Physical, Chemical, and Biological Characteristics of the Charlotte Harbor Basin and Estuarine System in Southwestern Florida–A Summary of the 1982-89 U.S. Geological Survey Charlotte Harbor Assessment and Other Studies

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Prepared in cooperation with the
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per year [(ft^3/s)/yr]	0.02832	cubic meter per second per year
gallon per day per acre [(gal/d)/acre]	0.00379	cubic meter per day per hectare
million gallons per day (Mgal/d)	0.4381	cubic meter per second
ton per day (ton/d)	0.9072	megagram per day

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in report:

µg/g = micrograms per gram
µm = micrometers
(mg C/m^3)/h = milligrams carbon per cubic meter per hour
mg/m^3 = milligrams per cubic meter
(mg/m^3)/h = milligrams per cubic meter per hour
mg/L = milligrams per liter
nm = nanometers
ppt = parts per thousand
pCi = picocuries
pCi/L = picocuries per liter
pCi/yr = picocuries per year
Pt-Co = platinum-cobalt

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By Benjamin F. McPherson, Ronald L. Miller, *and* Yvonne E. Stoker

Abstract

The Charlotte Harbor estuarine system, having a surface area of about 270 square miles, averages about 7 feet in depth and is connected to deep water of the Gulf of Mexico through several passes and inlets between barrier islands. Three major rivers flow into the estuary ---the Peace, the Myakka, and the Caloosahatchee. Freshwater and tidal flushing transport nutrients and other constituents from the basin through the estuary into the gulf. Flushing characteristics were evaluated using a two-dimensional hydrodynamic model. The model indicated that the time required to flush injected dye (simulated) from some subareas of the harbor was longer for reduced freshwater inflow than for typical freshwater inflow. After 30 days of simulation of reduced freshwater inflow, 42 percent of the dye injected into the upper harbor remained in the upper harbor, compared to 28 percent for typical freshwater inflow.

The Charlotte Harbor estuary is usually well mixed or partially mixed in the vertical, but vertical salinity stratification does occur, primarily during late summer when freshwater inflows are greatest. A box model was developed that incorporated vertically averaged salinities to account indirectly for three-dimensional transport processes associated with vertical stratification. The box model predicts that under high (7,592 cubic feet per second) and average (2,470 cubic feet per second) freshwater inflows from the Peace and Myakka Rivers, 50 percent of the original water (present at the start of the model run) would be flushed from the northern part of the estuarine system into the Gulf of Mexico in 10 days and 20 days, respectively.

The distribution of plant nutrients in the Charlotte Harbor Estuary is affected by nutrient inputs, freshwater and tidal flushing, mixing, and recycling processes in the estuary. The distributions of total phosphorus and orthophosphate are affected mainly by river input and physical mixing. The distribution of ammonia nitrogen is variable and is related more to recycling within the estuary than to input from the rivers. Ammonia concentrations increase in deeper water, probably in response to vertical salinity stratification and low concentrations of dissolved oxygen that foster regeneration of ammonia from bottom sediments. The distribution of nitrite plus nitrate nitrogen is nonconservative--concentrations are high in the rivers and decrease more rapidly in the estuary than expected due to dilution with sea water, probably because of phytoplankton uptake.

Phytoplankton productivity and biomass are usually greatest during late summer near the mouths of the tidal rivers when freshwater inflow and nutrient loading are greatest. The highly colored freshwater runoff reduces light penetration and phytoplankton productivity in regions of the estuary where salinity is less than

about 10 parts per thousand, but the nutrient-rich, colored water is diluted by seawater at midsalinities (10-20 parts per thousand) so that availability of light increases and inorganic nitrogen concentrations are still high enough to stimulate productivity and growth of phytoplankton. In much of the estuary, salinity is greater than 20 parts per thousand, and availability of inorganic nitrogen, not light, limits productivity and growth.

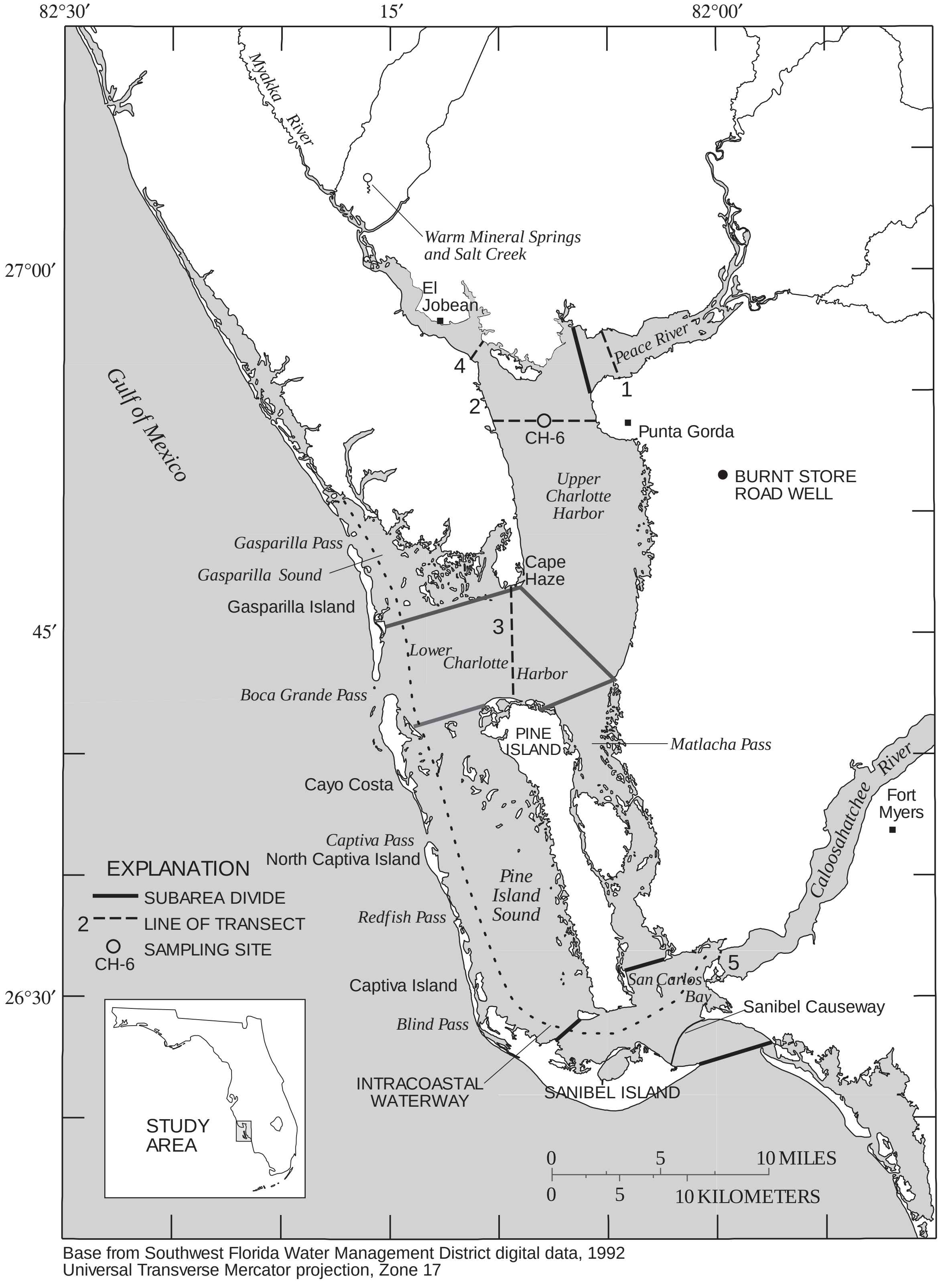
Although the Charlotte Harbor estuarine system is relatively undisturbed, much of its basin has been altered by human activities. Streamflow decreased substantially during 1931-84 in parts of the Peace River, probably because of ground-water withdrawals in the basin. Nutrient concentrations generally increased in the rivers during 1970-85, because of an increase in the flow of wastewater and agricultural runoff. The concentrations of phosphorus are naturally high in the Peace River because of extensive phosphate deposits in the basin. The phosphate deposits also are relatively rich in radionuclides of the uranium-238 series, including radium-226. In the upper basin, these deposits are exposed in the riverbed. Extensive phosphate mining and processing have exposed additional deposits to surface runoff. Periodic spills of phosphate sediments (slimes) have contributed additional phosphorus and radium-226 to the river and estuary. A single spill can contribute a phosphorus load equal to the annual loading in the Peace River at Arcadia.

The projected increase in population in the basin by the year 2020 would generate an additional 60 million gallons per day of domestic wastewater over that generated during 1980, which would increase nitrogen loading in the basin by more than 3 tons per day. Intensified agricultural and industrial developments, particularly expanding citrus production and phosphate mining, could generate additional loads of nutrients and a variety of inorganic and organic contaminants. Increased inputs of nutrients, particularly nitrogen, could encourage growth and increase abundance of phytoplankton and benthic and epiphytic algae. If water were less colored as a result of reduced freshwater inflow, undesirable algal growth could be exacerbated because of increased availability of light. Increased abundance of phytoplankton and other algae could likely change dissolved-oxygen concentrations in the estuary, resulting in greater day-to-night fluctuations and the possible depletion of dissolved oxygen in deep water. At the present time, near-anaerobic conditions occur for days or weeks in the deep water (more than 9 feet) of the northern harbor during late summer. These conditions could become more persistent with time and over wider areas, if phytoplankton and other algae increase in abundance and in their contribution to benthic oxygen demand. An increased abundance of phytoplankton and other algae also would reduce light penetration and adversely affect seagrasses.

INTRODUCTION

Charlotte Harbor, a coastal-plain estuarine system in southwestern Florida (fig. 1), is a vital resource of the State and the Nation. The estuary is one of the largest in Florida (McNulty and others, 1972) and one of the most productive for commercial and sport fisheries (Barnett and others, 1980). Its water and surrounding land provide food and habitat for about 40 endangered and threatened species (Florida Department of Natural Resources, 1984). In recognition of the biological significance of the estuary, the State has established four aquatic preserves that encompass about 90 percent of the surface-water area in the estuary. In 1987, Charlotte Harbor was ranked sixth in priority among water bodies designated for restoration or preservation as part of the Surface Water Improvement and Management (SWIM) Act of Florida (Southwest Florida Water Management District, 1988).

The Charlotte Harbor estuarine system is being subjected to increased environmental stress by rapid population growth and development within its drainage area. Based on 1980 population numbers, more than 500,000 new residents could live in the area that drains into the harbor by the year 2020 (Hammett, 1990). Industrial and agricultural development also could increase. Growth and development will cause an increased demand for freshwater and a corresponding increase in urban, agricultural, and industrial wastes. The inflow of freshwater is essential to the integrity and health of the estuarine system. Increased freshwater withdrawal or diversion and increased wastewater discharges in the rivers and streams that flow into the estuary will create environmental stress in the estuary.



Base from Southwest Florida Water Management District digital data, 1992
Universal Transverse Mercator projection, Zone 17

Figure 1. Charlotte Harbor estuarine system and selected data-collection sites.

The Governor of Florida established a committee of representatives from local, regional, State, and Federal agencies to evaluate what course of action Florida should take to protect the Charlotte Harbor estuarine system. Working in cooperation with the committee, the U.S. Geological Survey developed a plan of study for the estuary and in 1982 began a 7-year (1982-89) multi-disciplinary assessment of the estuary and its inflow area in cooperation with the Florida Department of Environmental Protection (formerly the Florida Department of Environmental Regulation). The assessment included an evaluation of the environmental conditions in the Charlotte Harbor area in 1982-89, as well as an evaluation of historic conditions and possible future conditions. The U.S. Geological Survey prepared 16 reports as part of the assessment. This report summarizes information from the previous 15 reports, as well as the information from other literature sources that relate to environmental conditions of the area (the 15 reports are listed in the reference section and indicated by a *). The report is also intended to be an overview that links the major findings of the assessment.

Purpose and Scope

The overall objective of the U.S. Geological Survey Charlotte Harbor assessment (1982-89) was to describe recent and historic trends in water-resource conditions and to project the effect of future development on water-related resources of the Charlotte Harbor Estuary. Specific objectives were to evaluate: (1) freshwater runoff in the major tributaries, (2) salinity distribution in the estuary; (3) land and water use in the basin; (4) loading and chemical characteristics in the major tributaries; (5) circulation and flushing; and (6) water-quality characteristics of the estuarine system, including physical, optical, chemical, radiochemical, and biological properties, and their relation to freshwater runoff and nutrient loading.

Study Area

The Charlotte Harbor estuarine system (fig. 1) consists of Charlotte Harbor proper (which is divided into upper and lower Charlotte Harbor), Pine Island Sound, Matlacha Pass, San Carlos Bay, and the tidal reaches of the Myakka, Peace, and Caloosahatchee Rivers. The estuarine system is divided into a northern part north of Pine Island and a southern part south of lower Charlotte Harbor. The inflow area (fig. 2) consists of the Myakka, Peace, and Caloosahatchee River basins and the coastal area and islands that drain directly into the harbor. The estuary has a surface area of about 270 mi^2. The inflow area is more than 4,500 mi^2.

The Charlotte Harbor estuarine system averages about 7 ft in depth. The northern part of the estuarine system is several feet deeper on average than the southern part. The estuary is separated from the Gulf of Mexico by barrier islands and is connected to the gulf by two major inlets at Boca Grande and San Carlos, and by several smaller passes. The shoreline is mostly undisturbed, except along the Caloosahatchee River where urban and residential development is prevalent. Mangrove forests (fig. 3) dominate most of the estuarine shoreline, but saltmarsh (fig. 4) is dominant in places, such as along parts of the tidal Myakka and Peace Rivers and in some intertidal regions landward of the mangrove forest (Taylor, 1975). Seagrasses, including *Thalassia testudinum, Syringodium filiforme,* and *Halodule wrightii*, grow in large areas seaward of the mangroves, particularly in Pine Island Sound, San Carlos Bay, and Matlacha Pass (figs. 3 and 4). In northern Charlotte Harbor, seagrass grows in relatively thin bands near the shore.

