Salinity Distribution and Variation with Freshwater Inflow and Tide, and Potential Changes in Salinity due to Altered Freshwater Inflow in the Charlotte Harbor Estuarine System, Florida

By Yvonne E. Stoker

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Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
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
million gallons per day (Mgal/d)	0.04381	cubic meter per second
ton, short	0.9072	megagram

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
$°C = 5/9 \times (°F-32)$

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:

µS/cm microsiemens per centimeter at 25 degrees Celsius
ppt parts per thousand

Additional abbreviations:

R^2 coefficient of determination

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Abstract

Charlotte Harbor is a shallow estuarine system in southwest Florida. The approximately 300-square-mile estuary has a drainage area of 4,670 square miles, an average depth of 7.0 feet, and receives inflow from three rivers—the Peace, Myakka, and Caloosahatchee. The estuary currently (1991) supports large and diverse sport and commercial fisheries, as well as many environmentally sensitive species. The Charlotte Harbor basin is being rapidly developed, with a 56-percent increase in population projected between 1990 and 2020. This increase in population will result in an increased demand for water supply, an increased wastewater output, and an alteration of runoff characteristics from the basin. The changes due to population increases could ultimately affect the salinity characteristics of the estuary.

Salinity fluctuates in response to seasonal variation in freshwater inflow from the rivers. 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 in salinity at a site generally increased with increased freshwater inflow.

Salinity was vertically stratified—lower at the surface than near the bottom—in the harbor during periods of high freshwater inflows. Stratification occurred to some degree during the wet season at all measured sites, but was most pronounced at the northern and western parts of the upper harbor. Near-surface salinity was as much as 20 parts per thousand lower than near-bottom salinity near the mouth of the Peace River during a period of high freshwater inflow in June 1982.

Changes in the basin due to increased population that would likely affect salinity distribution in the harbor are a decrease in freshwater inflows and a change in runoff characteristics. A decrease in freshwater inflows would result in an increase in salinity. The upper limit on salinity increases would be the salinity in the Gulf of Mexico, but hypersaline conditions could occur in some areas of the harbor. Expansion of urban areas would affect the runoff characteristics, resulting in a rapid increase in streamflow during rainfall and a rapid return to base flow, which in turn would cause more rapid changes in salinity before and after a storm.

INTRODUCTION

Estuaries are characterized by salinity variations that range seasonally and areally from fresh to marine. These variations are controlled by the timing and quantity of freshwater inflow and are influenced daily by tidal water motions. Diverse biotic communities are adapted to these fluctuations of salinity, and many species are dependent on estuarine salinity variations for survival. Many species are endemic to estuaries and many more spend at least part of their life cycle in estuaries. Most of the fish species valued by sport and commercial fisheries spend some part of their life cycle in estuaries (Beaumariage and Stewart, 1977). Alterations in the timing and amount of freshwater inflow to estuaries modify natural salinity patterns and can disrupt estuarine chemical and biological processes.

Charlotte Harbor (fig. 1) presently supports large and diverse sport and commercial fisheries. In 1987, commercial finfish and shellfish landings in Lee County (fig. 2) were the sixth largest in the State, with an annual landing of 12.1 tons (Florida Department of Natural Resources, written commun., 1988). The total annual landing for Charlotte County in 1987 was 3.5 tons. In Charlotte and Lee Counties, black mullet comprised 66 and 62 percent, respectively, of total finfish landings; blue crabs, 96 and 88 percent of shellfish landings (excluding shrimp); and pink shrimp comprised 98 and 95 percent of shrimp landings, respectively. Snook, tarpon, redfish, and spotted seatrout are important gamefish in the estuary (Florida Department of Administration, 1978). Salinity in Charlotte Harbor is an important variable in seasonal composition and abundance of fish (Wang and Raney, 1971; Fraser, 1981) and phytoplankton (Stoker, U.S. Geological Survey, written commun., 1992).

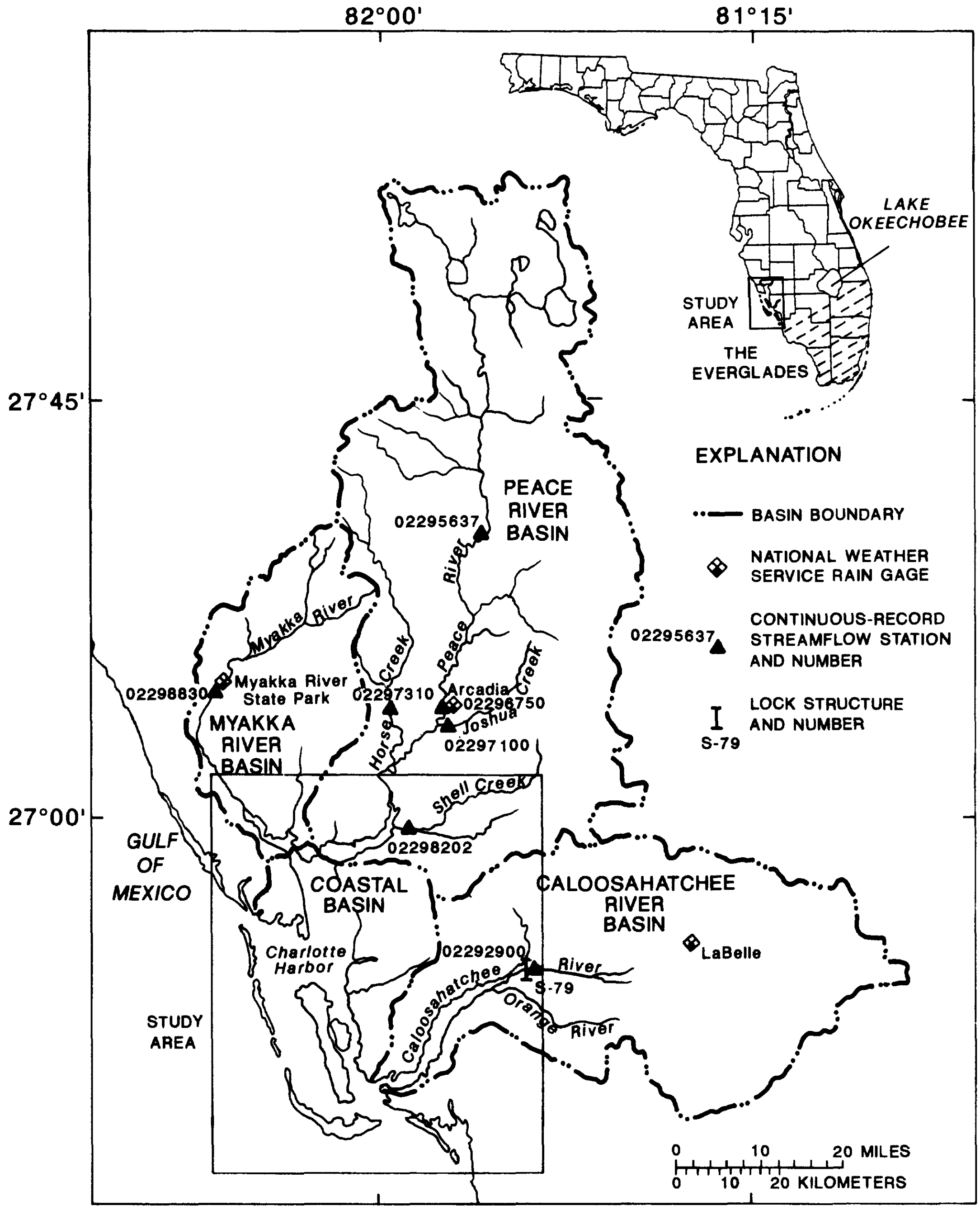


Figure 1. Study area and drainage basins.

The ecosystems of the harbor support more than 300 species of birds, about 400 species of mollusks, and many rare, threatened, or endangered species, such as the American bald eagle, brown pelican, wood stork, and several species of sea turtle (Florida Department of Administration, 1978). Approximately 40 percent of the State's endangered and threatened species are found in the Charlotte Harbor area (Barnett and others, 1980). The State of Florida has recognized the esthetic, environmental, and economic value of this resource and has designated more than 90 percent of the Charlotte Harbor estuarine system as an aquatic preserve. The overall management goal is the "maintenance of essentially natural conditions, the propagation of fish and wildlife, and public recreation..." (Florida Department of Natural Resources, 1983).

The Charlotte Harbor basin is a rapidly growing area. A 56-percent increase in population (405,000 additional people) in the basin is projected between 1990 and 2020 (Hammett, 1990). The expected increase in population is expected to result in increased demands for water supply, increased wastewater output, and potential alteration of runoff characteristics from the contributing basins. To properly plan for such a large population growth, State and local planners needed more information on the potential effects of growth on the Charlotte Harbor estuarine system.

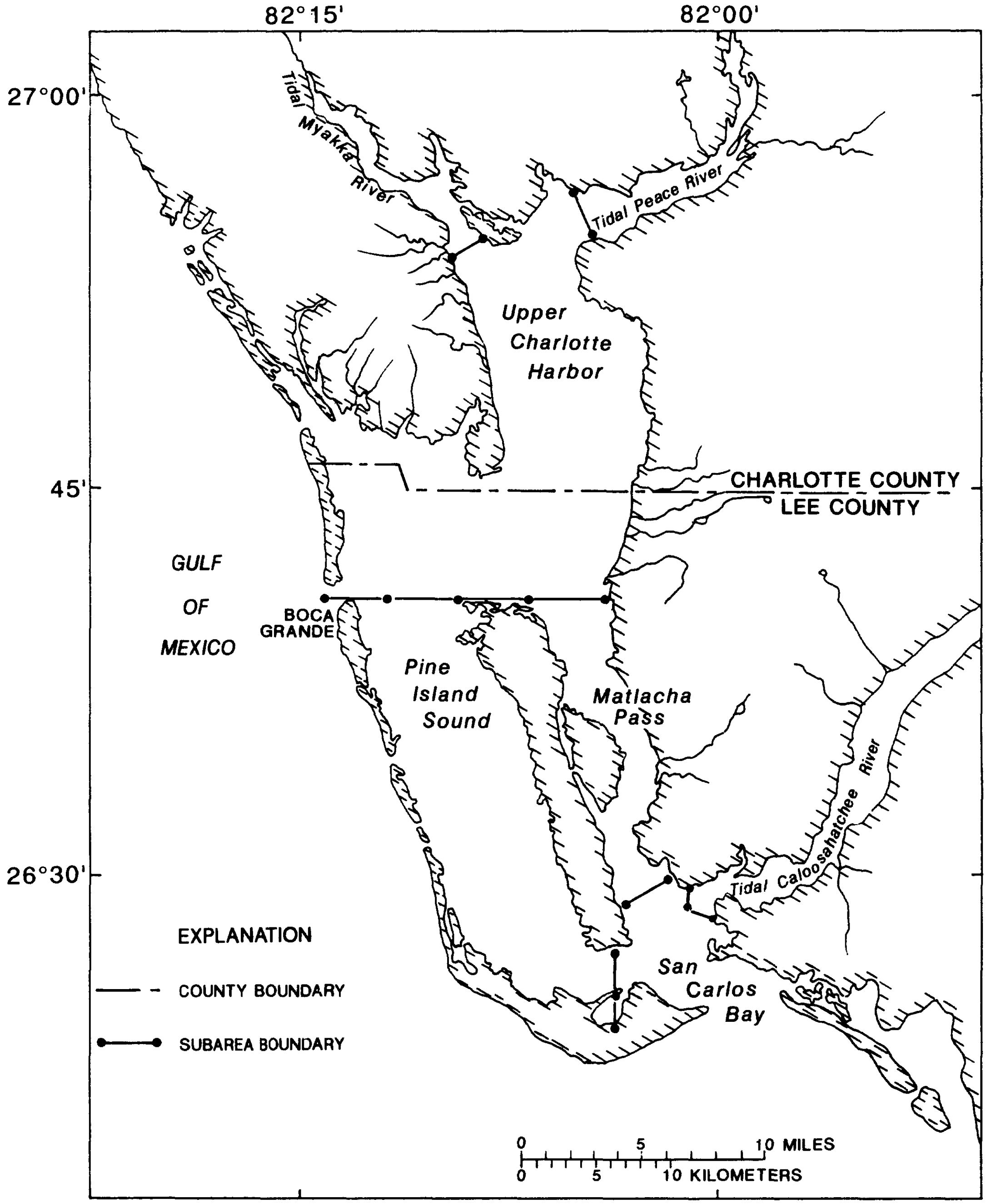


Figure 2. Charlotte Harbor and subarea boundaries.

The U.S. Geological Survey, in cooperation with the Florida Department of Environmental Regulation, began an environmental assessment study of the Charlotte Harbor estuarine system in 1982. The study included assessments of land and water use in the drainage basin and water quality, phytoplankton, benthic invertebrates, light characteristics, circulation, and salinity in the harbor. The overall goal of this study was to describe existing environmental conditions in Charlotte Harbor and to project future changes in the harbor that might result from changes in population and land use.

Purpose and Scope

This report presents the results of a study to (1) define the temporal and spatial salinity variability in Charlotte Harbor, (2) relate this variability to freshwater inflow and tide conditions, and (3) evaluate potential changes in salinity that might result from altered freshwater inflow to the harbor. The study area includes upper Charlotte Harbor, Pine Island Sound, Matlacha Pass, San Carlos Bay, nearshore waters of the Gulf of Mexico, the tidal Caloosahatchee River, and the lower reaches of the tidal Peace and Myakka Rivers (fig. 2). Data were collected from June 1982 to May 1987.

Previous Studies

Salinity is a variable that frequently is included in environmental studies. Numerous studies of the Charlotte Harbor estuarine system also included salinity data (Gunter and Hall, 1965; Alberts and others, 1970; Wang and Raney, 1971; U.S. Environmental Protection Agency, 1973; Estevez, 1986; and Fraser, 1986). Most of these studies, however, did not focus on salinity conditions of the harbor, but rather presented salinity measurements as ancillary data. Fraser (1986) looked at long-term water-quality characteristics, including salinity, at one site in the upper harbor. Salinity characteristics in the tidal Peace and tidal Myakka Rivers are described in detail in Stoker and others (1989) and in Hammett (1992), respectively. The Environmental Quality Laboratory Inc., in Port Charlotte, Fla., has collected salinity data in the tidal Peace River and upper harbor since 1976 as part of the requirements for a consumptive use permit for General Development Utilities, Inc. These data have been published annually and are included in reports listed in the selected references section of this report. Other agencies have collected salinity data as part of monitoring programs or specific studies, but have not published the data. Salinity data are available in files of the South Florida Water Management District, Lee County Environmental Laboratory, the Florida Department of Environmental Regulation, and the Florida Department of Natural Resources.

Acknowledgments

The author is grateful to the many people who participated in the collection of field data and in the maintenance of the salinity recorders used in this study. Special thanks go to William Sheftall and Roger Clark (former Aquatics Preserve Managers of the Charlotte Harbor Aquatic Preserve, Florida Department of Natural Resources) for their assistance in the field.

DESCRIPTION OF THE STUDY AREA AND FACTORS AFFECTING SALINITY VARIATION

Charlotte Harbor is a shallow estuarine system in southwest Florida. It has a surface area of about 300 mi^2, a drainage area of 4,670 mi^2, and an average depth of 7.0 ft. Charlotte Harbor has five major inlets to the Gulf of Mexico and receives inflow from three major rivers—the Peace and the Myakka at the northern end and the Caloosahatchee at the southern end (fig. 3). For discussion purposes, Charlotte Harbor can be divided into several regions. In this report, the tidal Peace, Myakka, and Caloosahatchee Rivers are defined as the river reaches from the mouth upstream to the limit of tidal fluctuation; the upper harbor (about 180 mi^2 in surface area) is defined as the area from Boca Grande east and north to the Peace and Myakka Rivers; and the lower harbor (about 120 mi^2 in surface area) is defined as the area that includes Pine Island Sound, Matlacha Pass, and San Carlos Bay (fig. 2).

Average depths in the harbor during mean lower low water are shown in figure 3 (National Oceanic and Atmospheric Administration, 1985). The upper harbor has an average depth of 8.6 ft, and the lower harbor has an average depth of 5.4 ft. The deepest parts of the harbor are at the passes. At the northern edge of Boca Grande depths exceed 50 ft. Within the harbor, depths are much shallower, and the harbor bottom generally has gentle slopes in natural, undredged areas. Parts of the Intracoastal Waterway in the tidal Caloosahatchee River and Pine Island Sound are maintained at a minimum depth of 9 ft by periodic dredging. Bottom materials from initial dredging activities were placed adjacent to the channel of the Intracoastal Waterway.

The climate in the area is subtropical and humid. Normal annual rainfall (1951-80) is 50 in. with 75 percent of the annual rainfall typically occurring from May through October. The mean annual temperature is 73°F, and mean monthly temperatures range from 83°F in July and August to 63°F in January (National Oceanic and Atmospheric Administration, 1985).

The physiography of an estuarine system, combined with the energy from tidal movements, freshwater inflow, and wind, influences circulation and mixing patterns, which, in turn, affect salinity patterns in the estuary. Density gradients between freshwater and saline water can inhibit mixing under certain conditions, causing vertical salinity gradients. The following sections summarize freshwater inflow and tide conditions in Charlotte Harbor, and subsequent parts of the report relate these to salinity patterns in the harbor.

Freshwater Inflow

Seasonal fluctuations in salinity in Charlotte Harbor occur primarily in response to seasonal fluctuations in freshwater inflow from the Peace, Myakka, and Caloosahatchee River basins (fig. 1). Streamflows in the Peace and Myakka Rivers are unregulated, except for one low-water dam in the upper Myakka basin. Discharges from the Peace and Myakka Rivers tend, therefore, to correspond to rainfall patterns in the basin. Streamflow in the Caloosahatchee River also is influenced by rainfall in the basin, but discharge to the harbor is regulated by Franklin Lock (structure S-79 in fig. 1).

