the water column evidently allowed us to assess distributional trends within the LMR study area (Hopkins 1965, Alldredge and King 1985, Orsi 1986, Walters 1988). Cursory examination of discrete depth samples from our survey revealed that mysids and amphipods were at times abundant in the top 0.5 m of the water column even during low flow conditions, but catches were generally still higher in the bottom 0.5 m. The estuarine mysid *Neomysis mercedis* has been observed to consistently occupy surface waters at night, regardless of flow conditions. During the day, displacement away from the entrapment zone of the upper estuary is compensated by selectively occupying upstream flowing water masses during flood tides or when two-layered circulation is established (Orsi 1986).

Table 4. Dominant potential fish prey organisms collected by Niskin bottle (N) and plankton net (P): numbers of individuals caught (n) were estimated using split samples; f is collection frequency, which is the sample size used in statistical tests; S_D is density-weighted mean salinity at capture; location of A_{max} is location (km) with the highest mean abundance; and KW is the probability value for significant variation among location mean densities as calculated using the Kruskal-Wallis ANOVA.

TAXON	STAGE	GEAR TYPE	n	f	$\bar{S}_D$	LOCATION OF A_{max}	KW
Copepods	nauplii	N	1491981	240	26.4	BAY	p<0.001
Oithona colcarva	copepodites/adults	N	242731	179	25.7	BAY	p<0.001
Acartia tonsa	copepodites/adults	N	92377	187	22.6	BAY	p<0.001
Parvocalanus crassirostris	copepodites/adults	N	29503	118	26.9	BAY	p<0.001
Harpacticoids	copepodites/adults	N	23917	236	12.3	7.1	NS
Pseudodiaptomus coronatus	copepodites/adults	N	7954	132	25.1	BAY	p<0.001
Eurytemora hirundoides	copepodites/adults	N	2991	87	1.8	14.2	p<0.001
Polychaetes	larvae	N	63622	230	24.3	BAY	p<0.001
Bivalves	larvae	N	38706	173	22.7	3.8	p<0.001
Cladocera							
marine	all	N	5562	81	25.7	BAY	p<0.01
freshwater	all	N	151	51	6.8	14.2	p<0.01
Ostracods	all	N	1521	155	19.0	BAY	p<0.001
Decapods	zoea larvae	P	3418360	243	22.9	0.0	p<0.001
	mysis larvae	P	483267	141	20.3	0.0	p=0.01
	megalopa larvae	P	26714	26	14.7	0.0	NS
Mysids	all	P	830986	351	13.1	7.1	p=0.001
Amphipods	all	P	777599	232	9.7	7.1	p=0.03
Cumaceans	all	P	575794	157	25.0	BAY	p<0.001
Copepods	adults	P	198057	85	25.3	BAY	p=0.001
Lucifer faxoni	all	P	107084	45	25.9	BAY	NS
Chaetognaths (Sagitta)	adults	P	57771	46	26.7	BAY	p=0.05
Ostracods	adults	P	54345	36	25.3	BAY	NS
Cladocerans	adults	P	51517	25	23.7	BAY	p=0.01
Isopods	all	P	12011	21	11.3	7.1	NS
Insects	larvae/pupae	P	5376	27	0.8	14.2	NS

Feeding Relationships in the Tidal River

As indicated by Sheridan (1978, 1979), the diets of some fishes may vary with location. A recently initiated trophodynamic study of fishes in the LMR estuary suggests that variation in diet occurred along the sampled transect. Stomachs of juvenile bay anchovies collected from the mouth of the river and nearby Tampa Bay tend to contain calanoid and cyclopoid copepods, cumaceans, bivalve larvae, cladocerans and decapod larvae (Peebles, unpublished data). This assemblage of food items conforms with the planktivorous trophic position reported from other studies of this species conducted in open water, high salinity estuarine habitats (e.g., Carr and Adams 1974, Sheridan 1978, Johnson et al. 1990).

In contrast, bottom-associated material generally dominates the juvenile anchovies' diet in the upper estuarine area where they congregate. Amorphous detritus[1], harpacticoid copepods, amphipods, benthic foraminiferans, sand grains, and very large numbers of substrate-associated (mostly pennate) diatoms were frequently encountered in the stomachs of bay anchovies collected from the upper tidal river.

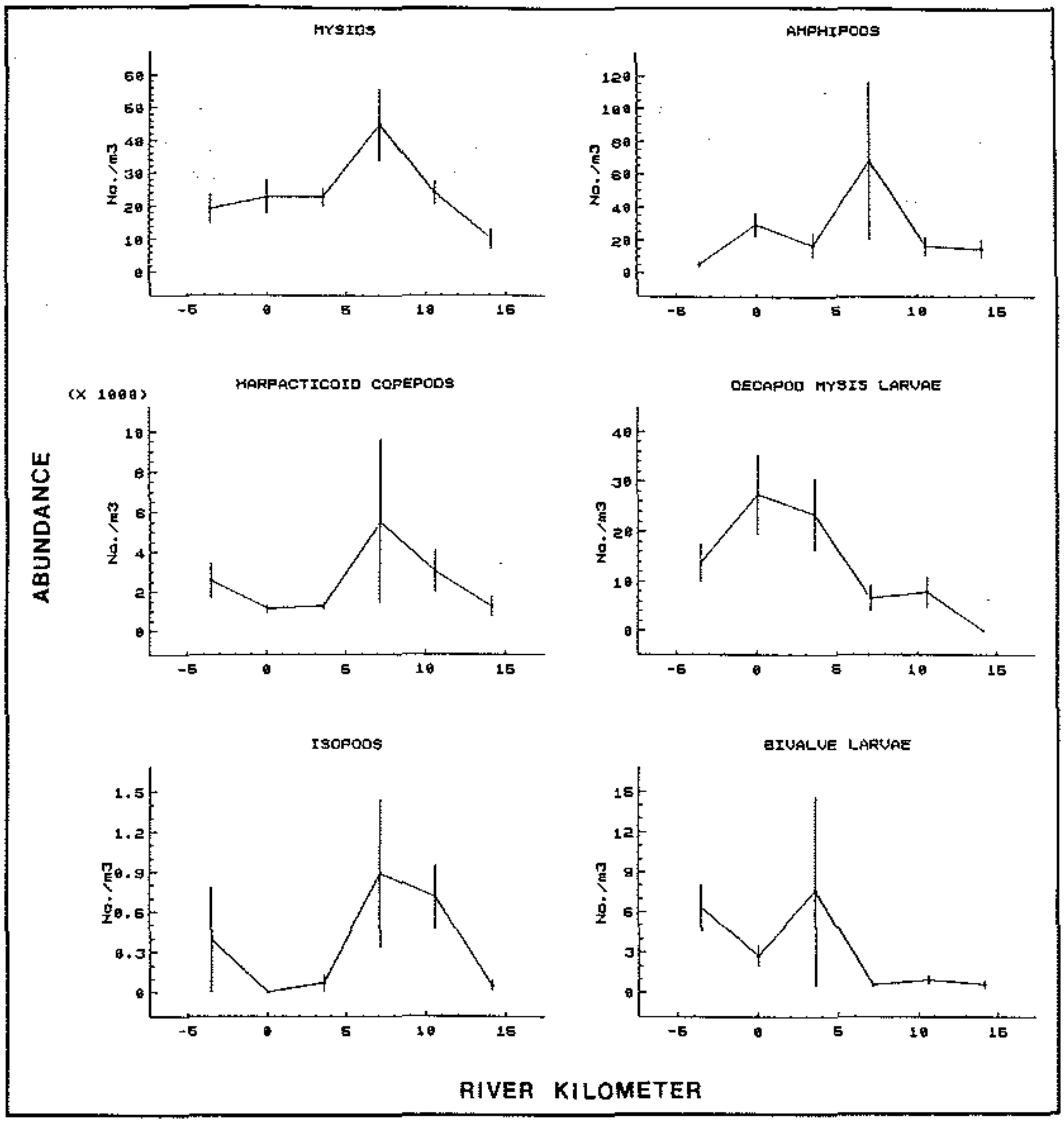

Figure 9. Mean abundances and associated standard errors for potential fish prey organisms in the LMR estuary.

Ostracods were ingested by anchovies in both the upper tidal river and bay. The assemblage of items found in bay anchovy stomachs from the upper tidal river suggests that the fish are ingesting either surface or suspended substrate while in this area. Virtually identical material was found in juvenile menhaden stomachs from the same area. Ingestion of bottom material by menhaden has been previously reported by Hildebrand (1963). Organically rich substrate is linked to the production of benthic macroinvertebrates. Estuarine mysids feed primarily on detritus and diatoms but will consume smaller crustaceans if given the opportunity (Fulton 1982, Zagursky

[1]The virtual absence of amorphous detritus in stomachs of anchovies from Tampa Bay and the association of this material with recently ingested meiobenthos and diatoms in upper-estuarine anchovies both suggest that this material is not a residual byproduct of digestion. Bowen (1984) described a similar material as being precipitated organic matter, which he found to be as abundant as vascular plant detritus in various temperate and tropical lakes and streams. Bowen also demonstrated that precipitated leaf leachate is more digestible than the vascular detritus considered by the majority of detrital studies.

and Feller 1985). Gammarid amphipods are also opportunistic omnivores; they grow rapidly when fed diatoms but are capable of surviving on an exclusive diet of detritus or its microbial degradation byproducts (Stuart et al. 1985, Baerlocher and Howatt 1986). Mysids, amphipods, harpacticoid copepods and juvenile bay anchovies were found to be dominant food items consumed by young sand seatrout while in the upper estuary. The importance of the bay anchovy as forage for larger predatory species is evident throughout most of the estuarine waters of eastern North America (Vouglitois et al. 1987).

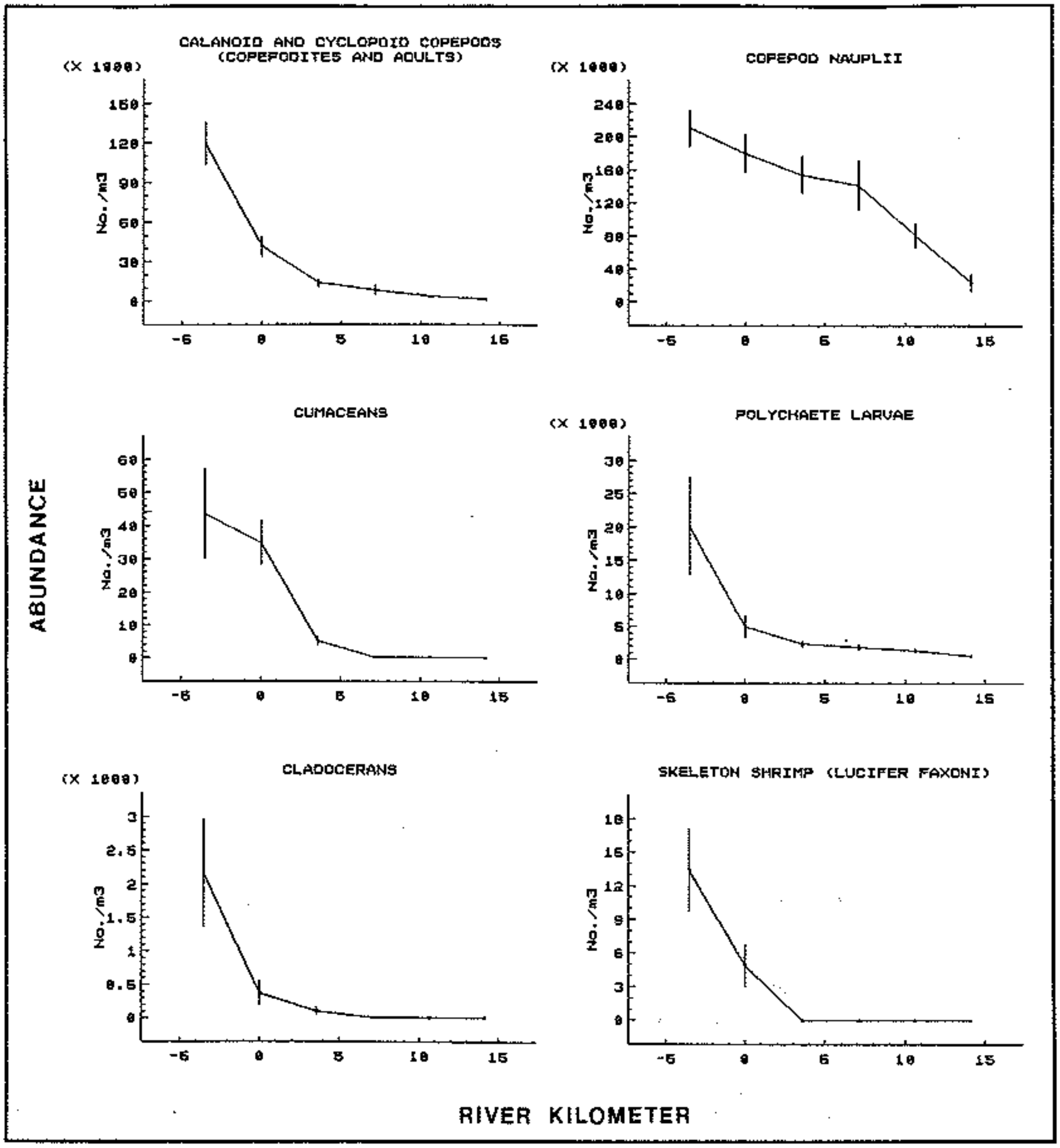

Figure 10. Mean abundances and associated standard errors for potential fish prey organisms in the LMR estuary.

In general, the differences in feeding behavior between the upper and lower parts of the tidal river coincide with differences in food item availability. Additionally, the migration of some of the young, strongly predatory fishes away from Tampa Bay's rich planktonic food supply and into the tidal river appears to coincide with development of the ability to ingest larger organisms (see Govoni 1981).

SUMMARY

The tidal portion of the Little Manatee River is heavily utilized as nursery habitat by an economically important assemblage of fishes. Most of the fish species collected from the LMR estuary did not appear to spawn within the river but instead migrated there as postlarvae or early juveniles. Those fishes which did appear to spawn within the tidal river tended to be diminutive or cryptic species such as blennies, gobies, skilletfish, wormfish, toadfish, pipefish, killifish and livebearers (poeciliids). Spawning grounds of the remaining fishes appeared to be located anywhere between Middle Tampa Bay (spotted seatrout, sand seatrout, silver perch, kingfishes, bay anchovy, striped anchovy) and the Gulf of Mexico on the inner continental shelf or beyond (menhaden, spot, striped mullet).

Migrations into the tidal river were evident in relationships between fish length and salinity at capture and also in age-specific plots of fine-scale spatial distribution. Spatial peaks in the abundance of most fishes were not apparent in the tidal river until the postlarval or early juvenile stage. Peak abundances of these later stages were located between river kilometers 0 and 16. The assemblage of young, euryhaline fishes which concentrated in this part of the river included snook, red drum, striped mullet, sand seatrout, spot, menhaden and bay anchovies. The tidal river is used year-round as nursery habitat for estuarine-dependent fishes, with peak diversity occurring in spring and early summer.

Because salinity is a principal determinant of species composition in estuaries, variation in discharge rate is likely to determine the extent of the competitive advantage held by the young euryhaline fishes which utilize the tidal river as nursery habitat. Typical freshwater discharge into the tidal estuary is less than 4 m^3/s. Salinity zone volumes respond to fluctuations within this range in a nonlinear manner; relatively small increases in discharge rate can cause large increases in salinity zone volumes, therein shifting access to local food resources toward the more euryhaline fishes.

On average, the chlorophyll *a* maximum was located at the upper reach of the tidal estuary. Nutrient loadings and dissolved organic carbon delivery to the tidal river increased with increasing river flow, while chlorophyll *a* levels decreased. Substrate-associated diatoms, apparently ingested along with surface or suspended substrate, were found to be an important food item for young anchovies and menhaden within the upper river. Spatial peaks in the abundances of mysids, amphipods, harpacticoid copepods, and isopods were located in the middle and upper tidal river, apparently in association with productive benthic communities. Toward the mouth of the tidal river and in nearby Tampa Bay, calanoid and cyclopoid copepods, cladocerans, cumaceans, polychaete larvae, skeleton shrimp, and decapod zoea and megalopa larvae were more dominant. The Tampa Bay plankton assemblage invaded the lower river during periods of low discharge and appeared to be more susceptible to advective displacement during periods of elevated discharge than did invertebrates associated with the river's benthic detrital community. Stomach content analysis revealed that food resource utilization differed between the river and bay, in general agreement with trends in prey distribution.

Nutrients and organic carbon are imported from the watershed and contribute to the overall production of food resources used by estuarine-dependent fishes in the tidal river. This importation process is dependent on hydrological and land use patterns in the watershed and as such constitutes direct linkage between watershed management and fisheries production.

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INCREASED NUTRIENT LOADING AND BASEFLOW SUPPLEMENTATION IN THE LITTLE MANATEE RIVER WATERSHED

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ABSTRACT

The Little Manatee River has been the site of an interdisciplinary study of the ecological linkages between a watershed and its receiving estuary. This paper examines spatial and temporal trends in the quantity and quality of streamflow in the basin. Analyses of long-term rainfall-runoff relationships show that dry season streamflow in April and May has significantly increased since the mid-1970s while rainfall for those months has decreased or risen only slightly. Streamflow records for six sites gaged during 1988 showed that the highest rates of yearly runoff were from subbasins with the highest rates of agricultural water use. Increased basin outflows are attributed to the direct contribution of irrigation waters or land and water use practices that increase runoff potential. Water quality was measured biweekly for one year at the six streamflow stations and at a seventh station where flows were estimated. The site with the least intensive land use had concentrations of sulfate, nitrate-nitrite, total suspended solids, particulate nutrients and specific conductance that were significantly less than for most other stations. High specific conductance and sulfate concentrations in certain tributaries in the watershed were attributed to mineralized ground water from the Floridan aquifer entering those streams as a result of irrigation runoff. Nitrate-nitrite concentrations were negatively correlated with flow in less impacted, upstream areas, but comparatively high concentrations were observed during high flows at more impacted sites. Turbidity and suspended solids showed a much stronger response to flow increases at the more impacted sites. Areal flux rates for dissolved inorganic and particulate nitrogen differed by an order of magnitude between the least and most impacted subbasins. Long-term data at the Highway 301 bridge show that marked increases of specific conductance, nitrate-nitrite and sulfate concentrations have occurred in the river since the mid-1970s. Average midafternoon dissolved oxygen concentrations during the summer were relatively low (3.4 to 4.2 mg/l) throughout much of the estuary, and further perturbations to water quality of the river and estuary could result in the decreased biological diversity and productivity of this system.

INTRODUCTION

Among the principal creeks and rivers flowing to Tampa Bay, the Little Manatee River (Figure 1) is considered to be the stream that is in the best hydrobiological condition. For this reason, the Little Manatee was selected as the site for an interdisciplinary study of the ecological linkages between a watershed and its receiving estuary. The upstream, freshwater component of the project has emphasized natural and anthropogenic influences on hydrology and water quality, utilizing physical (soils, topography) and land use/cover data available from a Geographic Information System assembled for the project. The downstream portion of the study has examined estuarine water chemistry plus phytoplankton, zooplankton, and larval and juvenile fish communities in the tidal regions of the river and adjacent areas of Tampa Bay (Peebles et al.; Vargo et al., this volume). The goals of the project are two-fold. First, biological data from this study serves as valuable basic information on how tidal creek and river habitats are utilized by the biota of Tampa Bay. Second, the findings of the study will be used to formulate a series of management recommendations specific to the Little Manatee River watershed so that the qualities of this system can be maintained in the wake of expected population growth.

This paper discusses spatial and temporal trends in the quantity and quality of streamflow in the river and its tributaries and compares these trends to the distribution of land and water uses in the basin. These findings are presented as preliminary since we are in the early stages of analysis, and a final report will be available in early 1992 from the Southwest Florida Water Management District (SWFWMD) with contributions by Dames & Moore and the Florida Department of Natural Resources Marine Research Institute. That report will expand the use of GIS data to examine relationships of physical and land-use factors to the delivery of fresh water and nutrients from the basin. At this time, however, several trends are apparent which have important implications for the ecology of the river and Tampa Bay. Dry season flows in the Little Manatee River are supplemented by irrigation waters, and nitrogen loading from the basin appears to have increased significantly in recent years. Recognition of these trends and the development of appropriate management strategies are of immediate concern if the effects of these factors on estuarine productivity and eutrophication are to be controlled.

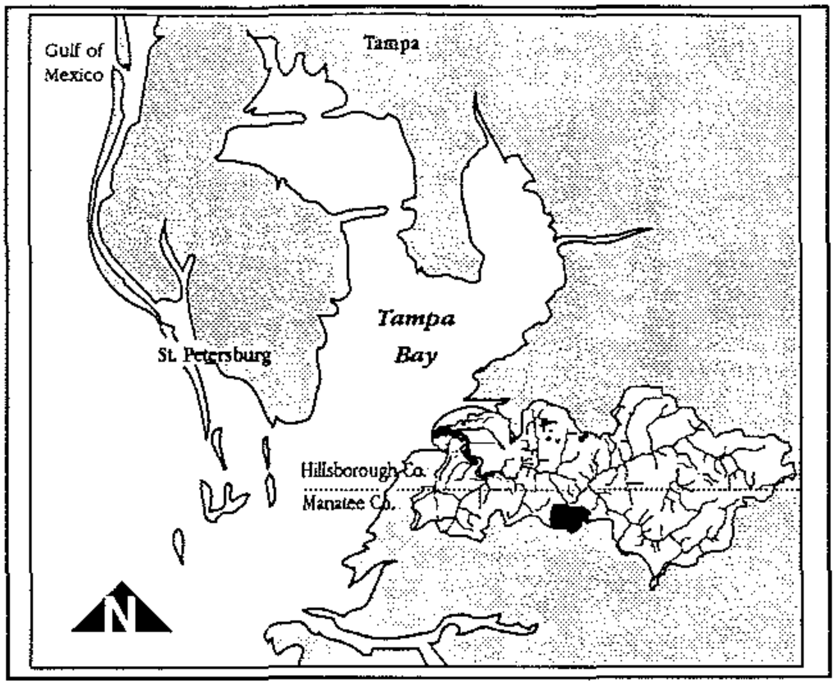

Figure 1. Location of the Little Manatee River watershed.

METHODS AND DATA SOURCES

Seven rainfall stations with daily records are available within or near the Little Manatee River watershed (Figure 2). The periods of record for these stations are of short to intermediate length, ranging from three to twenty years. A thiessen polygon network was constructed from five of these stations to estimate average rainfall in the basin during the period of this study (1988 and 1989). Long-term rainfall in the basin must be estimated from several long-term (77 to 89 years) stations in the Tampa Bay region (e.g., Tampa, Bradenton, Bartow). For the period of record for each intermediate-term station, stepwise multiple linear regression analysis was used to develop a predictive equation for monthly rainfall at the intermediate station as a function of monthly rainfall at a combination of long-term sites. These equations were then used to generate synthetic records for the intermediate stations prior to data collection at those sites. Long-term trends in rainfall for the basin were then evaluated based on the combined synthetic and measured data for the intermediate-term stations.

The U.S. Geological Survey (USGS) maintains and reports daily streamflow records for three gaging stations in the Little Manatee River (LMR) watershed (LMR near Wimauma, LMR near Ft. Lonesome, and Cypress Creek). For this study, three additional gaging stations were established by the USGS and operated from October 1987 to January 1989 (Figure 2). Daily streamflow values for this period were estimated for a seventh station (LMR North Fork) based on differences between nearby stations and adjustment factors for subbasin area. Using reported daily streamflow values from the six gages and estimated values for North Fork, runoff and nutrient loading per unit area were calculated for a total of seven subbasins in the watershed (Figure 2).

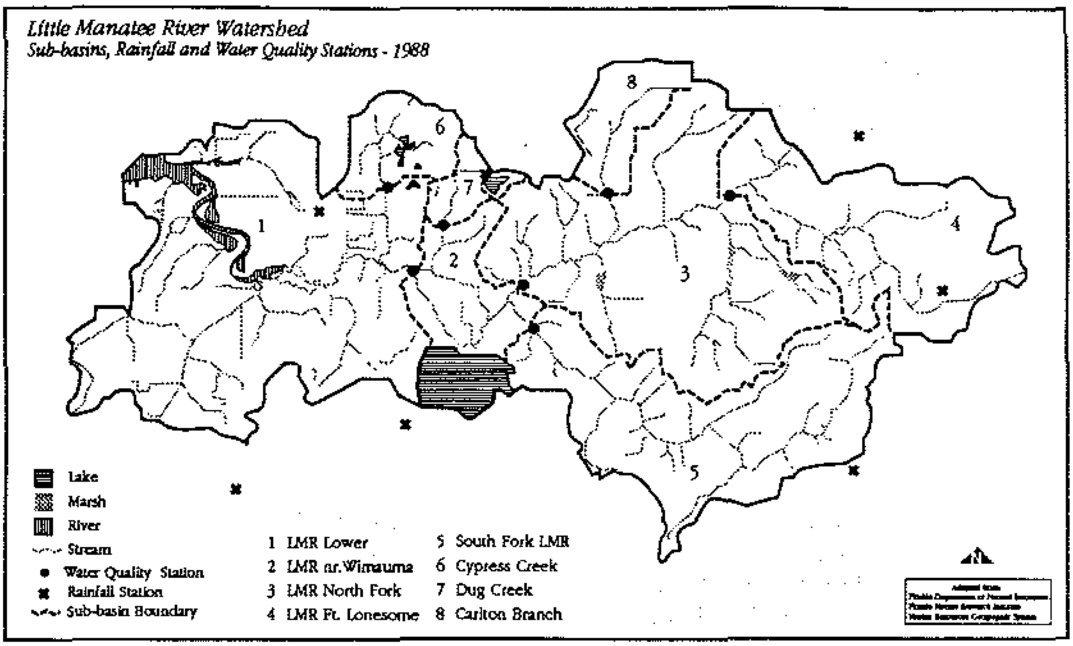

Figure 2. Subbasins, rainfall and water quality stations monitored during the first year of study.

Water quality was monitored by the SWFWMD at biweekly intervals during the first year of study (January 26, 1988 to January 24, 1989) at the seven streamflow sites shown in Figure 2. Measurements of temperature, specific conductance, pH and dissolved oxygen were taken in the field using a Hydro-Lab water quality meter. Duplicate water samples for chemical analysis were collected from a depth of 0.25 meters, or shallower if necessary, placed on ice and returned to the SWFWMD laboratory where analyses were performed according to methods described in EPA (1983), APHA (1983), and the Perkin-Elmer Corporation (1987). Duplicate water samples for chlorophyll *a* determination were collected from three sites and transported in water baths at ambient river temperature to the Department of Natural Resources Laboratory in St. Petersburg where filtrations were performed early that afternoon. Chlorophyll *a* values expressed in this report were calculated using the equations of Jeffrey and Humphrey (1975). Water chemistry, Hydro-Lab, and chlorophyll measurements were continued on a monthly basis for the second year of study (January 1989 to January 1990) at the LMR near Wimauma station. Concurrent with the freshwater sampling regime, water quality monitoring was conducted for both study years at seven stations in the estuarine portion of the river and adjacent areas of Tampa Bay. Details regarding station locations and methods for the estuarine sampling are provided elsewhere in these proceedings (Peebles et al., Vargo et al.). Water quality values reported in this paper also include data collected for the river by the USGS and the Hillsborough County Environmental Protection Commission (HCEPC).

Nutrient loading rates for the seven subbasins were calculated as follows. For each station, total daily loads (kg/day) were calculated separately for the 26 biweekly sampling events by multiplying the constituent concentrations * average flow on that day. These daily loads were then log-transformed and regressed against the logarithm of same day flow for each sample date to yield predictive equations for daily loadings as a function of same-day flow. Using daily streamflow records, these equations were then used to predict daily loadings for each day of the study year. Values for total monthly or yearly loads were then summed from the predicted daily loadings, and flux rates (kilograms/hectare/year) were calculated by dividing the yearly load by the subbasin area.

All spatial geographic data were stored and analyzed using the Marine Resources Geographic Information System (MRGIS) at the Florida Department of Natural Resources Marine Research Institute. MRGIS applications software include the commercially available ERDAS, Inc. raster-based package and ESRI's ARC/INFO vector-based package. The MRGIS also uses ELAS, a nonproprietary image processing software developed by NASA. Numerous data layers are being implemented on the MRGIS and represent a variety of sources (Haddad and McGarry 1989). Land cover data were interpreted from the SPOT satellite base map (imaged April 1988) and aerial photography. Watershed subbasins were digitized based on United States Geological Survey delineations.

THE STUDY AREA

Physiographic and Hydrogeologic Setting

The Little Manatee River watershed drains approximately 222 mi^2 (576 km^2) in southern Hillsborough and northern Manatee Counties, discharging to Middle Tampa Bay on its eastern shore. The headwaters of the river lie in the Polk Uplands physiographic province (White 1970), where land elevations are in excess of 100′ above sea level (NGVD). Immediately to the west, much of the drainage system crosses a small northern lobe of the DeSoto Plain, and the lower third of the watershed lies in the Gulf Coast Lowlands, where elevations range from sea level to 50′ NGVD.

The maximum length of the river is about 40 miles. The two principal tributaries to the river are the North and South Forks, which join about 22 miles above the river mouth at Tampa Bay (the North Fork is generally labeled as the Little Manatee River on maps). In most areas, the channels of the two forks are narrow and well incised. Channel-slope gradients for both forks are comparatively high for peninsular Florida, reported at about 0.13% for the North Fork near the Ft. Lonesome gage (Dames and Moore 1975). Near the USGS stream gage at Highway 301, the channel gradient of the river becomes gentler and minor tidal water level fluctuations are observed during low flow periods. In its lower 10 mile (16 km) reach, the river channel and floodplain become much wider and numerous tidal features such as tidal creeks, bayous, and mangrove-dominated islands become prevalent.

Hydrogeologically the Little Manatee River area is characterized by three distinct groundwater systems: the surficial, intermediate, and Floridan aquifers. The surficial aquifer system is an unconfined system which consists of marine and nonmarine quartz sands, clayey sand, shell and phosphorite. The water table in the surficial aquifer generally follows the topographic relief, with local flow patterns that lead to surface water drainage or depressional features. Below the surficial aquifer is the intermediate system which consists of water-bearing and confining units. The confining beds of the intermediate aquifer impede the vertical exchange of water between all three systems. Estimated recharge rates from the surficial to the intermediate and Floridan aquifers are very low (<2"). This low rate of recharge can partially explain the high runoff potential of the watershed. Below the intermediate system is the Floridan aquifer, which is the principal ground water supply source used within the basin. The Floridan aquifer is a series of limestone formations that begins 200-300′ below land surface and is 1200-1400′ thick. Water quality in the Floridan aquifer is generally good, but deteriorates with depth and proximity to the coast.

Land Use/Cover

The distribution of major land use and cover types are shown in Figure 3. This information is also presented in Table 1, where land use/cover types are expressed as percentages of area for the subbasins shown in Figure 2. Compared to most basins draining to Tampa Bay, the Little Manatee River watershed is lightly urbanized. The combined urban-suburban coverage comprises only 6.6% of the entire watershed. The two principal urban centers, Ruskin and Sun City Center, are located in the western half of the watershed; residential development is minor in the eastern areas. Domestic wastewater facilities in the watershed include a number of small, privately owned plants near Ruskin, which discharge to percolation ponds or drain fields, and the South Hillsborough County wastewater treatment plant which discharges via spray irrigation and industrial reuse.

Industrial land uses in the watershed are primarily for two purposes, phosphate mining and electrical power generation. Most conspicuous is the Florida Power and Light Corporation's power generation facility located near the southern edge of the watershed. A 1,616-hectare offstream reservoir, shown as a lake in Figure 2, is used to store waters for power plant cooling purposes. Phosphate mines, which comprise 0.9% of the total area, are located in the easternmost portions of the watershed where there is a permitted discharge to the river from the Four Corners Mine. At present, the IMC Fertilizer Corporation is in the Development of Regional Impact review process to gain regulatory approval to mine substantially more of their land holdings in the watershed, which lie primarily in the Ft. Lonesome subbasin (Figure 2).

The most notable characteristic of the Little Manatee River watershed is its large amount of agricultural land use. Lands used for row crops and citrus total 27.3% of the watershed while pasture comprises another 26.3%. Vegetable row crops are distributed throughout the basin, but are particularly concentrated in the central and southwestern regions. Citrus, which comprises 8.8% of the watershed, is widely distributed with one area of concentration in the north central region near Carlton and Pierce Branches. Pasture, which includes both improved and unimproved classifications, is concentrated near the I-75 corridor and in the eastern portions of the watershed. Tropical fish farms comprise 0.6% of the watershed and are located in the eastern and central regions.

Apart from agriculture, vegetative land covers comprise approximately 35% of the watershed. The largest vegetation category is wetlands forest (12.6%), which is primarily associated with the stream channels of the river network. Herbaceous wetlands (3.9%) are scattered throughout the basin and estuarine wetlands are located near the river mouth. Upland communities are comprised of hardwoods, pine flatwoods, and range (shrub and brush) which combined total 17.7% of the watershed.

Water Use

A total of 100.4 million gallons per day (mgd) average pumpage is permitted from the Little Manatee River watershed, predominantly from groundwater sources. Total permitted quantities for four major water use categories (agricultural, industrial, recreational and domestic supply) are listed in Table 1 for the entire watershed and the subbasins shown in Figure 2. Industrial water use represents 23.1% of the permitted use in the watershed, with IMC Fertilizer, Inc. and Florida Power and Light Corporation comprising most of this amount. Under an agreement with the SWFWMD, Florida Power and Light Corporation diverts water from the Little Manatee River to maintain their cooling-water reservoir. Water can be diverted when streamflow in the river is over a monthly minimum flow level, and the diversions have averaged 10.6 cfs per day since reservoir filling was completed in 1977. Domestic water supply use in the watershed is very low (0.6 mgd), consisting of small, private water supply systems. There is also a small amount (0.5 mgd) of recreational water use (golf course irrigation) in the watershed.

Agricultural water use comprises about three-fourths (76%) of the total water use in the basin. This use is almost entirely from ground water, using deep wells that tap the Floridan aquifer. Of the subbasins shown in Figure 2, agricultural water use is highest in the lower LMR and North Fork subbasins. Based on a ratio of water use to subbasin size, however, agricultural water use rates are highest in the Carlton

Branch, Cypress and Dug Creek subbasins (0.22 to 0.24 mgd/km^2) and lowest in the Ft. Lonesome and South Fork subbasins (0.07 to 0.10 mgd/km^2).

Supplemental irrigation is typically provided for citrus and vegetable production while little to no irrigation is provided for pastures. Crop irrigation primarily occurs throughout the dry season (October to June). Although irrigation rates can be high in the fall for strawberries and fall vegetables, the highest seasonal pumpage rates typically occur in the spring when crop water demands are the greatest. For citrus and strawberries, short-term periods of high pumpage can occur during the winter for frost-freeze protection.

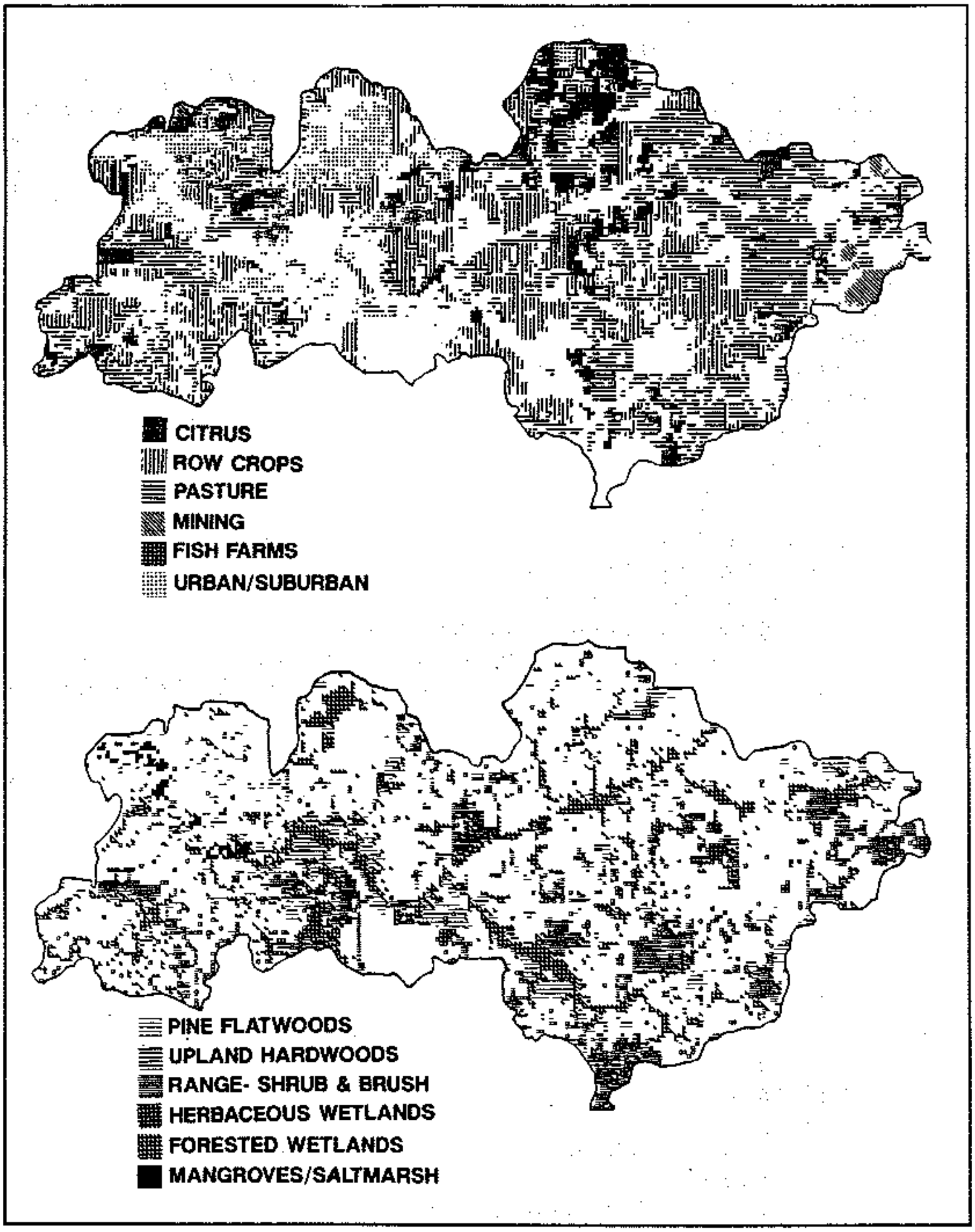

Figure 3. Distribution of major land use and land cover types in the Little Manatee River watershed during 1988.

Table 1. Area, percent coverage of major land use/cover types, and permitted water use for the subbasins shown in Figure 2. The FP&L offstream reservoir is not included in the area and percent coverage data for the LMR-Wimauma subbasin, but the permitted water use associated with the power plant is listed for that subbasin. Water use data were retrieved from the SWFWMD Regulatory Data Base for permits active in May 1991.

	TOTAL	1. LMR LOWER	2. LMR NEAR WIMAUMA	3. LMR NORTH FORK	4. LMR FT. LONESOME	5. SOUTH FORK	6. CYPRESS CREEK	7. DUG CREEK	8. CARLTON BRANCH
Area-(Km^2)	575.9	170.6	28.3	132.8	79.8	100.4	20.5	8.4	21.8
PERCENT COVERAGE									
Urban-Suburban	6.6	12.6	7.6	1.2	0.3	0.2	43.4	15.1	5.3
Citrus	8.8	6.4	6.0	10.5	7.8	7.4	0.7	10.2	41.5
Row Crops	18.5	20.2	25.0	27.7	1.4	16.9	18.0	28.5	15.5
Pasture	26.3	19.3	15.9	26.4	52.1	29.9	3.8	4.0	26.4
Fish Farms	0.6	1.14	2.9	0.3	0.0	0.1	0.0	0.0	0.3
Mining	0.9	0.2	0	0	5.8	0.1	0.0	0.0	0.0
Uplands-Hardwoods	2.4	2.9	1.6	2.5	2.1	3.2	0.3	0.3	0.4
Uplands-Pinelands	6.6	7.7	15.7	4.2	3.1	9.6	4.0	17.7	1.5
Uplands-Shrub and Brush	8.7	5.8	7.3	11.2	11.0	13.3	0.8	8.9	0.2
Wetlands-Herbaceous	3.9	4.9	1.2	3.7	3.6	4.9	1.0	2.0	1.5
Wetlands-Forest	12.6	12.3	16.0	12.0	12.2	14.3	21.4	12.2	7.0
Mangroves & Saltmarsh	0.6	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	3.7	4.5	0.6	0.4	0.6	0.2	6.6	1.1	0.4
WATER USE (MGD)									
Domestic Supply	0.6	0.5	0.04	0.02	0.01	0	0	0	0
Industrial	23.2	0.3	10.45	1.6	10.8	0	0	0	0
Agricultural	76.1	21.2	3.67	23.9	5.9	10.2	4.4	1.9	5.0
Recreational	0.5	0.001	0	0	0	0	0.5	0	0

The two primary irrigation methods employed in the watershed are micro-irrigation and seepage. Micro-irrigation uses drip or miniature sprinkler systems to apply water directly or in proximity to the soil root zone, resulting in high irrigation efficiencies. Seepage or subirrigation uses lateral ditches and the soil to transport water to the plants. Essentially, an artificial water table is created in close proximity to the root zone which provides a constant supply of water by capillary rise. Irrigation efficiencies for seepage irrigation systems are usually low, and the potential for runoff is high under all weather conditions due to the saturated soil conditions.

RESULTS AND DISCUSSION

Rainfall

The typical seasonal rainfall pattern for the Little Manatee River watershed is shown in Figure 4, where average monthly rainfall totals are shown for the Bradenton and Bartow weather stations. These stations are not in the Little Manatee watershed, but along with the Tampa station, represent the nearest long-term sites. Average rainfall for the 1933 to 1989 period was about 54" for both the Bradenton and Bartow sites. Rainfall at these stations is highest during the summer months of June through September, representing about 60% of the annual rainfall. The summer rainy season is caused by the frequent occurrence of convective thunderstorms in the region and the periodic influence of tropical depressions and storms. A fall to spring dry season extends from October to May, with a minor rainfall peak in February and March due to an increase in rains resulting from cold fronts.

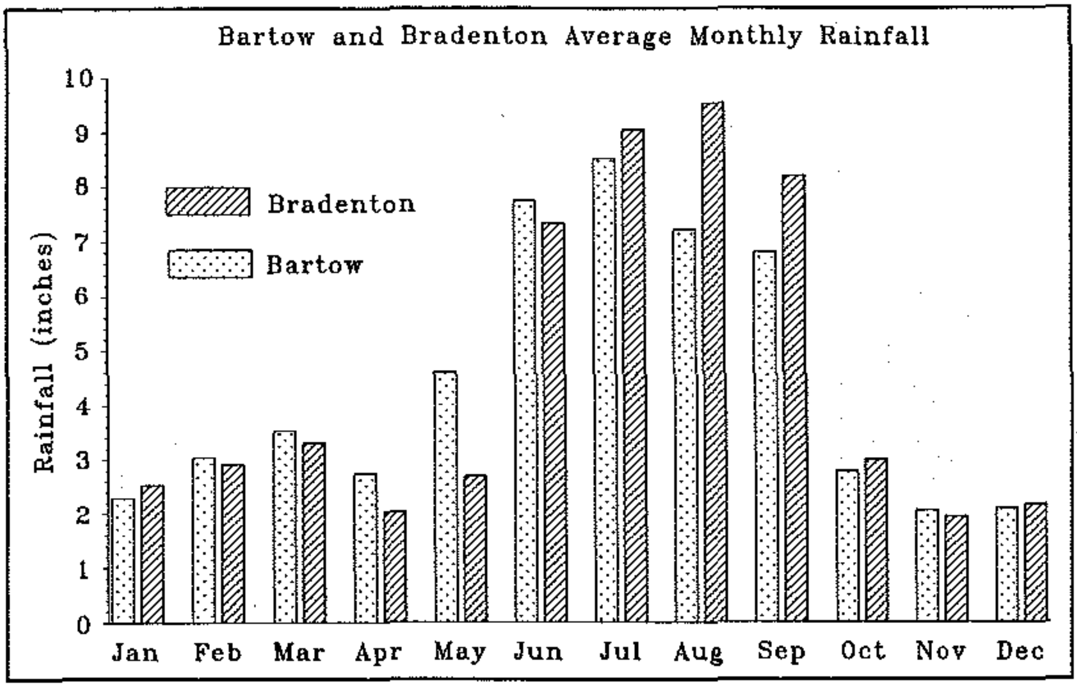

Figure 4. Average monthly precipitation at the Bartow and Bradenton rainfall stations.

Analyses of yearly rainfall records for the Bradenton, Bartow and Tampa stations indicate that portions of the Tampa Bay watershed have experienced a prolonged dry period since 1960. All the stations experienced an extreme wet period around 1960 that was well above the long-term average, but Bartow and Tampa exhibited a significant decrease in the long-term average rainfall after 1960 while the Bradenton station did not. Bradenton's average annual rainfall decreased approximately an inch between the pre-1961 and post-1960 time periods whereas the Bartow and Tampa average rainfalls decreased between 5 and 6 inches. Most of the decreases at Bartow and Tampa occurred between the months of April through October, whereas Bradenton exhibited only a minor redistribution of the monthly rainfall totals (Table 2). As described, stepwise multiple linear regression analysis was used to generate predictive equations for monthly rainfall at stations within or near the LMR watershed as a function of records at the long-term sites. Based on these statistical relationships, the predicted average annual rainfall since January 1961 ranged from 51" in the southern portion of the LMR watershed to 49" in the northern regions. This is in comparison to predicted average annual rainfalls of 56" and 54", respectively, for these regions during the pre-1961 time period.

Table 2. Changes in average monthly and yearly rainfalls from the pre-1961 to the post-1960 period. Values in the top row for each station are differences in inches, whereas the values in parentheses are expressed as percent change.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
BARTOW	0.02	0.46	-0.06	-1.39	-0.43	-1.48	-0.79	-0.89	-0.94	-1.10	0.50	0.29	-5.81
	(0.8)	(17)	(-1.8)	(-45)	(-8.8)	(-17)	(-9.1)	(-11)	(-13)	(-32)	(29)	(14)	(-10.4)
BRADENTON	0.04	0.13	0.43	-1.33	-0.34	0.85	-0.23	0.03	0.27	-1.05	0.17	0.10	-1.01
	(-1.5)	(4.6)	(15)	(-52)	(-11)	(12)	(-2.5)	(0.3)	(3.4)	(-31)	(9.0)	(4.6)	(-1.8)
TAMPA	-0.18	0.46	-0.03	-1.24	0	-1.53	-1.67	-0.02	-0.42	-0.78	0.27	0.20	-5.12
	(-8.1)	(17.9)	(-0.1)	(-52)	0	(-21.8)	(-20.5)	(-2.5)	(-6.4)	(-28.1)	(17.5)	(9.9)	(-10.4)

Spatially averaged rainfall for the watershed during the first study year (January 1988 to January 1989) totaled 54.6", a near normal amount. The seasonal distribution of rainfall was somewhat exaggerated, however, with an unusually dry spring and a wet late summer. Basin-average rainfall from mid-March to early June totaled only 3.4", providing an excellent opportunity to study low-flow conditions in the river. Early the following September, tropical air masses brought over nine inches of rain to the basin during a four-day period, resulting in flooding conditions on the river and a basin-average rainfall of 12.2" for the month of September.

Streamflow — Runoff

The U.S. Geological Survey has reported daily streamflow records for the Little Manatee River near Wimauma gaging station since 1939. This station is located about 15 miles upstream from the river mouth, and measures flow from approximately 67% of the river's watershed. Average yearly flows at the LMR near Wimauma station are plotted versus time in Figure 5A. A trend line derived from a linear regression of flow against year indicates there may be a slight decreasing trend in average yearly flows, but this relationship was not statistically significant. On the other hand, a plot of yearly minimum flows, or the lowest daily flow during a year, shows a definite increasing trend (Figure 5B), which was found to be statistically significant (α=.05, Kendall tau-b test, line plotted using linear regression). The figure also shows that yearly minimum flows typically occur during the months of April through June. Thus, although there has been no significant trend for yearly flows in the basin, baseflow levels in the spring appear to be increasing.

Double-mass curves of accumulated rainfall in the basin and streamflow at the LMR near Wimauma site were examined to see if there has been a change in rainfall-runoff relationships for the basin. The resultant straight line relationship shown in Figure 5C indicates there has been no significant change in the overall rainfall-runoff relationship over the period of record. However, since it was expected that baseflow increases are a seasonal phenomenon, double-mass curves of rainfall and runoff were plotted for individual months. This approach contains a large potential source of error, since average streamflow levels for a month can be strongly affected by antecedent conditions (high flows at the end of a preceding month). The double-mass curve for May shows a similar slope for the periods of 1940 to 1954 and 1960 to 1979. However, there are distinct changes in slope between 1954 and 1960 and from 1979 to 1989. The 1954 to 1960 rise in slope appeared related to antecedent conditions, since there were a number of relatively wet Aprils during that period. For the 1979 to 1989 period, however, April rainfall was below normal while May rainfall showed a small positive net change. Therefore, it appears that during the last decade, greater amounts of streamflow are generated during the spring for given amounts of rain, indicating flow supplementation and/or a change in factors controlling storm-generated runoff.

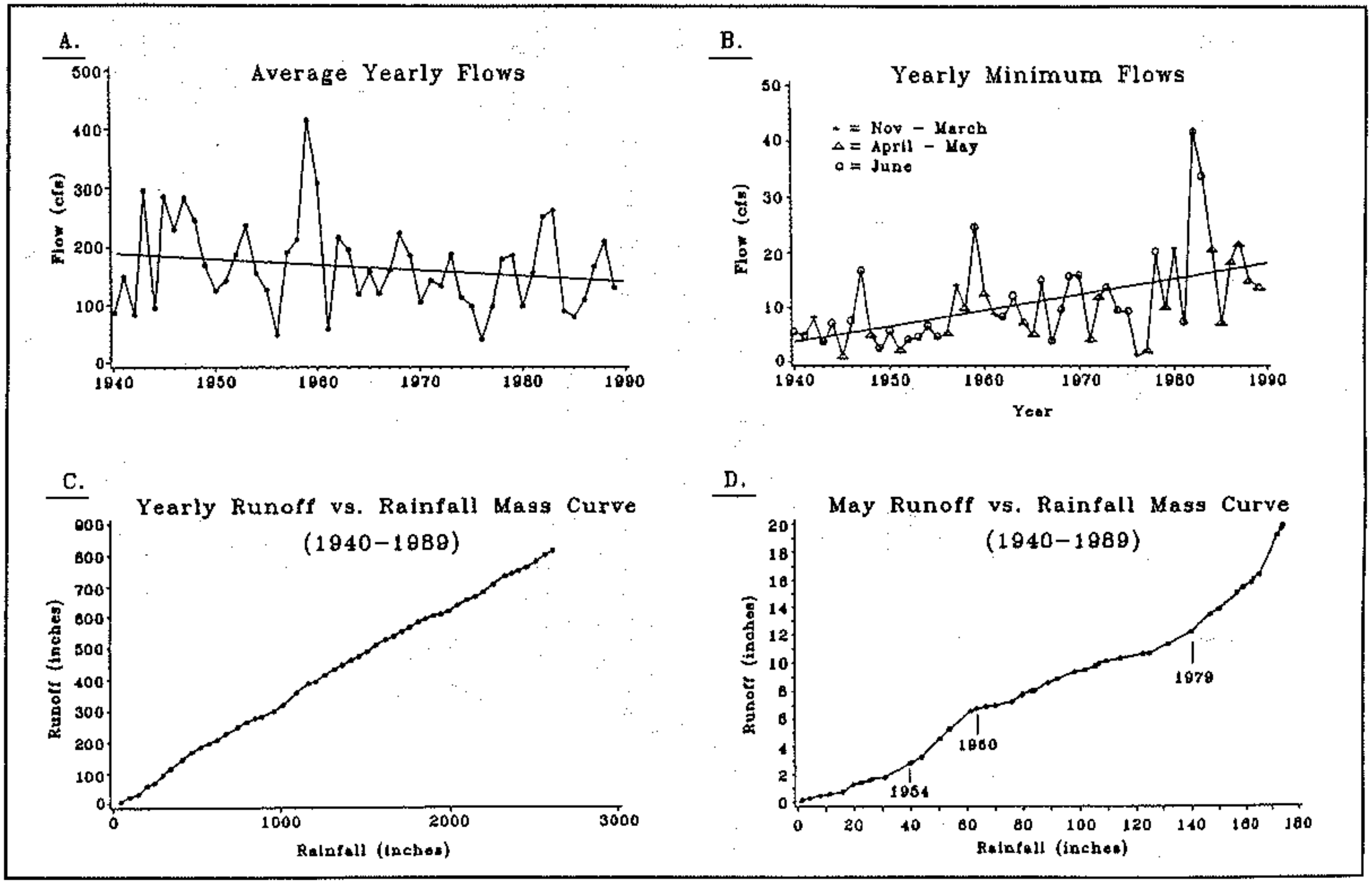

Figure 5. Plots of average yearly flows (A) and yearly minimum flows (B) versus year and double mass curves of cumulative rainfall versus cumulative runoff for yearly totals (C) and totals for May (D) for the period 1940 to 1989.

To further examine possible changes in seasonal levels of streamflow, average monthly flows for the pre-1976 and post-1976 periods were compared (Figure 6). The year 1976 was chosen as a division point since yearly minimum flows indicated a significant increase in values around that time. 1976 was not included in either of these two periods because large non-metered withdrawals from the river by Florida Power and Light Corporation occurred during that year. A comparison of the average monthly flows for the pre-1976 and post-1976 periods (Figures 6A and 6B) shows that flows in April and May increased while flows in the summer and fall (June through October) decreased between the two periods. The decreases in summer and fall streamflow were attributable to corresponding decreases in rainfall (Figure 6C). Increases in streamflow for April and May, however, were not accompanied by similar increases in rainfall. April flows increased by 23% between the two periods despite a 33% decrease in rainfall. In May, streamflow increased by 170% while rainfall increased by only 24%. Other months which showed opposite trends for rainfall and streamflow between the two periods were December and February.

From field observations made during the study it appears that much of the streamflow supplementation of the river comes from agricultural irrigation runoff. These observations are supported by a comparison of net runoff from the seven subbasins monitored during the study. In Figure 7, a smoothed daily hydrograph is shown for runoff from the Carlton Branch and Ft. Lonesome subbasins. The Carlton Branch subbasin contained 57% of its area in citrus and row crops while these land uses comprised only 9.2% of the land in the Ft. Lonesome subbasin. Figure 7 compares the runoff from each gaged area in units of inches to adjust for differences in basin areas. Runoff from the two subbasins exhibited similar temporal patterns, but during the drier months of April through June and October through December, Carlton Branch exhibited higher runoff than Ft. Lonesome. These months correspond to periods of significant irrigation for citrus and vegetable crops. Consequently, the higher runoff rates for Carlton Branch are attributed to either direct irrigation contributions to baseflow or indirect effects which increase the runoff potential of the area.

Yearly runoff rates for the six subbasins from which streamflow was directly monitored during 1988 are listed along with average yearly flows (cfs) in Table 3. The highest runoff rates were observed for the Carlton Branch, Cypress and Dug Creek subbasins (23.2" to 27.0" per year), which have the highest permitted agricultural water use per unit area. The yearly runoff rates for the remaining stations ranged from 21.2" to 21.6". Yearly precipitation totals for the seven rainfall stations monitored during 1988 did not show any spatial pattern that would explain these differences in runoff. The average rate of basin runoff for fifty years of record at the Little Manatee River near Wimauma gage is 15.4" per year. The high rates of runoff observed for all the stations during 1988 were due to the effects of a flood in September 1988, which corresponded to between a one-in-10 and one-in-25 year event.

Water Quality

The water quality results presented below are largely restricted to the biweekly monitoring data collected by the SWFWMD during the first year of study. This is done because of the balanced sampling design and consistency of analytical techniques employed for the seven subbasin sites. For some parameters, however, data available from other sources (USGS, HCEPC) are used to support observed trends. The following discussion characterizes water quality in the Little Manatee River watershed by first examining differences in mean concentrations for the seven monitored stations, and then contrasting water quality at these sites during periods of low flow and storm runoff. Mean values for water quality parameters at each station are listed in Table 4.

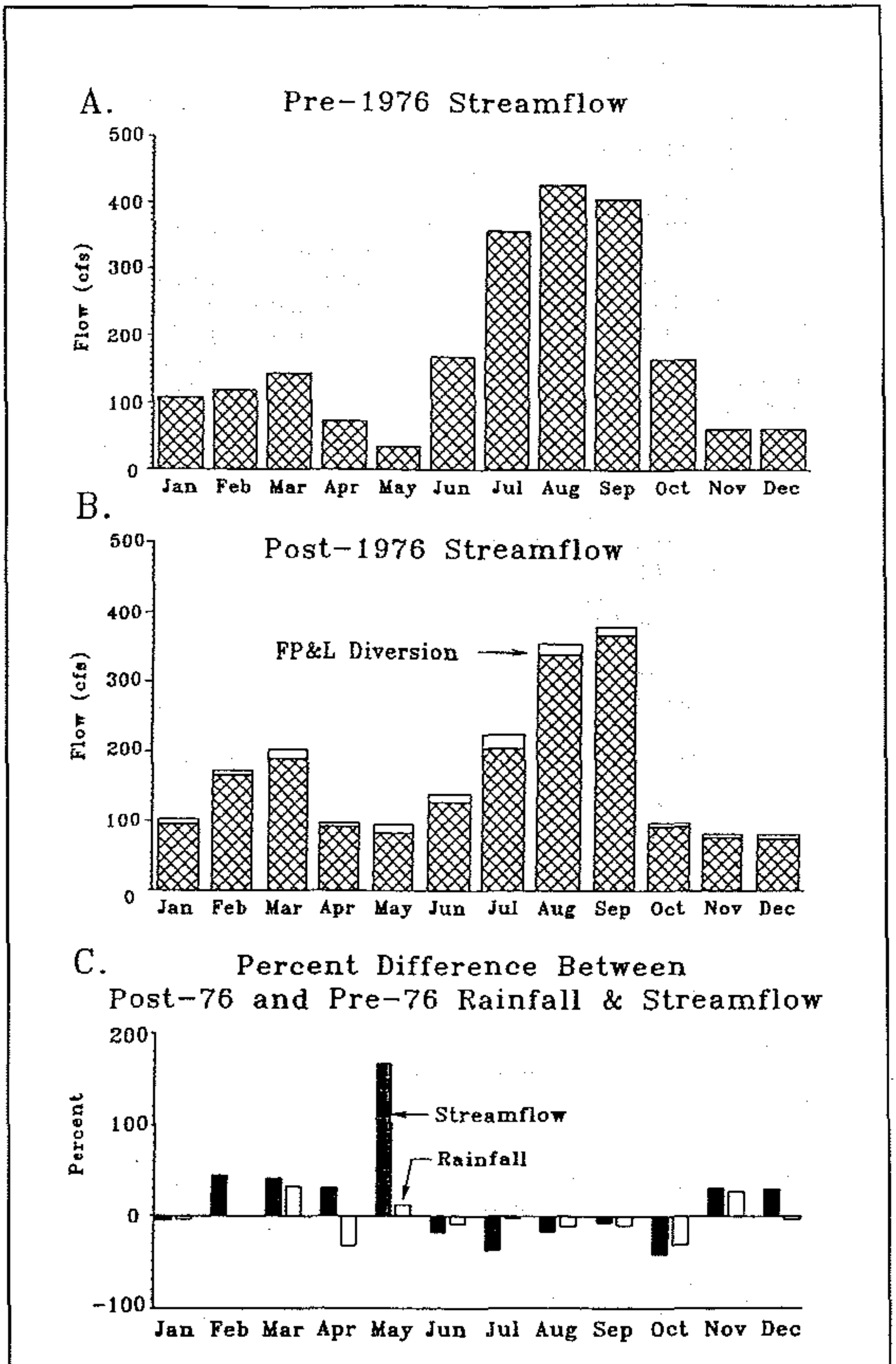

Figure 6. Pre-1976 and post-1976 average monthly flows for the Little Manatee River near Wimauma and percentage changes in monthly rainfall and streamflow between these two periods.