Three rivers flow into the estuary--the Peace, the Myakka, and the Caloosahatchee. The Peace River drains an area of 2,350 mi^2 (D.W. Foose, U.S. Geological Survey, written commun., 1986). The headwaters of the Peace River are a group of lakes in northern Polk County. The river flows southward for about 75 mi to the harbor. Land-surface altitudes range from about 200 ft above sea level near the headwaters to sea level at the mouth. There are canals and control structures between lakes in the headwaters of the Peace River. Downstream of these lakes, flow in the river and its tributaries is virtually uncontrolled except for a dam on Shell Creek (fig. 2).

The Myakka River drains an area of 602 mi^2 (Foose, 1981). The river originates in northeastern Manatee County and flows about 50 mi in a southerly direction to the harbor. Land-surface altitudes range from about 115 ft above sea level at the headwaters to sea level at the mouth. The upper reaches of the river have a slope of about 5 ft/mi, but near the mouth, the slope is less than 1 ft/mi. Away from the stream channels, the topography is flat. In some of the lower reaches of the river, the flood plain is about 3 mi wide (Hammett and others, 1978). During low flow, the river is tidally affected more than 20 mi upstream from the mouth (Hammett, 1992).

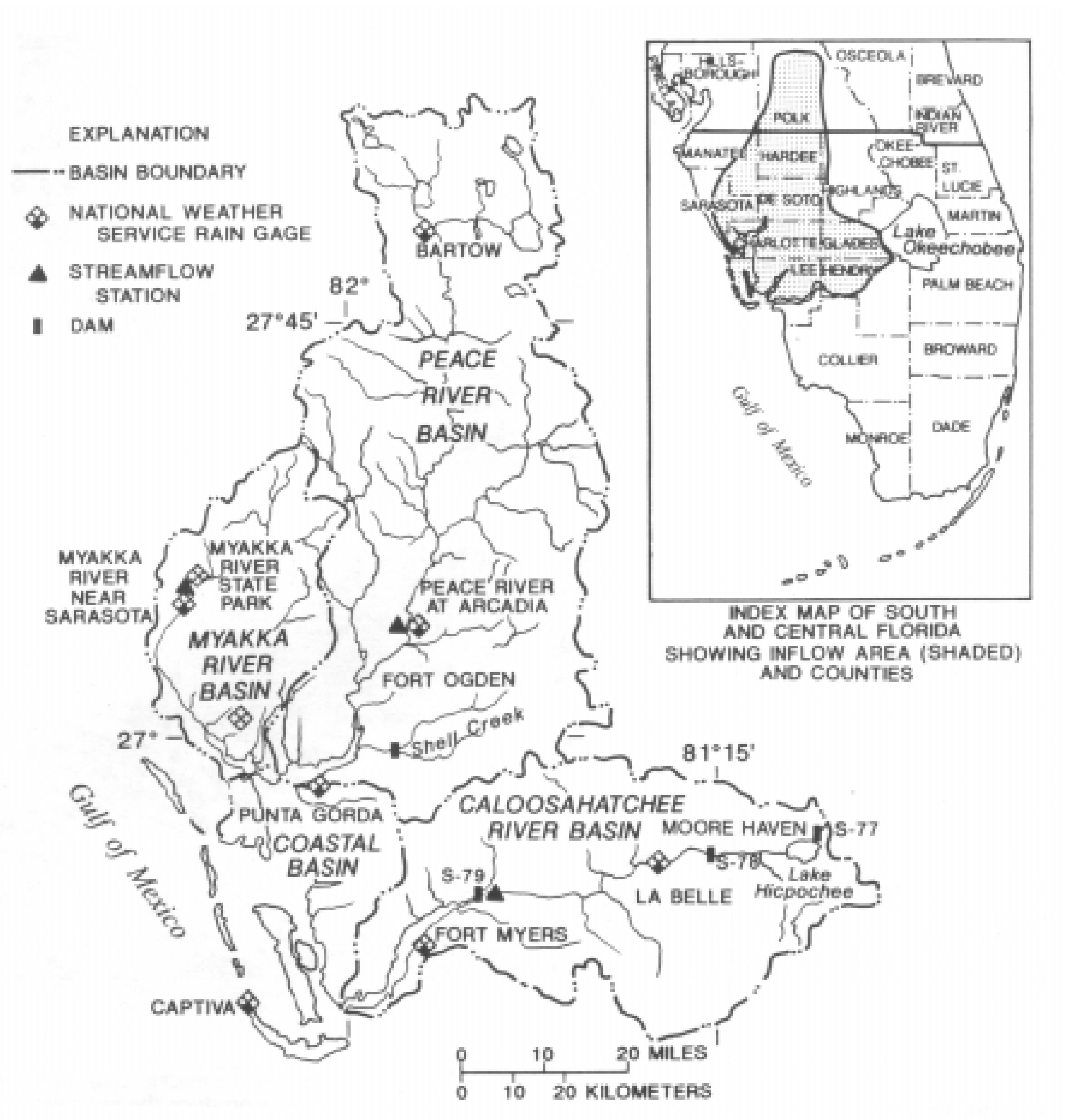
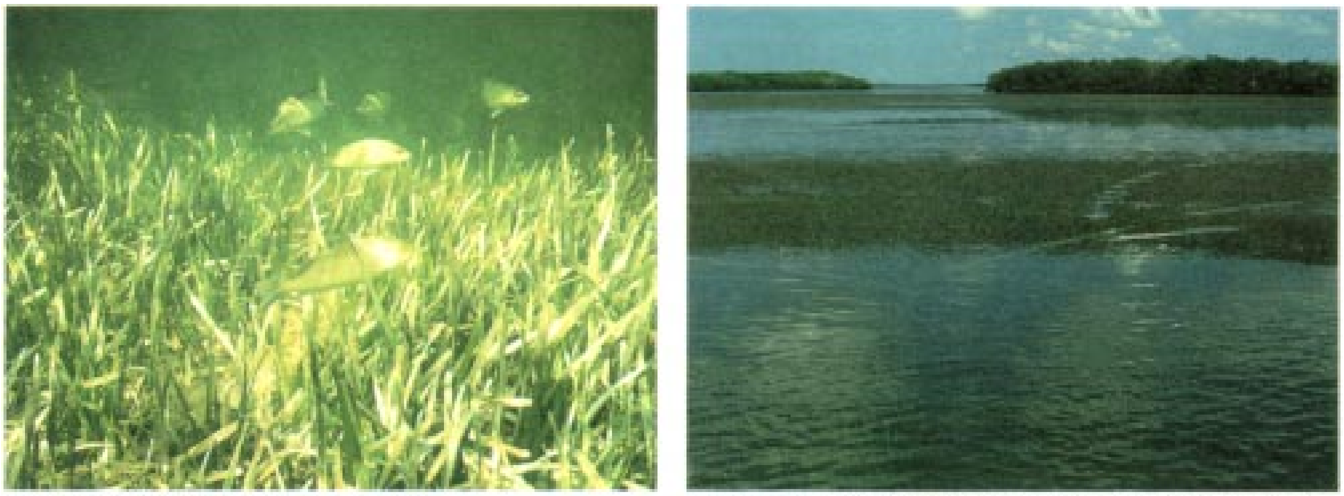


Figure 2. Charlotte Harbor inflow area and estuary (modified from Hammett, 1990).

The Caloosahatchee River drains an area of 1,378 mi^2, and, because it is connected by a canal with Lake Okeechobee, it can be affected by activities in the drainage basin of the lake, an additional 5,650 mi^2. The Caloosahatchee River was originally a shallow, meandering stream having its headwaters near Lake Hicpochee. In its natural state, the river could go dry during the dry season, and the saltwater front could move as far upstream as the present structure S-78, Ortona Lock (Fan and Burgess, 1983). Dredging and straightening of the channel began in the 1880's at the upper end of the river. The U.S. Army Corps of Engineers continued to straighten, widen, and deepen the channel in the 1930's. Moore Haven Lock (structures S-77) and Ortona Lock (structure S-78) were completed by the Corps of Engineers in 1937. The Corps of Engineers did extensive dredging and installed Franklin Lock (structure S-79) in the 1960's. Water is released from the river to the estuary at structure S-79.

Climate

The climate of the study area is subtropical and humid. Average temperature is about 72 °F. Temperature ranges from an average of about 80 °F during the summer to about 60 °F in December and January. Freezing temperatures occur occasionally.



A. Turtlegrass, *Thalassia testudinum*

B. Seagrass meadows and mangrove forest, San Carlos Bay

C. Red Mangrove, *Rhizophora mangle*

D. Black mangrove, *Avicennia germinans*

Figure 3. Biological communities and principal species in coastal south Florida.

Temperature for the coastal areas is moderated by the Gulf of Mexico and temperature extremes most frequently occur inland. Annual rainfall averages about 52 in., of which more than half occurs from June through September during local thundershowers and squalls. Rain during fall, winter, and spring is usually the result of large frontal systems and tends to be more broadly distributed than rain associated with local thundershowers and squalls. The period from October through February is characteristically dry, with November usually being the driest month. The months of April and May also are characteristically dry. Low rainfall in April and May coincides with high evaporation and generally results in the lowest streamflow, lake stage, and ground-water level of the year (Hammett, 1990).

Tropical cyclones produce the most severe weather conditions in the study area. The high tides and heavy rain associated with tropical cyclones can produce coastal and riverine flooding. These storms have the potential for changing the physiography of the harbor and coastal basin. In the past, some of the barrier islands have been completely overtopped, and passes into the harbor have been opened or closed. The heavy winds and tidal action associated with hurricanes and tropical storms also stir up bottom sediments that significantly affect water quality in the estuary. An average of more than two land-falling tropical storms or hurricanes per 100 years occurs along each 10 nautical mi of the Charlotte Harbor coastal area (Ho and others, 1975).

Storm surges and tides are considered to be the most damaging force in hurricanes, but tropical

A. Pine Island Sound looking north over seagrass meadows and mangrove islands.

B. Boca Grande pass and sandy beaches of Gasparilla Island.

C. Tidal Peace River and saltmarshes, looking southwest to Charlotte Harbor.

D. Intertidal flats on Pine Island, looking west across the Sound.

Figure 4. Shoreline of Charlotte Harbor estuarine system.

cyclones also are capable of producing rains that can affect the area for days or weeks. Heavy rain, even from storms passing more than 100 mi away, can produce abnormally high streamflow. Hurricane Agnes, which was centered 200 mi offshore, produced more than 5 in. of rain at Fort Myers, Punta Gorda, and Myakka River State Park during a 3-day period in 1972. A subtropical storm that passed about 100 mi north of Charlotte Harbor in June 1974 produced more than 9 in. of rain at Fort Myers and more than 12 in. at Punta Gorda (Hammett, 1990).

Hydrogeology

The Charlotte Harbor area is underlain to great depths by limestone. Low sea levels stands have resulted in karst development and erosion, and high sea levels have caused both deposition and erosion. The transition from an exclusively carbonate system to a siliciclastic system began in the Miocene time and is continuing. The topography of the present estuary is controlled by the underlying antecedent topography. During periods of low sea level, the area was above sea level and exposed to vertical drainage and karst development that resulted in sinkholes and troughs. During high sea level periods, these depressions were filled by fluvial, estuarine, and marine deposits. The fine material has tended to restrict vertical drainage locally. Sea-level fluctuations have resulted in numerous cycles of deposition, erosion, and karst development over the last 10 million years (Evans, 1989).

The geology of the study area has been described in many publications and is summarized by Hammett (1990). The thickness of the sedimentary strata and water-bearing units varies throughout the area. The Floridan aquifer system is a primary source of ground-water supply in the upstream sections of the Peace and Myakka River basins. Water from the Floridan aquifer system is highly mineralized near the coast and in much of the Caloosahatchee River basin. The surficial aquifer system and the intermediate aquifer system are the primary sources of ground-water supply in these areas.

Throughout much of the study area, the intermediate aquifer system and the deeper Floridan aquifer system are confined. Where confining beds are thin, absent, or breached by springs and uncased wells, water flows upward from the intermediate and Floridan aquifer systems into the surficial aquifer system and, subsequently, into the rivers and Charlotte Harbor (Wilson, 1977; Wolansky, 1983).

BASIN CHARACTERISTICS

The Charlotte Harbor inflow area includes four basins---the Peace, Myakka, and Caloosahatchee River basins and the coastal basin (fig. 2). The basin characteristics, as described by Hammett (1990), are summarized in this section.

Land Use and Water Use

Land use and land cover data in the study area, compiled from 1972-73 aerial photography, indicated agricultural land and rangeland comprised about 70 percent of the total land area of the Peace, Myakka, and Caloosahatchee River basins. Phosphate strip mining was a significant type of land use in the Peace River basin, particularly in the northern part of the basin. Urban development in the study area was present primarily along the shoreline of the harbor, but limited development was present in small interior towns. Urban land area ranged from about 1 percent of the Myakka River basin to about 7 percent of the coastal basin. Wetlands accounted for 11 to 14 percent of the land in the river basins and for more than 30 percent of the land in the coastal basin (Hammett, 1990).

Estimated freshwater use in the Charlotte Harbor inflow area totaled about 565 Mgal/d in 1980 (Hammett, 1990). Irrigation accounted for most of the water use overall, but industrial supply was important in the Peace River basin (fig. 5). Estimated water use in the inflow area totaled about 981 Mgal/d in 1990 (Richard Marella, U.S. Geological Survey, written commun., 1993). This represents an increase in freshwater use of nearly 74 percent during the 10-year span. Agricultural irrigation accounted for most of the water use during both periods.

Streamflow

Hammett (1990) analyzed freshwater flow in the Charlotte Harbor inflow area for the period of record through 1986. Total freshwater inflow from the three river basins, the coastal area, and direct rainfall amounts to an average of about 6,000 ft^3/s, or more than 3,500 Mgal/d. Inflow from the Caloosahatchee River (1966-86) generally ranges from 1,900 to 2,100 ft^3/s. The Peace River (1931-86) contributes an average flow of 2,010 ft^3/s. Inflow from the Myakka River (1936-86) averages 630 ft^3/s, only about one-third as much as either of the other two rivers. Inflow from the coastal basin averages about 300 ft^3/s, less than 5 percent of the total freshwater entering Charlotte Harbor. Rainfall directly onto the harbor contributes the equivalent of 1,030 ft^3/s of freshwater. Streamflow is diverted or augmented at several points in the inflow area (Hammett, 1990).