The Caloosahatchee River has been extensively modified by human activities. The river originally flowed as a shallow, meandering stream with its headwaters located west of Lake Okeechobee. About 1880, a canal was dredged to connect the river with Lake Okeechobee to lower the lake level and to begin draining The Everglades. In the 1930's and again in the 1960's, the river was extensively dredged to widen, deepen, and straighten the channel (LaRose and McPherson, 1980). A series of three locks and dams controls discharge from the

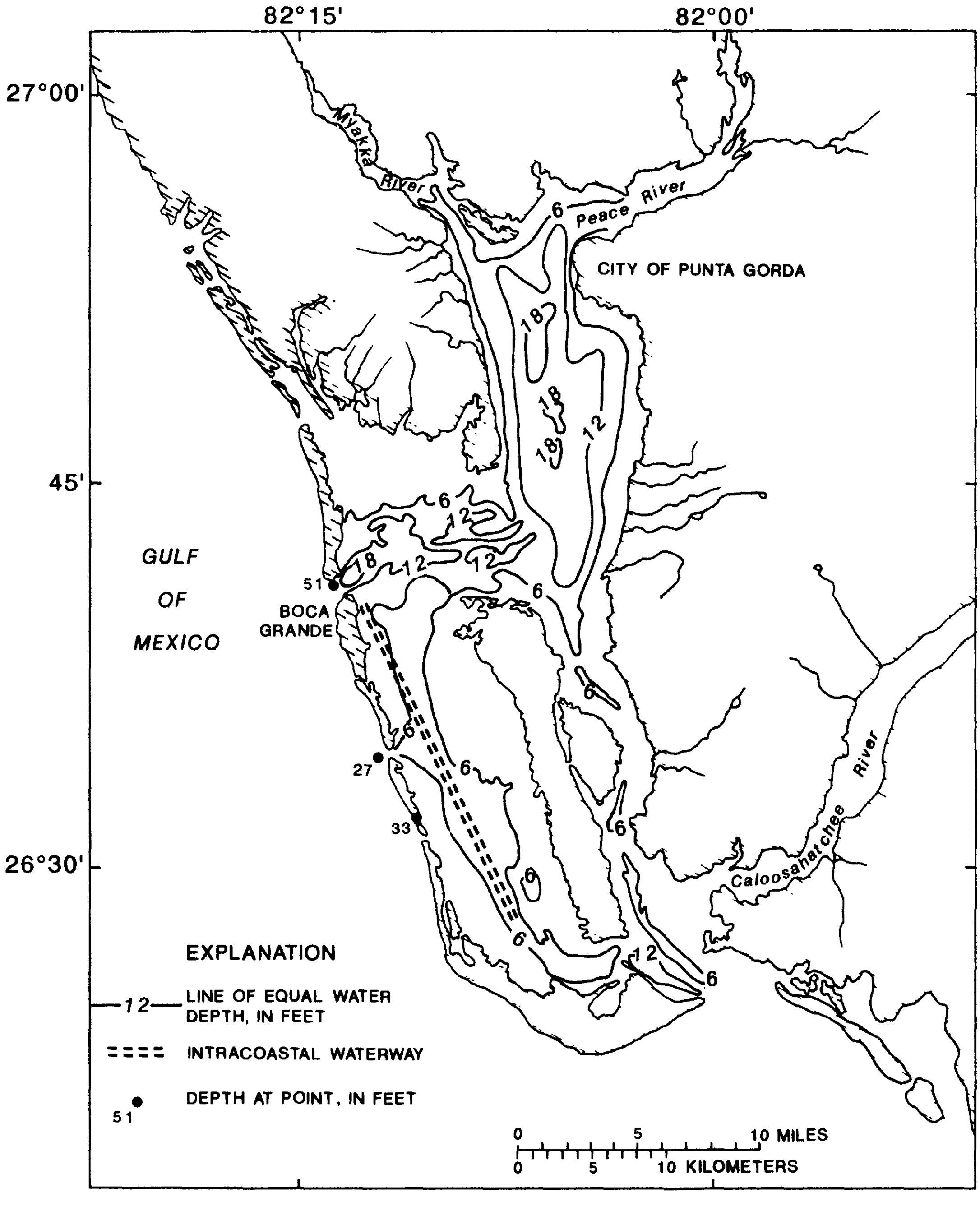


Figure 3. Depth of the Charlotte Harbor estuarine system.

river to Charlotte Harbor. Releases at structure S-79, the most downstream structure, which is located about 27 mi upstream of the mouth, do not always correspond to rainfall patterns in the basin. At times, additional freshwater is released at structure S-79 to flush encroaching saline water from the upstream reaches of the river, to flush algal blooms that have occurred upstream, or to lower water levels in Lake Okeechobee (Boggess, 1972; Henry LaRose, U.S. Geological Survey, oral commun., 1989).

The Caloosahatchee River upstream of structure S-79 is the major source of freshwater to the tidal reach of the river. Other sources of freshwater inflow to the tidal reach include rainfall, stormwater runoff from adjacent areas, flow from the Orange River (which enters the Caloosahatche River about 20 mi upstream of the mouth) and several smaller tributaries, ground-water seepage, flow from manmade canal systems, and domestic and industrial effluent. Nine facilities discharge domestic effluent and one facility discharges industrial effluent into the tidal reach of the river. The total permitted discharge to the river is 22.1 Mgal/d, or 34.2 ft^3/s (Hammett, 1990). The basin surrounding the tidal Caloosahatchee River is highly urbanized and has extensive shoreline and drainage alterations. The basin north of the river near the mouth has been extensively altered by dredging of

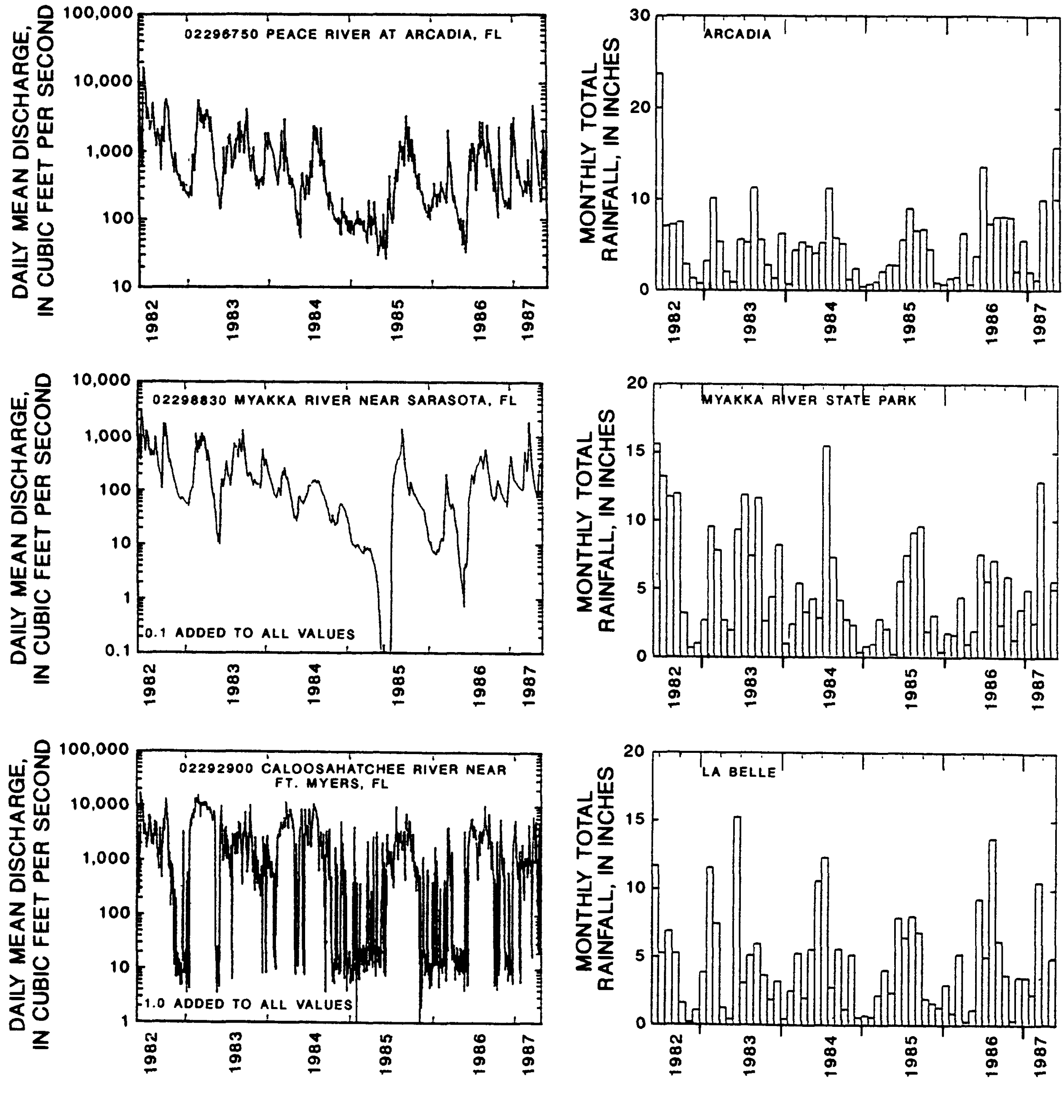


Figure 4. Daily mean discharge and monthly rainfall in the Peace, Myakka, and Caloosahatchee River basins, June 1982 to May 1987.

tidal canal networks and filling of adjacent low-lying areas for residential development of the city of Cape Coral (Goodwin, 1991). The 400 mi of dredged canals within the 104-mi^2 area of Cape Coral have altered historic drainage patterns to the lower tidal Caloosahatchee River. The canals receive freshwater from direct rainfall, runoff from the basin adjacent to the canals, freshwater inflow from inland canals, and seepage from the surficial aquifer (Goodwin, 1991). This freshwater eventually enters the tidal Caloosahatchee River about 3 mi upstream of the mouth.

Hydrographs of daily mean discharge for the most downstream gages on the Peace, Myakka, and Caloosahatchee Rivers and corresponding monthly rainfall at one site in each basin are shown in figure 4. Gage locations are shown in figure 1. Factors of 0.1 and 1.0 ft^3/s were added to the daily mean discharges for the Myakka and Caloosahatchee Rivers, respectively, to allow use of a semilog plot. Minimum discharges at these gages are actually 0 ft^3/s. Discharges measured at the Peace and Myakka River gages shown in figure 4 represent 58 and 38 percent, respectively, of the drainage in the basins. The drainage area of the Caloosahatchee River is indeterminate. Small tributaries and drainage from the basin downstream of the gages contribute to the total inflow from the rivers into Charlotte Harbor. For this study, discharges at the gages are assumed to be proportional to the total discharges to the harbor.

Discharge in the Peace and Myakka Rivers tends to peak in August and September when rainfall generally is at a maximum. Isolated storm systems such as tropical depressions or hurricanes, however, can have a major effect on discharge. In mid-June of 1982, heavy rainfall occurred over several days in south-central Florida and caused flooding in the Peace and Myakka Rivers. The peak discharges that resulted from this event had recurrence intervals of about 10 and 3 years, respectively (Bridges, 1982). This means that, in any given year, there is a 10-percent probability that such a peak discharge would occur at the Peace River at Arcadia, and a 33-percent probability that such a peak discharge would occur at the Myakka River gage. Flooding did not occur in the Caloosahatchee River at this time. Peak discharge in the Caloosahatchee River occurred in March 1983 as a result of excessive rainfall in the basin. Because discharge in the Caloosahatchee River is regulated, an analysis to determine the recurrence interval of the March 1983 peak discharge would not be statistically valid.

Discharge in the Peace and Myakka Rivers declines during the dry season, with lowest streamflow typically occurring in April or May. During the study, a long-term rainfall deficit occurred between July 1984 and July 1985. This deficit resulted in extended periods of low flow in the three rivers (fig. 4). The lowest mean 30-day discharge during the study for each river, the date at the end of each 30-day period, and the associated recurrence intervals are given below:

River	Lowest mean 30-day flow, in cubic feet per second	Date	Recurrence interval in years
Peace	46.8	May 23, 1985	45
Myakka	0	June 23-July 17, 1985	5
Caloosahatchee	[1]2.8	January 16, 1982	(2)

[1]Flow affected by regulation.

[2]Recurrence interval not computed due to regulation.

Tide

Tide is defined as the periodic rise and fall of water resulting from gravitational interactions between the Sun, Moon, and Earth. Meteorological conditions such as wind and barometric pressure also can influence the tide (National Oceanic and Atmospheric Administration, 1987). There are three types of tides based on the characteristic forms of the tide curve: (1) diurnal—one high water and one low water in each day, (2) semidiurnal—two high waters and two low waters of approximately equal height, and (3) mixed—two high waters and two low waters of unequal height. Mixed tides occur along the west coast of Florida, including Charlotte Harbor.

Water movements created by tides are called tidal currents. Ebb currents are the movements of water away from shore or down a tidal river or estuary, and flood currents are the movements of water toward the shore or up a river or estuary. Tidal currents can result in a large volume of water movement. Estuaries, by definition, are water bodies that contain a mixture of freshwater and saltwater in which the salinity is not areally constant. Salinity in an estuary increases with increasing distance from freshwater sources. Because of this longitudinal salinity variation, salinity at a fixed location in an estuary, or tidal river, will fluctuate daily as a result of ebb and flood tidal currents. During flood currents, salinity increases as saline offshore waters are pushed upgradient into an estuary, and salinity decreases as ebb currents carry these more saline waters back out of the estuary. Superimposed on tidal currents are currents created by freshwater inflows to an estuary. These freshwater currents can have a major effect on tide stage.

In the Charlotte Harbor estuarine system, barrier islands restrict tidal mixing of estuarine water with water in the Gulf of Mexico. The passes to the Gulf of Mexico concentrate tidal energy because of their physical restriction of flow. This concentration in tidal energy results in high velocities in the passes and large volumes of water passing through a relatively small area. The tidal energy is dispersed inside the harbor and influences the harbor and tidal rivers as much as 25 to 27 mi upstream from the mouths of the rivers. There is about a 2-hour lag between tide phases at Boca Grande and tide phases in the upper harbor near the mouth of the Peace River.

The tidal reaches of rivers play an important role in estuaries. Fresh and saline waters begin to mix in these reaches, and many chemical and biological processes occur. In the Peace River, the tidal reach extends from the mouth (river mile 0) near Punta Gorda (fig. 3) upstream to about river mile 26. The location of the freshwater-saltwater interface (the point at which the salinity is 0.5 ppt) moves upstream and downstream daily with the tide and seasonally with the volume of freshwater inflow. The average high-tide location of the interface is around river mile 13. The maximum upstream encroachment of saltwater was estimated to be river mile 32 where the streambed elevation approximately equals the maximum expected tide (Stoker and others, 1989).

The tidal reach of the Myakka River extends more than 25 mi upstream from its mouth. In this river, the average high-tide location of the freshwater-saltwater interface was 14.6 mi upstream from the mouth. A control structure at river mile 28.7 prevents saltwater encroachment beyond that point (Hammett, 1992).

The drainage area of the Caloosahatchee River is indeterminate because modification of the basin and the flat terrain make delineation of the basin impossible. For the purposes of this report, the mouth of the Caloosahatchee River was chosen as the downstream boundary of hydrologic cataloging unit number 03090305 (U.S. Geological Survey, 1974) (shown as basin boundary in fig. 1). The tidal reach of the Caloosahatchee River extends 27 mi from the mouth to the downstream side of structure S-79 (fig. 1). Prior to construction of structure S-79 in 1966, the river was tidally influenced as far as Ortona, 55 mi upstream from the mouth (Fan and Burgess, 1983). Although the structure acts as a salinity barrier, some saltwater has been known to move as much as 11 mi upstream from the structure as a result of operation of the lock (Boggess, 1970b). To reduce the upstream migration of saltwater through the lock, a bubbler system was installed at the structure in early 1986 (U.S. Army Corps of Engineers, oral commun., 1991).

Water Density

Density differences between freshwater and saline water influence vertical salinity patterns in an estuary. On the basis of mixing characteristics, estuaries can be classified as well mixed, partially mixed, or stratified. Mixing characteristics are influenced by water density, tides, discharge, and wind. Fresher, less dense water tends to flow over more dense saline water. This results in vertical salinity stratification that can be pronounced under certain conditions. In extreme cases, freshwaters are sharply separated from saline waters, and water in the two masses may be quite distinct and even move in different directions (fig. 5).

Horizontal gradients in salinity typically are gradual due to mixing by diffusion, circulation patterns, and wave action, but sharp gradients can be present during certain conditions. During periods of stormwater runoff, a large volume of freshwater flows into the estuary in a relatively short time. During a floodtide, saline waters may not immediately mix with fresher water inside the estuary, possibly due to temperature as well as salinity effects on density. The result can be a "tidal line" that often can be seen as a distinct change of water color between the two water masses, with a line of flotsam accumulated at the interface of the two water masses. Such features have been documented near the passes in Charlotte Harbor during summer runoff conditions.

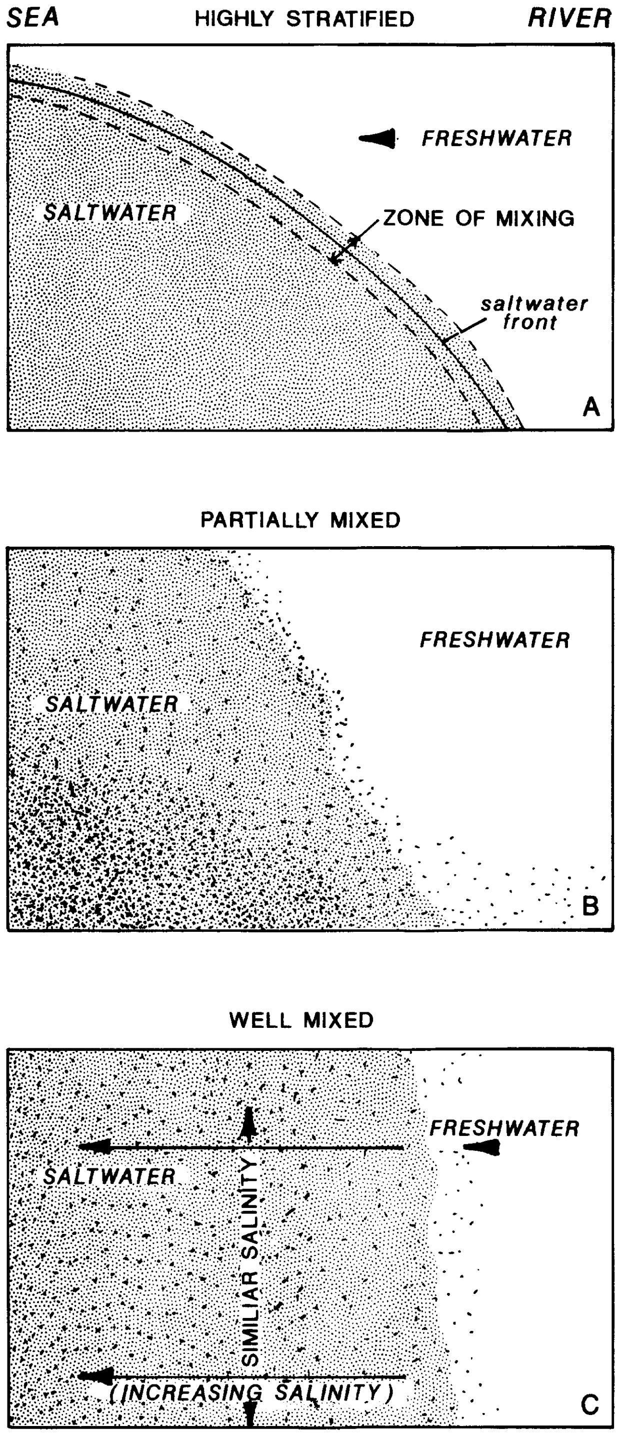


Figure 5. Generalization of highly stratified, partially mixed, and well-mixed salinity patterns in an estuary. (From Hammett, 1992.)