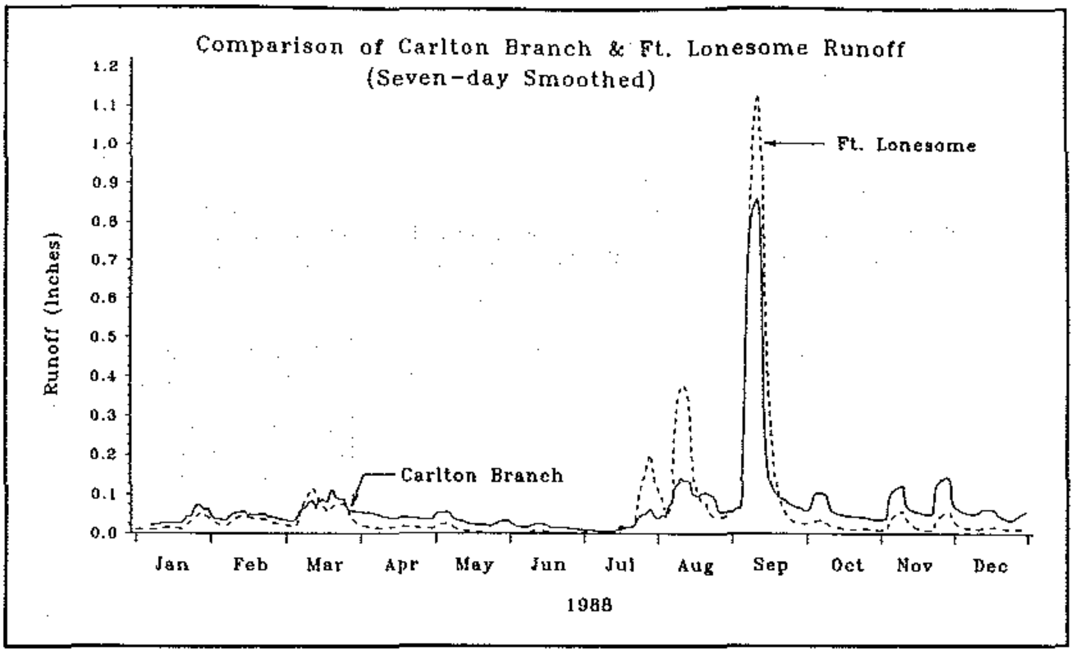

Figure 7. Smoothed hydrograph (seven-day moving average) for runoff in inches for the Carlton Branch and Ft. Lonesome subbasins during 1988.

Table 3. Yearly runoff and average streamflow rates for six subbasins monitored during 1988.

	LMR* NEAR WIMAUMA	FT. LONESOME	SOUTH FORK	CYPRESS CREEK	DUG CREEK	CARLTON BRANCH
Runoff (inches/year)	21.2	21.6	21.5	27.0	23.2	24.8
Streamflow (cfs)	220.9	46.6	61.4	15.7	5.5	15.3

*FP&L withdrawals included.

In order to compare the similarities of water quality at the seven monitored sites, cluster analysis (average linkage method, SAS 1989) was performed on mean values for nine of the parameters listed in Table 4. A dendrogram illustrating the results of this analysis is shown in Figure 8. The horizontal axis of the figure represents the degree of similarity between clusters, with groupings toward the right having increased similarity. To better illustrate spatial trends in the watershed, mean water quality values for the seven stations are discussed in groupings corresponding to the results of the cluster analysis.

Ft. Lonesome and South Fork

Of particular interest are the data for the LMR near Ft. Lonesome station. Mean values for sulfate, total suspended solids, and particulate phosphorus were all significantly less for this station compared to all other sites (Tukey's studentized range test, α=.05). The lowest mean values for specific conductance, nitrate-nitrite, turbidity, pH, and particulate carbon and nitrogen were also observed for the Ft. Lonesome station, with all but pH and turbidity being significantly different from four or five of the other sites. Conversely, mean concentrations of color and dissolved organic carbon were highest at this station.

Table 4. Water quality values for the first study year at the seven stations shown in Figure 2. Value on the first row for each station is the mean for 26 biweekly samples. On the second row from left to right are the averages for five low-flow and five high-flow events among the biweekly samples. Value on the bottom row for four stations is the average from three high-flow and two additional storm samples. Positive or negative sign indicates that parameter concentrations were significantly (α=.05) correlated with flow, with an r value either less than or greater than zero. All values expressed as mg/l except pH or as noted.

	LMR NEAR WIMAUMA	LMR NORTH FORK	LMR FT. LONESOME	SOUTH FORK	CYPRESS CREEK	DUG CREEK	CARLTON BRANCH
pH	6.5 (-) 7.1 6.1 6.4	6.4 (-) 7.3 5.8	6.2 (-) 7.3 5.7 5.8	6.3 (-) 6.8 5.8	6.4 6.5 6.2 6.4	6.8 6.9 6.6	6.7 (-) 7.2 6.2 6.2
Turbidity (NTU)	4.5 (+) 1.3 9.9 43.2	4.3 (+) 1.7 7.2	2.3 (+) 1.3 4.4 9.3	3.2 (+) 1.9 6.9	7.1 6.3 7.5 13.9	5.6 (+) 2.1 14.2	3.7 (+) 2.8 7.4 14.8
Color (PCU)	113 (+) 35 253 189	120 (+) 39 270	142 (+) 69 293 250	117 (+) 37 281	78 (+) 41 92 75	39 (+) 16 71	38 (+) 14.1 83 99
Specific Conductance (umhos/cm)	271 (-) 369 156 267	287 (-) 410 143	154 (-) 198 117 128	204 (-) 297 145	430 (-) 499 386 393	528 (-) 699 400	322 (-) 324 288 299
Ammonia-N	.08 .06 .12 .18	.07 .05 .14	.06 .02 .17 .12	.07 .06 .15	.24 (-) .40 .14 .19	.10 .05 .15	.08 .04 .25 .20
Nitrate/ Nitrite-N	.55 .32 .41 .70	.60 .27 .37	.19 (-) .24 .11 .23	.53 (-) .49 .17	.39 (-) .74 .12 .14	1.1 1.4 .86	1.7 1.2 1.8 2.1
Particulate Nitrogen	.05 (+) .01 .12 .60	.08 (+) .10 .09	.03 .04 .08 .10	.04 (+) .02 .09	.11 (+) .06 .16 .27	.11 (+) .05 .22	.08 (+) .07 .17 .16
Ortho-phosphorus	.34 (+) .24 .52 .53	.37 (+) .27 .55	.37 (+) .30 .53 .42	.27 (+) .20 .42	.04 (+) .02 .03 .03	.10 (+) .07 .24	.27 (+) .18 .38 .49
Particulate phosphorus	.03 .02 .05 .29	.04 .02 .04	.01 .01 .02 .10	.03 (+) .02 .05	.07 .02 .06 .25	.04 (+) .03 .07	.03 (+) .03 .05 .10
Total Suspended Solids	5.2 (+) 1.6 9.9 44.3	7.0 (+) 2.6 8.6	2.0 (+) 1.6 2.8 5.2	4.1 (+) 2.1 8.3	8.6 (+) 5.1 11.2 23	6.2 (+) 3.4 13.1	5.8 (+) 5.1 8.6 10.7
Dissolved organic carbon	15.3 (+) 11.8 21.2 16.4	14.4 (+) 11.4 21.3	18.2 (+) 14.9 23.0 19.0	13.6 (+) 9.0 18.4	16.2 (+) 18.0 16.2 13.8	10.5 (+) 11.6 13.4	8.7 (+) 8.2 12.0 13.8
Particulate carbon	.80 (+) .24 1.8 8.7	.93 (+) .43 1.32	.45 (+) .28 .88 1.4	.74 (+) .43 1.4	1.13 (+) .62 1.6 2.9	1.23 (+) .61 3.0	1.15 (+) 1.3 1.8 2.6
Sulfate	60 (-) 99 18 29	64 (-) 105 12	16 (-) 33 9.6 14	38 (-) 91 5	93 (-) 124 76 57	168 233 146	56 64 47 28
Silicon	6.0 (-) 9.0 3.7 3.3	6.4 (-) 10.5 3.4	4.5 (-) 6.6 3.3 2.7	6.4 (-) 10.6 3.8	3.9 (-) 6.0 2.6 1.9	7.4 (-) 13.6 3.9	7.0 (-) 10.5 4.9 3.7
Chlorophyll a (mg/m^3)	2.6 2.9 6.0	2.9 4.8 2.7		1.3 2.1 1.6			

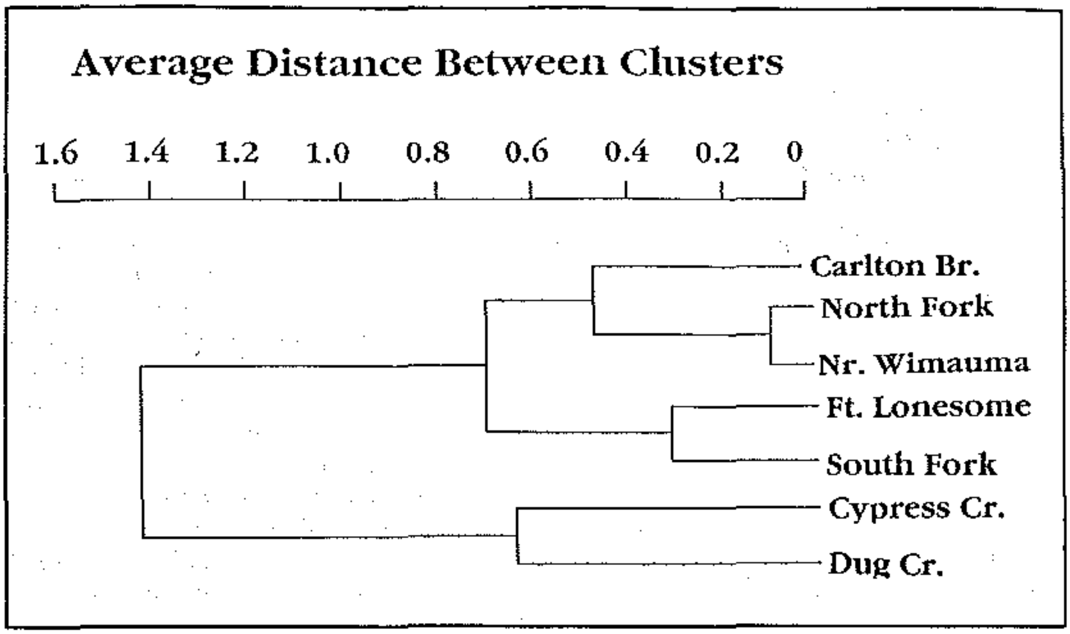

Figure 8. Cluster dendrogram for the seven stations based on mean values of nine water quality parameters. Clusters joined toward the right have greater similarity.

Although water quality at the Ft. Lonesome station has been impacted to some degree, during our study this site best represented the water quality of a natural stream in the basin and can be viewed somewhat as a control site. Over 50% of the land use in the subbasin is improved or unimproved pasture. There is virtually no urban development in the subbasin and citrus and row crops combined are only about 9% of the land area. Much of the land in this subbasin is owned by IMC Fertilizer Inc., and by 1988 approximately 5.8% of the subbasin had been mined for phosphate. This mine was inactive from 1986 through 1988, and average monthly discharges from the one permitted NPDES site were generally small (0.5 to 2.2 cfs) during the study. Larger wet season releases occurred in August and September 1988, when average monthly discharges were 4.8 and 11.3 cfs, respectively. Mining resumed in the subbasin in 1989, and it is emphasized the data presented in this report for the Ft. Lonesome station do not represent any potential influences of recent discharges. The IMC Corporation is currently in the Development of Regional Impact review process for plans to mine substantially more of their land holdings in the Ft. Lonesome area in the next thirty years.

The station that exhibited the greatest similarity to the Ft. Lonesome was the South Fork. Next to Ft. Lonesome, this station had the second lowest mean values for turbidity, specific conductance, sulfate, suspended solids, and particulate nitrogen and carbon. For most land use categories, this subbasin had similar percentage breakdowns as the Ft. Lonesome subbasin, except that it has very little mining and substantially more row crops (16.9% vs. 1.4%).

Cypress and Dug Creeks

Two other stations, Cypress and Dug Creeks, showed similarities distinctly apart from the other five monitored sites (Figure 8). These stations had significantly greater concentrations of specific conductance (430 and 528 μmhos/cm) and sulfate (93 and 168 mg/l) compared to other sites. As elaborated later, high concentrations of these parameters are indicative of pumped ground water entering the streams, primarily as irrigation runoff. The Cypress and Dug Creek stations also shared the characteristic of having significantly lower mean ortho-phosphorus values than the other sites. This was particularly the case for the Cypress Creek, where the mean value (0.04 mg/l) was less than the means of the five highest ranked stations by factors of about 7 to 9, and individual observations showed much reduced variation about the mean compared to other stations.

The Cypress and Dug Creek stations were also similar in that they had comparatively high values for turbidity, total suspended solids, and particulate nutrients. This was especially true for Cypress Creek, which had relatively high turbidity and suspended solids values even during periods of low flow (see low-flow averages in Table 4). The Cypress Creek station represented the only substantially urbanized subbasin in the study, with a combined urban-suburban coverage of 43.4%. During the study, extensive construction work was performed on State Road 674 upstream of the Cypress Creek station and this may have been related to the high turbidity and suspended solids observed at this site. Row crops also comprise a significant proportion (18.7%) of this subbasin, and combined agricultural and golf course irrigation caused this subbasin to have one of the highest rates of groundwater use per unit area (Table 1). The Dug Creek subbasin also contains a significant proportion (15%) of combined urban development, mostly as clustered houses and 34 hectares of golf course, but contains substantially more row crops (28.5%) and citrus (10.2%), which are probably the principal sources of groundwater inputs to this stream.

LMR Near Wimauma, North Fork and Carlton Branch

The remaining three stations were all in the central part of the watershed. The LMR near Wimauma and North Fork sites, along with Ft. Lonesome, are "in-line" stations along the main channel of the river. The Wimauma site represents drainage from 67% of the entire watershed and is the site most often referenced to describe net water quality in the Little Manatee River. The North Fork site, in turn, contributes 35% of the drainage measured at the Wimauma gage. Not surprisingly, water quality at these two stations showed a high degree of similarity and mean concentrations for most parameters were very close.

It is interesting to note that the Ft. Lonesome station was more closely allied to the South Fork than to the immediately downstream North Fork station, and mean values for all parameters except color, ammonia and ortho-phosphorus were significantly different between the Ft. Lonesome and the North Fork sites. These differences were particularly large for nitrate-nitrite, sulfate and particulate nutrients, for which mean values were about 2 to 4 times higher at the North Fork site. This dramatic change in water quality between these two stations reflects the intense agricultural land use in the drainage area between them, much of which occurs in close proximity to natural or man-made drainage channels. An exception to this pattern was ortho-phosphorus, which had similar mean values for the Ft. Lonesome, North Fork and Wimauma sites.

The remaining station, Carlton Branch, was also located upstream of the North Fork site. Mean water quality values indicate that Carlton Branch receives substantial amounts of pumped ground water, as evidenced by high concentrations of specific conductance and sulfate and low concentrations of color. The most distinctive result from Carlton Branch is the high mean nitrate-nitrite concentration (1.7 mg/l), which was significantly greater than for all other stations except Dug Creek. Along with Dug Creek and the North Fork subbasins, Carlton Branch has high percentages of land use in croplands, and by far the highest percentage in citrus production.

Dry Season Characteristics

In addition to mean water quality values (n=26), Table 4 lists average values calculated from five low-flow and five high-flow events at the seven monitored stations. Also shown is a symbol indicating whether the concentration of each parameter was significantly positively or negatively correlated with flow. In general, water quality during low-flow periods was characterized by reduced concentrations of turbidity, ortho-phosphorus and particulate materials, slightly higher pH, and increased concentrations of sulfate, silicon and specific conductance. Color and dissolved organic carbon concentrations were generally near minimum values in the low-flow samples, presumably due to reduced drainage through humus containing soils and vegetation.

It is interesting to note that at the three stations where it was measured, average chlorophyll *a* concentrations were relatively low (2.1 to 4.8 mg/m^3) for the low-flow samples. The 4.8 mg/m^3 average for the North Fork site was influenced by one reading of 10.2 mg/m^3, as values from the other four dates ranged from 2.0 to 4.9 mg/m^3. Based on the one year of data, it appears that algal blooms are uncommon in the nontidal portions of the Little Manatee River, despite the occurrence of abundant nutrients. This is probably due in part to short residence times in the river, for even during low flows the elevational gradient of the channel maintains significant downstream currents. Using average channel velocity data available from USGS streamflow rating measurements, we estimate that transport times from the headwaters to the estuary are no more than three to four days during low flows.

In order to more widely characterize dry season water quality in the watershed, two additional sampling trips were performed in May 1988 and May 1990, during which a total of 21 stations were sampled (Figure 9). For most parameters, concentrations at the stations were similar between the two dates, verifying the spatial trends observed. Average specific conductance values calculated for these two dates showed large variation between tributaries to the North Fork of the river. Values upstream of Carlton Branch were comparatively low, ranging from 190 to 306 µmhos/cm. Four stations in Carlton Branch showed progressively increasing values along the length of the Branch, increasing from 185 µmhos/cm in the upstream reaches to 411 µmhos/cm near the confluence with the river. Highly mineralized waters were observed on three downstream tributaries to the North Fork, with average conductance values exceeding 800 µmhos/cm at these sites. Correspondingly, average conductance values in the North Fork progressively increased downstream, from 222 µmhos/cm at the Ft. Lonesome station to 595 µmhos/cm near the confluence with the South Fork. The South Fork of the river, which had only two accessible sampling sites, similarly showed increased concentrations progressing downstream, but was generally less mineralized than the North Fork as shown by its lower average value (380 µmhos/cm) near the confluence.

Sulfate concentrations for the two May sampling trips showed the same spatial pattern observed for specific conductance, and concentrations of these two parameters were highly correlated ($r=.93$) throughout the study. Data from headwater reaches in this study and historic values from the USGS indicate that specific conductance values for natural surface waters in the region during the dry season are well under 200 µmhos/cm. Conversely, specific conductance values for wells tapping the Floridan aquifer in the region are typically in the range of 300 to 1,300 µmhos/cm, with sulfate values ranging from less than 20 to over 400 mg/l (USGS 1990). Because of the heavy agricultural water use in the region, it is reasonable to conclude that high instream concentrations of these parameters are indicative of mineralized water from the Floridan aquifer reaching these streams via groundwater pumping. Mineralization of the aquifer increases with depth and proximity to the coast; therefore, the spatial patterns shown in Figure 9 are not entirely indicative of relative amounts of groundwater supplementation since the contributing well waters may have very different mineral concentrations.

Response of Water Quality to Increased Streamflow

The response of various water quality parameters to increased flow was examined through Pearson product-moment correlation analysis of instream concentrations and same-day average flows at the seven sites (Table 4). Additional water samples were taken at four stations (LMR near Wimauma, Ft. Lonesome, Cypress Creek and Carlton Branch) during two storm events during the study. Along with three dates from the regular biweekly sampling, a total of five sampling trips occurred on the rising limb of storm hydrographs at these four stations. Average values calculated for these five storm events at the four stations are listed separately in Table 4, along with averages calculated from a total of five high-flow events for the regular biweekly sampling at all stations (three dates are shared between the high flow and storm averages).

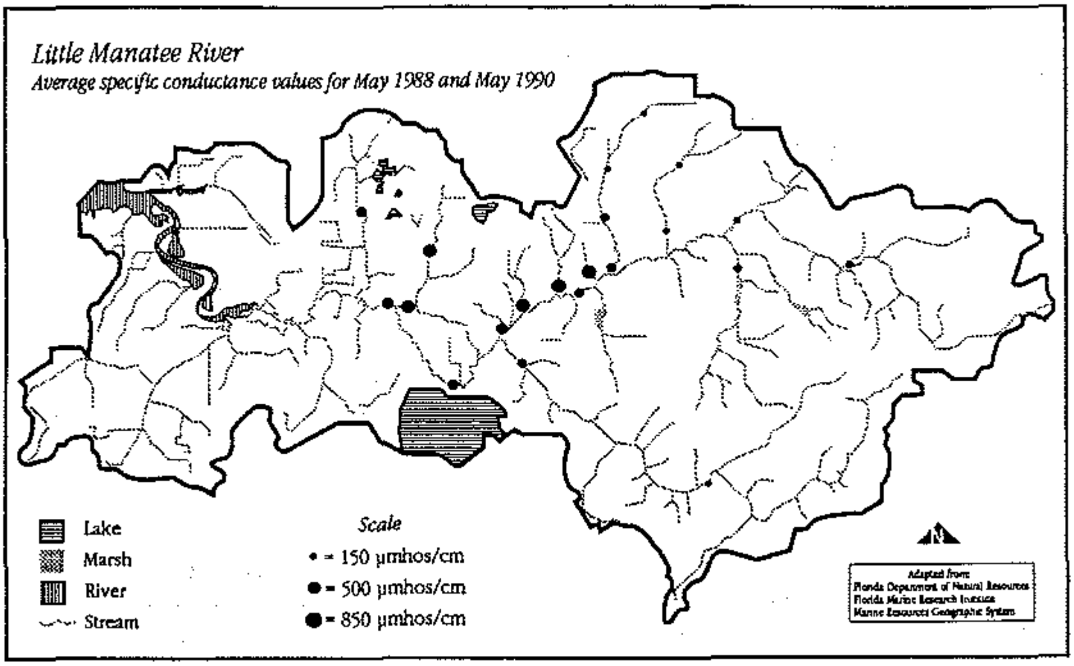

Figure 9. Average specific conductance values for 21 stations sampled during May 1988 and May 1990.

As expected, concentrations of turbidity and particulate materials were positively correlated (α=.05) with flow at most stations. Turbidity was highly correlated with flow at all sites except Cypress Creek, where the relationship was not significant, and average turbidity values were relatively high (6.3 NTU) during low-flow periods. Total suspended solids and particulate carbon and nitrogen were positively correlated with flow at all sites, with the exception of particulate nitrogen at Ft. Lonesome. Interestingly, particulate phosphorus was significantly correlated with flow at only three of the sites, where the corresponding correlation coefficients were less than for the other particulate nutrients.

Although turbidity, suspended solids, and particulate carbon and nitrogen were positively related to flow at most sites, the magnitude of the response of these variables to flow showed large variation throughout the watershed. Average concentrations of suspended solids at Ft. Lonesome for five regular high-flow events were less than the high-flow averages for the other stations by factors of 3.0 to 4.7. Averages for turbidity and particulate nutrients were also lowest at this station. The highest concentrations of turbidity and suspended materials were observed for Dug Creek, followed by Cypress Creek or the LMR near Wimauma site. Dug Creek was not sampled on the extra storm sampling trips, but the storm sample averages listed in Table 4 for Cypress Creek and LMR-Wimauma show very high turbidity and particulate concentrations, especially for the LMR-Wimauma station. Storm averages for turbidity and suspended solids at LMR-Wimauma were 43 NTU and 44 mg/l, respectively, or about 2 to 4 times the averages for Cypress Creek and Carlton Branch, and more than 4 and 8 times the storm averages for turbidity and suspended solids, respectively, at Ft. Lonesome. Comparison of the data from the Ft. Lonesome and LMR-Wimauma sites indicates that land use alterations between these locations have had substantial impact on the loadings of particulate materials to the river system.

Compared to particulate materials, the response of dissolved constituents to streamflow was more varied. Significant negative correlations with flow were observed for sulfate, silicon and specific conductance at all sites, with the exception of sulfate at Dug Creek and Carlton Branch. The reduction of these parameters with increasing flow reflects the reduced proportion of ground water in these streams during periods of increased storm runoff. Ammonia concentrations showed no general pattern, being unrelated to flow at four of the stations, negatively correlated with flow at Cypress Creek, and demonstrating a positive trend at Carlton Branch (α=.06). Ortho-phosphorus did show a consistent trend being positively correlated with flow at all stations.

Nitrate-nitrite concentrations were negatively correlated with flow at three stations and a nonsignificant negative trend with a lower confidence level (α=.08) was observed at Dug Creek. One exception to this pattern was Carlton Branch, where nitrate-nitrite concentrations showed little relationship to flow (r=.02) and high concentrations (>2.0 mg/l) occurred during both high and low flows. For the other stations, plots of nitrate-nitrite concentrations versus flow showed two general types of patterns. For better illustration, and because the 1988 and the combined data sets show consistent relationships, nitrate-nitrite values from the combined SWFWMD-USGS-HCEPC data for the LMR-Wimauma and Ft. Lonesome stations are plotted versus flow in Figure 10. The flow ranges shown for the stations are those flows which were exceeded 10% of the time for the period of the data shown (1982 to 1990). Older nitrate-nitrite values were not used because there has been a significant increase in this parameter over time at the LMR-Wimauma station.

The first thing apparent from Figure 10 is that nitrate-nitrite concentrations at the Wimauma station fluctuate over a much wider range, as only one value from the Ft. Lonesome site exceeded 0.5 mg/l, whereas 56% of the observations from the LMR-Wimauma site exceeded that amount. Second, the basic shapes of the two curves are different; nitrate-nitrite concentrations decreased rapidly with flow below 20 cfs at Ft. Lonesome and remained below 0.2 mg/l at higher flows. There was much more scatter in this relationship at the LMR-Wimauma site, with concentrations above 0.5 mg/l continuing to occur at higher flows and a significant negative correlation was not found with flow. The difference in these two plots indicates that storm runoff in the Ft. Lonesome catchment carries much less nitrate-nitrite than does runoff from areas farther downstream. It is possible that this downstream enrichment occurs in both the surface drainage and the interflow components of the storm hydrograph, but the relative magnitude of these components is not known. It does seem likely that crop fertilization in the basin could enrich nutrient concentrations in the surficial aquifer, potentially increasing instream concentrations via ground-water interflow where agricultural lands are near water table gradients toward stream channels.

Nutrient Loading Rates

The collection of streamflow and water quality data allowed for the computation of nutrient loading rates for the seven subbasins. Yearly flux rates (kilograms per hectare per year) for seven dissolved and particulate constituents from the monitored subbasins during the first study year are listed in Table 5. The flux rates listed for the LMR-Wimauma and the North Fork stations include all areas upstream of those gages. The total areas used for computation of flux rates from those subbasins are as follows from Table 1: North Fork = subbasins 3+4+8; LMR-Wimauma = subbasins 2+3+4+5+7+8. As such, the LMR-Wimauma gage integrates loadings from 67% of the watershed. Cypress Creek represents loading from another 3.6%, so loading from 30.4% of lower river basin was not measured by this study.

Similar to the results for instream concentrations, flux rates for all constituents except dissolved organic carbon and ortho-phosphorus were lowest from the Ft. Lonesome subbasin. The ratio of yearly fluxes of dissolved inorganic nitrogen (ammonia plus nitrate-nitrite) to ortho-phosphorus from the Ft. Lonesome subbasin was 0.34, which is unusually low. This was due to the high ortho-phosphorus concentrations in the stream and the opposite correlative relationship of nitrate-nitrite (negative) and phosphorus concentrations (positive) to flow. Ortho-phosphorus flux rates were similar (2.36 to 2.63 kg/ha/yr) to Ft. Lonesome at three other stations (LMR-Wimauma, North Fork, Carlton Branch), but markedly lower at Cypress and Dug Creeks (0.31 and 0.82 kg/ha/yr).

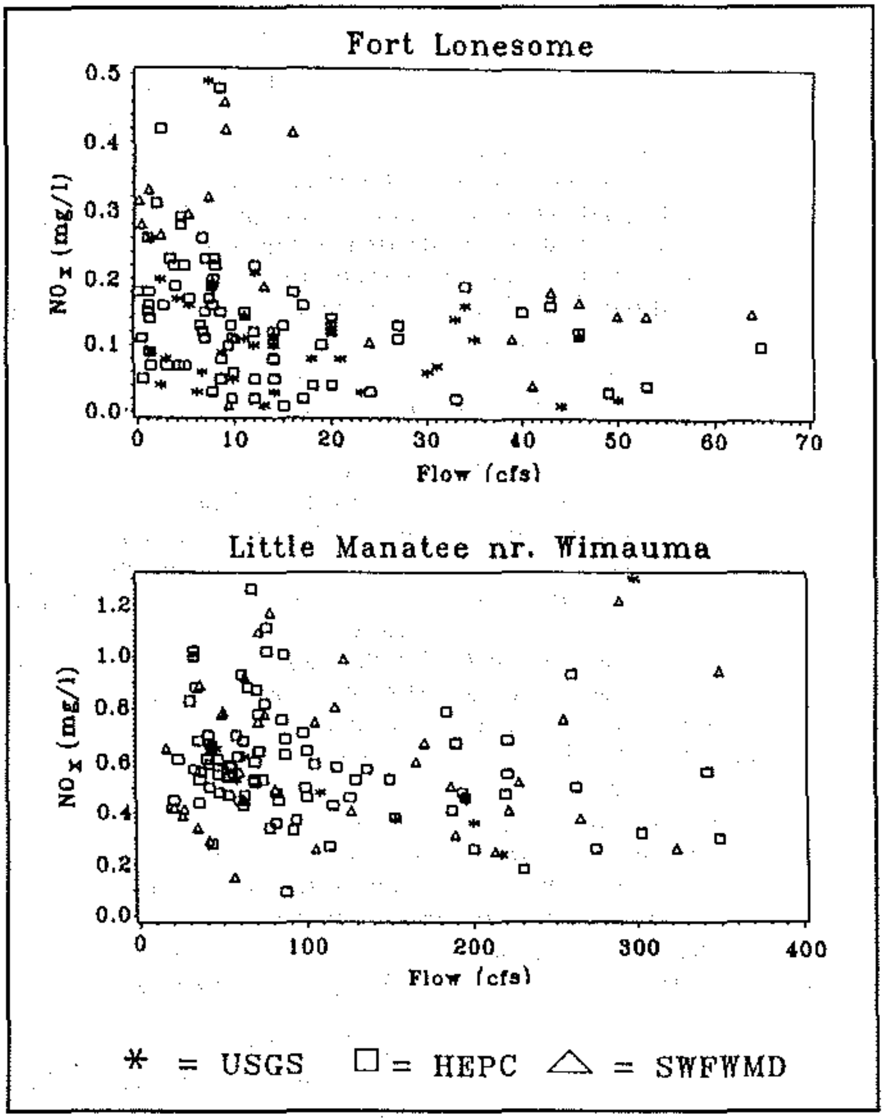

Figure 10. Concentrations of nitrate-nitrite versus streamflow for the Ft. Lonesome and Little Manatee River near Wimauma monitoring stations for 1982 to 1990. Maximum flows shown correspond to the 10% exceedance flow at each station for that period. One outlier for Ft. Lonesome not shown (flow=5.7 cfs, NO_x=0.78 mg/l).

Dissolved inorganic nitrogen (DIN) fluxes were more than twice as high for Carlton Branch than for all other subbasins, and an order of magnitude higher than at Ft. Lonesome. The Dug Creek subbasin, which like Carlton Branch has a high percentage of agricultural land use, had the second highest flux rate for DIN (3.51 kg/ha/yr). The DIN flux for the downstream LMR-Wimauma site was 2.56 kg/ha/yr, and the ratio of DIN and ortho-phosphorus fluxes at this station was approximately one. Readers are reminded these N/P flux ratios do not include particulate nutrients or dissolved organic nitrogen. Dissolved organic nitrogen is less available for plant growth and was not measured in our study. Inclusion of this constituent would increase reported N/P concentration and flux ratios.

Table 5. Yearly material fluxes (kilograms per hectare per year) for the seven monitored subbasins shown in Figure 2. Values expressed for the LMR-Wimauma and North Fork were calculated using the entire drainage areas upstream of those gages.

	LMR NEAR WIMAUMA	LMR NORTH FORK	LMR FT. LONESOME	SOUTH FORK	CYPRESS CREEK	DUG CREEK	CARLTON BRANCH
Dissolved inorganic nitrogen (NH_4+NO_x)	2.56	2.47	0.81	1.78	1.72	3.51	8.96
Particulate nitrogen	0.76	0.53	0.11	0.46	1.10	1.12	0.58
Ortho-phosphorus	2.43	2.63	2.38	2.23	0.31	0.82	2.36
Particulate phosphorus	0.17	0.18	0.08	0.18	0.33	0.39	0.43
Total suspended solids	60.91	62.55	12.82	40.78	79.80	67.40	55.66
Dissolved organic carbon	114.1	118.3	128.9	106.4	124.3	77.6	66.6
Particulate carbon	10.48	8.54	2.95	7.22	10.79	12.63	9.16

The flux rates for particulate materials were highest at the Cypress and Dug Creek stations. In general, differences in particulate flux rates for the seven subbasins were generally less than the range of fluxes observed for dissolved constituents. With the exception of Ft. Lonesome, the highest and lowest flux rates for total suspended solids and particulate nitrogen differed by factors of 1.9 and 2.4, respectively, while the high and low fluxes for DIN and ortho-phosphorus differed by factors of 5.0 and 8.5. Again, the Ft. Lonesome subbasin had flux rates for particulate materials that were markedly lower than the other stations. This was particularly true for total suspended solids and particulate nitrogen, for which fluxes at Ft. Lonesome were about three to four times less than the next lowest subbasin (South Fork), and about five to seven times lower than the net basin flux expressed at the LMR-Wimauma site.

In addition to yearly nutrient flux rates, a few points regarding seasonal nutrient loadings are noteworthy. First, the supplementation of flows by irrigation runoff resulted in very large differences in nutrient loadings between subbasins in the dry season. For example, the computed DIN flux from the Carlton Branch during May 1988 was 35 times higher than the same monthly flux from the Ft. Lonesome subbasin. Second, loading to the estuary is very seasonal, and can be strongly influenced by large storms. In Figure 11, the monthly loadings of DIN and ortho-phosphorus during 1988 are plotted for the sum of the Cypress Creek and the LMR-Wimauma subbasins, or about 70% of the entire watershed. The vertical bar representing the loadings in September has a broken scale to show the effect of a flood event which occurred that month. That flood, which was caused by an average of 9.6" of rain in the basin over four days, raised the peak-day flow to 9,720 cfs at the LMR-Wimauma site, corresponding to between a one-in-10 and one-in-25 year event. Due in large part to this flood, September loadings represented 39% and 58% of the yearly loads of DIN and ortho-phosphorus, respectively.

To indicate seasonal nutrient loading in a more typical year, we adjusted the streamflow records by holding the maximum daily flows observed in September to the maximum daily levels observed in August. This involved changing flows for six days at the LMR-Wimauma and Cypress Creek stations, reducing the peak flow in September to a level that on the average is exceeded about three days in that month. The adjusted September load is indicated by the tops of the shaded bars in Figure 11. This adjustment probably better represents the typical seasonal pattern of loading for these constituents. Although the majority of nutrients continue to be delivered in the late summer, a secondary peak occurs in March, which might have an important role in stimulating primary productivity in the estuary during the spring.

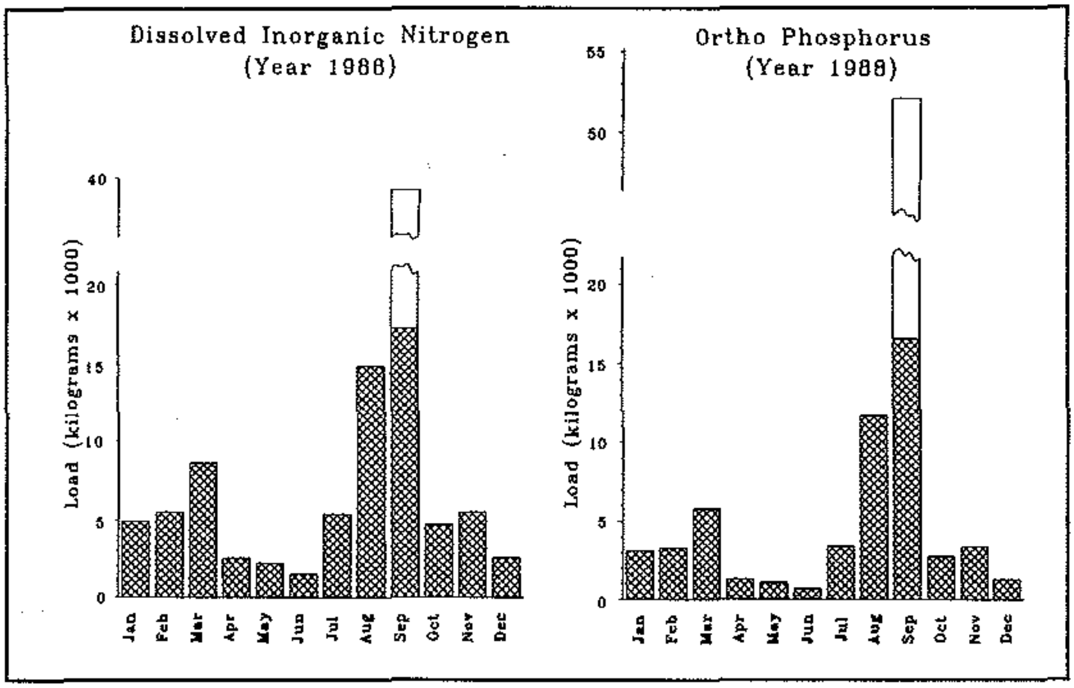

Figure 11. Monthly loadings of dissolved inorganic nitrogen and ortho-phosphorus for the sum of the Cypress Creek and LMR-Wimauma subbasins during 1988. Top of clear bar for September indicates actual load, whereas top of shaded bar indicates loading if combined peak September flows held to peak flows observed in August (1166 cfs).

Finally, it is apparent from Figure 11 that the occurrence of the September flood strongly affected the yearly nutrient fluxes expressed in Table 5. We recalculated total yearly loadings using the adjusted streamflow data and found that the four day flood event accounted for 39%, 22%, and 54% of the total yearly loadings for ortho-phosphorus, DIN, and dissolved organic carbon, respectively. The reason for the high percentage reduction of dissolved organic carbon was that concentrations were highly correlated with flow, so calculated loadings were especially high during the flood. Therefore, it is emphasized that the yearly flux rates listed in Table 5 be used primarily to compare stations within the watershed, and be used with caution if compared to values from other basins.

Long-Term Trends: Other Data Sources

Long-term water quality data from other sources were reviewed to see if temporal trends in water quality mimic the spatial variations we observed between subbasins during 1988. Water quality data for a few parameters are available back to the 1950s from the USGS, and fairly extensive data sets are available back to the mid-1970s when the Hillsborough County Environmental Protection Commission began sampling programs in the region. Data were retrieved from these two sources and merged with the SWFWMD data to create a combined data set for the basin. For constituents that were measured by different labs and expressed in the same units, these values were combined as a single variable. We have not as yet closely checked the methods used by the different labs, but intend to do so to the degree possible. For some parameters, such as specific conductance, there is good confidence that the data are comparable. For some nutrient parameters, such as nitrate-nitrite, very old data may be of questionable resolution, but data for the last 10 to 15 years should be comparable. Kendall tau-b nonparametric correlation analysis was performed to test for significant relationships of constituent concentrations with time (date). Where trends are reported in the following discussion, at least 150 observations were analyzed over periods of ten years or greater. Since the simple Kendall tau-b test does not account for possible seasonality or serial correlation within the data, reported trends are presented as preliminary, and we are currently developing programs to perform the more rigorous seasonal Kendall test (Hirsh and Slack 1984).

The two stations with the most long-term water quality data are the LMR-Wimauma and Ft. Lonesome, which currently have very different water quality characteristics. At the Ft. Lonesome site, Kendall tau-b tests indicated there were significant (α=.05) increasing trends for specific conductance, pH, turbidity and sulfate. For conductance and sulfate, plots of the data versus time showed a rise in the values around 1985 and a stable trend thereafter. Means calculated for the pre-1985 and post-1984 periods for specific conductance rose from 125 to 191 µmhos/cm, for sulfate from 18.3 to 44.0 mg/l, and for pH from 6.5 to 6.9 units. Based on a considerable number of observations, there were no significant trends for total suspended solids or nitrate-nitrite.

Much stronger trends were observed for the LMR near Wimauma station. Specific conductance showed an increasing trend over time with sharp increases in concentrations since the mid-1970s (Figure 12A). Because specific conductance is a very easy and reliable measurement to perform, there should be good confidence in these data. The degree of enrichment since the early 1970s is substantial; the average value for the last three years (n=70) is 320 µmhos/cm compared to average value of 83 µmhos/cm for the period 1955 to 1972 (n=131). Although not shown here, the plot for sulfate showed a similar trend with mean values of 7.8 and 124 mg/l for the pre-1973 and post-1987 periods, respectively. We expect the barium chloride turbidimetric technique was used for the early sulfate measurements and have little reason to doubt those data are reliable. The data indicate that the Little Manatee River has become much more mineralized in the last two decades. As previously discussed, we expect that increased groundwater pumping and irrigation runoff are the primary reasons for the increased mineralization of the river.

Significant trends for increasing concentrations were also observed for turbidity, pH, and nitrate-nitrite. The Kendall tau-b coefficients for turbidity and pH were relatively low (.25 and .22), but plots showed a rise in pH values in the mid-1970s, similar to the pattern observed for conductance and sulfate. The average pH value for dates between 1955 and 1972 was 6.5 (n=104), whereas the average for dates after 1972 was 7.1. A very strong trend was observed for nitrate-nitrite (Figure 12B). The plot of nitrate-nitrite concentrations versus time shows an increasing trend began in the middle to late 1960s and has continued upward in a steady manner. There was no significant trend for ortho-phosphorus concentrations dating back to the 1960s, indicating that the basin is naturally high in phosphorus compounds.

Overall, observations of the long-term data at the LMR-Wimauma station are very striking. Assuming the data from the 1950s and early 1960s are reliable, the Little Manatee was a slightly acid stream with low specific conductance and inorganic nitrogen concentrations. Average values for specific conductance, sulfate, and nitrate-nitrite from the LMR-Wimauma station during early 1970s indicate that water quality there was similar to what is now observed at the Ft. Lonesome site. Independent measurements (pH, sulfate, nitrate-nitrite) show major changes in water quality began occurring in the basin in the 1970s. We have not examined old aerial photographs or other records to examine if dramatic changes in land or water use have occurred since that time. However, the temporal trends at the LMR-Wimauma station correspond to the spatial differences currently observed between highly developed and less impacted subbasins, indicating that intensifying land and water use have been the principal causative factors.

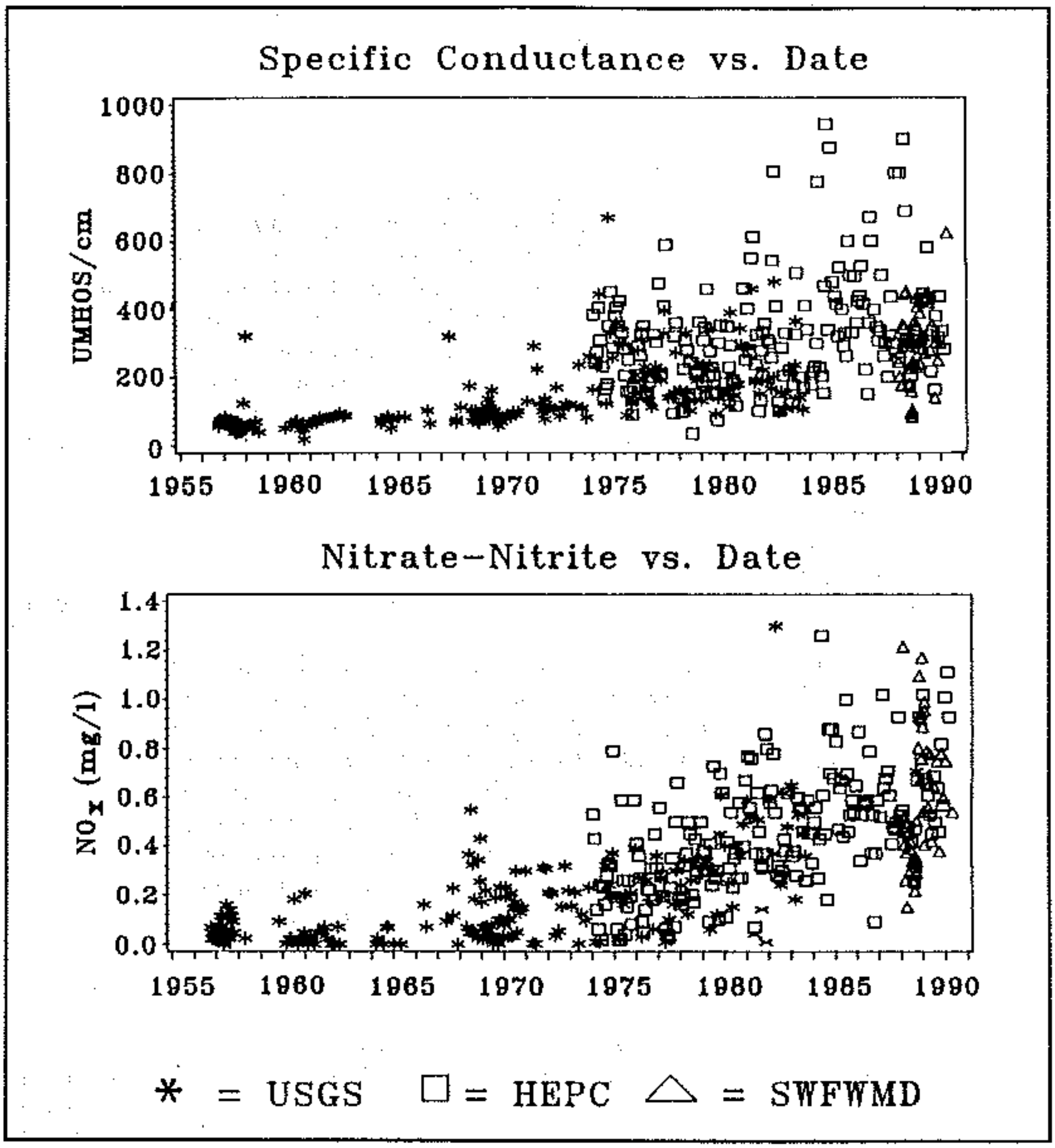

Figure 12. Specific conductance and nitrate-nitrite concentrations versus date for the Little Manatee River near Wimauma station. Symbol indicates source of the data.

Overview — Estuarine Considerations

The focus of this paper has been the freshwater reaches of the Little Manatee River, for much of our estuarine analyses are now in progress and will be published in early 1992 (SWFWMD and Dames & Moore, in prep.). At this time, however, some considerations regarding potential impacts to the estuary are apparent and are discussed below.

The popular perception that the Little Manatee River represents the healthiest river flowing to Tampa Bay is probably correct, but our study indicates there have been significant changes in the streamflow and water quality characteristics of the river in the last 20 years. The nitrate enrichment of the river has particular relevance to Tampa Bay, because phytoplankton production in the bay is nitrogen limited (Fanning and Bell 1985, Palmer and McClelland 1988). The relationships of nitrate-nitrite concentrations to streamflow shown in Figure 10 and the plot of nitrate-nitrite vs. time in Figure 12 indicate that nitrate concentrations in storm runoff have significantly increased due to changes in land use. The Little Manatee River represents approximately 10% of the entire drainage basin for Tampa Bay and contributes approximately the same percentage of tributary flow (Hutchinson, 1983; Flannery, 1989). Obviously, the observed increases for nitrate-nitrite concentrations in the river have important implications for the overall nitrogen budget of Tampa Bay.

The second general conclusion of this report pertains not to the open waters of Tampa Bay, but to the tidal river habitats upstream of the river mouth. Data from companion biological studies of the Little Manatee River (Peebles et al., Vargo et al., this volume) indicate that various estuarine zones along the freshwater to bay gradient differ significantly in their response and sensitivity to eutrophication. One interesting finding was the relative stability of chlorophyll concentrations and phytoplankton numbers near the mouth of the river compared to higher and more variable levels in the upper estuary. The reasons for these spatial patterns are unclear, but may involve differences in biological factors (zooplankton grazing or benthic filter feeding) or physical factors (tidal exchange near the mouth of the river) affecting phytoplankton abundance in these two environments. Algal blooms in the upper estuary were common in the spring and fall during times of low streamflow. Like Tampa Bay, phosphorus is present in excess throughout the riverine estuary and nitrogen appears to be the macronutrient controlling phytoplankton growth (Vargo et al., this volume). Although the effects of nitrogen enrichment in the river during times of low streamflow might be of minor importance to the yearly loading of nutrients to Tampa Bay, increased dry season loading could have important implications for maintaining high algal biomass in the upper estuary.

Field observations and water quality data indicate the upper estuary is rich in organic material in both dissolved and particulate forms (Peebles et al., this volume). Estuaries, because of rapidly changing water chemistry and occurrence of estuarine circulation, are known to accumulate fine-grained and organic materials in upper estuarine mixing zones (Postma 1967, Pritchard and Schubel 1981). Although historical data are scarce, comparison of the recent data from the seven monitored subbasins indicates that land use changes have increased the loading of particulate carbon and nitrogen to the estuary. Particulate organic materials serve as food sources in detrital food webs (Knox 1986), but in excess can lead to low dissolved oxygen concentrations depending on the oxidizable nature of the materials and the potential for high microbial respiration (Aston 1980, Kennish 1986).

Dissolved oxygen concentrations were measured throughout the length of Little Manatee River estuary during the two year estuarine study. During the summer months of July through September, mean water column dissolved oxygen concentrations averaged about 5.2 mg/l for stations near the mouth of the river, with percent saturation values averaging about 77%. Dissolved oxygen concentrations at stations in the middle and upper reaches (above mile 4) were considerably lower, with average concentrations between 3.4 and 4.2 mg/l and percent saturation values in the range of 47% to 56%. These values were all midafternoon readings, and dissolved oxygen concentrations may have been lower during late night or early morning hours. In highly colored Florida waters, and estuaries in general, naturally occurring processes or hydrographic factors can contribute to low dissolved oxygen concentrations

(Belanger et al. 1985, Tyler 1986). It is difficult to discern to what degree the relatively low dissolved oxygen concentrations in the Little Manatee estuary are the result of natural processes versus anthropogenic effects. It can be concluded, however, that summertime dissolved oxygen conditions are marginal with regard to a healthy aquatic system (Friedemann and Hand 1989, F.A.C. 1990), and any perturbations which further lower these concentrations could result in diminished biological diversity and productivity of the system.

In summation, this study emphasizes that estuarine relationships to the quantity and quality of freshwater flows should be examined not only in the open waters of the bay but also in the gradient of ecological zones upstream of tidal creek and river mouths. Because of the important role these areas play with regard to fisheries production, their proper management is of obvious importance. Potentially, these tidal creek/river habitats can be impacted by either point or nonpoint sources. Seasonal nutrient loadings that seem small compared to the overall nutrient budget of the bay may exert important effects in low salinity areas. Fortunately, the total drainage area of Tampa Bay is relatively small, about 2,184 mi^2 (5,650 km^2), and most of the tributary flow originates in one of three counties. Hopefully, the localized nature of tributary flows to Tampa Bay can allow for the development of effective nonpoint source control strategies through the cooperation of the public and private entities involved.

ACKNOWLEDGEMENTS

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ECOSYSTEM-LEVEL RESPONSES TO ESTUARINE EUTROPHICATION: COMPARATIVE ANALYSIS OF RELATIONSHIPS BETWEEN NUTRIENT LOADING AND ALGAL BIOMASS IN CHESAPEAKE BAY AND FOUR TRIBUTARY ESTUARIES

J. H. Garber
W. R. Boynton

ABSTRACT

The Maryland Chesapeake Bay Monitoring Program has, since its inception in 1984, sought to provide a synoptic picture of the causes and consequences of eutrophication of Chesapeake Bay. Individual components of this on-going program have compiled a record of nutrient loadings, water quality parameters, and ecosystem processes (primary productivity, zooplankton herbivory, organic matter deposition rates, benthic recycling rates, etc.) of unprecedented spatial and temporal completeness. The purpose of this work is to examine these data for relationships between rates of nutrient loading and processes that affect estuarine algal stocks and water quality. Our approach is based on comparisons of processes among four subsystems of the Chesapeake Bay basin.

Nitrogen loading of these four systems ranged from about 80 million kg TN/year for the northern mainstem Chesapeake Bay to 1.4 million kg TN/year in the Choptank River. Phosphorus loadings ranged from 3.6 million kg TP/year (mainstem) to 0.11 million kg TP/year (Choptank). In most cases riverborne nutrients represent the single most significant source of N and P.

Based on newly compiled nutrient budgets for these systems, we estimate that the amount of N exchanged across the seaward boundaries of these systems varied from less than 10% of annual inputs in the Patuxent Estuary to more than 50% of inputs to the northern mainstem. One system, the Choptank, appears to import N from the mainstem Bay. The fraction of total inputs exported across the downstream boundary increased as the loading rates of the systems increased. Conversely, nutrient recycling rates were inversely related to the inputs of new nutrients.

In spite of uncertainties in nutrient budgets and interannual variability, we have found a strong relationship (r^2=0.81) between the annually averaged chlorophyll *a* concentration (integrated through the water column in mg/m) and annual N loading of these systems adjusted for size, depth, and hydraulic retention time. The slope of the relationship suggests that an increase of nitrogen equivalent to ½ mg N/m^2/day would produce an increase in average intregrated chlorophyll biomass of nearly 1 mg/m^2. This relationship did not emerge as strongly when P was substituted for N. A similar relationship was found during the eutrophication gradient experiment in the MERL mesocosms, although the slope of the chlorophyll vs. loading curve from the MERL tanks was considerably greater. These results support the general eutrophication hypothesis in estuarine waters to the extent that a measure of algal biomass can be linked to rates of nutrient loading and that nitrogen is a particularly important element in these interactions.

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DISTRIBUTION OF SEDIMENTS AND SEDIMENTARY CONTAMINANTS IN TAMPA BAY

G. R. Brooks
L. J. Doyle

ABSTRACT

Tampa Bay is a drowned river valley filled with as much as 20 meters of unconsolidated sediments reflecting a wide variety of depositional environments that existed during the late Pleistocene sea level fluctuations. Surface sediments consist of a mixture of quartz sands, shell material and muds containing variable amounts of organic matter. Mud-size (<63μ) material comprises the highest percentage of sediments in relatively sheltered, low energy zones around the periphery of the bay, and in localized bathymetric depressions within the open bay. Around the bay periphery, mud-size sediments tend to concentrate in dead-end canals adjacent to heavy development. Localized concentrations of mud-rich sediments within open portions of west central Hillsborough Bay and central Old Tampa Bay have been found to correlate with bathymetric depressions, which act as fine-grained sediment sinks by providing shelter from the surrounding higher energy environments. Toward the bay mouth and in areas less developed, mud-size sediments tend to comprise lower percentages of the whole sediments.

Based upon existing data bases, the distribution of sedimentary contaminants, including nutrients, metals, petroleum and chlorinated hydrocarbons, and radionuclides, appears to parallel that for mud-size sediments. The percentage of mud-size sediments, therefore, provides a mechanism that can be used to identify and locate fine-grained sediment sinks, which are potential "hot spots" for contamination.

Although existing data bases for contaminants in sediments are adequate for a general description of some parameters, several problems exist that prohibit the intergration of these data bases, and therefore, a thorough evaluation of contamination in Tampa Bay surface sediments. Work is currently underway, concentrating efforts on these fine-grained "hot-spots", to thoroughly evaluate the extent to which sediments are contaminated and eventually aid in determining the resulting impacts to the Tampa Bay ecosystem.

INTRODUCTION

The discipline of sedimentology deals with the study of textural and compositional characterization of sediments and processes influencing their distribution. Sedimentological information is important for those concerned about pollution and management of estuarine systems for several reasons. First, it has long been axiomatic in sedimentology that contaminant content is inversely correlated with grain size in marine and estuarine sedimentary systems. One reason for this is simply that fine-grained particles are more reactive than coarse-grained ones. Knowledge of the distribution of fine-grained sediments, therefore, is useful for locating "hot spots" of contamination. Second, sedimentologic characteristics such as texture, mineralogy, and organic content are important for determining the origin of sediments and, therefore, associated contaminants. Finally, the identification of sedimentary processes and controls on sediment distribution patterns are important for determining how contaminants are distributed throughout the bay, how they exchange various components with the water column, and in predicting how contaminants may be distributed in the future.

Contaminants that are of concern in estuarine sediments have been identified in many previous studies around the world, by the United Nations, by the Environmental Protection Agency, the Corps of Engineers, and by many state and local agencies. Preston (1989) reviewed marine pollution, including and even emphasizing pollution in estuaries. He lists the parameters of universal concern—those that managers of any marine system, including Tampa Bay, must be cognizant of and conversant with the specifics of, with regard to their particular area. These are:

- petroleum hydrocarbons;
- persistent organic compounds, specifically pesticides and other chlorinated hydrocarbons;
- sewage, including microbes and nutrients;

- trace metals; and
- radionuclides.

To that group we have added fine-grained sediments, those <63μ diameter that are often considered a pollutant (if increased by man's activities) because they cause elevated turbidity when suspended, with lowering of light levels to the bottom and accompanying adverse effects to organisms on the bottom and in the water column. Preston's review (1989) stresses the need to tie contaminants to the biota and to man as applicable.