Analyses of long-term streamflow trends in the Charlotte Harbor inflow area have indicated statistically significant (at the 1 percent confidence level) decreases in streamflow at two stations in the Peace River, but not for other stations in the inflow area (Hammett, 1990). The decrease in streamflow is apparent after about 1950 in the 5-year moving averages of annual mean discharge for the Peace River at Arcadia (fig. 6). Some of the decrease in streamflow in the Peace River can be attributed to deficient rainfall between 1961 and 1978, but rainfall probably is not the sole cause of the decrease. If rainfall were the controlling factor, streamflow at all stations in the area would have similar trends, which is not the case (Hammett, 1990).

The long-term decrease of streamflow in the Peace River probably is related to the increased use of ground water and the subsequent decline of the potentiometric surface of the upper Floridan aquifer (Hammett, 1990). There has been a tremendous increase in the use of ground water during the period of record of stream flow stations (1931-86), and the decline of the potentiometric surface of the Upper Floridan aquifer in the upper Peace River basin as a result of ground-

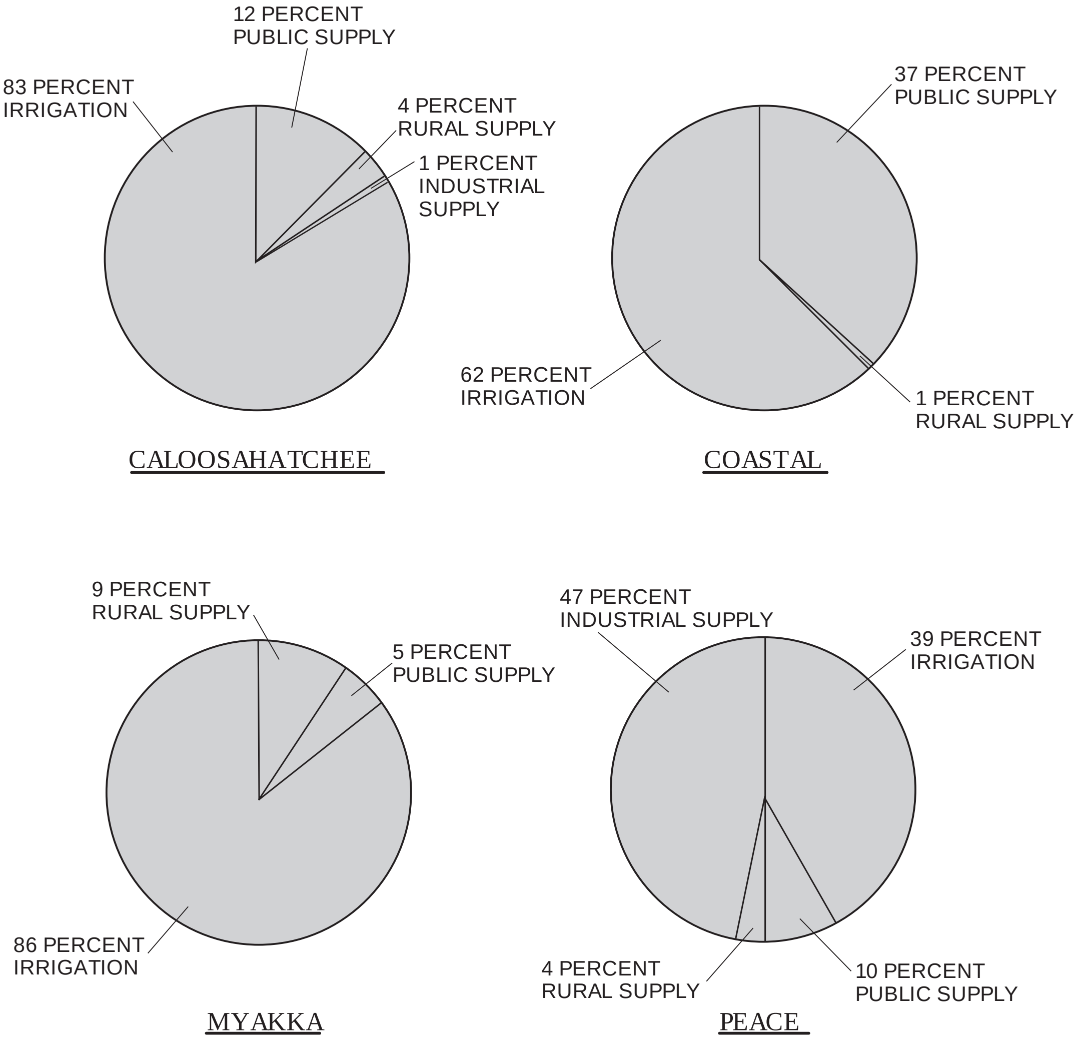


Figure 5. Water use by river basin, 1980 (Hammett, 1990).

water pumping is amply documented (Peek, 1951; Wilson, 1977; Yobbi, 1983). Kaufman (1967) estimated that the phosphate industry in Polk and Hillsborough Counties pumped about 8,000 Mgal/yr in 1934. In 1975, the phosphate industry in Polk County alone pumped about 88,000 Mgal/yr. Kaufman (1967) estimated citrus irrigation water use in the Peace and the Alafia River basins at about 20,000 Mgal/yr in 1956. In 1980, irrigation ground-water use in only the Peace River basin was about 42,000 Mgal/yr, about 80 percent of which was for citrus (Leach, 1983).

Water Quality

In 1984, 114 facilities were permitted to discharge domestic or industrial effluent to water bodies

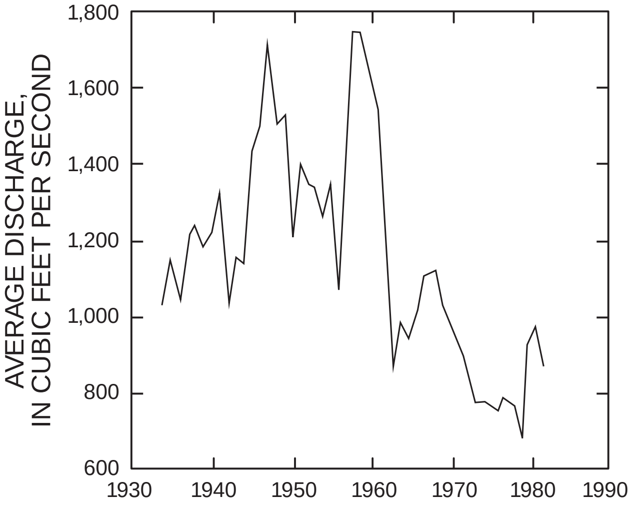


Figure 6. Trend in 5-year moving averages of annual mean discharge for the Peace River at Arcadia, 1931-84 (Hammett, 1990).

tributary to Charlotte Harbor (Hammett, 1990). Of these facilities 1 is in the Myakka River basin, 11 are in the coastal basin, 14 are in the Caloosahatchee River basin, and 88 are in the Peace River basin. Seventy of the permitted outfalls are in Polk County. Effluent discharged to some lakes in Polk County may reach the Peace River only during highwater conditions. Citrus and phosphate-ore processing account for most of the industrial effluent.

Several locations in the headwaters of the Peace River showed substantial effects as a result of receiving wastewater effluent. At some locations, dissolved-oxygen concentrations were lower than 2.0 mg/L, the minimum State standard for any class of surface water (Hammett, 1990).

The quality of water of several lakes in the headwaters of the Peace River has been affected by citrus-processing effluent (Hammett, 1990). Citrus processing produces a strongly buffered, high-carbon waste that can contain inorganic debris from washing, can have a residue of pesticides, and contains toxic peel oils (Lackey, 1970). The degradation of the waste produces objectionable odors and a high biochemical oxygen demand.

Hammett, 1990, reported that "Citrus production involves the use of numerous chemicals, including fertilizers, insecticides, herbicides, and fungicides. Benomyl, bromocil, diuron, dicofol, chlorobenzilate, ethylenedibromide, and aldicarb have been used. The trace elements copper, manganese, and zinc also are applied to citrus (Rutledge, 1987)." Runoff or ground-water seepage from citrus groves has the potential of transporting any of these substances to the stream system.

The mining and processing of phosphate ore in the drainage basin is another potential source of contaminants. Phosphate industry ore-processing plants use a mixture of organic chemicals, including kerosene and fuel oil, to facilitate separation of phosphate ore from unwanted sand and clay. Runoff from sand tailings can represent diffuse sources of organic-chemical contamination (Rutledge, 1987). The chemical processing of phosphate ore into phosphoric acid produces a highly acidic process water. Organic chemicals, including phenols, also are used in the chemical processing of phosphate ore. The gypsum stacks, cooling ponds, and recirculation ditches of the chemical-processing plants are a potential source of contamination of the surficial aquifer (Miller and Sutcliffe, 1984). Runoff from phosphate mines may increase turbidity and exclude light in receiving bodies of water (Miller and Morris, 1981). The structural failure of retaining dikes has resulted in the discharge of clayey wastes, known as slimes, to the Peace River. The effects of these slime spills have been seen as long as 2 years after the spill (Martin and Kim, 1977).

There are other potential sources of nutrient and contaminant loads. Ground-water inflow to the rivers and harbor is an apparent source of radium-226 (Miller and Sutcliffe, 1985; Miller and others, 1990). Background levels of radium-226 in the rivers and harbor reported by Miller and others (1990) are an order of magnitude higher than those found in other parts of the United States (Elsinger and Moore, 1980). Runoff from pasture and cropland carries nutrients and, at times, pesticides to the river system. Septic-tank drain fields are another source of nutrients and a potential source of bacterial contamination. Runoff from urban areas can carry heavy metals, nutrients, bacteria, viruses, and pesticides (Lopez and Giovannelli, 1984). Marinas contribute oil and gasoline as well as wastewater and metals to the rivers and estuarine system. Rainfall and dustfall also are sources of contaminants and nutrients in the river system and estuary.

Hammett (1990) analyzed long-term trends in water quality at 3 sites in Charlotte Harbor tributaries. Of the 51 trend analyses, 19 were significant at the 5-percent confidence level. Seventeen of these analyses indicated increases and 2 indicated decreases. Increases in specific conductance, chloride, sulfate, and dissolved solids at the Myakka River near Sarasota probably resulted from increased runoff from irrigation during the period of record (1963-85) at the station. Ground water, which has greater concentrations of chloride, sulfate, and dissolved solids than surface water, is the primary source of irrigation water in the Myakka River basin. Total phosphorus increased at a median rate of about 7 percent per year at the Myakka River near Sarasota. At the Peace River at Arcadia (1957-85), total organic nitrogen increased about 6 percent per year. Total nitrogen increased about 5 percent per year and total phosphorus about 6 percent per year at the Caloosahatchee River at structure S-79 over the period of record (1966-85). The upward trends in nutrients probably reflect increases in wastewater effluent and agricultural runoff.

High concentrations of phosphorus are present in the Peace River as a result of both natural geologic and hydrologic processes and human activity.

Hammett (1990) and Smith and others (1982) reported a long-term downward trend for phosphorus in the Peace River at Arcadia. Hammett (1990) also reported that total orthophosphorus showed a downward trend, but it was only significant at the 10-percent confidence level. Gilliland (1973) has suggested that all groundwater discharge from industrial processing actually dilutes the normally high concentrations of phosphorus in the river water. Fraser (1986) speculated that a decline in orthophosphate concentration in the Peace River at Arcadia after 1982 was related to changes in phosphate industry activities in the basin.

In much of the upper Peace River basin, phosphate deposits are exposed in the riverbed, and extensive phosphate mining and processing have exposed additional deposits to surface runoff. Periodic spills of phosphate industry sediments (slimes) have contributed additional phosphorus to the river and harbor. Miller and Morris (1981) reported 22 phosphate slime spills into the river between 1933 and 1980. A single spill could contribute a phosphorus load to the river or estuary equal to the average annual loading in the river at Arcadia (Miller and McPherson, 1987).

The rivers tributary to Charlotte Harbor transport substantial loads of dissolved solids and nutrients. The Myakka, Peace, and Caloosahatchee Rivers transport an average of more than 2,000 ton/d of dissolved solids. More than 17 ton/d of nitrogen are transported by the three rivers, of which about 55 percent is transported by the Peace River, 40 percent by the Caloosahatchee River, and 5 percent by the Myakka River. About 85 percent of the phosphorus load is transported by the Peace River (Hammett, 1990).

PHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERISTICS OF THE ESTUARY

The Charlotte Harbor estuarine system extends from the upper reaches of its tidal rivers to the Gulf of Mexico (fig. 1). The characteristics of the estuarine system have been described in reports produced as part of the U.S. Geological Survey assessment of the estuary and are summarized in the following sections based primarily on these reports.

Hydrodynamics

Tides along the west coast of peninsular Florida in the vicinity of Charlotte Harbor typically have a range of from 1 to 4 ft and are of the mixed type, having characteristics intermediate to those that are predominantly either diurnal or semidiurnal (Goodwin and Michaelis, 1976). The mixed type of tide generally has two high water levels and two low water levels that occur during each tidal day and have large inequalities between the two highs and the two lows. The spring and neap tidal cycle occurs fortnightly with spring tides in conjunction with new- and full-moon phases and neap tides in conjunction with quarter-moon phases. Spring tides (those having the largest range) sometimes have only one high and low water level per day, whereas the neap tides (those having the smallest range) approach semidiurnal conditions of two nearly equal high and low water levels per day. Tidal characteristics in the Gulf of Mexico are nearly uniform along the western shores of Gasparilla, Cayo Costa, North Captiva, Captiva, and Sanibel barrier islands, but are of larger range off the southern shore of Sanibel Island (Goodwin, 1996).

