# TIDAL-FLOW, CIRCULATION, AND FLUSHING CHARACTERISTICS OF KINGS BAY, CITRUS COUNTY, FLORIDA

By K.M. Hammett, C.R. Goodwin, and G.L. Sanders

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## CONVERSION FACTORS, VERTICAL DATUM, AND ADDITIONAL ABBREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| inch (in) | 2.54 | centimeter |
| foot (ft) | 0.3048 | meter |
| inch per day (in/d) | 2.54 | centimeter per day |
| foot per second (ft/s) | 0.3048 | meter per second |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |

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.

### Additional Abbreviations

| | |
|---|---|
| GIS | Geographical Information System |
| ppt | parts per thousand |
| SWIM | Surface Water Improvement and Management |

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## ABSTRACT

Kings Bay is an estuary on the gulf coast of peninsular Florida with a surface area of less than one square mile. It is a unique estuarine system with no significant inflowing rivers or streams. As much as 99 percent of the freshwater entering the bay originates from multiple spring vents at the bottom of the estuary.

The circulation and flushing characteristics of Kings Bay were evaluated by applying SIMSYS2D, a two-dimensional numerical model. Field data were used to calibrate and verify the model. Lagrangian particle simulations were used to determine the circulation characteristics for three hydrologic conditions: low inflow, typical inflow, and low inflow with reduced friction from aquatic vegetation. Spring discharge transported the particles from Kings Bay through Crystal River and out of the model domain. Tidal effects added an oscillatory component to the particle paths. The mean particle residence time was 59 hours for low inflow conditions, 50 hours for typical inflow conditions, and 56 hours for low inflow with reduced friction; therefore, particle residence time is affected more by spring discharge than by bottom friction. Circulation patterns were virtually identical for the three simulated hydrologic conditions. Simulated particles introduced in the southern part of Kings Bay traveled along the eastern side of Buzzard Island before entering Crystal River and exiting the model domain.

The flushing characteristics of Kings Bay for the three hydrodynamic conditions were determined by simulating the injection of conservative dye constituents. The average concentration of dye initially injected in Kings Bay decreased asymptotically because of spring discharge, and the tide caused some oscillation in the average dye concentration. Ninety-five percent of the injected dye exited Kings Bay and Crystal River within 94 hours for low inflow, 71 hours for typical inflow, and 94 hours for low inflow with reduced bottom friction. Simulation results indicate that all of the open waters of Kings Bay are flushed by the spring discharge. Reduced bottom friction has little effect on flushing.

## INTRODUCTION

Kings Bay is immediately west of the town of Crystal River in Citrus County on the west coast of peninsular Florida (fig. 1). In most estuarine systems, tributary rivers and streams flow into an estuary that flows into an ocean. Kings Bay is unique because there are no significant inflowing rivers or streams and most of the freshwater entering the bay originates from multiple spring vents at the bottom of the estuary. These spring vents have diameters ranging from several feet to fractions of an inch. Kings Bay empties into Crystal River, which discharges into the Gulf of Mexico about 7 mi west of Kings Bay.

The clear, spring-fed waters of Kings Bay have historically served as a major attraction for many water sports enthusiasts, especially scuba divers who visit the resort community of Crystal River. Since 1960, *Hydrilla verticillata* has gradually displaced the native vegetation in Kings Bay. *Hydrilla* is a rooted plant that rapidly grows in long strands to reach the surface of the water and is considered a nuisance vegetation. After 1985, *Lyngbya woolei*, a filamentous blue-green alga, appeared and further detracted from the quality of the estuary. The *Hydrilla* and *Lyngbya* have impacted boat navigation and recreational use of the bay; also, the decaying vegetation can cause noxious odors and is aesthetically displeasing. If it is not removed, the decaying vegetation recycles nutrients back into the water. Near-surface sections of *Hydrilla* are routinely removed with mechanical harvesters, but because it has a growth rate of 2 to 4 inches per day, it continues to reduce the recreational potential of the bay.

In order to develop a plan for restoration and preservation as part of the SWIM (Surface Water Improvement and Management) program, the Southwest Florida Water Management District needed basic information about the hydrodynamics of Kings Bay. In 1988, the U.S. Geological Survey began a cooperative project to evaluate the circulation and flushing characteristics of Kings Bay. The reasons for the overgrowth of nuisance vegetation are not fully understood, but changes in water clarity or water temperature and increased nutrient loading from wastewater treatment plant effluent, stormwater runoff, and septic tank drain fields are among the factors suspected of contributing to the overgrowth. The interacting hydrodynamic characteristics of Kings Bay, the springs, Crystal River, and the Gulf of Mexico provide the physical mechanisms for constituent transport and residence

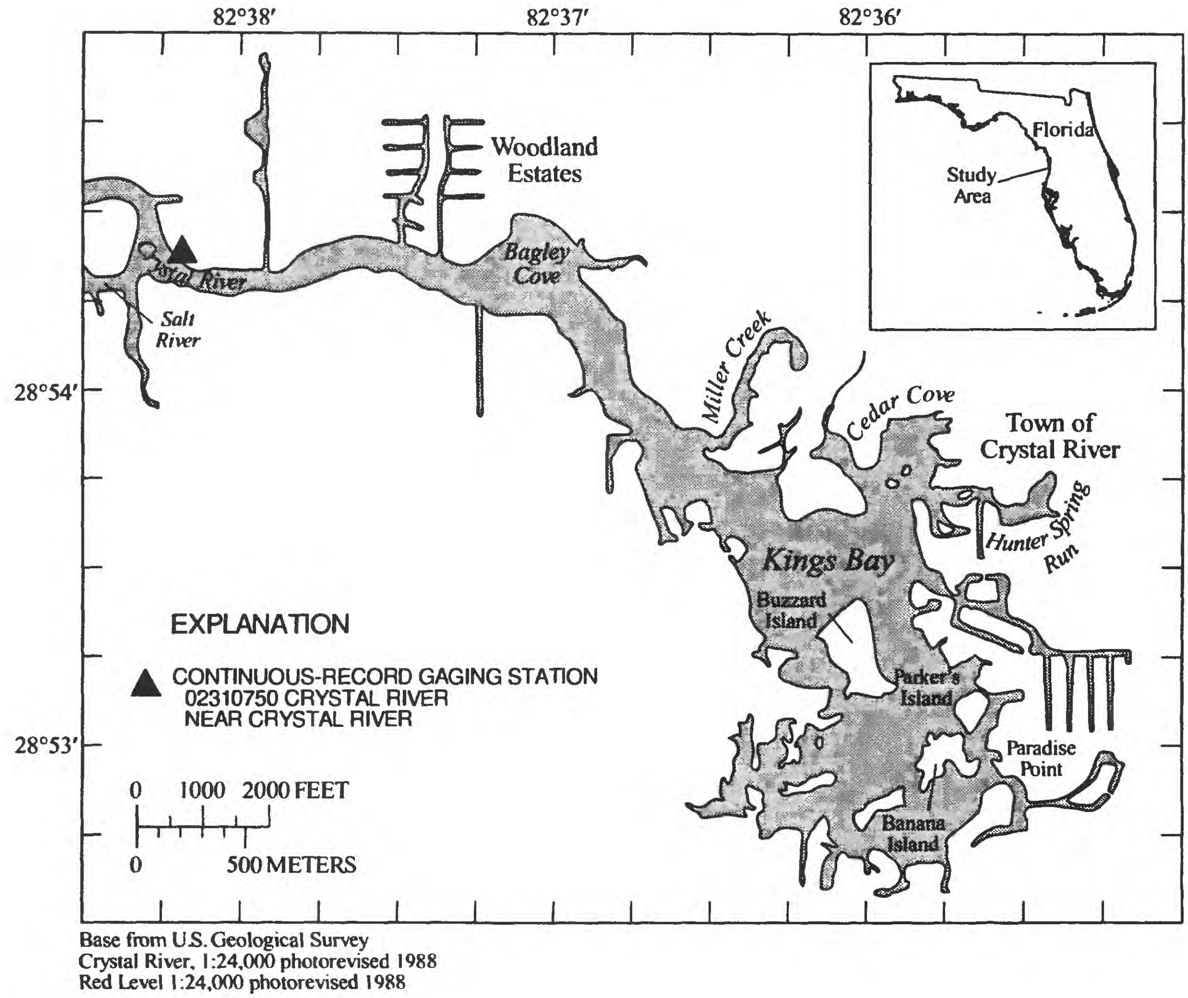



Figure 1. Location of Kings Bay and Crystal River, Citrus County, Florida.

time that can affect water-quality characteristics in the estuary. If the estuary is to be restored and preserved, an understanding of hydrodynamic characteristics is necessary to identify factors that may have contributed to the appearance of nuisance vegetation.

## Purpose and Scope

This report describes tidal-flow, circulation, and flushing characteristics of Kings Bay by presenting results from a two-dimensional, estuarine-circulation, and constituent-transport model. A network of 13 sites was established to collect data for tidal stage, direction and velocity of flow, and salinity that were used in the calibration and verification of the model. Additionally, field measurements were made at 28 major springs that discharge into Kings Bay to determine the magnitude and salinity of discharge from those springs. An intensive data collection effort was conducted in June 1990, during low-inflow conditions. Three conditions were selected for simulation: (1) low inflow, (2) typical inflow, (3) low inflow with reduced bottom friction to simulate reduced aquatic vegetation. The circulation characteristics of Kings Bay were determined by simulating Lagrangian particle tracks and the flushing characteristics were determined by simulating the injection of conservative dye constituents. Particle residence times and the time required to flush injected dye from subareas of the estuary are used to describe the results of the simulations.