STUDY METHODS

Salinity was originally defined as "the total amount of solid material in grams contained in one kilogram of seawater when all carbonate has been converted to oxide, all the bromine and iodine replaced by chlorine, and all the organic material oxidized" (Pearse and Gunter, 1957). Early determinations of salinity were made by various laboratory analytical techniques. In the 1950's, electrical conductance began replacing the laboratory techniques as a means of estimating salinity (Culkin and Ridout, 1989).

Two approaches were used to gather salinity data for this study. The first approach was to measure specific conductance (electrical conductance standardized to 25°C) from boats using handheld instruments to define vertical profiles at selected sites in the harbor. The second approach was to install instruments to continuously record specific conductance at selected depths at fixed sites. All specific conductance measurements were converted to salinity concentrations, in parts per thousand, prior to analyses and interpretation. Salinity was calculated using the following equations (R.L. Miller, U.S. Geological Survey, written commun., 1985):

For specific conductance less than or equal to 21,000 µS/cm,

$$CHL = [0.000035+(0.00613077 \cdot LOG_{10}(COND))] + [2.5320848 \times 10^{-4} \cdot (COND)] + [7.9668632 \times 10^{-9} \cdot (COND)^2] - [3.21700173 \times 10^{-13} \cdot (COND)^3] + [5.36563289 \times 10^{-18} \cdot (COND)^4]; \quad (1)$$

for specific conductance greater than 21,000 µS/cm,

$$CHL = [0.00011 - (0.0072051 \cdot LOG_{10}(COND))] + [2.9999076 \times 10^{-4} \cdot (COND)] + [2.07552734 \times 10^{-9} \cdot (COND)^2] - [2.3034224 \times 10^{-14} \cdot (COND)^3] + [1.4427584 \times 10^{-19} \cdot (COND)^4]; \text{ and} \quad (2)$$

$$salinity = CHL \cdot 1.8065, \quad (3)$$

where CHL is chlorinity, in parts per thousand;
COND is specific conductance, in microsiemens per centimeter at 25 degrees Celsius; and
LOG_{10} is base 10 logarithm.

The term "salinity" will be used hereafter to describe the values computed using the equations listed above.

Continuous recording instruments to measure salinity were placed at six sites in the harbor (fig. 6). The periods of data collection are shown in figure 7. The instruments recorded near-bottom salinity at 15-minute intervals. Near-surface salinity also was recorded during selected periods at sites R-2 and R-3 in the upper harbor to determine the vertical variations in salinity and the degree of density stratification for various tide and freshwater inflow conditions.

Submersible instruments were deployed at eight sites in Charlotte Harbor and the Gulf of Mexico for the month of July 1986 (fig. 6). The instruments measured near-bottom conductance, temperature, velocity, and direction at 10-minute intervals. Conductance readings were converted to specific conductance by increasing or decreasing the recorded conductance by 2 percent for every degree Celsius that the corresponding temperature was below or above 25°C. Salinity was then computed using equations 1 through 3. Because of problems with excessive barnacle growth on the instruments, only selected periods were used in the data analyses.

Field measurements of salinity were made by boat at 15 to 50 sites in the harbor to further define areal and vertical salinity variation in the harbor. Attempts were made to measure salinity during high slack tide, but this was logistically difficult to accomplish over such a large area. Measurements were made near the surface, near the bottom, and at sufficient intervals in the water column to define the vertical distribution of salinity.

SALINITY DISTRIBUTION IN CHARLOTTE HARBOR

Data from the six continuous-record salinity instruments (gages) were used to describe short-term (daily) and long-term salinity characteristics at the salinity stations shown in figure 6. Daily mean salinity at each station for the period from May 1983 to December 1986 is shown in figure 8. Areas where the line plot is not continuous represent missing data. In some cases, data were missing due to equipment malfunction. In other cases (large gaps in the records for stations R-3 and R-5), the gages were discontinued for selected periods.

Seasonal salinity patterns occurred in response to the volume of freshwater inflow. The highest measured daily mean salinity occurred during an extended period of low flow during July 1984 to July 1985 (figs. 4 and 8). As freshwater inflow increased, salinity concentrations throughout the harbor decreased.

The distribution of daily mean salinity at the long-term salinity stations is shown in figure 9. Median salinity was lowest at station R-6 in the tidal Caloosahatchee River and was highest at the north and south ends of Pine Island (stations R-4 and R-5). Variability in daily mean salinity at each station was greatest in the tidal river sites (stations R-1, R-2, and R-6) and least at the harbor stations at the north and south ends of Pine Island. It should be noted that the maximum and minimum salinity at each station may have been exceeded during periods of missing record.

Near-bottom salinities during the period of July 9-23, 1986, at six stations within Charlotte Harbor and two stations in the Gulf of Mexico are summarized in figure 10. Locations of these stations are shown in figure 6. The highest salinity and lowest variability occurred in the Gulf of Mexico (stations SI-9 and SI-10). Salinity measured at these stations is representative of the salinity of incoming tidal water through the passes to Charlotte Harbor. Salinity is lowest in the northern part of the harbor at station SI-1, but increases to near-Gulf of Mexico salinity in northern Pine Island Sound (station SI-6). Salinity in Pine Island Sound decreased from north to south during this period (stations SI-6 to SI-8).

Seasonal variations in daily mean salinity and daily range in salinity at stations R-1 through R-6 are shown in figure 11. Median daily mean salinities generally were lowest during the July through September wet season and highest during January through March. The seasonal patterns in salinity shown in figure 11 are influenced by the extended drought that occurred during the study. Seasonal patterns during normal freshwater inflow conditions would show lower salinities during the July through September wet

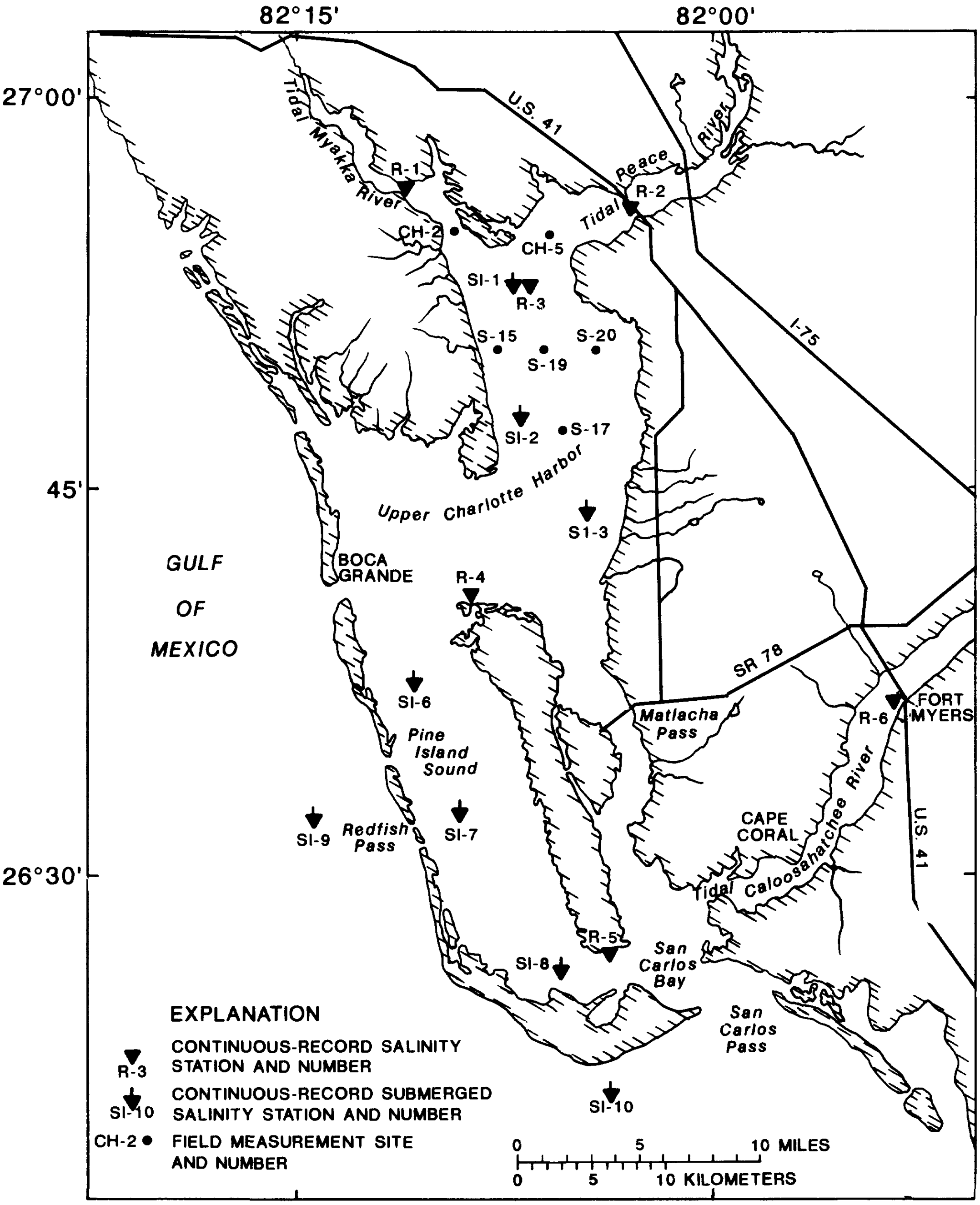


Figure 6. Location of continuous-record salinity stations and selected field measurement sites.

season. The largest daily range in salinity occurred near the mouth of the Peace River at station R-2. The median daily range in salinity at that station was 8.3 ppt and the maximum range exceeded 30 ppt on some days. A previous investigation of the tidal Peace River demonstrated that the U.S. Highway 41 and Interstate 75 bridges had an effect on salinity characteristics in the tidal river (Stoker and others, 1989). The constriction at the bridges combined with relatively large tide-driven movement and freshwater inflows from the Peace River caused the high daily salinity fluctuations. The least variation in daily range in salinity occurred in the tidal Caloosahatchee River (station R-6) and in the upper harbor (station R-3). The median daily range in salinity at these stations was about 2.5 ppt and exceeded 8 ppt less than 5 percent of the time. Seasonal changes in daily range in salinity varied between stations.

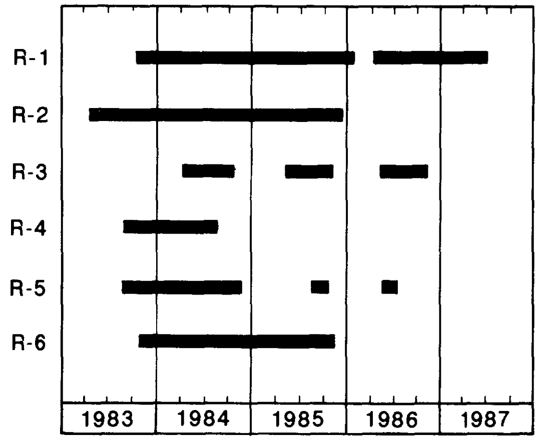


Figure 7. Period of record at continuous-record salinity stations.

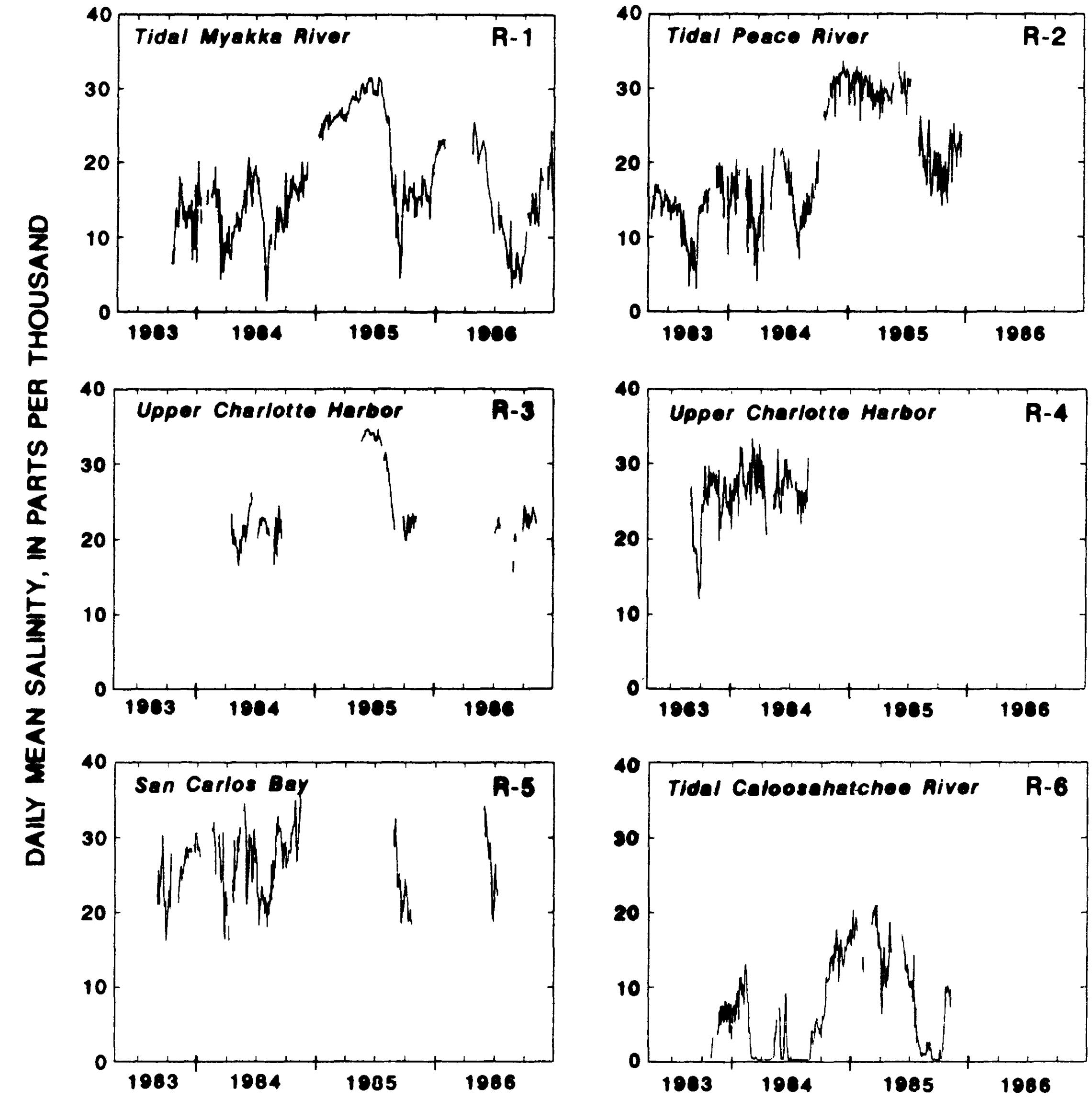


Figure 8. Daily mean salinity at the continuous-record salinity stations, May 1983 to December 1986.

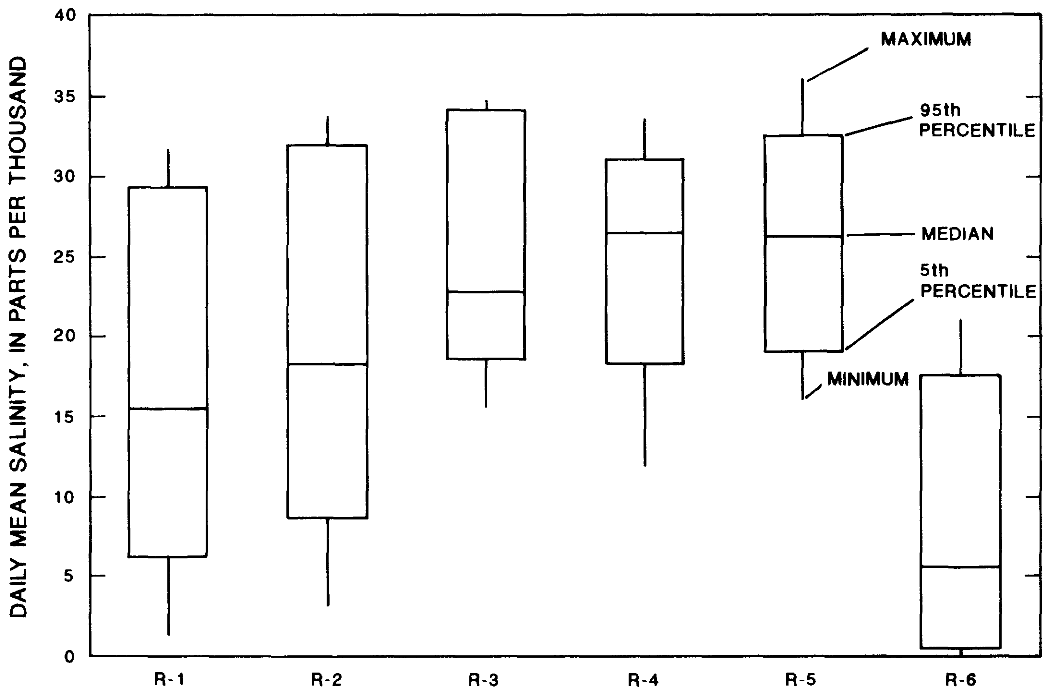


Figure 9. Distribution of daily mean salinity at the continuous-record salinity stations.