Tidal water is exchanged between the Gulf of Mexico and Charlotte Harbor through a number of inlets. The water transported through Boca Grande Pass is about twice the amount that is transported through San Carlos Bay and three to four times the amount transported through Captiva and Redfish Passes. Transport through Blind Pass is insignificant (Goodwin, 1996).

Goodwin (1996) used a two-dimensional circulation and constituent-transport model, SIMSYS2D, to simulate water motion and transport in the Charlotte Harbor estuarine system. The model was driven by tidal stage at the seaward boundary in the Gulf of Mexico and included freshwater inflows from the Myakka, Peace, and Caloosahatchee Rivers. The model was calibrated and verified using field observations of tidal stage at eight sites, tidal discharge at five major inlets, and tidal velocity and direction at nine sites. The calibration and verification periods included spring and neap tide ranges, respectively. Standard errors of simulated tidal stage for the calibration and verification periods averaged about 0.1 ft, which represents an average of about 3 percent of the stage range at the measurement sites. Standard errors of simulated discharge through the tidal inlets ranged from 3 to 10 percent of the range of flow measured in the inlets for the calibration period.

Goodwin (1996) reported that application of the model is limited to conditions that can be depth averaged, which excluded density stratification of the water column. Depth-averaged baroclinic terms were included in the model, but the model could not reproduce the bottom landward residual flow and the seaward surface residual flow that may be present. Model simulations were performed without wind forcing, so wind-induced residual circulation was not considered.

Following calibration and verification, Goodwin (1996) used the model to simulate hydrodynamic and constitutent transport for three different conditions. The first simulation represented the existing physical configuration of the estuarine system, typical tidal patterns, and typical freshwater inflow from the three major tributaries. Boundary conditions for the three major tributaries were set equal to freshwater inflows recorded at gaging stations during the calibration period. Recorded streamflows were adjusted using drainage-area ratios to account for additional inflow downstream from the monitoring stations. Freshwater inflows were 526, 1,728, and 1,616 ft^3/s (total of 3,870 ft^3/s; referred to as "typical flow") for the Myakka, Peace, and Caloosahatchee River basins, respectively. The same physical configuration and tidal patterns were used for the second simulation, but freshwater inflow from the tributaries was substantially reduced (420, 40, and 245 ft^3/s for the Peace, Myakka, and Caloosahatchee River, respectively, for a total 705 ft^3/s). The third simulation used the same tidal patterns and freshwater inflow as the first, but the model configuration was altered to represent physical conditions that might exist if the Sanibel Causeway were removed.

Goodwin (1996) evaluated residual circulation patterns for the three simulations using Lagrangian particle tracks. He reported that "for the current physical configuration, the residual flow patterns were similar for both typical and reduced freshwater inflow. Residual flow from the Myakka River moves southward along the western shore of upper Charlotte Harbor. Residual flow from the Peace River moves southward along either the western or eastern shore of the upper harbor. Both upper and lower Charlotte Harbor have a seaward residual flow along the shoreline and a landward residual flow in the deep center channel... The residual flow in Gasparilla Sound is toward Gasparilla Pass. Most of the residual flow that enters San Carlos Bay from the Caloosahatchee River moves into Pine Island Sound, but some moves north into Matlacha Pass and some moves south into the Gulf of Mexico. The northerly residual flow in southern Pine Island Sound is stronger in the relatively deeper center channel than it is in the surrounding shallow water. The residual flow in Matlacha Pass is small and northward. The Gulf of Mexico has a southerly residual flow, and water mass that enters the gulf through a northern pass can reenter the estuarine system through an inlet farther south" (Goodwin, 1996).

"A decrease in freshwater inflow reduced the residual flow in some parts of the estuary. The residence time in the upper harbor of water from the Myakka River was about five times greater for reduced freshwater inflow than it was for typical freshwater inflow, and the residence time of water from the Peace River was about two times greater for reduced freshwater inflow" (Goodwin, 1996).

"The particle tracks do not conclusively indicate the effect of removing the Sanibel Causeway on the northerly residual flow in Pine Island Sound. Causeway removal did not significantly affect residual flows in Matlacha Pass, Gasparilla Sound, the Gulf of Mexico, or the upper and lower Charlotte Harbor" (Goodwin, 1996).

In addition to Lagrangian particles, Goodwin (1996) used simulated injections of dye to analyze the flushing characteristics of the estuary. For each of the three 65-day simulations, dye was "injected" into one of four subbasins of Charlotte Harbor. He found that results of the dye injections confirm the residual circulation patterns observed with the Lagrangian particles and provide quantitative information on the flushing times.

Goodwin’s simulation of typical freshwater inflow indicated that after 15 days, 57 percent of the dye injected into upper Charlotte Harbor remained in the upper harbor, 48 percent of the dye injected in the lower harbor remained in the lower harbor, 36 percent of the dye injected into Pine Island Sound remained in the sound, and 24 percent of the dye injected into San Carlos Bay remained in the bay. The upper harbor has a relatively long flushing time, probably because it is not directly connected to the gulf and some of the dye that exits to the lower harbor returns to the upper harbor by way of the landward residual flow in the deep center channel. The lower harbor has a substantial tidal exchange with the Gulf of Mexico through Boca Grande Pass, which provides flushing, but the landward residual flow into the upper harbor retards flushing. Most of the dye injected into Pine Island Sound entered the gulf relatively quickly because of the tidal exchange through Captiva and Redfish Passes; residual flow in the sound is seaward. San Carlos Bay has a relatively short residence time, but the residual flow from San Carlos Bay is into Pine Island Sound, not directly into the gulf, so most of the injected dye was landward of the barrier islands for longer than 15 days (Goodwin, 1996).

Goodwin (1996) reported that for model simulation of reduced freshwater inflow the "residence times in some subareas increased as the freshwater inflow decreased. Dye injected in upper Charlotte Harbor remained in the harbor longer with reduced freshwater inflow than with typical freshwater inflow. After 15 days, 65 percent of the injected dye mass remained in the upper harbor for reduced freshwater inflow compared to 57 percent for typical freshwater inflow... After 30 days of simulation of reduced freshwater inflow, 42 percent of the dye injected into the upper harbor remained in the upper harbor, compared with 28 percent for typical freshwater inflow... Reduced freshwater inflow significantly reduced the seaward residual transport from the upper to the lower harbor, and the result was a net increase in landward residual transport. The flushing time of Pine Island Sound was reduced only slightly by the simulated reduction in freshwater inflow. Reduced freshwater inflow slightly decreased the residual transport from San Carlos Bay to Pine Island Sound and slightly increased the residual transport from the bay to Matlacha Pass" (Goodwin, 1996).

"The simulated injection of dye indicated that removal of the Sanibel Causeway slightly affected flushing of the southern study area. Residual flow from San Carlos Bay into Pine Island Sound was increased, and residual flow from the bay into Matlacha Pass was decreased. Upper and lower Charlotte Harbor were not affected by removal of the causeway. Residual circulation was affected more by the simulated difference in freshwater inflow than by the simulated removal of the causeway" (Goodwin, 1996).

The usefulness of the two-dimensional hydrodynamic model to predict circulation and flushing in the northern part of the system decreases as freshwater inflows increase because of vertical salinity stratification and the increased three-dimensional nature of estuarine circulation. Miller and McPherson (1991) used a box model to estimate flushing time in the northern part of the estuarine system. The box model used vertically averaged salinities to indirectly account for three-dimensional transport processes. Under conditions of high (7,592 ft^3/s) freshwater inflows from the Peace and Myakka Rivers, the box model predicts that 75 and 50 percent of the original water (present at the start of the model run) would be flushed from the northern part of the estuarine system (see fig. 1) into the Gulf of Mexico in 20 days and 10 days, respectively (table 1). Under conditions of average (2,472 cubic feet per second) freshwater inflow, the box model predicts that 75 and 50 percent of the original water would be flushed from the northern part of the estuarine system into the gulf in 60 and 20 days respectively. Under conditions of typical river (Peace and Myakka Rivers) inflow, 2,254 ft^3/s, the two-dimensional hydrodynamic model predicts that 42 percent of the dye injected into the upper harbor would remain in the upper and lower harbor (an area close in size to that used for the box model) after 60 days, which indicates that 58 percent of the dye would have been flushed from these two areas of the harbor.

The box model was also used to estimate the time required for a small parcel of water or constituent, injected into the most upstream box, to leave the estuary. The residence time will always be longer if the parcel is introduced into the upper estuary rather than the lower estuary, because the parcel must migrate to the mouth of the estuary before any removal can occur. Under average river inflow the box model predicts that 75 percent of the original parcel injected into the most upstream box would be flushed from the northern part of the estuary into the gulf in 100 days (table 1).

Table 1. Estuary residence times and pulse residence times in Charlotte Harbor (northern part of the estuarine system) at average and high river inflows

[ERT, time to flush entire volume of estuary; PRT, time to flush a pulse from the head of the estuary (Miller and McPherson, 1991)]

Percentage of original mass left	ERT (days)		PRT (days)	
	Average[1]	High[2]	Average [1]	High [2]
50	20	10	70	30
37	40	20	80	30
25	60	20	100	40
5	130	50	180	70

[1] Long-term average flow of Peace and Myakka River basin, gaged plus ungaged flow of 2,472 ft^3/s (Fletcher and others, 1986).

[2] High flow of 7,592 ft^3/s is near the flow that is equaled or exceeded 10 percent of the time (Hammett, 1990).

Models, like the 2-dimensional and 1- dimensional ones used in Charlotte Harbor, can provide useful approximations of flushing behavior in an estuarine system. Model results are most meaningful when all the simplifyling assumptions that are used to imitate the behavior of the real system are met. Typically, however, real systems are much more complex than the models, and the modeling assumptions are not completely met. Because of differing assumptions, one model may produce different results than another for the same system. Oreskes and others (1994) believe that verification and validation of numerical models is impossible and that such models are most useful when challenging existing assumptions, rather than validating them.

Salinity

Large variations in salinity are characteristic of many estuaries. These variations are controlled by the amount and timing of freshwater inflow and are influenced by daily tidal flow and the bathymetry of the estuary. Estuaries sometimes stratify because of salinity variation with depth. Persistent stratification can cause oxygen depletion in bottom waters and have significant effects on the chemistry and biology. The distribution and occurrence of biota are strongly affected by salinity and many species are dependent on estuarine salinity variations for survival.

Salinity in the Charlotte Harbor estuarine system ranges from freshwater to about that of sea water. Seasonal changes in salinity occur primarily in response to changes in freshwater inflow from the Peace, Myakka, and Caloosahatchee River basins. Other sources of freshwater, including direct rainfall, runoff from coastal areas, ground-water seepage, and domestic effluent, have smaller and usually more local effects on salinity in the estuary. The estuary is usually well-mixed or partially-mixed in the vertical, but vertical stratification does occur, particularly near the large rivers.

Stoker (1992) described salinity characteristics in the Charlotte Harbor estuarine system based on data collected from June 1982 to May 1987. Salinity generally was lowest during the July through September wet season and was highest from January through March. Salinity also varied daily in response to tidal fluctuation. Peak salinity occurred near floodtide stage, and minimum salinity occurred near ebbtide stage. The daily range of salinity at a location generally increased with increased freshwater inflow. Salinity was vertically stratified to some degree throughout most of the estuary during periods of high freshwater inflow and rainfall, but stratification was most pronounced in the northern and western parts of the upper harbor. During a period of high freshwater inflow in June 1982, near-surface salinity was as much as 20 ppt less than near-bottom salinity near the mouth of the Peace River.

Vertical salinity stratification in upper Charlotte Harbor is a common seasonal occurrence (Environmental Quality Laboratory, Inc. 1979). The degree and persistence of salinity stratification depend primarily upon the amount of freshwater runoff and wind velocity. Large freshwater discharges and relatively calm conditions that generally occur in late summer favor stratification.

Chemical Characteristics

The estuarine chemical environment is related primarily to the compositional gradients associated with mixing of freshwater and seawater (Burton, 1976). The chemical properties of an estuary also are strongly influenced by physical factors related to circulation and flushing, and for some chemicals, to chemical and biological processes in the estuary and basin.

Nutrients

Nutrient availability is a key factor in the regulation of primary productivity in estuarine and coastal water (Ketchum, 1967). Recycled nutrients sustain much of the productivity in these waters (Nixon, 1981). Basin runoff and direct atmospheric deposition add "new" nutrients and contribute to the relatively high estuarine productivity compared with that of offshore waters. Increased loading of "new" nutrients also may increase the rate of recycling and the flux of nutrients from bottom sediments to the water column after a lag time of weeks to months (Boynton and others, 1991). Increased loading of nutrients related to the urban development of coastal basins has been implicated in estuarine enrichment, increased phytoplankton productivity and biomass (Jaworski, 1981), and declines in seagrass communities (Orth and Moore, 1983; Casper and others, 1987).

The distribution of nutrients in the Charlotte Harbor estuarine system is mainly the result of nutrient input from rivers, freshwater and tidal flushing, and recycling processes in the estuary (Froelich and others, 1985; McPherson and Miller, 1990). The rivers exhibit a major influence in estuarine nutrient distribution by contributing substantial nutrient loads and by flushing nutrients seaward. Human activities have generally increased nutrient concentrations in the rivers that flow into the estuary.