## Previous Studies

Measurements of instantaneous flow and water quality from selected springs that flow into Kings Bay are reported in Rosenau and others (1977). Seaburn and others (1979) measured the flow and water quality of Crystal River in April 1974 as part of an evaluation of a digital water quality model.

Yobbi and Knochenmus (1989) related salinity characteristics in Crystal River to tidal stage and river flow. Their report suggests that springs discharging from the saltwater-freshwater transition zone of the Upper Floridan aquifer might cause elevated salinity concentrations in Kings Bay.

A waste-load allocation study by the Florida Department of Environmental Regulation (Nearhoof, 1989) evaluated the effect of sewage treatment plant effluent that is discharged into two canals tributary to Kings Bay. Results from dye tracer tests were included in that study.

Kochman and others (1983) described the occurrence of manatees in Kings Bay, and Romie (1990) discussed the factors contributing to the growth of *Lyngbya spp.* in the estuary.

## Acknowledgments

The authors express their appreciation to personnel from the Southwest Florida Water Management District, Florida Marine Patrol, Citrus County Marine Science Station, and many private citizens from the town of Crystal River and Citrus County who assisted during the tidal-cycle measurement on June 7-8, 1990. The U.S. Fish and Wildlife Service provided information about the location of various springs. The Citrus County Department of Public Works, Division of Aquatic Services, provided maps and information on selected areas of Kings Bay. Locations and elevations of various benchmarks were provided by Henigar & Ray Engineering Associates, Inc.

## Description of the Study Area

Kings Bay is in Citrus County on the west coast of peninsular Florida. The estuary measures about 1.5 mi north to south and about 0.5 mi east to west and has a surface area of less than 1 $mi^2$. Romie (1990) estimated that the estuary receives direct runoff from an area of about 2.7 $mi^2$. The land around Kings Bay is low and flat, with land-surface elevations averaging about 5 ft above sea level. Saltmarsh covers much of the area between Kings Bay and the Gulf of Mexico. Throughout most of this part of Florida, limestone bedrock is overlain by a thin layer of sandy soil, but, in some areas, the limestone protrudes at land surface. The bottom of Kings Bay is exposed limestone with a multitude of submarine springs and seeps (Yobbi and Knochenmus, 1989).

The average depth in Kings Bay is about 8 ft (fig. 2), but the shallow tidal flats in the southwestern part of the bay are sometimes exposed at low tide, and one of the major springs south of Banana Island has a depth of about 65 ft. Along the channel of Crystal River, depths are typically 8 to 12 ft. In the early 1960's, a network of 75-ft-wide canals was dredged along the

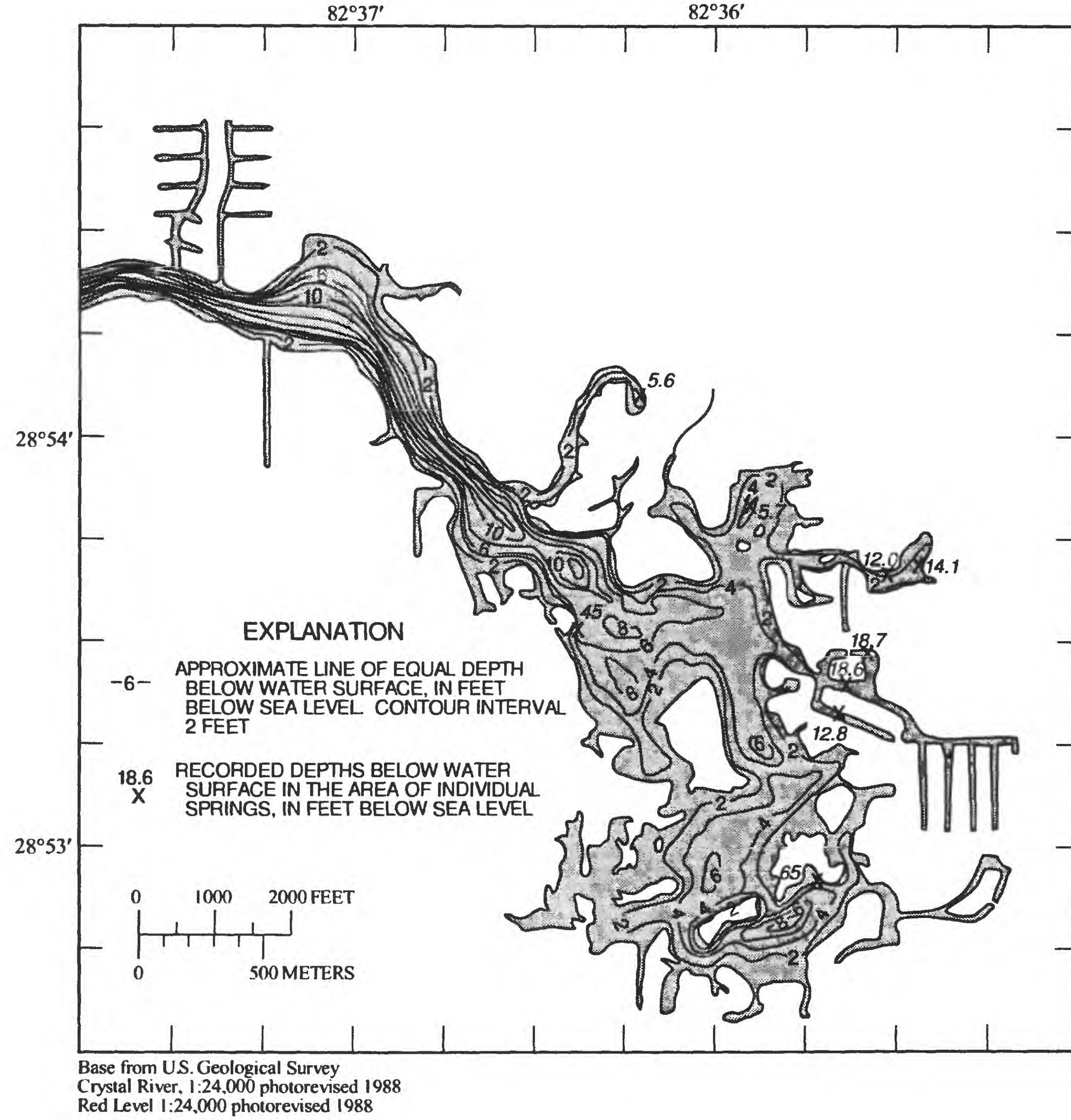



Figure 2. Generalized depth contours for Kings Bay and Crystal River, Citrus County, Florida.

eastern edge of the bay as part of waterfront residential development (Fox and others, 1988). The depths of the canals are not shown in figure 2, but the average depth is about 6 ft.

Kings Bay discharges into Crystal River at the northwest corner of the bay. For the 13-year period from 1965 to 1977, the discharge at gaging station 02310750 (fig.1), near the town of Crystal River and about 2 mi downstream from the mouth of Kings Bay, averaged 975 $ft^3/s$ (Yobbi and Knochenmus, 1989). The main channel of Crystal River measures about 7 mi from the mouth of Kings Bay to the Gulf of Mexico. Because there are no major stream inlets to Kings Bay, virtually all of the freshwater inflow into Crystal River is the result of spring discharge.

All of Crystal River and Kings Bay are tidally affected. Flow reversals associated with incoming tides are commonplace in the canals and ditches. For typical tidal oscillations, the range in stage in Kings Bay is from 3 to 4 ft from low to high tide.

## DATA COLLECTION

A variety of continuous and periodic data were collected to calibrate and verify a hydrodynamic model and to describe hydrodynamic characteristics. A network of 13 sites was established in the study area to measure stage, velocity, discharge, and specific conductance. Measurements made at these sites during the intensive data collection effort of June 7-8, 1990, were used for model development and calibration. Data collected during June 15-16, 1990, were used for model verification.