The objective of this report is to discuss what we know about sediment distribution patterns in Tampa Bay, the processes and controls governing distribution, and how sediment studies can be used to evaluate bay contamination. This will be based upon data currently available, collected over the past 30 years, as well as data currently being collected for the purpose of filling in the gaps.

GEOLOGIC HISTORY

In order to fully appreciate modern sediment distribution patterns in Tampa Bay, one must start with the geologic history. The Tampa Bay estuary owes its modern geologic configuration to events that started as far back as the late Pleistocene. During glacially induced sea level lowstands, small streams that drain into the bay became rejuvenated. With base level in excess of 100 m below present and exposed land extending at least 160 km farther to the west, the streams cut a shallow valley into the underlying Tertiary formations, thereby forming the modern Tampa Bay. Within this valley, channels were cut as deep as 20 m, forming the series of paleochannels we see underlying the surface. The valley floor itself was subaerially exposed and some karst features such as sinkholes developed in the limestone surface (Willis 1984). As their gradients and hence velocity increased, the ability for rejuvenated streams to carry sediment increased along with their erosional capacity. Rejuvenated streams carried quartz sand eroded from Tertiary sea level highstand terrace deposits that mantle much of central Florida.

As sea level began to rise following the last lowstand, approximately 18,000 years ago, downcutting ceased, river valleys were drowned, and streams began to adjust their base level and fill the channels. When that part of the valley now known as Tampa Bay began to flood, channels and interchannel areas became filled with a complex of deposits ranging from muds and peats, to oyster bars and death assemblages of clams, to almost pure quartz sand. Based upon ^{14}C dates of sediment cores, initial flooding of present Tampa Bay probably began about 6,000-8,000 years ago (Brooks and Doyle 1989). As sea level continued to rise the stream mouths began to be drowned by rising Gulf waters; as a result, they became less competent and began to deposit their sediment load directly into Tampa Bay. As in the past, sources of river-derived sediments are the Tertiary terrace deposits that veneer central Florida, although today's loads have been decreased to very little sand and only limited quantities of fine-grained material. Sea level reached its present position between 3,000 and 5,000 years ago, and river-derived sediment loads dropped to the low levels we see at present. While loads are considered low, however, we do not have good quantitative data about the actual suspended sediment levels, and virtually none about bed load.

MODERN SEDIMENT DISTRIBUTION PATTERNS

Surficial sediments in modern Tampa Bay are, at least in part, a manifestation of the recent sea level drowning event discussed in the previous section. Sediments are of two distinct types; land derived (termed terrigenous clastic) and marine derived. Terrigenous clastic sediments consist dominantly of quartz sands and silts, with various amounts of organic material and small percentages of clay minerals. Quartz sand-size sediments are not being added to the bay at present but are left over from early flooding when rivers had the capacity to carry sand-sized sediments into the

Bay. Quartz sands are found throughout the bay, dominating in areas accumulating little modern sediment such as the open portions of Middle Tampa Bay where they may comprise greater than 90% of the sediment (Fig. 1). Terrigenous clastic sediments being added to the bay at present consist dominantly of muds rich in quartz and organic matter with some clay minerals. Much of the organic matter may be produced within the bay itself (Sackett et al. 1986). Therefore, technically speaking, this would be of marine origin. The sources of these fine-grained sediments are the low gradient, slow moving rivers and creeks entering the bay, and the sheet flow runoff from the mostly impermeable, urbanized regions immediately adjacent to the bay. Unfortunately, we have no good estimates of the quantity of material being added by these sources.

Fine-grained terrigenous clastic sediments entering the bay accumulate primarily in low energy, poorly flushed zones around the bay periphery, especially in the upper reaches of Hillsborough Bay and Old Tampa Bay immediately adjacent to sources of entry (Fig. 1). In more open portions of the bay fine-grained sediments accumulate in broad, shallow bathymetric depressions where they are sheltered from the surrounding higher energy environment. This bathymetric control of fine-grained sediment distribution, however, holds only for Hillsborough Bay, Old Tampa Bay and the upper portion of Middle Tampa Bay; the energy level is too high in open portions of the lower bay to support fine-grained sediment accumulation. Fine-grained sediment accumulation in these bathymetric depressions can be substantial as muddy deposits in west central Hillsborough Bay attest. Surface sediments in west central Hillsborough Bay may consist of greater than 90% mud-size (<63μ) material (Fig. 1) (Brooks and Doyle 1989, Johansson and Squires 1989). Some of these sediments have a mean grain size of 6-8 ϕ (fine silt to clay size) and contain in the range of 10% organic matter (Fig. 2; Brooks and Doyle 1989, Johansson and Squires 1989). These fine-grained, organic-rich sediments, termed "muck", have been found to occupy an estimated 15% to 20% of Hillsborough Bay bottom, generally occurring at depths greater than 12′ where normal wave and tidal forces are relatively weak (Johansson and Squires 1989). Core samples collected from these muck deposits show that fine-grained sediments have been accumulating in bathymetric depressions for approximately the last 5,000 years at rates averaging from 31 to 49 cm per 1,000 years, rates consistent with those reported for many other estuaries with minimal fluvial input (Davis 1978).

Marine-derived sediments consist almost entirely of calcium carbonate, originating primarily from marine animal shell material dominated by molluscan fragments with subordinate amounts of barnacles, foraminifera, echinoids, and others. Considering their origin, carbonate sediments almost exclusively occupy the sand or larger size fractions. Marine-derived, carbonate-rich sediments may be produced *in situ* or transported into the bay from the adjacent Gulf of Mexico by tidal currents as has been proposed by Stahl (1970). Marine carbonate sands are dominant in open portions of the lower bay where they mix with residual quartz sands (Fig. 3), reflecting well-flushed, open marine conditions and a lack of dilution by fine-grained terrigeneous clastic input (Goodell and Gorseline 1961, Doyle et. al. 1985). A general increase toward the bay mouth (Fig. 3) signifies an increase in open marine influence. Localized accumulations of carbonate rich sediments intercalated within fine-grained deposits in the upper bay and around the bay periphery (Figs. 1 and 3) may represent *in situ* production by biological communities such as oyster bars, or winnowing and deposition during high energy events such as storms (Brooks and Doyle 1989).

DISCUSSION

The distribution of surficial sediments of Tampa Bay, consisting of a mixture of modern and residual marine- and land-derived material, is controlled by a combination of factors. Coarse-grained, marine-derived sediment distribution is controlled principally by physical processes and provenance. Provenance, or sediment source, controls the overall distribution in that the percentage of marine-derived sediments increases toward the bay mouth where more open marine conditions prevail. Provenance also controls the distribution on a local scale, as isolated carbonate sand concentrations intercalated within fine-grained sediments may be the product of *in situ* production in the form of oyster bars or other carbonate producing biologic assemblages. Physical processes such as waves and tidal currents control distribution by the transport of marine sands into the bay and redistribution within the bay, during high energy events such as storms, and during strong tides. During periods when energy is high but not high enough to actually transport coarse-grained sediments, such as normal tidal conditions in open portions of Lower Tampa Bay, physical processes winnow fine-grained material leaving coarse-grained sands behind as a lag deposit.

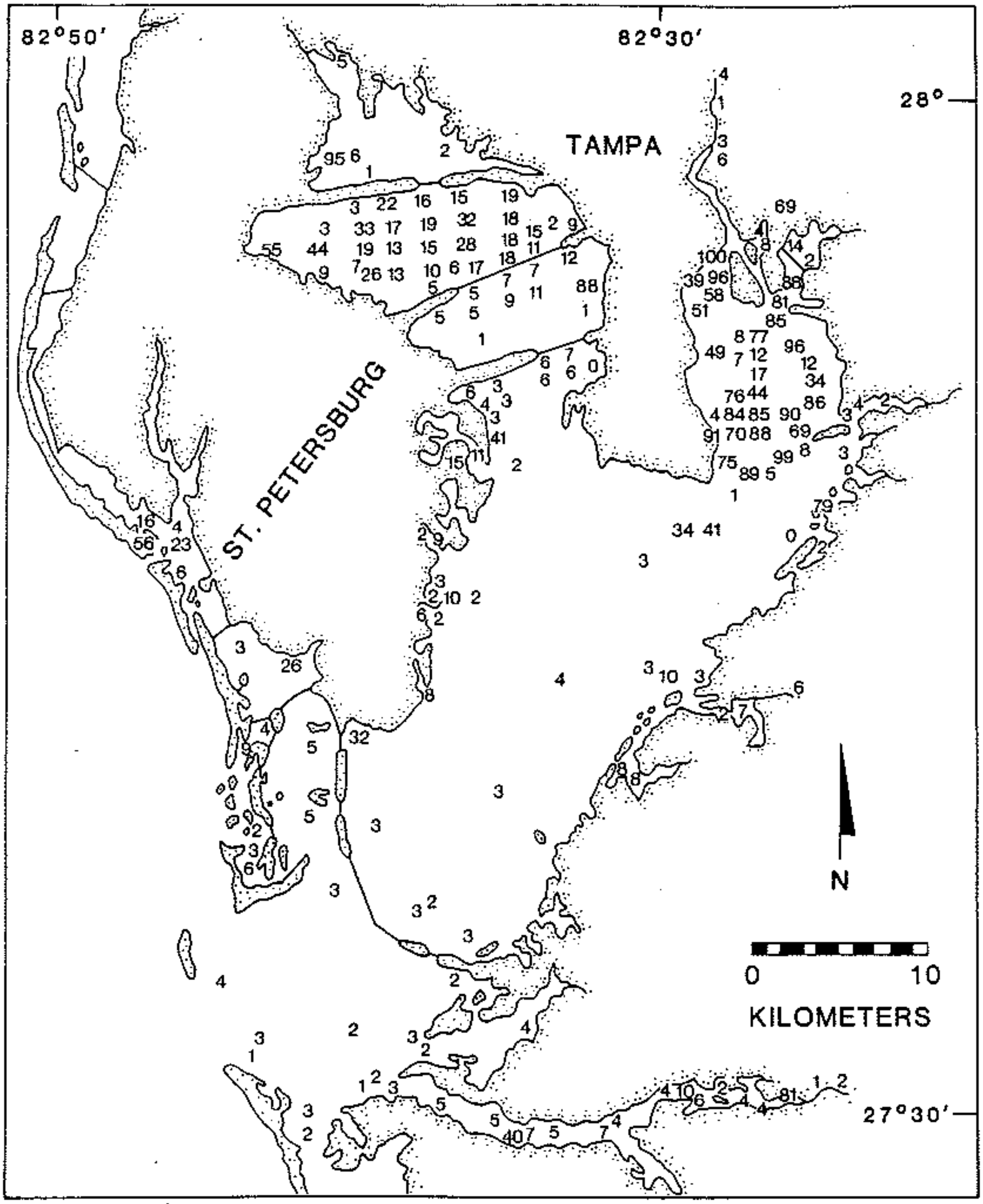
The distribution of terrigenous clastic quartz sands is controlled principally by physical processes operating within the bay. Quartz sands are no longer being input into the bay by rivers, and probably a limited amount is being input from the adjacent Gulf by the processes described above. Concentrations in the open portions of the central and lower bay are residual and dominate due only to a lack of accumulation of modern sediments. Quartz sands are continuously being redistributed by high energy events such as storms and strong tides.

The distribution of fine-grained terrigeneous clastic sediments is controlled by provenance, physical processes, and bathymetry. Accumulations around the bay periphery are controlled by provenance in that they are commonly located adjacent to sources of input, and by physical energy in that they are located in low energy areas such as dead end canals. Fine-grained sediment accumulations in open portions of the upper bay are controlled by bathymetry and physical energy. Muds have been accumulating in broad, shallow bathymetric depressions which provide shelter from the surrounding high energy environment. As mentioned, energy levels in the middle and lower portions of the bay are sufficiently high to prohibit significant accumulation of fine-grained sediments, even in bathymetric depressions. It is these accumulations of fine-grained, terrigenous clastic sediments that are of primary interest when attempting to evaluate contaminants in Tampa Bay sediments.

IMPLICATIONS FOR SEDIMENT CONTAMINANT DISTRIBUTION

Existing data on sedimentary contaminants in Tampa Bay are incomplete for several reasons. First, there have been relatively few studies concentrated on evaluating contaminant concentrations in sediments. Second, data that are available have often been collected at widely differing time intervals, concentrated on only specific locations within the bay, collected and analyzed by a variety of techniques, and reported in different formats, thereby rendering them incompatible. Nevertheless, data show a general pattern of contamination concentrated in areas where we know fine-grained sediments are accumulating.

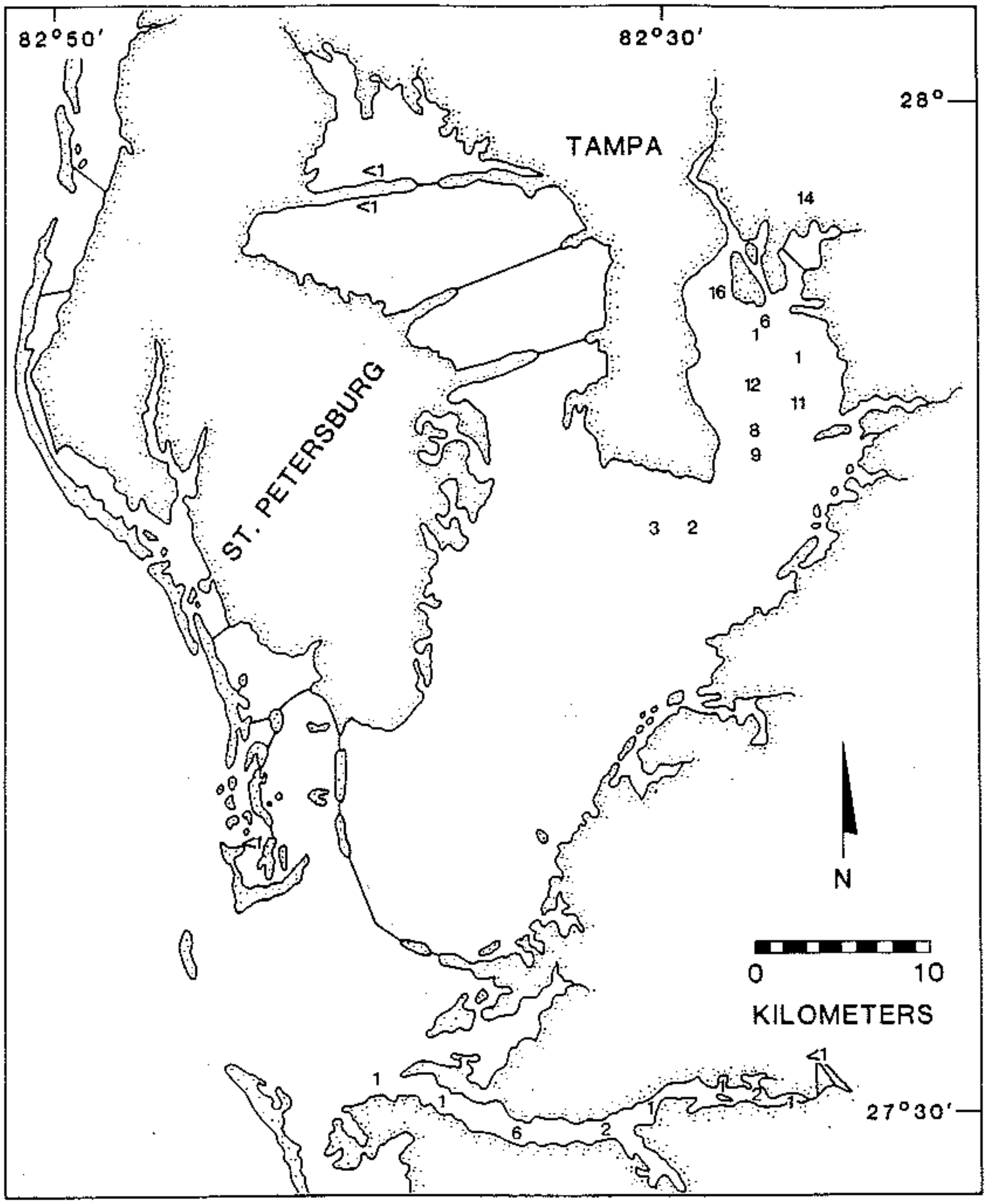
Sediment trace metal data in Tampa Bay are patchy and sparse. Studies have concentrated on Hillsborough Bay and Upper Tampa Bay. Coverage of metal concentrations in the remainder of the bay is too sparse to determine gradients throughout the bay. Old Tampa Bay is especially poorly covered. Fine-grained Hillsborough Bay sediments appear to be particularly enriched in lead and zinc, followed by cadmium (Table 1). Chromium, copper, nickel, and mercury are enriched in some areas but to a lesser degree than lead and zinc (Doyle et al. 1989, FDER 1988). Data suggest that heavy metal levels in Hillsborough Bay are well mixed and that, over time, Hillsborough Bay may represent a strong source for metals to the rest of Tampa Bay. Although the main body of Tampa Bay appears to be relatively clean, data are lacking around the periphery where point sources are found. Where data do exist, they suggest that metal concentrations can be high in areas where inputs are large compared to flushing rates. For example, concentrations of cadmium, lead, zinc, and mercury in fine-grained sediments adjacent to storm drains in the Bradenton Municipal Marina were reported (Wade-Trim 1988) that were similar to those found in Hillsborough Bay.



TEXTURE (% <63μ)

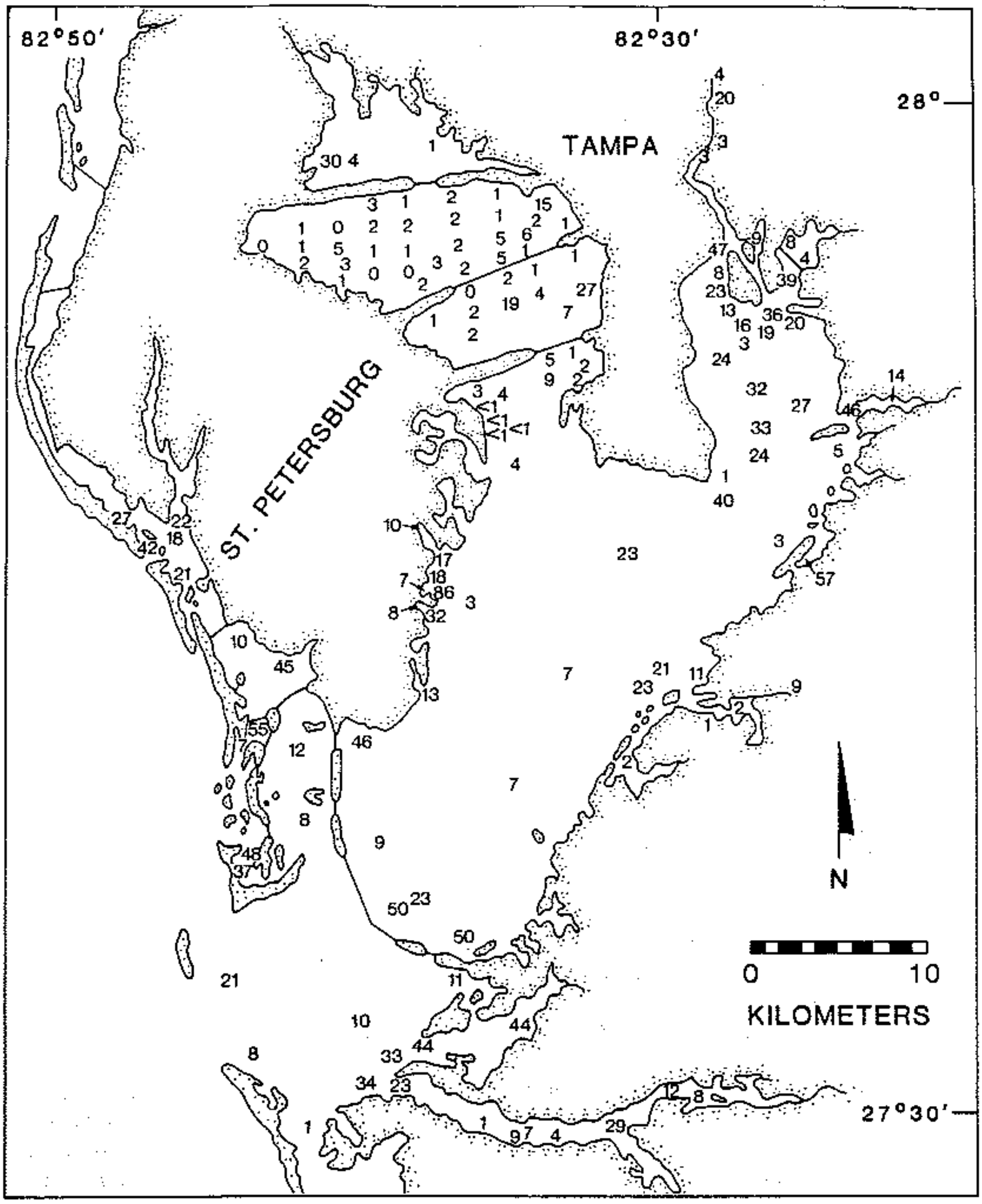
Figure 1. Texture map of Tampa Bay showing the percentage of mud-size (<63μ) surface sediments (from Doyle et al. 1989).

There is a small data base in Tampa Bay dealing with the occurrence of petroleum hydrocarbons and chlorinated hydrocarbons (pesticides). The most heavily impacted areas of Tampa Bay are the lower Hillsborough River and upper Hillsborough Bay. Doyle et al. (1985) and Van Vleet et al. (1986), with many of their sampling stations located around the periphery of the bay, showed that there are also local hot spots near specific industrial or municipal discharge points, around marinas, housing canals, and other high usage areas that may have local fine-grained sedimentary deposition occurring (Fig. 4).



%TOC (LOSS ON IGNITION METHOD)

Figure 2. Map of Tampa Bay showing the percentage of surface sediments consisting of organic matter (from Doyle et al. 1989).



% CO_3

Figure 3. Map of Tampa Bay showing the percentage of surface sediments consisting of calcium carbonate (from Doyle et al. 1989).

Review of sedimentary nutrient chemistry showed that organic nitrogen (N; Fig. 5) and phosphorus (P; Fig. 6) may be exerting a strong influence over at least parts of the bay ecosystem. Nitrogen and phosphorus levels in fine-grained sediments in Hillsborough Bay (the area of most dense sample coverage) appear to have increased since the 1960s (Figs. 7 and 8). Preliminary measurements suggest that there are high ammonia and phosphate fluxes out of Hillsborough Bay sediments. The review indicated that bay sediments may be a major source of fertilizer for Bay phytoplankton, increasing the potential for eutrophication and continued loss of seagrasses due to resultant shading.

Table 1. Metal to aluminum ratios of selected Tampa Bay sediments (from Brooks et al. 1988).

METAL	LOCATION	METAL:AL	COMMENTS
Silver	TBHB	1.3×10^{-3}	Third highest among measurements at 51 sites along U.S. Gulf coast
Arsenic	TBMK	$>8 \times 10^{-4}$	Highest of 51 sites
Cadmium	TBHB	7.4×10^{-2}	Highest of 51 sites
Chromium	TBHB	3.8×10^{-3}	-
Copper	TBCB	1×10^{-3}	-
Mercury	TBPB/TBMK	1.6×10^{-5}	Two of three highest sites among 51 along Gulf coast
Manganese	TBCB	4.9×10^{-2}	Second highest site among 51 sites
Nickel	TBPB	1.5×10^{-3}	Highest of 51 sites
Lead	TBHB	4.8×10^{-3}	Highest of 51 sites
Antimony	TBMK	8×10^{-5}	Highest of 51 sites
Selenium	TBMK	1.3×10^{-4}	Second highest among 51 sites
Tin	TBCB	2.8×10^{-4}	Highest among 51 sites
Zinc	TBMK	5.3×10^{-3}	Highest among 51 sites

TBHB - Tampa Bay, Hillsborough Bay
TBPB - Tampa Bay, Papys Bayou
TBCB - Tampa Bay, Cockroach Bayou
TBMK - Tampa Bay, Mullet Key

Little radionuclide data are available. Observations are limited to the mouth of the Alafia River and outfalls associated with Gardiner, Inc. and include only measurements of radium-226 and radon-222. Radionuclidic content of Tampa Bay sediments has apparantly been examined only by Upchurch et al. (1976, 1985) in the mouth of the Alafia River. Fanning et al. (1982) showed that there were high levels of radon-222 in bay waters compared to the Gulf of Mexico.

The positive correlation between fine-grained sediment accumulations and contaminant concentrations enables us to use what we know about fine-grained sediment distribution patterns to locate "hot spots" of potential contamination, and thereby more clearly evaluate the extent of contamination in Tampa Bay sediments. As mentioned, controls on fine-grained sediment accumulation include bathymetry, physical energy, and provenance, or proximity to point source inputs. By concentrating efforts in bathymetric depressions in the open, upper regions of the bay, and low energy, poorly flushed zones around the bay periphery, especially those adjacent to contaminant sources, we are currently attempting to gain a close approximation of the extent of contaminated sediments in Tampa Bay. Figure 9 shows 75 sites located in areas of expected fine-grained accumulations within the bay, where we are concentrating research. Knowledge of the controls and processes governing fine-grained sediment distribution, therefore, is an efficient way in which we can identify contaminant "hot spots", on which we can then concentrate future efforts to determine the flux of contaminants back into the water column, and eventually determine the impacts to the Tampa Bay ecosystem.

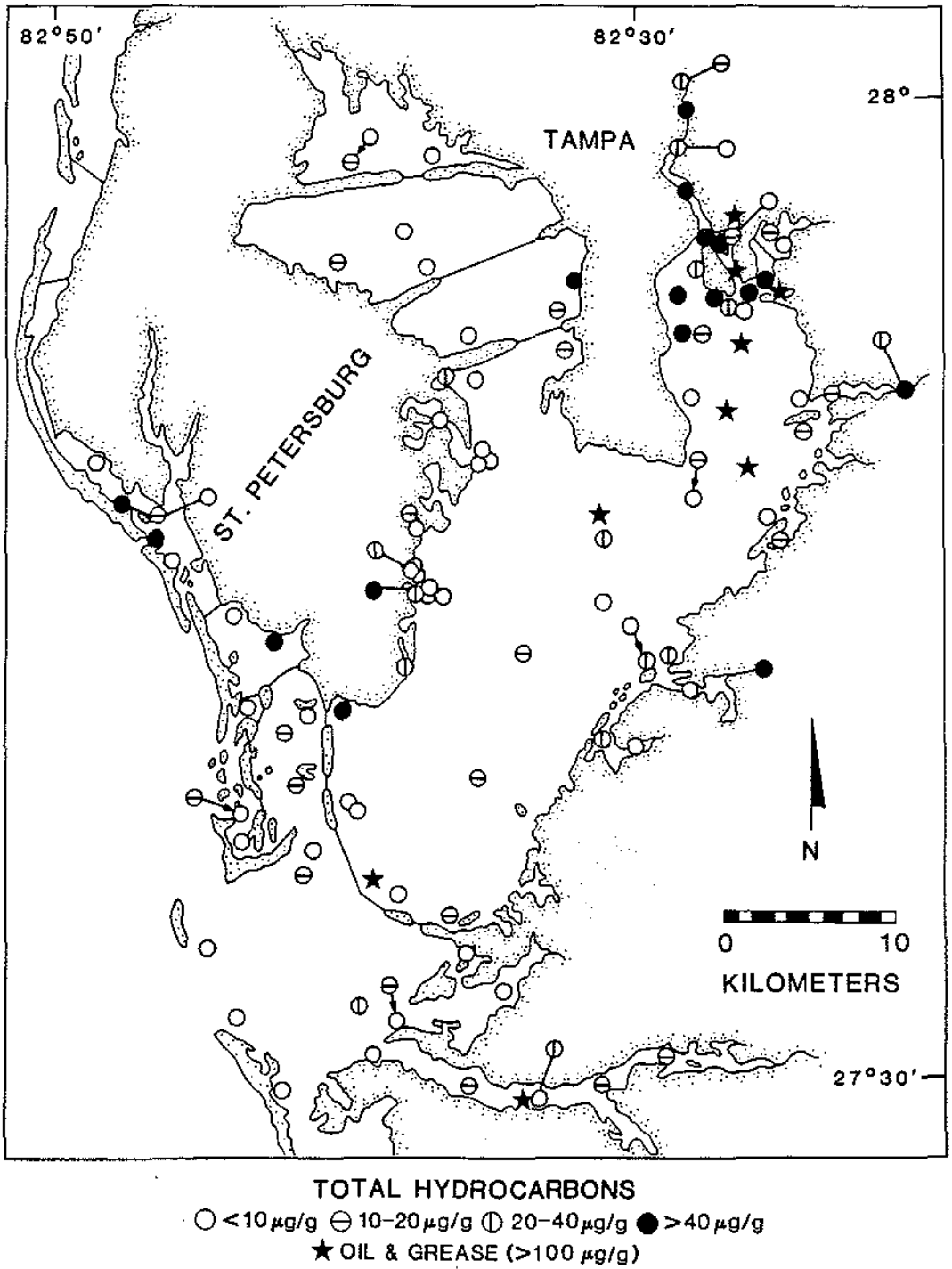
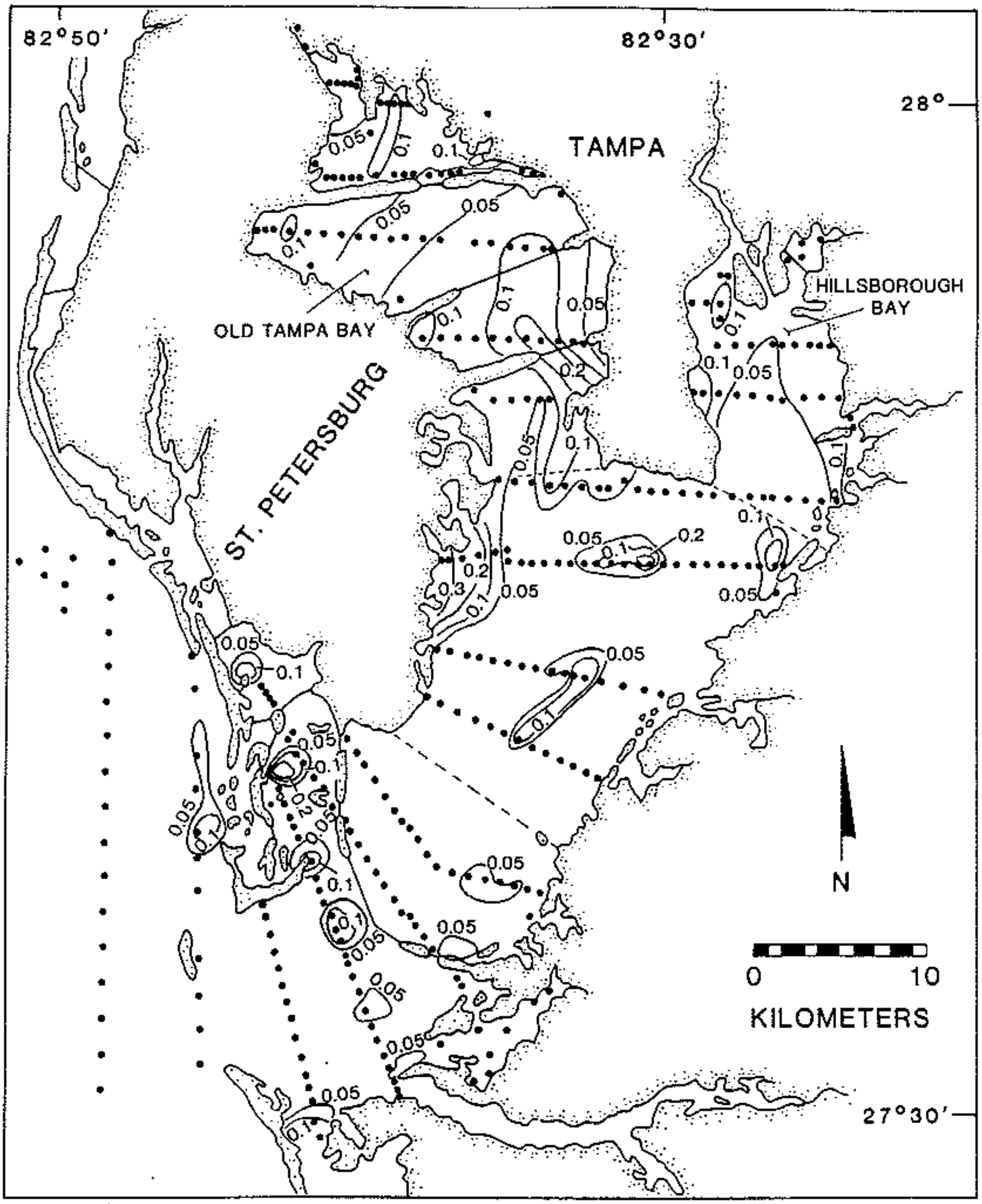
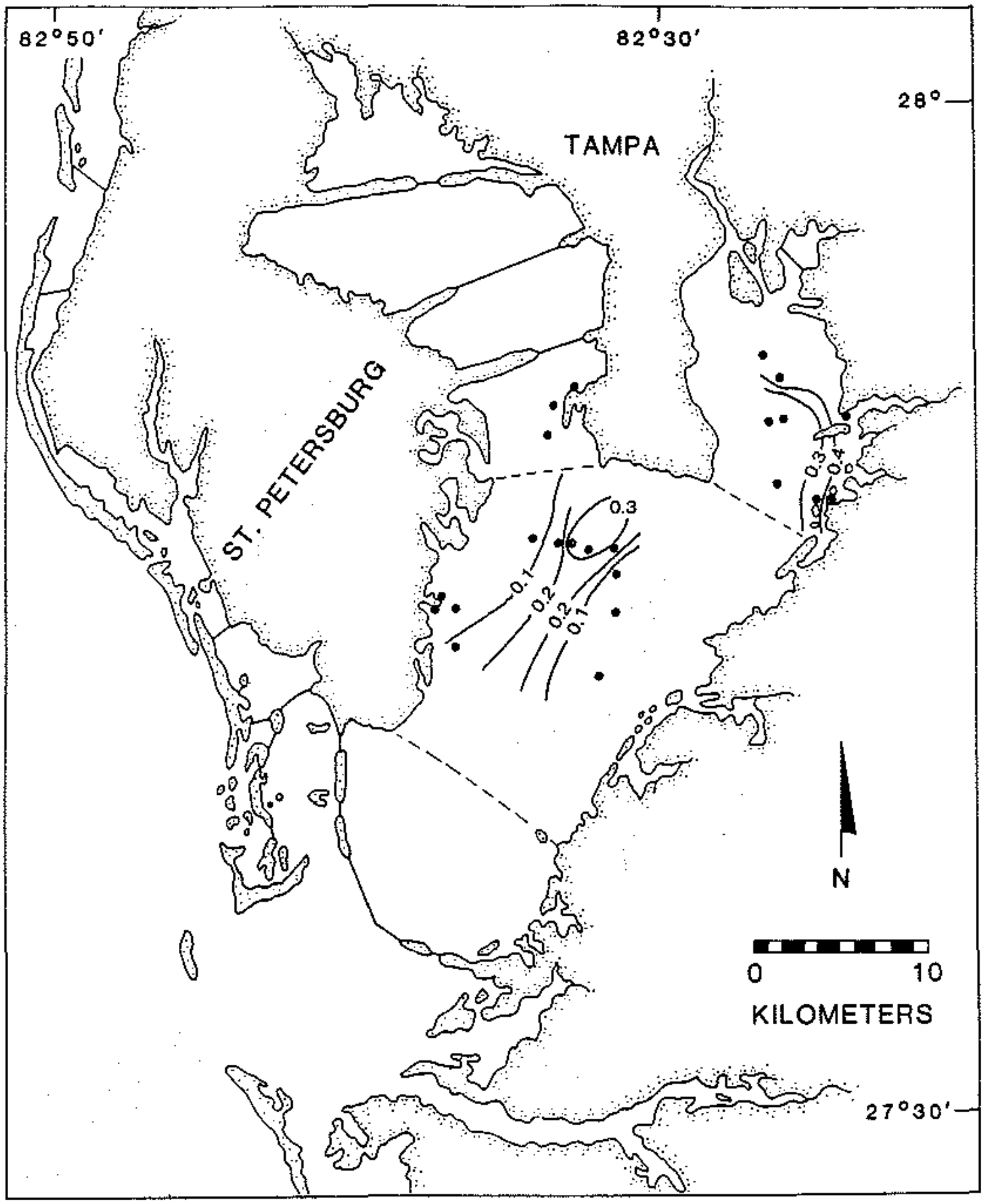


Figure 4. Map of Tampa Bay showing the concentrations of total hydrocarbons in surface sediments (from Doyle et al. 1989).



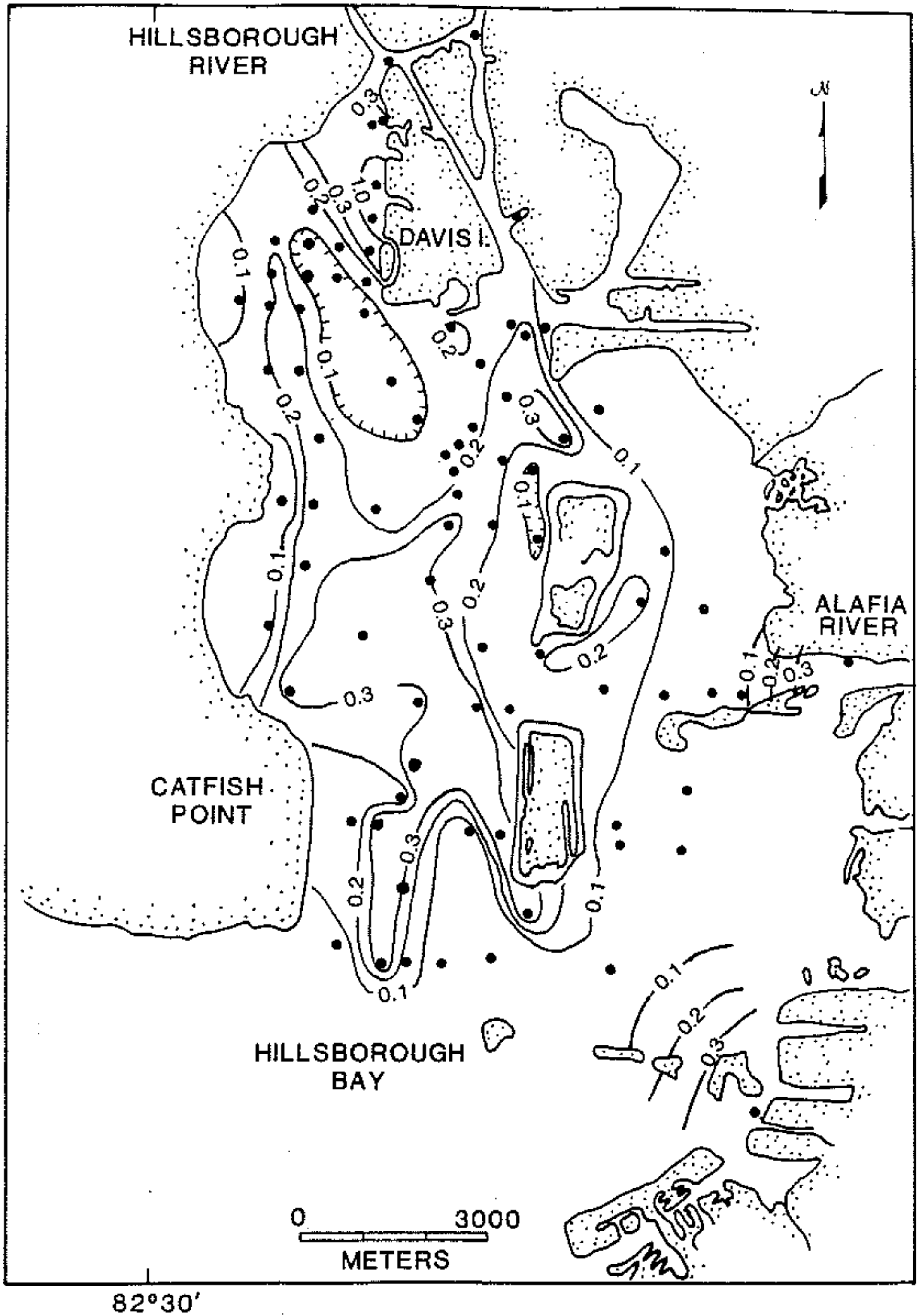
TOTAL ORGANIC NITROGEN IN TAMPA BAY, 1963
CONTOURS IN DRY WEIGHT % ORG-N

Figure 5. Map of Tampa Bay showing the percentage of total organic nitrogen (1963 data base) in surface sediments (from Doyle et al. 1989).



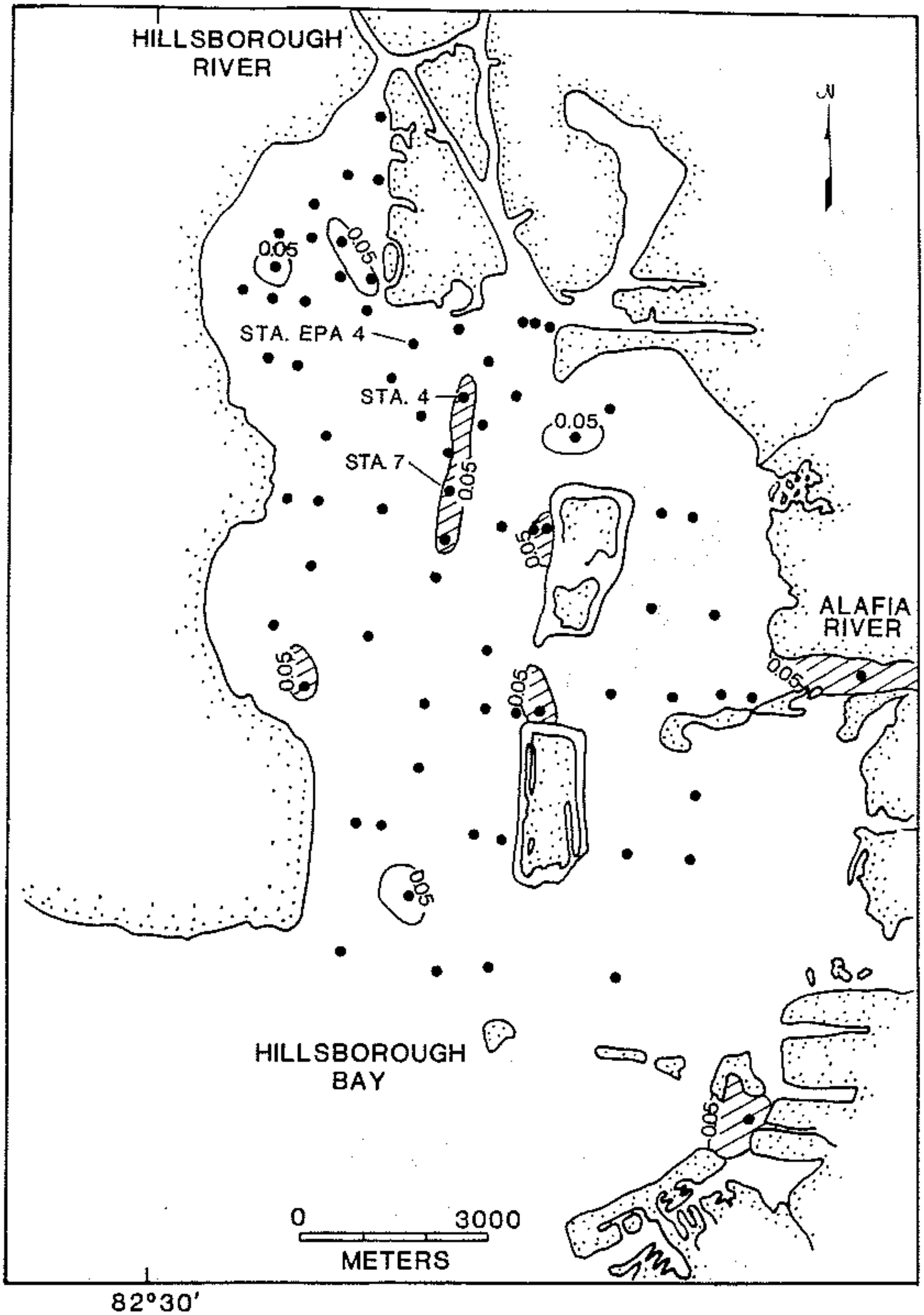
TAMPA BAY SEDIMENT 1982-6
DRY WEIGHT % PHOSPHORUS

Figure 6. Map of Tampa Bay showing the percentage of phosphorus (1982-1986 data base) in surface sediments (from Doyle et al. 1989).



SEDIMENTARY NITROGEN IN HILLSBOROUGH BAY, 1986
CONTOURS IN DRY WEIGHT %N

Figure 7. Map of Hillsborough Bay showing the percentage of nitrogen (1986 data base) in surface sediments (from Doyle et al. 1989).



HILLSBOROUGH BAY SEDIMENT, 1986
DRY WEIGHT % PHOSPHORUS

Figure 8. Map of Hillsborough Bay showing the percentage of phosphorus (1986 data base) in surface sediments (from Doyle et al. 1989).

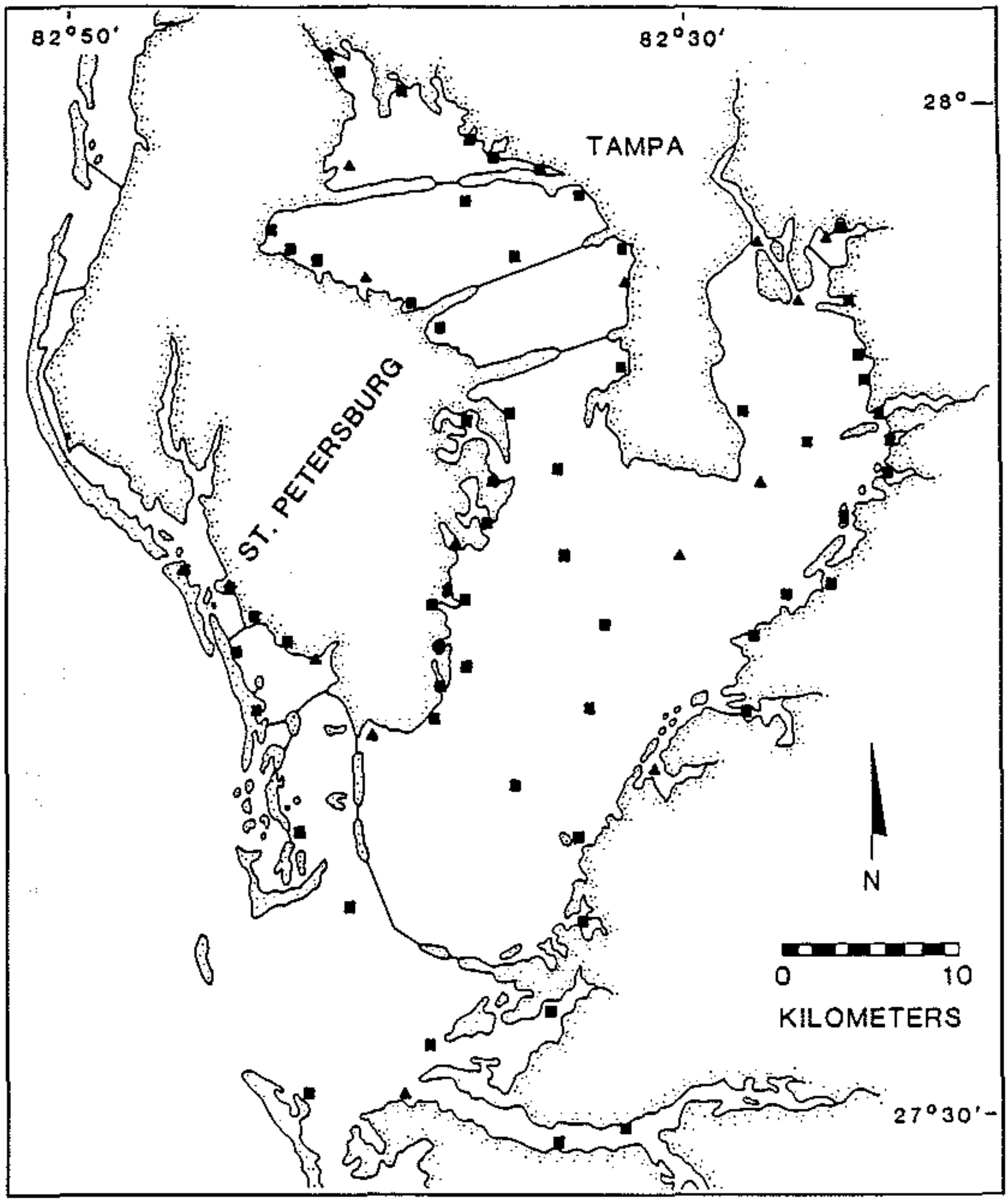


Figure 9. Map of Tampa Bay showing 75 sampling sites. Triangles denote reoccupied sites from 1984-1985 hydrocarbon study (Doyle et al. 1985); squares denote remainder of 75 sites.

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WATER COLUMN DISSOLVED OXYGEN, SEDIMENT OXYGEN DEMAND, AND SEDIMENT ORGANIC CONTENT NEAR A WASTEWATER TREATMENT PLANT OUTFALL IN TERRA CEIA BAY, FLORIDA

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K. W. Pearce

ABSTRACT

Water column dissolved oxygen concentrations and sediment percent volatile residue were measured at 52 stations in Terra Ceia Bay, Florida. Sediment oxygen demand rates were determined at six stations. Results indicated that dissolved oxygen concentrations were most closely correlated with seagrass coverage and sampling time. Productivity appeared greater in the lower bay area which receives the City of Palmetto wastewater treatment plant 1.4 MGD discharge than for background (upper bay) stations. Sediment oxygen demand and percent volatile residue data indicated that the lower bay has greater sediment oxygen demand rates and sediment organic percentages than background stations. Sediment oxygen demand and percent volatile residue data also suggest that the City of Palmetto wastewater treatment plant and the Bird Key rookery may be significant contributors to Terra Ceia Bay sediment organic loads and oxygen demand.

INTRODUCTION

Terra Ceia Bay (Figure 1) is a shallow embayment, approximately four square miles in area and 1′ to 12′ deep. The bay has two tidal inlets; the Snead Island Cutoff connects the bay to the Manatee River to the south, and a much larger unnamed inlet connects to Tampa Bay to the west. Tides are typically semi-diurnal. The bay experiences a tidal range of about 2′ and salinities range from approximately 19 to 31 ppt. Terra Ceia Bay is a State Aquatic Preserve and is designated an Outstanding Florida Water. The City of Palmetto wastewater treatment plant (WWTP) discharges 1.4 MGD of very highly treated reclaimed water to Terra Ceia Bay.

The City of Palmetto WWTP outfall location (Figure 2) is located in the lower portion of Terra Ceia Bay at a depth of 6′ to 8′. The boil is evident from the surface. Sediments in the lower bay range from medium sand to silty sand to sandy silt (Davis et al. 1990). Mangrove forests, seagrass beds, oyster bars and hard bottom areas comprise the habitat types in the lower bay (Davis et al. 1990). Mangrove forests appear along the eastern, southern and northwestern portions of the lower bay. A large mangrove island, Bird Key, is south of the WWTP outfall and presently houses a large rookery. Seagrass beds consist of monotypic or mixed communities of Cuban shoal weed (*Halodule wrightii*), manatee grass (*Syringodium filiforme*) and turtle grass (*Thalassia testudinum*) (Davis et al. 1990). Seagrass beds occur along a wide band on the eastern and southern periphery and a narrower band on the western periphery of the lower bay.

Water quality surveys were conducted in August and October 1989 by Conservation Consultants, Inc. These surveys were designed to assess the water quality characteristics of Terra Ceia Bay, particularly in the vicinity of the outfall from the City of Palmetto WWTP. Results indicated that dissolved oxygen (DO) concentrations were depressed by 2 to 4 mg/l in the vicinity of the outfall for the summer sampling event, although the depression was not seen in the fall data. The data also indicated that the depression resulted from a benthic DO demand. Although the WWTP is a source of both nitrogen and phosphorus in Terra Ceia Bay, these nutrients did not appear to be elevated in the vicinity of the outfall, indicating rapid dilution, settling, or uptake of the nutrients. The WWTP did not appear to be a significant source of carbonaceous biochemical oxygen demand or suspended solids to the bay since effluent concentrations for these constituents were below ambient bay concentrations during the time of the surveys.

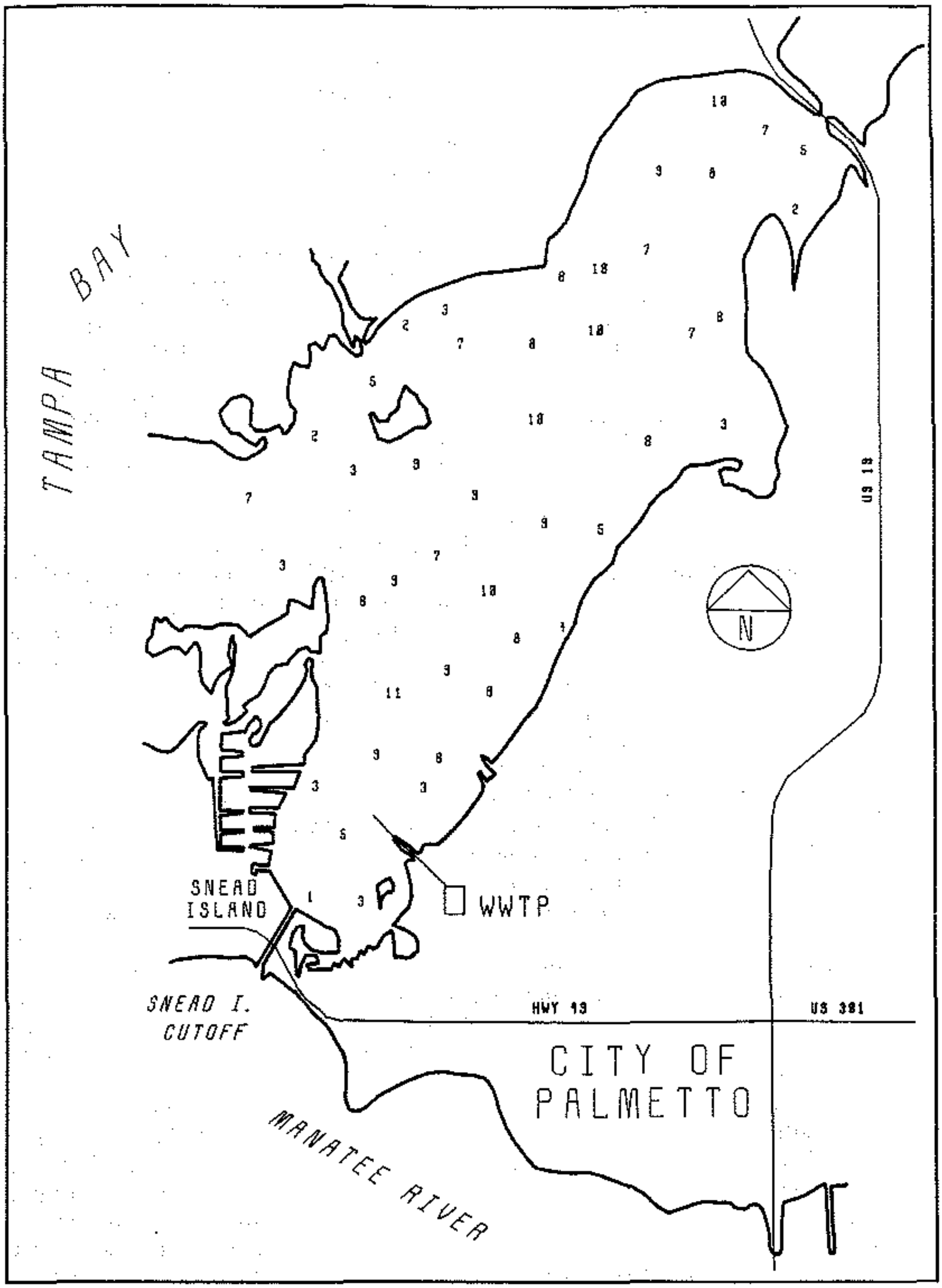

Figure 1. Terra Ceia Bay, with depths.

To further assess the patterns indicated by these results, the Florida Department of Environmental Regulation, in cooperation with the U.S. Environmental Protection Agency and Conservation Consultants, Inc., undertook additional studies August 28-30, 1990. The studies were performed on a falling tide during a period of diurnal tides. To define DO patterns, DO concentrations were measured in a grid pattern in the vicinity of the City of Palmetto WWTP outfall. Sediment oxygen demand (SOD) was measured at six stations to quantify and define patterns in benthic DO demand. Sediment samples were obtained and analyzed for total volatile residue. Total volatile residue is used as a measure of sediment organic content. Results were used to correlate DO patterns to sedimentary processes and the WWTP outfall location.

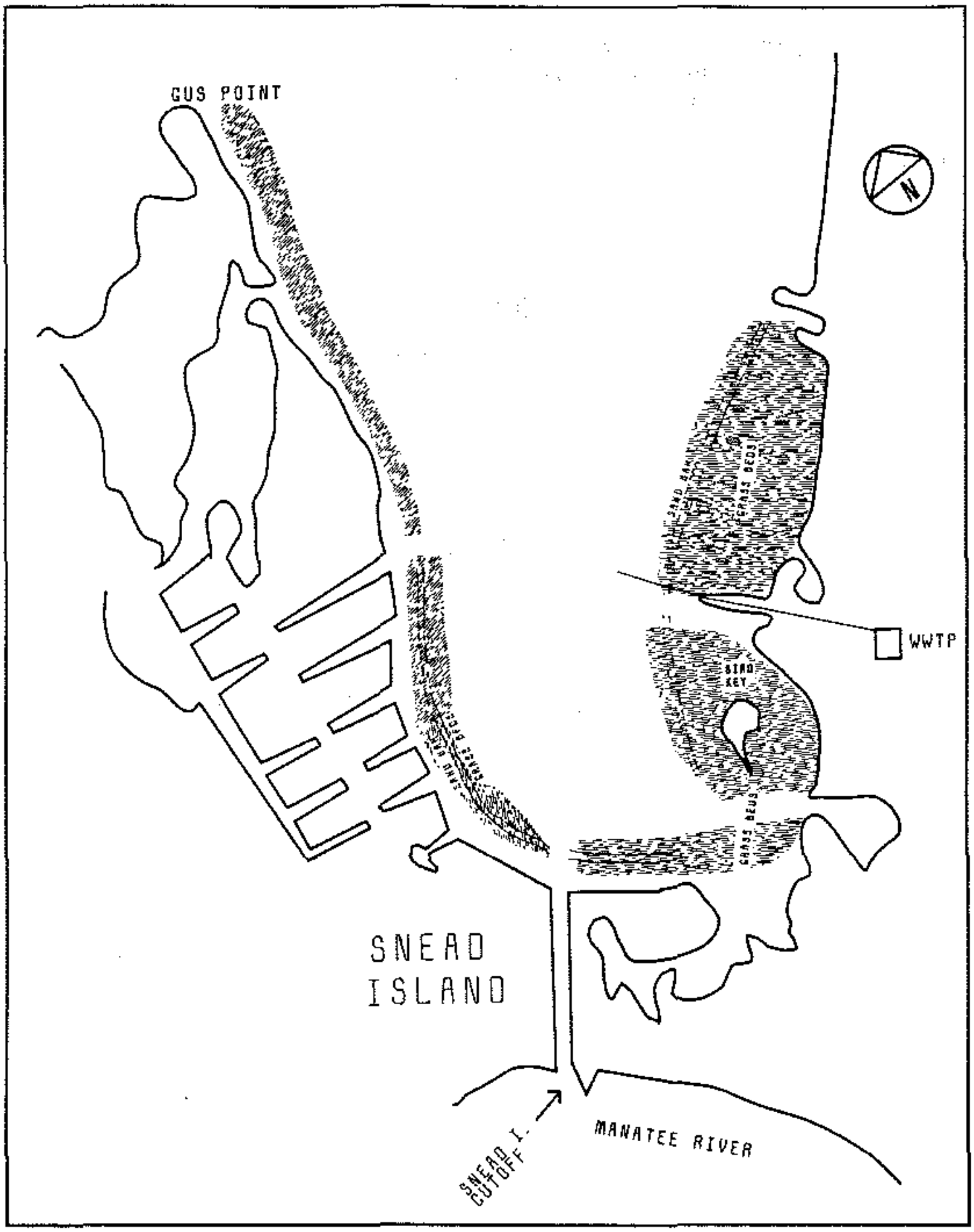

Figure 2. Terra Ceia Bay, showing relative locations of grass beds and WWTP outfall.