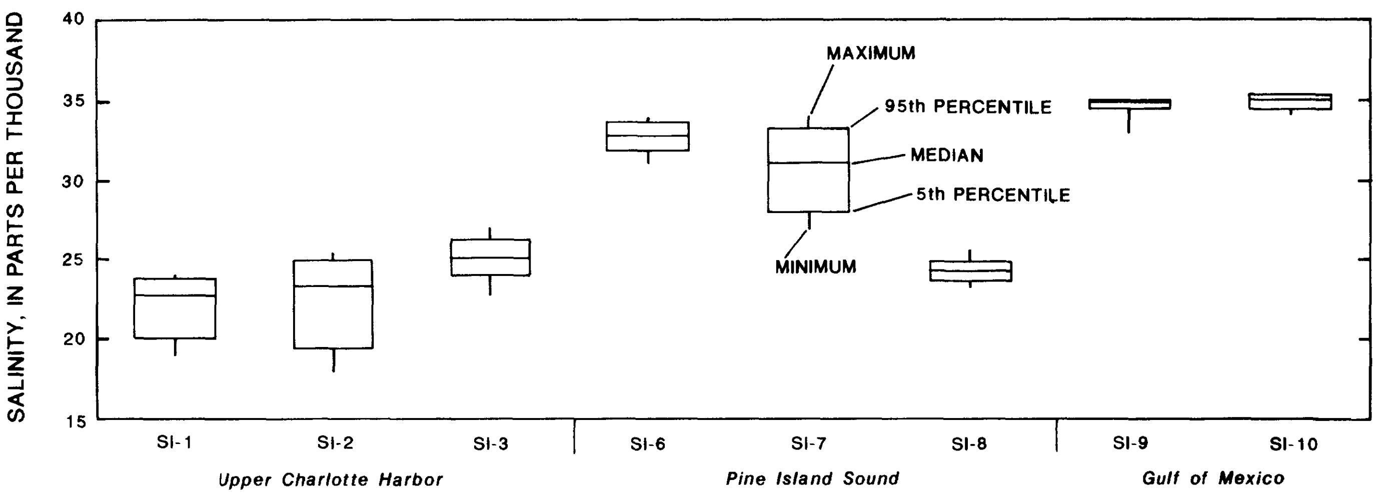


Figure 10. Distribution of salinity at stations in and near Charlotte Harbor, July 9-23, 1986.

SALINITY VARIATIONS WITH FRESHWATER INFLOW AND TIDE

Data from the study were analyzed using correlation and regression techniques to describe the relation between salinity, freshwater inflow, and tide at selected sites. Various combinations of untransformed and log-transformed stream discharge data were related to daily salinity statistics (minimum, maximum, mean, and range) at the six continuous-record salinity stations shown in figure 6. Combinations of stream discharge that were tested in the correlation analyses included 1-, 5-, 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, and 50-day averages at each gage. Streamflow data for the Myakka, Peace, and Caloosahatchee Rivers and their gaged downstream tributaries were included (fig. 1). Daily mean tide data at El Jobean (station R-1) also was included in the regression analyses.

Daily minimum, maximum, and mean salinity was inversely related to freshwater inflow, whereas daily range in salinity was directly related to freshwater inflow. In other words, as freshwater inflow increased, salinity at a station decreased, and daily range or variability in salinity increased. In most cases, longer term average discharges (20- to 50-day averages) resulted in higher correlation coefficients than 1-day or other combinations of discharge. The Myakka River tends to go dry in drought conditions and, therefore, stream discharge for the Myakka River did not correlate well with salinity at most of the stations.

The discharge variable with the highest correlation coefficient was used in subsequent regression analyses to estimate daily mean salinity at each station. Multiple linear regressions, using discharges at each gage as independent variables provided relatively good preliminary results (coefficients of determination ranged from 0.77 to 0.84, and

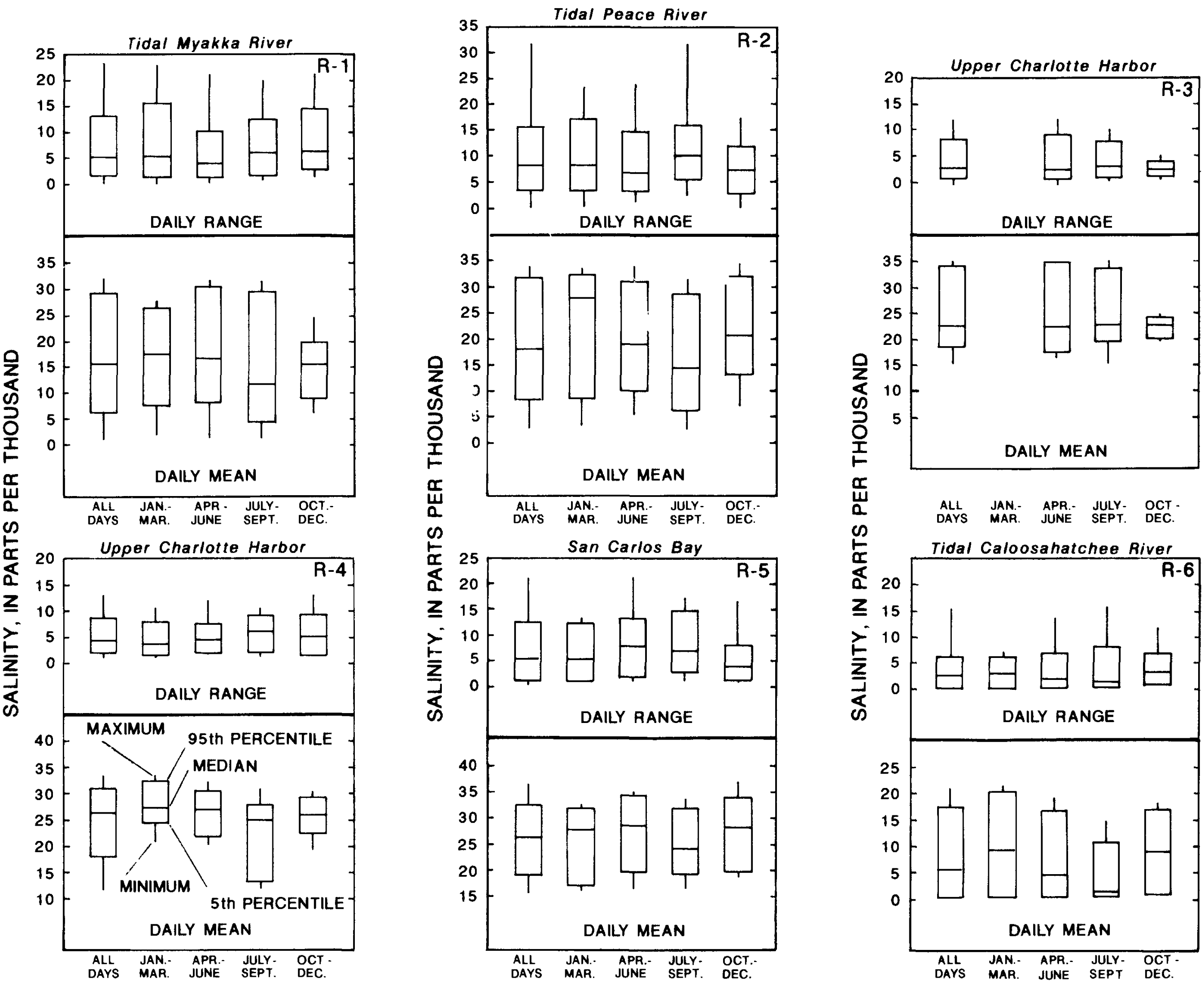


Figure 11. Seasonal distribution of daily mean salinity and daily range in salinity.

Table 1. Regression equations relating daily mean salinity at selected stations to daily mean discharge
[R^2 is the coefficient of determination; N is the number of observations; ppt, parts per thousand; ft³/s, cubic feet per second]

Equation	Adjusted R^2	Standard error (ppt)	N	Salinity (ppt)		Discharge (ft^3/s)	
				Minimum	Maximum	Minimum	Maximum
(A) Station R-1							
$S = -7.5633 \cdot [\log_{10}(H_{35})] + 29.3960$	0.72	3.6	1,114	1.4	31.6	0.4	555
(B) Station R-2							
$S = -13.9073 \cdot [\log_{10}(P_{40})] + 56.3773$	.78	3.6	819	2.9	33.7	48.2	2,860
(C) Station R-2 (near surface)							
$S = -12.4972 \cdot [\log_{10}(Q_{35})] + 55.4109$	.79	3.2	490	5.0	32.7	69.0	3,090
(D) Station R-6							
$S = -1.8437 \cdot [\log_{10}(C_{35})^2] + 25.0172$	.81	2.6	651	.2	21.1	27.2	6,850

where S = daily mean salinity, in parts per thousand;
$\log_{10}$ = base 10 logarithm;
H_{35} = 35-day mean discharge at Horse Creek, station 02297310;
P_{40} = 40-day mean discharge at Peace River, station 02296750;
Q_{35} = 35-day mean discharge summed from Myakka River, station 02298830; Peace River, station 02296750; Horse Creek, station 02297310; Joshua Creek, station 02297100; and Shell Creek, station 02298202; and
C_{35} = 35-day mean discharge at Caloosahatchee River, station 02292900.

standard errors ranged from 2.0 to 3.5 ppt), but the results did not always make sense hydrologically. Discharge at a gage occasionally had a positive coefficient in the final equation, which implied that salinity was positively related to discharge at that gage. To avoid such errors, either the discharge at only one site in a basin was used, or the sum of discharges at all the gages in the basin was used in the final regression results. Final regression results and valid ranges of discharge for the equations are presented in table 1. Plots of residuals and independent variables, coefficients of determination, and standard errors were evaluated to choose the appropriate equations for each station. Regression results for stations R-3 and R-5 are not included in table 1 because the residuals were strongly dependent upon the magnitude of the independent variable.

In most cases, tide was a significant variable at the 1-percent significance level. However, because the addition of a tide variable did not decrease the standard error of estimate by more than 0.2 ppt, and, because tide data were not available for all measured daily mean salinities, the final regression equations given in table 1 do not include tide.

Daily mean salinity was satisfactorily described by discharge at the three salinity stations in the tidal rivers (stations R-1, R-2, and R-6). Daily mean salinity at the stations in the harbor (stations R-3, R-4, and R-5), however, could not be adequately described using regression techniques. Although stream discharge plays a major role in determining salinity at a station in the harbor, other factors, such as circulation and mixing patterns, also play an important role and could not be described in simple regression equations.

Daily mean salinity data are useful in describing general trends in salinity at a station, but they do not reflect the normal daily fluctuations that occur because of tidal currents or seasonal fluctuations due to freshwater inflow. The degree of daily salinity variation is influenced by several factors: the daily range in tide, volume of water moving past the station, the horizontal variation in salinity upgradient and downgradient of a station, effects of increasing or decreasing wind on tides, and volume of freshwater inflow upgradient of a station. The following sections describe in more detail salinity changes due to freshwater inflow and tides.

Variations with Freshwater Inflow

Variations in freshwater inflow are among the factors having the greatest effect on salinity in Charlotte Harbor and the tidal reaches of the major tributaries. The relations between freshwater inflow and salinity in the tidal Caloosahatchee River and in the upper and lower parts of the harbor are described in the following sections.

Tidal Caloosahatchee River

Salinity measurements were made at selected locations in the tidal Caloosahatchee River to define vertical and longitudinal salinity characteristics of the river under various freshwater inflow conditions. To minimize the effects of daily tide variation on salinity measurements, vertical distribution of salinity was measured at the mouth near high slack tide and at about 1- to 2-mi intervals upstream until freshwater was encountered (see river mile locations in fig. 12).

High-tide salinity profiles in the tidal Caloosahatchee River and the associated 30-day average discharge at the Caloosahatchee River at structure S-79 are shown in figure 13. A 30-day average discharge was used instead of a 1-day discharge because, first, a long-term average discharge minimized the effects of traveltime of freshwater from the gage to the estuary, and second, salinity in the estuary at any one time is influenced by antecedent salinity and freshwater inflow conditions. A 30-day average partially accounted for these effects.

An average depth for each site was computed from field measurements and was used to show the bed profile. These depths are not corrected for differences in tide or for errors associated with measurement angles between the actual measurement and true vertical depth and should, therefore, be considered approximate. River miles upstream from the mouth were computed in accordance with recommendations by the U.S. Water Resources Council (1967).

The following technique was applied to place the plots shown in figure 13 in a logical order (other than by date of collection) and to assist in the interpretation of the salinity profiles. It was assumed that a freshwater inflow volume equal to one half of the total volume contained in the tidal river would have a significant effect on salinity in the tidal river. The total volume of the tidal Caloosahatchee River was determined to be 3.7x10^9 ft^3 (G.L. Sanders, U.S. Geological Survey, written commun., 1990). The volume of daily mean freshwater inflow was summed from the date of measurement back in time until a total volume of 1.85x10^9 ft^3 was accumulated. The number of days, including and prior to the date of measurement, that were required to accumulate this volume was calculated for each measurement. The plots shown in figure 13 are ordered according to the number of days required to accumulate inflows equivalent to one half of the volume of the tidal river. During extended periods of low flow, it took longer to accumulate the necessary volume (fig. 13, plot A) than during periods of higher inflows (fig. 13, plots G-I). This technique was developed because the freshwater inflow from structure S-79 can vary as much as 5,000 ft^3/s from day to day.

The 30-day average discharge at structure S-79 ranged from 34.4 to 4,410 ft^3/s and the number of days of discharge equivalent to one-half the total volume of the tidal river (1.85x10^9 ft^3) ranged from 130 to 4, respectively. As 30-day average discharge increased, salinity in the upstream reaches of the tidal Caloosahatchee River generally decreased and the water tended to stratify vertically. For example, the location

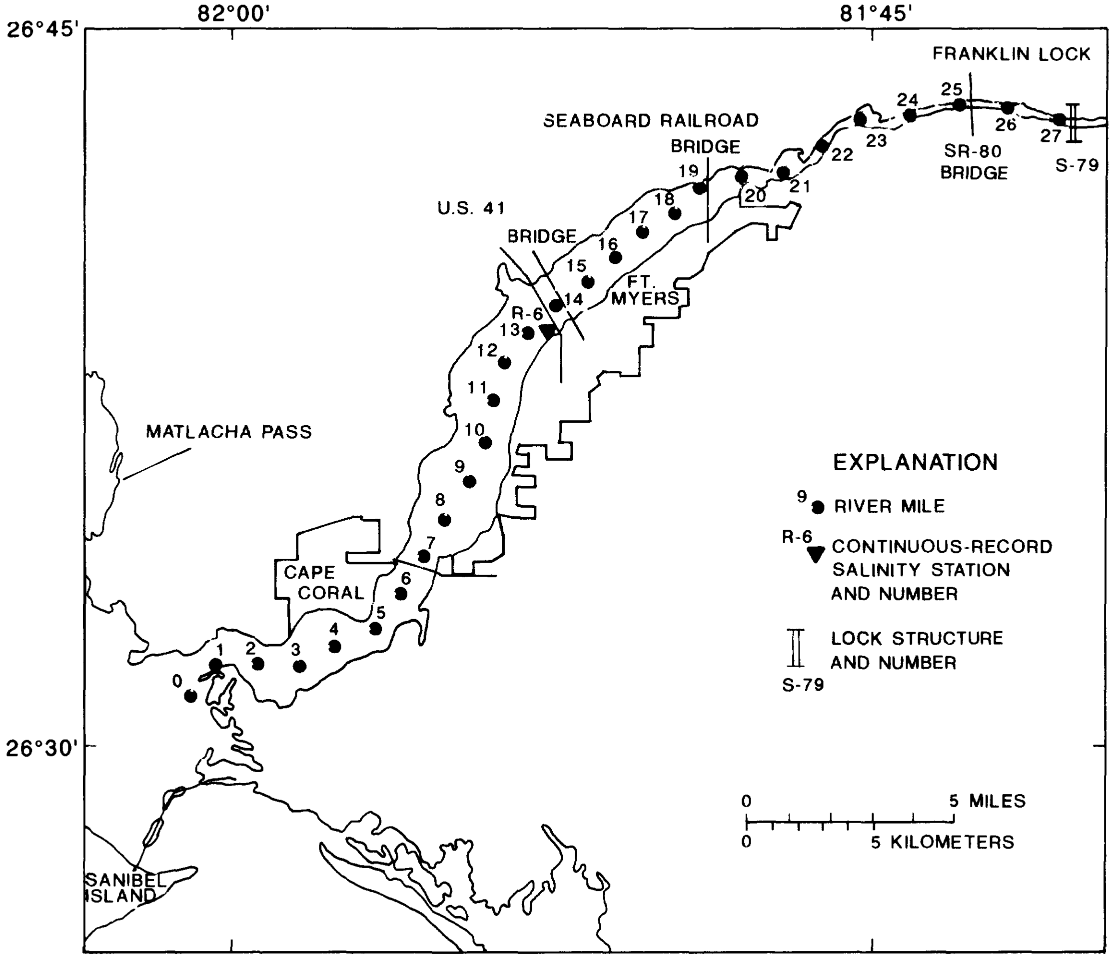


Figure 12. Tidal Caloosahatchee River.