McPherson and Miller (1990) evaluated the sources and distribution of nutrients in the Charlotte Harbor estuarine system by plotting nutrient concentration against salinity (fig. 7) and by developing nutrient dilution curve models. Theoretical nutrient

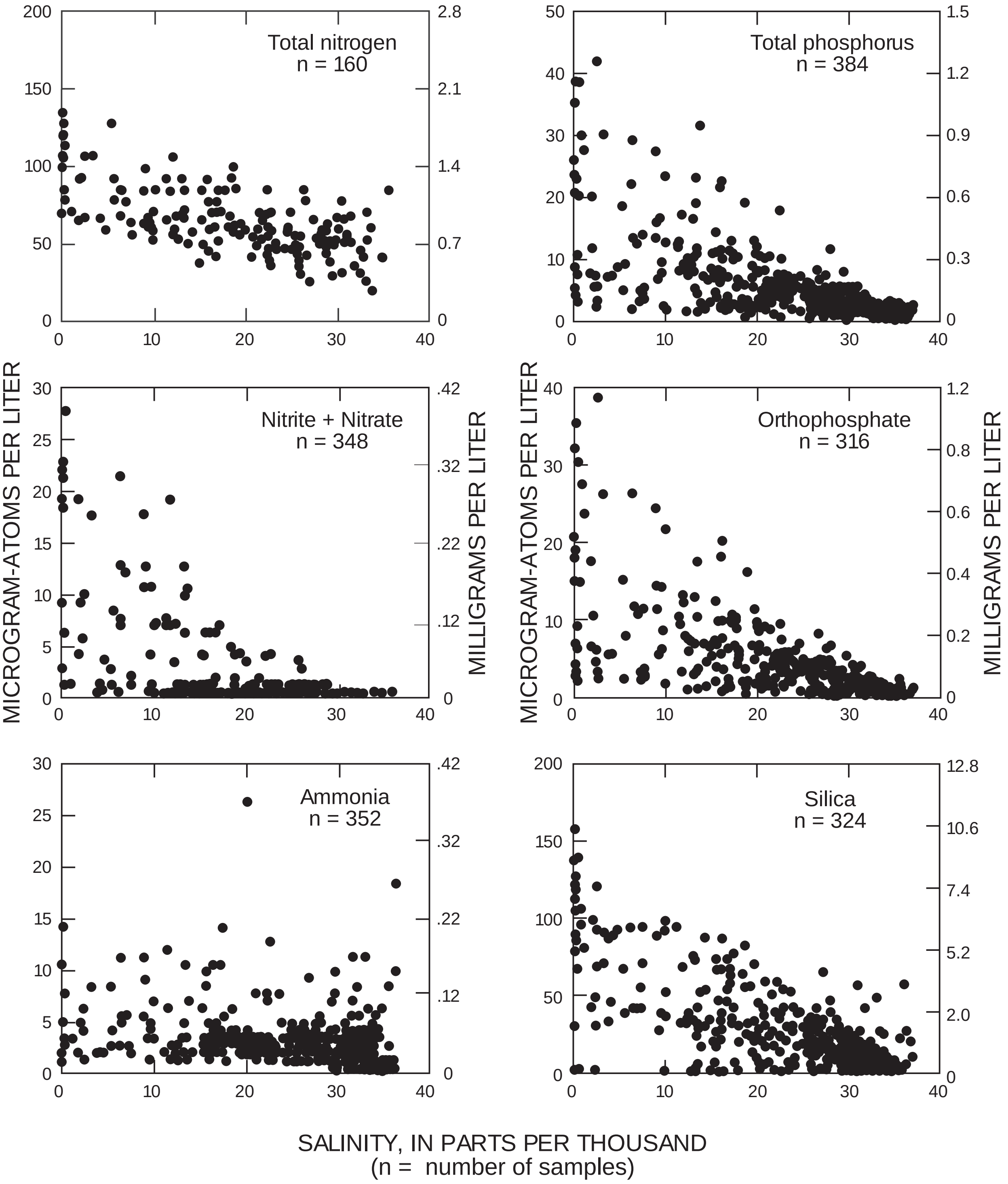


Figure 7. Nutrients as a function of salinity in the Charlotte Harbor estuarine system (modified from McPherson and Miller, 1990).

dilution curves represent nutrient distribution along the salinity gradient by assuming steady-state conditions and conservative nutrient characteristics. If nutrient characteristics are conservative, the theoretical and measured curves are in close agreement; if nonconservative, the theoretical and measured curves deviate from each other.

The distributions of phosphorus in the Charlotte Harbor estuarine system were nearly conservative and a function of river phosphorus concentration, flow, and physical mixing (McPherson and Miller, 1990). Phosphorus concentrations were greatest in the freshwater of the Peace River and were diluted in the tidal river and estuary. Large discharges from the Peace River resulted in high concentrations throughout the northern part of the estuary, but the southern part was not greatly affected by the phosphorus-rich river water. Concentrations of total phosphorus averaged about 0.08 mg/L in Pine Island Sound, 0.15 mg/L in the tidal Caloosahatchee River, and 0.62 mg/L in the tidal Peace River (McPherson and Miller, 1990).

The distribution of dissolved silica was variable along the salinity gradient (McPherson and Miller, 1990). In some situations, the distribution seemed conservative; more frequently, concentrations of dissolved silica deviated from the theoretical curve, which indicated nonconservative behavior or river source variability. Usually, measured concentrations were below the theoretical curve, which would indicate a sink or region of silica uptake. In higher salinity water (greater than 20 ppt), observed concentrations sometimes increased, which could indicate a source of silica. Diatoms constitute a substantial part of the phytoplankton in the estuary (Y.E. Stoker, U.S. Geological Survey, written commun., 1991), and their uptake and release of silica might explain variability in the distribution pattern of dissolved silica. Fraser and Wilcox (1981) reported sharp decreases in dissolved silica along the salinity gradient from the mouth of the Peace River to Boca Grande Pass. They attributed the sharp decrease in silica concentration to growing diatom populations that removed the silica from solution.

Concentrations of ammonia were highly variable along the salinity gradient (fig. 7) and were in about the same range as concentrations in the rivers (McPherson and Miller, 1990). The variability of ammonia probably is related to variations in water column and bottom sediment nitrogen regeneration and uptake in the estuary. Excretion of ammonia by zooplankton is an important process of nitrogen regeneration in offshore water and, to a lesser extent, in shallow coastal water (Stearns and others, 1987). Zooplankton typically are patchy in distribution; therefore, their contribution to regenerated ammonia would vary with location and might explain some of the variability in ammonia concentration in the estuary. Benthic regeneration is another source of ammonia (Dugdale and Goering, 1967). Nutrient flux measurements by the U.S. Environmental Protection Agency at six stations in the Charlotte Harbor estuarine system during wet and dry seasons in 1984 and 1985 indicated that bottom sediments released ammonia to the water in 23 flux-chamber measurements, removed ammonia in 4 measurements, and had no net flux in 16 measurements (Philip Murphy, U.S. Environmental Protection Agency, written commun., 1985; 1986). Ammonia concentrations increased in the deeper water of Charlotte Harbor during summer (Fraser, 1986). Ammonia enrichment probably was related to density stratification and to low concentrations of dissolved oxygen in bottom waters that favored regeneration of ammonia from bottom sediments.

Concentrations of nitrite plus nitrate nitrogen were nonconservative and decreased sharply along the salinity gradient (McPherson and Miller, 1990). Most nitrite plus nitrate nitrogen values were below detectable concentrations (0.02 mg/L) in water with salinities greater than 20 ppt (fig. 7). The sharp sag in the nitrite plus nitrate nitrogen dilution curves in the low salinity regions indicates a substantial removal of nitrogen from the water column. The removal of nitrite plus nitrate nitrogen in the estuary is doubtlessly caused by biological uptake.

The relatively low concentrations of inorganic nitrogen could, at times, limit plant growth in the estuary (McPherson and others, 1990). The availability of nitrogen to the phytoplankton and other algae is determined by inputs of new nitrogen, primarily from rainfall and runoff, and by recycling processes in the estuary. Freshwater runoff from the basin is a major source of new nitrogen to the Charlotte Harbor Estuary. The new nitrogen stimulates phytoplankton productivity. Peak phytoplankton productivity and chlorophyll-*a* concentrations occur in the estuary near the river mouths during late summer when freshwater runoff and nutrient loading are greatest (R.T. Montgomery, Environmental Quality Laboratory, Inc., written commun., 1989).

Most of the nitrogen in the rivers and estuary is organic nitrogen (McPherson and Miller, 1990). Organic nitrogen concentrations decreased over the salinity gradient, indicating river input as a source. Organic nitrogen generally is not as readily available for plant uptake, although some forms of dissolved organic nitrogen can be used for growth by marine phytoplankton (Remsen, 1971; McCarthy, 1972; Wheeler and others, 1974). Dissolved organic nitrogen constitutes about 80 percent of the total organic nitrogen in the estuary. The forms of organic nitrogen that are not directly available for plant uptake could be mineralized by bacteria and other microorganisms and made available over time (McPherson and Miller, 1990).

Dissolved Oxygen

Dissolved oxygen has been a major constituent of interest in water-quality investigations. It is significant in the protection of aesthetic qualities of water as well as for the maintenance of fish and other aquatic life. The aesthetic qualities of water require sufficient dissolved oxygen to prevent septic conditions and attendant malodorous emissions. Insufficient dissolved oxygen in the water column causes the anaerobic decomposition of any organic materials present. Such decomposition tends to cause the formation of noxious gases, such as hydrogen sulfide, and the development of carbon dioxide and methane in the sediments, which bubble to the surface or float settled sludge as mats.

Dissolved oxygen concentrations in the near-surface water of Charlotte Harbor esuarine system ranged from about 6 to 8 mg/L during daylight sampling in 1982-84 (Stoker, 1986, p. 14). Dissolved oxygen concentrations of near-bottom water of the estuary generally are lower than near surface concentrations. Dissolved oxygen in bottom water in September 1980 ranged from less than 4 mg/L in the northern part of the estuary to more than 5.5 mg/L in the southern part of the estuary (Estevez, 1986, p. 19).

Dissolved-oxygen concentrations were measured monthly during 8 years (1976-84) at site CH-6 (fig. 1) in upper Charlotte Harbor (Fraser, 1986). The average monthly near-surface concentrations declined from 8.5 to 6.7 mg/L from January to July and then began to rise (fig. 8). An increase in the average dissolved-oxygen concentration occurred in September, probably as a result of increased phytoplankton photosynthesis. Statistical analyses indicated a decreasing trend (1976-84) in near-surface dissolved oxygen concentration.

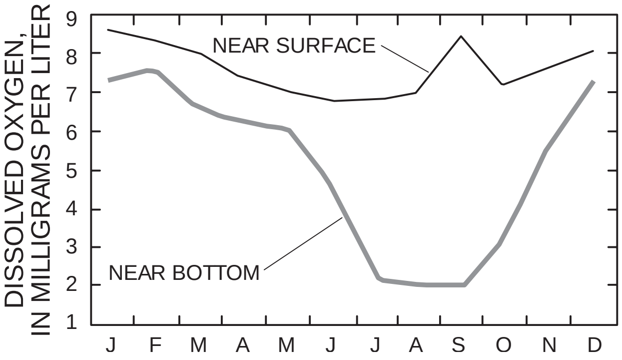


Figure 8. Average monthly concentration of dissolved oxygen in upper Charlotte Harbor, site CH-6, 1976-84 (Fraser, 1986).

Near-bottom average monthly concentration at CH-6 was highest in February, declined slowly through May, and then declined more rapidly until July (Fraser, 1986). The low near-bottom concentrations (less than 4 mg/L) that occur each year during summer (fig. 9) are attributed to restricted reaeration as a result of density stratification and to biological respiration. Dissolved-oxygen concentration increased from October to December after breakup of the density stratification.

Trace Elements

U.S. Geological Survey reconnaissance sampling of five locations (transects shown in fig. 1) in the Charlotte Harbor estuarine system in December 1982 did not indicate abnormally high concentrations of

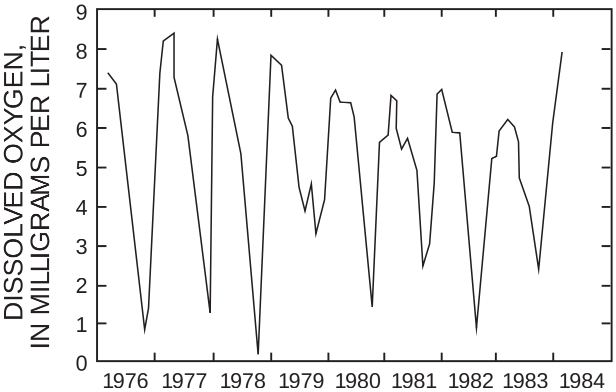


Figure 9. Three-month moving average of near-bottom dissolved-oxygen concentrations in upper Charlotte Harbor, site CH-6, 1976-84 (Fraser, 1986).

Table 2. Concentrations of selected trace elements in bottom sediments collected at transects 1 through 5, December 1982 (From Stoker, 1986)

[Samples were collected along transects (see fig. 1 for location) and composited into one sample per transect. µg/g, micrograms per gram; <, less than. Modified from Stoker, 1986]

Transect	Date	Time	Aluminum, recoverable from bottom material (µg/g)	Arsenic, total in bottom material (µg/g)	Cadmium, recoverable from bottom material (µg/g)	Chromium, recoverable from bottom material (µg/g)	Cobalt, recoverable from bottom material (µg/g)	Copper, recoverable from bottom material (µg/g)	Iron, recoverable from bottom material (µg/g)
1	12-14-82	1030	430	<1	1	10	<10	3	4,000
2	12-14-82	1530	280	<1	1	6	<10	2	2,600
3	12-15-82	1000	340	<1	2	20	10	3	3,100
4	12-15-82	1300	280	<1	<1	6	<10	1	1,700
5	12-16-82	1100	7,100	<1	1	3	<10	2	1,400

Transect	Date	Time	Lead, recoverable from bottom material (µg/g)	Manganese, recoverable from bottom material (µg/g)	Mercury, recoverable from bottom material (µg/g)	Molybdenum, recoverable from bottom material (µg/g)	Nickel, recoverable from bottom material (µg/g)	Selenium, total in bottom material (µg/g)	Zinc, recoverable from bottom material (µg/g)
1	12-14-82	1030	10	13	0.56	3.0	<10	<1	10
2	12-14-82	1530	10	10	.92	<1.0	10	<1	8
3	12-15-82	1000	20	17	.21	4.0	10	<1	10
4	12-15-82	1300	10	7	.18	< .1	<10	<1	4
5	12-16-82	1100	<10	11	.28	3.0	<10	<1	5

trace elements (table 2). Concentrations of arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc were near those of baseline concentrations for uncontaminated coastal sediment and were substantially below those of contaminated sediments (de Groot and others, 1976, table 10). The Florida Department of Environmental Protection sampled bottom sediment at 18 sites in the Charlotte Harbor Estuary for trace elements and normalized concentrations against concentrations of aluminum (Schropp and Windom, 1988). Most trace element concentrations were within natural ranges, except for several sites in the upper tidal Caloosahatchee River, which were slightly enriched in cadmium, lead, or zinc (Schropp and Windom, 1988; Schropp and others, 1990).