METHODS

Station Locations

A series of seven northwest- to southeast-oriented transects were established (Figure 3). The transects were located in the bay segment bounded by Gus Point on the northwest and the Snead Island Cutoff on the south. Each transect contained six to eight station locations. An additional background transect (Figure 4) containing four stations was established between Beville Point and the southern side of the mouth of Peterson Bayou. Each transect was marked with two floats located at stations 2 and 5. The background transect was marked at stations 1 and 4. Unmarked stations were located by interpolation between marked stations. The WWTP outfall is located near station D-5 (Figure 3).

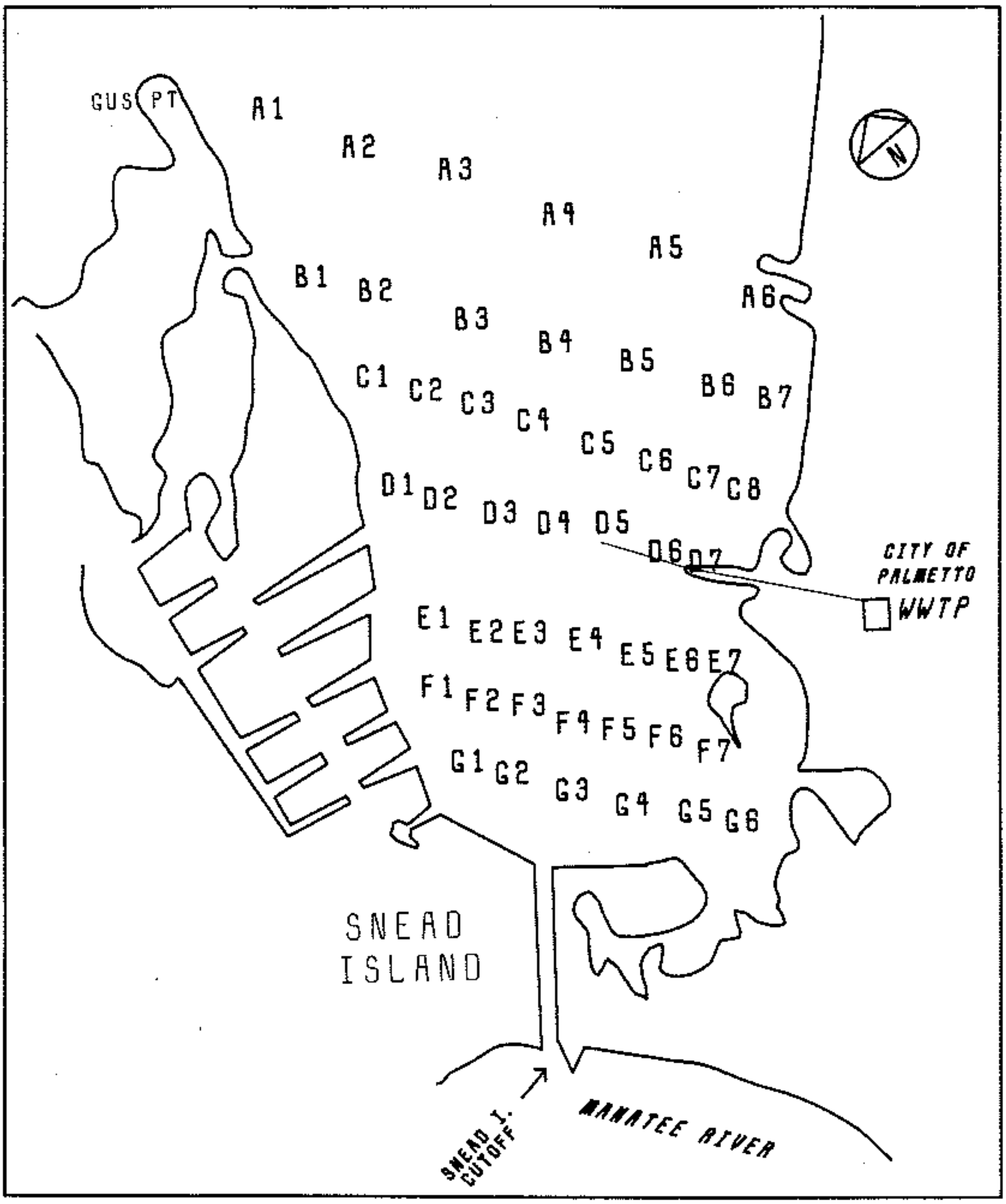

Figure 3. Terra Ceia Bay, transects.

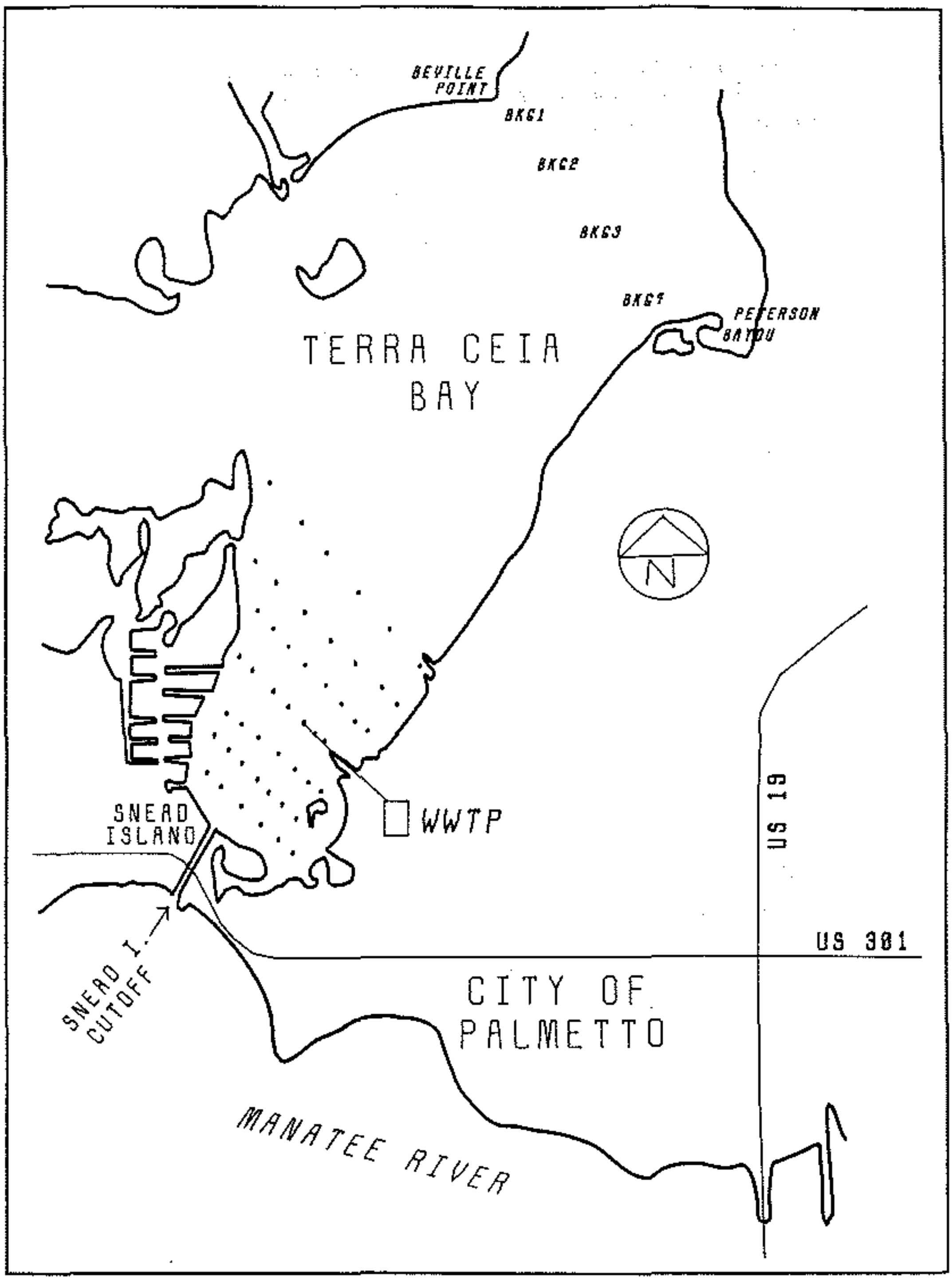

Figure 4. Terra Ceia Bay, background transect.

Dissolved Oxygen

Dissolved oxygen measurements were obtained by two teams using Hydrolab model 4010 DO meters. Temperature, pH, and conductivity were also measured. Measurements were obtained at 1′ depth intervals twice per day at each station for a period of two days. Sampling events started at approximately 0800 hours and 1200 hours each day. The station sampling sequence was reversed on the second day in order to minimize sampling time bias. Meters were air calibrated and cross-calibrated each day prior to the 0800 hour event, between the 0800 and 1200 hour events, and following the 1200 hour event. Measured DO concentrations were corrected for salinity by the method of Green and Carritt (1967).

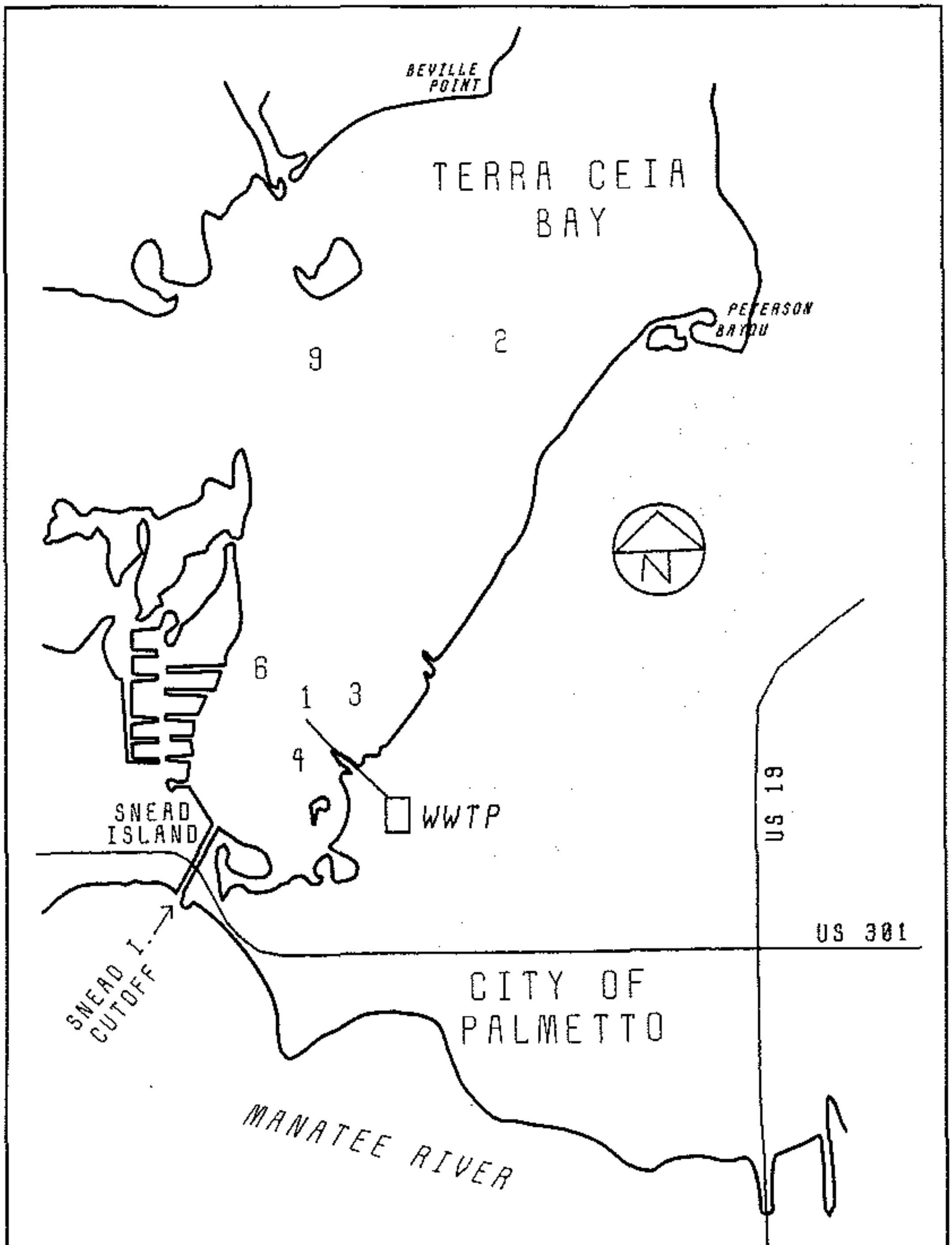

Figure 5. Terra Ceia Bay, sediment oxygen demand sampling stations.

Sediment Oxygen Demand

Sediment oxygen demand was measured by the *in situ* chamber method of Murphy and Hicks (1985) at the six stations shown in Figure 5. Two stations per day were analyzed during the period August 28 through 30, 1990. The method involves deployment of four replicate chambers and two blank (water column respiration) chambers in which dissolved oxygen depletion is meaured for a period of one to four hours. Measured rates were corrected to 20°C.

Sediment Samples

Replicate sediment samples were obtained at each transect station. Samples were obtained using a ponar dredge or scoop sampler. Samples were stored in Ziploc® freezer bags on ice until returned to the lab (within 24 hours) and were then frozen until analysis. Sediment samples for each station were analyzed for total volatile residue.

Total volatile residue was analyzed by standard method 209F (APHA 1985). Samples were evaporated to dryness at 103°C in a weighed dish, cooled in a desiccator and reweighed. Samples were then combusted at 550°C for one hour, cooled in a desiccator and again weighed. Results were expressed as percent volatile residue.

RESULTS

Dissolved oxygen concentrations ranged from 1.5 to 13.7 mg/l, with a mean of 5.9 mg/l. DO saturation concentration is a function of temperature and salinity. Salinity can be calculated from conductivity measurements. The method of Benson and Krause (1984) was used to calculate DO saturation values for the Terra Ceia Bay data. Calculated DO saturation concentrations ranged from 6.0 to 6.5 mg/l. Measured DO concentrations were divided by calculated saturation concentrations to give percent saturation values. Terra Ceia Bay DOs ranged from 23.5% to 226.5% saturation with a mean of 94.1% saturation during the survey period. Most supersaturated DO concentrations occurred during late morning and afternoon hours.

To construct DO concentration contours, data for both days were combined and grouped into surface (depth=1′), mid-depth, and bottom subsets. Since relative DO concentration patterns were the primary focus of this study and salinity measurments varied by only approximately 3 ppt (27.7 to 30.9 ppt) during this survey, DO concentrations were not salinity corrected for contour plots. Depth subsets were further divided into four time windows: 1) 8 A.M. to 10 A.M., 2) 10 A.M. to 12 P.M., 3) 1 P.M. to 3 P.M., 4) 3 P.M. to 5 P.M. Data were grouped into time windows to minimize the influence of sampling time.

Contour plots (Figures 6-8) were produced for each time window of each depth subset. Contour plots for surface and mid-depth data during the morning hours (Figures 6 and 7) indicate the lowest DO concentrations at the periphery of the bay and the highest DO concentrations in the center of the bay. The pattern reversed during afternoon hours with the highest DO concentrations at the periphery and the lowest DO concentrations in the center. Contour plots for bottom data (Figure 8) indicate lowest DO concentrations at the periphery and highest concentrations in the center only for the early morning (8 A.M. to 10 A.M.) time window. Highest DO concentrations were at the periphery and lowest DO concentrations in the center for the late morning and afternoon time windows.

Mean sediment oxygen demand rates (Table 1) ranged from 1.3 $gO_2/m^2/day$ to 2.3 $gO_2/m^2/day$. SOD rates (Figure 9) were highest at station 4 and lowest at station 6 (Figure 5). The averaged SOD rates for stations 1, 3 and 4 nearest the outfall were higher than station 6 on the opposite side of the bay ($p<.05$) and the averaged rates for background stations 2 and 9 ($p<.10$). Statistical comparisons between SOD stations are shown in Table 2.

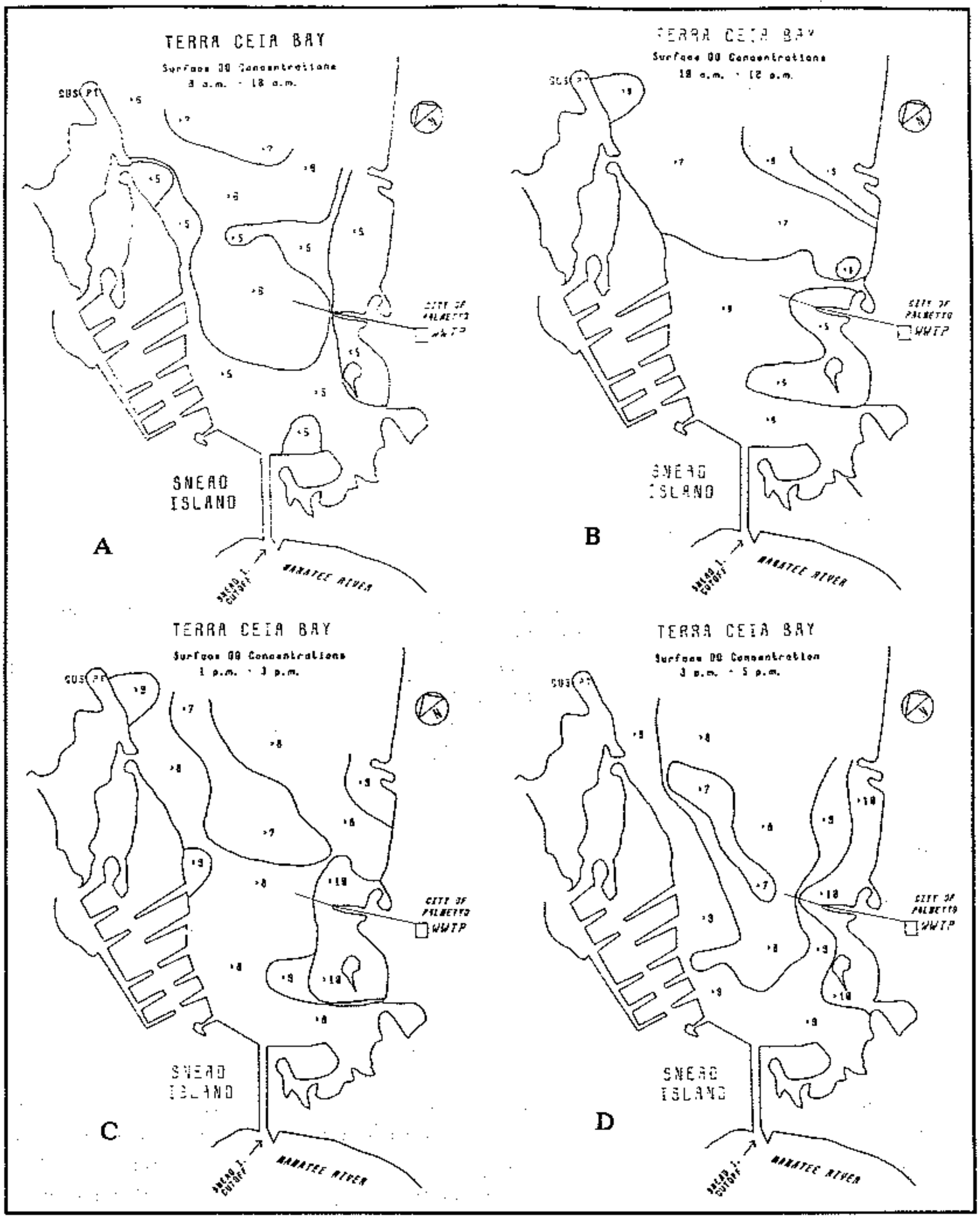

Figure 6. Terra Ceia Bay, surface DO concentrations: A, 8 A.M. - 10 A.M.; B, 10 A.M. - 12 P.M.; C, 1 P.M. - 3 P.M.; D, 3 P.M - 5 P.M.

The contour plot for percent volatile residue (Figure 10) indicates the highest sedimentary organic concentrations (from 2.0% to greater than 10.0% volatiles) to be in the center of the bay. Lowest sedimentary organic concentrations (less than 1.0% volatiles) are found along the western periphery of the bay. The data suggest that sedimentary organic concentrations in the lower bay are greater than for background stations, although the relationship was not significant (p>.10) due to data variability and unequal sample sizes.

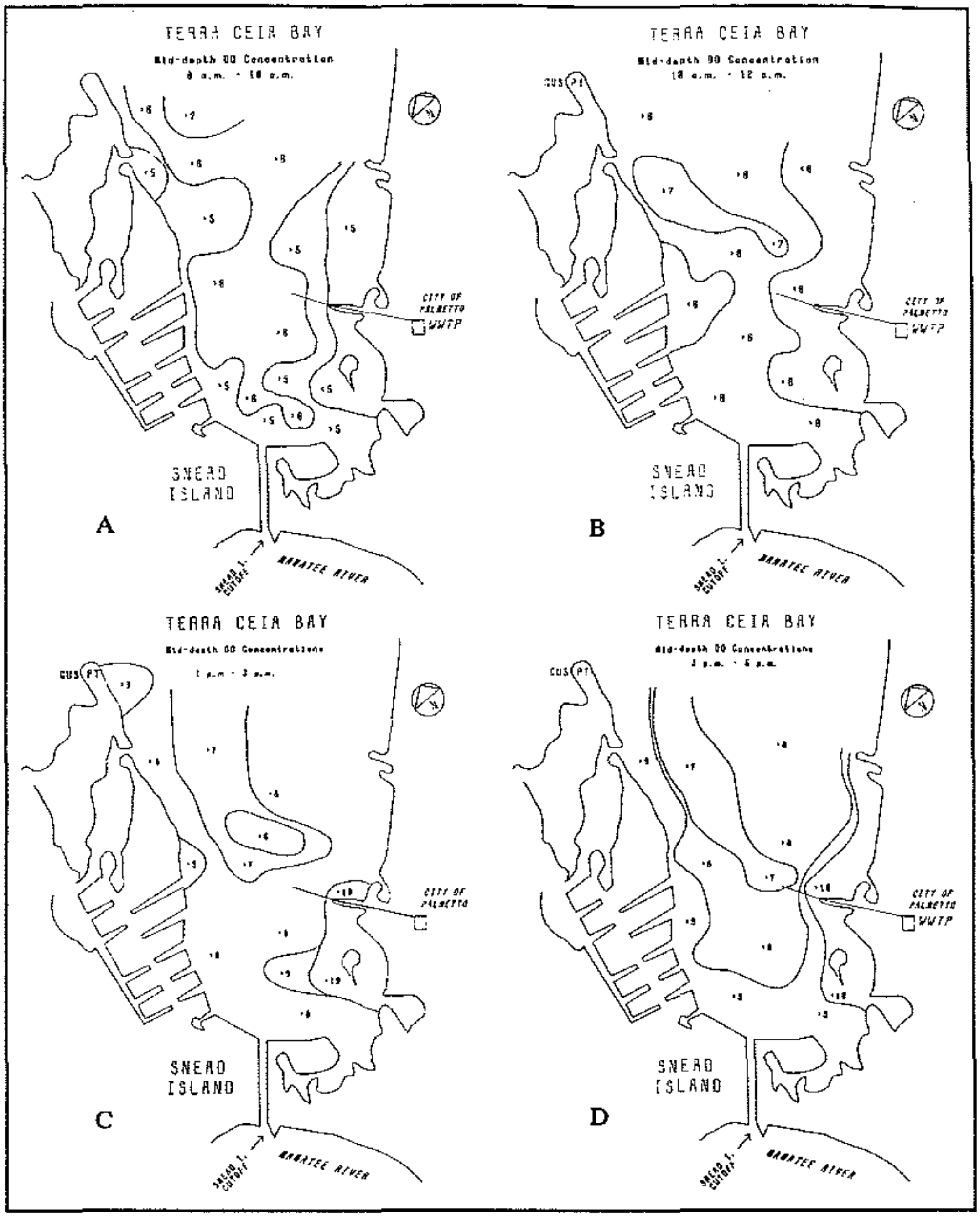

Figure 7. Terra Ceia Bay, mid-depth DO concentrations: A, 8 A.M. - 10 A.M.; B, 10 A.M. - 12 P.M.; C, 1 P.M. - 3 P.M.; D, 3 P.M - 5 P.M.

DISCUSSION

Lower bay (transects A-G) dissolved oxygen concentrations were not significantly ($p>.20$) different from the background stations. None of the DO concentration contour plots indicated any relationship between DO concentration and the outfall location. During the survey period, DO concentrations in the surveyed area of Terra Ceia Bay appeared to be primarily correlated to productivity. Bottom percent saturation contour plots indicate that low early morning DO concentrations (Figure 11A) and supersaturated afternoon DO concentrations (Figure 11B) were associated with the seagrass meadows located on the periphery of the bay.

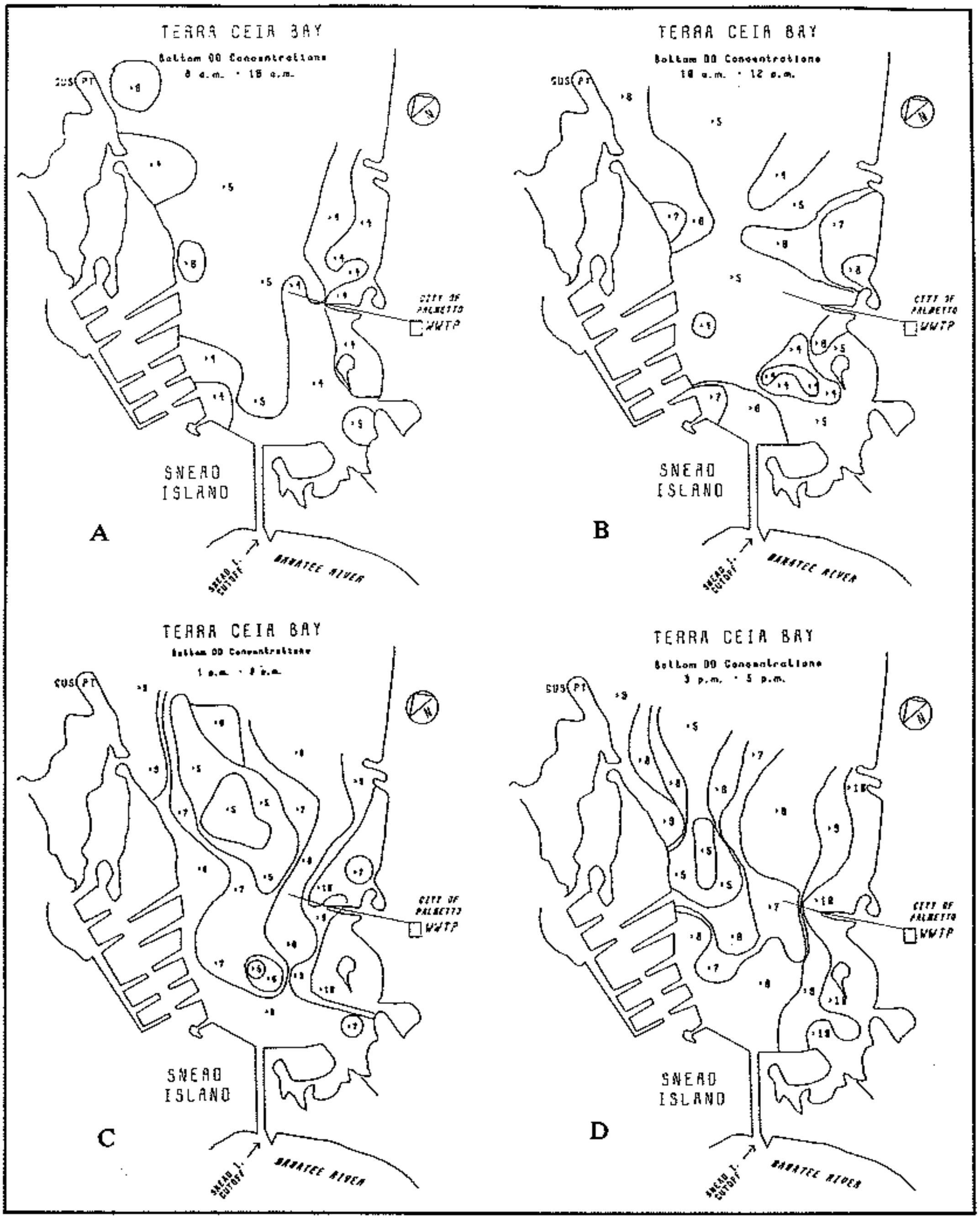

Figure 8. Terra Ceia Bay, bottom DO concentrations: **A**, 8 A.M. - 10 A.M.; **B**, 10 A.M. - 12 P.M.; **C**, 1 P.M. - 3 P.M.; **D**, 3 P.M - 5 P.M.

Although the relationships were not significant (p>.10) due to data variability and unequal sample sizes, the bottom DO concentration data suggest that lower bay DO concentrations are less than background station DO concentrations in the early morning time window and greater for the afternoon time windows. This pattern suggests that productivity may be greater for the lower bay than for background stations.

Table 1. Terra Ceia Bay intensive survey SOD rates, August 1990.

STATION	SOD RATE	MEAN	STD. DEV.	RESP. RATE
1	2.01	1.74	0.21	7.08
1	1.46			
1	1.65			
1	1.84			
3	1.93	1.79	0.11	5.47
3	1.71			
3	1.87			
3	1.65			
4	2.52	2.33	0.42	8.61
4	2.65			
4	2.54			
4	1.61			
6	1.11	1.31	0.15	5.85
6	1.34			
6	1.47			
2	2.21	1.72	0.34	8.40
2	1.63			
2	1.26			
2	1.80			
9	1.73	1.49	0.42	9.49
9	1.70			
9	1.78			
9	0.76			

SOD rates are in $gO_2/m^2/day$; respiration rates are in $mgO_2/l/day$.

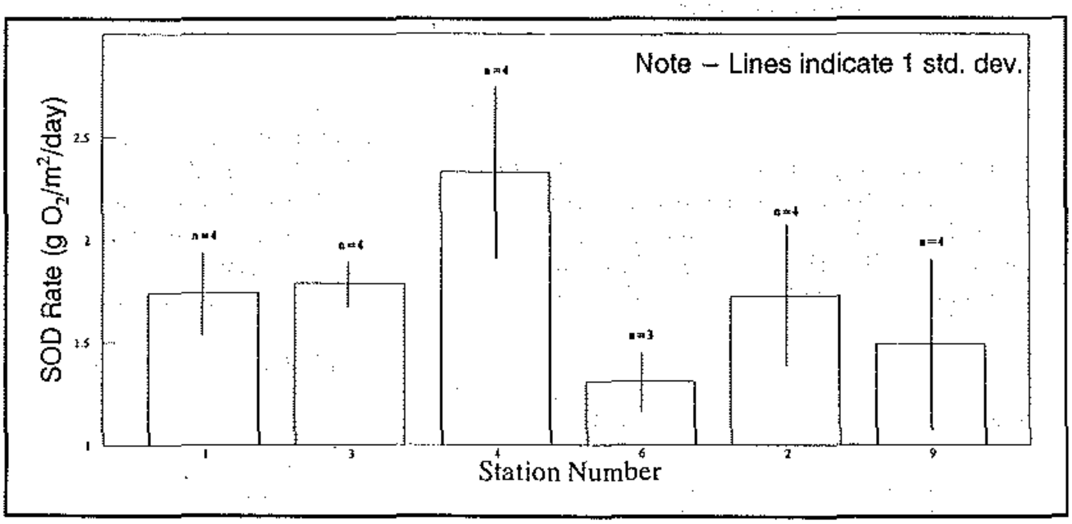

Figure 9. Terra Ceia Bay, sediment oxygen demand rates.

DO-demanding processes include sediment oxygen demand and water column respiration. Measured SOD rates for Terra Ceia Bay ranged from those for estuarine mud (1-2 $gO_2/m^2/day$) to those for outfall vicinity sludge (2-10 $gO_2/m^2/day$) (Bowie et al. 1985). Terra Ceia Bay SOD rates compare to measured SOD rates for Tampa Bay and the Manatee River of 0.5-9.1 $gO_2/m^2/day$ and 1.8-4.3 $gO_2/m^2/day$, respectively (Palmer and McClelland 1988, DeGrove 1984). The highest mean Terra Ceia Bay SOD rate of 2.33 $gO_2/m^2/day$ was measured at SOD station 4 (Figure 5). This station was located near the Bird Key rookery which undoubtedly contributes substantial oxygen-demanding substances to nearby sediments. SOD measurements indicated higher rates in the eastern portion of the bay than in the western portion and higher rates in the lower bay than for background stations. Lowest early morning DO concentrations also occurred at the eastern periphery of the bay; however, insufficient SOD station coverage exists to investigate the significance of the relationship between SOD and DO concentrations.

Table 2. Terra Ceia Bay SOD station statistical comparisons.

STATIONS	STATIONS	TEST STATISTIC	D.F	P-VALUE
1	6	2.182	5	<.05
2	6	1.480	5	<.10
3	6	3.379	5	<.01
4	6	2.995	5	<.025
1&3	6	2.987	9	<.10
1&3	2&9	0.711	14	>.10
1,3,4&6	2&9	0.645	21	<.25
1,3&4	6	2.310	13	<.025
1,3&4	2&9	1.354	18	<.10
1	4	1.777	6	<.10
2	4	1.570	6	<.10
3	4	1.759	6	<.10
9	4	2.000	6	<.05
6	9	0.528	5	>.25

Water column respiration rates ranged from 5.5 to 9.5 $mgO_2/l/day$. These rates are approximately one order of magnitude higher than the SOD rates averaged across the depth of the water column. This suggests that water column (algal) productivity is also very high in the bay and that SOD only exerts a localized (near-bottom) effect on DO concentrations. Depth DO concentration profiles indicate a sharp decrease in DO near the bottom for most stations.

Percent volatile residue values ranged from 0.6% to 10.7%. These values compare to a range of from 0.6% to 6.8% volatile residue for samples from upper Old Tampa Bay (Shaw and Wilkins 1974), an embayment of comparable depth and size. Since the Old Tampa Bay samples were taken during a period when Tampa Bay was considered to be in its worst condition (T. Cardinale, pers. comm.), the Terra Ceia Bay values must be considered to be fairly high. Percent volatile residue contours suggest that both the City of Palmetto WWTP and the Bird Key rookery may be significant contributors to sediment organic loads. Since Terra Ceia Bay is connected through two dissimilar-sized tidal inlets, tidal patterns in Terra Ceia Bay are complex; however, velocity patterns indicate that particulate loads from the City of Palmetto WWTP and the Bird Key rookery would primarily be distributed along the longitudinal axis of the bay, resulting in sediment contours such as those of Figure 10.

Percent volatile residue values were regressed versus bottom DO concentrations for each of the four time windows. The regressions indicated little correlation (r^2=.003, .094, .007, .002) between sediment organic content and bottom DO concentration for any time window.

SUMMARY

Terra Ceia Bay is a highly productive embayment in which dissolved oxygen concentrations are most closely correlated with seagrass coverage and time of day. The data suggest that productivity may be greater in the lower bay compared to background stations. Sediment oxygen demand and percent volatile residue data indicate that the lower bay has greater SOD rates and sediment organic percentages than background stations. Although SOD data are not significantly different from historical data for adjacent waters, percent volatile residue values are comparatively high. SOD and percent volatile residue data suggest that the City of Palmetto wastewater treatment plant and the Bird Key rookery may be significant contributors to Terra Ceia Bay sediment organic loads and oxygen demand; however, the data are insufficient to quantitatively apportion their relative contributions.

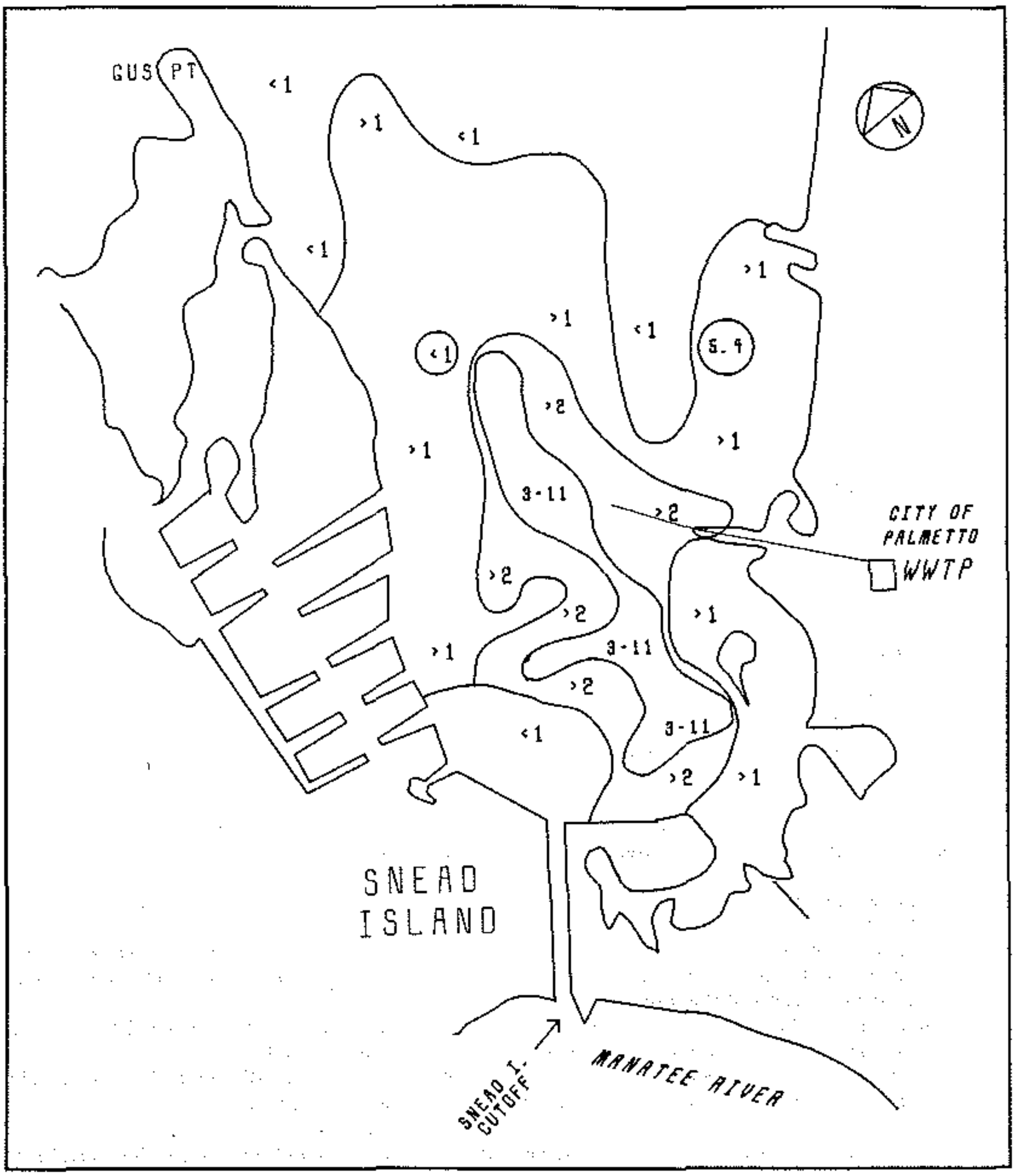

Figure 10. Terra Ceia Bay, percent volatile residue.

ACKNOWLEDGEMENTS

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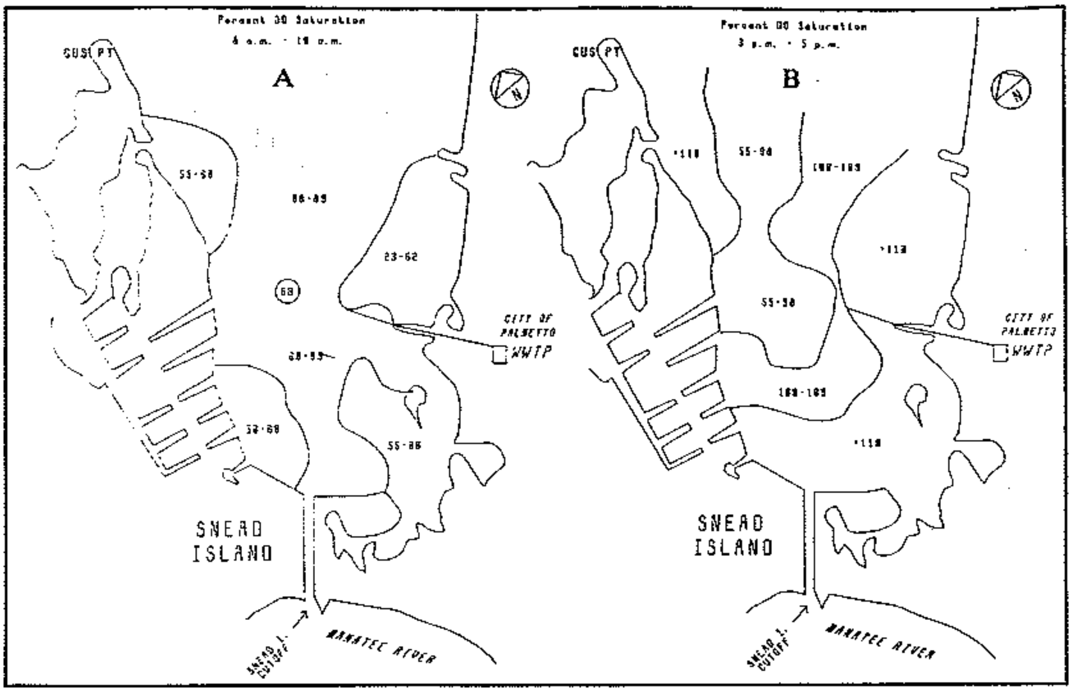

Figure 11. Terra Ceia Bay, percent DO saturation: A, 8 A.M. - 10 A.M.; B, 3 P.M. - 5 P.M.

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TRIBUTARY STORM RUNOFF AND VESSEL-GENERATED SEDIMENT RESUSPENSION AT THE PORT OF ST. PETERSBURG, FLORIDA

D. H. Schoellhamer

ABSTRACT

Bayboro Harbor and the port of St. Petersburg form a manmade basin adjacent to Tampa Bay that may supply turbid water to the bay and thus affect light availability in the bay. To investigate the variations in water quality in this basin, tributary storm discharge and resuspension of bottom sediments by a cruise ship were studied by the U.S. Geological Survey in cooperation with several local agencies. The storm discharge from two tributaries and the effect of the tributary storm runoff on the water quality of the harbor were studied during a storm on November 9, 1989. Booker Creek, which drains an urban watershed, was stratified with a thin layer of turbid freshwater flowing into the harbor over a layer of less turbid saltwater. Salt Creek, which primarily drains Lake Maggiore, was only partially stratified and less turbid. The turbid water from the creeks only slightly increased the turbidity of the harbor, probably because of mixing with less turbid water and particle settling. Sampling and measurements were conducted throughout the port during a cruise ship departure in 1988 and again during a cruise ship arrival in 1990. The maneuvering of the cruise ship resuspended bottom sediments, but these sediments settled rapidly (within about two hours). Tidal currents and wave action were not large enough to prevent suspended particles from settling in the basin. Thus, the basin provides mixing and settling, which diminish or eliminate the potentially adverse effect on Tampa Bay from tributary storm runoff and large vessel traffic in the basin.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the City of St. Petersburg, the City of Tampa, Hillsborough County, Pinellas County, the Southwest Florida Water Management District, and the Tampa Port Authority, is studying sediment resuspension and light attenuation in Tampa Bay, Florida. The objectives of the study are to determine the effect of resuspended sediment on light attenuation in the water column and to determine the mechanisms that cause sediment resuspension. The port of St. Petersburg and Bayboro Harbor form a large and nearly enclosed manmade basin on the western shore of central Tampa Bay (Fig. 1). Increased turbidity and suspended solids in the waters of the port of St. Petersburg, and possibly Tampa Bay, potentially could be caused by storm runoff from two tributaries and resuspension of bottom sediments by large vessels using the port. This paper summarizes the results of water quality monitoring in the port during a storm and during the arrival and departure of a cruise ship.

TRIBUTARY STORM RUNOFF SAMPLING

During the early morning of November 9, 1989, rainfall developed northwest of Tampa Bay in association with a cold front moving rapidly to the southeast toward the Tampa Bay area. This storm followed two other small storms in the area; one produced 0.20" of rain on October 24, and the other produced 0.10" of rain on November 4, 1989 (measured at St. Petersburg). The November 9 storm produced 0.50" of rain between 0700 and 1000 hours at the St. Petersburg Bayfront Center approximately one-half mile north of the port of St. Petersburg.

Discharge measurements were made and depth-integrated and point water samples were collected from Booker Creek (Fig. 1, site A) and Salt Creek (Fig. 1, site B) at Third Street during and after the storm. Booker Creek drains part of downtown St. Petersburg and flows into Bayboro Harbor near its southwestern corner. Salt Creek drains Lake Maggiore (located about two miles southwest of Bayboro Harbor) and a less urbanized watershed and flows into the basin from the south. Other sources of runoff into the harbor are storm culverts and nonpoint runoff from adjacent lands. Water samples were analyzed for specific conductance, turbidity, and total and volatile suspended solids (Fishman and Friedman 1989).

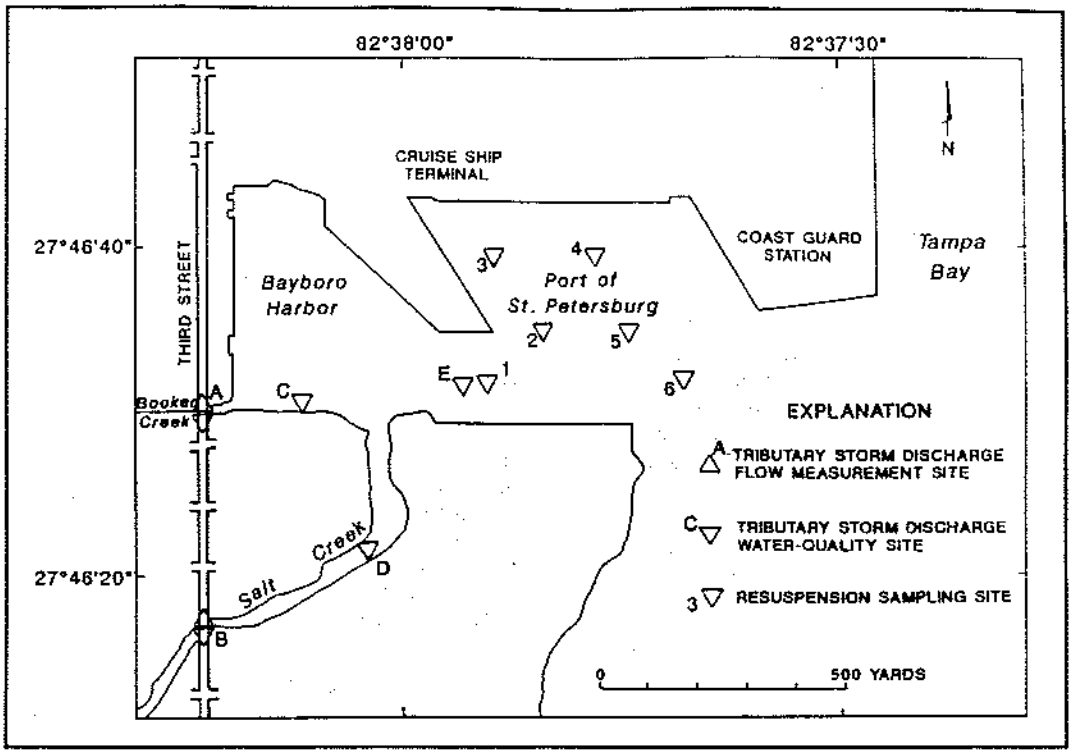

Figure 1. Study area and locations of measurement sites.

Water quality measurements were made and water samples were collected downstream from the Third Street bridges from a sampling boat. Several sites in Bayboro Harbor were sampled during the morning of November 9 to determine the condition of the harbor. During the early afternoon, sampling was limited to three harbor sites: south side of the harbor (Fig. 1, site C), Salt Creek bend (Fig. 1, site D), and south of the peninsula (Fig. 1, site E). The water quality measurements included vertical profiles of temperature, specific conductance, and optical backscatterance (OBS), which is related to turbidity and suspended solids concentration in the water. Depth-integrated and point water samples were analyzed for specific conductance, turbidity, and total and volatile suspended solids.

Booker Creek Results

The initial observations and measurements of velocity in Booker Creek at approximately 0920 hours on November 9, 1989, showed that there was virtually no net discharge under the Third Street bridge (Fig. 1, site A). A high tide occurred at about 1100 hours. The flood tide that preceded the high tide apparently offset the freshwater inflow from Booker Creek. Thus, no significant storm discharge flowed past the bridge until the intensity of the flood tide diminished shortly before high tide. At approximately 1030 hours, a significant discharge from Booker Creek began to flow into the harbor.

Booker Creek was stratified with a thin layer (about 1.5′) of freshwater flowing over relatively stagnant saltwater. For example, at 1530 hours, the specific conductance was 2,730 μS/cm (microsiemens per centimeter at 25°C) at a depth of 1′ and 38,400 μS/cm at a depth of 3′. Because of tidal action and stormwater runoff, the velocities in Booker Creek were unsteady. Estimates of the freshwater discharge were made from the field velocity measurements and are shown in Figure 2 as a function of the time of day during which a set of velocity measurements was taken. For example, the data from 1200 to 1245 hours produced an estimated freshwater discharge of about 12 ft^3/s, but the instantaneous discharge at 1200 hours was probably greater than 12 ft^3/s, and the instantaneous discharge at 1245 hours was probably less than 12 ft^3/s. The estimated freshwater discharge peaked rapidly as the flood tide slackened before 1100 hours and then steadily declined during ebb tide.

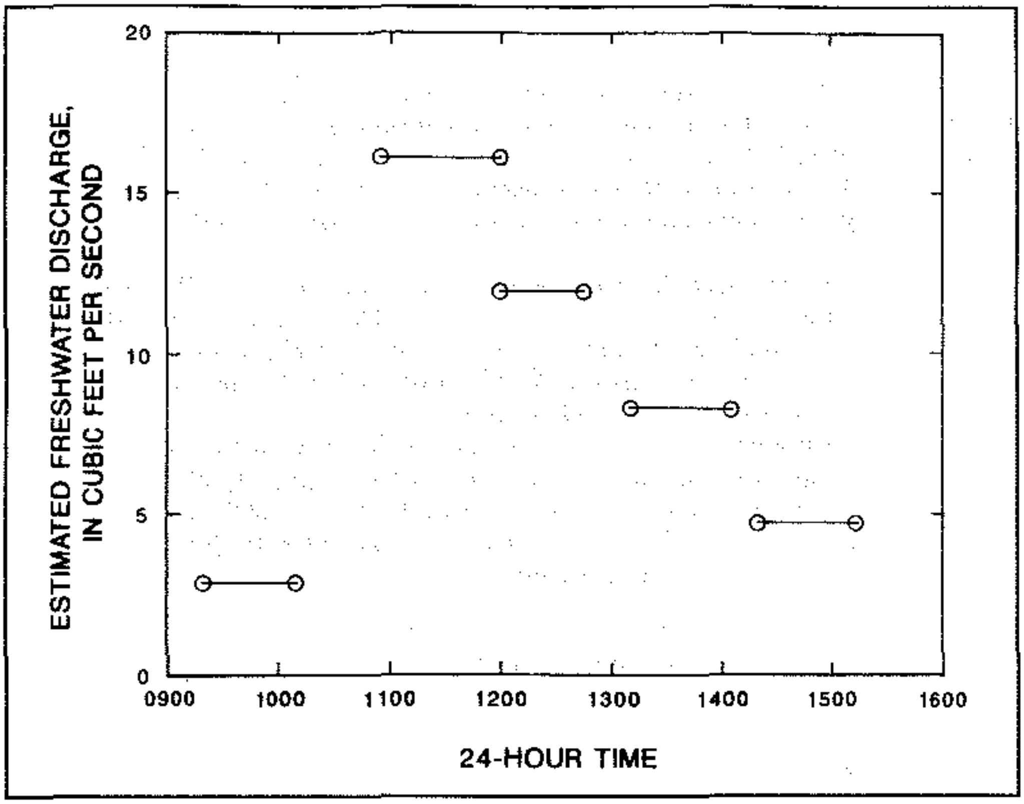

Figure 2. Estimated freshwater discharge at site A on Booker Creek, November 9, 1989.

The depth-integrated specific conductance data confirm that as the flood tide slackened and reversed, freshwater discharged from Booker Creek. Before 1000 hours, the depth-integrated specific conductance indicated that the water under the Third Street bridge at Booker Creek was predominately saltwater. Although the rain had been falling for about two hours, the specific conductance indicates that the flood tide delayed the introduction of freshwater runoff from Booker Creek into the harbor. The depth-integrated specific conductance decreased to a minimum at 1215 hours because of dilution from freshwater runoff and then increased as the freshwater runoff decreased in the afternoon.

The depth-integrated turbidity was inversely related to the specific conductance because the freshwater runoff was more turbid than the saltwater. In addition, point samples collected at 1530 hours showed that the turbidity at 1′ and 3′ below the water surface was 10 and 2.1 NTU, respectively. The suspended solids data did not vary coherently in time and did not correlate with either freshwater runoff or turbidity. Poor correlation between suspended solids concentration and turbidity in Tampa Bay at turbidities less than 10 NTU has been observed by Goodwin and Michaelis (1984), and may be caused by the difficulty of measuring small differences in turbidity below 10 NTU and the sensitivity of low turbidity measurements to small differences in clay content.

The turbidity of the freshwater runoff can be estimated from the depth-integrated specific conductance and turbidity data using mixing theory and assuming values for the turbidity and specific conductance of saltwater and the specific conductance of freshwater. The estimated freshwater turbidity was approximately 20 NTU prior to 1500 hours when it decreased to about 12 NTU. This estimated value was in good agreement with the turbidity of a sample collected 1′ below the surface at 1530 hours (10 NTU).

Salt Creek Results

The discharge from Salt Creek (Fig. 1, site B) during the storm runoff sampling on November 9, 1989, is shown in Figure 3. Because of the variability in discharge, the starting and concluding times of the seven discharge measurements are shown. A high tide occurred at about 1100 hours, shortly before the discharge measurements began, and the maximum discharge occurred at about 1200 hours. The extent to which the high tide delayed the introduction of freshwater runoff into the harbor is unknown.

Salt Creek was partially stratified and did not have a well defined layer of freshwater at the surface as did Booker Creek. The magnitude and fluctuation in turbidity of Salt Creek was less than that of Booker Creek, probably because of the differing watershed characteristics. As with Booker Creek, there was no correlation between turbidity and total suspended solids.

Some measurements of physical characteristics were made and water samples were collected upstream of the first bend in Salt Creek (Fig. 1, site D). The specific conductance near the surface at this site was 1,100 to 4,600 µS/cm less than the specific conductance near the bottom. This is consistent with the partially stratified conditions observed upstream at the bridge.

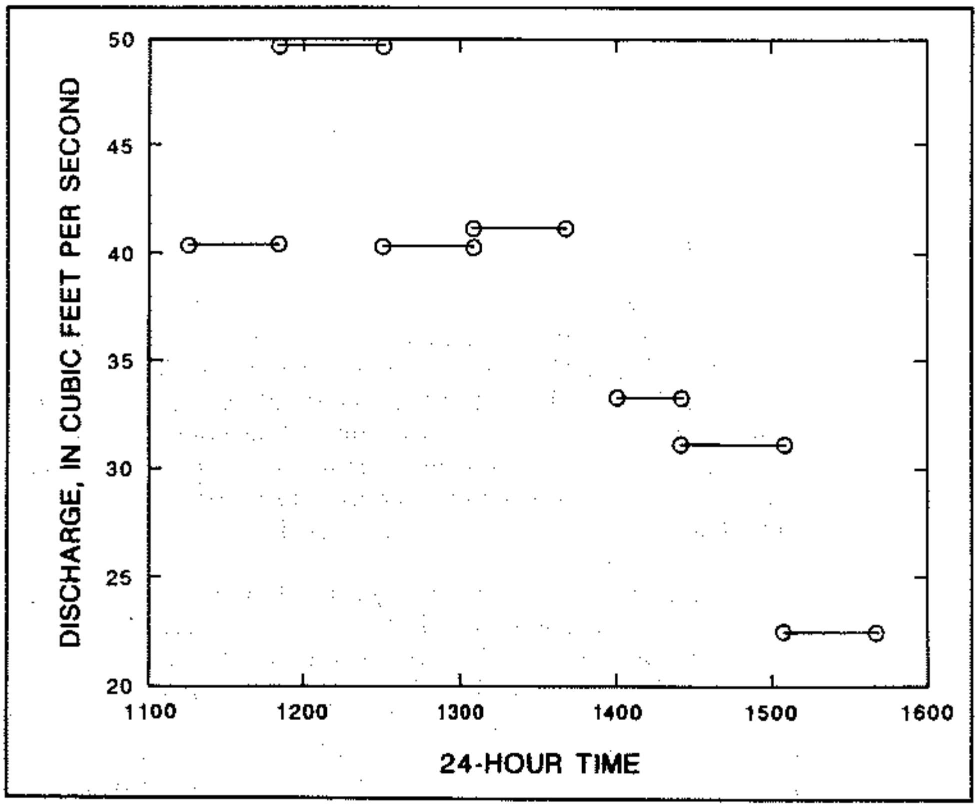

Figure 3. Discharge at site B on Salt Creek, November 9, 1989.