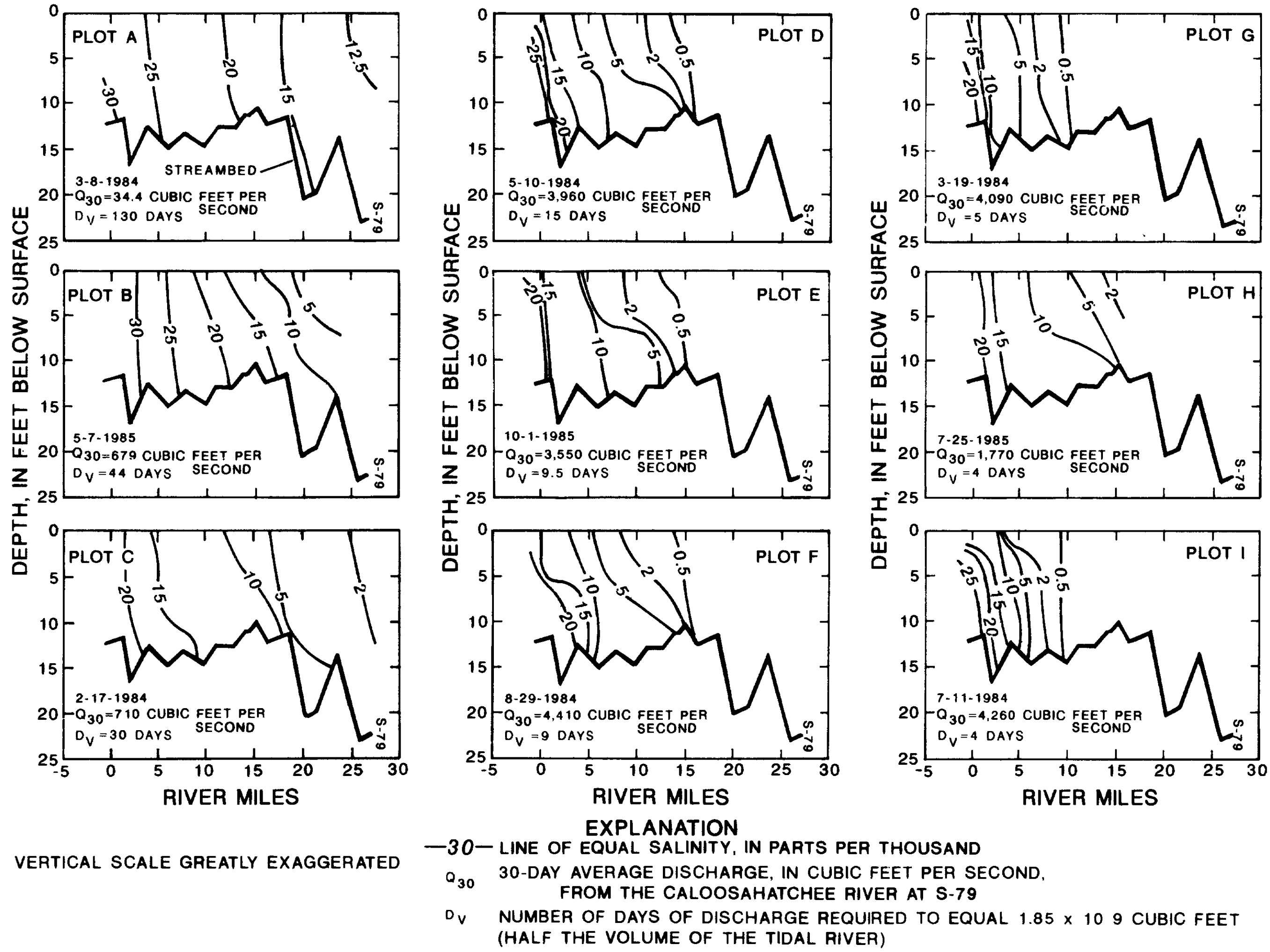


Figure 13. Salinity profiles in the tidal Caloosahatchee River during various freshwater inflow conditions.

of the near-surface 15-ppt line of equal salinity is around river mile 18 during extended low-flow conditions (fig. 13, plot A) and is pushed 17 mi downstream near the river mouth during a period with a 30-day average discharge of about 3,500 ft^3/s (fig. 13, plot D). Note also that vertical salinity stratification increased during increasing inflows (fig. 13, plots C-I).

Salinity near the mouth (river mile 0) typically was high (greater than 20 ppt) during all ranges of freshwater inflow. The mouth of the Caloosahatchee River is adjacent to San Carlos Pass (fig. 6), and saline Gulf of Mexico waters are introduced daily to this region of the river. As noted previously, all field measurements were made near slack high tide and show the maximum upstream salinity locations for that day.

Plots A and B in figure 13 show salinity conditions in the river during low-flow conditions. Relatively little vertical variability in salinity was observed, but gradual horizontal mixing occurred between structure S-79 and the river mouth. Salinity on the downstream side of structure S-79 was 12 to 15 ppt in March 1985 (fig. 13, plot A), reflecting the low inflow during this period. As the volume of freshwater inflow increased, salinity in the river became partially mixed, with near-bottom salinity higher than near-surface salinity. Plots G through I show salinity during high-flow conditions when the 30-day average discharge at structure S-79 ranged from 1,770 to 4,260 ft^3/s, and only 4 to 5 days of discharge equaled half the volume of the tidal river. Salinity in plot H is higher than in plots G and I and does not seem to reflect the short time required to reach this volume (4 days). This illustrates, however, the importance of antecedent conditions in the salinity response to freshwater inflow conditions.

The July 1985 measurement (fig. 13, plot H) was made after an extended period of low inflow that resulted in high salinity in the river (fig. 13, plots A and B). Although short-term discharges in July 1985 were comparable to those in March and July 1984, more saline water was present in the tidal reach before the high inflow began, which resulted in higher salinities after the freshwater was introduced into the tidal river. The 30-day average discharge of 1,770 ft^3/s in July 1985 reflects these antecedent low-flow conditions. Salinities in the river were much higher prior to the July 1985 measurement (fig. 13, plot B) than before the July 1984 measurement (fig. 13, plot D).

Upper Charlotte Harbor

Upper Charlotte Harbor is relatively shallow (average depth 8.6 ft) (fig. 3) and receives freshwater inflow at the north end from the Peace and Myakka Rivers. As was demonstrated in the discussion on the salinity patterns in the tidal Caloosahatchee River, a 1-day discharge variable alone could not adequately describe salinity conditions in the estuary. To better describe the volume of freshwater that flowed into the upper harbor, 1-day and 30-day discharge values were computed by summing discharges at the four gages in the lower Peace River basin and the gage on the Myakka River (fig. 1).

Near-surface and near-bottom salinity contours in Charlotte Harbor during selected freshwater inflow conditions are shown in figures 14 through 16. Salinity in the upper harbor is generally lower at the north end, increasing toward the Gulf of Mexico (figs. 14-16). Salinity also tends to be lower on the west shore of the upper harbor (figs. 14 and 15), except during dry-season conditions (fig. 16) when salinity was high and well mixed. Vertical salinity stratification occurred during moderate to high freshwater inflow conditions (figs. 14 and 15).

Salinity profiles during various freshwater inflow conditions along the *A-A'* and *B-B'* cross-section lines delineated in figure 17 are shown in figures 18 and 19. Bottom profiles at all cross sections were taken from depths shown on National Oceanic and Atmospheric Administration chart 11426 and were adjusted to depths below sea level. The number of days of discharge required to accumulate a volume of 3.4098×10^9 ft^3, which is one-quarter of the total volume in the upper harbor above section *B-B'*, is included on figure 18.

Pronounced vertical salinity stratification in the upper harbor occurred during peak flood discharges in June 1982 (fig. 18, plot A). Total discharge for June 26, 1982, was about 26,000 ft^3/s, and the number of days of discharge that equaled a volume of 3.4098×10^9 ft^3 was 1.5 days. Near-surface salinities were about 20 ppt lower than near-bottom salinities. As discharge upstream decreased, salinity increased, but the upper harbor still was stratified on July 13 more than 2 weeks after peak flood discharges (fig. 14; fig. 18, plots A-C). On July 13, 1982, near-surface salinity in the upper harbor ranged from almost fresh near the river mouths to 23 ppt at Boca Grande and was about 5 to 10 ppt lower than near-bottom salinity. Total daily discharge was 5,870 ft^3/s on July 13, and 6.5 days of discharge would have equaled 3.4098×10^9 ft^3.

In April 1987, vertical stratification of 1 to 10 ppt again occurred in the upper harbor (fig. 15; fig. 18, plot F). Total daily discharge was higher on April 2 and 3, 1987, than in July 1982, and the number of days required to accumulate 3.4098×10^9 ft^3 was less, implying that salinities would be expected to be lower than those on July 13, 1982. The 30-day

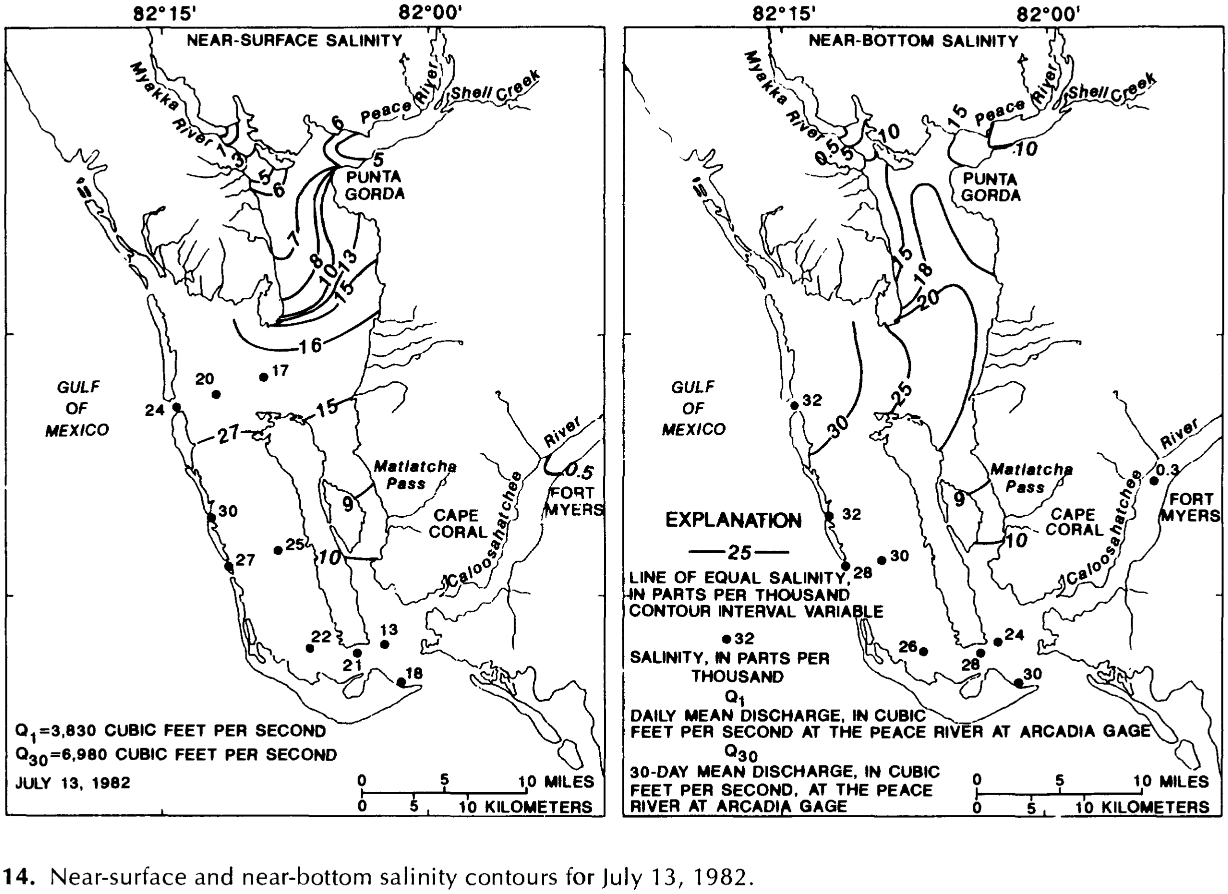


Figure 14. Near-surface and near-bottom salinity contours for July 13, 1982.

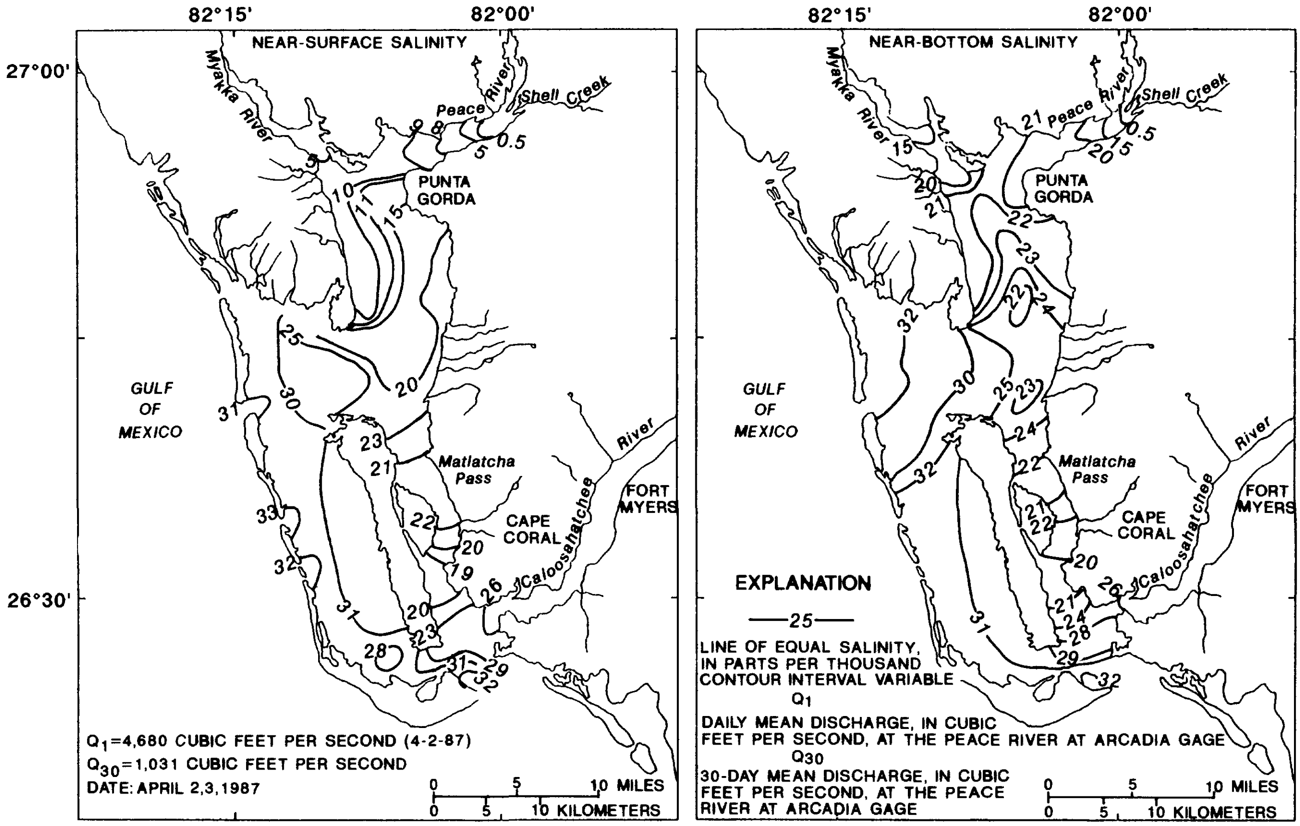


Figure 15. Near-surface and near-bottom salinity contours for April 2-3, 1987.

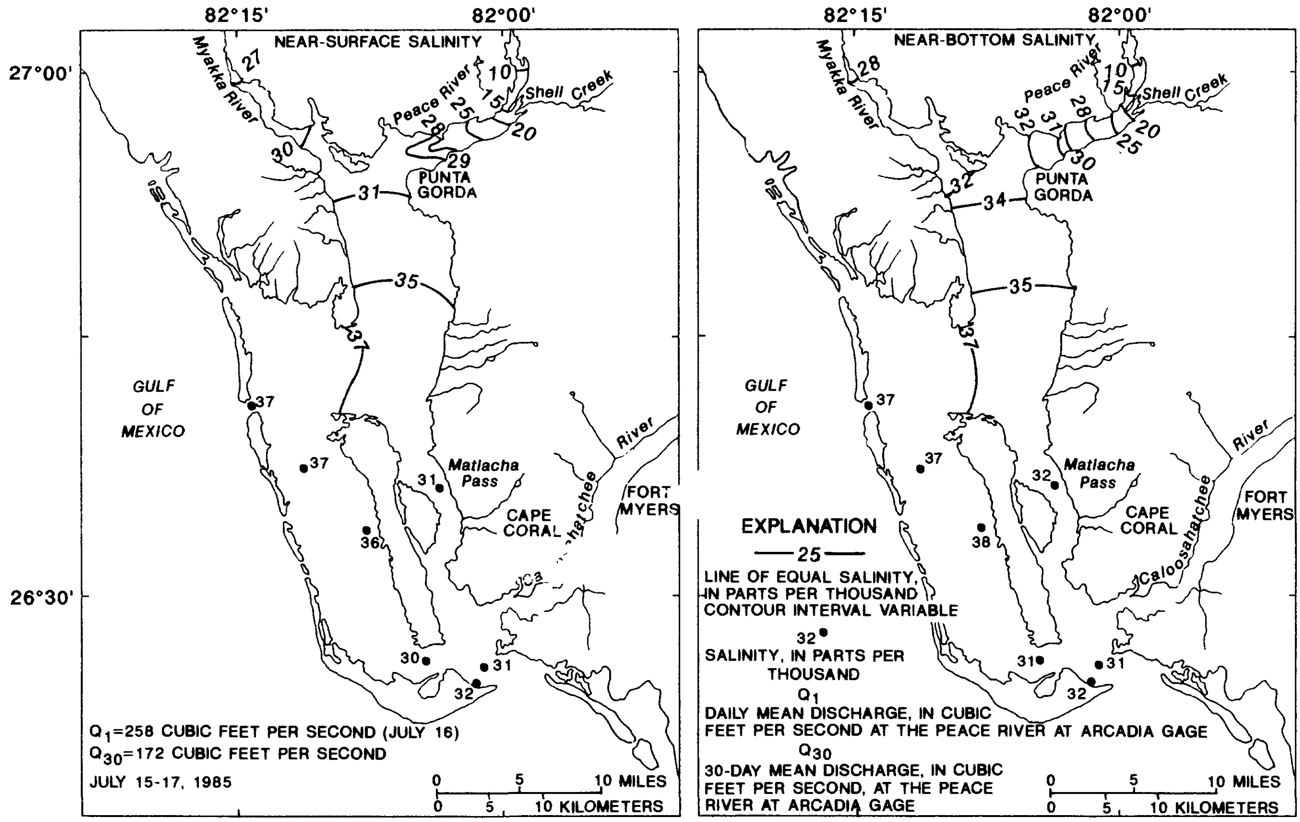


Figure 16. Near-surface and near-bottom salinity contours for July 15-17, 1985.

discharge at each gage, however, was about 55 to 85 percent lower in April 1987 than in July 1982 (figs. 14 and 15; fig. 18, plots C and F). Salinity in the upper harbor was higher in April 1987 than in July 1982 because of higher antecedent salinity conditions in April 1987. Surface salinity in April 1987 ranged from 5 ppt near the Peace and Myakka River mouths to 31 to 33 ppt near Boca Grande Pass.