Pesticides and Hydrocarbon Compounds

A U.S. Geological Survey reconnaissance sampling at five locations (transects shown in fig. 1) in the Charlotte Harbor estuarine system in December 1982 did not indicate abnormally high concentrations of pesticides and other organic compounds in bottom sediment. Of the 80 pesticides and the other organic compounds analyzed (table 3), only four compounds were above analytical detection limits--chlordane at 1.0 µg/kg and DDE at 0.9 µg/kg at transect 1 and DDD at 0.2 µg/kg and DDE at 0.1 µg/kg at transect 5.

Hydrocarbon compounds in bottom sediment and five commercially important species of marine organisms (oyster, blue crab, pink shrimp, mullet, and sea trout) were measured throughout the Charlotte Harbor estuarine system during the winter and summer seasons of 1982 (Pierce and others, 1982; 1983). Total hydrocarbon concentrations were measured, as well as various components, including napthalene, phenanthrene, dibenzothiophene, pyrene, o-terphenyl, and androstane. The analyses were designed to detect chemical characteristics of hydrocarbons that would indicate a petroleum source, such as those compounds mentioned above. Adult and juvenile organisms were analyzed separately, when available, to assess differences in hydrocarbon content due to age. Two different types of tissue also were studied (muscle and liver or gonad tissue) to detect potential for hydrocarbon intake by people that consume seafood.

Table 3. Concentrations of pesticides and other organic compounds analyzed in bottom sediments collected at transects 1 through 5, December 14-16, 1992

[All concentrations were at or below analytical detection limits except for the following: chlordane, 1.0 µg/kg at transect 1; DDD, 0.2 µg/kg at transect 5; DDE, 0.9 µg/kg at transect 1, 0.1 µg/kg at transect 5 (from Stoker, 1986)]

Acenaphthylene
Acenaphthene
Anthracene
Benzo(b)fluoranthene
Benzo(k)fluoranthene

Benzo(a)pyrene
Bis(2-chloroethyl)ether
Bis(2-chloroethoxy)methane
Bis(2-chloroisopropyl)ether
N-Butylbenzyl phthalate

Chrysene
Diethyl phthalate
Dimethyl phthalate
Fluoranthene
Fluorene

Hexachlorocyclopentadiene
Hexachloroethane
Indeno(1,2,3-cd)pyrene
Isophorone
N-nitrosodi-n-propylamine

N-nitrosodiphenylamine
N-nitrosodimethylamine
Nitrobenzene
4-Nitrophenol
4,6-Dinitro-2-methyl phenol

2,3,7,8-Tetrachlorodibenzo-p-dioxin
Phenol
Naphthalene
Pentachlorophenol
Perthane

Bis(2-ethylhexyl)phthalate
Di-n-butyl phthalate
Benzidine
Polychlorinated naphthalenes
Aldrin

Lindane
DDT
Dieldrin
Endosulfan
Endrin

Ethion
Toxaphene
Heptachlor
Heptachlor epoxide
Parachlorometacresol

Phenanthrene
Pyrene
1,12-Benzoperylene
1,2-Benzanthracene
1,2-Dichlorobenzene

1,2,4-Trichlorobenzene
1,2,5,6-Dibenzanthracene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
2-Chloronaphthalene

2-Chlorophenol
2-Nitrophenol
Di-n-octyl phthalate
2,4-Dichlorophenol
2,4-Dimethylphenol

2,4-Dinitrotoluene
2,4-Dinitrophenol
2,4,6-Trichlorophenol
2,6-Dinitrotoluene
3,3'-Dichlorobenzidine

4-Bromophenyl phenyl ether
Polychlorinated biphenyls
Malathion
Parathion
Diazinon

Methyl parathion
Hexachlorobenzene
Hexachlorobutadiene
Mirex
Trithion

Methyl trithion
Methoxychlor
2,4-D
2,4,5-T
Silvex

Total hydrocarbon concentration in sediment ranged from a low of about 1 µg/g of dry sediment in mid-Charlotte Harbor and the Gulf of Mexico to a high of 87 µg/g in the Caloosahatchee River near Fort Myers. Sediments from most of the sites contained hydrocarbons in concentrations that ranged from 1 to 5 µg/g. A few high concentrations of hydrocarbons were detected in sediments from residential canals and near commercial marine operations. These high concentrations were probably related to the use of petroleum products in the area (Pierce and others, 1982).

Oyster tissue samples also contained low concentrations of hydrocarbon compounds, except those collected near residential and commercial marina development. The edible portion of all other shellfish and fish had no detectable concentrations of hydrocarbon contamination. Liver and gonad tissue produced some complex hydrocarbon patterns, but subsequent analysis by gas chromatography-mass spectroscopy verified a predominance of biogenic material. Pierce and others (1982) established that Charlotte Harbor has experienced little hydrocarbon contamination from petrochemical products such as oil and gasoline, except in isolated areas associated with residential and industrial development.

Radium

Radium-226 activities are greater in coastal areas of southwestern Florida than in other coastal areas (Fanning and others, 1981; 1982). The greater activities in coastal water are attributed to enrichment as a result of circulation of water from the Gulf of Mexico through deep, uranium-rich limestone of the Florida Peninsula (Fanning and others, 1981), as well as to the extraction of radium from phosphatic ores that underlie much of the area (Upchurch and others, 1985). Water in phosphatic strata is enriched in radionuclides of the uranium-238 decay series, including radium-226 (Miller and Sutcliffe, 1985) and radon-222 (Kaufmann and Bliss, 1977). Radium-226 can be transported to the coastal estuaries by ground water and streamflow. Phosphate mining and processing expose the phosphate deposits and may accelerate transport of suspended radium-226 in streams (Upchurch and others, 1985).

Miller and others (1990) reported the radium-226 and radon-222 activities are greater in the estuarine waters of upper Charlotte Harbor and lower tidal Peace and Myakka Rivers, than in either the freshwater reaches of the rivers or waters of the lower estuary and the Gulf of Mexico. The activity of radium-226 in the tidal rivers increases with decreasing river inflow, with a maximum value of 2.47 pCi/L (548 dpm/100L) measured in the tidal Myakka River. The source of the high activity of radium-226 and radon-222 is predominantly ground water inflow. Because of the large ground water input, the contribution of radium-226 from suspended and bottom sediments is a smaller fraction of the total radium-226 input than in many other estuaries. Although ground water radium-226 activity in the area varies widely, artesian ground water inflow to the tidal rivers was estimated to be similar in magnitude to the flow of the rivers above the tidal reach during the dry season.

Phosphate mining activities are another source of radium-226 to Charlotte Harbor. Slimes that are transported into estuarine water of the tidal river and harbor release radium-226 to the water by ion exchange. In the Peace River, two slime spills for which there are volume data (Miller and Morris, 1981) would transport about $2x10^{10}$ to $4x10^{10}$ pCi of exchangeable radium-226 (Miller and McPherson, 1987). For comparison, the annual transport of dissolved radium-226 in the Peace River and the annual ground-water inflow are about $2x10^{11}$ and $9x10^{11}$ pCi, respectively. Suspended sediment contributes an additional load that is dependent on the amount of exchangeable radium-226 per gram of sediment. An estimate of the upper limit for exchangeable radium in suspended sediment, based upon the amount of exchangeable radium-226 phosphate industry slimes, is about $7x10^{10}$ pCi/yr. Natural sediments probably would contribute less than this amount. From these estimates, it seems that some slime spills can contribute about as much radium-226 to the estuary as the annual sediment load and that there is a possibility that a large spill might contribute more than the annual loading from all sources (Miller and McPherson, 1987).

Light Environment

The amount of photosynthetically active radiation (PAR) in natural water is of fundamental importance in determining the growth and vigor of aquatic plants. Absorption and scattering of light by water and dissolved and suspended matter determine the quantity and the spectral quality of light at a given depth (Jerlov, 1968; 1976; Prieur and Sathyendranath, 1981), which in turn affect the photosynthesis of aquatic plants.

Estuaries usually are enriched with plant nutrients, compared with most offshore waters (Ketchum, 1967). Where nutrients are abundant, phytoplankton populations may flourish in the upper, sunlit water to the extent that they shade themselves as well as benthic algae and seagrass (Orth and Moore, 1983). Dissolved matter that colors the water and suspended sediment from land runoff and from resuspension of bottom material also is more abundant in estuaries than in the sea (Thompson and others, 1979). The combined effects of dissolved and suspended matter and phytoplankton can greatly reduce estuarine light availability (Kirk, 1983). Seagrass communities are particularly vulnerable to reduced light because, unlike phytoplankton that would be transported into and out of the euphotic zone by turbulent water movement, seagrass remains in the same position in the water column.

Dissolved and suspended matter are the major causes of light attenuation in the Charlotte Harbor estuarine system: phytoplankton chlorophyll *a* is generally a minor cause of attenuation (McPherson and Miller, 1987). On average, nonchlorophyll suspended matter (which includes detritus, cellular material, and minerals) accounted for 72 percent of light attenuation, dissolved matter (water color) accounted for 21 percent, phytoplankton chlorophyll for 4 percent, and water for the remaining 3 percent. For individual determinations, suspended nonchlorophyll matter, dissolved matter, suspended chlorophyll, and water each accounted for as much as 99, 79, 21, and 18 percent, respectively, of light attenuation. Attenuation by suspended matter was greatest near the mouth of the northern tidal rivers and was variable throughout the rest of the estuarine system. Attenuation by dissolved matter was greatest in the brackish tidal rivers and decreased with increasing salinity (fig. 10).

In low-salinity regions of Charlotte Harbor, water color can account for much of the light attenuation (McPherson and Miller, 1987). The source of the water color is dissolved organic material that comes from swamps and streams of the basin. Humic acids that color water and are typically in high concentrations in the streams and rivers of Florida (Thurman, 1985) are highly absorbent at the short wavelength range of PAR (Kirk, 1976). Maximum transmittance of PAR shifted from 500 to 600 nm in the gulf to 650 to 700 nm in the colored waters of the tidal Peace River (fig. 11). Not only does water color reduce total PAR in parts of the Charlotte Harbor Estuary, but it

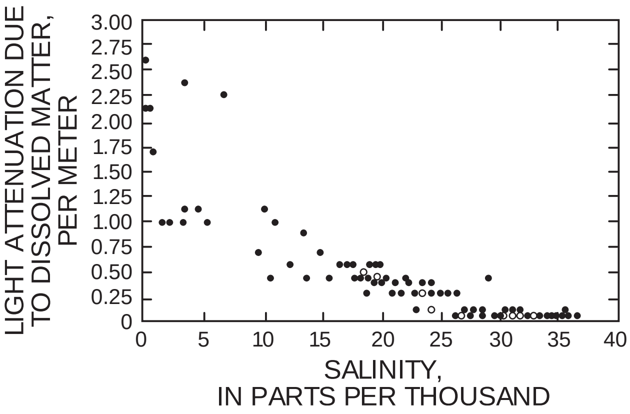


Figure 10. Light attenuation due to dissolved matter as a function of salinity. (Open circles indicate more than one value. From McPherson and Miller, 1987.)

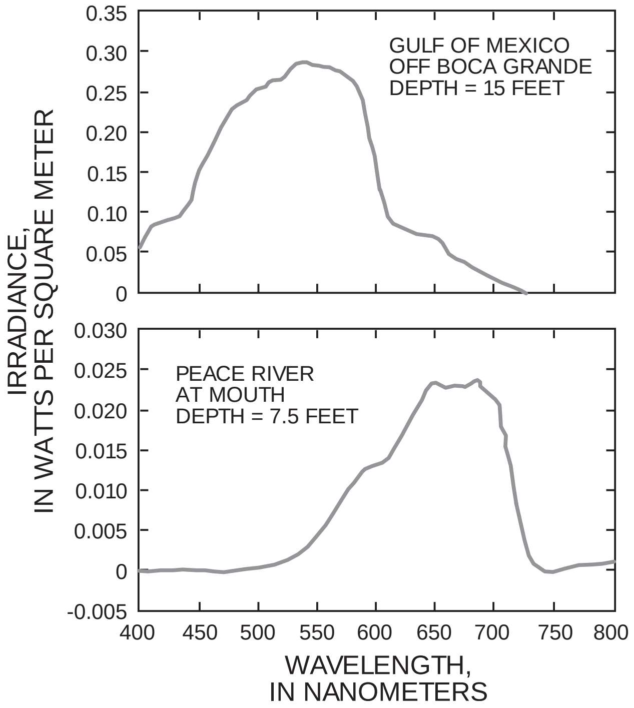


Figure 11. Irradiance at 5-nanometer intervals. (From McPherson and Miller, 1987).

also selectively reduces the shorter wavelengths (400-500 nm) where some of the absorption peaks for chlorophyll *a* and its associated pigments occur (Prieur and Sathyendranath, 1981; Lewis, Warnock, and Platt, 1985).

Dissolved matter had little effect on light attenuation in much of the southern part of the estuary, as indicated by low color (less than 5 Pt-Co units), even during periods of heavy runoff in the basin. Matlacha Pass and parts of San Carlos Bay were affected by local runoff and discharges from the Caloosahatchee River, but Pine Island Sound was dominated by non-colored water from the Gulf of Mexico. Suspended matter was the major cause of light attenuation in the southern part of the estuary where most seagrass meadows are present. The source of much of the suspended matter probably was the bed of the estuary, which consisted of very fine to fine sand (Huang, 1966) and organic detrital material (McPherson and Miller, 1987).

Biological Communities and Functions

Biological communities include primary producers, consumers, and decomposers that interact and form food webs. The primary producers in coastal and estuarine waters are of two types--those that live within the water column, which includes the phytoplankton, and those that are attached or associated with the bottom substrate, such as mangrove forest, saltmarsh, seagrass meadows, and benthic algae. The consumers include zooplankton, benthic invertebrates, fishes, birds, and marine mammals. The decomposers include various microbial groups, such as fungi and bacteria. These microbes are an important, but not well understood, link in the estuarine food web. Most of the nutrient regeneration and nutrient cycling in estuarine water and sediment are mediated by bacteria and other microorganisms.