Harbor Sites Results

Water quality measurements were made and water samples were collected in Bayboro Harbor at sites C and E (Fig. 1). Water quality at site C, at the south side of the harbor, was affected by the discharge from Booker Creek during the ebb tide part of the sampling period. The specific conductance in the upper 8′ of the water column at site C was as much as 8,000 µS/cm less than the specific conductance at depths greater than 8′. The specific conductance 3′ below the water surface slowly increased during the sampling period, indicating saltwater dilution of the freshwater inflow. Below a depth of 8′, the specific conductances did not vary with time. This site was partially stratified, indicating that the freshwater discharge from Booker Creek was quickly diluted by the more abundant saltwater in the harbor.

Turbidity and OBS data indicate that the turbid Booker Creek runoff had only a small effect on the turbidity of water in the southern part of the harbor. At 1146 hours, there was no indication that the turbid freshwater runoff from Booker Creek had reached site C. By 1345 hours, however, the depth-integrated turbidity had increased slightly (from 1.0 to 2.1 NTU), probably because of the arrival of turbid water from Booker Creek. Afterward, the turbidity decreased at site C. The small increase in turbidity may be due to mixing of the turbid runoff with the large volume of less turbid water in the basin and settling of particles in the quiescent waters of the basin.

Measurements were made and water samples were collected south of the peninsula at site E (Fig. 1). This site is the sampling site nearest Tampa Bay. The magnitude and rate of change of turbidity at site E did not correlate well with the turbidity at the other sites. For example, the turbidity at the harbor and Salt Creek sites (C and D) increased in the early and mid-afternoon and then decreased in the late afternoon, whereas the turbidity at site E decreased throughout the afternoon. A possible explanation is that the turbidity at this site may be affected more by local runoff from pavement and boatyards. Because this site was not noticeably affected by the tributary storm runoff, the effects on Tampa Bay from the two tributaries probably were minimal.

SEDIMENT RESUSPENSION DURING DEPARTURE AND ARRIVAL OF A CRUISE SHIP

The port of St. Petersburg is the home port of a passenger vessel that makes daily cruises to the Gulf of Mexico. The draft of the ship is 17′, and the average low tide depth in the port is about 22′, so bottom sediments are likely to be resuspended by the vessel. Bottom sediments in the port have an average of 45% fine material (particle size less than 62.5 microns) and an average mean particle size of about 95 microns. Water samples were collected, OBS measurements were made, and aerial photographs were taken in the port during a vessel departure at 1000 hours on June 21, 1988. Because the arrival of the vessel commonly requires more maneuvering within the port, a similar data collection effort was subsequently undertaken during the arrival of the vessel at 1700 hours on May 18, 1990.

Water samples were collected from selected depths and OBS measurements were made in the port at sites 1 through 6 (Fig. 1). Measurements with an OBS sensor were made to help identify areas of resuspension and to quantify the concentration of total suspended solids. Measurements were made and samples were collected before the vessel maneuvered in the port and as soon after the vessel passed as safety would permit. Sampling and OBS measurements at the most affected sites continued for about two hours until the resuspension plume was barely detectable. Aerial photographs were taken and aerial observations were used to help identify sites with substantial resuspension. Water samples were analyzed for specific conductance, turbidity, and total and volatile suspended solids (Fishman and Friedman 1989). After the samples were analyzed, the OBS sensor output was calibrated with the concentration of total suspended solids.

Departure June 21, 1988

At 1000 hours on June 21, 1988, a cruise ship departed from the terminal with the help of two tugboats. The background concentration of total suspended solids averaged about 21 mg/l throughout the basin before departure, and an ebb tide occurred during the late morning of June 21.

Sampling and measurements commenced in the port as soon as possible after the cruise ship departed. Of the six sites sampled, site 2 had the greatest concentration of total suspended solids because it was near the path of the ship, and it was sampled only 3 minutes after the ship passed. At 1020 hours, the water column at site 2 had a fairly uniform suspended-solids concentration of about 125 mg/l, as shown in Figure 4. At 1035 hours, the material was settling and the concentration 20' below the surface had increased slightly to almost 140 mg/l. The concentration decreased with distance above the bed, and the concentration 5' below the surface had almost returned to the background level. At 1048 hours, the suspended solids concentrations at site 2 had decreased to a range of 25 to 50 mg/l. For the measurements at 1059 hours and subsequent measurements, the concentrations were slightly above the background level and the vertical distribution of suspended solids in the water column was fairly uniform.

Site 3 also was near the path of the cruise ship, but the elapsed time from the passage of the ship to the initial sample at 1022 hours (10 minutes) was greater than that for site 2. The maximum concentration of suspended solids at site 3 (70 mg/l) was about half that measured at site 2. After about 1100 hours, the concentrations decreased to near the background levels.

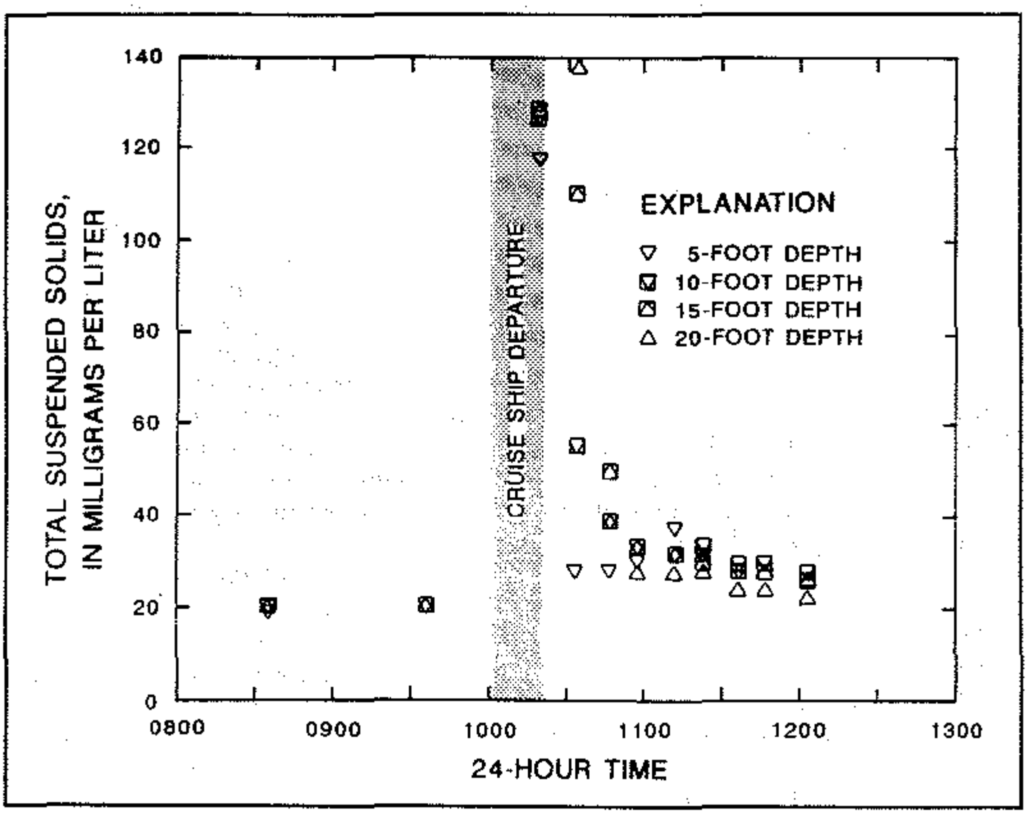

Figure 4. Total suspended solids at site 2 in the port of St. Petersburg, June 21, 1988.

Aerial photographs indicated that the plume of resuspended sediment was generated slightly west of site 4 and then drifted over this site with the ebb tide and inertia provided by the propellers of the cruise ship. At 1024 hours, vertically uniform suspended solids concentrations of about 80 mg/l were observed at site 4. The concentration of suspended solids at this site decreased rapidly thereafter. The primary resuspension locations were relatively remote from site 5 and the suspended solids concentration at this site after departure was generally less than about 40 mg/l.

No significant increase of the concentration of suspended solids was observed at either site 1, the western boundary of the port, or site 6, the eastern boundary of the port and the outlet to Tampa Bay. Thus, the resuspended sediments remained in the port. By 1200 hours, most of the resuspended sediment had settled to the bottom of the port and suspended solids concentrations had virtually returned to the background levels observed before departure. The port is protected from substantial wave action in Tampa Bay; tidal velocities in the basin are small; and the bottom sediments are fine sands and silt, so once the cruise ship leaves the basin, the resuspended sediments settle rapidly. The observed ebb tide did not generate sufficient velocities to transport resuspended sediments out of the basin and into Tampa Bay.

Arrival May 18, 1990

On May 18, 1990, a cruise ship arrived at the port of St. Petersburg at approximately 1700 hours. Before the arrival of the vessel, suspended solids concentrations in the basin ranged from 8 to 28 mg/l. At 1700 hours, the vessel entered the basin from the east at a speed of approximately 6 knots. At 1703 hours, the vessel was turning to starboard (right) as it left the channel and entered the port. At about this time, the vessel reversed its starboard propeller and probably its port (left) propeller to slow down and to help execute the sharp turn. At 1706 hours, the cruise ship had completed a 180° turn and was reversing its engines to back into the cruise ship terminal near the northwestern corner of the port. A plume of resuspended sediment off the stern (rear) and forward of the stern on the starboard side was probably caused by the prop wash of the reversing engines. Personnel in the sampling boat observed that the color of the water in the vicinity of the stern of the cruise ship was brown, as opposed to blue-green elsewhere, and that there was an odor of bottom sediments that had been detected previously during collection of bottom sediment samples in the basin. Neither discoloration of the water nor odor was noticed during the departure of the cruise ship in 1988. At 1711 hours, the cruise ship had virtually completed its docking maneuvers. Sampling and measurements commenced at sites 1 through 6 (Fig. 1) as soon as possible after the cruise ship had passed and continued until 1849 hours. A weak flood tide occurred during the sampling.

Site 3 was nearest the area where the cruise ship reversed its engines and had the highest concentrations of suspended solids. At 1711 hours, an odorous brown sediment was clearly visible at the water surface at this site. A water sample collected 5′ below the water surface had a suspended solids concentration of 127 mg/l, and the OBS sensor indicated that the suspended solids concentrations were 140, 130, and 220 mg/l at depths of 5′, 10′, and 15′, respectively, as shown in Figure 5. From 1711 to 1717 hours, the suspended solids concentration at site 3 increased, indicating that the sediment plume was expanding. At 1717 hours, a water sample collected 5′ below the water surface had a suspended solids concentration of 296 mg/l, and the OBS measurement indicated a value of 310 mg/l (shown in Fig. 5). This was the highest concentration sampled in the basin during the arrival of the cruise ship and was more than twice the highest concentration sampled during the departure of the cruise ship in 1988 (136 mg/l). By 1722 hours, the concentrations had decreased and ranged from 170 to 230 mg/l. As the plume expanded by diffusion and the resuspended sediment settled, the concentrations at site 3 decreased rapidly. By 1734 hours, the concentrations had decreased to a range of 40 to 75 mg/l. By 1748 hours, the rate of decrease in suspended solids concentrations had slowed as the concentrations approached background levels.

Site 4 was east of the origin of the main plume of resuspended sediment. The resuspended sediment plume spread by dispersion and arrived at site 4 between 1715 and 1729 hours. At 1729 hours, the suspended solids concentrations at this site ranged from 50 to 150 mg/l in the water column. From 1730 to 1800 hours, the concentrations decreased due to diffusion and settling. By 1800 hours, the suspended solids concentrations had virtually returned to background levels.

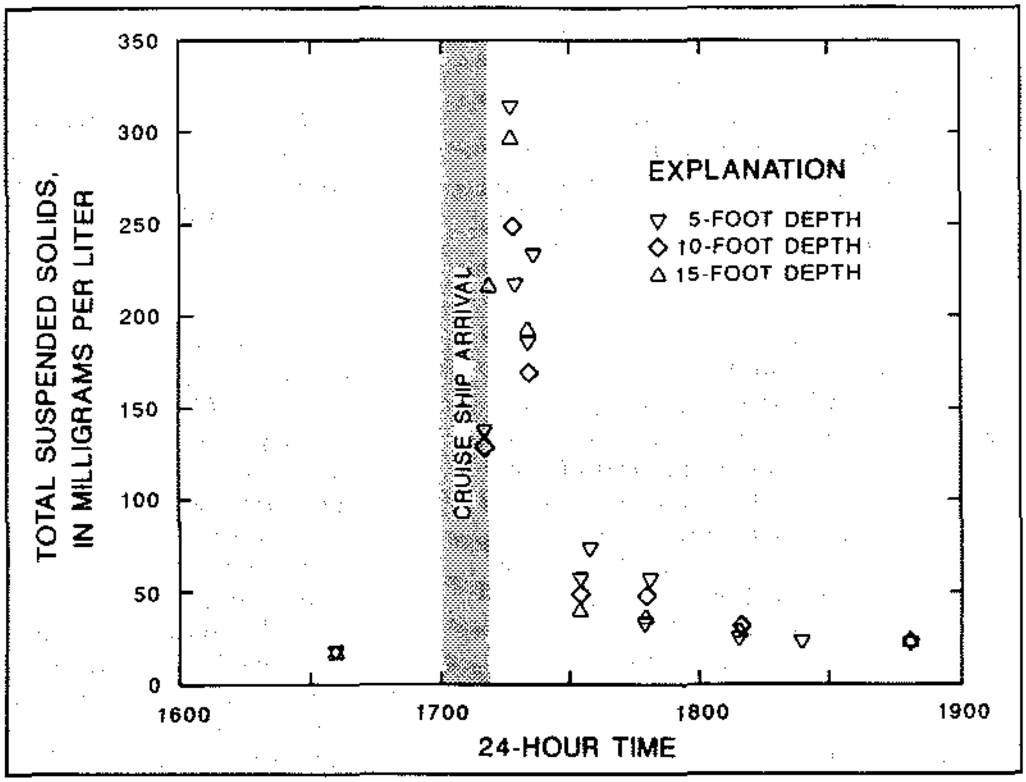

Figure 5. Total suspended solids at site 3 in the port of St. Petersburg, May 18, 1990.

Resuspension caused by the cruise ship was much less evident at the other sampling sites. OBS measurements at site 1 at the western boundary of the port at 1759 and 1840 hours indicated a slight increase in the suspended solids concentration 15′ below the water surface (from 19 to 30 mg/l). A water sample collected 15′ below the water surface at 1802 hours had a suspended solids concentration of 58 mg/l. At site 2, the suspended solids concentrations were no more than 10 mg/l above the background concentrations. At site 5, OBS measurements at 1811 and 1844 hours were at background levels. At site 6, in the channel near the eastern boundary of the basin in the channel, OBS measurements 15′ below the water surface at 1705 hours indicated that the suspended solids concentration was varying from 20 to 140 mg/l due to the passage of the cruise ship and resuspension in the entrance channel. No resuspended sediment was detected at depths of 5′ and 10′ below the water surface at site 6. By 1800 hours, OBS measurements indicated that the concentrations were virtually at background levels. The results indicate that the large plume of resuspended sediments observed at sites 3 and 4 did not enter the harbor to the west or Tampa Bay to the east.

SUMMARY AND CONCLUSIONS

Significant increases in light attenuation in Tampa Bay can adversely affect the ecology of the bay. Several nearly enclosed basins, like that containing Bayboro Harbor and the port of St. Petersburg, are adjacent to the bay and are potential sources of suspended solids and turbidity, which in turn can affect light attenuation in the bay. To evaluate the potential sources of suspended solids and turbidity, the U.S. Geological Survey, in cooperation with various local agencies, studied the effects of tributary storm runoff and vessel-generated sediment resuspension on water quality in the basin during 1988-90.

Tributary storm discharge and its effect on Bayboro Harbor were studied on November 9, 1989, when 0.50" of rain fell in a 3-hour period. The freshwater storm discharge to the harbor from Booker Creek, which drains part of the city of St. Petersburg, was delayed by a high tide. When the freshwater storm discharge began, Booker Creek became stratified with an approximately 1.5′ layer of turbid freshwater flowing downstream into the harbor over a relatively stagnant layer of less turbid saltwater. Salt Creek, which primarily drains Lake Maggiore, was less turbid and only partially stratified. The harbor became slightly stratified, with a thin layer of relatively fresh and turbid water above the less turbid seawater. The turbidity from the creeks only slightly increased the turbidity in the harbor, probably because of mixing with less turbid water and particle settling.

A cruise ship that sails daily from the port of St. Petersburg was observed to resuspend bottom sediments in the port. To evaluate the effects of ship traffic on turbidity in the port, water samples were collected and optical backscatterance measurements were made at six sites during a departure of the cruise ship on June 21, 1988, and upon arrival on May 18, 1990. The maximum concentrations of suspended solids in collected water samples was 136 mg/l during the departure and 296 mg/l during the arrival. Background concentrations of suspended solids were 20 to 30 mg/l. The cruise ship resuspended more sediment during arrival than during departure because upon arrival the vessel reverses its propellers to slow down, turn around, and back into the terminal. During the departure and arrival, most of the resuspended sediments settled within two hours once the cruise ship had either departed or docked. The lack of strong tidal currents, the lack of large waves, and the fine sand and silt-sized bottom sediments contributed to the rapid settling of the resuspended sediments. Small tidal currents transport constituents in the water column slowly, allowing sufficient time for suspended particles to settle before they can enter Tampa Bay.

Constituents that may adversely affect light availability in Tampa Bay can be introduced to the waters of the port of St. Petersburg and Bayboro Harbor basin by tributary storm runoff and large vessel traffic. The large volume and enclosed shape of the basin provide mixing and settling. These characteristics of the basin diminish or eliminate the potentially adverse effect on Tampa Bay from tributary storm runoff and large vessel traffic in the basin.

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HILLSBOROUGH COUNTY ENVIRONMENTAL PROTECTION COMMISSION EAST BAY STUDY

T. Cardinale
C. Dunn

INTRODUCTION

Hillsborough Bay has traditionally been the most polluted area of Tampa Bay and as such, has stimulated numerous studies by the Environmental Protection Agency (EPA), the Department of Environmental Regulation (DER) and the Environmental Protection Commission (EPC). The consensus of these studies has been that high nutrient loading (nitrogen and phosphorus) is the major contributor to water quality degradation.

This relatively high amount of nitrogen and other nutrients may be playing a major role in eutrophication. Excessive algal biomass, measured in the form of chlorophyll *a*, has been a problem in East Bay and Hillsborough Bay for a number of years. These nutrients directly and/or indirectly can affect the water clarity, fish production, fish kills, discoloration, seagrass bed production, and other critical indicators of the bay's condition.

Subsequently, efforts were made through the regulatory agencies to limit the nutrient loading to the bay by implementation of more stringent effluent quality constraints, for both domestic and industrial facilities. This can be illustrated by Hookers Point Wastewater Treatment Plant and Nitram, Inc., who in 1969 combined to contribute 123,980 lbs per day (or more than 70%) of nitrogen into Hillsborough Bay, compared to the 1989 quantity of 1250 lbs per day, despite the fact that flow rate from Hookers Point has increased from 28 MGD to over 50 MGD during that period.

The decreased nutrient loadings from major point sources has resulted in a corresponding improvement in water quality as evidenced by the sparse revegetation of seagrasses in Hillsborough Bay. However, during the same time period, it was observed, primarily through ambient water quality monitoring data, that the northern reaches of Hillsborough Bay (East Bay) were not improving at the same rate as the rest of the bay.

In September and December of 1989, the Environmental Protection Commission and the Florida Department of Environmental Regulation were briefed by the City of Tampa Sanitary Sewers Bay Study Group. This briefing, which was a result of the Study Group's own scientific studies in and around Hillsborough Bay, indicated that excessive nutrients (particularly nitrogen) may be coming from a number of previously undocumented sources in the East Bay Channel and turning basin. This information provided the impetus for the East Bay Survey.

STORMWATER SAMPLING

At the request of EPC staff, the City of Tampa Bay Study Group collected a series of water samples during rainfall events from various locations of East Bay (Figure 1). These samples were analyzed by the Environmental Protection Commission. All of these samples were collected by boat during rainfall events and represent stormwater discharges, normal effluent discharges, or some combination. The following are results of EPC's chemical analyses.

IMC

Discharges from five different locations were collected from IMC Port Sutton on three separate occasions. Ten different potential discharge points have been observed by boat from this facility. Samples from location S003 and S004 indicate that stormwater from these discharge locations is severely contaminated with fertilizer (Table 1). After the February 23, 1990 sampling, additional grab samples were collected at location S004 which appears to have a continuous discharge to the Port Sutton Channel (Table 2).

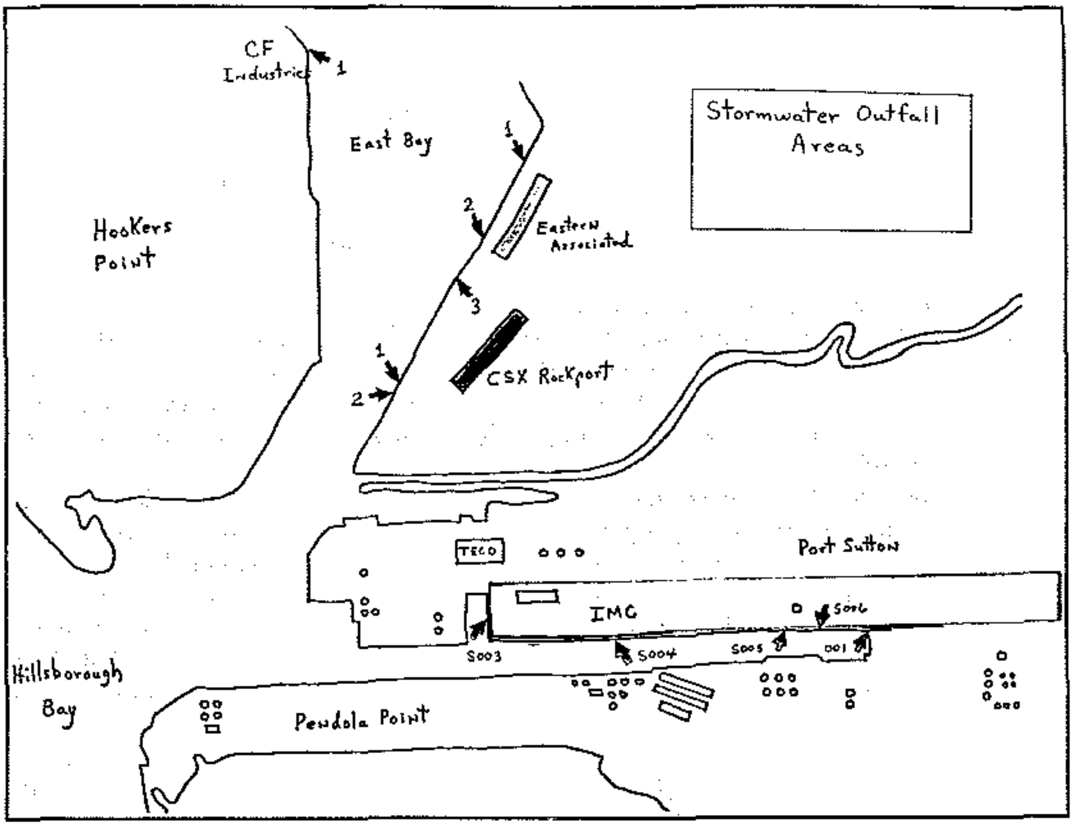

Figure 1.

Table 1. Results of sampling (expressed as mg/l) at IMC.

LOCATION	ORTHO P	TOTAL P	NO_2NO_3	NH_3N	KJEL N	TOTAL N
12-18-89:						
S005	8.81	30.31	7.30	1.04	0.40	8.34
S004	191.24	192.11	19.46	204.78	194.93	214.39
S003	267.92	280.20	21.01	277.08	269.68	298.09
12-20-89:						
S005	0.48	7.13	5.47	1.37	2.32	7.79
S004	34.60	37.59	11.56	41.07	41.38	52.94
S003	306.13	330.13	46.50	350.66	321.50	368.00
2-23-90:						
S005	7.72	75.69	8.26	5.98	24.23	32.49
S004	79.33	149.38	19.12	84.86	150.76	169.88
S006	2.12	19.97	4.46	1.21	20.75	25.21
001	2.87	18.37	2.20	1.59	16.59	18.79

Table 2. Additional sampling (expressed as mg/l) at IMC, S004.

DATE	ORTHO P	TOTAL P	NO_2NO_3	NH_3N	KJEL N	TOTAL N
5-4-90	0.83	1.52	0.07	0.88	0.68	0.75
5-10-90	44.05	78.01	18.36	69.80	143.90	162.26
8-14-90	85.67	213.00	0.50	0.60	2.11	2.61
8-22-90	-	139.83	5.08	15.50	10.70	15.78
9-5-90	90.52	129.78	1.13	3.48	2.82	3.95
9-19-90	7.29	31.72	1.91	6.49	3.85	5.76
9-25-90	4.08	4.94	1.70	0.27	1.80	3.50
10-10-90	14.43	39.17	4.19	10.96	8.61	12.80
10-10-90	103.37	147.43	12.09	48.88	48.48	60.57

CSX Rockport

Samples were collected from three different locations. Six or seven different potential discharge points were observed by boat during initial investigation. The data indicate that stormwater from this facility is being severely contaminated with fertilizer products (Table 3). Several discharge locations about one-half mile east of the mouth of Delaney Creek have yet to be sampled.

Table 3. Results of sampling (expressed as mg/l) at CSX Rockport, 12-20-89.

LOCATION	ORTHO P	TOTAL P	NO_2NO_3	NH_3N	KJEL N	TOTAL N
1	825.47	2868.62	1.02	872.35	1012.35	1013.37
2	1082.25	2443.00	1.46	945.00	963.25	964.72
3	281.01	538.60	51.38	558.08	303.68	355.06

Eastern Associated Terminal

At least two stormwater discharge points that appear to be coming from this facility have been sampled. Stormwater from this facility may also be draining towards Delaney Creek. These discharges also appear to be contaminated with fertilizer products (Table 4).

Table 4. Results of sampling (expressed as mg/l) at Eastern Associated Terminal.

LOCATION	ORTHO P	TOTAL P	NO_2NO_3	NH_3N	KJEL N	TOTAL N
12-20-89:						
1	114.98	111.39	4.00	68.40	79.14	83.14
2	30.43	58.97	1.32	19.79	20.36	21.68
2-23-90:						
2	69.85	79.72	11.48	60.11	100.80	112.28

Other East Bay Industries

Stormwater discharges from the four facilities listed in Table 5 were also sampled. Stormwater contamination from these sources appears to be considerably less than IMC, CSX and Eastern Associated. On-site inspections should be made in order to determine if all stormwater discharges have been sampled.

AMBIENT SAMPLING

EPC has been monitoring Tampa Bay since 1972. Seventeen of these monitoring stations are located in Hillsborough Bay (see Figure 1, Boler et al., this volume). None of the stations are located directly in East Bay. Station 54 is the closest station at the north end of East Bay. Station 52, just off Pendola Point, is near the southern tip of East Bay.

Table 5. Results of sampling (expressed in mg/l) at other East Bay industries.

LOCATION	ORTHO P	TOTAL P	NO_2NO_3	NH_3N	KJEL N	TOTAL N
CF Industries Hookers Point						
12-20-89						
1	1.68	1.57	6.23	0.97	2.42	8.65
Ideal Basic Industries (North) Port Sutton						
12-18-89						
1	0.14	0.14	0.14	0.81	0.95	1.09
Seminole Fertilizer Port Sutton						
12-20-89						
1	-	1.04	0.07	3.43	4.58	4.65
GATX Hookers Point						
2-23-90						
1	2.31	8.88	0.66	0.78	20.64	21.30
2	5.60	5.60	0.99	0.63	8.09	9.08

On February 14, 1990, East Bay was sampled by EPC at 19 locations (Figure 2) specifically for nutrients (Table 6). This date was selected because EPC's seventeen routine monthly locations were also sampled by another EPC crew that day. In addition, the City of Tampa Bay Study Group was also collecting samples in that area as part of their required compliance monitoring program. All of this data would provide a synoptic view of nutrients in Hillsborough Bay.

Another important consideration in selecting February 14 as the sampling date was the fact that no rain had fallen since the evening of February 10 when a fast-moving cold front dropped approximately 2.2" of rain. The object of this sampling was to determine relative nutrient concentrations after a dozen or so tidal cycles and mixing.

Table 6. Results of East Bay sampling (expressed in mg/l), 2-14-90.

STATION	TOTAL N	NH_3N	KJEL N	NO_2NO_3	TOTAL P	ORTHO P
1	1.11	0.11	1.08	0.03	0.53	0.47
2	1.28	0.13	1.26	0.02	0.52	0.46
3	0.99	0.05	0.98	0.01	0.54	0.46
4	1.41	0.06	1.40	0.01	0.55	0.46
5	1.06	0.11	1.04	0.02	0.51	0.45
6	0.77	0.06	0.76	0.01	0.49	0.44
7	0.87	0.19	0.86	0.01	0.50	0.65
8	1.15	0.26	1.11	0.04	0.52	0.49
9	0.84	0.09	0.80	0.04	0.48	0.47
10	0.99	0.27	0.89	0.10	0.55	0.50
11	1.54	0.44	1.34	0.20	0.67	0.78
12	2.53	0.58	2.24	0.29	0.98	0.95
13	1.80	0.38	1.64	0.16	0.76	0.75
14	0.89	0.13	0.86	0.03	0.53	0.48
15	3.89	1.48	3.15	0.74	2.70	2.72
16	1.09	0.18	1.03	0.06	0.63	0.56
17	1.14	0.26	1.10	0.04	0.89	0.81
18	0.98	0.10	0.95	0.03	0.69	0.61
19	0.95	0.08	0.93	0.02	0.51	0.46

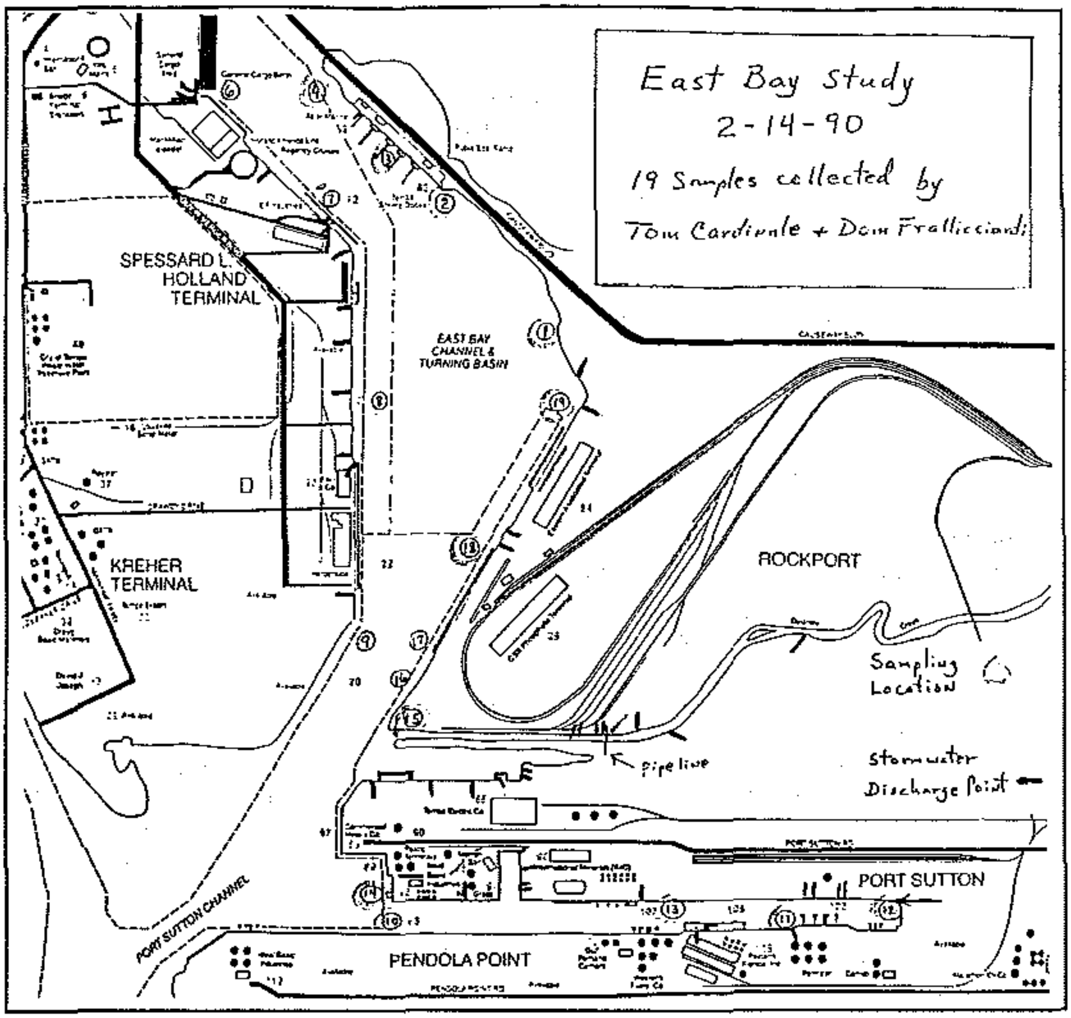

Figure 2.

Three areas of East Bay were found to have ammonia values 8 to 10 times higher than lower Hillsborough Bay. The mouth of Delaney Creek and the east end of the channel between Port Sutton and Pendola Point had the highest concentrations of ammonia.

Delaney Creek has received excessive nitrogen for many years but has recently shown dramatic improvements. The main source of the nitrogen measured on the February 14 sampling is believed to be coming from the CSX Phosphate Terminal. The IMC Port Sutton facility is the likely source of the nutrients observed in that area of East Bay having the second highest values, although other sources of fertilizer may also be contributing.

The third area of elevated nutrients was found along the east side of Hookers Point just south of CF Industries. It is possible that these nutrients are coming from or leaching from solid fertilizer deposits accumulating on the bay bottom in the vicinity of stormwater outfalls and/or shiploading facilities. This source could be verified by collecting water samples from various depths after a relatively long dry period (two to three weeks of no rain). Bottom sediment analysis would also be useful.

INDUSTRIAL INSPECTIONS

The purpose of the study was first to identify the pollution point sources, and second, to determine the extent of any stormwater contamination. Since the pollutants of concern were previously identified as nitrogen and phosphorus, any facility in the East Bay area handling products whose constituents included nitrogen and/or phosphorus were included in the survey. These facilities include:

- CSX Rockport Terminal
- International Mineral Corporation (IMC)
- Eastern Associated Terminal (EAT)
- Central Phosphate Industries (CFI)
- Pakhoed, Inc.
- GATX
- Seminole Ammonia Terminal
- Ideal Basic Industries

Inspections of the above referenced facilities began on February 19 and ended on March 16, 1990. These inspections were of the reconnaissance type in that the facility area was explored and any environmental concerns noted. Samples were taken at any discharging outfalls during the inspections. These results are listed in Table 7. A general overview of each site follows.

Eastern Associated Terminal

This facility is a bulk storage terminal located approximately one-half mile south of Causeway Boulevard on the eastern border of East Bay. The products handled at this site are monoammonium phosphate (MAP), diammonium phosphate (DAP) and triammonium super phosphate (TASP), all of which are very soluble in water. EAT was first inspected on February 19, 1990. As with all inspections, a site walk-through was made with environmental concerns pertaining to potential nutrient contaminated discharges noted. These areas of concern included:

- spillage from conveyor belts, especially in the areas where the belts change direction;
- pond used for storage of product contaminated water, which discharges to a storm water sump and ultimately to the Bay;
- waste product piles open to the atmosphere at the head of the ditch just north of substation 1 and also in the vicinity near the head of belt 5.

Five samples were collected at locations around the site based on their potential for discharge into East Bay. (Refer to Figure 3 and Table 7 for location and results.)

On February 23, 1990, approximately 16 hours after the beginning of a rain event, EAT was again inspected and four samples taken in an effort to obtain a definitive indication of the nutrient concentrations in the discharges. Results and sample locations can be referenced from Table 7.

CSX

This is a bulk storage facility located just south of EAT on Uceta Road. CSX handles the same products indicated above at EAT, plus a variety of others. These materials are received by rail, then transported to and from the storage facility by conveyor belts. On March 1, 1990, this facility was inspected, with the following concerns noted:

- spillage from conveyor belts, particularly in the areas where the belts change direction, resulting in piles of product directly under the belts;
- product spillage from rail cars, evidenced by numerous small piles of product along rail lines;
- discoloration of water within the storm water ditch system resulting in dissolution of product therein;
- piles of waste product exposed to the elements;

Table 7. Results of sampling (expressed in mg/l) in association with industrial inspections.

FACILITY	SAMPLE	TOTAL P	ORTHO P	TOTAL N	KJEL N	NO_2+NO_3	NH_3N
EAT, 2/16/90	1	152.17	113.00	261.74	261.58	0.16	117.54
	2	5153.00	1228.00	5378.33	5345.50	32.83	5884.01
	3	10116.00	9775.00	11556.12	11500.00	56.12	7529.00
	4	8168.40	7656.00	9159.54	9100.00	59.54	7505.50
	5	5541.50	2273.00	5922.56	5903.50	19.06	3191.00

Sample locations:
1 - tail of belt 10
2 - tail of belt 3
3 - wastewater retention pond
4 - at 4A station
5 - collection sump in front of ship loader

FACILITY	SAMPLE	TOTAL P	ORTHO P	TOTAL N	KJEL N	NO_2+NO_3	NH_3N
EAT, 2/23/90*	1	889.80	770.45	1043.20	974.20	69.00	726.50
	2	451.75	382.02	414.37	397.65	16.72	261.40
	3	330.30	290.74	424.38	400.35	24.03	283.00
	4	344.20	311.04	321.38	305.45	15.93	195.45

Sample locations:
1 - discharge from belt 2 sump to southern ditch
2 - head of south ditch
3 - outfall pipe to ditch from north end of C-4
4 - outfall into bay
*rain event sampling

FACILITY	SAMPLE	TOTAL P	ORTHO P	TOTAL N	KJEL N	NO_2+NO_3	NH_3N
IMC, 2/19/90	1	1119.35	1048.00	1879.15	1732.40	146.75	1879.15
	2	156.81	53.90	121.74	111.60	10.14	64.39
	3	4.40	2.83	8.95	8.93	0.02	1.11
	4	1.08	1.05	2.08	1.93	0.15	0.20
	5	3.52	3.80	55.47	25.14	30.33	9.25

Sample locations:
1 - stormwater sump at entrance gate
2 - outfall S004 to ship canal
3 - outfall S005 to ship canal
4 - permitted outfall 001
5 - easternmost stormwater drainage ditch

(continued)

Table 7 continued.

FACILITY	SAMPLE	TOTAL P	ORTHO P	TOTAL N	KJEL N	NO_2+NO_3	NH_3N
IMC, 2/23/90*	1	1450.60	1248.75	2058.46	2051.30	7.16	1384.50
	2	443.85	403.28	733.65	658.85	74.80	733.65
	3	436.90	388.90	692.20	621.70	70.50	444.55
	4	324.70	255.35	547.40	489.40	58.00	279.10
	5	425.30	381.88	678.90	611.00	67.90	410.70
	6	33.22	24.88	43.40	42.06	1.34	19.71
	7	17.03	8.12	22.40	22.01	0.39	3.03
	8	92.32	96.34	155.86	125.50	30.36	67.98

Sample locations:
1 - outfall S002
2 - outfall S003, pipe 1
3 - outfall S003, pipe 2
4 - outfall S001
5 - culvert to outfall S003
6 - west end of loading dock in canal
7 - east end of loading dock in canal
8 - outfall S004
*rain event sampling

CSX, 3/1/90	1	2704.80	2358.70	2778.00	2430.80	347.20	1773.40
	2	891.80	815.50	945.30	776.50	168.80	595.00
	3	6.82	4.25	17.94	2.19	15.75	0.10
	4	0.58	0.60	1.13	1.03	0.10	0.08
	5	224.04	209.00	387.72	296.32	91.40	250.04

Sample locations:
1 - storm ditch between tracks just north of station
2 - storm ditch "pop off" to tributary of Delaney Creek
3 - outermost ditch to the southeast of storage building
4 - Delaney Creek edge southeast of storage building
5 - storm ditch adjacent to storage building southeast corner

CF Industries, 3/8/90	1	155.97	100.77	78.72	73.99	4.73	71.87
	2	4.28	2.67	21.70	8.38	13.32	2.24

Sample locations:
1 - easternmost outfall to Hillsborough Bay
2 - drainage ditch south of storage shed

- paralleling the bay, there were voluminous deposits of product at every location where the gantry remains stationary during the ship loading operation.

Five samples were taken from the storm ditch in and around the site and from Delaney Creek. The locations and results are indicated on Figure 4 and Table 7, respectively.

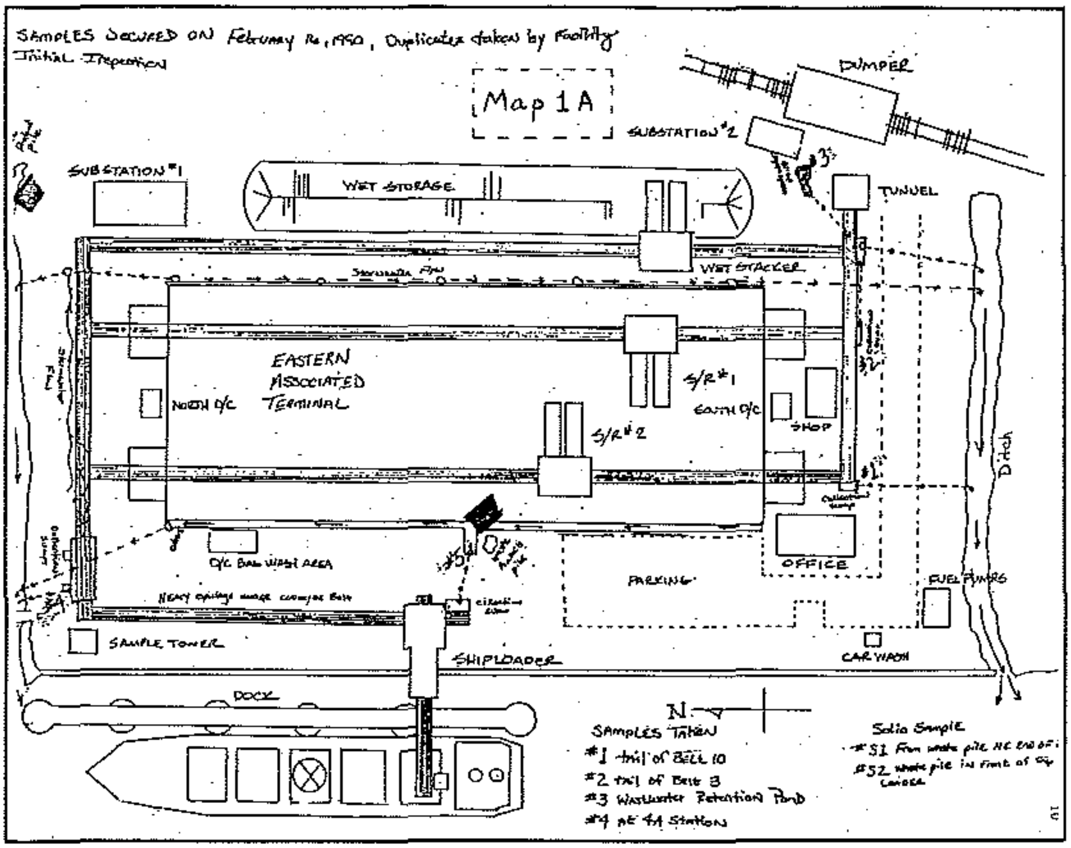

Figure 3.

CF Industries

This facility, leased from the Tampa Port Authority, is located on the western boundary of East Bay, off of Verger Boulevard. It stores and handles DAP, MAP and GTSP. As opposed to the other facilities, most of the product is received by truck rather than rail. On March 8, 1990, an inspection was conducted at the site, revealing the following concerns:

- spillage from the conveyor belts, especially in areas where the belt changes direction;
- product spillage in a stormwater ditch around the storage shed;
- product spillage from gaps in the walls of the storage shed, directly into the storm water ditch around the building.

One sample was taken from the drainage ditch south of the storage shed and another was taken from the outfall into East Bay. The results and location of these samples are indicated in Table 7 and on Figure 5, respectively.

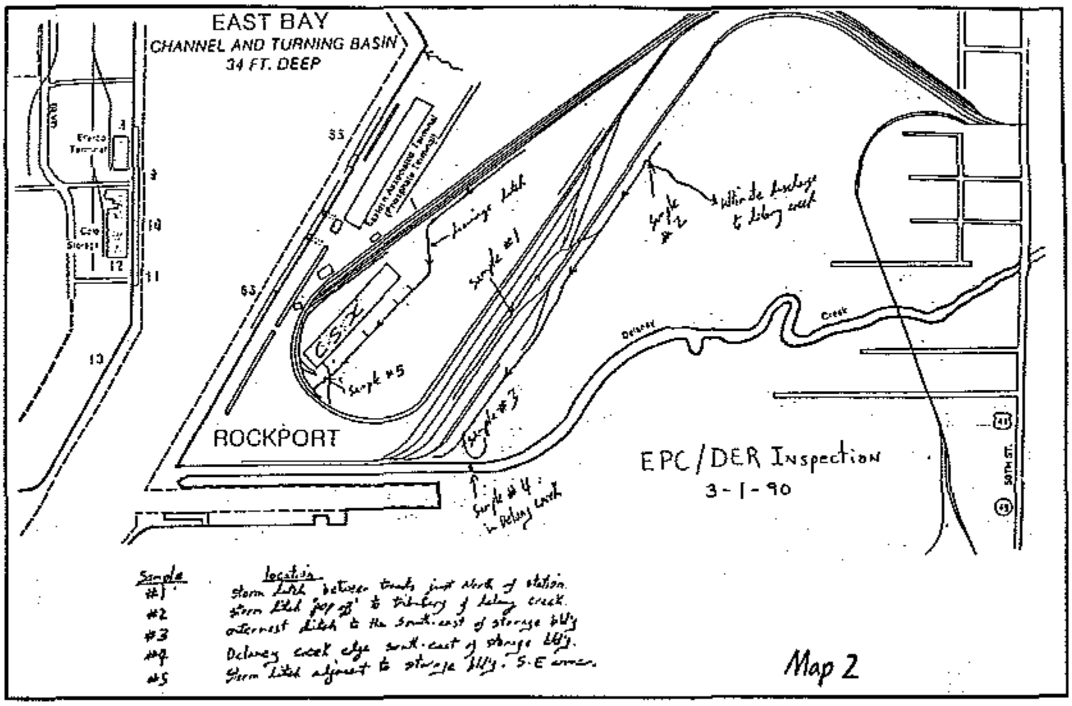

Figure 4.

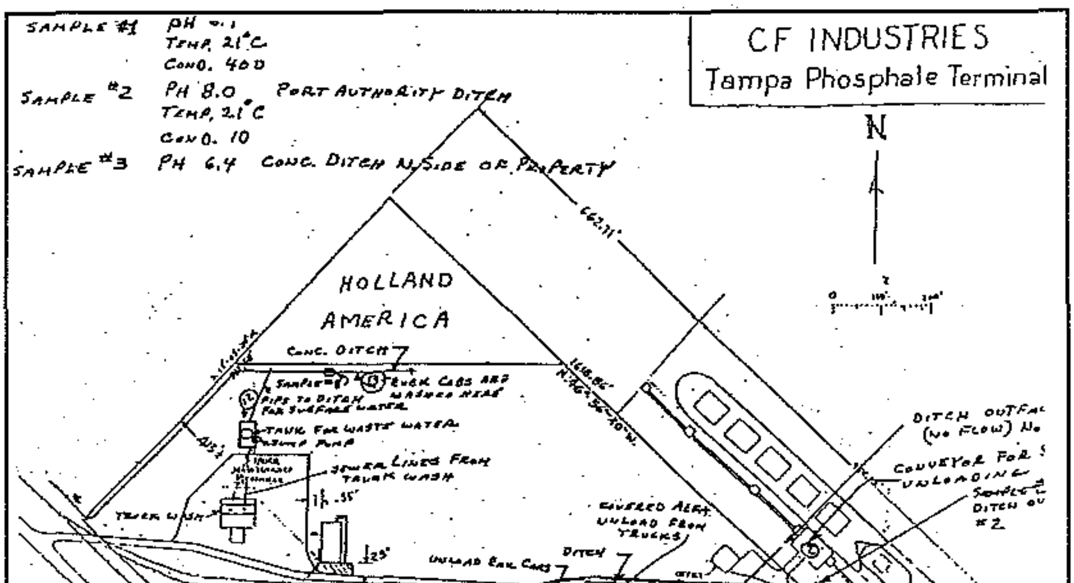

Figure 5.

Pakhoed

Located on Pendola Road, this facility handles a number of inorganic chemicals, including ammonium compounds and assorted nitrates, hence the inclusion in this survey. An inspection of this site on March 13, 1990 revealed the following environmental concerns:

- storage sheds generally antiquated and subsequently patched together; at the time of the inspection, sections of roof and side walls were being repaired.
- spillage of large amounts of product in the stormwater ditch between adjacent sheds, in the vicinity where the walls or roof had ruptured;
- leaks in the roofs of the storage sheds;
- bags of nitrate stored outside the storage shed;
- off-loading operation from a docked barge resulted in some spillage directly into the bay;
- puddles of water contaminated with dissolved products.

No samples were taken since there was no flow from any discharge pipes during the inspection. This site was again visited on March 16, 1990 at which time the events were recorded on video.

Seminole Ammonia Terminal

As the name implies, this is an ammonia storage facility located on Port Sutton Road. On March 13, 1990 an inspection revealed no environmental concerns as pertain to this survey. However, the permitted discharge of cooling water was sampled. Of the six facilities surveyed, Seminole Ammonia Terminal is a slightly different operation since it handles only liquid ammonia.

IMC

Located on Port Sutton Road, this bulk storage terminal handles the products produced at its inland mining and chemical operations. These include the family of ammonium phosphates, animal feed, and several grades of "wet rock" which are brought to the terminal by bulk trucks and rail. An inspection on February 19, 1990 indicated the following environmental concerns:

- stormwater ditches containing water discolored by dissolved product; this water was supposed to be contained and tested prior to discharge.
- spillages from the conveyor belt, particularly in a 360'-length in the vicinity of the loading area where the belt runs overhead, parallel to the channel boundary;
- general spillage alongside the loading dock area and a waste product pile in the same area where the overhead belts change direction.

Five samples were taken, the results and location of which are indicated on Table 7. On February 23, 1990, approximately 16 hours after the beginning of a rain event, this site was revisited in an effort to obtain more representative discharge samples. The location of this sample collection are indicated on Figure 6.

DISCUSSION

These inspections, though preliminary in nature, have revealed some definitive conclusions. Nutrient discharge concentrations, greater than 2000 mg/l in some cases, indicate a potential impact on the eutrophication of East Bay. Also, the associated toxicity of these discharge streams will ultimately need to be given more in-depth consideration in an attempt to establish limits based on the assimilative capacity of the receiving surface water body.

As indicated previously, the purpose of the survey was to both identify the pollution point sources and also to determine the method by which these unpermitted streams were being contaminated by industrial waste. Visual inspections revealed environmental concerns inherent in these types of facilities as they presently operate. None of the facilities was adequately controlling spillage off of their conveyor belts, especially in the areas where the belts changed direction. The equipment and methods used for both loading (evident at CSX) and off-loading (witnessed at Pakhoed) of ships and barges had inherent spillages which either directly or indirectly entered the bay.

Some of the facilities (CSX, Pakhoed and EAT), in addition to the associated operational problems, simply had poor waste management practices. This created a more vivid illustration of the environmental problem. However, examination of samples collected from IMC, which appears more aesthetically appealing, revealed that the stormwater contamination problem is inherent to these bulk storage terminals as they presently operate.

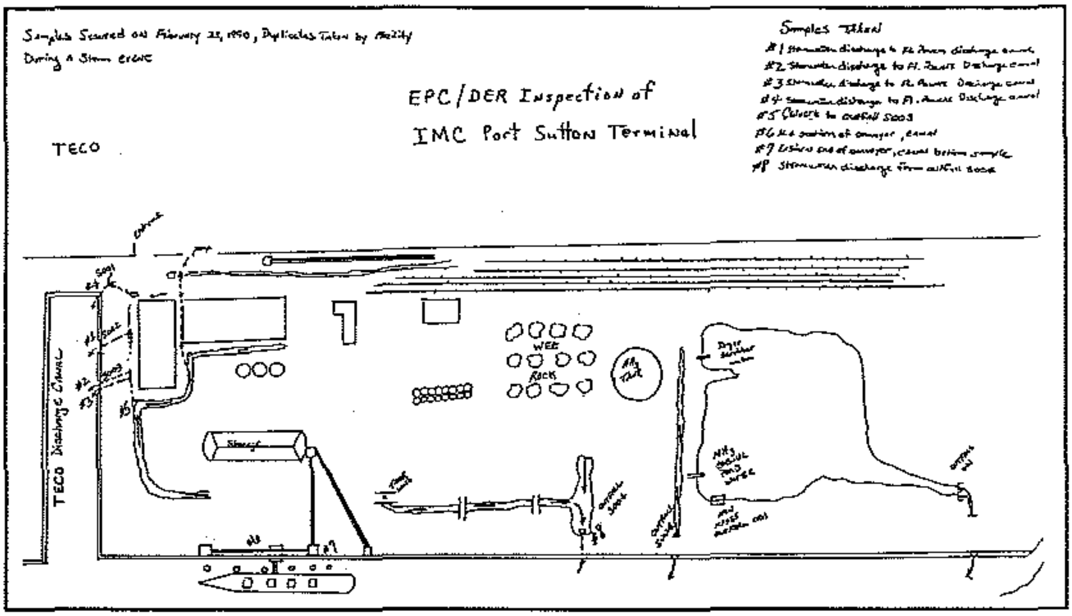

Figure 6.

Fertilizer Shipments

EPC is attempting to determine the potential and actual contribution of nutrients to the environment from the industry as a whole and from each of the five facilities. This information will be useful for setting enforcement priorities and penalties. An examination of gross shipping records from the ports of Tampa Bay is a way of determining potential nutrient contributions to the environment. Shipping records received from both the Tampa Port Authority and the Manatee County Port Authority were assembled into Table 8 and Figures 7 and 8. The phosphate rock records combine both wet and dry shipments. Phosphatic chemicals data include a mixture of products such as DAP (diammonium phosphate), TSP (triple superphosphate), and MAP (monoammonium phosphate). Liquid fertilizers such as phosphoric acid and ammonia are not included in these tables.

Figure 7 shows an overall decline in phosphate rock shipments and an increase in phosphatic chemical shipments. The decline in phosphate rock shipping is good news, environmentally speaking, because this product tends to be more of a fugitive dust problem. It is handled less carefully, shipped in open railcars, and often stored uncovered.

Phosphate rock is relatively insoluble compared to the phosphatic chemicals. The industry goes a step further, discussing it as if it was completely insoluble and therefore not a problem if exposed to rain. The large uncovered open piles at these facilities are usually wet phosphate rock. Most of the earthlike mounds of material between railroad tracks appear to be phosphate rock that has leaked from the cars.

Rock is potentially a pollutant if it gets into the bay in either a soluble or insoluble form. If it proves to be insoluble in water (both rainwater and seawater), then stormwater management becomes easier and less costly. If it is soluble or even partially soluble, then the industry may be facing major changes in the way they transport, handle and store this product. For example, all railcars may have to be covered to prevent contact with rainwater. In addition, the practice of stock-piling rock in large uncovered piles may have to cease.

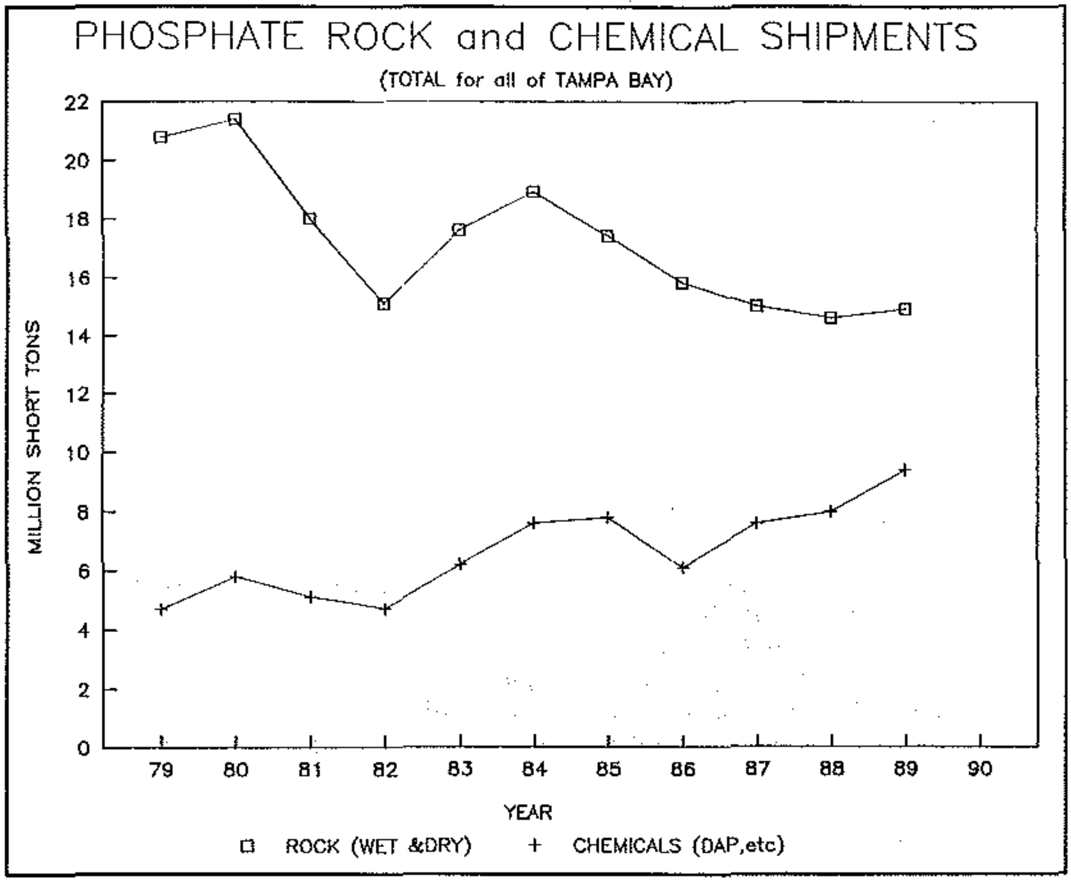

Figure 7.