During extended periods of low flow, salinity in upper Charlotte Harbor increased and very little vertical stratification occurred. Salinity in the upper harbor, measured near the end of a drought that occurred from July 1984 to July 1985, was well mixed vertically and high throughout the harbor (30 to 38 ppt, excluding the tidal rivers) and was similar to Gulf of Mexico salinity (fig. 16). Salinity was not as high during a low-flow period in December 1983 (fig. 18, plot E), although salinity was well mixed vertically. Daily and 30-day average discharges were low, and 45 days of discharge were required to accumulate 3.4098×10^9 ft^3. Salinity during both periods was slightly lower near the river mouths, increasing toward Boca Grande Pass.

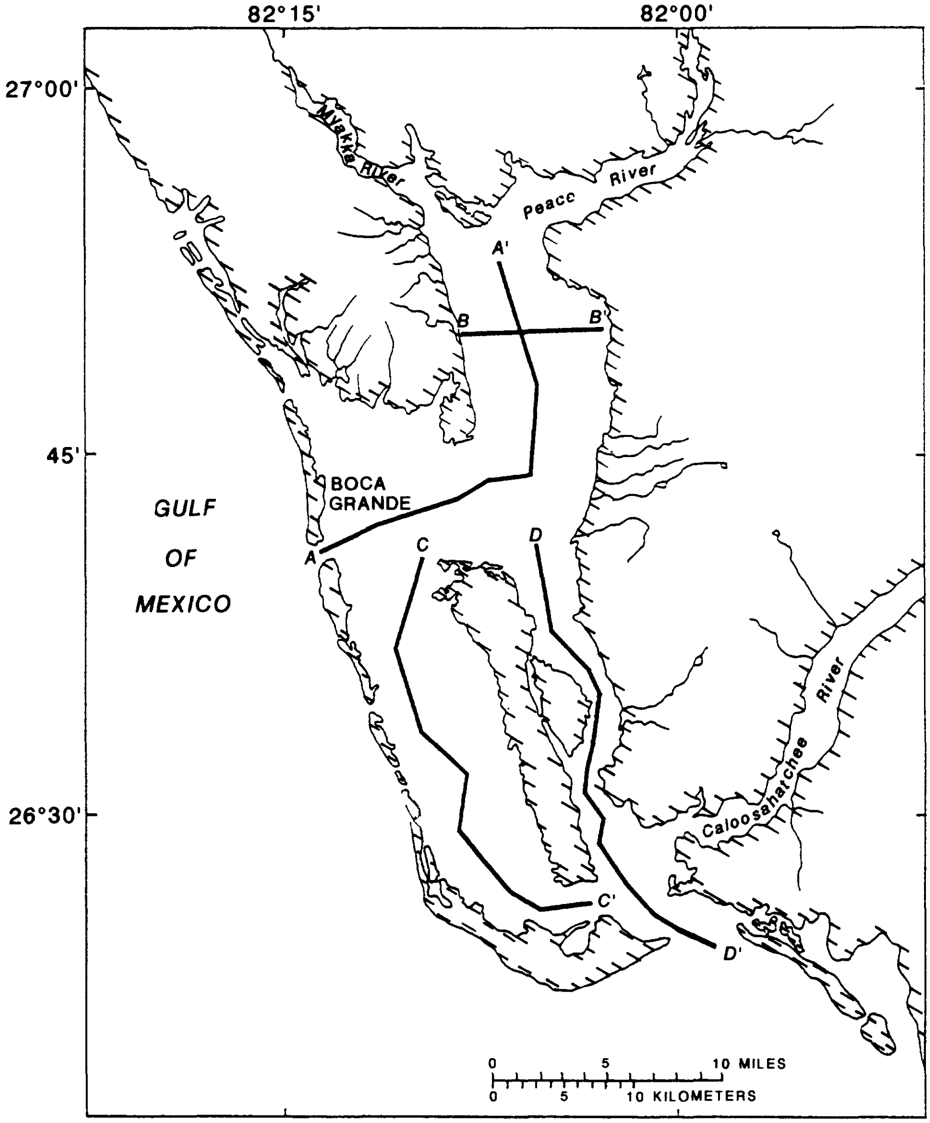
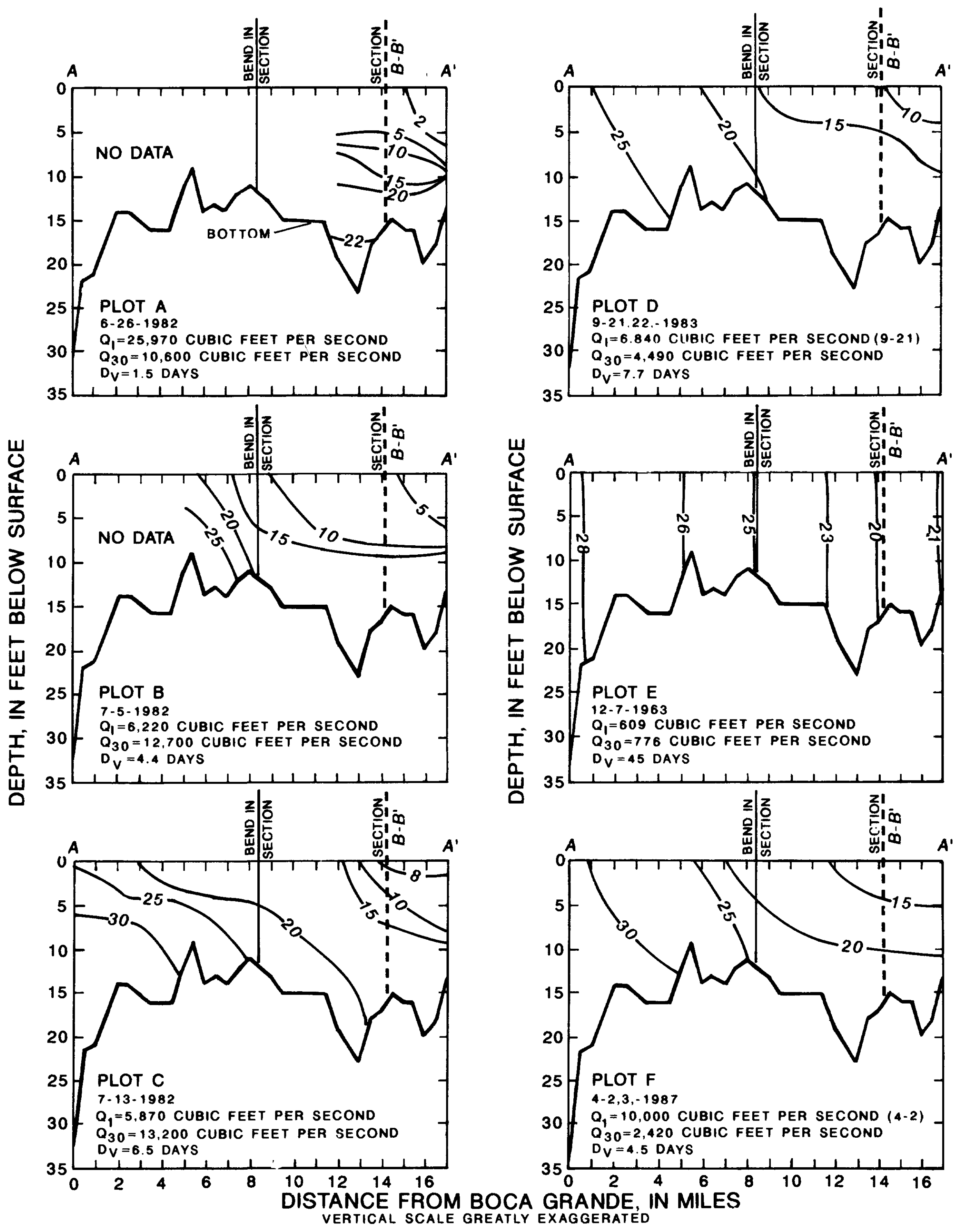


Figure 17. Location of cross sections.



EXPLANATION

—— 20 —— LINE OF EQUAL SALINITY, IN PARTS PER THOUSAND

Q_I TOTAL DAILY MEAN DISCHARGE, IN CUBIC FEET PER SECOND

Q_{30} TOTAL 30-DAY MEAN DISCHARGE, IN CUBIC FEET PER SECOND

D_V NUMBER OF DAYS OF DISCHARGE REQUIRED TO EQUAL 3.4098 x 109 IN CUBIC FEET (ONE QUARTER OF THE VOLUME IN THE UPPER HARBOR ABOVE SECTION B-B')

Figure 18. Salinity profiles from Boca Grande to the northern upper harbor during various freshwater inflows.

Salinity in the upper harbor typically is lower on the west bank than on the east bank. This pattern is apparent in the east-west cross section (*B-B'*) of salinity for selected periods (fig. 19, plots A, B, and D). During the June 1982 flood (fig. 19, plot A), about one-third of the cross section contained low salinity water (2.7 ppt) that was concentrated between the west bank and the center of the cross section. East-to-west salinity, however, was well mixed during low flow (fig. 19, plot C). Salinity patterns in the upper harbor can be examined to deduce general circulation and mixing patterns. Salinity contours (figs. 14 and 15) show that waters from the Peace and Myakka Rivers tend to mix with harbor waters and flow near the surface along the western half of the upper harbor, eventually exiting the harbor at Boca Grande. During low freshwater runoff conditions, salinities are higher and more evenly distributed, with incoming freshwater mixing more rapidly with harbor waters. During low runoff conditions, such as in July 1985 (fig. 16), tidal currents dominate circulation patterns.

On July 20-21, 1982, measurements of salinity were made at selected sites during one complete tide cycle (25 hours). These measurements are shown graphically in figure 20 with individual plots placed on the page by approximate geographic location (north to south, east to west) (fig. 6). Vertical stratification occurred to some degree at all of these sites, but was most pronounced at the northern and western parts of the upper harbor (CH-2, CH-5, R-3, S-15). The relation between vertical salinity distribution and the phase of the tide varied between sites. At site R-3, for example, near-surface and near-bottom salinity did not vary much over the tidal cycle, but middepth salinity did vary. At site CH-2 near the mouth of the Myakka River, salinity at all depths varied with tide.

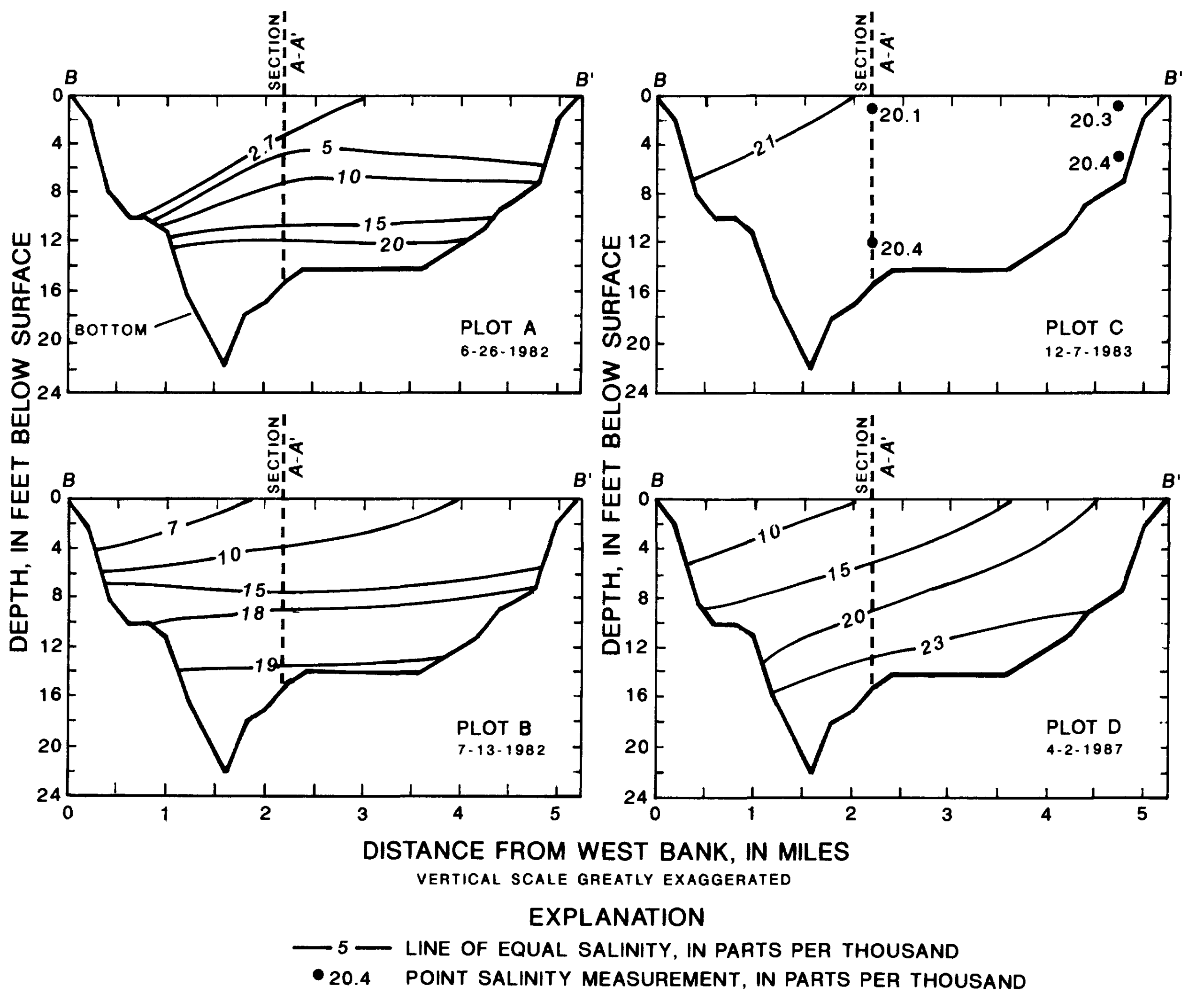


Figure 19. Salinity profiles from the west bank to the east bank of the upper harbor during various freshwater inflows.

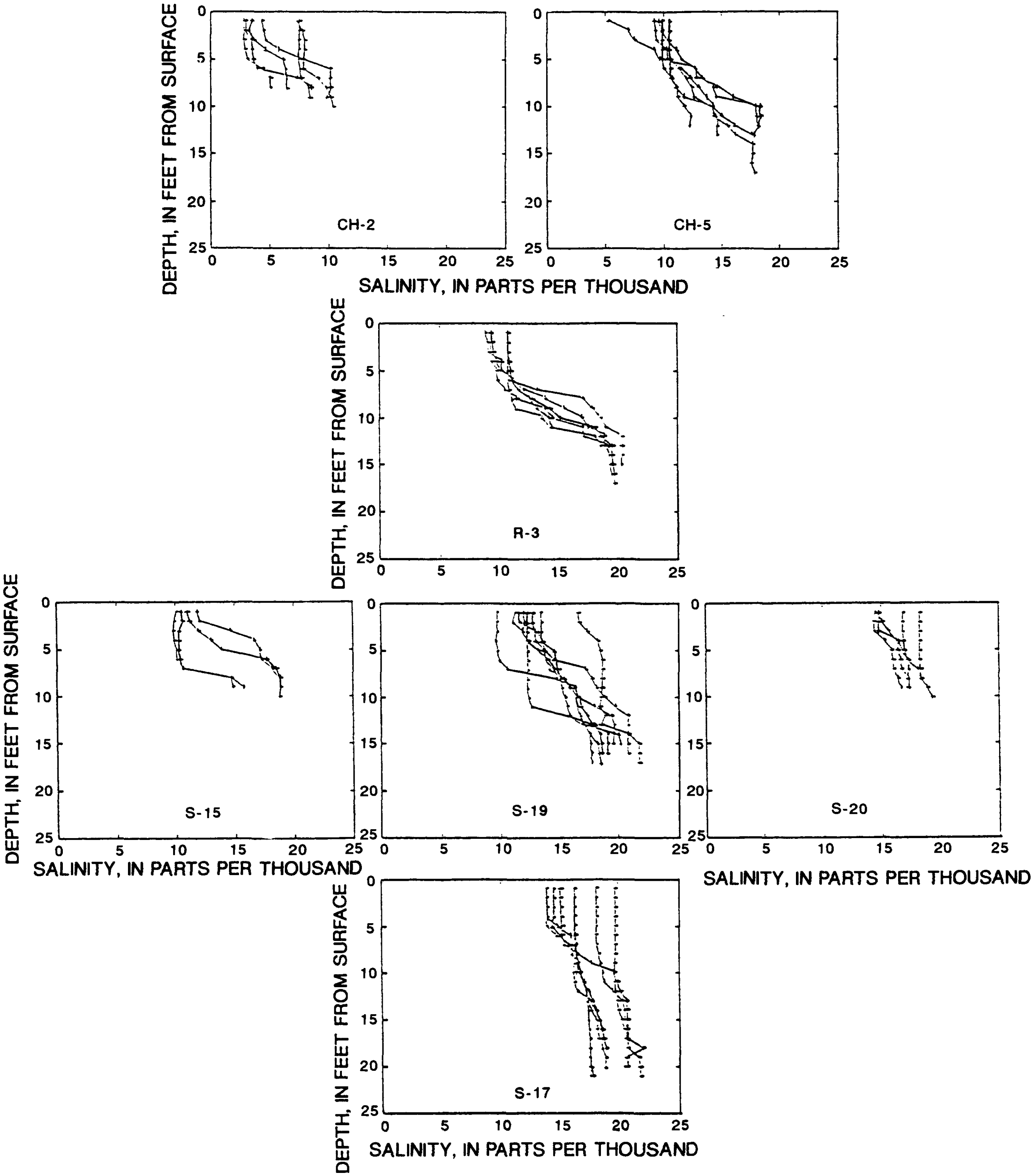


Figure 20. Vertical profiles of salinity during one complete tidal cycle on July 20-31, 1992.