### Tidal Stage

To complement stage data from the existing long-term Crystal River gaging station (fig. 1), two additional continuous stage recorders were installed, one at Kings Bay north at Magnolia Circle (site 1, fig. 3) and one at Kings Bay south at Crescent Drive (site 2, fig. 3). During the intensive field data-collection effort on June 7-8, 1990, stage readings were taken in conjunction with discharge measurements at Hunter Spring Run (site 3, fig. 3), Kings Bay Drive bridge (site 4, fig. 3), and Crystal River at Woodland Estates (site 5, fig. 3), and volunteer observers recorded stage readings at two other locations (sites 6 and 7, fig. 3). Stage readings were also made during

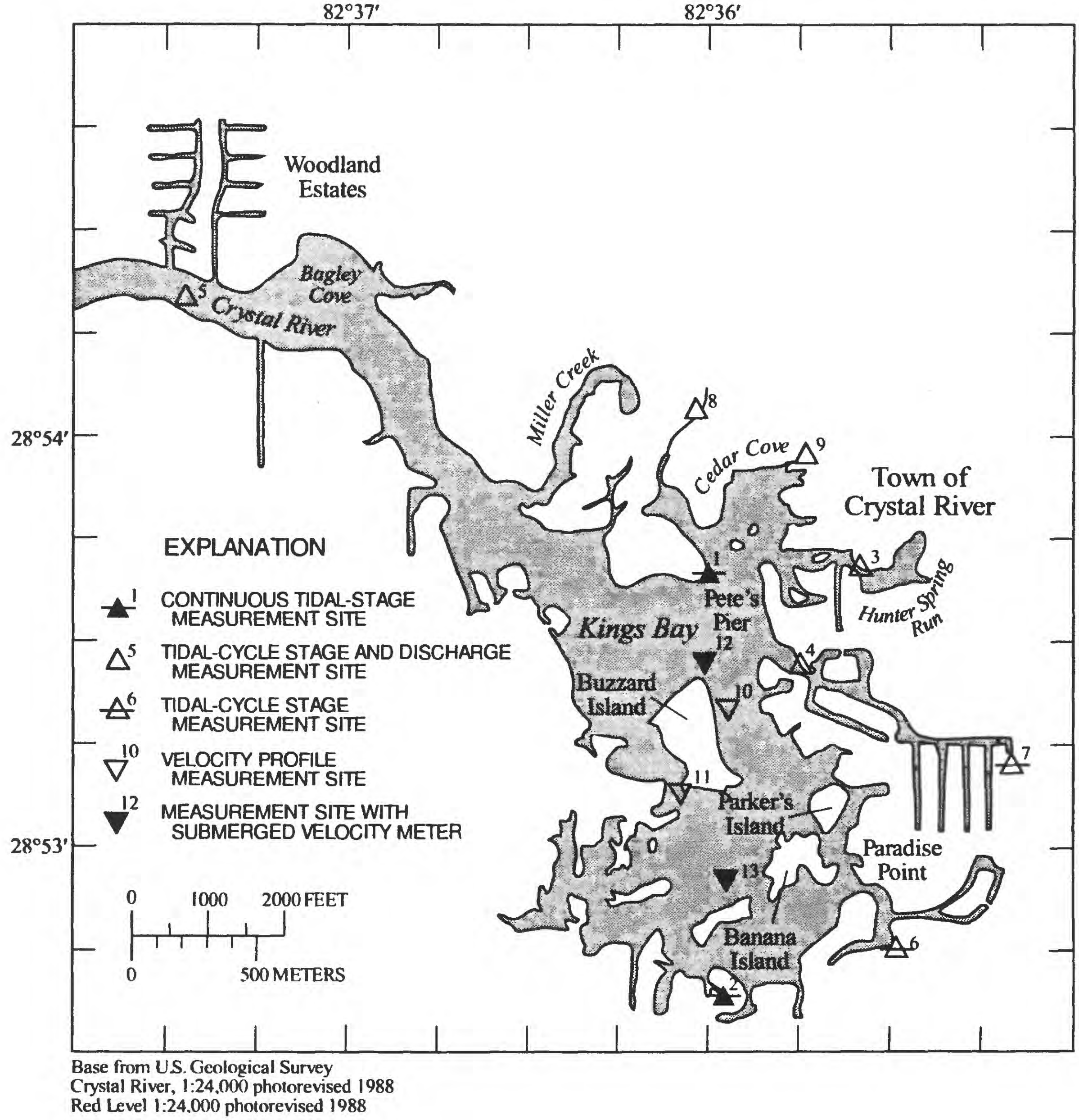



Figure 3. Tidal stage, discharge, and velocity measurement sites, Citrus County, Florida.

discharge measurements at the tributaries receiving effluent from the wastewater treatment plants (site 8 and 9, fig. 3). The sites and their periods of record are listed in table 1.

Table 1. Data-collection sites in Kings Bay, Kings Bay tributaries, and Crystal River

| Site number[1] | Site name | Location | | Period of record | Type of record |
|---|---|---|---|---|---|
| | | Latitude | Longitude | | |
| 1 | Kings Bay north at Magnolia Circle at Crystal River (02310744) | 28°53'40" | 82°36'00" | 5/22/89 - 2/01/91 | Continuous tidal-stage |
| 2 | Kings Bay south at Crescent Drive near Crystal River (02310732) | 28°52'40" | 82°35'59" | 7/06/89 - 12/23/90 | Continuous tidal-stage |
| 3 | Hunter Spring Run at Beach Lane at Crystal River (02310743) | 28°53'40" | 82°35'36" | 6/07/90 - 6/08/90 | Tidal-cycle stage and discharge |
| 4 | Kings Bay at Kings Bay Drive bridge at Crystal River | 28°53'25" | 82°35'45" | 6/07/90 - 6/08/90 | Tidal-cycle stage and discharge |
| 5 | Crystal River at Woodland Estates at Crystal River | 28°54'20" | 82°37'27" | 6/07/90 - 6/08/90 | Tidal-cycle stage and discharge |
| 6 | Kings Bay tributary at State Road 44 at Crystal River | 28°52'38" | 82°35'25" | 6/07/90 - 6/08/90 | Tidal-cycle stage |
| 7 | Kings Bay tributary at Southeast Fifth Avenue at Crystal River | 28°53'15" | 82°35'23" | 6/07/90 - 6/08/90 | Tidal-cycle stage |
| 8 | Kings Bay tributary at U.S. 19 and Northwest Seventh Avenue at Crystal River | 28°54'04" | 82°36'00" | 6/07/90 - 6/08/90 | Tidal-cycle stage and discharge |
| 9 | Kings Bay tributary at U.S. 19 and Northwest Second Avenue at Crystal River | 28°53'59" | 82°35'44" | 6/07/90 - 6/08/90 | Tidal-cycle stage and discharge |
| 10 | Kings Bay at Buzzard Island east at Crystal River | 28°53'18" | 82°35'53" | 6/07/90 | Velocity profiles |
| 11 | Kings Bay at Buzzard Island west at Crystal River | 28°53'08" | 82°36'05" | 6/07/90 | Velocity profiles |
| 12 | Kings Bay at Buzzard Island north at Crystal River | 28°53'31" | 82°36'10" | 6/04/90 - 6/21/90 | Continuous point velocity and azimuth |
| 13 | Kings Bay at Buzzard Island south at Crystal River | 28°53'03" | 82°35'54" | 6/06/90 - 6/22/90 | Continuous point-velocity and azimuth |

[1]Site locations are shown on figure 3.

The tidal stage recorded at Kings Bay south at Crescent Drive (site 2, fig. 3) during the summer of 1990 reflects the semidiurnal characteristic of the tides in Kings Bay (fig. 4). The 14-day spring-neap cycle was most clearly observed in August when the tide was not significantly affected by winds from storms. Winds from the west typically produce an increase in stage throughout the river and bay, and winds from the east and southeast typically produce a fall in stage. The intensive field data-collection effort of June 7-8, 1990, was scheduled to correspond with the predicted maximum tidal peaks in the spring-neap cycle so that measurements would reflect maximum tidal velocities. Maximum tidal peaks are also coincident with maximum tidal prism, which is the volume of water that enters or leaves the estuary between high slack water and low slack water (Goodwin, 1987, p. 8).

## Tidal Velocity and Discharge

Flow reversals occur throughout all of Crystal River and Kings Bay and were observed at both tributaries under U.S. 19 (sites 8 and 9, fig. 3) that connect Kings Bay with outflow from the Crystal River sewage treatment plant. Discharge measurements were made at five locations throughout Kings Bay (sites 3, 4, 5, 8, and 9; fig. 3). Maximum incoming and outgoing velocities and discharges and average net discharges measured at these locations during the intensive data-collection period of June 7-8, 1990, are summarized in table 2. Average cross-sectional velocities ranged from a maximum of 1.04 ft/s on an incoming tide and 1.12 ft/s on an outgoing tide at Crystal River at Woodland Estates (site 5, fig. 3) to a minimum of less than 0.01 ft/s at all of the measurement locations at slack tide. Discharges ranged from a maximum of about 5,300 $ft^3/s$ on an incoming tide and about 5,800 $ft^3/s$ on an outgoing tide at Crystal River at Woodland Estates to about zero at all of the measurement locations at slack tide. All net discharges were in the outgoing direction.