EPC tested the solubility of a sample of phosphate rock collected from one of IMC's Port Sutton piles. A measured quantity was placed into clean seawater having a pH of 8.2. The concentration of phosphorus and the rock's solubility was measured after various periods of time as indicated in Table 9.

At least 1% of the rock appears to dissolve in seawater after only a few days. EPC attempted to determine if any relationship (cause and effect) could be found between phosphate rock shipments and surface water quality. EPC has a sampling station about one mile north of the center of East Bay and a station about one mile south. The annual total phosphorus averages for each year, for these two stations, were combined and compared to rock shipping records. Figure 8 shows the relationship.

Shrinkage Estimates

From the above shipping records and knowledge of the nitrogen and phosphorus content of each product, a series of calculations were made to produce Table 8. A product loss (shrinkage) of 0.05% of the amount handled has been estimated by a middle east phosphate company located on the Gulf of Agaba (Marine Pollution Bulletin 16(7):281-285, 1985). Others have suggested losses as high as 0.1% and 1.0%.

Table 8. Phosphatic products shrinkage estimates, based on 1989 net shipments of 24.3 million short tons of product, of which 38.7% were chemicals and 61.3% were rock.

POSSIBLE LOSS percent	PRODUCT WT/YR lbs.	TOTAL NITROGEN lbs/yr	TOTAL PHOSPHORUS lbs/yr
0.01	4,860,000	338,548	823,041
0.05	24,300,000	1,692,738	4,115,205
0.10	48,600,000	3,385,476	8,230,410
0.50	243,000,000	16,927,380	41,152,050
1.00	486,000,000	33,854,760	82,304,100

Table 9. Solubility of 75% BPL rock in seawater.

SOAKING TIME	SOLUBILITY, %	CONC. AS P, mg/l
1	0.0067	0.01
2	0.0360	0.06
4	1.69	3.82
7	1.10	3.08

Aliquots of sample were filtered thru 0.45 micron membrane and sample was allowed to settle for at least 24 hours prior to analysis.

If the 0.05% loss applies to the facilities on Tampa Bay, then these facilities may be the largest sources of nitrogen and phosphorus to the bay. As indicated from Table 10, this industry could be releasing million of pounds of total nitrogen and total phosphorus to Tampa Bay each year (Figure 9).

The East Bay study will provide the foundation for more detailed and specialized studies to evaluate past, present and future impact associated with the day-to-day operation of the bulk storage terminals. These studies may include (but not necessarily be limited to) the following:

- sedimentation in the bay;
- toxicity to receiving surface water body;
- waste management technique/practices;
- improved and/or alternate equipment design.

These studies would be best managed by the regulatory agencies through an enforcement document. The document will clearly delineate time frames and appropriate controls.

Enforcement Action

As a result of these findings, EPC and DER jointly issued Warning Notices to five facilities on March 30, 1990. Each facility was asked to sign a Consent Order which provides an acceptable time schedule within which the violations will be corrected. The Consent Order also sets forth a settlement figure payable to the state and EPC in compensation for past and present violations of Florida Statutes, Chapter 84-446, as well as reimbursement of costs expended by the agencies in investigation and resolving this matter. The tentative settlement figures have ranged from about $80,000 to $140,000. It is hoped that the Consent Orders will be signed early in 1991 so that corrective action will proceed as soon as possible.

Most of the companies have already taken initial steps to curtail spillage and improve housekeeping. However, considerable additional measures may be required in order to satisfy both DER and EPC.

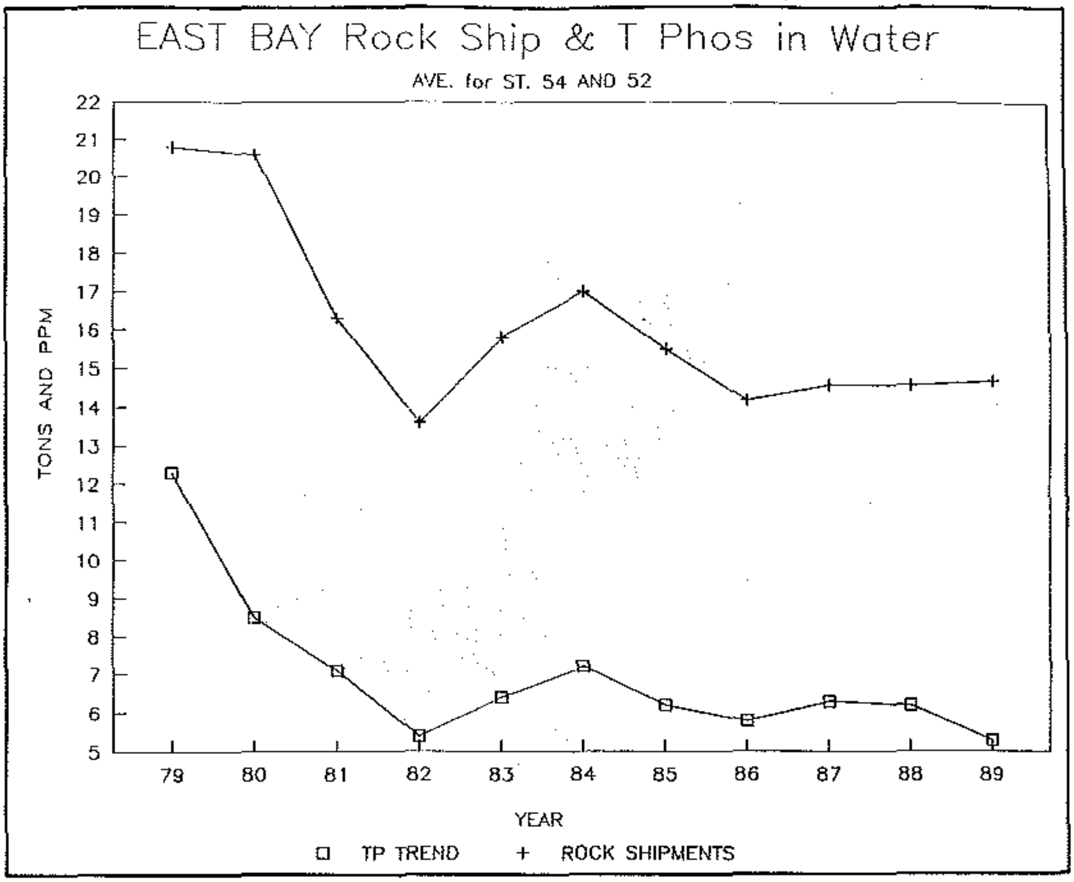

Figure 8.

Table 10. Phosphate loading to Hillsborough Bay for 1989.

SOURCE	LBS./YEAR	NOTES
Alafia	1,500,00	EPC estimate
Gardinier	18,992	company estimate
Hookers	940,857	DER MOR
Hillsborough River	200,000	EPC estimate
IMC	1,005,000	if .05% loss
CSX	1,075,000	if .05% loss
EAT	335,000	if .05% loss
CF	320,000	if .05% loss
Pachoed	295	if .05% loss
TOTAL	5,395,144	

FUTURE

The pollution discovered in the East Bay area brought to EPC's attention a number of problems that must be addressed in the near future.

Monitoring Networks. The excessive nutrients coming from these facilities should have been detected much sooner, by better industrial waste inspections and/or EPC's Ambient Surface Water Monitoring Program. Changes and improvements are needed by the regulatory agencies in order to prevent such a major source from going relatively unnoticed all these years. EPC must also re-evaluate its monitoring network by either adding stations and/or moving stations. Increasingly, point source discharges will be required to have surface water monitoring plans. To date, this requirement has been applied mostly to domestic waste sources but will soon also pertain to industrial discharges.

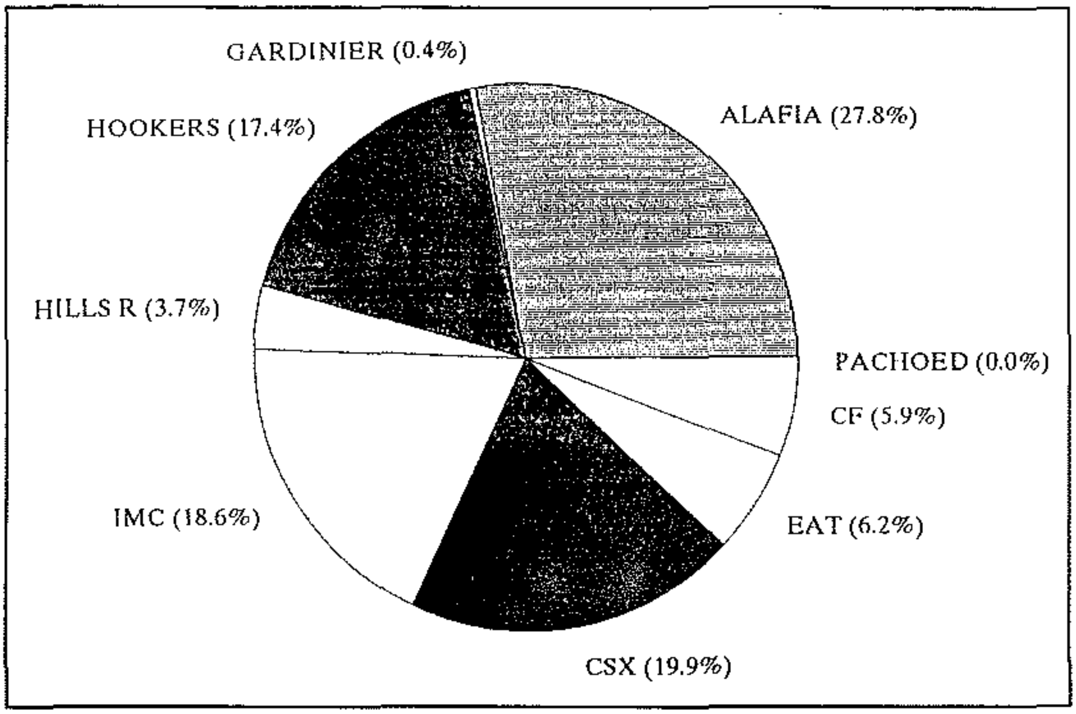

Figure 9. Phosphorus loading to Hillsborough Bay for 1989, at estimated .05% shrinkage. Shrinkage estimate applies only to IMC, CSX, EAT, CF, Pachoed.

Sedimentation. The question of how much solid fertilizer has accumulated at the various ship berths and stormwater outlets needs to be assessed. Maintenance dredging at these berths has been needed at all of these facilities. In light of the partial solubility of some of the products, spoil placement may become a serious problem. In the past, spoil from each berth has amounted anywhere from 1000 cubic yards to over 10,000 cubic yards. Just how this problem will affect the Tampa Port Authority's Harbor Maintenance Program has yet to be determined. Some special studies funded by the Southwest Florida Water Management District's Surface Water Improvement and Management (SWIM) program for sediment analysis in Tampa Bay may prove very useful for the regulatory agencies and the fertilizer industries.

Permitting. Many questions related to permitting need to be resolved. Does a permit to control air emissions create a water pollution problem? How far can the regulatory agencies go as far as requiring the latest available technology? For example, the technology used to move product to and from ships varies a great deal. Can we require the best of these systems? Should the use of clam buckets be prohibited? Can changes in rail transportation be required under a permit? Should rail transportation, which certainly has the potential for both air and water pollution, be permitted? What role will NPDES permitting play?

Effluent Guidelines. What effluent guidelines will be imposed on these industries? For example, the EPA Effluent Guidelines and Standards for fertilizer manufacturing are what DER will most likely use. However, a fertilizer shipping facility is really not a mine or a processor. Should the 35 ppm total phosphate daily average limitation guideline apply to the fertilizer shipper? What nitrogen limitation can be applied, since there is none listed for fertilizer manufacturing? In fact, why isn't there a nitrogen limitation?

This paper is an abbreviated form of the actual East Bay Study Report which is available from the Environmental Protection Commission, 1900 9th Avenue, Tampa, FL 33605 (813/272-5960).

ADDRESS: Hillsborough County Environmental Protection Commission, 1900 9th Avenue, Tampa, FL 33605.

WATER USE IN THE FLORIDA PHOSPHATE INDUSTRY

G. A. Weinman

INTRODUCTION

Benjamin Franklin said, "When the well's dry they know the worth of water." The phosphate industry knew the worth of water long before the well went dry. We knew it because we are extensive water users.

The word users is emphasized to call attention to the fact that this industry is a large water user, rather than consumer. Industrywide, over 90% of the water used in phosphate processing is recycled. Less than 10% of the water used to produce phosphate is withdrawn from the aquifer. First, let's explain why and how we use water. The most economical and efficient method of transporting and processing phosphate ore has been exhaustively studied and evaluated. Over the years, many innovations have been proposed and tried and have included a variety of methods. Among the transportation methods are truck, rail, and conveyor haulage. Processing methods have included direct acidulation of ore and air separation of fine particles. The methods that overwhelmingly remain as the most economical and efficient use water as the transportation and processing medium.

USE OF WATER IN PHOSPHATE PROCESSING

Water dependency begins in the mining field operations. Large electric draglines remove the overburden and place the ore (called matrix by the miners) into a sump or pit. This pit is constructed as a bermed depression in the ground by track type tractors. There the ore is reduced to a slurry by high pressure water jets or "guns" operating in excess of 200 psi and supplying from 9,000 to 10,000 gpm of recycled water to the slurry. The slurry is picked up by large centrifugal pumps and pumped through steel pipelines to the plant.

At the plant, the ore slurry is processed sequentially in two major sections. These consist of a washer and a flotation plant. Both of these areas rely heavily on water for treatment of the ore. In the washer, the slurry is subjected to a series of attrition machinery called log washers (from which the plant gets its name) and screens, and is processed by cleaning the ore with water to remove the clay. A phosphate pebble product is recovered by mechanically separating the coarser phosphate rock particles from the clay and other fine-grained material called feed. The clays are separated by hydrocyclones and transported to settling impoundments as a slurry. In the impoundments the clay settles and clear water is decanted from the pond and returned to the plant for reuse.

The fine-grained feeds are processed by froth flotation. This beneficiation takes place in a water medium where the small phosphate particles are separated from the gangue. A fine-grained phosphate product called concentrates is produced at this stage. The gangue or mill tailings is pumped as a slurry back to the excavated mine cuts. The tailings are used as reclamation fill to restore the mined lands to or near original grade. The tailings water is recycled back to the washer for reuse.

CONSERVATION AND CONSUMPTION

The Florida phosphate industry is a leader in the field of water conservation and management. It is the goal of every phosphate company to reduce fresh water pumping because it is not only environmentally preferred but also less costly. In the early 1970s, encouraged by the directives of the water management districts and the expense of pumping water from the aquifer, companies undertook major water reuse and conservation strategies to reduce pumping of water from the aquifer. The success of these efforts has been impressive. In 1970, 3,475 gallons of "new" water were required by the phosphate industry to process each ton of phosphate rock product.

Over the intervening years, state-of-the-art technology in conservation methods has resulted in significant reductions in consumption. In fact, according to figures published by the Southwest Florida Water Management District in 1988, only 1,183 gallons of water from the aquifer per ton of product was needed (Figure 1). This is a reduction in water consumption of 53% since 1970. During this period of time an increase in production of phosphate rock of 35% has been realized, yielding an overall reduction of 66% per ton of rock.

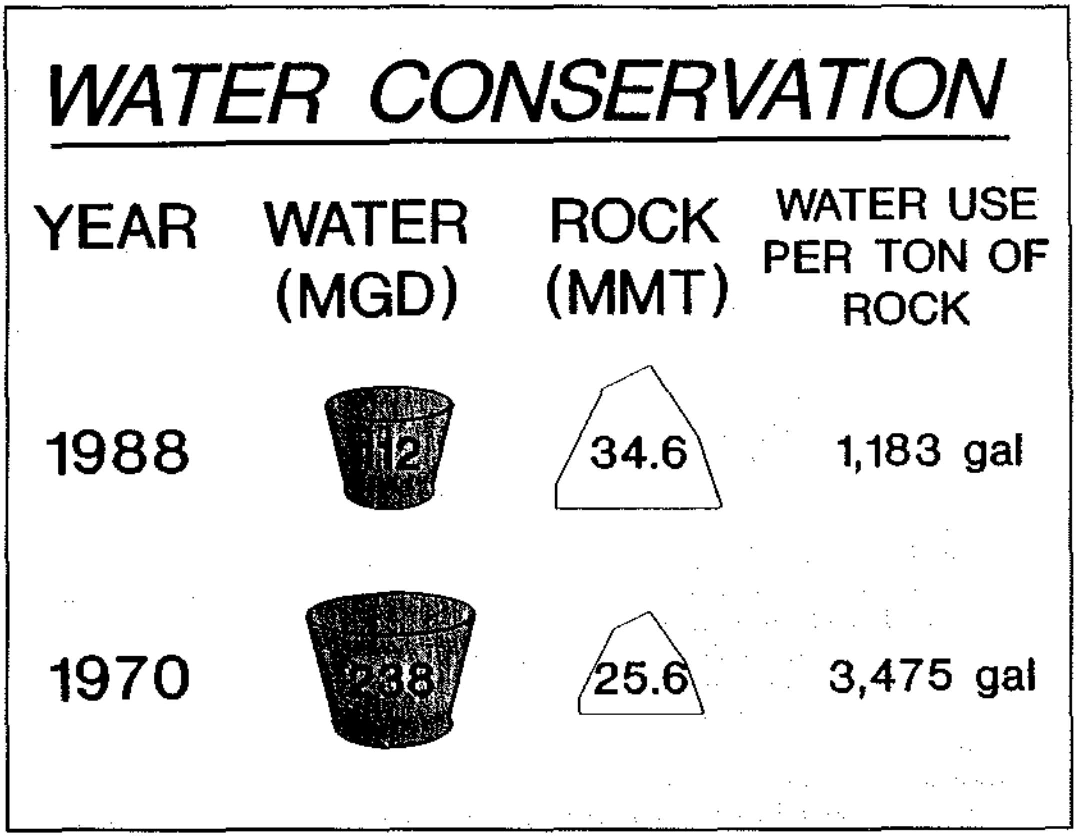

Figure 1.

The methods used to achieve this remarkable record have consisted of a variety of techniques generally evolving around the concept of recycling used water. Reuse is accomplished through the utilization of water containment areas which occupy company lands. These reservoirs, canals, and clay settling ponds receive water after use in mining and beneficiation. The water is stored and clarified for reuse again and again. It has been said that the industry uses its water until we wear it out. These containments also capture and store surface water from rainfall. This minimizes discharge into other water bodies and reduces the need for pumping. Storing water allows the industry to reduce pumping during the seasonal fluctuations that occur in Florida in the fall and winter seasons.

The phosphate industry has been required to meter all water pumped from the aquifer since January 1, 1975. Totalizing meters on all wells are read monthly and consumptive reports are submitted to the water management districts on a monthly basis. This assures an accurate and current tabulation of water use. Pumping data, along with discharge volumes from state permitted industrial wastewater discharge points and National Pollution Discharge Elimination System permit points, allow a reasonably accurate water balance for each mining and processing location.

The use of phosphate wetlands and containment areas to recycle municipal wastewater is also a current practice where practical. This provides for further treatment of municipal wastewater, improved water quality, and reuse or recharge of water that otherwise would be discharged.

The industry has further reduced fresh water demand by converting the flotation process to recycled water. The flotation area of the beneficiation plant utilized deep well water for both stages of the double flotation process for recovering fine phosphate. Research work on the metallurgy of the flotation process has allowed the first flotation stage, or the "rougher float" as it is called in the industry, to use recycled water instead of new water. The rougher concentrate flotation process is one of the larger water users in the beneficiation process. Research work continues on the second stage of flotation or the "cleaner circuit" to also change it to recycled water.

Other water conservation measures taken by the phosphate industry includes the use of recycled water to seal packing glands on the many centrifugal pumps utilized in the process, and the use of hydrothickners to provide a faster return of recycled water to the plant area. The result of this extensive water conservation effort by the phosphate industry has been a dramatic decrease in water consumption. The 53% reduction in water withdrawn from the aquifer by the industry has played a significant part in maintaining a favorable potentiometric surface in the Floridan aquifer in the phosphate region. It has also offset the increased consumption by other users. This is evident from a graph recently published in the Tampa Tribune and based on information derived from the water management district. The reduction in water consumed by industry from 1970 to 1988 is striking and was due primarily to the phosphate industry. During this 18-year period, public water supply demand rose about 230% (Figure 2). Agricultural use had a modest increase. These were both about offset by the reduction in water consumption by phosphate.

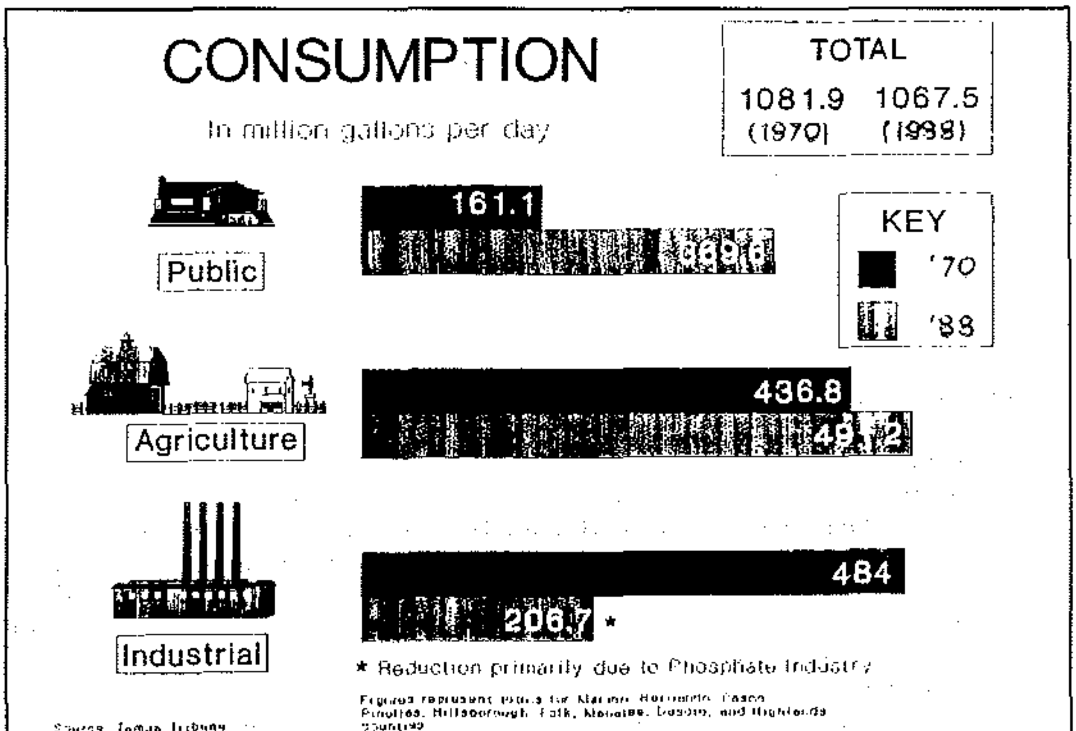

Figure 2.

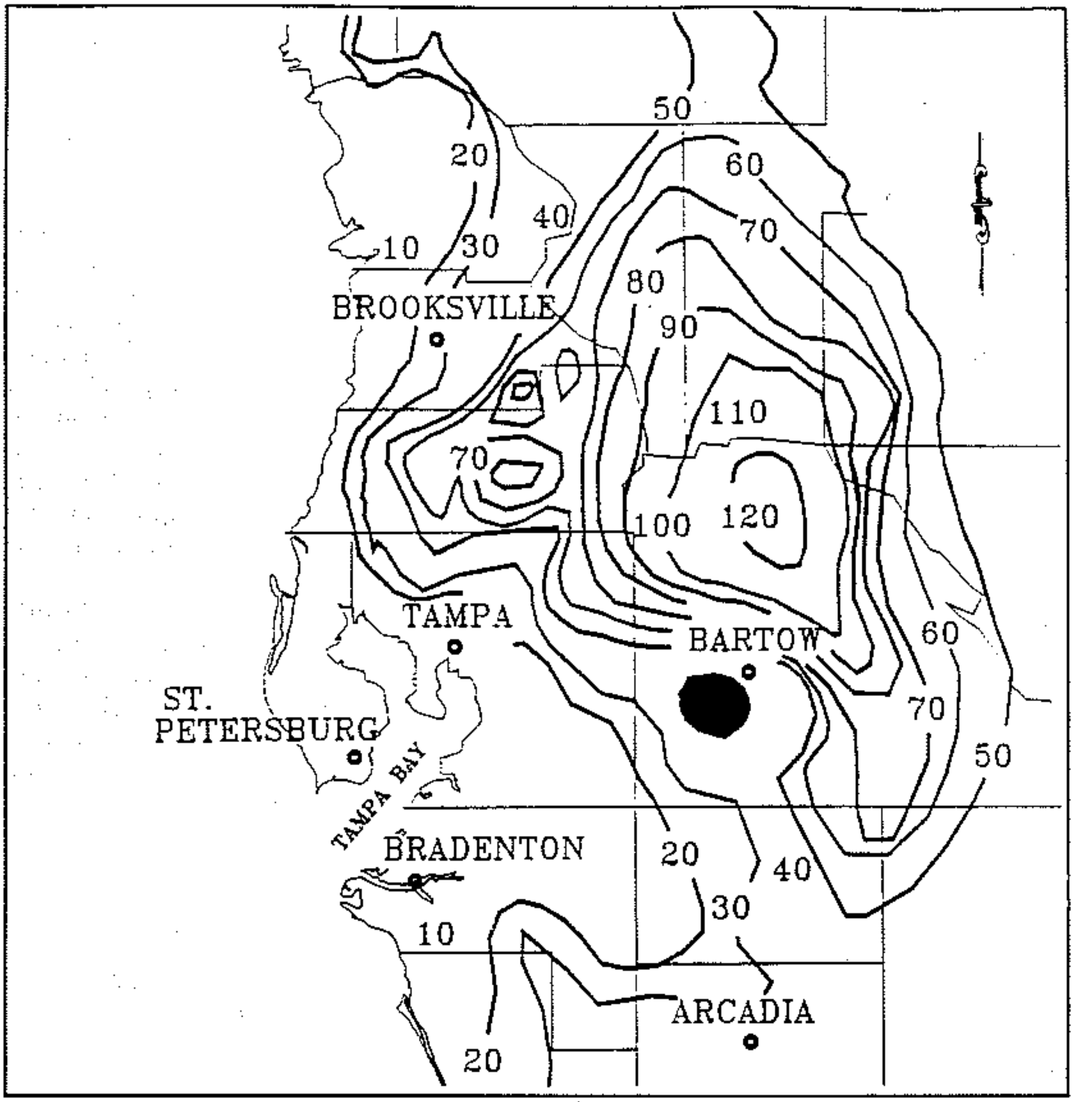

Figure 3. Potentiometric surface of Floridan aquifer (Southwest Florida Water Management District 1974 data).

The decrease in water consumption in the central Florida phosphate region has produced a subsequent increase or rise in the potentiometric surface of the Floridan aquifer in our area. In 1974, the potentiometric elevation of the aquifer, in an area centered generally southwest of Bartow, was less than 20′ above mean sea level according to studies published by the U.S. Geological Survey and the Southwest Florida Water Management District (Figure 3). This area was commonly referred to as the "red hole" by agency personnel. Industry water conservation efforts and reduced pumping have resulted in a 30′ rebound of the potentiometric elevation to about 50′ above mean sea level by 1989. This rebound occurred despite increased consumption by other users in the area. The rebound in the phosphate area coupled with subsequent increased demand in the coastal areas has caused a shift in the location of the now infamous "red hole". As shown in a recent map published in the Tampa Tribune (Figure 4), it is located in the southwest portion of the southern basin of the Southwest Florida Water Management District. It occupies portions of Hillsborough, Manatee and Sarasota Counties. Drawdown in this area has reduced elevations of the potentiometric surface in some areas to greater than 20′ below mean sea level.

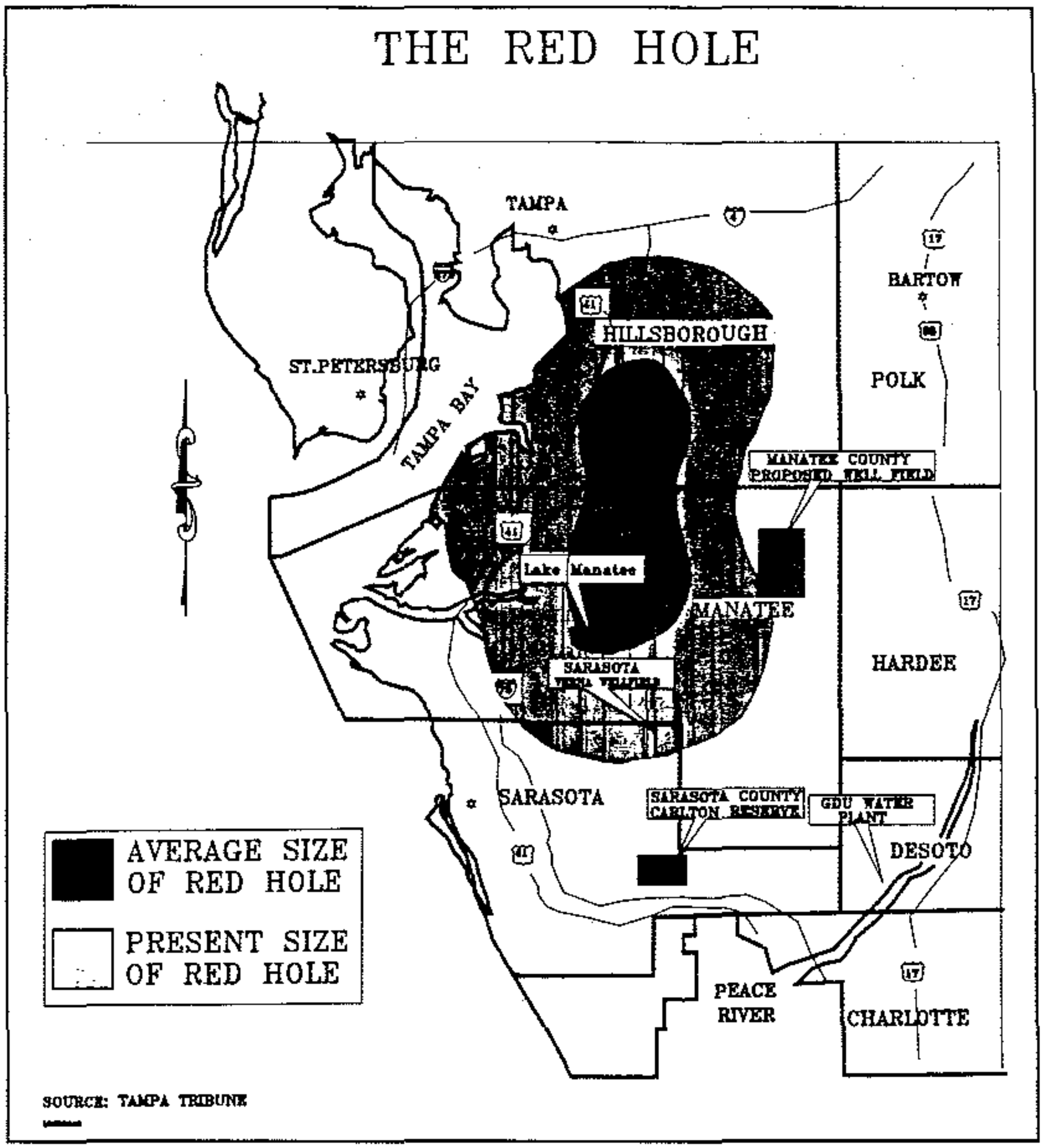

Figure 4.

Along with pumping, another major factor resulting in lower aquifer levels is a reduction in the average amount of rainfall received in the district. The deficit of rainfall has varied over the district and has reached a deficit high of 170" in the Bartow area (the phosphate district) since 1960. This is equivalent to approximately three years of rain at an annual average rainfall of 52". The impact of this lack of water on the aquifer is obvious.

The future water needs of the phosphate industry will vary according to production, which in turn is a function of domestic and world market demand. The Central Florida Regional Planning Council, under a grant from the Florida Phosphate Institute, has undertaken a study to identify future land use and mine-out estimates. This information is planned to be used to project future water demands of the industry using the most recent gallons per ton data. Preliminary projections by the phosphate industry to the year 2020 estimate water consumption may peak around 1996 at 146 MGD and then decline until the year 2000. It is personally believed that water consumption will level out around the year 2000 at approximately 110 MGD, corresponding to an annual production of 34 MMTPY. This rate will extend well beyond the year 2020.

The Florida phosphate industry has proven its commitment to Florida's water supply through its track record in water reuse. Today, as Florida plans for the future, the industry is working cooperatively with the water management districts to determine future water use needs by the industry. It is the intent of the phosphate industry to meet these needs in the most environmentally sound, economically feasible, and technically efficient manner to protect and preserve the available water resource. We enthusiastically join with others to assure a continued supply of clean potable water in areas where needed.

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A REVIEW OF HABITAT RESTORATION FOR TAMPA BAY

B. F. Henningsen
R. L. Whitman, Jr.

ABSTRACT

Previous studies have documented that since the 1800s, the Tampa Bay estuary has lost a minimum of 4423 ha of intertidal vegetated wetlands and 25,220 ha of submerged vegetated wetlands. Since 1971, wetland enhancement and restoration projects have begun the process of improving or replacing damaged/lost intertidal vegetated habitats. In addition, since 1978 wetlands damaged or lost because of development are being enhanced and/or replaced via mitigation projects as mandated by local, state, and federal permitting agencies. To assess trends in habitat losses versus restoration, summary data for Hillsborough, Pinellas, and Manatee Counties was procured by personal interviews, literature review, and research of permitting files of the following local, state, and federal agencies: Environmental Protection Commission of Hillsborough County; Department of Environmental Management of Pinellas County; Florida Department of Environmental Regulation (FDER); Florida Department of Natural Resources (FDNR); Southwest Florida Water Management District (SWFWMD); and U.S. Army Corps of Engineers.

Habitats typical of enhancement/restoration/mitigation include low and high intertidal salt marshes, mangrove forests, shallow water and tidal creek habitats, seagrass meadows, and uplands/hammocks. Although progressive permitting is trending toward restoration of wetland acreage in excess of that destroyed, for the period of 1978-90 Tampa Bay has no apparent net gain of wetlands due to mitigation projects. Mitigation projects for the tri-county area surrounding Tampa Bay total 65.39 ha: Pinellas — 33 sites (44.78 ha); Hillsborough — 41 sites (17.51 ha); Manatee — 2 sites (3.1 ha); mitigation projects ranged in size from 0.0039-15.75 ha, the average size being 0.98 ha. Unlike mitigation projects, habitat enhancement/restoration projects are beginning to offset habitat losses. Seagrass restoration efforts have resulted in 0.46 ha being replaced throughout county waters: Pinellas — five sites (0.32 ha); Hillsborough — 11 sites (0.1 ha); Manatee — two sites (0.04 ha). Intertidal vegetated habitats have proven more successful than seagrasses; acreages provided here represent maximal areas enhanced/restored by projects (adjustments incorporated if project success known). For the period 1971-90, 37.71 ha of intertidal vegetated and/or shallow water habitats have been enhanced/restored at 52 sites for the counties of Pinellas (16 sites, 15.85 ha), Hillsborough (25 sites, 20.46 ha), and Manatee (11 sites, 1.4 ha); project sizes ranged from 0.00081 ha to 5.7 ha, the average size being 0.77 ha. Accordingly, annual habitat additions during 1971-90 average 1.89 ha/yr. For intertidal/shallow water habitats, 75.6% (28.5 ha) of the total enhanced/restored acreage occurred during 1986-90.

The increase in number and acreage of enhancement/restoration projects is due primarily to project funding and implementation by the Surface Water Improvement and Management (SWIM) Program (SWFWMD); the Pollution Recovery Trust Fund (FDER); and the Marine Habitat Research and Restoration Program (FDNR). Between 1971-90, original emergent wetland losses of 43.99% (4423 ha) of the bay's original 10,053 ha have been reduced 0.38% (4385 ha or 43.61% decline). Project success has been variable, typically most dependent on project design, construction, planting methods and/or plant materials, acts of God, and human disturbance. The restoration of emergent vegetated habitats of Tampa Bay is occurring at a slow but accelerating rate. Seven needs must be addressed to help ensure the continued success of the rehabilitation of habitats of Tampa Bay:

1. Permanent and greater funding sources for enhancement/restoration projects;
2. Assurance of success of mitigation projects, coupled with compensation in excess of wetland impacts;
3. Availability of sites, particularly for large scale habitat enhancement/restoration;
4. Basic research examining community development and habitat functions (i.e., evaluating "success" of projects);
5. Improvements in project design and construction techniques, providing habitat mosaics inclusive of transitional and upland habitats;
6. Streamlining of permitting for enhancement/restoration projects;
7. Enlightenment of the public and public officials.

Project listings and locations are available from the SWIM Program of SWFWMD; future publication of data summaries is anticipated.

ADDRESSES: (B.F.H.) Southwest Florida Water Management District, Surface Water Improvement and Management Program, 7601 Highway 301 North, Tampa, FL 33637; (R.L.W.) Proctor & Redfern, Inc., Post Office Box 82066, Tampa, FL 33682.

FLORIDA'S MARINE STOCKING POLICY: MANAGEMENT CONCERNS AND ASSESSMENT CRITERIA

S. A. Willis
D. E. Roberts, Jr.

ABSTRACT

The Florida Marine Research Institute Stock Enhancement Research Facility has been fully operational since 1988. The goal of enhancement efforts is to restore a severely depleted or extirpated stock so that natural reproduction and recruitment can successfully occur. Interest in enhancement of marine fish stocks by release of hatchery-produced fish is at an all-time high. However, there is a paucity of scientific information concerning many aspects of enhancement. To approach stock enhancement in a meaningful manner and prior to initiation of fish releases, the Florida Marine Research Institute solicited scientific opinions from experts in the fields of population genetics, fish disease, and fish and hatchery management. A draft policy was formulated that identifies permitting procedures and requirements for collection of broodstock. The policy also delineates genetic, health certification, disease analysis, and mark/recapture procedures for fish released into the public marine waters of the state.

ADDRESS: Florida Marine Research Institute, 100 Eighth Avenue Southeast, St. Petersburg, FL 33701.

MARINE FINFISH STOCK ENHANCEMENT IN FLORIDA: AN INTEGRATED, MULTIDISCIPLINARY RESEARCH PROGRAM

D. E. Roberts, Jr.
W. G. Halstead
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ABSTRACT

In an effort to build an unbiased scientific database, the Florida Marine Research Institute (FMRI) developed an integrated, multidisciplinary, marine finfish stock enhancement research program, centered on Tampa Bay. The goal was to determine experimentally and to validate scientifically the cost/benefit of marine fisheries enhancement as a potential fisheries management protocol. Principal species studied are red drum, *Sciaenops ocellatus*, and snook, *Centropomus undecimalis*. The Stock Enhancement Research Facility was constructed during 1986 and 1987 to develop methods for mark/recapture, fish culture, fish production, and enhancement evaluation. The facility is located on a 22.26-ha site in Manatee County at Port Manatee. Pilot production consisted of twelve 0.38-ha earthen ponds. Eight 0.1-ha research ponds were constructed in 1990 to develop propagation methods, determine optimum culture parameters for larval fish, and initiate habitat restoration studies. With the passage of the Saltwater Fishing License Bill in 1989, the research program was expanded and regionalized. Effectiveness of fisheries restoration is being studied in the watersheds of Tampa Bay, Charlotte Harbor, Gordon River, Indian River, and Biscayne Bay.

Since actual research began in April 1988, over 40 million snook eggs and 175 million red drum eggs have been produced. Over 15,000 Phase I red drum (45 days old, 25-40 mm TL) were stocked into Spruce Creek, Volusia County, in 1988. During 1989, red drum fingerlings were released on both coasts of the state. In April and June, 4,360 Phase I and 123 Phase II red drum fingerlings, marked with binary coded wire tags, were released in Turnbull Creek, Volusia County. In June, 50,971 Phase I red drum fingerlings, marked with fluorescent pigment, were released in Redland Canal and Turnbull Creek, Volusia County. Also in June, 52,217 Phase I fingerlings were released in four locations in Tampa Bay. From August to November 1989, 8,347 Phase II red drum marked with either binary-coded wire tags or internal anchor tags were released in Redland Canal, Spruce Creek, and Murray Creek, Volusia County. In December, 4,332 Phase I red drum fingerlings marked with fluorescent pigment were released in Tampa Bay. In 1990, 6,572 Phase I and 64,974 Phase II red drum fingerlings were stocked by FMRI. In January, 2,572 fluorescent pigment-marked fish were released in Volusia County. In February, 21,051 Phase II binary-coded, wire-tagged fingerlings were released. Two thousand five of these fish were stocked into the Manatee River; 11,624 were stocked in Gordon Pass in Collier County, and 7,422 were released in Volusia County. In April, another 4,000 fluorescent-pigment-marked fish were released in Volusia County. During June and July, 43,923 Phase II fingerlings were released in Volusia County. All but fifteen of these fish were marked with binary-coded wire tags. The remaining fifteen were marked with internal anchor tags. Five thousand Phase II red drum fingerlings tagged with coded wire tags were released in Biscayne Bay in spring 1990. Seventeen hundred Phase II red drum fingerlings double-tagged with coded wire tags and internal anchor tags were released in fall 1990. Both releases were made north of Rickenbacker Causeway. Thirty-six tag returns were recorded from the Indian River watershed in Volusia County. Mean size at capture was 228 mm TL. Mean distance traveled was 0.77 km, and mean time of freedom before initial capture was 138.7 days. Mean daily growth

was 0.89 mm/day. Short-term survival experiments, predator/prey evaluations, and short-term movement patterns were reviewed. Project goals, protocols, organization, policies, and impact were discussed.

ADDRESS: Florida Marine Research Institute, 100 Eighth Avenue Southeast, St. Petersburg, FL 33701.

HABITAT'S CONTRIBUTION TO COMMERCIAL SHRIMP CATCH IN TAMPA BAY: THE MARGINAL PRODUCTIVITY APPROACH

D. Fuguitt

ABSTRACT

This paper demonstrates a methodological approach for valuing habitat, by estimating the marginal contribution of Tampa Bay habitat to commercial shrimp catch. A time-series regression analysis is performed with the Lynne production function, which recognizes that commercial catch is a function of several factors, including but not limited to habitat dimensions and fishermen's catch effort. Since annual data measuring Tampa Bay habitat do not exist, this study creates several habitat indices using existing data for seagrass, mangrove and tidal marsh acreages in Tampa Bay. NMFS data (unpublished) for shrimp catch and trips were obtained for Tampa Bay east of the Skyway Bridge, 1965-89. The relationship between shrimp catch and trips is unexpected, exhibiting increasing returns for trips during 1974-76. Evidence suggests the extra high catches were related to the spring 1974 red tide. A dummy variable representing the red tide effect is incorporated in the analysis, permitting separate calculation of the marginal productivity of habitat during years with and without the red tide effect. Estimation of the regression function for eleven different habitat indices showed remarkable stability. Annual marginal productivities (during years without the red tide effect) indicate an incremental acre of habitat makes a positive, though small, contribution to shrimp catch. Moreover, the marginal productivities are sensitive to how habitat is defined. The inclusion of seagrass, mangroves and tidal marsh as habitat results in smaller marginal productivity estimates (0.14 to 0.18 pounds of shrimp for an incremental acre) than if only seagrass (marginal productivity, 0.28 to 0.46), mangroves (0.39) or marsh (2.44) alone are considered. These results should not be interpreted to say tidal marsh is more beneficial (biologically) to shrimp than seagrass or mangroves. Rather, the results are consistent with the law of diminishing marginal returns. This study does not lead to specific management decisions concerning Tampa Bay habitat conservation, but rather demonstrates the methodology required to estimate the marginal productivity of bay habitat for commercial species.

INTRODUCTION

In recent decades, development in the Tampa Bay area has been closely associated with the decline of vital estuarine habitat (seagrass, mangroves and tidal marsh) needed to support marine and seabird populations. Rapid coastal development during the 1950s and 1960s resulted in massive destruction of bay habitat, especially seagrass (Taylor and Saloman 1968, Lewis 1977). Efforts since the late 1960s sought to prohibit large-scale dredge and fill projects and to control industrial and municipal waste discharges. However, Tampa Bay's habitat has still declined, though at a slower rate, as smaller-scale development projects and other activities—water pollution, high-speed boating, etc.—continue (Lewis 1986).

Tampa Bay habitat can be conserved as a natural resource to support marine populations; or, habitat can continue to be destroyed for coastal development purposes. Thus, an important estuarine management issue today is to determine the optimal quantity of habitat for preservation. In order to preserve habitat benefits, costs in the form of foregone coastal development, pollution controls, restricted recreational activities and/or habitat restoration will be incurred. Economic theory defines the optimum as occurring where the marginal benefits and costs to society are equal. For incremental units of habitat, if the marginal benefits exceed the marginal costs of conservation, the habitat should be preserved. For a marginal amount of habitat beyond the optimum, preservation costs are sufficiently high and habitat benefits low to warrant its destruction.

While preservation costs can often be measured using market prices, habitat's natural benefits are not so easily estimated. A thorough economic valuation of habitat must recognize its multiple social benefits, i.e., habitat simultaneously supports commercial and recreational fishing, provides existence value (the value received simply knowing habitat exists) and option value (the value of preserving habitat for future use or benefits not yet known) to non-users, and supports endangered species valued for their genetic diversity and aesthetics (Thibodeau and Ostro 1981, Farber and Costanza 1987, Peace and Turner 1990). Ideally, the marginal contribution of Tampa Bay habitat to each commercial, recreational and endangered species, as well as society's willingness to pay both for these marginal monetary contributions and for existence value and future options, could be estimated.

Limited data presently preclude such complete valuation for Tampa Bay habitat. The Tampa Bay species for which the most data are available are commercial (food) shrimp. The intent of this research is to demonstrate a methodological approach for valuing habitat by estimating the marginal contribution of Tampa Bay habitat to commercial shrimp catch. (The existence of a biological relationship between estuarine habitat and penaeid shrimp during the early months of the life cycle has been identified by several studies [Turner 1977, Boesch and Turner 1984].)

Marginal Productivity Analysis of Habitat

In recent years, economists have applied the Marginal Productivity approach to estimate the economic value of incremental acres of wetlands or seagrass (Batie and Wilson 1978, Kahn and Kemp 1985, Farber and Costanza 1987, Bell 1989). This approach recognizes that commercial catch is a function of several factors, including but not limited to habitat dimensions, fishermen's catch effort and fish stock size. It seeks to separate the contribution (marginal productivity) of the habitat from these other factors. The habitat's contribution can then be valued.

Lynne et al. (1981), hypothesizing that fish population size is a function of past catch, derived the following (the Lynne production function):

$$C_t = b_0 + b_1 \ln HAB_{t-1} {*} E_t + b_2 \ln HAB_{t-1} {*} E_t^2 + b_3 C_{t-1} \quad (1)$$

Annual data are required for three variables: catch (C), fishing effort (E), and habitat (HAB). Shrimp catch in year t is assumed to be a logarithmic function of the previous year's habitat times a quadratic specification of fishing effort. The inclusion of lagged catch as a determinant of catch in year t, while often accepted for many commercial species, is questioned for shrimp due to their fecundity and short life cycle (Bell 1989). Once estimated, the coefficients for $\ln HAB_{t-1} {*} E_t$ and $\ln HAB_{t-1} {*} E_t^2$ are substituted into a second equation (the production function's first derivative) to calculate habitat marginal productivity.

Estimation of this regression is not straightforward, as relevant data for Tampa Bay are limited. Annual time-series data measuring bay habitat do not exist. Moreover, the relative importance of different habitat qualities is not fully understood. While ideal data would detail various habitat dimensions, the present economic analysis creates several habitat indices using existing data: seagrass, mangrove and tidal marsh acreages in Tampa Bay.

HABITAT INDICES

Table 1 shows five sets of Tampa Bay seagrass acreage estimates for scattered years. In general, considerable caution must be prescribed when interpreting any of these estimates, as their accuracy can be affected by many factors, including flight altitude, aerial photo scale and resolution, time of year for photo and photointerpretation (Harris et al. 1983). Clearly, Tampa Bay seagrass data are both limited and conflicting.

Four indices of annual seagrass acreages were constructed based on two considerations. First, the acreages reported by Mangrove Systems and USFWS (for the 19 USGS quads) were preferred as base data sets, for their boundaries most closely approximate those defined by Lewis and Whitman (1985) for Tampa Bay. (DNR's seagrass acreages are viewed here as overestimates.) Second, historical reports suggest a variable trend in seagrass acreage since the 1940s. Thus, Palmer and McClelland's dramatic early decline and USFWS' more gradual decline (made bigger by using their trend for 21 USGS quads) were each imposed on Mangrove Systems' estimates to create two indices, MANPMC and MANUSF. Palmer and McClelland have been criticized because of their use of aerial photography with 1:80,000 scale (TBRPC 1986b). Yet, as Palmer and McClelland note (1988), their 1983 estimate compares well with Mangrove Systems' 1981 estimate, suggesting a basis for some confidence in their estimates. For the USFWS (19 Quads) base data, simple linear interpolation and imposition of the Palmer and McClelland trend generated the indices, USFLIN and USFPMC, respectively (Figure 1). Indices were calculated as follows: 1) for the trend data set, find the total change in acreage between early and late common years, then estimate the percentage of total change occurring between intermittent (observed) years; and 2) impose on the base data set the same percentage changes for intermittent years.

Table 1. Tampa Bay seagrass acreage estimates.

OBS. YEAR	MANGROVE SYSTEMS[a]	USFWS[b] 19 USGS quads	USFWS[c] 21 USGS quads	DNR[d]	PALMER & MCCLELLAND FDER[e]
c.1876	76,495.90				
c.1940					28,171
1943	47,896.62				
c.1952		36,916	40,324	41,657.91	
c.1963					14,030
1972		25,104	25,572		
1973					15,170
1979					13,961
1981	14,202.50				
1982		22,128	22,526	23,057.40	
1983					13,749
1984	14,300.10				
Percent change in acreage	-81% 1876-1981 -70% 1943-1981	-40% 1952-1982	-44% 1952-1982	-45% 1952-1982	-51% 1940-1983

[a]for Lewis and Whitman (1985) Tampa Bay boundaries (Lewis et al. 1985; Bauer, Lewis Environmental Services, pers. comm., 1990).
[b]includes a portion of Sarasota Bay (Bradenton quad) and omits north Boca Ciega Bay (USFWS 1986).
[c]for 19 USGS quads plus north Boca Ciega Bay and St. Joseph Sound, two areas reportedly characterized by extra heavy seagrass losses (Fehring 1986).
[d]for Lewis and Whitman boundaries; based on USFWS data converted to rastor data using a 30 meter square grid cell (McGarry, DNR, pers. comm., 1990).
[e]omits north Boca Ciega, Tampa Bay entrance, Manatee River as well as Terra Ceia and other small bays bordering Tampa Bay (Palmer and McClelland 1988).

Compared to seagrass, data are substantially more limited for mangrove and tidal marsh acreages in Tampa Bay. Available estimates are presented in Table 2. USFWS may underestimate the declining trend and, compared with Mangrove Systems, report high acreages; however, insufficient data precludes creating an index using Mangrove Systems' estimates. Thus, USFWS 19 quad estimates, with approximate Lewis and Whitman boundaries, are used here to generate indices. Figure 2 shows three indices constructed by linear interpolation for mangroves, marsh and mangroves/marsh combined.

Altogether, seven habitat indices were constructed. While alternative trends were imposed, all indices were projected from the 1940s/50s through 1989 via linear interpolation. Accordingly, these indices are presented as only preliminary indicators of possible annual seagrass, mangrove and marsh acreages. In future research, more sophisticated indices will be estimated using regression analysis with polynomial and spline functions to permit curvature in the trends. Also, the implied annual trend will be modeled from historical accounts of the causes (e.g., coastal development, dredge and fill, water pollution, etc.) of Tampa Bay habitat declines. This may be especially important for mangroves and tidal marsh, for which estimated acreage data are so scarce.

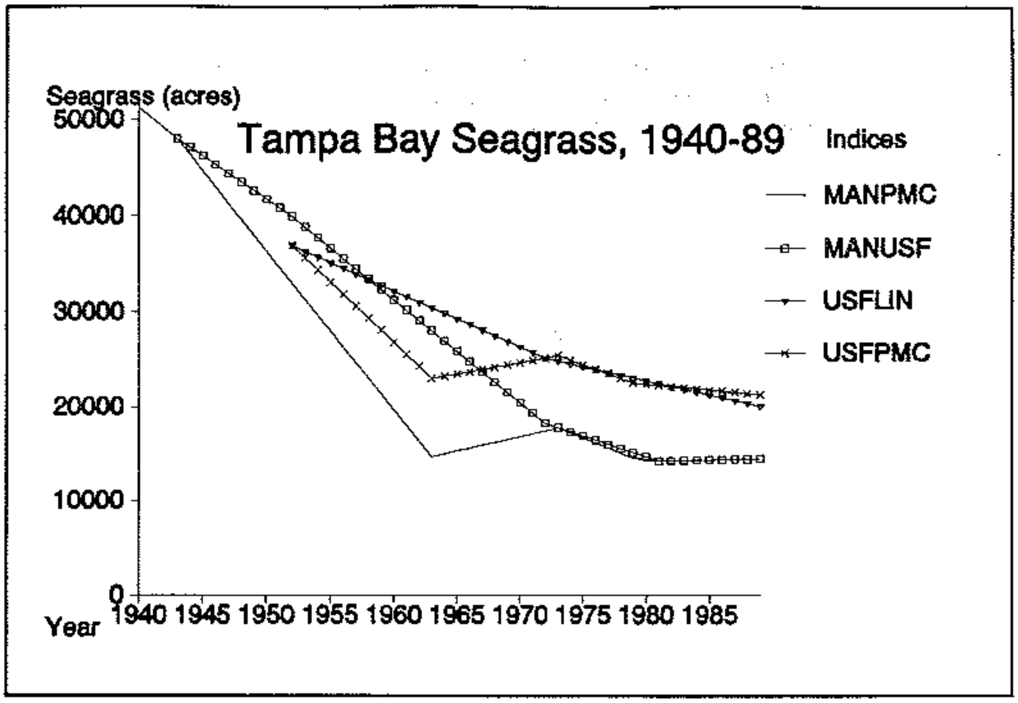

Figure 1.

Table 2. Tampa Bay mangroves and tidal marsh acreage.

OBS. YEAR	Mangroves and Tidal Marsh Combined: MANGROVE SYSTEMS[a]	MANGROVE SYSTEMS[b]	USFWS[c] 19 USGS quads	USFWS[d] 21 USGS quads
c. 1876	24,823.50			
c. 1952			22,205	23,317
1972			21,498	22,266
1976	13,907.10	17,696.30		
1982			20,735	21,268
Percent change	-44%		-7%	-9%
in acreage	1876-1976		1952-1982	1952-1982

	Mangroves: USFWS[c] 19 USGS quads	Mangroves: USFWS[d] 21 USGS quads	Tidal Marsh: USFWS[c] 19 USGS quads	Tidal Marsh: USFWS[d] 21 USGS quads
c. 1952	17,581	18,645	4,624	4,672
1972	17,899	18,656	3,599	3,610
1982	17,528	18,030	3,207	3,238
Percent change	-0.3%	-3%	-31%	-31%
in acreage	1952-1982	1952-1982	1952-1982	1952-1982

[a]for Lewis and Whitman's Tampa Bay boundaries (1985) excluding the Manatee River (Lewis 1977).
[b]for Lewis and Whitman's boundaries (including Manatee River) (Lewis 1977).
[c]includes a portion of Sarasota Bay (Bradenton quad) and omits north Boca Ciega Bay (USFWS 1986).
[d]for 19 USGS quads plus north Boca Ciega Bay and St. Joseph Sound (Fehring 1986).

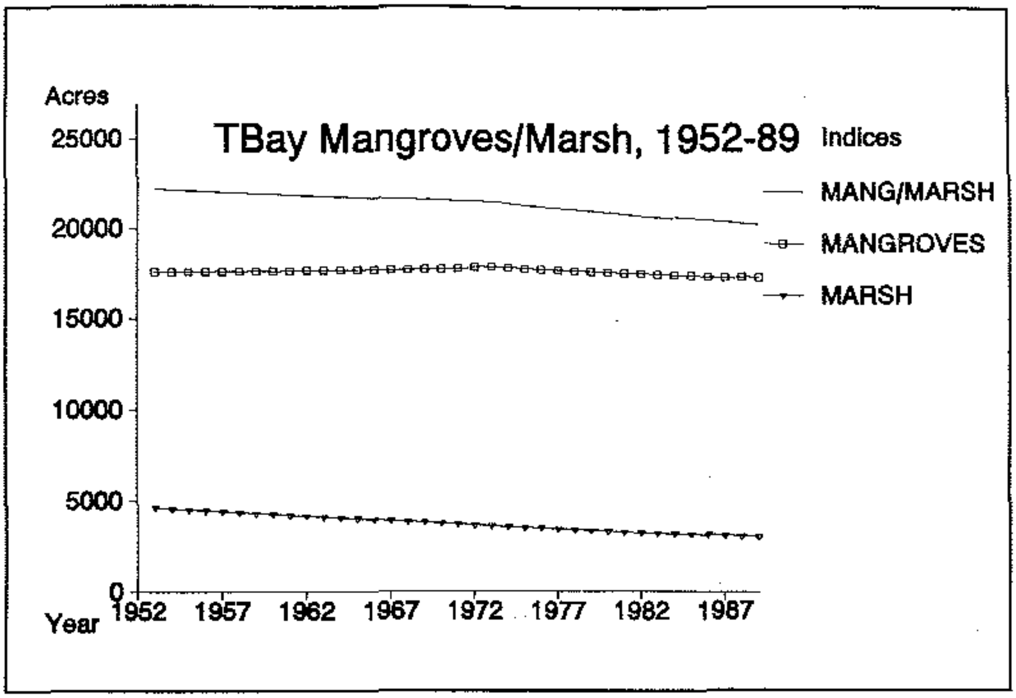

Figure 2.