Lower Charlotte Harbor

Salinity of the lower Charlotte Harbor area generally is uniform throughout and is higher than salinity in the upper harbor. Near-surface salinity in the lower harbor was about 1 to 10 ppt lower than near-bottom salinity about 2 weeks after the June 1982 flood. The highest vertical salinity stratification occurred near the mouth of the Caloosahatchee River, and the lowest salinity occurred in Matlacha Pass (fig. 14). Salinity in Pine Island Sound during July 1982, however, was high at 22 to 30 ppt (fig. 21, plot A). Vertical stratification was minimal in April 1987 compared to July 1982 conditions (fig. 15; fig. 21, plot C). Salinity in July 1985 ranged from 30 to 38 ppt during extended periods of low freshwater inflow with little vertical variation (fig. 16).

Flow from the Peace, Myakka, and Caloosahatchee Rivers appears to have little influence on salinity in Pine Island Sound and Matlacha Pass (figs.14-16). In Matlacha Pass, salinity typically is lowest near the State Road 78 bridge (fig. 6) due to freshwater inflow from a small tributary and a spreader canal system behind the eastern mangrove shoreline (figs. 14-16 and 22) (Henry LaRose, U.S. Geological Survey, written commun., 1984). Salinity increases to the north and to the south of State Road 78, even though the southern end of Matlacha Pass is near the mouth of the Caloosahatchee River. Some salinity stratification occurs in the deeper parts of Matlacha Pass.

Variations with Tide

Examples of short-term fluctuations in salinity and tide at selected sites during May 10-19, 1984, and August 1-10, 1984, are shown in figures 23 and 24. Salinity at the station on the Caloosahatchee River (R-6) was not shown in figure 24 because the water at that station remained fresh during this period and did not show any daily variation due to tide. During both periods, peak salinity occurred near floodtide stage, whereas minimum salinity occurred near ebbtide stage. This pattern generally existed throughout the full range of streamflow conditions encountered during the study. The salinity data shown in figure 23 represent dry-season conditions, and data shown in figure 24 represent early wet-season conditions. Daily mean 30-day discharges averaged 1,030 ft^3/s for the Peace, Myakka, and Caloosahatchee Rivers during May 10-19 and 2,740 ft^3/s during August 1-10. Salinity generally was higher during dry-season conditions in May than during wet-season conditions in August, with the exception of salinity concentrations at the north end of Pine Island at station R-4 (both periods about equal) and near the bottom at station R-3 (August lower than May). Although salinity near the bottom at station R-3 did not reflect increased freshwater inflow in August, those near the surface did, which resulted in a greater degree of vertical salinity stratification in August than in May.

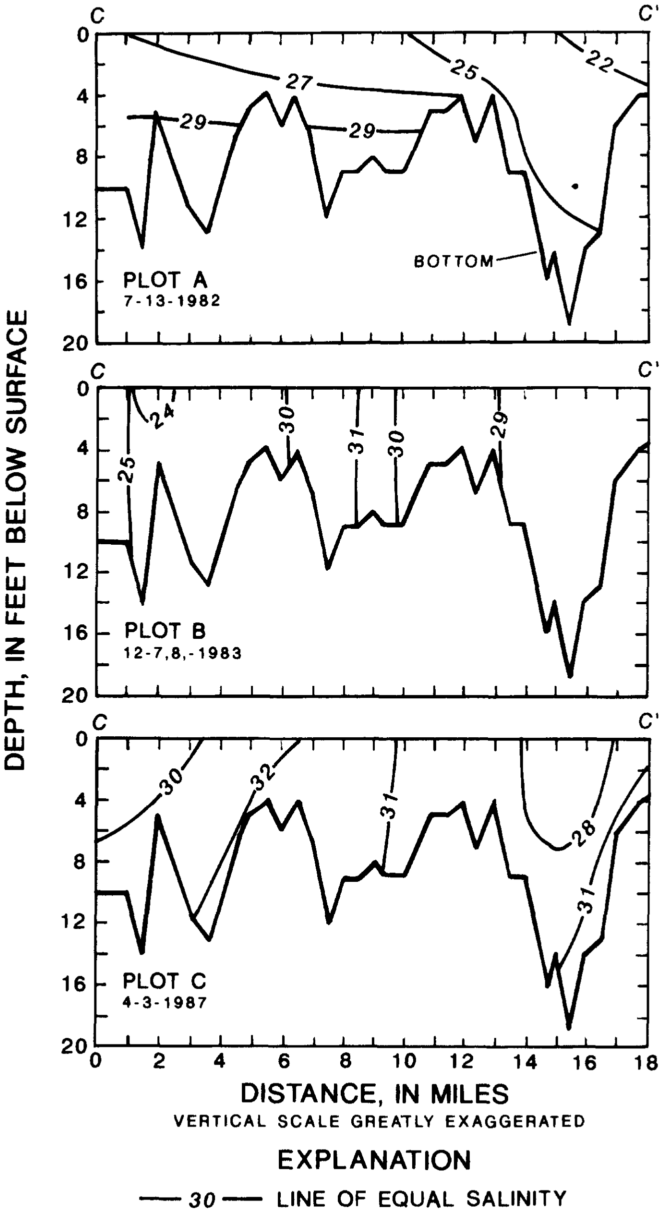


Figure 21. Salinity profiles in Pine Island Sound during various freshwater inflows.

Daily variations in salinity due to tide fluctuations during July 8-22, 1986, at the continuous-record salinity stations are shown in figure 25. Tidal variations occurred at every station, including the Gulf of Mexico stations (SI-9 and SI-10). The salinity variation in the Gulf of Mexico, however, was minimal, whereas daily salinity variations inside the harbor ranged from less than 1 to 8 ppt. Salinity at station SI-7 in central Pine Island Sound showed a relatively large daily variation (about 8 ppt) due to saline water from the Gulf of Mexico that was forced through Redfish Pass into Pine Island Sound during high-tide conditions. Daily mean 30-day discharges at the Peace, Myakka, and Caloosahatchee Rivers averaged 4,910 ft^3/s on July 15, 1986.

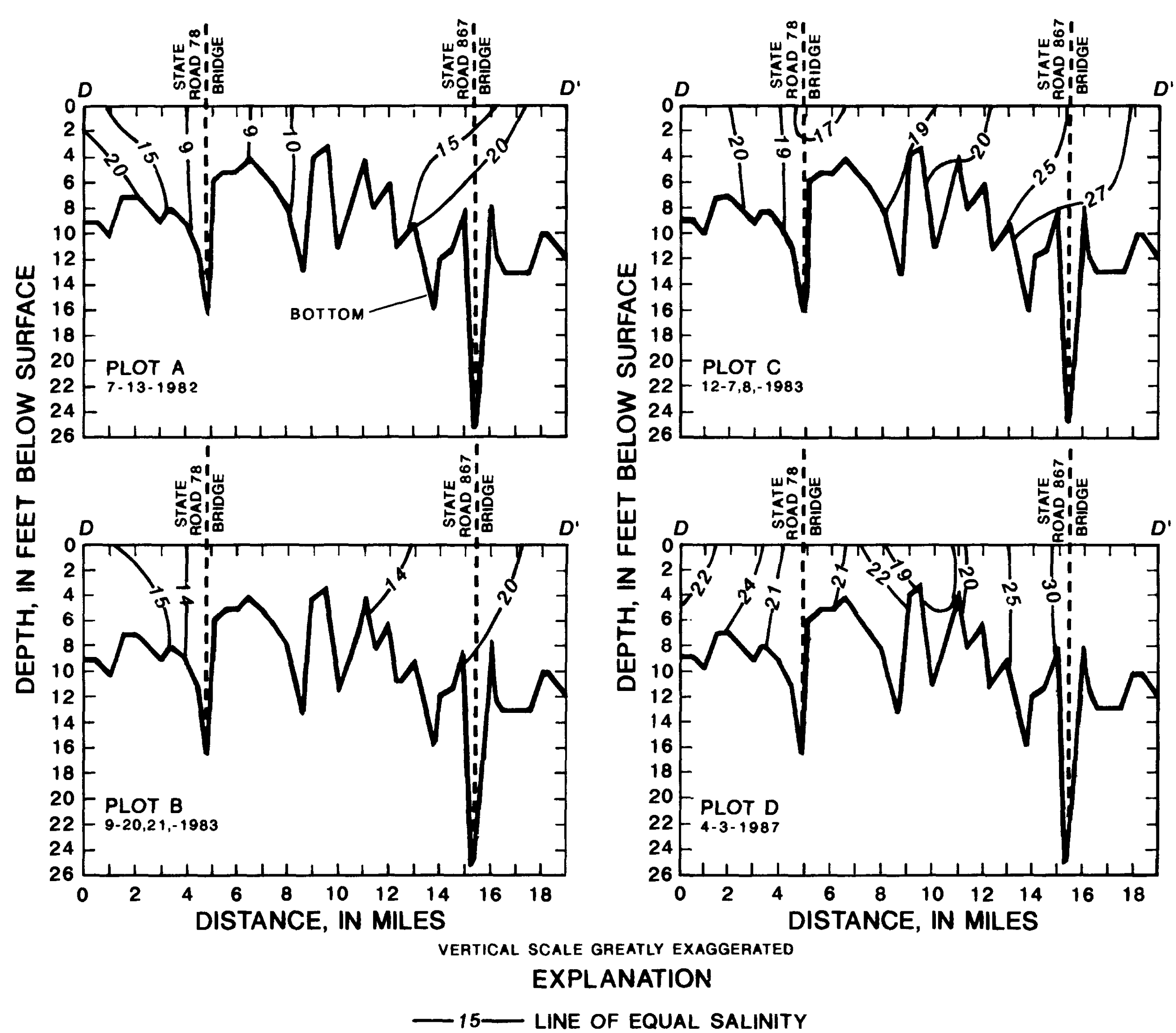


Figure 22. Salinity profiles in Matlacha Pass and San Carlos Pass during various freshwater inflows.

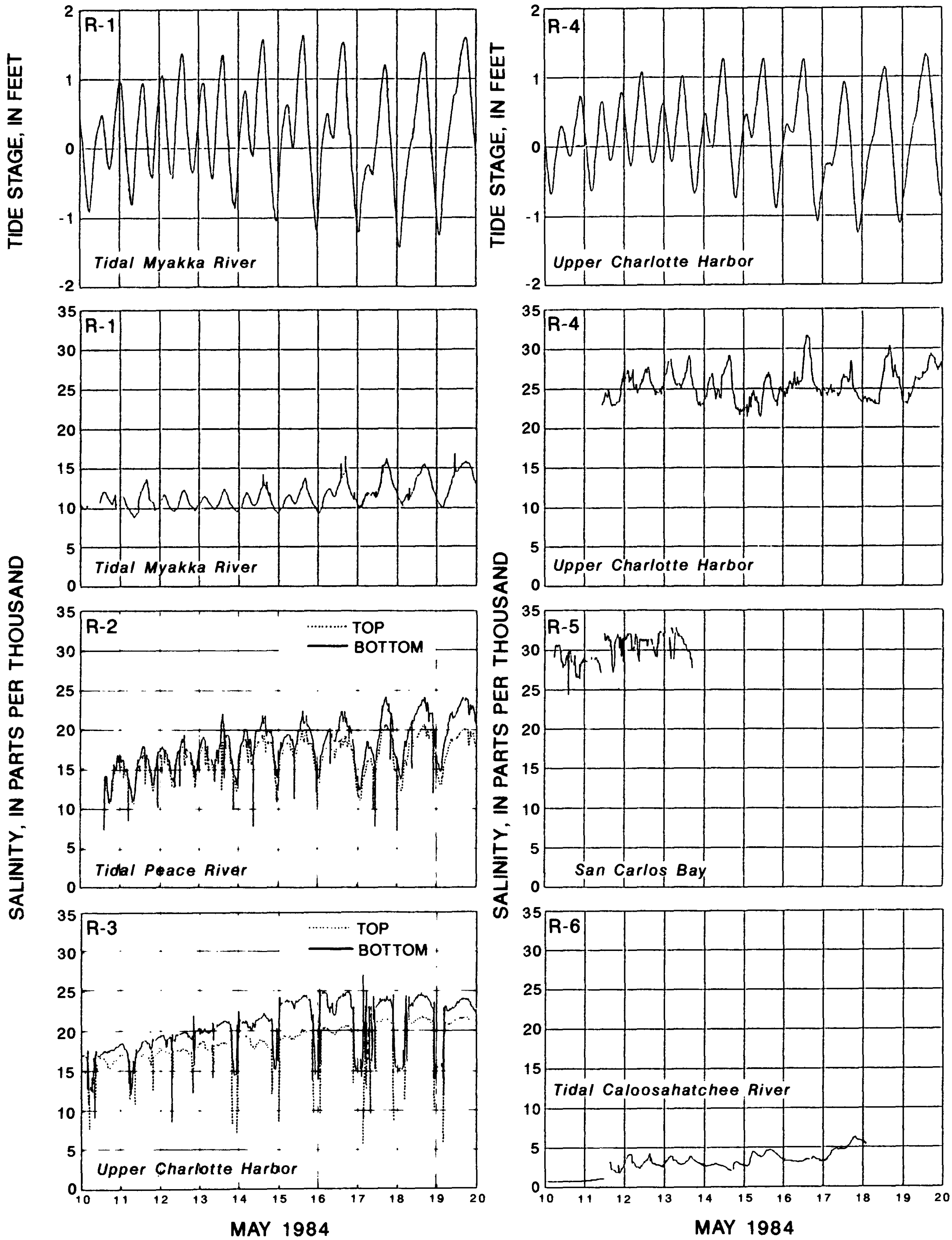


Figure 23. Daily salinity and stage fluctuations during dry season conditions.

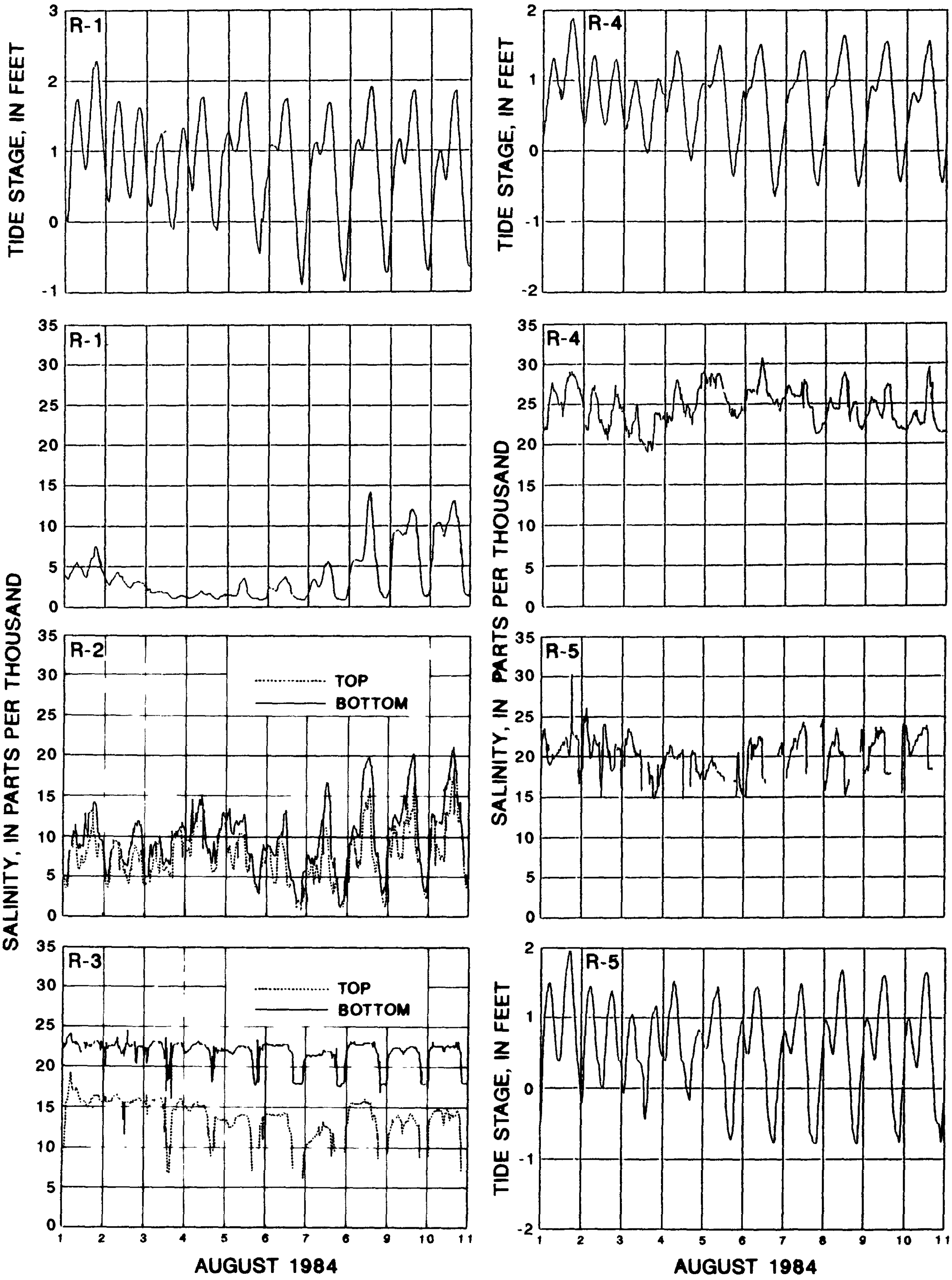


Figure 24. Daily salinity and stage fluctuations during early wet season conditions.