Nearly 70 percent of Florida’s recreational and commercial fishery species are dependent on estuaries such as Charlotte Harbor during at least part of their life (Harris and others, 1983). Shrimp and many fish species migrate offshore to spawn. The eggs are usually planktonic and develop into larvae that are transported toward shore by tidal currents. The larvae and juveniles enter estuarine water where they use an abundant food supply and derive protection from predators.

The Charlotte Harbor estuarine system provides a variety of habitats and salinity conditions necessary for the nursery function. Most of the shoreline of the estuary is unaltered and provides both food and refuge for juveniles of many species.

Phytoplankton

The phytoplankton community is a major primary producer in coastal and estuarine water.

Phytoplankton production generally is immediately available as a food resource, whereas seagrass, saltmarsh, and mangrove production become available through secondary microbial processes. The phytoplankton community responds more quickly to environmental disturbance compared with the responses of seagrass, saltmarsh, and mangrove communities. The phytoplankton community response to disturbances include changes in productivity and biomass and changes in species composition and abundance.

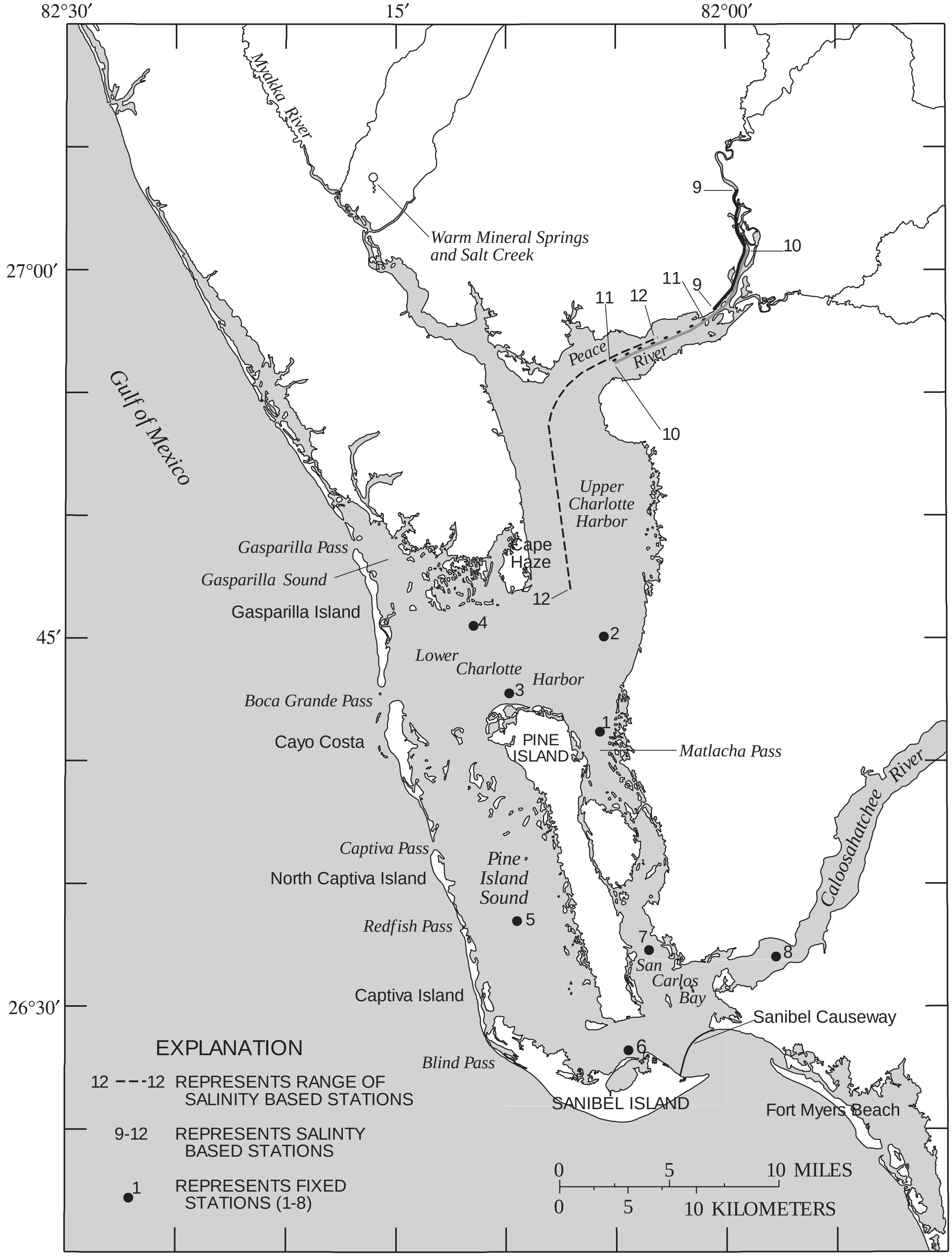
The temporal and spatial variability of phytoplankton productivity has been studied in a number of estuaries (Cloern, 1979; Pennock and Sharp, 1986). Generally, phytoplankton productivity and biomass maxima occur during the warmer seasons of the year (Boynton and others, 1982). Estuarine phytoplankton productivity usually is considered to be controlled by either nutrient or light availability, although one controlling factor in estuaries may replace the other depending upon location and season. Of the nutrients, nitrogen availability is cited most frequently as the controlling factor (Ryther and Dunstan, 1971; Boynton and others, 1982; Pennock and Sharp, 1986). In estuarine water where nutrient concentrations are relatively high, light may become the dominant controlling factor limiting productivity (Cole and Cloern, 1984). Most studies of estuarine phytoplankton productivity have been in temperate water, and few studies have addressed temporal and spatial variability of phytoplankton productivity in subtropical water.

The temporal and spatial variability of phytoplankton productivity and biomass in Charlotte Harbor have been investigated in studies by the Environmental Quality Laboratory, Inc. (EQL). EQL (1989) has measured carbon-14 productivity and chlorophyll-*a* concentrations monthly in upper Charlotte Harbor since June 1983. These measurements have been made *in situ* at four salinity-based stations (0,6,12, and 20 ppt) at a depth of 50 percent of surface light (fig. 12). Additional studies by EQL, supported by the U.S. Geological Survey, have evaluated: (1) areal and seasonal variability in productivity and biomass at 12 stations throughout the estuary from November 1985 to September 1986 (McPherson and others, 1990), (2) effects of nutrient additions on phytoplankton productivity (Montgomery and others, 1991), (3) the vertical distribution of productivity in the water column, and (4) short-term (3-4 days) variability in productivity and biomass (Environmental Quality Lab, Inc., written commun., 1989)

Phytoplankton productivity and biomass (as chlorophyll *a*) in the Charlotte Harbor estuarine system are relatively low most of the time. Productivity ranged from 5 to 343 (mg C/m^3)/h and averaged 59 (mg C/m^3)/h in the 1985-86 areal sampling of 12 stations shown on figure 12 (McPherson and others, 1990). Chlorophyll-*a* concentrations ranged from 1 to 46 mg/m^3 and averaged 8.5 mg/m^3. Average monthly productivity of carbon-14 ranged from 19 (mg C/m^3)/h in January to 100 (mg C/m^3)/h in September 1986, and average chlorophyll-*a* concentration ranged from 3 mg/m^3 in January 1986 to 13 mg/m^3 in July 1986 (table 4). Both productivity and biomass were greater during summer near the mouths of tidal rivers (McPherson and others, 1990). Long-term studies at the four salinity-based stations (fig. 12) have indicated that productivity and biomass generally were greatest at midsalinities (6 and 12 ppt) during summer (Environmental Quality Lab, Inc., written commun., 1989)

Phytoplankton productivity and biomass in the Charlotte Harbor estuarine system are affected by freshwater inflow that lowers salinity, increases nutrient availability, and reduces light penetration in the water column (McPherson and others, 1990). Freshwater inflow and nutrient loading reach their annual peaks during late summer, but the highly colored freshwater runoff greatly reduces light penetration in low salinity (less than 10 ppt) regions of the estuary and may limit phytoplankton productivity in these regions (McPherson and Miller, 1987). The nutrient-rich colored water is diluted by seawater at midsalinities (10-20 ppt) so that availability of light increases and enough nutrients remain available from the runoff to stimulate productivity and growth of phytoplankton in these areas. In the higher salinity water (more than 20 ppt), which includes much of the estuary, availability of nutrients, not light, limits productivity (McPherson and others, 1990).

Of the major nutrients needed for phytoplankton productivity in the Charlotte Harbor estuarine system, inorganic nitrogen is in lowest supply and most critical in limiting phytoplankton productivity and growth (Fraser and Wilcox, 1981). Concentrations of inorganic nitrogen commonly are at or below the laboratory detection limit throughout most of the high salinity (more than 20 ppt) regions of the estuary (McPherson and Miller, 1990). Nitrogen is a critical nutrient for phytoplankton in other estuaries (Boynton and others, 1982), and most of the needs for this nutrient are met by bacterial recycling and regeneration of



Base from Southwest Florida Water Management District digital data, 1992
Universal Transverse Mercator projection, Zone 17

Figure 12. Charlotte Harbor estuarine system and phytoplankton sampling stations.

nitrogen within the estuary (McCarthy, 1972; Eppley and others, 1979; LaRoche, 1983; Furnas and others, 1986; Kokkinakis and Wheeler, 1987). Presumably, the nitrogen needs of phytoplankton in much of Charlotte Harbor also are met by bacterial recycling within the estuary.

Table 4. Average monthly carbon-14 productivity and chlorophyll-*a* biomass at 12 stations in the Charlotte Harbor estuarine system

[mg/m^3 = milligrams per cubic meter; mg C/(m^3 E/m^2) = milligrams carbon per cubic meter per Einsteins per square meter; mg C/(m^3 h) = milligrams carbon per cubic meter per hour]

	Chlorophyll *a*	Carbon-14 Productivity	
	mg/m^3	mg C/(m^3 E/m^2)	mg C/(m^3 h)
November 1985	11	18	68
January 1986	3	5	19
March 1986	7	8	45
May 1986	6	8	40
July 1986	13	16	89
September 1986	12	19	100

Small (less than 5 µm) phytoplankton dominate productivity and biomass in the Charlotte Harbor estuarine system. The small size fraction accounted for about 59 percent of the productivity and biomass at 12 stations during 1985-86. Nano (5-20 µm) and net (more than 20 µm) phytoplankton accounted for about 15 and 26 percent, respectively. The small size fraction was dominated by cryptophyceae. Diatoms dominated the net phytoplankton size fraction at high salinity (more than 20 ppt) stations (R.T. Montgomery, Environmental Quality Lab, Inc., written commun., 1989).

The composition of the phytoplankton community in the Charlotte Harbor estuarine system varied with location and season (McPherson and others, 1990; Stoker, written commun., 1991). At intermediate and high salinity locations, the small size fraction often was dominated by Cryptophyceae (*Chroomonas* spp. and *Cryptomonas* spp.). Diatoms (*Skeletonema costatum, Asterionella glacialis, Odentella sinensis, Corethron criophilum, Coscinodiscus centralis, Chaetoceras* spp., *Rizosolenia* spp., and others) usually characterized the large (more than 20 µm) size fraction. However, Dinophycaeae (*Ceratium* spp. and *Peridinum* spp.) were seasonally important. Non-flagellated green cells, probably including both Cyanophyceae and Chlorophyceae, and phytoflagellates were abundant components of the small size fraction in low salinity water. The large size fraction at low salinities usually was characterized by a mixture of Chlorophyceae, diatoms, and blue-green algae (*Anabaena* spp. and *Anacystis* spp.).

Diatoms were dominant in 55 percent of 289 phytoplankton samples collected in the Charlotte Harbor estuarine system in 1983-84, cryptophytes in 35 percent, cyanophytes in about 6 percent, dinoflagellates in about 4 percent, and other classes in 1 percent (Stoker, written commun., 1991). Dinoflagellates and cyanophytes were more abundant and sometimes dominant during the late spring and summer. *Chroomonas* spp. were present in nearly all samples and were most numerous in 44 percent of the samples. *Skeletonema costatum*, *Thalassiosira* spp., and *Nitzschia* spp. were present in about 70 percent of all samples, and *S. costatum* was most numerous in 18 percent of the samples. Monospecific blooms occasionally occurred and were typically composed of *Chroomonas* spp. in the harbor waters north of Cape Haze and of *S. costatum* in the tidal reach of the Caloosahatchee River. Highest phytoplankton density, exceeding 18x10^6 cells per liter, was present in the tidal reach of the Caloosahatchee River (Stoker, written commun., 1991).

Mangroves and Saltmarshes

Mangrove forests are particularly important to the coastal environment. Their leaf litter and seeds add rich organic material to the tidal water. Leaf fall is greatest during the dry season, but seed production occurs during the rainy season when the likelihood of distribution by tropical storms is greatest. Different species of mangroves and their characteristic forest types are distributed in relation to the amount of tidal inundation and flushing (Lugo and others, 1988). For example, red mangrove grows in areas of greater flushing than does black mangrove (fig. 3), so their organic contribution to the estuaries and bays is larger and creates an extremely rich and nutritive habitat. It is estimated that 75 to 90 percent of marine commercial and sport species of fish in southern Florida utilize the estuarine habitats. Commercially important shrimp, lobster, and stone crabs also spend part of their juvenile lives in the estuaries and mangrove-lined bays. These fishes and crustaceans are called estuarine-dependent species, because their existence and abundance require estuaries, bays, and mangrove areas of suitable size and quality.

The coastal mangrove fringe functions as an effective buffer to the upland environment during storms. The mangrove line breaks the wind and high tides. In a similar manner, mangroves function as baffles that help keep the inland water free of floating debris and suspended sediment. Prevailing onshore winds push the coastal water through the tangle of mangrove roots where debris and sediment are trapped and filtered. Thus, mangroves not only enrich coastal water with organic material, but also help to improve water clarity. Improved water clarity and the resulting increase in light available to nearby submerged aquatic vegetation provides a more productive and healthy estuarine environment.