Commercial Shrimp: Catch and Effort

For Tampa Bay east of the Skyway Bridge, unpublished annual data (1965-89) for shrimp catch, measured in heads-off pounds, and number of trips have been obtained (Ernie Snell, NMFS, pers. comm., 1990). Figure 3 presents a scatter plot showing the relationship between Tampa Bay shrimp catch and trips. The data indicate an unexpected cubic relationship, with first decreasing and then increasing returns as trips increase. Observations for three years, 1974-76, account for the increasing returns. Investigation of Tampa Bay history and interviews with local shrimpers suggest the extra high catches were related to the spring 1974 red tide. This is consistent with other west Florida shrimpers' reports of increased catches after red tides (St. Petersburg Times 1972, Kilbourne 1980). Tampa Bay shrimpers who remembered the extraordinary catches considered it plausible that the red tide had both an immediate effect, attracting shrimp to the area to feed on the dead fish, and a longer-term (one to two year) impact due to predators being killed. Scientific studies, although not investigating shrimp populations, have found west Florida red tides have impacted coral and beach communities for as long as one or two years (Huntley 1974, Smith 1975).

Since red tide entered Tampa Bay in 1963, 1971 and 1974, alternative dummy variables were created to represent various durations for the three red tides' effects. Possibilities included: red tide might have no impact or instead it might impact immediately (a few weeks or months), for an entire season (fall to spring) or over two shrimp populations (two fall-spring seasons). Only the 1974 red tide (with assumed effect during spring 1974-spring 1976) tested as having a statistically significant impact on shrimp catch. This might be explained by its longer duration (Habas and Gilbert 1975), or by the co-existence of other unidentified environmental factors in 1974.

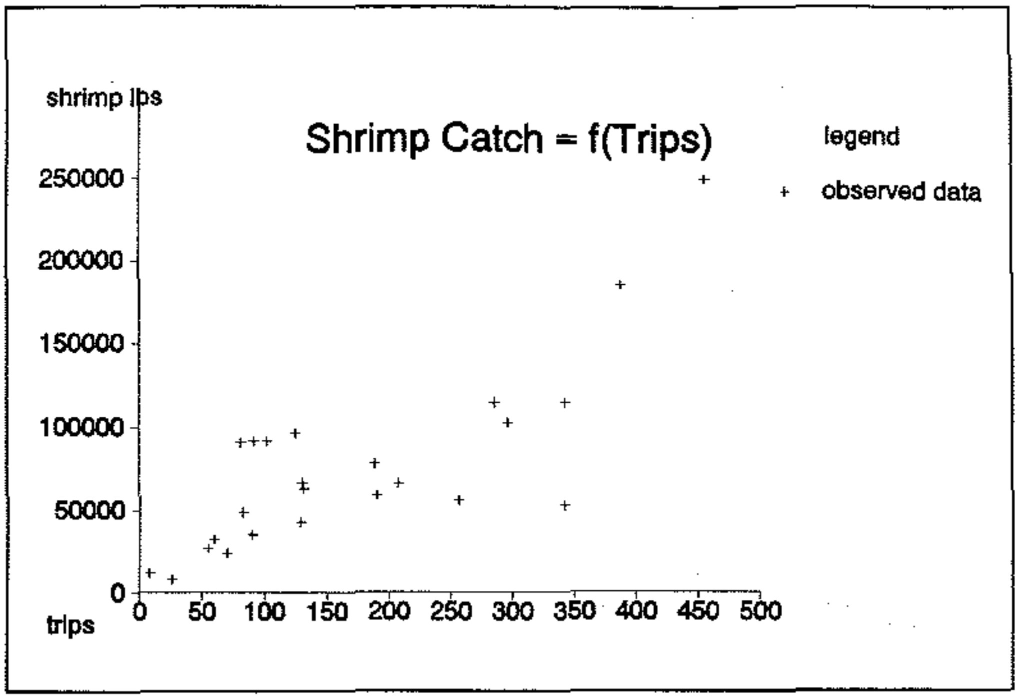

Figure 3.

MARGINAL PRODUCTIVITY CALCULATION

In order to estimate habitat's marginal contribution to shrimp catch in Tampa Bay, the Lynne production function was employed. Annual 1965-89 data were used for shrimp catch (C) and trips (E), while annual index estimates for 1964-88 gave lagged habitat (HAB_{t-1}). Besides the four seagrass and three mangroves/tidal marsh indices, four additional indices were created combining each seagrass index with mangroves and marsh for more comprehensive estimates of Tampa Bay habitat.

The production function (equation 1) was altered to incorporate the dummy variable (D) representing the red tide effect during 1974-76. For all eleven habitat indices, the best fitting regression function indicated that red tide had an interactive effect with both habitat and fishing effort:

$$(2)\quad C_t = b_0 + b_1 \ln HAB_{t-1} * E_t + b_2 \ln HAB_{t-1} * E_t^2 + b_3 \ln HAB_{t-1} * D_t + b_4 \ln HAB_{t-1} * E_t * D_t$$

Lagged catch was statistically insignificant in all specifications, as expected for shrimp, so it was dropped from the function.

Regression estimates for equation (2) are shown in Table 3 for each of the eleven habitat indices. The estimates show remarkable stability across the indices. The adjusted R^2s are high for all equations, and the Durbin-Watson d statistics provide no evidence of autocorrelation. In all cases, the t-ratios indicate b_0 is statistically insignificant, while the coefficients b_1, b_2, b_3 and b_4 are statistically significant at the .05 level. Concerning the intercept b_0, this is as expected; when there are no trips and habitat, then catch will be zero. The signs for the coefficients of $\ln HAB_{t-1} * E_t$ and $\ln HAB_{t-1} * E_t^2$ are consistent with economic theory's expectations of diminishing returns, indicating shrimp catch increases at a decreasing rate as trips or habitat increase (during years without red tide). The coefficients for $\ln HAB_{t-1} * D_t$ and $\ln HAB_{t-1} * E_t * D_t$ measure the differential impact of red tide. The positive coefficient for $\ln HAB_{t-1} * E_t * D_t$ is as expected, signifying that during red tide years, an increase in trips will cause catch to increase by $b_4 \ln Hab_{t-1}$ pounds more than during years without red tide. The estimated coefficient for $\ln HAB_{t-1} * D_t$ may seem surprising, as it implies that during years of red tide the intercept will be substantially less than without red tide. However, this has no economic meaning; $b_0 + b_3 \ln HAB_{t-1}$ simply indicates where the regression for red tide years crosses the y-axis, and this is well outside the observed range of estimates. More important is the combined effect of the two dummy variable terms, $b_3 \ln HAB_{t-1}{*}D_t + b_4 \ln HAB_{t-1}{*}E_t{*}D_t$, which explains the extraordinarily high catches during the years 1974-76.

Table 3. Annual catch of shrimp as a function of habitat, effort and red tide, Tampa Bay, 1965-89.

HABITAT INDICES	const.	lnHAB *E	lnHAB *E2	lnHAB *D	lnHAB *E*D	Adj. R2	D-W d	F
Seagrass								
MANPMC	2606	73.78	-0.159	-54129	173.64	0.832	1.811	30.74
	[.2]	[3.9]	[-2.9]	[-3.9]	[4.4]			
MANUSF	1056	74.93	-0.161	-54254	173.98	0.838	1.832	32.03
	[.08]	[4.0]	[-3.0]	[-4.0]	[4.5]			
USFLIN	2126	71.19	-0.153	-52142	167.48	0.833	1.809	30.98
	[.2]	[3.9]	[-2.9]	[-3.9]	[4.5]			
USFPMC	2759	70.60	-0.152	-51997	167.00	0.831	1.804	30.54
	[.2]	[3.8]	[-2.8]	[-3.9]	[4.4]			
Mangroves/Marsh								
MANG/MAR	2953	70.99	-0.153	-52552	169.05	0.830	1.798	30.37
	[.2]	[3.8]	[-2.8]	[-3.9]	[4.4]			
MANGROVES	3076	72.10	-0.156	-53469	172.04	0.830	1.796	30.29
	[.2]	[3.8]	[-2.8]	[-3.9]	[4.4]			
MARSH	2150	88.18	-0.190	-64565	207.33	0.833	1.809	30.96
	[.2]	[3.9]	[-2.9]	[-3.9]	[4.5]			
Combined Seagrass/Mangroves/Marsh								
MANPMC	2830	67.43	-0.145	-49758	159.89	0.831	1.803	30.51
	[.2]	[3.8]	[-2.8]	[-3.9]	[4.4]			
MANUSF	2139	67.94	-0.146	-49825	160.08	0.834	1.812	31.06
	[.2]	[3.9]	[-2.9]	[-3.9]	[4.5]			
USFLIN	2544	66.46	-0.143	-48950	157.35	0.832	1.803	30.67
	[.2]	[3.8]	[-2.9]	[-3.9]	[4.4]			
USFPMC	2870	66.18	-0.143	-48878	157.12	0.831	1.801	30.45
	[.2]	[3.8]	[-2.8]	[-3.9]	[4.4]			

t-ratios in brackets

During years without red tide, the marginal productivities (MP) of habitat and effort (trips) can be calculated using the following equations, respectively:

(3) $$MP_{HAB} = [b_1 - b_2 E_t]{*}(E_t / HAB_{t-1})$$

(4) $$MP_E = [b_1 - 2b_2 E_t]{*}\ln HAB_{t-1}$$

Substituting the regression coefficients for each of the eleven habitat indices into equations (3) and (4) yielded very consistent marginal productivity estimates. As an illustration, Figures 4 and 5 present marginal product curves for habitat and effort using the MANUSF seagrass index. Consistent with economic theory, MP_{HAB} is positive, but declines as acres of habitat increase, trips being held constant at the mean value. Thus, diminishing marginal returns exist to commercial shrimping in Tampa Bay. Similarly, the MP_E curve diminishes as trips increase, with acres of habitat held constant at the mean value. At high numbers of trips, however, the MP_E curve becomes negative, suggesting catch is beyond the maximum sustained yield given the mean acres of habitat.

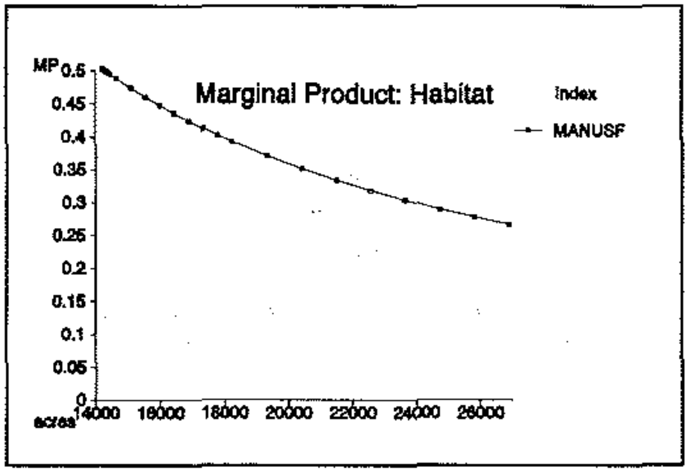

Figure 4.

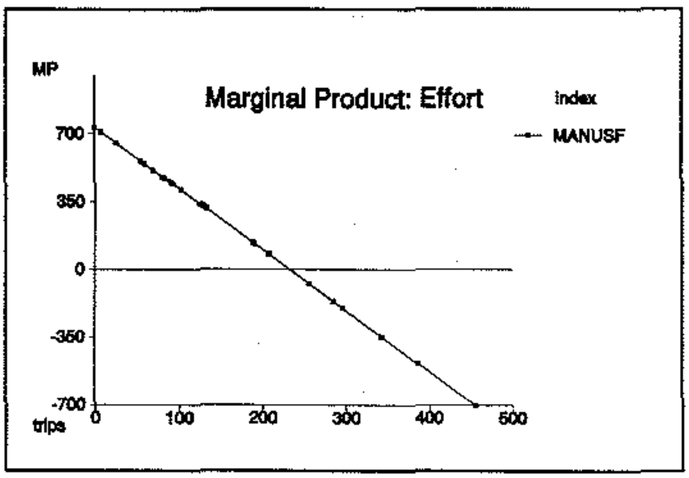

Figure 5.

The accepted practice in marginal analysis is to calculate the annual marginal productivities, equations (3) and (4), at the means of habitat and fishing effort (134.1 trips). Table 4 presents the annual marginal productivities computed for each habitat index and for effort, based on the 11 regressions. As can be seen in column 4, during years without red tide, the marginal productivity of trips was quite consistent for all habitat indices; an incremental trip generated approximately 300 pounds of shrimp, given the mean acres of habitat. For the habitat indices, the annual marginal productivities (column 3) indicate incremental acres of habitat make a positive contribution to shrimp catch. With the exception of tidal marsh, the marginal contribution ranged from 0.14 to 0.46 pounds of shrimp for an incremental acre of habitat annually. The variation in estimates is consistent with the law of diminishing marginal returns: the greater the mean quantity of habitat, the lower the estimated marginal productivity at that quantity. The marginal productivities are thus sensitive to how habitat is defined. If only seagrass is included as habitat, then an incremental acre will be more productive (0.28 to 0.46), as there are only 15-24,000 acres of seagrass on average. However, if mangroves and marsh are also included, then an incremental acre is less productive, simply because more acres of habitat are recognized. Given 36-45,000 acres of combined seagrass, mangroves and marsh, an incremental acre contributes only an estimated 0.14 to 0.18 shrimp pounds. In contrast, tidal marsh, with a small mean of 3,500 acres, yielded a substantially higher marginal productivity of 2.44. This should not be interpreted to say that tidal marsh habitat is more beneficial to shrimp (in a biological interactive way) than seagrass or mangroves, but rather, narrowly defined habitat will result in higher estimated marginal productivities.

Table 4. Annual marginal products of habitat and effort for commercial shrimp during years without red tide effect, Tampa Bay; 1965-1973, 1977-1989.

[1] HABITAT INDICES	[2] MEAN ACRES	[3] MP OF HABITAT (lbs shrimp per marginal acre)	[4] MP OF EFFORT (lbs shrimp per marginal trip)
<u>Seagrass</u>			
MANPMC	15,274	0.4607	300.38
MANUSF	17,972	0.3982	311.46
USFLIN	24,312	0.2792	303.59
USFPMC	23,057	0.2919	299.26
<u>Mangroves/Marsh</u>			
MANG/MAR	21,105	0.3206	297.89
MANGROVES	17,654	0.3893	297.08
MARSH	3,451	2.4369	303.41
Combined <u>Seagrass/Mangroves/Marsh</u>			
MANPMC	36,379	0.1767	298.77
MANUSF	39,077	0.1658	303.47
USFLIN	45,417	0.1395	300.66
USFPMC	44,162	0.1429	298.47

These marginal productivities are notably smaller than those estimated elsewhere in the literature. Bell (1989) reported the annual marginal productivity of west Florida salt marsh to be 5.68 pounds of shrimp, while Farber and Costanza [1987] calculated the marginal productivity of southern Louisiana's fresh and salt marsh to be 5.17 pounds of brown and white shrimp (3.04 pounds inshore). Part of the comparative smallness of the Tampa Bay estimates can be accounted for by the omission of shrimp caught west of the Skyway which benefited from Tampa Bay habitat when they were young. More importantly, this study's estimates suggest the bias imposed by how habitat is defined. For example, the exclusion of mangroves and seagrass from Bell's definition of west Florida habitat undoubtedly resulted in an overestimate of salt marsh marginal productivity.

Finally, marginal productivities for habitat and effort were calculated for the red tide effect years (1974-76) using the following equations:

(5) $$MP_{HAB} = -b_3/(HAB_{t-1}) + [b_1 + b_4 - b_2E_t]*(E_t/HAB_{t-1})$$

(6) $$MP_E = [b_1 + b_4 - 2*b_2TRIPS]*\ln HAB_{t-1}$$

Estimated for mean effort and habitat during those years, the marginal productivities ranged as follows: 0.37-0.45 for seagrass, mangroves and marsh combined, 0.73-1.10 for seagrass, 0.86 for marsh and mangroves combined, 1.05 for mangroves and 6.41 for marsh. As expected, these were higher than during years without the red tide effect, and again, these estimates illustrate the relationship between a more inclusive definition of habitat, with associated greater acreages, and lower marginal productivities.

This study's estimates understate the marginal contribution of Tampa Bay habitat to shrimp. Besides excluding shrimp caught after migration west of the Skyway, the NMFS data used here (as well as by Bell [1989] and Farber and Costanza [1987]) exclude both small shrimp boat and bait shrimp catches. Moreover, the nature of the data prohibits measurement of distinctive habitat qualities. The estimated marginal productivities of seagrass, mangroves and marsh combined treat each acre the same; they do not take into account the possibility of different contributions being made by each of the three habitats. (Unfortunately, the relative contributions could not be estimated by including three separate indices in a regression because of multicolinearity.)

CONCLUSION

A key issue for estuarine management is to determine the optimal quantity of habitat. Is the continued loss of small quantities of Tampa Bay habitat socially optimal? Or do the marginal benefits exceed the marginal costs of preserving (or restoring) habitat? In order to answer these questions, the hard-to-measure natural benefits provided by bay habitat must be estimated.

Several studies (Lewis 1977, TBRPC 1986a, Haddad 1987) imply, but do not statistically verify, that Tampa Bay habitat makes a positive contribution to commercial catches. This study takes a first, partial step to quantify the marginal contribution of Tampa Bay habitat, estimating a positive marginal productivity for shrimp catches. Appropriate management decisions concerning habitat conservation cannot be drawn based on this study's results; marginal productivities for other commercial, recreational and endangered species need to be estimated and then valued, capitalized into perpetuity. Summation of these marginal values will equal the marginal benefits of incremental units of habitat. The marginal benefits can then be compared with the more easily measured marginal costs of preservation to determine the optimal quantity of habitat. This study demonstrates the methodology which can be used to estimate the marginal productivity of Tampa Bay habitat for commercial species.

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IMPROVING BAY MANAGEMENT THROUGH CONSENSUS AND LOCAL SUPPORT WITH TECHNICAL JUSTIFICATION

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INTRODUCTION

Successes in bay management and restoration throughout the United States have been hard won. Rapid population growth in coastal areas with accompanying pollutants and overuse have resulted in stressed estuarine environments. The impacts have been subtle and have occurred slowly over the past several decades. In this light, restoration of bay resources will require similar time periods and subtle changes in policy (Alderson 1988).

Estuaries are the most productive biological systems in the world serving as principal spawning and nursery grounds for more than 70% of our nation's commercial and recreational fisheries. Estuaries also support or enhance a variety of water-dependent industries and provide irreplaceable recreational and aesthetic enjoyment (Roat and Alderson 1990).

The problems facing Sarasota Bay are typical of coastal communities throughout Florida and the United States. The bay has been adversely impacted by pollution, dredging, development and overuse, and restoring Sarasota Bay will be even more challenging given the 25% increase in local population projected over the next 5 years in the local area. Restoring Sarasota Bay will require financial assistance, public education, lifestyle changes and difficult decisions by the local community (Roat and Alderson 1990). The National Estuary Program provides this forum through a "management conference structure" consisting of members of state and local government, interstate and regional agencies, affected industries, public and private institutions, interest groups and the general public (EPA 1987). The Sarasota Bay National Estuary Program (NEP) will provide the mechanism for developing effective strategies for restoring Sarasota Bay while monitoring the effectiveness of existing programs.

HISTORICAL PERSPECTIVE

Successes in restoring and protecting marine environments throughout the United States are few. However, in bay areas which have been improved or successfully protected, key factors emerge. There has been:

- clear, straightforward and simple technical justification for action;
- public and political support;
- a strong and effective governing body; and,
- financial support of federal, state and local governments.

A review of other programs across the country support the need for these ingredients to success.

Great Lakes

In the Great Lakes, the United States and Canadian governments have cooperated on a long-term program since the 1960s to improve the quality of the Great Lakes. The International Joint Commission and the Great Lakes National Program Office have coordinated the restoration effort since 1972. The program initially focused on reducing phosphorus loads (nutrients) to the Great Lakes. Pollutant loading reduction goals were established for each of the lakes based on water quality modeling results. Over $8.5 billion in federal, state, local and private resources were spent for sewage treatment plant and related infrastructure improvements and non-point source control programs to achieve these goals. As a result of these efforts, nutrient loadings to the

Great Lakes have been reduced by 95%. More recently, the program is focusing on toxics, particularly in sediment (Alderson 1988). The success was driven by public support throughout the United States.

Chesapeake Bay

In the Chesapeake Bay, over $27 million in technical work was conducted by the Chesapeake Bay Program between 1977 and 1982 documenting the extensive problems facing the bay. The results of the research phase also predicted pollutant increases and habitat loss anticipated in the basin as a result of predicted population increases. The project also tested treatment scenarios for basinwide implementation of control programs and evaluated their effectiveness. The release of the Chesapeake Bay Program's findings, in combination with citizen support for action, generated the passage of 27 legislative and budget initiatives to restore and protect the bay in Maryland alone. The budget initiatives resulted in the State of Maryland appropriating hundreds of millions of dollars for bay protection and restoration, and increased staffing in their environmental program offices (State of Maryland 1986). Similar programs have been initiated in Virginia and Pennsylvania. The cleanup initiative is managed by the Chesapeake Bay Executive Council, consisting of the Governors of Maryland, Virginia and Pennsylvania and the Mayor of the District of Columbia. Recent data presented by the Chesapeake Bay Program indicates a 36% decline in phosphorus loadings to the mainstem of the Chesapeake Bay resulting in a 16% reduction in total phosphorus in the water column of the Chesapeake Bay (Williams and Lacy).

Potomac River, Maryland

In the Potomac River, a major tributary of the Chesapeake Bay, over $1 billion has been spent for capital improvements to sewage treatment plants, and local taxpayers are contributing more than $100 million annually for municipal treatment operations for river cleanup. Once considered the cesspool of the United States, the Potomac River now supports a strong recreational smallmouth bass fishery. The Potomac River cleanup succeeded because of sustained commitment of local agencies through the Washington Municipal Council of Governments (Alderson 1988).

Other Successes

A review of similar efforts in Tillamook Bay, Oregon, Rhode Island's Salt Pond Region, and in Apalachicola Bay, Florida, have also indicated similar ingredients to success. In Sarasota Bay, the National Estuary Program is using these lessons to build a major cleanup and restoration program. The program combines technical research, public education and early action to build local government support and institutional and financial commitment for action.

TECHNICAL JUSTIFICATION FOR ACTION

Although more than 348 technical studies have been conducted on Sarasota Bay over the past 20 years, a concerted comprehensive technical analysis of the severity and complexity of bay issues has not been conducted. The technical workplan developed by the Technical Advisory Committee (TAC) provides for this multidisciplinary and integrated analysis. The technical workplan was developed over a 6-month period during the spring and summer of 1989, and received extensive comment from local government officials and technical advisors who serve on the Technical Advisory Committee. The workplan supports National Estuary Program data needs as well as the local comprehensive planning process. Together, these projects will provide the technical basis of information to support action.

To be nominated and ultimately selected for the National Estuary Program, it was necessary to compile information known about Sarasota Bay. This information was presented in a "nomination" document which served as the basis of information for generating the technical workplan. Staff prepared a workplan in early spring 1989 based on the nomination document and experience with technical work supporting action in other areas of the country. The workplan was presented to the TAC in late spring and referred to the following subcommittees for review:

- Water Quality Monitoring
- Habitat
- Beach/Bay Access
- Data Management
- Point/Nonpoint Sources
- Fisheries

With contractual assistance, the program developed a proposed study plan based on comments from the respective technical talent on each subcommittee. During the summer of 1989, the TAC critically reviewed and ultimately approved the workplan. The projects were released for bid under a request for proposals and contractors were selected by a Technical Review Committee and recommended to the Management Committee of the Sarasota Bay National Estuary Program for selection. An overview of each technical project is given below.

Baywide Segmentation. This effort geographically segments Sarasota Bay. Segments will be used to develop strategies for effective management of bay regions.

Wetland Status and Trends. This documents historic loss of freshwater and intertidal marine wetlands, projects future losses and offers recommendations for action. The analysis includes an assessment of fire and freeze damage, encroachment by exotic plants, ditching and drainage effects on wetlands, and new wetlands created through development mitigation or other causes. Maps will delineate habitats for protection and habitat areas suitable for restoration. Wetlands will be classified with regard to quality using a system similar to the EPA advance identification system.

Estuarine Bottom Habitat Assessment. The project assesses historic loss of submerged aquatic vegetation and other submerged habitats, summarizing the current status of estuarine habitats and offering suggestions for restoration and protection. Importantly, it will also map and classify existing, historic and prospective seagrass beds.

Impacts of Sea Level Rise. The project will assess the impact of rising sea level on the local environment and cultural resources. Although the sea level rise predictions are speculative, this project could have major impacts on beach management, stormwater programs, wetland location and condition, and related permit processes.

Fishery Resource Assessment. The study reports on commercial and recreational fishing trends and assesses habitat use, requirements and relationships. Also included will be a basic inventory of the fish and crab species that occur in the bay, landings (both commercial and recreational), and habitat requirements for various life cycle stages. The project includes a recreational fishing survey and species diversity analysis throughout the bay.

Bivalve Shellfish Contamination Assessment. This project analyzes the level of shellfish contamination in various areas of the bay. Types of contaminants will be determined, potential sources of contaminants identified and the impact of the contaminants on shellfish will be assessed. Restoration and protection techniques will be suggested.

Baywide Circulation. This effort analyzes water circulation in Sarasota Bay, offering insight into movement of pollutants in the bay, flushing characteristics and zones of stagnant water. The project generates a computer model of baywide circulation that can be used to assess future management decisions.

Point and Nonpoint Pollutant Loading Assessment, Calibration, Verification and Projections. This project analyzes each basin and subbasin in the bay in terms of the nutrients, sediment, metals and other contaminants it receives from various sources.

The impact of shopping malls, golf courses, and residential canal front development areas on septic systems will also be addressed.

Resource Use and Facility Assessment. Sociological in nature, the project will examine the natural and cultural resources that support bay recreation. It will analyze limitations in resources, predict future trends, and recommend policies and practices to better manage recreational use of the bay's resources.

Data Management. The system will provide a mechanism for the Sarasota Bay project to store and analyze data collected, and to disseminate data to the public. It also provides for the future use of this important database, so critical to proper environmental management.

Baywide Monitoring. This effort is designed to measure the health of Sarasota Bay, and analyze water and sediment quality in the bay. The monitoring program includes 102 sampling stations. Samples are taken quarterly in a time-sequenced fashion on an incoming tidal cycle. Thirty-five parameters are being measured. The monitoring effort also includes analysis (at 35 sampling stations) of heavy metals and selected organic chemicals commonly found in pesticides.

In total, these projects include the majority of the technical work that will be conducted during the first two to three years of the project. Some projects will be ongoing, others one-time efforts, but the eventual outcome will be the most comprehensive analysis of Sarasota Bay ever conducted. The results will lead to implementable (and measurable) techniques for improved management for the bay.

PUBLIC AND POLITICAL SUPPORT

The Sarasota Bay National Estuary Program has embarked on a series of initiatives to help generate public support for bay restoration and action. It is important that strong communication be maintained between the Technical and Citizen Advisory Committees.

First, the program released the "State of the Bay" report characterizing what is known about Sarasota Bay, and the "Bay Repair Kit"—a homeowners guide to how people can help protect and improve the bay around their homes. Both reports have received broad attention from local newspapers in the area. Next, the program conducted a public opinion survey to gain an understanding of public knowledge of bay issues and problems. This survey will be used to gauge the success of public outreach and education programs.

The Sarasota Bay Project's Citizen Advisory Committee intensively reviewed and approved the "State of the Bay" report (Estevez 1988). This report helped focus citizen attention on problems and issues facing the bay:

- declines in living resources;
- growth;
- habitat loss;
- stormwater;
- sewage treatment;
- dredging; and,
- overuse.

The Citizen Advisory Committee is now implementing an action plan related to selected subject areas. The action plan is developing a series of workshops, bringing the constituents and affected organizations together to educate the public and develop workable solutions. The action plan further focuses on mangrove protection, seawalls, stormwater, sewage and Little Sarasota Bay. Elements of the public participation components of the Sarasota Bay Program are briefly described below.

Public Opinion Survey. This project developed an areawide questionnaire to evaluate the public perception of the priority issues and willingness to pay and adopt laws to protect resources. NEP guidelines provide assistance for obtaining the public's perception of the issues and problems of the bay. This project helped to meet that objective. The program will conduct a subsequent public opinion survey to determine effectiveness of the media and public outreach and education activities within the community.

Sarasota Bay Newsletter. These funds will provide for printing and distribution costs of four newsletters informing the public on program studies and status.

Media Plan and Productions. One of the most important components of the Sarasota Bay National Estuary Program public outreach program will be the development of a public relations campaign. This provides for the development of a media plan to review alternatives and professional recommendations for the use of television, radio and print media for public information and education on bay issues.

"Bay Repair Kit", A Sarasota Bay Users Guide. This document informs the public of what homeowners can do to help with bay cleanup efforts.

Public School Outreach. A priority technique for improving the understanding of the bay is through the public school system. This project will develop instructional materials and investigate alternatives for coordinating the introduction of estuarine education into the public school system.

Action Plan. This plan will guide the program's public education and involvement activities focusing on several priority bay problems:

- mangrove protection and restoration;
- seawalls;
- stormwater;
- sewage;
- Little Sarasota Bay.

EARLY ACTION DEMONSTRATION PROJECTS

The final component of the Sarasota Bay National Estuary Program is early action demonstration projects. These projects are funded to test management strategies and to develop cost estimates for basinwide application.

Seagrass Signage. This project, slated for completion in January 1992, investigates whether seagrass beds can be effectively protected from boat damage through marking. Markers were installed in an area of the bay near City Island, and New College students are monitoring the site. A survey of boaters' experiences with seagrass beds was conducted.

Clower Creek Stormwater Rehabilitation. This project investigates alternatives for stormwater management, with emphasis on improving runoff water quality in the Clower Creek basin.

City Island Habitat Restoration. This project will develop a productive intertidal habitat on 4.5 acres of City Island in Sarasota. Intertidal pools, 19,000 plants, and a nature trail with interpretive signs will be included. The site should be open to the public in summer 1991.

Leffis Key Habitat Restoration. This project is intended to develop a productive intertidal habitat on 34 acres near Coquina Beach in Manatee County. It is anticipated that approximately 10 acres will be restored.

Caples Shoreline Restoration. This project will restore a hardened segment of bay shoreline to a natural state through removing a seawall and planting vegetation.

Sister Keys Seagrass Assessment. This project provides for an intensive characterization of bottom habitats in the area surrounding Sister Keys, a group of undeveloped islands. Seagrass mapping, bathymetry, species diversity, and other environmental parameters will be included in the assessment.

LOCAL GOVERNMENT SUPPORT

The National Estuary Program has also achieved unprecedented support from local governments. This is achieved via two mechanisms, financial support and staff support provided through the Technical Advisory, Management and Policy

Committees. Each member of the Policy Committee has assisted in contributing resources for the program.

Since its inception in June 1989, the Sarasota Bay National Estuary Program has successfully secured more than $3.5 million in support with approximately 50% provided through state and local governments (SBNEP 1991). Cash contributions have been received from the State of Florida legislature, Manatee and Sarasota Counties, the Southwest Florida Water Management District, the City of Sarasota, and the Florida Department of Environmental Regulation. These key organizations will also be involved during the implementation phase.

APPROPRIATE MANAGEMENT STRUCTURE

Governance and financial cooperation for implementation are key issues yet to be addressed by the Sarasota Bay National Estuary Program. The conceptual strategy approved by the Board overseeing the program calls for the recommendations to be dealt with in a comprehensive manner subsequent to the release of the technical work scheduled for completion in August 1992. The comprehensive strategy will include funding commitments and responsible organizations for completing the strategy. In addition, much thought was given to membership on the Policy, Management, Technical Advisory, and Citizen Advisory Committees overseeing the program. Membership is critical as actions may be required from all to improve the bay.

SARASOTA BAY PROGRAM STRATEGY

At the direction of the Sarasota Bay National Estuary Program's Policy Committee, three major documents, supported by many other reports, will be developed over the five-year project. Together they will form the strategy for restoring Sarasota Bay. An initial product of the program was the "State of the Bay" report. The report addresses current knowledge the bay and justifies the technical and public participation work to be completed (Roat and Alderson 1990).

The second major report will document the findings and recommendations of the technical studies and early action projects, and will present a preliminary restoration strategy for the program. This report, entitled "A Framework for Action", will be completed by August 1992.

The program's final document—the "Comprehensive Conservation and Management Plan"—will be completed no later than October 1994. The CCMP will focus on funding commitment and institutional arrangements.

SUMMARY

The Sarasota Bay National Estuary Program has embarked on an aggressive program to help forge actions required to protect and restore Sarasota Bay. The program has three major components: technical, public education and early action. It is hoped that the lessons learned from other areas of the country can be used to save time and resources to ultimately develop an effective plan of action.

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COMPREHENSIVE PLANNING — AN IMPORTANT KEY TO THE FUTURE OF TAMPA BAY

J. F. Stowers

INTRODUCTION

Tampa Bay is one of the largest estuaries in the United States. The flow of fresh water into an estuary is its life blood. Management of Tampa Bay requires the coordinated effort of all communities which affect the freshwater flows entering the estuary. Significantly affecting the physical and environmental impacts of the freshwater flows are the land uses and regulatory programs which go into the development or alteration of upland properties around Tampa Bay. The state of Florida, in 1985, took a significant step in land management with the adoption of the Local Government Comprehensive Planning Act as well as the State Comprehensive Plan. This legislation was promulgated to foster a comprehensive approach to managing growth in Florida while recognizing the varied natural, cultural, historic and economic resources of a community. This paper describes the available opportunities for communities around Tampa Bay to utilize the mandated growth management legislation and all of its implications in land management to effectively provide management opportunities for Tampa Bay.

We have all heard the list of horrible examples of mismanagement of Tampa Bay, but Florida can be changed. Stetson Kennedy, author of Palmetto Country, states "Actually, Florida is fortunate in that much of what has been lost (taken would be better word) could be restored" (Kennedy 1942). As communities, local government must take the opportunity to make changes.

Local Government Comprehensive Planning Act

The alteration of land and the subsequent development of that property will be managed in each local government's comprehensive plan and their adopted land development regulations. Many opportunities are available for communities to establish initial corrective measures to the historic negative impacts caused by development which have resulted in a reduction of freshwater flows entering Tampa Bay. Additionally, each plan must adopt futuristic goals, far-sighted objectives, and implementable policies which will not allow the sins of the past to continue, and which can protect and manage the uplands around Tampa Bay, thus assisting in managing the estuary. Through the utilization of the local governments' Comprehensive Plans, land development regulations, capital improvement plans, and other outlined programs in comprehensive planning, Tampa Bay can truly be managed as it should—as a significant portion of the whole community.

Comprehensive Planning in Florida

Florida is the only state in the nation that has a legislatively adopted Comprehensive State Plan which requires that each community set goals, objectives, and policies for what the community shall recognize in the adoption of their plans. The Local Government Comprehensive Planning Act (Chapter 163, Florida Statutes) requires that each community shall adopt a local comprehensive plan which furthers the State Comprehensive Plan. The development of that plan requires the utilization of Florida Administrative Rule 9J-5 under the guidance of Chapter 163, Florida Statutes and the State Comprehensive Plan. The process is one that requires research, analysis, policy decisions, a tremendous amount of citizen input, and the recognition of many existing data banks and much information already currently available.

Chapter 163 requires that goals, objectives and policies be established for each element necessary in the Comprehensive Plan. The important decisions regarding Tampa Bay center around those elements which involve coastal zone management,

management of wetlands, land uses, and management of surface waters. These represent only a small portion of the entire requirement of Chapter 163 and Rule 9J-5 that the community must address. Figures 1-4 illustrate a stepped process utilizing one goal from the State Comprehensive Plan—Number 10, Natural Systems and Recreational Lands. The 9J-5 rule requirements are addressed (Figure 2), then examples of how Pinellas County's Comprehensive Plan sets up implementation strategies through land development ordinances (Figures 3 and 4) are illustrated. It's obvious from this review that a community has the opportunity and, in fact, the requirement to look at a comprehensive or holistic approach before allowing development or land use decisions to move forward on a particular piece of property.

STATE COMPREHENSIVE PLAN

Chapter 187.201 STATE COMPREHENSIVE PLAN ADOPTED - The legislature hereby adopts as the State Comprehensive Plan the following specific goals and policies;

(10) Natural Systems and Recreational Lands

(a) Goal - Florida shall protect and acquire unique natural habitats and ecological systems ... and restore degraded natural systems to a functional condition.

(b) Policies

(1) Conserve forest, wetlands ... and wildlife to maintain their environmental, economic, aesthetic, and recreational values.

(4) Establish an intergraded regulatory program to assure the survival of endangered and threatened species within the Sate.

(6) Encourage multiple use of forest resources ... to provide for ... wildlife habitat, water shed protection, erosion control, and maintenance of water quality.

(10) Emphasize the acquisition and maintenance of ecologically and taxed systems in all lands and water planning, management, and regulation.

Figure 1.

LAND USE DECISIONS RELATED TO WATERSHED MANAGEMENT

An estuary is a functioning biological machine that utilizes the tidal prism of the saltwater marine environment, the nutrient-rich shorelines of the intertidal production of the mangrove forest system, and the inflow of fresh waters from the watersheds around the bay. Tampa Bay is thousands of acres of potentially rich estuary water; however, many more acres, approximately 23,000, provide the other portion of the overall estuary system, i.e. the upland contribution through which fresh water flows to Tampa Bay.

The land use designations of a community often hold many opportunities to assist in the watershed management of land draining to Tampa Bay. Another important element of each local government plan is its land use. Following are some examples of how Pinellas County addressed land use designations as a management tool in watersheds.

Historically, we have not addressed the estuary with a holistic approach. The effects of zoning decisions, land development regulations, channelization, discharge for flood water, and disregard for pollutant discharges upstream have historically been overlooked in all of these development activities. They were each separately implemented devoid of relationships with each other, and more importantly, their relationships to Tampa Bay. Old timers thought that Tampa Bay, with its large volume of water, could assimilate and use/cleanse the various impacts. Forest lands were destroyed, altering wetland freshwater drainage, all in the interest of human needs, or was it greed—economic development if you would.

Associated Chapters in the F.A.C.

9J-5. 013(2) GOALS, OBJECTIVES AND POLICIES

2(a) Goals One or more goals statements which ...

2(b) Objectives For each goal, one or more objectives ... which ...

(3) Conserve, appropriately use and protect ... soils and native vegetative communities including forests; and

(4) Conserve, appropriately use and protect ... wildlife, wildlife habitat ...

2(c) POLICIES For each objective, one or more policies ...

(3) Protection of native vegetative communities from destruction by development activities;

(5) Restriction of activities known to adversely affect the survival of endangered and threatened species;

(6) Protection and conservation of the natural function of existing ...

Figure 2.

PINELLAS COUNTY COMPREHENSIVE PLAN
CONSERVATION ELEMENT

Native vegetation and wildlife species

7. GOAL: TO CONSERVE, PROTECT, AND APPROPRIATELY MANAGE THE NATURAL VEGETATIVE COMMUNITIES, ...

7.1 Objectives: By October 1, 1990, Pinellas County shall develop a management program for the conservation of native vegetative communities, ...

7.1.3 Policy: Pinellas County shall preserve native vegetative communities ... wildlife species which occur naturally in Pinellas County.

7.1.4 Policy: Pinellas County shall review and amend ... existing ordinances in order to protect and conserve native vegetative communities.

Figure 3.

The requirement of comprehensive planning provides the avenue and the impetus for each community to address at least those lands which have not already been altered. It allows the opportunity for retrofit where necessary and affords (requires) the opportunity to alter what has occurred in the past. It has taken years for the degradation of Tampa Bay because it could and did in fact assimilate much of man's past activities. The process of developing a Comprehensive Plan allows for protection of existing natural systems and the retrofit of older developed systems.

PINELLAS COUNTY HABITAT MANAGEMENT & LANDSCAPE
Ordinance #90-16, Section 9.

UPLAND BUFFERS ADJACENT TO WETLANDS

A. Purpose

It is the purpose of an upland buffer to further protect wetlands, their associated wildlife and water quality and quantities attributes from adjacent development impacts such impacts ...

B. Upland Buffer Requirements

Upland buffers shall be required immediately adjacent to a wetland in accordance with Table 1 ... The buffers must be shown on the site plan and must be preserved during site development. Platted ...

The upland buffers shall be recorded in Public Records of Pinellas County as conservation easements in accordance with Chapter 704.06, ...

TABLE 1

		UPLAND BUFFERS
1.	Isolated wetlands	15 feet
2.	Creeks, channels, ... waterways which are not designed as preservation which are ... rights of the State ...	15 feet outside the top of bank or contiguous wetland whichever is greater
3.	Pinellas county approved retention ponds adjacent to wetlands	15 feet from edge of wetlands to top of bank of retention pond
4.	All other wetlands	50 feet

Figure 4.

A requirement of Chapter 163, in the coastal management element and Rule 9J-5 both, is that this element shall be consistent with coastal resource plans prepared and adopted pursuant to general or special land. Thus the designation of Tampa Bay as a Southwest Florida Water Management District Surface Water Improvement and Management (SWIM) Program priority project requires that local government recognize the SWIM plan for Tampa Bay in the development of their comprehensive plans.

Designation of Environmentally Sensitive Lands — A Tool

One of the important decisions that a comprehensive plan makes is to establish land use criteria for properties. Land use has typically been thought of as representing zoning categories such as residential or commercial. However, the placement of land in either preservation or open space is probably one of the more significant roles that a community can play in order to protect the freshwater flows to an estuary system.

Often, the delineation of land uses which offer management alternatives requires sound technical background to justify the restriction on development potential. In Pinellas County, we undertook a three-year study to establish the 100-year floodplain of some of our major remaining unaltered wetland riverine systems. For instance, the Brooker Creek Basin's floodplain was established through modeling, and the property was set aside through a preservation land use designation. This provides a tremendous source of cleansing potential and natural system inflows to Lake Tarpon which ultimately flows into Tampa Bay, albeit currently through an outfall canal because of a Southwest Florida Water Management District management program. This is not a perfect system. However, the designation of the land use is the important issue in this particular case.

When the task of delineating all environmentally sensitive lands within Pinellas County was undertaken, two major classifications of environmental constraints were identified:

- Preservation Areas—the most environmentally sensitive areas, those considered to have no development potential without a severe loss of natural system functions and benefits; and
- Conservation Areas—those areas whose environmental sensitivity varies according to the type of environmental feature(s) found on the property (these properties can be developed to an intensity limited by their existing environmental constraints).

Preservation areas are illustrated on the countywide future land use map by a preservation designation, while conservation areas are generally placed under an open space land use designation.

The overall intent of the preservation/open space land use classifications is to designate and protect environmentally sensitive areas and functional open space areas essential to the health, safety, and welfare of the County's residents. Appropriate uses within the preservation category include wildlife and natural system preserves, such as fresh and saltwater wetlands, stream and natural drainage corridors, the 25-year floodplain, coastal beaches and dunes, shoreline vegetation, and other unique ecological features.

The open space category includes passive recreational uses which are predominantly undeveloped, permeable, vegetated land such as public parks, future park sites, picnic areas, golf courses, and active recreation uses, including some developed physical facilities. Figure 5 illustrates the type of map which is generated by the process. The darker areas represent preservation land uses.

The utilization of land use in the designation of environmentally sensitive lands, in conjunction with the land development ordinances, has thereby provided a viable tool for the protection of environmentally sensitive areas. Implementation of the land use plan, however, must be handled in a reasonable and legally defensible manner. Technical and professional staffs need to be objective in their interpretation of environmentally sensitive areas and in their review of site plans, for misapplication of land use designations and their subsequent use restrictions could be construed as a taking of private development rights. Consequently, the designations must be realistic in their goals and objectives, continually updated, and involve a cooperative effort on behalf of all technical departments within the County.

Implementation Strategies

In addition to land use designations, local governments must enact land use controls in the form of land development ordinances, as required under the Local Government Comprehensive Planning Act of 1985. Some examples include tree protection ordinances, floodway ordinances, site plan regulations, habitat management, and zoning regulations. The Comprehensive Plan has the full force and effect of law, and functions as the legal basis for the implementation of such ordinances. As a result, Pinellas County's environmentally sensitive lands are being protected through a multi-tiered approach, utilizing countywide land use designations and a series of more specific ordinances enforced by the local governmental entities.

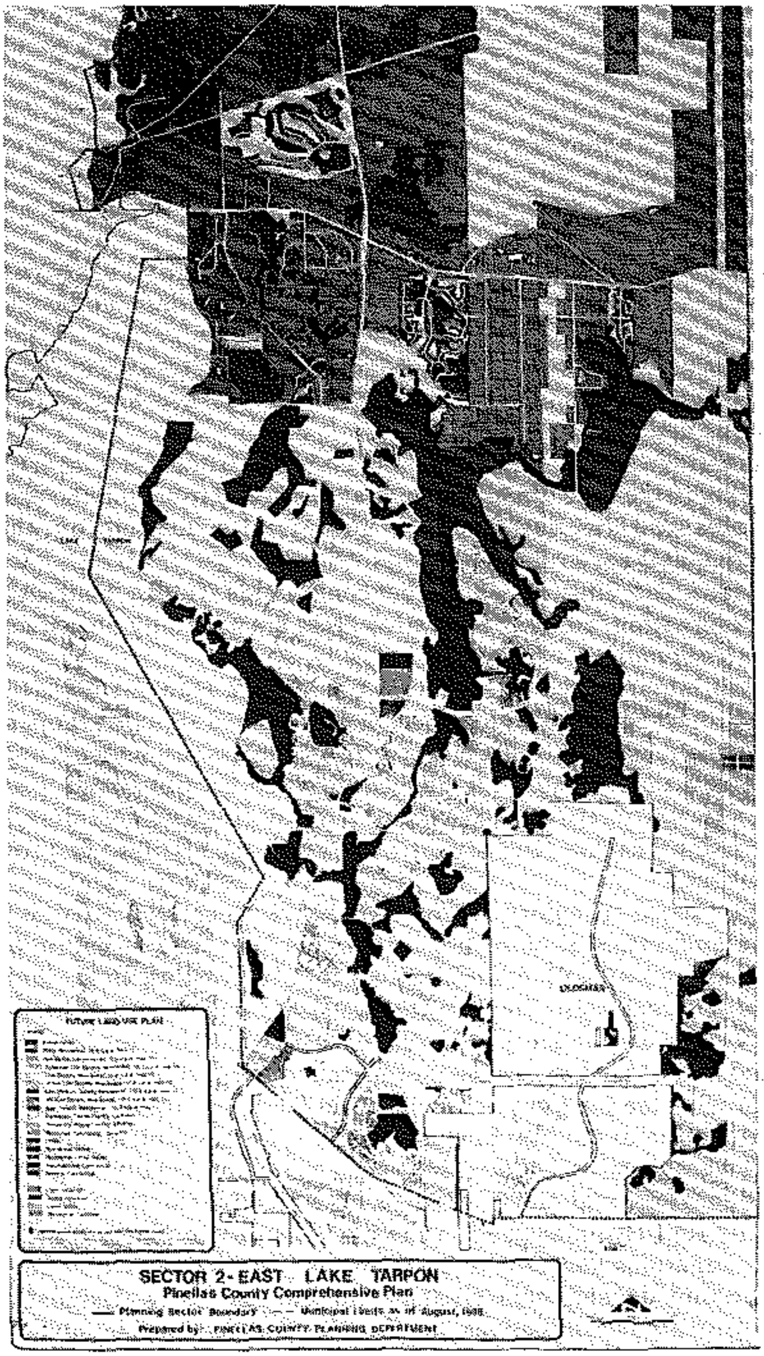

Figure 5. Pinellas County land use map.

The significance of the detailed studies, analyses, and modeling that produced the preservation lines for the Brooker Creek floodway is brought to light when the development rights of individuals owning property within and adjacent to this flood zone are considered. In the adopted Comprehensive Plan, these preservation areas meet the goals, objectives and policies as outlined in many of the elements; coastal zone element, floodway prevention, surface water management, wildlife habitat, etc. are all addressed through this process. The multi-tiered approach is beneficial because the act of one ordinance or one land use has a far reaching effect on many other objectives of a comprehensive plan. In order to address, for instance, the property rights of the owner whose property was placed in preservation, zoning regulations allow a transfer of density from the preservation properties. Albeit low, it does provide utilization of some rights for the property which is a legally defensible position and therefore does not necessarily require the purchase of the preservation in order to retain the natural functional use of these upland properties. As a regulatory agency, Pinellas County can only mandate preservation areas based upon detailed and legally defensible findings. Numerous other environmentally sensitive properties throughout the County have been protected in a similar manner.

The level of involvement of a community is limited only by their desire to implement a program. Another example in Pinellas is specific management plan development for important natural resources in the county. A management plan for Lake Tarpon is being prepared with Pinellas County being the lead among several agencies which have responsibility for the lake's management. The plan will set the future direction for the uses on the lake.

CONCLUSION

The example that has been presented outlines the potential opportunity available to communities to manage the upland properties and ultimately, the watersheds adjacent to Tampa Bay. Tampa Bay, as the downstream receiving water body, has historically been overlooked, as indicated through the historic destruction and alteration of the bay. Other examples are Boca Ciega Bay and other dredge and fill projects, the outfall of major point sources, which has recently been corrected, as well as the separation of watershed development activities from the impacts that they had on the bay. Until recently, these have not been looked at in most situations. The comprehensive planning process requires that the "whole picture" be reviewed in order to allow development to proceed.

In the last decade, major advances in technology, analysis of the bay, and studies have been undertaken by various groups—the Agency on Bay Management, the SWIM program, and most recently, the designation of Tampa Bay as a National Estuary Program. All of these, in combination with comprehensive planning, will, if properly utilized, lead Tampa Bay on the road to recovery. The bay will become a significant, active biological community as well as an economic and recreation focus for the communities around it.

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MANAGEMENT DIRECTIONS AND NEEDS FOR TAMPA BAY TIDAL TRIBUTARIES

P. A. Clark

ABSTRACT

Numerous programs have been initiated over the past decade to restore tidal tributary conditions in the Tampa Bay watershed. Land use decisions, permitting requirements, infrastructure needs, and public restoration programs all affect the balance between natural resource protection and the needs of a growing population. An inventory of recent programs and activities is used to document challenges to tidal tributary management and restoration in the watershed. The Bay Area Scientific Information Symposium 2 is constructed to compile watershed characterization summaries to advance local understandings. Results will be used to develop management and restoration criteria for Tampa Bay tributaries.

INTRODUCTION

Tampa Bay is the largest open water estuary in the State of Florida, totaling approximately 398 square miles (1,030 km^3) in size on a high tide (Lewis and Whitman 1985). The watershed, or land area which drains into the bay system, approximates 2,300 square miles (3,700 km^3) and includes all of Pinellas and Hillsborough Counties, most of Manatee County and smaller segments of Pasco, Polk and Sarasota Counties (Dames & Moore 1990).

Tributaries maintain the estuarine character and much of the biological resources of the Tampa Bay estuary. Tributaries in general provide the following functions:

- distribute freshwater flows;
- maintain water quality;
- provide nutrients as a food source;
- create habitat for fish and wildlife;
- supply sediments to downstream systems;
- provide economic benefits to man, including:
  - food sources (fish, fowl)
  - potable, irrigation and industrial water supplies
  - recreational value (boating, fishing), and
  - flood protection.

The Hillsborough, Alafia, Manatee and Little Manatee Rivers are the four major rivers which collectively drain approximately 75% of the bay's watershed (Flannery 1989) and contribute 85% of the total freshwater to the bay system (Lewis and Estevez 1988).

Due to the many values tributaries provide to area residents and tourists, tributaries are often the focus of development. Tributaries have been altered by man in the following manners:

- hardening—seawalls, erosion control, berm construction;
- filling—upland construction, airports, mosquito control;
- channelization—agricultural, flood control, navigation;
- point source pollution—wastewater effluent, industrial discharges;
- nonpoint pollution—urban, industrial and agricultural runoff;
- consumptive water withdrawals—potable, irrigation, cooling water, industrial uses.

These systematic impacts have contributed to the decline in populations of commercially valuable fish and shellfish, the complete collapse of such fisheries as those for scallops and oysters, and major reductions in bait shrimp, red drum, and spotted sea trout fisheries.

The Tampa Bay Regional Planning Council (1986a) identified 44 minor tributaries to Tampa Bay and characterized the conditions of the tidal portion of each creek (Figure 1). Table 1 indicates that more minor tributaries remain either in restorable or natural condition than in stressed condition. However, because of the

Pinellas County
1) Salt Creek
2) Booker Creek
3) Tinney Creek
4) Grassy Creek
5) Long Branch Creek
6) Allen Creek
7) Alligator Creek
8) Mullet Creek
9) Bishop Creek
10) Moccasin Creek

Hillsborough County
11) Double Branch Creek
12) Channel A
13) Rocky Creek
14) Brushy Creek
15) Dick Creek
16) Woods Creek
17) Peppermound Creek
18) Sweetwater Creek
19) Fish Creek
20) Coon Hammock Creek
21) Broad Creek
22) Delaney Creek
23) Archie Creek
24) Bullfrog Creek
25) Little Bullfrog Creek
26) Newman Branch
27) Wolf Branch
28) Cockroach Creek
29) Piney Point Creek

Manatee County
30) Little Redfish Creek
31) Frog Creek
32) Cabbage Slough
33) McMullen Creek
34) Wares Creek

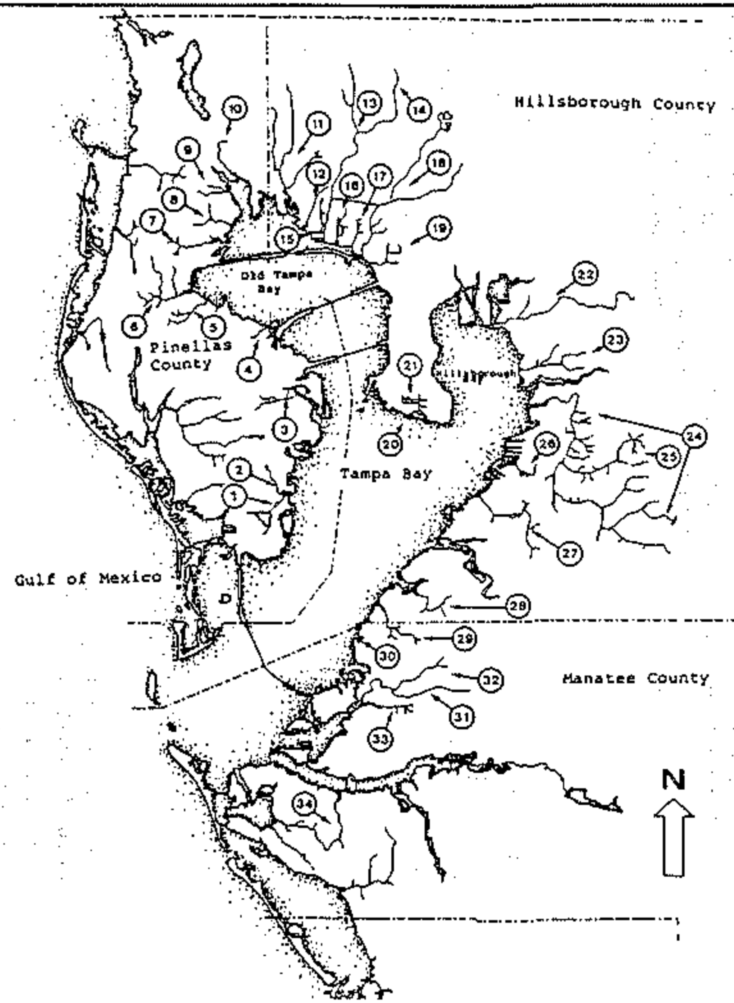

Figure 1. Classified tidal creeks and relative location in the Tampa Bay region (TBRPC 1986a).

rapid urbanization occurring in the Tampa Bay region, it is imperative to evaluate existing programs and employ protective strategies to prevent additional tributaries from becoming stressed.

Table 1. County classification summary (TBRPC 1986a).

COUNTY	STRESSED	RESTORABLE	NATURAL	OTHER	TOTAL
Pinellas	5	2	3	0	10
Hillsborough	5	8	3	3	19
Manatee	1	1	2	1	5
TOTAL	11	11	8	4	34

CONDITION AND MANAGEMENT

Physical Features

Every Tampa Bay tributary has been affected by channelization, flow alterations, or shoreline hardening that has changed its physical integrity to various degrees. Historically, the most common alteration of rivers and creeks has been channelization activities. Since the region is characterized by little topographic relief, the land surface promotes slow runoff, which has encouraged landowners to channel and divert potential floodwaters into surface waterbodies. The Tampa Bypass and Delaney Creek Pop-off Canals are typical examples of floodwater diversion. Additionally, the following tributaries have also experienced major channelization activities in the tidal reaches:

- Allen, Rocky and Sweetwater Creeks—residential and commercial development;
- Fish and Broad Creeks—airport construction;
- Booker and Ware Creeks—downtown urban development;
- Newmans Branch and Wolf Branch—agricultural runoff.

Further, rivers and creeks have been channelized to enhance boat access, as in Salt Creek and the Alafia River. Channelization activities often lead to hardening of the shoreline and bottom to prevent erosion. Shoreline hardening frequently prevents establishment of natural communities, accelerates distribution of freshwater runoff, and encourages upland development in floodplain areas. Reinforced shorelines are constructed to limit maintenance activities and prevent shoreline erosion.

A significant restoration project has been accomplished in the lower Delaney Creek Pop-off Canal in Hillsborough County by Cargill, Inc. (formally Gardinier, Inc.), using funds from a pollution violation by the company in 1988. Figure 2 illustrates the original creek in 1957 (A), two completed channelization projects in 1968 (B) and 1981 (C), and the current channel after restoration in 1989 (D). Restoration activities included pushing the channel berms back into the canal, raising the elevations sufficiently to create broad littoral zones for planting of estuarine vegetation, and opening backwater areas to enhance water quality and biological access.

The provision of adequate quantities of freshwater to Tampa Bay is critical to its function as a productive estuary. The water must be provided at ecologically relevant times, and it must naturally fluctuate to stimulate those biological resources which are timed to hydrological cycles (fisheries, manatees). All four major rivers flowing to Tampa Bay are subject to water withdrawals, with the Hillsborough and Manatee Rivers containing in-stream reservoirs as a source of potable water. The Little Manatee contains an off-stream reservoir to provide a cooling water supply for a power generating facility and the Alafia River is tapped for phosphate mining process water needs. Figure 3 (from Flannery 1989) illustrates average yearly streamflows and withdrawals for the eight largest tributaries to Tampa Bay.