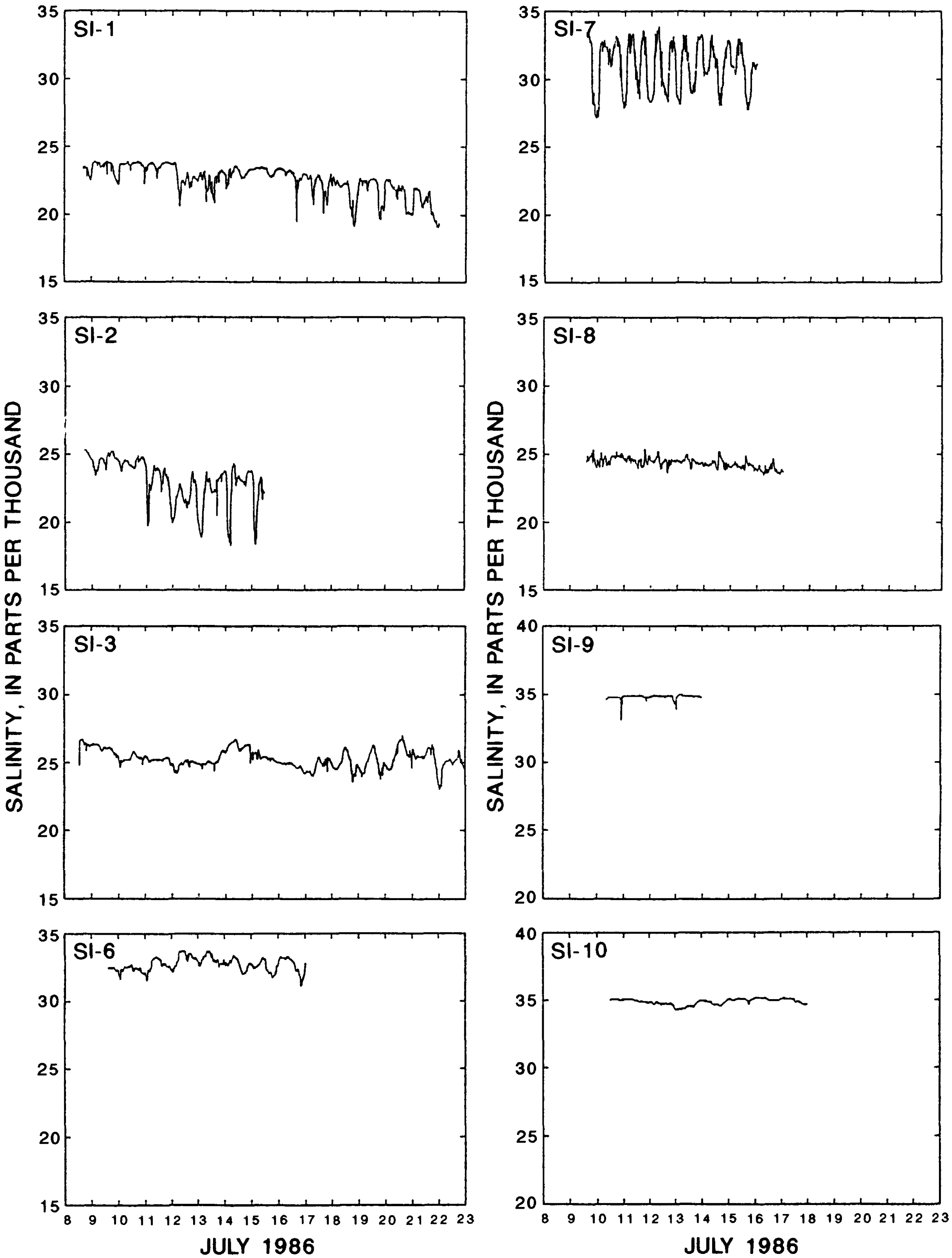


Figure 25. Instantaneous salinity at the submerged continuous-record salinity stations, July 8-22, 1986.

POTENTIAL SALINITY CHANGES DUE TO ALTERED FRESHWATER INFLOW

Potential changes in the Charlotte Harbor basin due to projected increases in population are described in detail by Hammett (1990) and are summarized below. Population in the coastal areas surrounding the harbor is expected to increase dramatically, whereas rural, interior areas of the basin are not expected to grow as rapidly. Population increases will result in increased demands for water supply and increased wastewater volumes. Construction of additional buildings and parking lots will increase the impervious area in the basin, ultimately resulting in less recharge to the ground-water system and more stormwater runoff.

One of the changes in freshwater inflow characteristics that could be expected as a result of projected increases in population will most likely be a decrease in total inflow to the harbor. A significant decreasing trend in streamflow at several gages in the Peace River basin has been documented by Hammett (1990). This decrease in streamflow was attributed partially to deficient rainfall, but rainfall was not the sole cause of the decline because decreasing trends in flow were not observed at the gages in the Myakka River or the Caloosahatchee River basins. According to Hammett (1990), a large increase in ground-water pumpage of the Floridan aquifer system has occurred in the last 50 years. The subsequent decline of the potentiometric surface of the aquifer most likely is the cause of declining discharges in the Peace River. If the current trend in streamflow continues at the same rate, the Peace River at Zolfo Springs (fig. 1, station 02295637) could be dry in about 100 years.

A permanent reduction in streamflow would result in increased salinity in the harbor. As demonstrated earlier, the Peace River is a major source of freshwater to the upper harbor. With declining freshwater inflow, salinity in much of the upper harbor would increase and might approach that in the Gulf of Mexico (approximately 35 to 40 ppt) during much of the year. Hypersaline conditions could occur if evaporation exceeds rainfall and freshwater inflow in areas of the harbor that receive limited tidal exchange with the Gulf of Mexico. Short-term runoff would occur during and after storms, resulting in some decrease in salinity from the tidal rivers to Boca Grande.

Another expected change in freshwater inflow characteristics due to increased population is a change in stormwater runoff characteristics. The land use of the Charlotte Harbor basin is expected to change from undeveloped or agricultural (including rangeland) to urban or developed (including industrial). Major effects of urbanization on water resources include reduced infiltration of rainwater to the ground-water system, increased flood potential, and degradation of the quality of receiving bodies of water (Lopez and Giovannelli, 1984). Some of these effects can be minimized by the use of stormwater retention or detention areas. At the time of publication of this report, new construction projects of more than 100 acres are required to retain, or detain with filtration, the runoff from the first 1 in. of rainfall (Florida Department of Environmental Regulation, 1988). Rainfall associated with tropical depressions, storms, and hurricanes, however, often exceeds 1 in. The effects of urbanization on runoff characteristics during periods of high rainfall would be a more rapid increase in streamflow and a more rapid return to base flow. This in turn would result in more rapid changes in salinity before and after a storm.

SUMMARY AND CONCLUSIONS

As part of a study of Charlotte Harbor in southwestern Florida, a study of the temporal and spatial variability of salinity in the harbor was conducted from 1982 to 1987. The results of this study indicate that seasonal fluctuations in salinity in Charlotte Harbor occur primarily in response to seasonal fluctuations in freshwater inflow from the Peace, Myakka, and Caloosahatchee River basins. Other sources of freshwater to the harbor are rainfall, runoff from coastal areas, ground-water seepage, and domestic and industrial effluent. Streamflow in the Peace and Myakka Rivers is unregulated, except for one low-water dam in the upper Myakka basin. Discharge in these rivers, therefore, tends to correspond to rainfall patterns in the basins. The Caloosahatchee River has been extensively modified by human activities, and discharge does not always correspond to rainfall patterns in the basin.

Discharge in the Peace and Myakka Rivers tends to peak in August and September when rainfall totals generally are greatest. Discharges are usually lowest in April and May. A flood with a 10-year recurrence interval occurred in the Peace River in the early part of the study (1982). An extended drought also occurred during the study from July 1984 to July 1985. The lowest 30-day discharge in the Peace River had a recurrence interval of 45 years.

Tidal mixing between Charlotte Harbor and the Gulf of Mexico is restricted by barrier islands. The major passes are Boca Grande and San Carlos Pass. Tidal energy is concentrated at the passes because of the physical restriction, resulting in high velocities associated with the large volume of water moving through the passes. This tidal energy is dispersed inside the harbor and influences the harbor and tidal rivers as much as 25 to 27 mi upstream from the mouths of the rivers. There is about a 2-hour lag between tide phases at Boca Grande and tide phase in the upper harbor near the mouth of the Peace River.

Long-term salinity changes were monitored at six sites in the harbor. Median salinity generally was lowest during July through September and highest during January through March. Median salinity was lowest at the gage in the tidal Caloosahatchee River and highest at the north and south ends of Pine Island. The largest daily range in salinity occurred near the mouth of the Peace River.

Correlation analyses showed that daily minimum, maximum, and mean salinities at the continuous-record salinity stations were inversely related to discharge from the rivers, whereas the daily range in salinity was directly related to stream discharge. In most cases, long-term average discharges (20- to 50-day averages) resulted in higher correlation coefficients than 1-day or short-term average discharges.

Salinity near the mouth of the tidal Caloosahatchee River typically was high (greater than 20 ppt) during all ranges of freshwater inflow conditions during the study. Salinity throughout the tidal reach was well mixed vertically during periods of low freshwater inflow, with a gradual increasing gradient between the S-79 structure upstream and the mouth of the river. As volume of freshwater inflow increased, salinity in the tidal river became partially mixed, with near-bottom salinity higher than near-surface salinity. Salinity in the river at any one time was related to antecedent salinity conditions, as well as current freshwater inflow conditions.

Although the upper harbor is relatively shallow (average depth 8.6 ft), vertical stratification occurs during periods of moderate and high freshwater inflows. Vertical stratification can be persistent, remaining weeks after a flood. Vertical stratification occurred to some degree at all stations, but was most pronounced in the northern and western parts of the upper harbor.

Salinity in the upper harbor typically is lower on the west bank than on the east bank due to circulation and flow patterns of incoming freshwater. These patterns indicate that waters from the Peace and Myakka Rivers tend to mix with harbor waters and flow near the surface along the western part of the harbor, eventually exiting the harbor at Boca Grande.

Salinity of the lower Charlotte Harbor area generally is uniform throughout and is higher than salinity in the upper harbor. Flow from the Peace, Myakka, and Caloosahatchee Rivers appears to have little influence on salinity in Pine Island Sound and Matlacha Pass. In Matlacha Pass, salinity typically is lowest near the State Road 78 bridge due to freshwater inflow from a local tributary and a spreader canal system.

Salinity at the salinity stations within the harbor and at two temporary stations in the Gulf of Mexico varied daily with the tide phase. The variation in salinity in the Gulf of Mexico, however, was much less than salinity variations within the harbor. Peak salinity occurred near floodtide stage, whereas minimum salinity occurred near ebbtide stage.

Population in the coastal areas surrounding Charlotte Harbor is expected to increase dramatically. Population increases will result in increased demands for water supply, increased wastewater volume, and an alteration in freshwater runoff characteristics. A decreasing trend in annual mean discharge has been documented for several gages in the Peace River basin. If the reduction in streamflow continues, salinity in Charlotte Harbor probably will increase.

Land-use changes associated with increasing populations probably will affect water resources by reducing infiltration of rainwater to the ground-water system, increasing flood potential, and degrading the quality of receiving water bodies. The effects of urbanization on runoff characteristics during periods of high rainfall would be a more rapid increase in streamflow and a more rapid return to base flows. This in turn would result in more rapid changes in salinity before and after a storm.

SELECTED REFERENCES

Alberts, James, Mattraw, Harold, Harriss, Robert, and Hanke, Albert, 1970, Studies on the geochemistry and hydrography of the Charlotte Harbor Estuary, Florida: Sarasota, Mote Marine Laboratory, 34 p.

Barnett, B.S., Fernald, R.T., Goetsfried, A., and Lau, S.R., 1980, Fish and wildlife resources of the Charlotte Harbor area: Florida Game and Fresh Water Fish Commission, Office of Environmental Services, 211 p.

Beaumariage, D.S., and Stewart, V.N., 1977, The estuary—What's it to you?, *in* Seaman, William, and McLean, Richard, eds., Freshwater and the Florida coast, southwest Florida: Southwest Florida Water Management District Report no. 1977-1, p. 133-143.

Boggess, D.H., 1970a, A test of flushing procedures to control salt-water intrusion at the W.P. Franklin dam near Ft. Myers, Florida: Florida Bureau of Geology Information Circular no. 62, part 1, p. 1-15.

——— 1970b, The magnitude and extent of salt-water contamination in the Caloosahatchee River between La Belle and Olga, Florida: Florida Bureau of Geology Information Circular no. 62, part 2, p. 17-39.

——— 1972, Controlled discharge from the W.P. Franklin Dam as a means of flushing saline water from the fresh-water reach of the Caloosahatchee River, Lee County, Florida: U.S. Geological Survey Open-File Report FL-72028, 45 p.

Bridges, W.C., 1982, Technique for estimating magnitude and frequency of floods on natural-flow streams in Florida: U.S. Geological Survey Water-Resources Investigations 82-4012, 44 p., 1 sheet.

Culkin, Frederick, and Ridout, Paul, 1989, Salinity: Definitions, determinations, and standards: Sea Technology, v. 30, no. 10, p. 47-49.

Environmental Quality Laboratory, Inc., 1979, Hydrobiological monitoring, January 1976 through October 1978, lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 124 p., plus appendices.

——— 1980, Hydrobiological monitoring, November 1978 through January 1980, lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 197 p.

——— 1981, Hydrobiological monitoring, February 1980 through February 1981, lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc. 248 p.

——— 1982, Hydrobiological monitoring program, report for the period from March 1981 through February 1982 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 232 p.

——— 1983, Hydrobiological monitoring program, report for the period from March 1982 through February 1983 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 115 p.

——— 1984, Hydrobiolobical monitoring program, report for the period from March 1983 through February 1984 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 218 p.

——— 1985, Hydrobiological monitoring program, data report for the period from March 1984 through February 1985 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 114 p.

——— 1986, Hydrobiological monitoring program, data report for the period from March 1985 through February 1986 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 75 p.

——— 1987, Hydrobiological monitoring program, data report for the period from March 1986 through February 1987 covering the lower Peace River and Charlotte Harbor: Port Charlotte, Fla., Environmental Quality Laboratory, Inc., 92 p.

Estevez, E.D., 1986, Infaunal macroinvertebrates of the Charlotte Harbor estuarine system and surrounding inshore waters, Florida: U.S. Geological Survey Water-Resources Investigations Report 85-4260, 116 p.

Fan, Andrew, and Burgess, Raymond, 1983, Surface water availability of the Caloosahatchee basin: South Florida Water Management District Technical Memorandum, 79 p.

Florida Department of Administration, 1978, Charlotte Harbor: A Florida resource: Division of State Planning, DSP-BLWM 39-78, 41 p.

Florida Department of Environmental Regulation, 1988, Regulation of stormwater discharge: Chapter 17-25, *in* Florida Administrative Code.

Florida Department of Natural Resources, 1983, Charlotte Harbor aquatic preserves management plan: Division of Recreation and Parks, Bureau of Environmental Land Management, 120 p.

Fraser, T.H., 1981, Variation in freshwater inflow and changes in a subtropical estuarine fish community, in Cross, R., and Williams, D., eds., Proceedings of the National Symposium on Freshwater Inflow to Estuaries: U.S. Fish and Wildlife Service, FWS/OBS-81/04, p. 296-319.

——— 1986, Long-term water-quality characteristics of Charlotte Harbor, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4180, 43 p.

Goodwin, C.R., 1991, Simulation of the effects of proposed tide gates on circulation, flushing, and water quality in residential canals, cape coral, Florida: U.S. Geological Survey Open-File Report 91-237, 43 p.

Gunter, Gordon, and Hall, G.E., 1965, A biological investigation of the Caloosahatchee Estuary of Florida: Gulf Coast Research Laboratory Reports, v. 2, no. 1, p. 1-72.

Hammett, K.M., 1990, Land use, water use, streamflow characteristics, and water-quality characteristics of the Charlotte Harbor inflow area, Florida: U.S. Geological Survey Water-Supply Paper 2359-A, 64 p.

——— 1992, Physical processes, salinity characteristics, and potential salinity changes due to freshwater withdrawals in the tidal Myakka River, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4054, 20 p.

Heil, D.C., Porter, W.B., Sprague, M.K., Sams, S.L., and Roberts, B.S., 1984, Comprehensive shellfish growing area survey, Myakka River, Charlotte County, Florida: Tallahassee, Florida Department of Natural Resources, 87 p.

LaRose, H.R. and McPherson, B.F., 1980, Hydrologic and land-cover features of the Caloosahatchee River basin, Lake Okeechobee to Franklin Lock, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-732, 1 sheet.

Lopez, M.A., and Giovannelli, R.F., 1984, Water-quality characteristics of urban runoff and estimates of annual loads in the Tampa Bay area, Florida, 1975-1980: U.S. Geological Survey Water-Resources Investigations Report 83-4181, 76 p.

National Oceanic and Atmospheric Administration, 1985, Climatological data, annual summary, Florida, 1984: U.S. Department of Commerce, v. 88, no. 13, 34 p.

——— 1987, Tide tables 1988, high and low water predictions, east coast of North and South America, including Greenland: U.S. Department of Commerce, 289 p.

Pearse, A.S., and Gunter, Gordon, 1957, Salinity, *in* Hedgpeth, J.W., ed., Treatise on marine ecology and paleoecology, v. 1, Ecology: Geological Society of America Memoir 67, p. 129.

Stoker, Y.E., Henderson, S.E., and McPherson, B.F., 1989, Hydraulic and salinity characteristics of the tidal reach of the Peace River, southwestern Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4162, 37 p.

U.S. Environmental Protection Agency, 1973, Finger-fill canal studies, Punta Gorda and Big Pine Key, Florida: Athens, Ga., Surveillance and Analysis Division, 128 p.

U.S. Geological Survey, 1974, Hydrologic unit map-1974, State of Florida: scale 1:500,000, 1 sheet.

U.S. Water Resources Council, 1967, River mileage measurement: Committee on Hydrology Bulletin 14, 13 p.

Wang, J.C.S., and Raney, E.C., 1971, Distribution and fluctuations in the fish and fauna of the Charlotte Harbor Estuary, Florida: Sarasota, Fla., Mote Marine Laboratory, 56 p., plus appendices.

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