Crystal River at Woodland Estates (site 5, fig. 3) was the discharge measurement site farthest downstream during the intensive data collection period. At this site, velocity measurements were made simultaneously from five boats anchored across the river. Velocity profiles were measured every 15 minutes and discharge was then computed from the velocities and cross-sectional area of the river. A numerical integration of the computed 15-minute discharges resulted in an average net discharge of 735 $ft^3/s$ during the

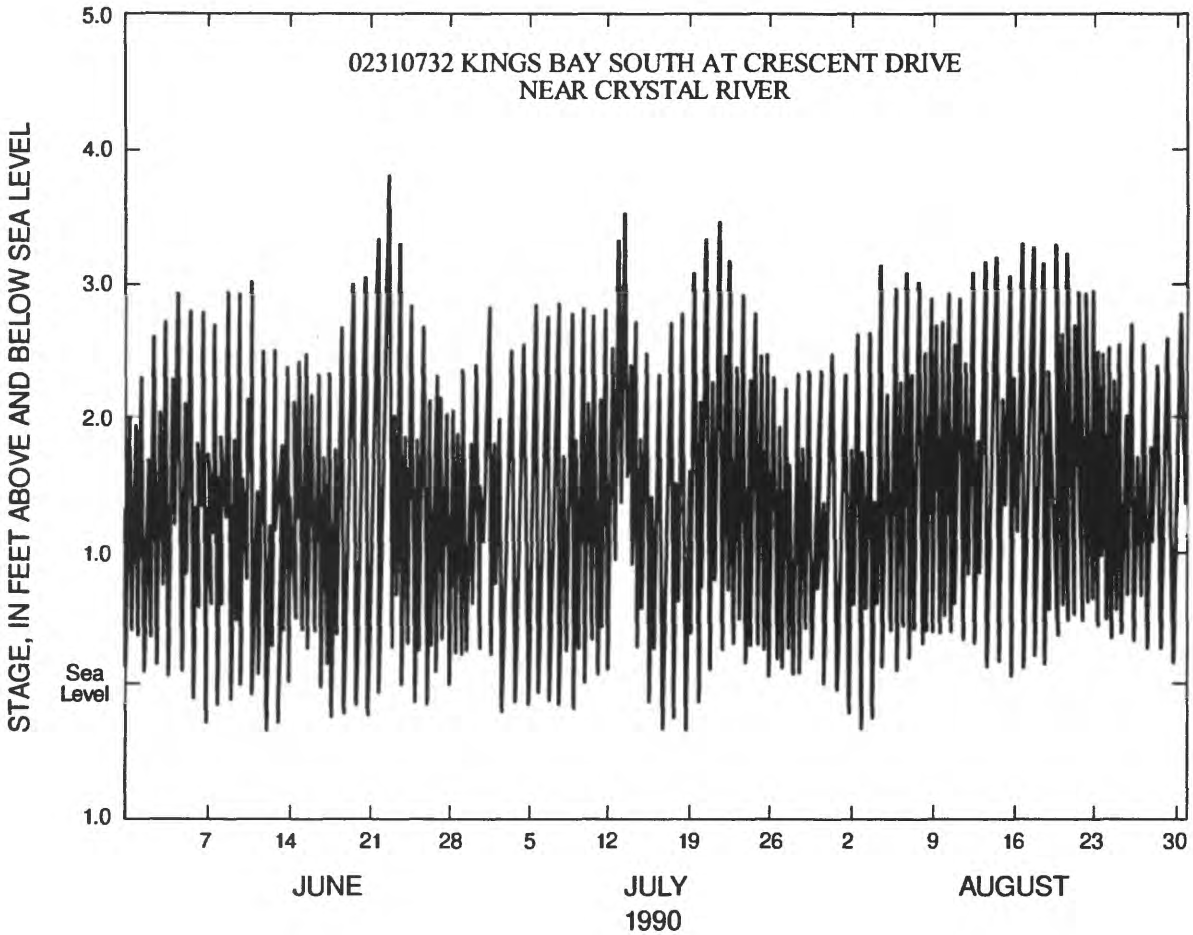



Figure 4. Tidal-stage characteristics in Kings Bay, Citrus County, Florida.

tidal cycle measurement of June 7-8, 1990. This discharge represents the average net flow from all of the springs in Kings Bay combined with minimal inflow from tributaries discharging into the bay. The discharge computed for the tidal cycle (June 7-8, 1990) is about 25 percent lower than the 975 $ft^3/s$ average discharge reported for the long-term gaging station at Crystal River near Crystal River (fig. 1). Cumulative rainfall for the 6 months ending May 31, 1990, was about 2.5 in. below normal in north-central Florida (National Oceanic and Atmospheric Administration, 1990) and the discharge measured during the intensive data-collection effort reflects drier than normal conditions.

Boat measurements of discharge were made throughout the tidal cycle at Hunter Spring Run. Bridge measurements of discharge were made at Kings Bay Drive bridge. The average net discharge at Hunter Spring Run was computed to be about 42 $ft^3/s$, or about 6 percent of the total flow out of Kings Bay. At Kings Bay Drive bridge, average net discharge was computed to be about 110 $ft^3/s$, or about 15 percent of the total flow out of the bay.

The Crystal River sewage treatment plant discharges an average of 0.75 Mgal/d (about 1.2 $ft^3/s$) of effluent into a canal system that empties into Kings Bay through two tributaries (sites 8 and 9, fig. 3). Natural springs and seeps also discharge into the canal system and significantly increase the total flow from the tributaries. Wading measurements were made throughout the tidal cycle at each tributary. Net discharge at sites 8 and 9 (table 2) were computed to be about 2 $ft^3/s$ and 6 $ft^3/s$, respectively, or about 1 percent of the total flow that discharged from Kings Bay during the data collection period of June 7-8, 1990.

On June 7, 1990, vertical velocity profiles were determined from measurements made at locations east and west of Buzzard Island (sites 10 and 11, fig. 3). Marsh-McBirney model 527 directional velocity meters were used at both sites and readings were taken at 0.2, 0.4, 0.6, and 0.8 of total depth.

Two submersible velocity meters were deployed for about a 15-day period in early June 1990 (table 1). A General Oceanics model 6011 velocity meter was placed about 6 ft above the bottom of the bay just north of Buzzard Island (site 12, fig. 3). At the time of deployment on June 4, surrounding Hydrilla was cleared to the mud line for a radius of about 10 ft. When the velocity meter was recovered on June 21, Hydrilla had grown to a height of about 5 ft, and data recorded during the last 3 days of the deployment were considered invalid because of the apparent effects of the Hydrilla on meter readings. In the north-south direction, velocities were consistently less than 0.1 ft/s, which is the velocity detection limit of the meter. Velocities ranged from 0.65 ft/s in a westerly direction to 0.30 ft/s in an easterly direction. The mean velocity for the valid data collection period was 0.11 ft/s in a westerly direction. During the tidal cycle measurement on June 7-8, peak velocities were 0.5 ft/s to the west and 0.2 ft/s to the east.

A Marsh-McBirney model 512 velocity meter was deployed just south of Buzzard Island (site 13, fig. 3). Hydrilla was not observed at the site when the meter was deployed on June 6 or when the meter was retrieved on June 22. The north-south velocity component of the meter malfunctioned during deployment. The mean velocity in the east-west direction was 0.06 ft/s to the east and ranged from 0.26 ft/s in the easterly direction to 0.12 ft/s in the westerly direction.

## Freshwater Inflow

During the tidal cycle measurement of June 7-8, 1990, net total freshwater inflow from the tributaries and springs in Kings Bay was measured at Crystal River at Woodland Estates (site 5, fig. 3) and averaged 735 $ft^3/s$. The distribution of flow from individual spring vents also can affect circulation patterns in Kings Bay; therefore, an attempt was made to quantify discharge from selected springs in the estuary.

An inventory of 28 major springs was compiled based on information presented in Rosenau and others (1977) and from interviews with local divers and personnel from the U.S. Fish and Wildlife Service and Citrus County Division of Aquatic Services. A scuba diver then visited each area in which a spring had been identified. A few of the springs have a single vent with a uniform cross section at the opening, but most of the springs are made up of multiple vents with openings of various sizes and shapes. To estimate the discharge from the various springs, a scuba diver first measured the cross-sectional area of the vent. A velocity probe was then placed in the spring vent and velocity was measured; temperature, specific conductance, and water-depth readings were made at the same time. Using this technique, springs throughout the bay were located and measured.

Because spring discharge was expected to vary with tidal stage, spring 1 (fig. 5) was used as a reference from which discharges could be adjusted based on tidal stage. During June and August 1990, several measurements of discharge with varying stages were made at spring 1. A least-squares linear regression equation was then computed from the discharge and stage data and is shown below:

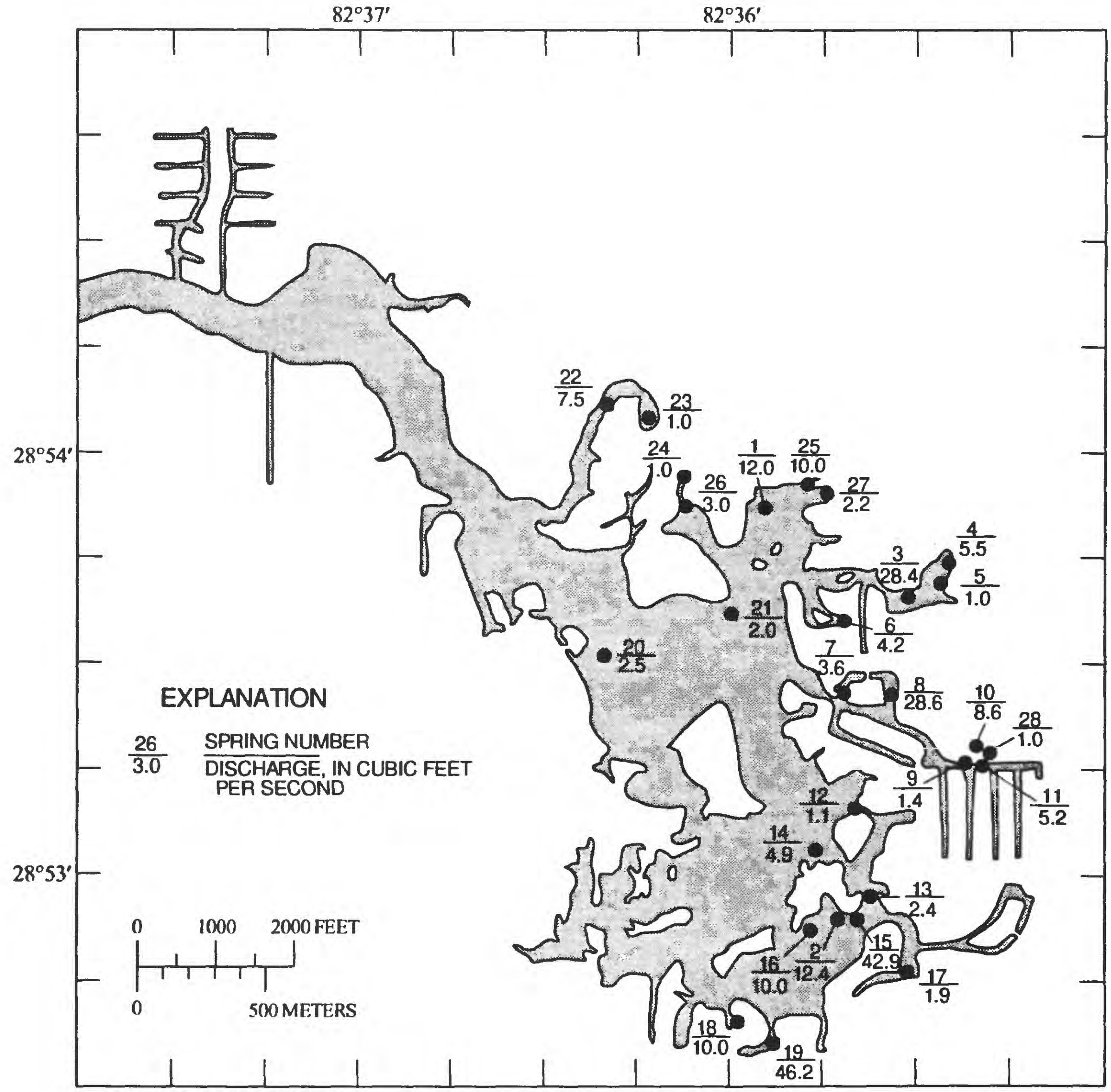
$$Q = 16.79 - (4.25 * S) \qquad (1)$$

where Q is discharge from spring 1, in cubic feet per second,
S is tidal stage at station 02310744, Kings Bay north at Magnolia Circle at Crystal River (site 1, fig. 3), in feet.

Equation 1 is significant at the 1 percent level and has a correlation coefficient of 0.91.

To estimate the relative magnitude of concurrent inflow from all 28 major springs, field measurements from the individual springs were adjusted to a consistent tidal stage. Equation 1 was used to compute the discharge from spring 1 over the full range of tidal stage. Each time one of the other 27 springs was measured, the stage was determined, and a ratio of discharge at the measured spring to discharge at spring 1 (computed using equation 1) was calculated. The concurrent discharges from all 28 major springs were then computed by multiplying the discharge from spring 1 at the selected tidal stage times the ratios for the individual springs. This methodology assumes that the relation between discharge and tidal stage defined by equation 1 is characteristic of all the springs in the estuary. It further assumes that the relation is applicable for the range of ground-water flow conditions that occurred during the measurement of springs in June and August 1990.

During the intensive data collection effort of June 7-8, 1990, tidal stage averaged 1.0 ft, and figure 5 shows the relative discharge from each of the 28 major springs at that average stage. Four of the springs had discharges greater than 20 $ft^3/s$ and 17 others had discharges greater than 2 $ft^3/s$. The sum of the stage-adjusted discharges is about 270 $ft^3/s$. There was virtually no surface or stormwater runoff during the intensive data collection effort because of dry conditions. Of the 42 $ft^3/s$ average net discharge measured at Hunter Spring Run (table 2), about 37 $ft^3/s$ was measured from springs 3, 4, and 5 and the remaining 5 $ft^3/s$ is from uninventoried




Base from U.S. Geological Survey
Crystal River, 1:24,000 photorevised 1988
Red Level 1:24,000 photorevised 1988

Figure 5. Spring discharge measurement sites, Citrus County, Florida.

springs or seeps. The 110 ft$^3$/s average net discharge at Kings Bay Drive bridge (table 2) includes about 50 ft$^3$/s from springs 7, 8, 9, 10, 11, and 28 and 60 ft$^3$/s from uninventoried springs and seeps. When the 270 ft$^3$/s stage-adjusted discharge from the 28 major springs is combined with an additional 5 ft$^3$/s from Hunter Spring Run, 60 ft$^3$/s from Kings Bay Drive bridge, and 8 ft$^3$/s from the sewage treatment plant tributaries, the total is 343 ft$^3$/s. More than half of the average 735 ft$^3$/s (table 2) flow measured at Crystal River at Woodland Estates originates from springs and seeps other than those identified in the inventory and located downstream from the measurement sites at Hunter Spring Run and Kings Bay Drive bridge.

Table 2. Maximum incoming and outgoing velocities and discharges, and average net discharges measured June 7-8, 1990

[ft/s, feet per second, ft$^3$/s, cubic feet per second]

| Site number[1] | Site name | Maximum velocity (ft/s) | | Discharge (ft$^3$/s) | | |
|---|---|---|---|---|---|---|
| | | | | Maximum | | |
| | | Incoming | Outgoing | Incoming | Outgoing | Net |
| 3 | Hunter Spring Run at Beach Lane at Crystal River (02310743) | 0.22 | 0.39 | 109 | 121 | 42 |
| 4 | Kings Bay at Kings Bay Drive bridge at Crystal River | .25 | .77 | 151 | 264 | 110 |
| 5 | Crystal River at Woodland Estates at Crystal River | 1.04 | 1.12 | 5,270 | 5,790 | 735 |
| 8 | Kings Bay tributary at U.S. 19 and Northwest Seventh Avenue at Crystal River | 1.89 | 2.32 | 10.9 | 8.9 | 1.9 |
| 9 | Kings Bay tributary at U.S. 19 and Northwest Second Avenue at Crystal River | 0.26 | 0.63 | 13.8 | 19.0 | 6.4 |

[1]Site locations are shown on figure 3.

## Salinity

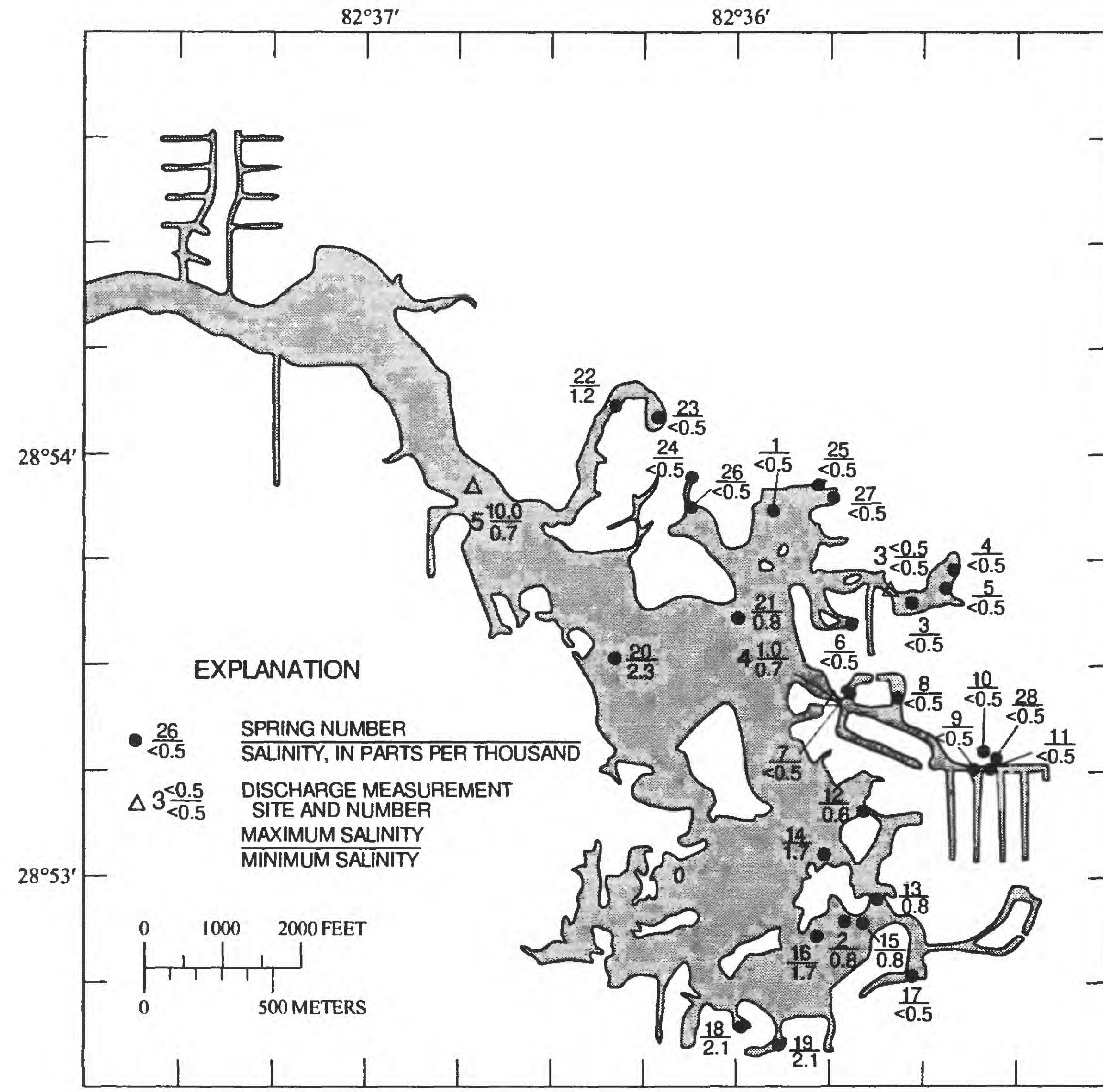
Within an estuary, freshwater from upland streams or springs mixes with salty ocean water. Salinity is a conservative dissolved constituent that can be used as a natural tracer to aid in describing circulation characteristics or in calibrating a numerical model of circulation. Salinity was calculated from measurements of specific conductance using an algorithm described by Miller and others (1988).