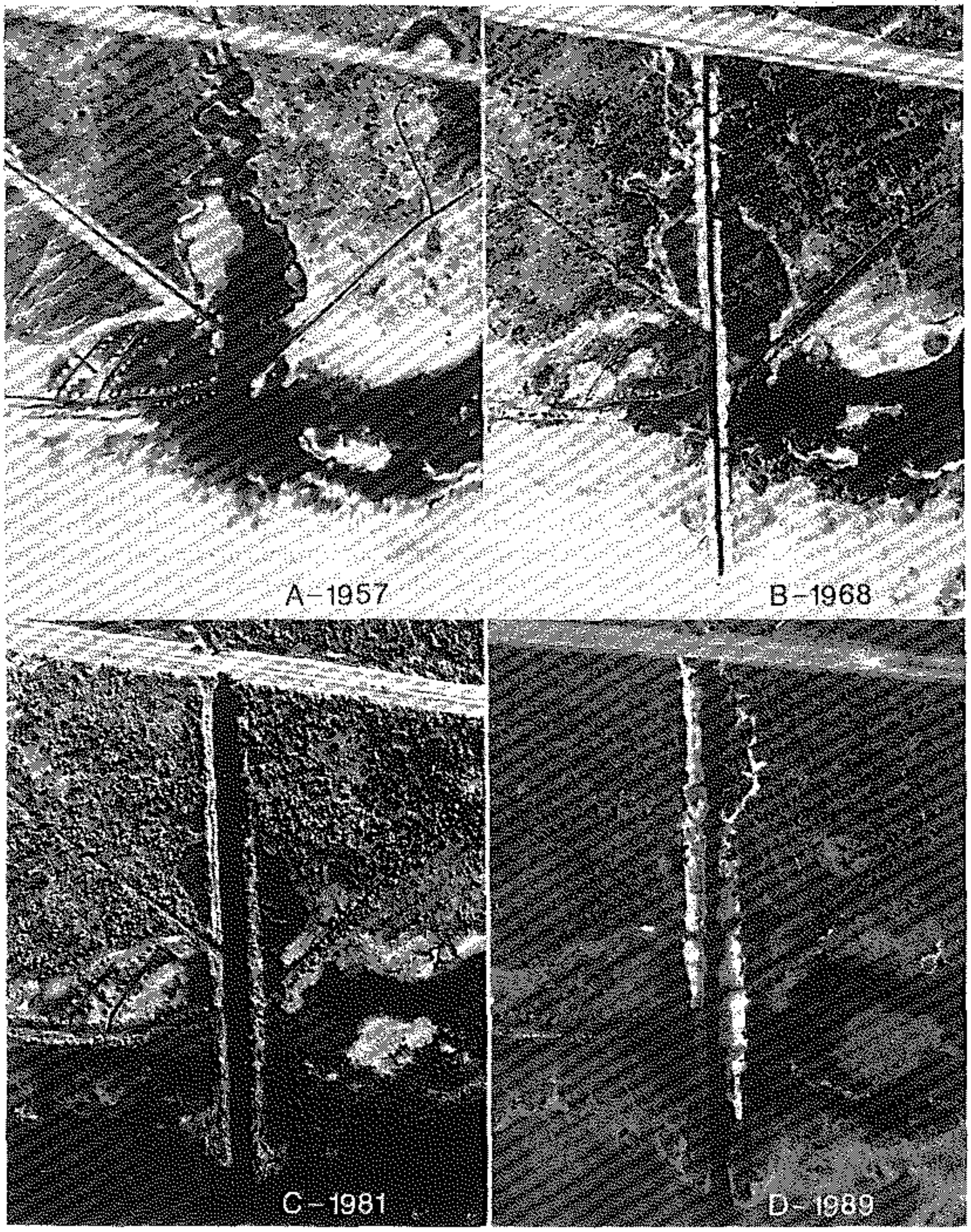

Figure 2. Delaney Creek Pop-off restoration project.

Maintenance and timing of freshwater flows from the larger tributaries is the focus of recent Water Use Permit (WUP) renewals as regulated by the Southwest Florida Water Management District. The Hillsborough River/Tampa Bypass system serves as an important source of potable water for the City of Tampa. Concern for downstream conditions in both the river and canal were identified during the permit renewal process, requiring further evaluation by the City.

In 1990, Manatee County applied for renewal of the operating permit for the Lake Manatee reservoir WUP. Many local scientists and bay management organizations identified low freshwater discharges currently being allowed through the dam to downstream estuarine systems. Due to the significant structural habitat components downstream, the use of the lower river by biological resources can be greatly enhanced through coordination of salinity regimes with nursery areas, feeding grounds, and other habitat components provided by the lower river.

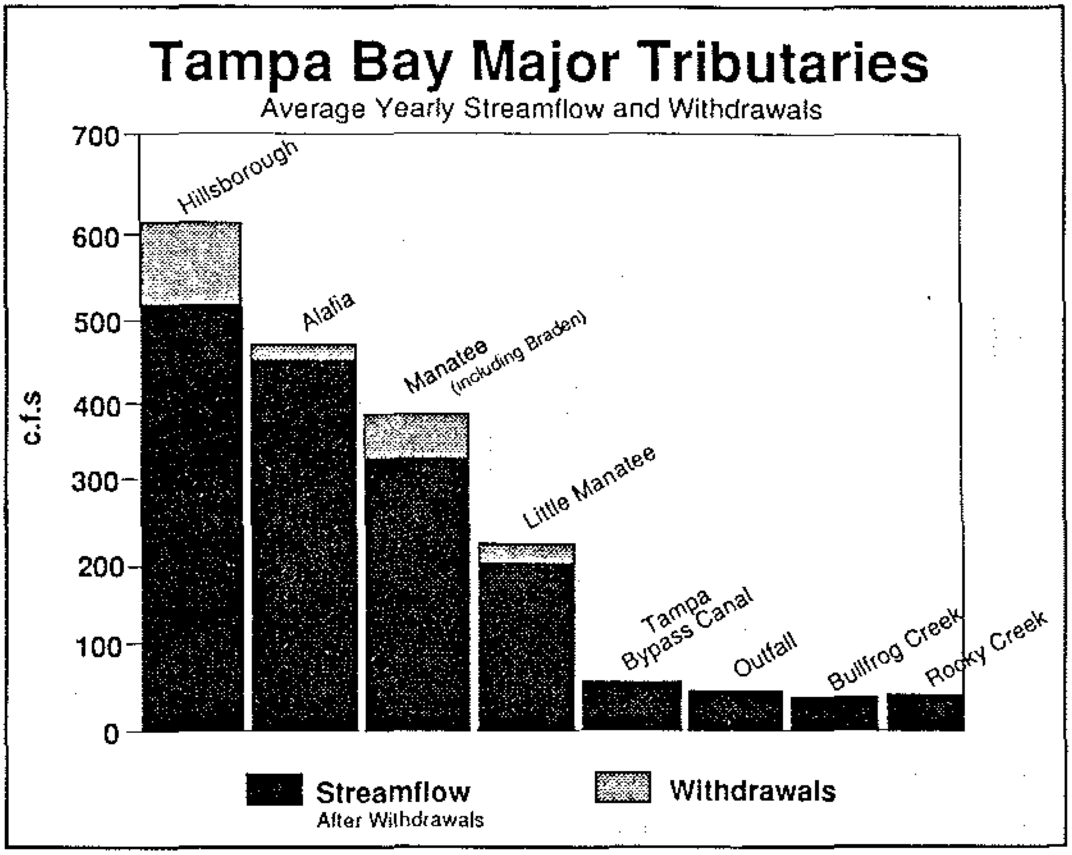

Figure 3. Average yearly streamflow and withdrawals from eight tributaries to Tampa Bay (Flannery 1989).

Freshwater flows have also been increased in Tampa Bay tidal tributaries. Rocky Creek in Hillsborough County receives advanced wastewater treatment (AWT) effluent from three regional treatment plants, representing an increase of 57% over the tributary's existing baseflow. The addition of 8 million gallons per day (mgd) by 1991 and another 15 mgd by 2005 would cause a total increase in the base flow of Rocky Creek by 91% and 157% respectively (Boyer and Clark 1989). The authors recommended balancing anticipated increases in freshwater flow between Rocky Creek and Channel "A", a flood bypass channel which flows only during larger rainfall events. Figure 4 illustrates streamflow augmentation alternatives for Channel "A" that would enhance water quality in the manmade channel and buffer Rocky Creek from the input of excessive, highly treated effluent.

Chemical Contamination

The input of point source discharges into area rivers and streams has been reduced through the permitting process over the last twenty years. Historically, tributaries provided convenient receptacles for discharge of municipal and industrial waste. Delaney Creek has suffered significant water quality perturbations from battery and fertilizer manufacturing plants. Heavy metals, polyvinyl chlorides and other materials from past industrial and port activities can still be documented in sediment "hot spots" downstream of discharge points in tributaries and Tampa Bay.

In the past, poorly treated wastewater effluent has led to overnutrification and coliform contamination in receiving water bodies. Point source discharges have predominately been identified and quantified, leading to reductions in pollutant loadings. However, loadings from large quantities of highly treated effluent and illegal discharges may continue to affect water quality conditions.

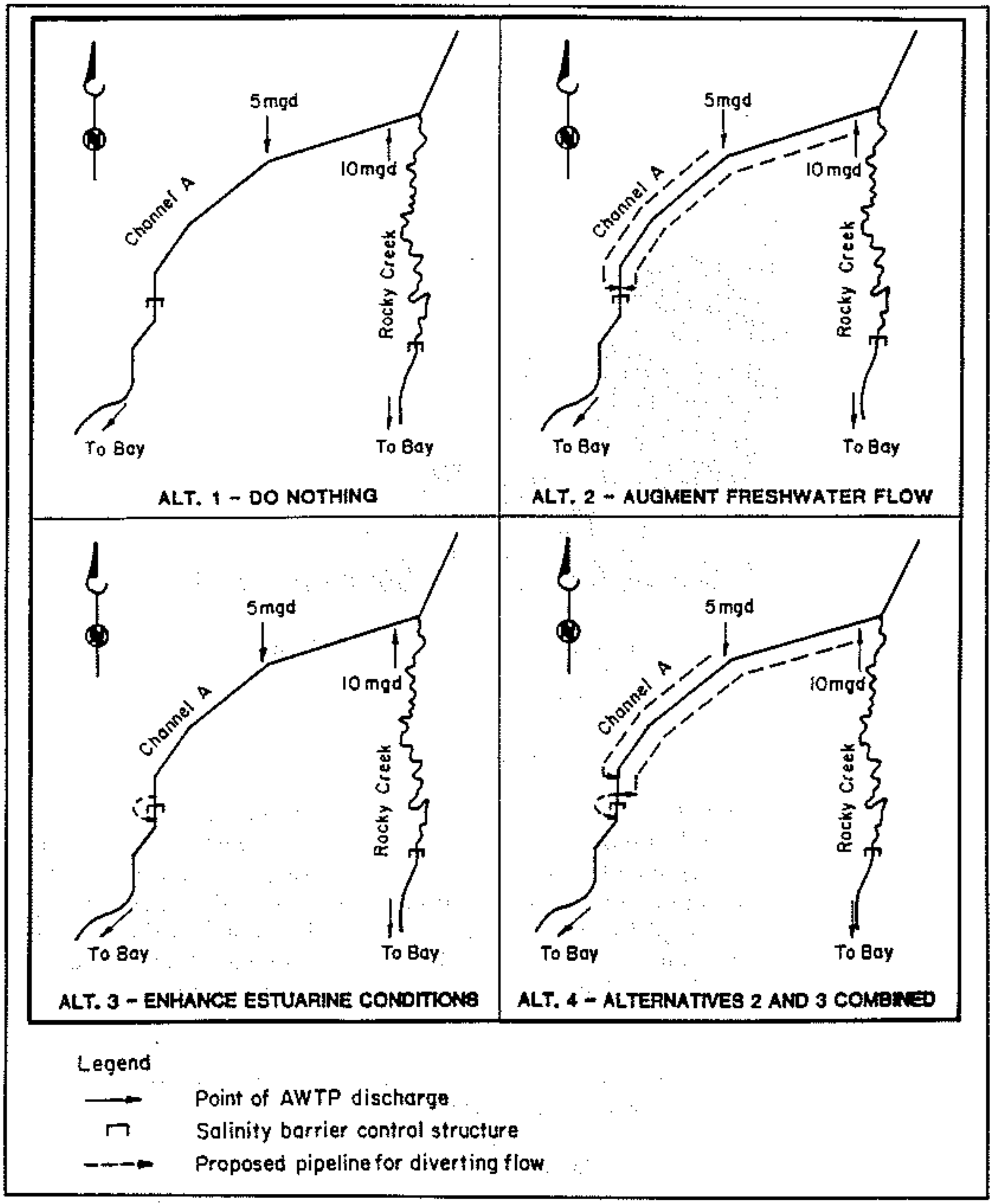

Figure 4. Stream flow augmentation alternatives for Channel "A" (Boyer and Clark 1989).

Stormwater runoff from urban and agricultural areas is considered the major source of water quality impact to Tampa Bay. Dames & Moore (1990) evaluated the relationship of land uses and stormwater runoff in the Tampa Bay watershed and reported,

> While more intense residential and commercial uses generate high levels of nutrients and metal, agricultural areas are also contributors of significant nutrient amounts. In general, nutrient and metal loadings were highest in the most urbanized parts of the watershed: lower Pinellas County, Tampa and urban parts of surrounding Hillsborough County and Bradenton. Also high in nutrient loadings are mining and agricultural regions of the watershed, including some of the Little Manatee River, Manatee River and much of the Manatee River basins.

New development is required to conform to stormwater management regulations (Chapter 17-25, F.A.C.) administered by the Florida Department of Environmental Regulation, and Chapter 40D-4 of the Southwest Florida Water Management District (SWFWMD). However, the majority of the watershed was developed prior to stormwater legislation in 1982, posing a particularly intractable problem. Constructing stormwater controls in developed areas, termed retrofitting, requires large tracts of land and financial resources. Regional treatment areas, possibly using parks or borrow pits, will help to alleviate water quality impacts created by urban stormwater runoff. Illegal discharges continue to be problematic in residential areas where waste oil, paints, lawn clippings, septic haulers and carpet cleaners dump inappropriate wastes into storm drains, ultimately impacting the receiving water body.

Incentives to reduce stormwater runoff from agricultural areas are needed to limit loadings of nutrients, fertilizers and pesticides. Protective strategies can include maintaining a buffer between agricultural areas and tributaries, and control of fertilizer and pesticide use, and irrigation runoff. Local governments are developing stormwater utility fees to provide sufficient revenue for the regulation, maintenance and rehabilitation of stormwater management systems and the construction of new controls in developed areas (TBRPC 1989). The utility fees should also support the development of watershed management plans to comprehensively evaluate and control stormwater within problematic drainage basins.

Consideration will be required to balance costs with water quality benefits for urban and agricultural areas. The Dames & Moore (1990) analysis, funded through the SWFWMD Surface Water Improvement and Management (SWIM) program, provides the baseline for determining watershed subbasins with the highest pollutant loading rates, based on land uses and runoff conditions. Development of prioritized watersheds for implementation of stormwater controls will support state and local government initiatives to improve water quality runoff from developed areas.

Biological Consequences

Tampa Bay serves as the focal point for urbanization activities in the region, both historically and today. Man's presence in the region has encroached upon many of the river and creek systems while retaining the natural character of others. The Tampa Bay Regional Planning Council (1986b) established a land use analysis of the region between 1957 and 1982 based on aerial photography. Urban land uses expanded 214% (171,000 acres) over the 25-year time frame, accounting for drastic reductions in natural communities. Wetland communities tributary to the bay suffered monumental losses; freshwater emergent vegetation declined by 56% (11,000 acres), and estuarine marsh vegetation also decreased by 56% (4,400 acres) from its 1957 coverage (TBRPC 1986b).

Historically, the tidal tributaries to Tampa Bay were immensely productive systems, providing critical habitat, protective cover, feeding and breeding grounds for early developmental stages of marine and estuarine life forms. In understanding the role of tributaries as fishery habitat, Lewis et. al. (1985) reviewed the life history stages of recreationally and commercially important species of fish and shellfish including snook, redfish, tarpon, spotted seatrout and pink shrimp, and reported,

> First, all of the species are near-shore oceanic spawners. Secondly, all use a multitude of habitats throughout their life cycle (i.e., none spend their entire lives in mangroves). Thirdly, all of the species show a preference for a low salinity nursery habitat that often includes marshes or mangroves at the upper limit of tidal influence in tidal freshwater streams.

The Little Manatee River is currently the focus of a basin-wide assessment to develop an extensive data base that describes basic relationships between land use, freshwater runoff, and biological cycles and productivity in the estuary. Fishery analyses by the Florida Department of Natural Resources (FDNR) in the Little Manatee River identify the location of juvenile fish species associated with salinity regimes, as illustrated in Table 2.

Table 2. Little Manatee River percent biweekly catch of juvenile fish per unit effort, 1988 (from Dr. Ed Matheson, Florida Marine Research Institute, personal communication, 1991).

	STATION					
	1	2	3	4	5	6
Silver perch	61	18	7	10	4	0
Sand seatrout	0	25	75	0	0	0
Spotted seatrout	50	20	10	20	0	0
Spot	25	39	20	12	4	0
Red drum	5	30	40	20	5	0
Striped mullet	9	11	30	50	0	0
Mean salinity (ppt)	20.4	12.4	7.8	2.2	0.8	0.2

Extrapolating the station location with percent fishery catch, Figure 5 identifies approximately the location of critical juvenile fishery habitat in the Little Manatee River for the red drum (*Sciaenops ocellatus*) based on the DNR sampling. The Little Manatee River intensive survey provides a guide that can be applied to other rivers and streams. Protection and restoration activities can then balance fishery needs with enhancement of juvenile habitats.

Tampa Bay is home to a rich, diverse assemblage of 25 species of colonially nesting waterbirds including pelicans, anhingas, cormorants, herons, egrets, ibis, spoonbills, gulls, terns, skimmers, and oystercatchers. Because they feed on fish and aquatic invertebrates, all of these species depend upon productive bay waters and wetland systems for survival. By annually monitoring breeding numbers and nesting success, inferences can be drawn about the causes of population changes and management recommendations can be developed:

> In this highly abbreviated summary, the health of Tampa Bay colonial birds is limited to three important factors: drought, continuing loss or degradation of wetlands, and predation. Their impact is illustrated by population changes in two species ... White Ibis numbers in Tampa Bay remained "stable" at 1989 levels—about 5000 breeding pairs. "Stability" is, however, an illusion, for the population total represents just half of the numbers of the early

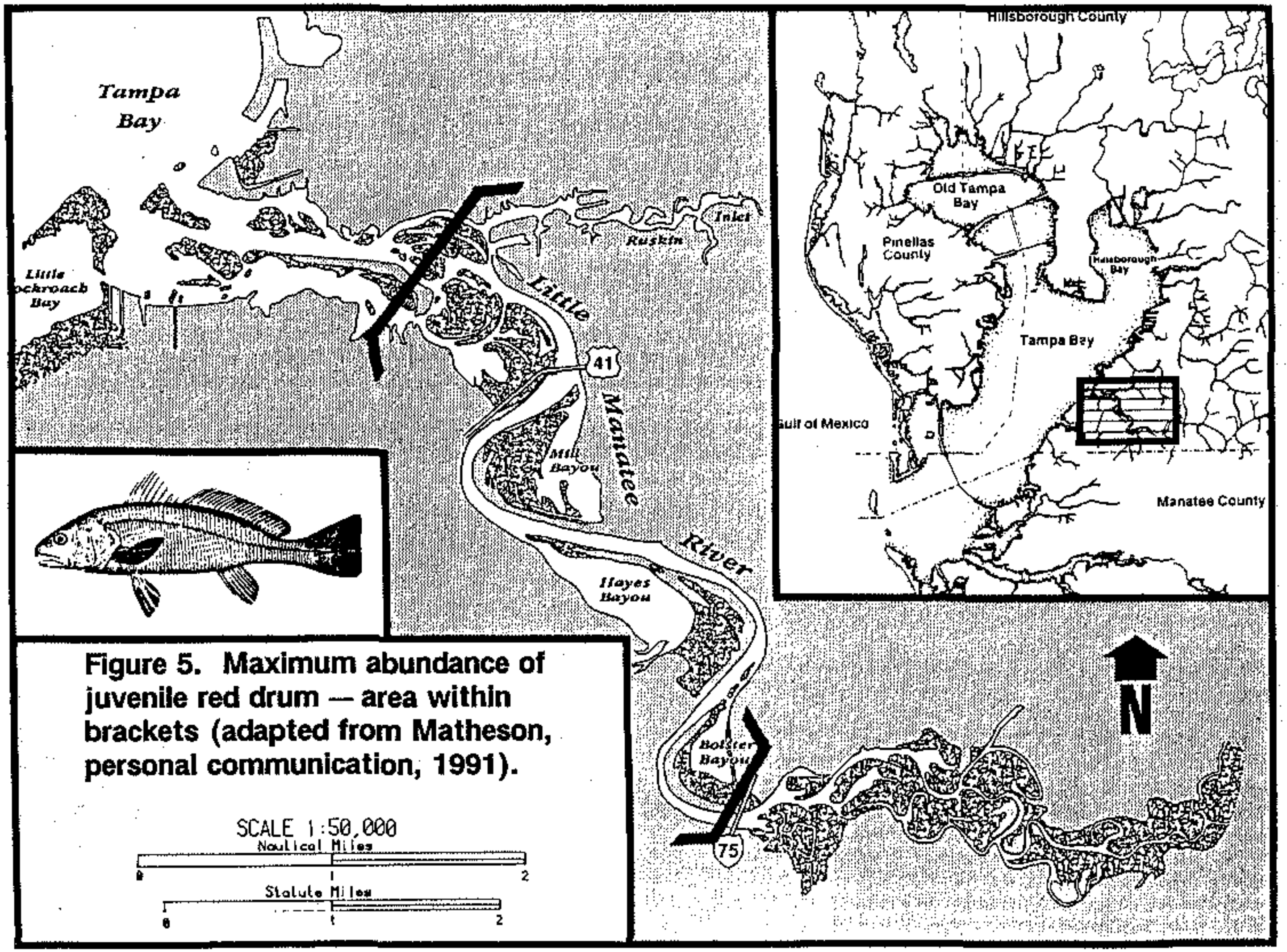

Figure 5. Maximum abundance of juvenile red drum — area within brackets (adapted from Matheson, personal communication, 1991).

> 1980s, and only 10% of the population in the 1940s! This population crash mirrors the losses reported for the Everglades system over the same period. The decline is attributed to the combined impacts of residential/commercial development of pasturelands and wet prairies, and the drought.... Other species thought to be similarly affected (by the loss of freshwater wetland forage habitat), both in 1990 and in the long term, included the Little Blue Heron, Snowy Egret, Great Egret, and Glossy Ibis. (Paul 1991).

The decline in freshwater wetland systems equates to a reduction of important forage area for birds, and is reflected by the declining trend in population of colonial birds in Tampa Bay, miles away from the feeding grounds.

TOOLS FOR MANAGEMENT

As our level of understanding increases for tributaries, research, restoration and protection will become more commonplace in our efforts to enhance the natural environment. It is of equal importance to identify those tools which are available now to begin management efforts for regional tributaries.

Permitting Process

Resource protection efforts were greatly expanded in the 1980s with adoption of wetland protection and stormwater management regulations by the Florida Legislature. Water Use Permits (WUPs) are administered by the SWFWMD and are used to govern freshwater withdrawals from ground and surface water sources. The WUP process offers the opportunity to evaluate major activities that affect freshwater distribution to the Tampa Bay estuary. WUP renewals and new applications need to be tied to the SWFWMD SWIM Plan for Tampa Bay. The potential exists to balance reservoir use with fish and wildlife requirements through innovative management strategies, such as:

- management of water release from dam structures to maintain optimum freshwater flows;
- construction of off-stream reservoirs or expansion of existing reservoirs to augment storage capacity and allow additional downstream flows; and,
- storage of wet weather flows in groundwater geological structures to provide additional capacity during the dry season.

Domestic wastewater permits, administered by FDER, can be a source of AWT wastewater effluent to supplement potable water supplies in reservoirs. However, public perception may limit the use of AWT effluent in potable water supplies. Highly treated effluent can also enhance freshwater flow to the estuary in areas where flow has been reduced. Highly treated effluent can be used to achieve ideal salinity gradients in impacted or manmade tributaries (i.e., Channel "A" or the Adamsville Fish Farm project) or to improve circulation and flushing.

The stormwater permitting process, through Chapter 17-25, F.A.C. administered by the Florida Department of Environmental Regulation, and Chapter 40D-4 administered by the SWFWMD, provides the conduit to balance freshwater flows in tributaries and buffer water quality impacts while increasing wetland habitats. An environmentally sound stormwater treatment system can provide water quality treatment through construction of vegetated littoral shelves while gradually releasing freshwater to the receiving water body. The treatment height of the pond can be designed to enhance adjacent wetland communities by restoring historic hydroperiods.

Delaney Creek is an example of a watershed classified as a "peak sensitive area" by Hillsborough County in that it is susceptible to flooding due to the inability of the outfall to discharge runoff volumes. Additional storage volumes and subsequent reduction of runoff times can alleviate the pulse of freshwater after rainfall events and the flooding of downstream areas.

Wetland modification permits (or dredge and fill permits) administered by the FDER and local governments should be coordinated with stormwater permits to restore channelized tributaries by reducing shoreline slope, increasing cross-sectional area, and planting with native aquatic plants. Developments can combine wetland mitigation and stormwater treatment in some cases by constructing a meandering tributary alignment with a high and a low flow passage from a previously channelized system. Agricultural ditches and flood control channels recontoured along one side will allow habitat and water quality improvements, while maintaining the other side for future maintenance activities.

Comprehensive Planning

In 1985, the population growth and related development experienced by the Tampa Bay region, and the state of Florida as a whole, prompted the Florida legislature to take an historic step by passing the State and Regional Planning Act (Chapter 186, Florida Statutes). The Florida legislature established an integrated planning process—comprised of the State Comprehensive Plan, state agency functional plans, comprehensive regional policy plans and local government comprehensive plans—designed to manage future growth.

In accordance with Chapter 163, Part II, Florida Statutes, and Chapter 9J-5, F.A.C., local governments in the Tampa Bay region and throughout the state are required to prepare and adopt local comprehensive plans that are consistent with and further the State Plan and the applicable regional plan. Although not required to address specific state and regional plan goal areas, local plans must address a minimum number of "elements"—future land use, coastal management and conservation—that are directly related to the State Plan, agency functional plans, and the regional plan. As an example, the purpose of the coastal management element is to have local government plan for, and where appropriate restrict, development activities where such activities would damage or destroy coastal resources.

Local government plans provide the conduit to construct and implement basin-wide resource protection goals and policies which then can be implemented though local zoning and land use ordinances. Land use designations should also consider locations within the watersheds. Staggered densities along tributary systems will buffer runoff impacts, wetland losses, and maintenance of habitats from often unintentional impacts.

Another concept which is receiving greater attention in the Tampa Bay region is the creation of "protective overlay districts" for specific drainage basins. Protective overlay districts recognize unique conditions within a watershed and establish land use criteria that allow for development while protecting those natural communities and recreational areas from development that is inconsistent with the resource. Geographical overlays are delineated on local government land use maps, while supporting text is included in the comprehensive plan and land use regulations. Currently, the Tampa Bay Regional Planning Council's Agency on Bay Management is working with Hillsborough County to develop a protective overlay district for the Cockroach Bay basin.

Tributary Management Programs

The Surface Water Improvement and Management (SWIM) Act of 1987 identifies Tampa Bay and its tributaries as a priority water body in need of restoration and preservation. The development of the SWIM Plan for Tampa Bay (SWFWMD 1988) identified numerous priority projects, including:

- prioritization of urban sub-basins;
- urban stormwater retrofit projects;
- habitat restoration;
- agricultural soil and water conservation plans;

- model environmental and land use ordinances; and,
- modeling of the Tampa Bay ecosystem.

The SWIM program continues to play a lead role in the development of vital research information and construction of habitat restoration projects. The ability of the SWFWMD and its basin boards to maintain current funding levels for the SWIM program is critical to the continued restoration of the Tampa Bay system.

Additional SWIM objectives can include the development of stormwater management programs to be implemented by the SWFWMD and local governments, using technical information acquired from the Little Manatee River assessment, urban stormwater assessment (Dames & Moore 1990), ongoing nutrient budget analysis, and other SWIM funded research activities. As previously mentioned, the SWIM program should review WUP and wetland modification applications for consistency with SWIM program objectives. It is imperative that research efforts be included within land use controls and the permitting process if protection efforts are to be coordinated.

The Council's Agency on Bay Management and the Environmental Protection Agency's (EPA) National Estuary Program (NEP) for Tampa Bay represent two regional bay management activities that are directed to monitor and manage the bay and its watershed. The recently created Tampa Bay NEP is charged with the construction of a Coordinated Comprehensive Management Plan (CCMP) that will potentially commit federal, state and local governments to a management plan created through the consensus building process. The CCMP can recommend protective strategies for governments to fund and implement, ultimately leading to the restoration of benefits that the bay provides.

The Hillsborough River receives added protection through the efforts of the Hillsborough River Board and Technical Advisory Committee (TAC), administered by the Hillsborough County City-County Planning Commission. The committees have completed a river master plan and continue to monitor activities that affect the river, promote public awareness, and establish communication between the many different agencies involved with protecting the Hillsborough River. The 1991 Florida Legislative Session is considering expanding the River Board and TAC to include the Alafia and Little Manatee Rivers as well.

Citizen Activities

Several citizen initiatives have established basin protection programs. The Little Manatee Preservation Committee organized residents along the Little Manatee River to provide a voice on resource protection issues such as commercial fishing and land development, and have led efforts to purchase environmentally sensitive lands at the river mouth and in Little Cockroach Bay. Similar activities are also being accomplished by the Citizens for Alafia River Preservation (CARP).

The Lake Manatee Watershed Advisory Committee was established by Manatee County to advise on protection of the Manatee Reservoir water supply, mining and agricultural development, and protection of natural areas and recreational resources in the drainage basin. The Sierra Club has been active in land acquisition efforts in Hillsborough County to provide a wildlife corridor between the Alafia and Little Manatee Rivers, and to expand the Cockroach Bay Aquatic Preserve into the Little Manatee River.

Hillsborough Community College has assisted in the coordination and development of citizen programs through Riverquest conferences. Technical speakers provide background presentations for each tributary and the public is then encouraged to identify problems and develop solutions (see Hillsborough Community College 1989). The Riverquest conference has been held every two years since 1987.

Land Acquisition Programs

The purchase of environmentally significant lands provides the following benefits to residents in the Tampa Bay Region:

- preserves wildlife habitats;
- provides recreational areas;
- protects land from development;
- yields land for habitat restoration and stormwater enhancement efforts; and,
- sets aside land at current costs.

Land acquisition programs are strongly supported in the three counties surrounding Tampa Bay and serve to provide local support for state programs. Agencies involved with land acquisition for the bay include:

- Conservation and Recreational Lands (CARL) program administered by FDNR with approval by the Florida Cabinet.
- Preservation 2000, the 1990 Legislature assigned the Land Acquisition Advisory Council (LAAC) the task of preparing a Preservation 2000 Needs Assessment.
- Save Our Rivers Program administered by the Water Management Districts
- Environmental Lands Acquisition and Protection Program - Hillsborough County
- Pinellas County Endangered Lands Acquisition Program

In addition, Manatee County is active in land purchases to buffer the Manatee River watershed and Emerson Point on Tampa Bay. The Nature Conservancy and the Trust for Public Lands are private land purchasing programs.

The Council's Agency on Bay Management took the initiative in 1990 to establish the Land Evaluation and Acquisition Forum (LEAF) to assist governmental agencies and non-profit organizations with protection of natural areas for preservation and recreation. Objectives of LEAF are to:

- coordinate acquisition activities around Tampa Bay;
- develop a regional land acquisition priority list;
- expedite acquisition by supporting on-going programs; and,
- support the development and security of local and state land acquisition programs.

Since there are numerous agencies involved with land acquisition efforts, it will be advantageous to coordinate and support agency initiatives through the Agency's LEAF committee.

SUMMARY OF RECOMMENDATIONS

Tributaries maintain the estuarine character of the Tampa Bay system while providing critical habitat, refugia, breeding areas and food sources for many fish and wildlife species. A priority objective of bay managers will be to evaluate freshwater flow conditions and remaining habitat components to assimilate and construct conditions which support and enhance the bay's resources. Many papers in this volume provide the baseline data to develop optimum tributary salinity gradients that support remaining habitats. Compilation of the information should:

1. Evaluate historic and existing freshwater flows and salinity patterns in rivers and larger tributaries to Tampa Bay;
2. Analyze remaining natural communities and potential restoration areas to reestablish those communities that have been displaced, and consider management of the saltwater wedge/productivity zones to coincide with remaining structural habitat; and,
3. Combine established optimum salinity gradients and habitat elements onto existing land use maps and develop a list of tactics for each responsible agency to enhance the tributary systems.

Management of downstream flows will require innovative wastewater treatment plant effluent disposal techniques and improved reservoir controls to coordinate the saltwater interface. Ultimately, as resource needs are identified for specific species, bay managers can target salinity regimes for restoration of that particular resource (e.g., snook, redfish, white ibis).

It is also imperative to tie together existing management efforts with permitting agencies and comprehensive planning. Development of watershed management plans, as a function of a bay management plan, will provide the framework for permitting activities and land use decisions. Finally, the general public continues to benefit from education and awareness programs that identify restoration and protection needs. Ultimately, the public will be required to fund renewal activities, while protecting the resources in their backyard. Importantly, Tampa Bay has had a successful record in improving the bay environment which results in many positive benefits to the region.

ACKNOWLEDGEMENTS

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Tampa BASIS 2 Student Poster Award
CERTIFICATE OF EXCELLENCE
Graduate Student

NITROGEN ENRICHMENT OF TAMPA BAY AND LITTLE MANATEE RIVER PHYTOPLANKTON POPULATIONS

P. Rodriguez
Advisor: G. A. Vargo

ABSTRACT

Samples from a fixed location in Tampa Bay and the 12 ppt salinity zone of the Little Manatee River (LMR) were collected monthly and enriched with five nitrogen levels and with silicate. Final yields for all experiments at both locations displayed positive, linear relationships with added nitrogen for the total size fraction in 7 of 11 samples from Tampa Bay and 10 of 11 samples from the LMR when yield was expressed as chlorophyll, particulate carbon or nitrogen. A more hyperbolic relationship between yield and nitrogen addition, possibly indicative of limitation by other nutrients, characterized the samples from April through July in Tampa Bay and April in the LMR. Increases in the yield of the less than 12 and 5 µm size fractions was minimal in all experiments. Growth rates for the total size fraction from both locations generally displayed a hyperbolic response to added nitrogen with saturation between 5 and 25 µm. Diatoms dominated the final yield in all experiments. There was no indication of silicate limitation since its addition to selected nitrogen levels did not increase final yields. The positive, linear relationships between final yield and nitrogen addition for the total size fraction indicate that nitrogen was the only nutrient limiting long-term growth and biomass in bay and river phytoplankton populations.

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Tampa BASIS 2 Student Poster Award
CERTIFICATE OF EXCELLENCE
Undergraduate Student

THE EFFECTS OF NITROGEN AND PHOSPHORUS ON PERIPHYTON IN A MARINE ENVIRONMENT: HILLSBOROUGH BAY, TAMPA, FLORIDA

A. Clendennen
Advisor: B. H. Rosen

ABSTRACT

The stimulation of the periphytic algal community by nutrients was examined in Hillsborough Bay, Tampa, Florida. Eight artificial nutrient-releasing substrates (clay flower pots) which contained 0.5 M nitrogen (N) or phosphorus (P) or both of these nutrients, as well as a non-nutrient control, were positioned in a 25 m^2 grid in the littoral zone of Hillsborough Bay. After two weeks, the substrates were collected and the algae that had colonized and grown on each substrate were counted and identified. The non-nutrient control substrates averaged 106,279 cells/cm^2; the N-releasing substrates averaged 137,494 cells/cm^2; the P-releasing substrates averaged 65,162 cells/cm^2, and the combined N and P averaged 81,034 cells/cm^2. In addition to the overall increase in the number of cells on the N-releasing substrates compared to the control, the growth of specific organisms that had colonized the substrates was stimulated. Navicula and Achnanthes were stimulated by the N-releasing substrates, with more cells/cm^2 compared to the number of cells on the non-nutrient releasing substrates. In contrast, the N-releasing substrates hindered the growth of Nitzschia and Amphora. Phosphorus-releasing substrates suppressed the growth of most periphyton that colonized; the number of Navicula and Cocconeis cells/cm^2 were fewer than on control substrates. Only Achnanthes was stimulated by this treatment. The combination of N and P, with both stimulatory and inhibitory effects, caused the periphyton to show an intermediate growth response in cell number.

Certain algae appeared to be nutrient-independent because they occurred in equal numbers on all the substrates. These results indicated that certain species were not inhibited or enhanced by the concentration of N or P used in this experiment. Enteromorpha was an example of a nutrient-independent alga. The total number of species of organisms was fairly constant in each of the treatments; however, the density of individual species showed that nutrients can alter the periphyton community in Tampa Bay.

INTRODUCTION

Periphyton are a vital constituent of aquatic life in the Tampa Bay estuarine system. They contribute oxygen through photosynthesis and provide food for invertebrates and larval fish. Most periphyton are photoautotrophic, utilizing light along with inorganic nutrients for growth and the synthesis of new biomass. Several nutrients are essential for growth; however, nitrogen (N) and phosphorus (P) are the major elements that govern growth and succession in most habitats.

One nutrient that must be extensively examined is N and its relationship to P. The Tampa Bay estuary has excess P and is apparently N-limited. Nitrogen to phosphorus ratios have been extensively studied and these two elements work opposite one another; if N is limiting, P is not and if P is limiting, N is not. Therefore, if the estuary is truly limited by N, the concentration ratio between N:P should be below 10:1. Most algae are considered limited by N at this ratio, although each organism has an optimum ratio (Smith 1983), and any given ratio will cause competition between species.

Excess nutrients in the Tampa Bay may promote the growth of an undesirable algal species and exclude desirable and sensitive species. Although we know that P is in abundance in the Tampa Bay, the interactive effects between N and P have not been examined. This study used artificial nutrient-releasing substrates to examine manipulated levels of N and P on periphyton growth.

MATERIALS AND METHODS

Artificial nutrient-releasing substrates were constructed from clay pots. These pots were soaked in 10% hydrochloric acid (24 hr) to remove contaminants, rinsed in deionized water until the rinse water had a neutral pH, and then dried. A petri dish was attached to the wide part of each pot with silicon cement to make a chamber. Duplicate pots were filled with nutrient solutions with 0.5 M nitrogen (from $NaNO_3$) and/or 0.5 M phosphorus (from NaH_2PO_4) and solidified with 2% agar. Non-nutrient releasing substrates which served as controls contained only 2% agar. Previous studies on similar substrates showed a release rate of 9.3 and 8.6 mmole/day for N- and P-releasing substrates, respectively (Fairchild et al. 1985). Rubber stoppers, with a piece of 4-inch dowel inserted into each, were glued to the bottom of the petri dish to anchor the pots in the sand/rubble bottom of Hillsborough Bay. The substrates were placed randomly in a 25 m^2 grid, 0.5 meters apart and at an average depth of 0.75 meters at high tide. After two weeks, the substrates were removed from the Bay, placed in plastic bags, and processed on the day of collection. A razor blade was used to scrape the periphyton from the pots (surface area of 49.17 cm^2) into an enamel pan and the entire sample was preserved with gluteraldehyde. Care was taken to remove all of the periphyton and quantitively transfer samples. Two sub-samples of preserved periphyton were enumerated at 400x from each duplicate substrate using a nannoplankton counting chamber.

RESULTS

A total of 20 different genera were found on the substrates. The maximum number of genera in any treatment was 18 while the minimum was 12. The most abundant organism in all treatments was the diatom *Navicula*, which was stimulated by the N treatment and inhibited by the P treatment. *Achnanthes*, another diatom, was stimulated by both nutrient treatments, separately and together, while *Amphora* and *Nitzschia* were inhibited by the nutrient treatments. *Cocconeis* and *Gyrosigma* were inhibited by the P treatment, and were not affected by the N or combined treatment relative to the control. *Enteromorpha,* a green alga, was found on all substrates but showed little variation in cells/cm^2. Some algae found, such as *Coscinodiscus, Biddulphia* and *Skeletonema* were enumerated but not addressed because they represent planktonic organisms rather than a normal constituent of the periphyton community.

DISCUSSION

If one species can utilize and grow with a nutrient concentration that is limiting for another, a competitive advantage may be established. Nutrient uptake kinetics have been demonstrated to regulate competition in algae (Kilham 1971). The N:P ratio has been the target of recent investigations on periphyton of freshwater communities (Carrick et al. 1988, Fairchild et al. 1985) but has been neglected in marine periphyton studies. Excess P, a condition in the Tampa Bay and most coastal waters (Round 1981), creates periphyton that are N-limited. In our study, the addition of extra P suppressed growth of the overall periphyton community and probably exerted its effect by creating a N:P ratio that enhanced N deficiency. Nitrogen deficiency can cause a repression of the cell division, as demonstrated by Admiraal (1977), where growth of nitrogen-limited organisms approaches zero when high levels of phosphorus were found.

Phosphorus influences many metabolic processes in algal cells, such as the generation of ATP during photosynthesis. An adequate supply of P is vital to the maintenance of these metabolic processes, which ultimately translates into cell growth and division. Phosphorus has also been shown to affect carbon pathways (Harris and Piccinin 1983) and N uptake (Terry 1982), thereby directly affecting cellular growth rate. In this study, we have shown that P has a complex effect on the periphyton community by stimulating certain organisms and inhibiting others.

The response to nutrients did not cause a shift from a diatom-dominated community, although other taxonomic groups were present. One ubiquitous green alga, *Enteromorpha*, was equally distributed on all of the nutrient-releasing substrates and apparently was nutrient-independent. For an organism such as *Enteromorpha*, the availability of substrates to attach to is probably the limiting factor and not nutrients. In addition, this organism grows erect from the substrate and would not acquire nutrients directly from contact with it. These findings clearly indicate the complexity and adaptability of the periphyton community. Guilds of functionally related organisms along nutrient gradients have been demonstrated in fresh water (Carrick et al. 1988) and this study indicated the probability of these kinds of guilds in the marine habitat as well.

Thursby and Davis (1984) considered *Nitzschia*, *Navicula*, *Achnanthes*, *Cocconeis*, *Amphora* and *Cymbella* to be pollution-tolerant species. Other than the suppressed growth of *Cocconeis* and *Amphora*, our study agrees with this. Changes in the nutrient status in the periphyton community, even substantial ones, are accommodated by the periphyton.

Periphytic communities can be an indicator for degrees of pollution. Organisms such as *Nitzschia*, are known to be tolerant to certain chemicals, and it can remain reproductively active in habitats with extreme environmental conditions (Lange-Bertalot 1979). Several species of *Navicula* are also tolerant to poor environmental conditions (Admiraal 1977). This study illustrates the complexity of the periphyton community and contributes to the much needed information about the effects of nutrients on periphyton which are a vital part of marine ecosystems.

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Tampa BASIS 2 Student Poster Award
CERTIFICATE OF MERIT
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WATER QUALITY IN THE URBAN DRAINAGE BASIN OF SWEETWATER CREEK

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Advisor: R. Brinkmann

ABSTRACT

Several water quality parameters of a cypress swamp within the Sweetwater Creek drainage basin in Hillsborough County, Florida, were investigated to determine if there are excess nutrients present. The swamp receives overflow from urban stormwater runoff retention ponds. The surface of the cypress swamp drainage basin contains 20% lawn, 20% impervious surface, 24% water and wetland, and 36% pasture/woods. Samples collected from the overflow ponds and the swamp during a dry, no-flow period do not contain excess nutrients. In contrast, one sample collected from Sweetwater Creek, which receives direct urban runoff, contains a high level of phosphate.

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SAWGRASS LAKE PARK: WATER QUALITY IN AN URBAN WETLAND

M. R. Hafen
Advisor: R. Brinkmann

ABSTRACT

In order to assess the effects of urbanization on the water quality of wetlands, the Sawgrass Lake drainage basin and its associated red maple swamp, which are located in Pinellas County in west central Florida, were analyzed. The parameters of pH, dissolved solids, and conductivity were measured quantitatively; ammonia, chlorides, chlorine, chromium, copper, cyanide, iron, nitrates, phosphates, and sulfides were analyzed qualitatively. Based upon the results of the study, urbanization within the Sawgrass Lake drainage basin has not deleteriously affected the water quality of wetlands in the area. Further studies which would analyze a broader array of water quality parameters are suggested.

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BOATER INTERVIEWS REGARDING SEAGRASS PROP SCARS

B. Israel
Advisor: J. Morris

ABSTRACT

Prop scars are increasingly evident in the seagrass beds of Florida's bays. Given the ecological import of such grasses, people are beginning to recognize the need for influencing boater behavior. In Sarasota, as part of the Seagrass Signage Project of the National Estuary Program, we conducted 243 boater interviews in March of 1990. Our goal was to learn more about the boater population—their behaviors, attitudes, and awareness—with respect to the seagrass flats. Through this study, we have improved our appreciation of the boaters who are using the bay's resources. It is our hope that management techniques which acknowledge the needs and attitudes of boaters will be effective in trying to curtail the frequency and extent of prop scars.

According to self-reports, most boaters do not run aground in the seagrass beds. Forty-one percent of the boaters interviewed report that they run aground in the seagrass beds occasionally (36%) or often (5%). The majority of boaters (59%) report that they never run aground. While this indicates that a minority of boaters are running aground in the seagrass beds, it represents a large and critical population. Furthermore, with record growth in southwest Florida and the subsequent increase in boater registrations, the base number becomes increasingly serious. The threat to the grass flats is also aggravated by less severe types of seagrass interaction, such as mud churning and local turbidity. The probability of such occurrences accentuates the need for managing boater behavior.

RESULTS AND DISCUSSION

Majority Populations

Our interview population, chosen from local boat ramps, is heavily skewed. Eighty-two percent are male; 93% own their boats; 82% are full year residents; and 64% are sport anglers. With the exception of sport anglers, there was no significant increase or decrease in the rate of seagrass interaction based upon these groups. About 46% of boaters who are sport anglers run aground occasionally, while only 41% of the total population runs aground occasionally.

Conditions for Running Aground

Boaters were asked which conditions cause them to run aground in the seagrass beds. One quarter (25%) of the boaters blamed general unfamiliarity as a causal factor. This percentage, however, must be qualified. When we examine only those boaters who actually run aground, the number of people who blamed "unfamiliarity" drops significantly. While 46 boaters in total stated "unfamiliarity" as a condition for seagrass interaction, only 9 of those boaters who run aground claimed that "unfamiliarity" is an important factor.

We can identify two distinct categories of boaters who are running aground in the seagrasses. For the first group, channel and seagrass markers would be effective. For the second group, such markers would not be effective. Thirty-eight percent of the responses of boaters who run aground stated that a "lack of markers" is a primary condition for seagrass interaction. For this group, we can assume a positive result if we place markers in appropriate locations throughout the bay.

Thirty-four percent of the responses of boaters who run aground stated that "misjudged tides" and/or "fishing in the grass flats" are primary conditions for seagrass interaction. Of the responses, 20% blamed misjudged tides, while 14% blamed fishing. We should assume that these boaters are familiar with the seagrass beds, and have entered them intentionally. Therefore, managers should consider strategies other than markers for preventing scars from these boaters.

Escape Behavior

Escape behavior is an important aspect of seagrass interaction. How a boater chooses to get out of a grass bed will often determine the extent and degree of scarring. A small minority of boaters (15%) feel that using the boat's motor is the most effective method for escaping a grass flat. It is thought that the motor release methods are responsible for many of the large scars visible from aerial photographs. Most boaters (51%) simply walk their boats to deeper water. Other methods include paddling (11%), poling (13%), and waiting for the tide (7%).

Interestingly, a larger percentage of people using the motor release method admit to running aground than the general population. While only 41% of the general population run aground in the grass beds, two-thirds (67%) of those using the motor release method run aground.

Acclimating Boaters

A major aspect of changing boater behaviors will revolve around education. Education refers specifically to seagrass markers, boat ramp signs, brochures, public speaking engagements, and safety courses. What should be the content or message of such efforts? What did we learn from the boater interviews that might aid in the development of educational materials?

Boaters' attitudes indicate that educational materials should focus on potential ecological damage, as opposed to damage to boats, possible inconvenience, or legal implications. Our goal, then, should be to acclimate boaters to the bay's biological and chemical functions. Such an approach would be appropriate to the goal of habitat preservation, and would be effective in changing behaviors, according to the boaters interviewed.

This conclusion is supported from a number of questions, including an in-depth "scenario" proposition. Boaters were asked to respond to a hypothetical scenario in which they were responsible for placing signs around the seagrass beds. Boaters were told to create the sign which would be most effective or persuasive to the largest number of people. The boater was instructed to disregard the message he or she might personally find convincing, and think only about motivating others.

Nearly half of all responses said that the signs should focus on habitat, wildlife, nursery, or grass destruction. This represents 131 responses. Meanwhile, only 30 people mentioned possible damage to boats, and only 12 people thought that mentioning possible inconvenience would be effective. Twenty-six boaters felt that posting legal implications would be persuasive; another 35 people suggested that the signs simply read, "Keep out — shallow water".

ACKNOWLEDGEMENTS

The Boater Interview Project was written and compiled by the author. The project was supervised by Ruth Folit and Julie Morris at the Environmental Studies Program of New College, University of South Florida, Sarasota. The interviews were conducted as part of the Seagrass Signage Project, in affiliation with the National Estuary Program of Sarasota Bay, which is part of the U.S. Environmental Protection Agency. Interviewers were the following New College students: Carrie Carrel, Deborah Graves, Lisa Milot, Catherine Molteno, and Dayna Ayers.

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EPIBENTHIC FAUNA OF SCARRED AND NONSCARRED PORTIONS OF A SEAGRASS BED

R. Corletta
T. Hunt
S. Barbeaux
A. Artis
L. Holland
Advisor: S. Gilchrist

ABSTRACT

Two field studies were undertaken to investigate whether motor boat propeller scars have an effect on the epibenthic faunal composition of a Thalassia testudinum seagrass bed. Although the latter of the two studies was a continuation of the first, for purposes of analysis the studies are treated separately. The first study was done in January and February of 1990 and the second was done in April and May of 1990. Both studies were sponsored by the Environmental Studies Program of New College of the University of South Florida which is under contract from the National Estuary Program's Sarasota Bay Project.

Our hypothesis for both studies was that there is no difference in faunal composition between scarred and nonscarred areas of seagrass beds. Equal numbers of scarred and nonscarred transects were chosen and swept by a seine net to analyze the epibenthic faunal composition. The data from both studies suggest possible differences between scarred and nonscarred transects. During the January-February study there was a greater number of species in the nonscarred transects, while the later study indicated the opposite. The data we obtained suggest that specific species may occur in either a scarred or nonscarred portion of the seagrass bed. The data also indicate that the biomass of drift algae recovered affects the number of species obtained. The data obtained from both studies fail to support our hypothesis.

The data we collected were intended to be baseline data. For this reason we do not yet put forth possible causes for the differences observed. Further studies of these communities should incorporate seasonality as well as individual species preference and floral/faunal relationships; only then can possible conclusions be drawn.

INTRODUCTION

Because of their value and proximity to man, seagrass beds have been the topics of many studies. Orth et al. (1984), Heck and Orth (1980), and Heck and Whetstone (1977) have dealt with the effects on faunal composition that the character of a seagrass community has. Orth et al. (1984) addressed the effects seagrass can have on predator-prey relationships as well as correlating distinct aspects of plant morphology (the root-rhizome mat and the plant canopy) and certain species abundance. Although these are only a few examples of recent literature, they reflect the type of research typical of the field.

The effects of motor boat propeller scars on the ecology of a seagrass community is a subject that has not received enough attention. Zieman (1976) produced the first published study in the primary literature addressing this subject. To our knowledge, a faunal study comparing scarred and nonscarred areas of a seagrass bed has yet to be conducted. Our hypothesis is that there is no difference in faunal composition between scarred and nonscarred areas of a seagrass bed. The combined studies are an attempt to assess the biological composition of scarred and nonscarred areas. Both scarred and nonscarred areas were sampled by seine net and the specimens recovered were identified and counted. These samples were then compared and trends in biological composition were noted.

METHODS

The project consisted of two field studies of the seagrass bed between Coon Key and City Island in Sarasota Bay, Florida. This particular seagrass bed was chosen because it is surrounded by four channels, making it quite susceptible to motor boat propeller scars. Sampling of the eastern portion of the seagrass bed took place between January 18 and February 2, 1990, while sampling of the western end occurred between April 14th and May 6th of the same year. Scarred and nonscarred portions of the seagrass bed were selected and transects were established in each. The transects were measured to 30 m; wooden dowels were then placed at each end to be used as sights while sampling and also as points of reference for headings. Water depth, time, cloud cover, water and air temperature, and wind velocity were noted prior to the sampling of each transect. A one-eighth inch seine net, 3 m in length, was used to sample the transects, which were swept into the prevailing current. In the laboratory, organisms were sorted, identified and counted, and a representative of each species was preserved for future reference.

Some changes in methodology were made in the second field study (April and May sampling). Both scarred and nonscarred transects were swept simultaneously to obtain a certain amount of control over the prevailing abiotic parameters (i.e., cloud cover and time of day). Also, algal dry weight was recorded to evaluate its potential importance to faunal composition.

RESULTS

In the first study, the average number of species in the nonscarred transects was 32, while the average number in the scarred transects was 21. The data obtained from the second study indicated the opposite. There may not be such an obvious difference when one looks at average number of species data (35 scarred, 32 nonscarred) but it becomes quite clear when each sampling day is looked at separately. Because scarred and nonscarred transects were sampled simultaneously in the second study, average number of species data becomes less relevant than the analysis of each sampling day as an individual unit. For both studies, we chose to analyze the ten most populous species. Analysis suggests that an individual species may occur in a particular type of transect. Occurrences in both scarred and nonscarred transects were almost even among the most populous species.

The amount of drift algae recovered during sampling was recorded for four out of five sampling days during the second study. There seems to be a direct correlation with the amount of drift algae recovered and species number. This was most apparent with some gastropods, amphipods, and shrimp.

DISCUSSION

Although our studies suggest a difference in the faunal composition of scarred and nonscarred transects, the data do not show a common trend. Our average number of species data for both scarred and nonscarred portions of the seagrass bed may exemplify variability that is naturally built into the rich seagrass community. The data also show that certain species may occur in either the scarred or nonscarred areas of a seagrass bed. This would seem to imply either differences between the two areas or perhaps an edge effect (Gilchrist, pers. comm.).

The amount of algae recovered was greater in the scarred transects on three out of four sampling days. This does not necessarily mean that there was actually more drift algae in the scarred transects. Our sampling technique may not have represented the actual amounts of algae in the scarred and nonscarred transects adequately. This is important to consider because of the strong algae/species number correlation.

CONCLUSIONS

These baseline data suggest differences in the scarred and nonscarred transects when considering faunal composition. However, these possible differences are not very significant because of the inconsistency between the two studies. Since there is no common trend in our data, we may be simply observing the variability that is inherent to a seagrass community. Our data also indicate that some species may take advantage of the physical differences between scarred and nonscarred areas. In addition, drift algae may become trapped in the scars, providing an alternative means of shelter for particular organisms. The briefness of our study and the inconsistencies of our results would make it premature to dispute our hypothesis. Future research on the faunal composition in scarred and nonscarred areas of seagrass beds should account for seasonality, biomass, and density of all floral components of the seagrass community. It may also be more valuable to observe a specific group of organisms rather than a larger portion of the faunal community.

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GRAIN SIZE ANALYSIS OF THE LITTLE MANATEE RIVER

L. Kaylor
Advisor: R. Brinkmann

ABSTRACT

The grain size of sediments of the Little Manatee River were analyzed to determine if there was a relationship between mean grain size and distance from the mouth of the river. Eighteen samples were collected from the bottom of the stream at approximately one-half mile intervals beginning at the mouth of the Little Manatee River. Samples were sieved at one-half phi increments to determine the distribution of grain size within the samples. The results were graphed on histograms and on cumulative frequency curves. Generally, there is a decrease in grain size from the headwaters of the Little Manatee River to its confluence with Tampa Bay. These results may have implications for pollution transport in the bay coastal rivers of west central Florida.

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TAMPA BAY RAP

I'm gonna sing a song about the Tampa Bay,
So gather 'round me closely to hear what I say.
You know about the climate and the bright sunshine,
Lots of people come here and they feel real fine.

There are swimming pools and golf and it's a chef's delight,
After lying on the beach all day, we party at night.
What is all this fuss about the rate of growth?
Bring on fish <u>and</u> people 'cause we like 'em both.

There's tons of shrimp and oysters and that ain't no lie,
Enough to keep my tummy full before I die.
So why all the hassle 'bout pollution controls?
Some environmental nuts want us to set strict goals.

They say we need to better plan our flows and watershed,
I say they've lost their marbles and have water in the head.
Then they say there's acid and high sedimented loads,
That causes "eutracation" when the rain runs off the roads.

They don't know where it comes from, so they say it's "nonpoint" source,
That to me's a cop out, and it only gets worse.
There's little circulation and the light won't penetrate,
If we don't soon mend our ways, then it just may be too late.

Fletcher said the sea is up, Hess' model validates,
Browder called for higher flows, Victor's light attenuates.
Woodham pushed for weighing loads, Roy for habitat,
McMichael wants to monitor, Nearhoof looks for scat.

Boynton made comparisons 'tween Ches. and Tampa Bays,
He used a "Vollen" model that just added to our craze.
He scoffed at politicians, but was nice to Doctor Rote,
Gee, wouldn't it be great, if manatees could vote!

We heard the seagrass beds have begun to reappear,
Is it due to less pollution, or because of two dry years?
One mystery's been solved — where the little fishes go,
The snook and drum and tarpon <u>leave</u> the Gulf of Mexico.

What to do? Not much is clear,
But thanks to Dave, "the muck stops here".
Oh, let's not fret, please don't dismay,
There's a place out west in <u>real</u> decay.

With twice the people and half the smarts,
California will win your hearts.
Everybody's headed for the "Golden State",
There's plenty of sun there, and they don't discriminate.

. . . .

But there isn't any water, and the air's all filled with smog,
The roads are clogged with autos, and the schools are in a fog.
The prisons bulge with inmates and the toxic dumps are full,
If they don't do something soon, there will be no strings to pull.

So what's the bottom line? What can a fella do?
Do we really have to take this crap, and sit around and stew?

Of course not — 'cause there's an answer — KANSAS!

"East is east and west is west, and the wrong one we have chose,
Let's go where they have clean air, and the fish are jumpin'
And the corn is high, and there ain't no people in mid-July."

Just a joke, don't you move one inch,
NEP and SWIM will help us in a pinch.
And to top that off, I've heard the President,
Has ordered "no net loss", and it will not cost a cent.

Well, at BASIS One, we had a lot of fun,
At BASIS Two, we thought of what to do.
So, remember what we said, and don't forget my plea,
I hope to see you all again — when we meet for "BAY-SIS" Three!

Jim Rote
March 1, 1991