Mangrove forests and associated saltmarsh grow along much of the shoreline of the Charlotte Harbor estuarine system. Harris and others (1983) estimated that, in 1982, mangrove forest covered 56,631 acres and that saltmarsh covered 3,547 acres in the estuary. Mangrove forest increased by 10 percent during 1945-82 and saltmarsh decreased by 51 percent (Harris and others, 1983). State and local regulations that protect the mangrove fringe surrounding Charlotte Harbor were enacted prior to any large-scale destruction. Consequently, few mangrove areas have been dredged or filled, and areal coverage has increased by 5,107 acres. Increases can be explained by natural growth. Much of the mangrove increase could be related to an 8,158-acre loss of nonvegetated tidal flat that occurred over the same period (Harris and others, 1983). Tidal flats provide suitable locations for mangrove seedlings to lodge and germinate. If conditions are suitable for growth, new mangrove stands can be propagated. Other factors, such as rising sea level, spoil island creation, marsh succession and restoration can explain increases, but they are probably minor in this case (Harris and others, 1983). The loss of saltmarsh between 1945 and 1982 can be directly attributed to land development and drainage of low-lying uplands (Harris and others, 1983).

Seagrass Meadows

Seagrass communities are an important component of the estuarine and coastal environment (fig. 3). They provide food, shelter, and nurseries for a variety of marine organisms, including commercially important species. Seagrass communities also stabilize sediments, baffle waves and currents, improve water clarity, and cycle nutrients from bottom sediment into the food web (Zieman, 1982; Lewis and others, 1985).

Seagrass communities have decreased in area and distribution in various parts of the world in recent years. Some of these declines are attributed to a deterioration of water clarity. Seagrass photosynthesis and growth are sensitive to light intensity. Unlike phytoplankton, which may require as little as 1 percent of incident light for net photosynthesis, seagrass requires at least 15 to 25 percent of the incident light just for maintenance because of the large metabolic demands of their nonphotosynthetic root and rhizome tissues (Kenworthy and Haunert, 1991). Also, because seagrass is rooted on the bottom, it is not transported upward into the photic zone by turbulent water movement.

Seagrass abounds in the southern part of the Charlotte Harbor estuarine system, but is less common in the deeper, northern part of the estuary. Attenuation of PAR by dissolved matter that is flushed into the harbor by basin runoff probably has contributed to the limited development of seagrass meadows in the deeper water of the northern half of the estuary. Much of the bottom in the northern part of the estuary is below the depth to 1 percent of surface light (McPherson and Miller, 1987). Sustainable seagrass productivity requires light intensities well above this 1-percent level (Drew, 1979; Short, 1980; Williams and McRoy, 1982; Bulthuis, 1983; Fourqurean and Zieman, 1991; Kenworthy and Haunert, 1991).

The dissolved matter in northern Charlotte Harbor has not only contributed to the total reduction of PAR, but it has altered the spectral distribution of that radiation by selectively reducing the shorter wavelengths (400-500 nm) (McPherson and Miller, 1987). Although it is not clearly established, altered spectral quality could affect seagrass (Buesa, 1974; Kirk, 1976; 1979).

Seagrass meadows covered about 58,500 acres of the Charlotte Harbor estuarine system in 1982 and had decreased in area by 29 percent since 1944 (Harris and others, 1983). Little direct destruction of seagrasses has occurred; most of the loss has been in deeper parts of the estuary, at the fringing bars, and in lagoonal areas (Harris and others, 1983). Although specific causes of the seagrass decline cannot be proven, Harris and others (1983) speculated that the decline could be related to changes in circulation patterns and to increased stormwater runoff. Construction of the Sanibel Causeway and dredging of the Intracoastal Waterway through San Carlos Bay and Pine Island Sound in the 1960’s changed circulation patterns and probably increased turbidity (Harris and others, 1983). The large decline in seagrass meadows in mid and lower Pine Island Sound (13,936 acres; Harris and others, 1983) would make bottom materials more susceptible to resuspension and transport because seagrass blades baffle currents and increase sedimentation (Ginsburg and Lowenstam, 1958; Fonesca and others, 1982; Bulthuis and others, 1984; Ward and others, 1984) and would further reduce light availability to the remaining meadows. Seagrass thrives in low-nutrient, clear water. Stormwater runoff could damage seagrass by increasing nutrient concentrations, turbidity, and toxins. Increased nutrient loading would be detrimental to seagrass as it would increase the growth of epiphytic algae and phytoplankton, both of which can usually outcompete seagrass for light.

Unvegetated Estuary Bottom

The unvegetated bottom environment provides habitat for a variety of algal and invertebrate species that are important in both energy and material flows of the food web. Benthic algae fix carbon and contribute to estuarine productivity. Benthic invertebrates are capable of filtering water, feeding on deposited material, or cycling nutrients, trace elements, and dissolved gases between sediments and the overlying water column, as well as contributing to the deposition of sediment. An unvegetated, sandy bottom is a common benthic environment in the Charlotte Harbor estuarine system. Unvegetated tidal flats covered about 11,000 acres of the estuary in 1945, but only about 2,700 acres in 1982 (Harris and others, 1983). The large decline is attributed to increased mangrove coverage during this span.

The Charlotte Harbor estuarine system has a diverse assemblage of benthic macroinvertebrates that are associated with unvegetated estuary bottoms. Estevez (1986) reported finding 546 species representing 15 phyla from a total of 25 intertidal and subtidal stations sampled during May through June and during September 1980. Bottom salinity, dissolved oxygen, and the number of species increased along a gradient toward the south and west, especially in September. Macroinvertebrate densities were highest at river mouths and in Pine Island Sound (May-June) or in coastal Charlotte Harbor (September).

POSSIBLE EFFECTS OF FUTURE DEVELOPMENT AND CHANGES

Changes in the estuarine environment can be expected as a result of human activites within the basin and on a global scale. Projected development in the basin can substantially change the quality and quantity of basin runoff over the next several decades. The estuarine environment might also undergo changes as a result of global processes such as global warming.

Increasing atmospheric concentrations of carbon dioxide and other gases generated as a result of human activities generally are expected to warm the earth a few degrees celsius in the next century by a process commonly known as the "greenhouse effect." Such a warming could alter climates and raise sea levels by melting glaciers and expanding ocean water. Climate change could affect the Charlotte Harbor Estuary primarily because of changes in rainfall and temperature, although changes in cloud cover, wind, humidity, and other weather conditions also could have some effect. Changes in rainfall could alter the amount and temporal distribution of streamflow and ground-water recharge and discharge to streams in the basin and the frequency and duration of extreme hydrologic events, such as major storms and droughts. Changes in temperature and other climatic variables could affect rates of evapotranspiration and subsequently alter both streamflow and ground-water recharge and discharge to streams. Changes in rainfall and other climatic variables also could alter chemical and biological processes in the basin and estuary. A rise in sea level would accompany global warming (Titus, 1988). Estimates for the rise in sea level expected for the year 2025 range from 5 to 15 in. above current sea level; the rise could be almost 7 ft by 2100 (Titus, 1988). The combined effect of a rising sea and a change in freshwater inflow could substantially alter the salinity of the estuary.

Sea level rise in the Charlotte Harbor estuarine system could alter coastal wetlands. A rise of several feet will shift coastal mangrove forests inland along an undeveloped coastline. However, loss of mangrove forest and marsh could occur where bulk heads and other development prohibit tidal intrusion (Titus, 1988). The future loss of tidal wetland forest in Charlotte Harbor as a result of sea level rise will depend upon the amount of development that occurs near the tidal zone.

Stress on the environment caused by development within the Charlotte Harbor inflow area can be expected to continue and perhaps accelerate. By the year 2020, the population is projected to be probably more than double the 1980 population (table 5). Increased population, even without any increased industrial or agricultural development, will produce substantial additional waste loads and demands for water supply. By the year 2020, the projected population increase will generate 60 Mgal/d more domestic wastewater than that generated during 1980, which could result in an additional 3 ton/d of nitrogen (table 6) and 0.65 ton/d of phosphorus (Hammett, 1990). Urban runoff with its nutrient and contaminant loads also can be expected to increase. More than 150 mi^2 of land are projected to be converted to urban uses which will produce another 0.25 ton/d of nitrogen in runoff (table 6). Intensified agricultural and industrial developments, particularly expanding citrus production and phosphate mining, could generate additional loads of nutrients and a variety of inorganic and organic contaminants.

Table 5. Population projections through the year 2020 by river basin

[Values are in thousands. From Hammett, 1990]

River basin	Census		Population projections		
	1970	1980	2000	2010	2020
Caloosahatchee - -	60	114	220	251	279
Coastal - - - - - - - -	33	65	129	147	163
Myakka - - - - - - -	38	64	111	127	141
Peace - - - - - - - - -	191	278	426	487	541
Total - - - - - - - -	322	521	886	1,012	1,124

Table 6. Increased total nitrogen loads that could be generated as a result of increased population and stormwater runoff through the year 2020 (Modified from Hammett, 1990)

River basin	1990	1995	2000	2010	2020
Increased total nitrogen from wastewater[1]					
Caloosahatchee - -	0.31	0.42	0.57	0.73	0.83
Coastal - - - - - - - -	.16	.26	.31	.42	.52
Myakka - - - - - - -	.16	.21	.26	.31	.42
Peace - - - - - - - - -	.42	.63	.78	1.10	1.36
Total - - - - - - - -	1.05	1.52	1.92	2.56	3.13
Increased total nitrogen from urban stormwater runoff [1]					
Caloosahatchee - -	.024	.034	.044	.056	.068
Coastal - - - - - - - -	.014	.020	.026	.034	.040
Myakka - - - - - - -	.011	.015	.019	.026	.032
Peace - - - - - - - - -	.033	.048	.061	.086	.108
Total- - - - - - - - -	.082	.117	.150	.202	.248

[1] Represents amount above 1980 levels. Values are in tons per day.

Estimates of future loads also can be obtained by extrapolating existing trends. Total organic nitrogen concentration at the Peace River at Arcadia is increasing at a rate of 0.035 mg/L per year (Hammett, 1990). At an average discharge of 1,141 $\text{ft}^3\text{/s}$, that is equivalent to a loading increase of a little more than 0.1 ton/d each year. Without adjusting for a downward trend in streamflow, the load of total organic nitrogen would increase by about 3.8 ton/d by the year 2020. Adjusting for the decreasing trend in discharge (7.6 $(\text{ft}^3\text{/s})\text{/yr}$) at the Peace River at Arcadia, the load of total organic nitrogen would increase by about 3.4 ton/d by the year 2020 (Hammett, 1990). By extrapolating the trends for the Caloosahatchee River at structure S-79, the total nitrogen load would increase by more than 9 ton/d by the year 2020, and total organic nitrogen would increase by nearly 7 ton/d (Hammett, 1990).

The projected increases in nutrient loads to the Charlotte Harbor estuarine system probably will be accompanied by decreases in freshwater inflow (Hammett, 1990). Freshwater flow in the Peace River has declined over a span of about 50 years (1934-84), probably as a result of ground-water pumping. If this trend in flow continues, parts of the river north of Arcadia could be dry year-around in about 100 years. A decrease in freshwater inflow would decrease flushing and increase salinity in the estuary. For example, if the 7-day, 2-year low flow in the Peace River were reduced by 50 percent, the location of the near surface 0.5-ppt salinity line would move upstream more than 2 river miles (Stoker and others, 1989). Increases in salinity as a result of reduced freshwater runoff might be further increased by effects of a rising sea level. Under low freshwater inflow, hypersaline (more than 36 ppt) conditions could develop in areas of the estuary that have poor circulation and flushing.

Projected basin population growth and development could have two major adverse effects on the Charlotte Harbor estuarine system: (1) decreased freshwater inflow or altered timing of the inflow and (2) increased input of contaminants, such as metals or pesticides, or of nutrients beyond those needed to sustain productivity and health of the ecosystem. Seasonal freshwater inflow is important in maintaining a balanced estuarine ecosystem. The freshwater mixes with seawater to create a range of salinity. Many species are adapted to specific salinity ranges and to seasonal fluctuations of salinity. A number of juvenile marine species require low salinity water. Species also derive benefit from freshwater inflow because it transports nutrients and other constituents into the estuary that sustain productivity and provide food. Freshwater inflow into the harbor also adds water color in low salinity (less than 10 ppt) regions and greatly reduces light penetration and algal growth. Changes in the amount or the timing of freshwater runoff would adversely affect many organisms that depend on the present combination of salinity, tide, current, nutrients, light, and other environmental factors.

Increased input of nutrients, particularly nitrogen, would foster increased phytoplankton growth and abundance. Benthic and epiphytic algae also might increase in the extensive areas of shallow water where sufficient light is available. If the water were less colored as a result of reduced freshwater inflow, undesirable algal growth could be exacerbated because of increased availability of light.

Increased abundance of phytoplankton and other algae would change dissolved-oxygen concentrations in the estuary. In shallow water, daytime concentrations would increase because of photosynthesis, and nighttime concentrations would decrease because of increased respiration. In deeper water, similar changes might occur under well-mixed conditions, but under stratified conditions, bottom water could be depleted of oxygen. At the present time, near-anaerobic conditions exist for days or weeks in the deep water (more than 9 ft) of the northern harbor during late summer. These conditions could become more persistent with time and occupy larger areas of the estuary if phytoplankton and other algae increase in abundance and in their contribution to benthic oxygen demand as dead algal cells settle to the bottom.

Increased nutrient input to the Charlotte Harbor estuarine system would be detrimental to seagrass communities. Seagrass thrives in low nutrient, clear water. In turbid water, seagrass is restricted to shallow depths where light is adequate, but if the water is nutrient-rich, epiphytic and drift algae could cover seagrass and compete for the light (Cambridge and McComb, 1984). In deeper areas, phytoplankton can best compete for light and can shade benthic plants. Increased nutrient input to the estuary would favor phytoplankton and other algal communities and probably would accelerate the decline in seagrass communities.

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