Specific conductance was measured at spring vents as part of the spring discharge measurements discussed previously. Specific conductance also was measured at each of the discharge measurement sites and at multiple points throughout the estuary during the June 7-8, 1990, tidal cycle. Salinity values for the springs (fig. 6) represent midday values from June 7, 1990. A range of salinity is presented for the discharge measurement sites. Spring 1 was the only location where salinity measurements were made for a range of tidal stage and ground-water conditions. Salinity was consistently less than 0.5 ppt for all conditions measured at spring 1, but it is not possible to determine from existing data whether salinity at other springs remains steady throughout the range of conditions.

## HYDRODYNAMIC MODEL DEVELOPMENT

A four-step approach was used in this study. First, existing data were compiled and a preliminary, two-dimensional, hydrodynamic model was developed so that results of the preliminary model could be used to design intensive data-collection efforts for boundary conditions and tidal-cycle synoptic measurements. Second, field data were collected and analyzed. Third, the preliminary model was modified to reflect conditions observed in the field and was calibrated and verified against field measurements of stage, velocity, spring discharge, and salinity. Fourth, the calibrated and verified model was applied to simulate the response of the estuarine system when inflows were increased to typical levels and when bottom roughness was smoother than calibration conditions.

Hydrodynamic simulations were accomplished using SIMSYS2D, a two-dimensional, estuarine-simulation system described by Leendertse and Gritton (1971). Equations that describe the physical laws governing water and constituent motion in two dimensions are applied at every location where simulated information is desired. These equations are solved at successive time steps to provide a close approximation of the time history of tidal stage, water transport, tidal velocity, and constituent transport at corresponding locations in the real system. The model has been applied successfully to several other estuaries around the world and to Tampa Bay, Hillsborough Bay, and Charlotte Harbor on the west-central coast of Florida (Goodwin, 1987; 1991; 1996).




Base from U.S. Geological Survey
Crystal River, 1:24,000 photorevised 1988
Red Level 1:24,000 photorevised 1988

Figure 6. Salinity measurements, June 7-8, 1990, Citrus County, Florida.

## Governing Equations

Water motion in estuaries is governed by the physical laws of conservation of mass and conservation of momentum. The two-dimensional, estuarine simulation system (SIMSYS2D) applied in this study uses vertically integrated forms of the equations that describe conservation of mass and conservation of momentum, as presented by Leendertse (1987, p. 6):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \qquad (2)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV + g\frac{\partial \zeta}{\partial x} + \frac{g}{2}\frac{H}{\rho}\frac{\partial \rho}{\partial x} + RU$$

$$- \frac{\Theta \rho_a W^2 \sin \Psi}{\rho H} - k\left[\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right] = 0 \qquad (3)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU + g\frac{\partial \zeta}{\partial y} + \frac{g}{2}\frac{H}{\rho}\frac{\partial \rho}{\partial y} + RV$$

$$- \frac{\Theta \rho_a W^2 \cos \Psi}{\rho H} - k\left[\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right] = 0 \qquad (4)$$

where f is the Coriolis parameter,

g is the acceleration of gravity,

h is the distance from the bottom to a reference plane,

H is the temporal depth (= h + $\zeta$),

k is the horizontal exchange coefficient,

R is the bottom stress coefficient,

U is $[1/(h + \zeta)]\int_h^\zeta u\,dz$, vertically averaged velocity component in x direction,

V is $[1/(h + \zeta)]\int_h^\zeta V\,dz$, vertically averaged velocity component in y direction,

W is wind speed,

$\zeta$ is the water-level elevation relative to a horizontal reference plane,

$\Theta$ is the wind-stress coefficient,

$\rho$ is the density of water,

$\rho_a$ is the density of air, and

$\Psi$ is the angle between wind direction and the positive y direction.

Equation 2 expresses conservation of mass in two dimensions. Equations 3 and 4 express conservation of momentum in the x- and y- Cartesian coordinate directions, respectively. Baroclinic effects are treated in the momentum equations by the density gradient terms:

$$\frac{g}{2}\frac{H}{\rho}\frac{\partial \rho}{\partial x} \text{ and } \frac{g}{2}\frac{H}{\rho}\frac{\partial \rho}{\partial y}$$

where g, H, and $\rho$ are the same as defined for equations 3 and 4.

Equations 2 through 4 are vertically integrated, or vertically averaged, over the water depth. Vertical integration is valid if the vertically varying flow and transport can be represented by a single value (flow is two-dimensional). Estuarine circulation, however, can have a three-dimensional structure. Longitudinal density gradients in estuaries can cause a nontidal circulation pattern with landward flow near the bottom and seaward flow near the water surface (Filadelfo and others, 1991; Smith and others, 1991). Two-dimensional models that include longitudinal density gradients in the equations of motion are unable to reproduce the vertical structure of the circulation, but they are able to reproduce the vertically integrated circulation patterns observed in well- and partially-mixed estuaries (McAnally and others, 1984; Smith and Cheng, 1987; Jin and Raney, 1991). The model used in this study includes longitudinal density (or baroclinic) effects in equations 3 and 4. Vertical density stratification is another physical condition that invalidates vertical averaging. Previously, vertical density stratification has been shown to be insignificant for the hydrologic conditions assumed by this study. Wind can generate a surface flow with the wind and a bottom return flow against the wind (Pritchard and Vieira, 1984; Hunter and Hearn, 1987) and can significantly affect circulation patterns (Smith and Cheng, 1987). This study does not consider wind-induced circulation.

Transport of dissolved constituents is governed by large-scale advective or translatory motion and by fine-scale dispersive or turbulent mixing. The transport simulation capability of SIMSYS2D allows for constituent sources and sinks, as given by Leendertse (1987, p. 6-7):

$$\frac{\partial(HP)}{\partial t} + \frac{\partial(HUP)}{\partial x} + \frac{\partial(HVP)}{\partial y} + \frac{\partial(HD_x \partial P/\partial_x)}{\partial x} + \frac{\partial(HD_y \partial P/\partial y)}{\partial y} - S = 0 \qquad (5)$$

where H, U, and V are the same as defined for equations 2, 3, and 4;

$D_x$ and $D_y$ are the diffusion coefficients of dissolved substances;

P is the vector of dissolved constituent concentrations; and

S is the source of fluid with dissolved substances.

As with the velocities U and V, P is the vertically integrated average mass concentration of the constituent given by:

$$P = \frac{1}{H} \int_{-h}^{\zeta} p_A \, dz \tag{6}$$

where H, h, and $\zeta$ are the same as defined for equations 2, 3, 4, and 5; and

$p_A$ is the local mass concentration of constituent substance, A.

Except in regions of large constituent concentration gradients, mass transport by longitudinal dispersion is often very small compared with mass transport by advection (Holley, 1969, p. 628). Therefore, Leendertse (1970, p. 13) concluded that small errors in assigning values to the longitudinal dispersion coefficient would not substantially change the solutions. He proposed that dispersion could be adequately defined by two components: an isotropic component representing the effect of lateral mixing and a directional component approximating longitudinal effects. The dispersion coefficients, $D_x$ and $D_y$, used in SIMSYS2D are given by Leendertse (1970, p. 14-15):

$$D_x = dHU g^{0.5} C^{-1} + D_w \tag{7}$$

$$D_y = dHV g^{0.5} C^{-1} + D_w \tag{8}$$

where $D_x$, $D_y$, H, U, V, and g are the same as defined for equations 2, 3, 4, and 5;

d is an empirical dimensionless constant similar to that presented by Elder (1959);

C is the Chezy roughness coefficient; and

$D_w$ is the diffusion coefficient representing wave, wind, and lateral mixing effects.

Densities are derived from salinity, water temperature, and an equation of state. Salinity is calculated as a conservative constituent in the transport equation (eq. 5), and temperature is assumed constant throughout the model area as it is only slightly related to density. The relation between salinity and density is provided by the following equation of state (Eckert, 1958, p. 250) and is applied throughout the time and space domain of the model area:

$$\rho = [5890 + 38T - 0.375T^2 + 3s] \;/\; [(1779.5 - 11.25T - 0.0745T^2) - (3.8 + 0.01T)s + 0.698(5890 + 38T - 0.375T^2 + 3s)] \qquad (9)$$

where T is temperature, in degrees Celsius; and
s is salinity, in parts per thousand.

## Numerical Methods

Partial-differential equations 2 through 5 describe the general relations that exist between the forces that govern water motion and solute transport in estuaries. Because the equations cannot be solved analytically for most real-world conditions, procedures have been devised that provide approximate solutions by using computers to perform enormous arrays of numerical computations.

The numerical procedure used in SIMSYS2D is described in detail by Leendertse (1987) and is summarized below. Equations 2 through 5 can be approximated throughout a region in time and space by a large number of finite-difference equations. Each finite-difference equation is similar to the parent equation, but is applicable at only one point in time and space and is separated from all other points by finite time and space increments. Such a finite-difference approximation is valuable because, by using the approximation, a differential equation is reduced to a series of simultaneous algebraic equations involving quantities at defined locations. Each finite-difference equation contains known and unknown terms. As long as the number of equations is equal to the number of unknown terms, the system is solvable. The method of solution for the unknown terms involves a point-to-point, iterative, stepwise procedure that incorporates previously computed values and input data as appropriate.

## Grid and Model Creation

A space-staggered grid scheme (fig. 7) is used in the SIMSYS2D model. Water levels ($\zeta$) and solute mass density (P) are defined at integer values of $m$ and $n$. Water depths, referenced to sea level, are defined at points midway between integer values of $m$ and $n$. Velocities in the $x$ direction (U) are defined at points midway between integer values of $m$ and at integer values of $n$. Velocities in the $y$ direction (V) are defined at points midway between integer values of $n$ and at integer values of $m$. The grid extends to the boundaries of the modeled area in the positive ($x$) and negative ($y$) directions. For land areas, water depths (h) are replaced by land altitudes ($h<0$), and water velocities are computed only when water levels exceed land altitudes. Time (t) also is simulated in a stepwise manner, with computational elements defined at integer points and midway between integer points. Leendertse (1987) provides a complete description of how equations 2 through 5 are structured at each ($x$, $y$, and t) point and how unknowns in each equation are solved. An overview of the solution scheme also is given by Cheng and Casulli (1982, p. 1665).

The area modeled (fig.8) includes all of Kings Bay and extends down Crystal River to just upstream of the confluence with the Salt River (fig. 1). The river was included so that the model boundary would be away from Kings Bay, which was the primary area of interest. The size of each cell of the model grid was 125 ft square, which is small enough to provide resolution of most of the features in the estuary, yet large enough to be computationally feasible. Many of the small canals are less than 125 ft wide and these were simulated by a series of cells that had volumes and frictional characteristics that were hydraulically equivalent to the systems of canals. The computational grid extended a total of 132 cells in the $m$, or east direction, and 108 cells in the $n$, or north direction. The model time step was varied from 0.1 to 0.5 minute to test for mathematical stability. A time step of 0.25 minute was found to be the largest time step that would provide computational stability and was selected for use in the model.

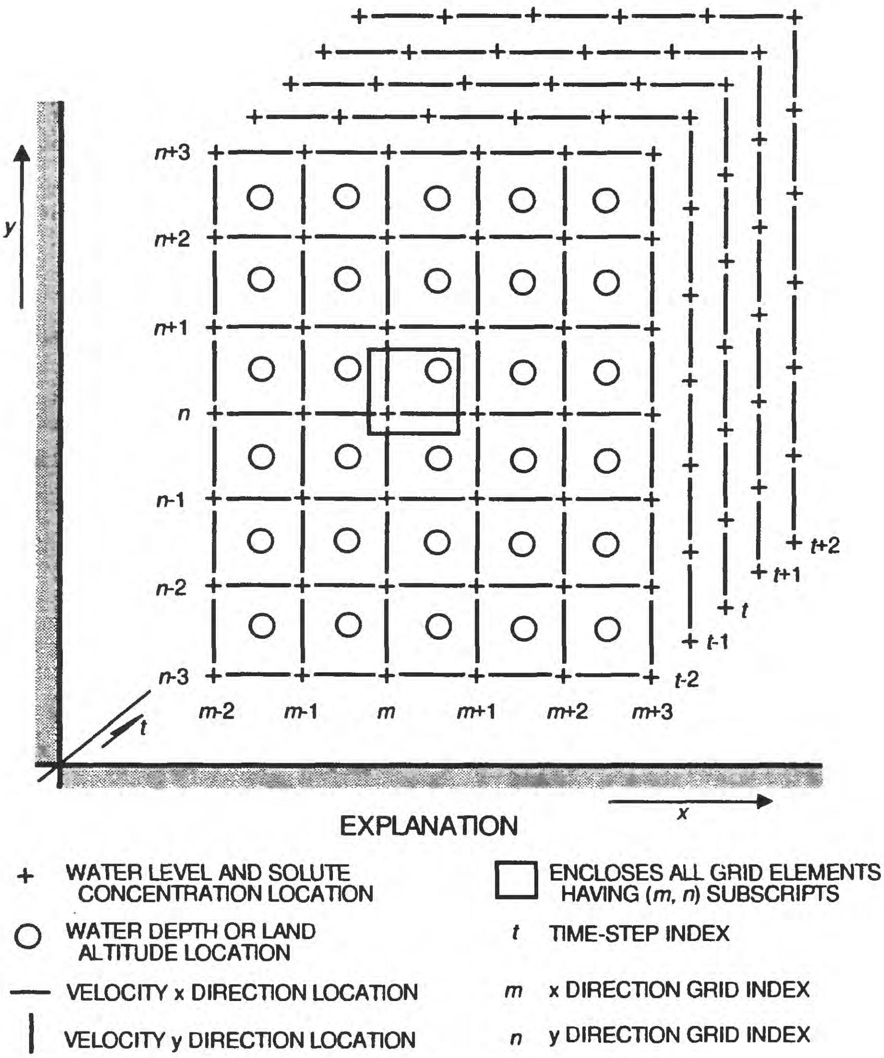



Figure 7. Space-staggered finite-difference grid used in SIMSYS2D. (From Goodwin, 1987.)

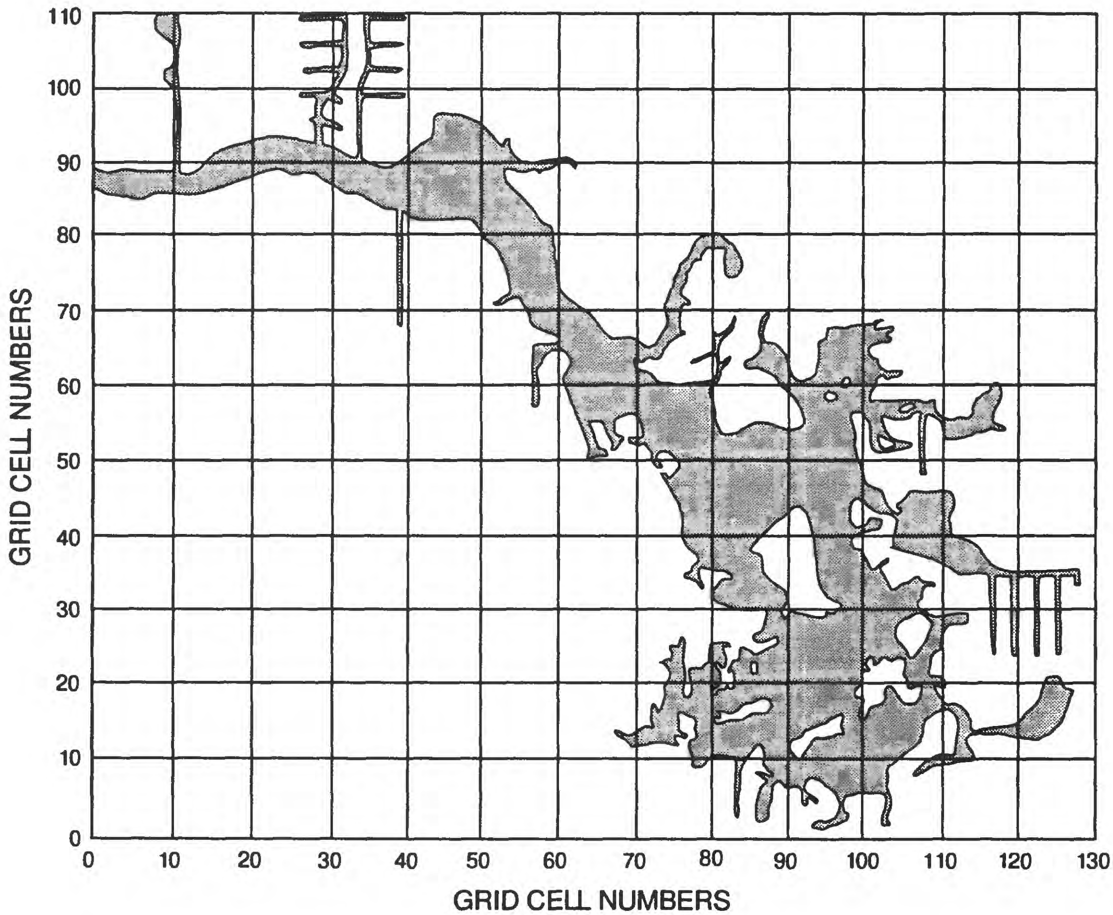



Figure 8. Model grid used for Kings Bay, Citrus County, Florida.

Various physical features of Kings Bay must be provided as input to SIMSYS2D. The bottom configuration, defined as water depth at each grid cell, is the most important element in model development. ARC/INFO, a Geographical Information System (GIS), was used to merge bathymetric data from various sources to produce depths for the cells. The shoreline of the river and bay was digitized from a map prepared by Henigar and Ray, Engineering Associates, Inc., revised April 1983. Because there were no nautical charts for the bay and river, data from a previous study by Kochman and others (1983) and from fathometer surveys were used to produce depths.

## Model Calibration and Verification

Calibration and verification are necessary steps preceding any model application. During calibration, parameters that cannot be precisely measured in the field are adjusted so that simulated hydrodynamic features in the model match field observations of hydrodynamic features as closely as possible. During verification, field observations from another time period are compared with simulated hydrodynamic features and the degree of similarity is defined statistically. No adjustment of parameters is made during verification.

The data used for model calibration were collected June 7-8, 1990, and included tidal-stage measurements at sites 1 through 9 (fig. 3); periodic measurement of vertical profiles of tidal-current speed and direction, salinity, and temperature at sites 10 and 11 (fig. 3); continuous measurement of tidal-current speed and direction at sites 12 and 13 (fig. 3); and tidal-cycle measurement of discharge at Hunter Spring Run, Kings Bay Drive bridge, and at Crystal River at Woodland Estates (sites 3, 4, and 5; fig. 3). The time period selected for calibration was based on the availability of the greatest amount of data. The data used for model verification were collected June 15-16, 1990, and included tidal-stage measurements at sites 1 and 2 (fig. 3) and continuous measurement of tidal-current speed and direction at sites 12 and 13 (fig. 3).

Stage data from the long-term gaging station at Crystal River near Crystal River (fig. 1) were used to define the tidal driving function at the boundary of the model. Characteristics of the boundary tides during the calibration and verification periods are shown in figure 9. The model was then calibrated through adjustment of roughness coefficients (Manning's $\underline{n}$) and the distribution of inflow.

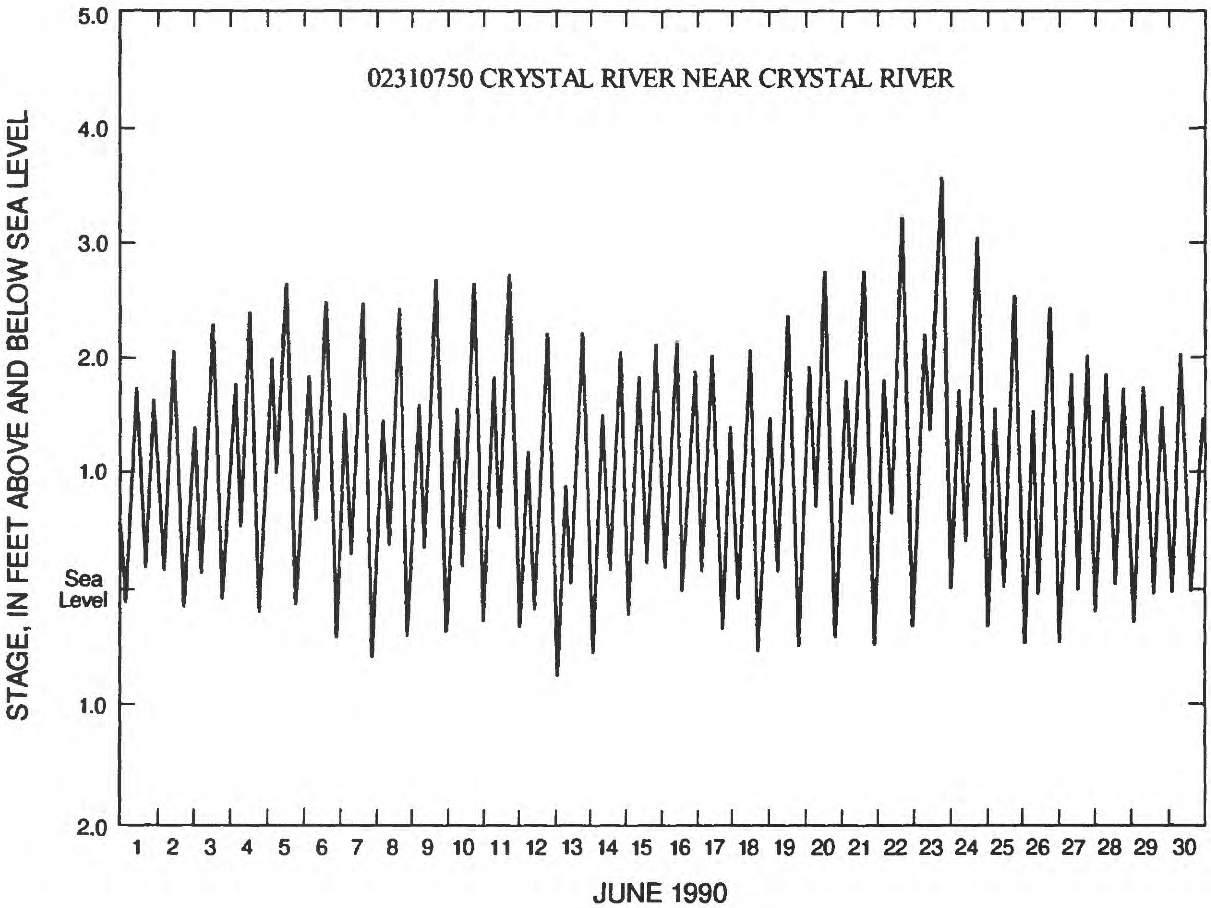



Figure 9. Tidal driving function for the calibration and verification periods.

The bottom of the bay was treated as a fixed boundary that causes resistance to the free movement of water. Resistance increases as the roughness of the bottom material increases. Manning's n is an empirical coefficient of roughness that is assigned to each cell of the model. Manning's n values that have been used in previous estuarine models range from 0.010 to 0.035 (Goodwin, 1987). In calibrated hydrodynamic models for the Tampa Bay and Charlotte Harbor estuaries of west-central Florida, n values ranged from 0.020 to 0.028 (Goodwin, 1987; 1996) For the initial model runs for Kings Bay, n values between 0.018 and 0.028 were assigned to reflect variations in bottom roughness in the estuary. Because of the need to simulate the effects of Hydrilla, the final values of n for the calibrated Kings Bay model were somewhat higher than those used in previous models. The main channel of Crystal River, which does not have a standing crop of Hydrilla, had an n value of 0.012 assigned, which was the lowest, or "smoothest," n used in the model. Bagley Cove on the north side of Crystal River and the central part of Kings Bay had a final n of 0.040. Manning's n for the tidal flats in the southwestern part of the bay was set at 0.050. In Cedar Cove and Hunter Spring Run, a value of 0.080 was used because of the large amount of Hydrilla present during the calibration period. Throughout the canal systems a value of 0.060 was used.

Inflow from springs into the estuary was modeled by specifying average inflow at selected grid points. As noted in the previous discussion of freshwater inflow, field measurements from the 28 major springs, along with flow measurements at Hunter Spring Run, Kings Bay Drive bridge, and the sewage treatment plant outflows accounted for about half of the average flow measured at Crystal River at Woodland Estates during the calibration period. The other half of the freshwater inflow was simulated by specifying inflow sources at 22 other grid points in the estuary. The distribution of flow among these 22 grid points was based on point velocity readings, miscellaneous field observations, and then uniform distribution of the remaining inflow.

A level water surface, equal to the starting water level of the tidal driving function, was assumed throughout the bay at the start of each model run. The bay was assumed to be motionless, and all tidal currents were set to zero. For the first calibration runs, an initial salinity concentration of 0.4 ppt was set throughout the bay. The first 12 to 24 hours of real time were simulated before the effects of initial stage, current, and circulation characteristics disappeared. This first 12 to 24 hours of real time was considered "start-up," and model output for the period was disregarded. To develop a better initial salinity distribution, the model was run for 50 days with a repeating tide. The salinity distribution stabilized after about 21 days and that distribution was subsequently used as the "start-up" salinity distribution for model runs.

Simulated and observed tidal stages at four sites for the calibration period are presented in figure 10. The differences between simulated and observed stages at all nine stage sites also were evaluated statistically, and the standard errors are presented in table 3. Standard errors in tidal stage were less than 0.1 ft throughout most of the bay, or less than about 4 percent

Table 3. Statistical comparison of simulated and observed tidal stage for the calibration period

| Site number[1] | Site name | Standard error[2] (feet) | Nominal error[3] dimensionless |
|---|---|---|---|
| 1 | Kings Bay north at Magnolia Circle at Crystal River (02310744) | 0.047 | 0.02 |
| 2 | Kings Bay south at Crescent Drive near Crystal River (02310732) | .065 | .02 |
| 3 | Hunter Spring Run at Beach Lane at Crystal River (02310743) | .068 | .03 |
| 4 | Kings Bay at Kings Bay Drive bridge at Crystal River | .092 | .04 |
| 5 | Crystal River at Woodland Estates at Crystal River | .092 | .03 |
| 6 | Kings Bay tributary at State Road 44 at Crystal River | .312 | .10 |
| 7 | Kings Bay tributary at Southeast Fifth Avenue at Crystal River | .113 | .04 |
| 8 | Kings Bay tributary at U.S. 19 and Northwest Seventh Avenue at Crystal River | .054 | .03 |
| 9 | Kings Bay tributary at U.S. 19 and Northwest Second Avenue at Crystal River | .062 | .04 |

[1]Site locations are shown in figure 3.

[2]Standard error = $\frac{\Sigma \left| \text{computed} - \text{measured} \right|}{\text{number of observations}}$

[3]Nominal error = $\frac{\text{standard error}}{\text{range of observations}}$, dimensionless

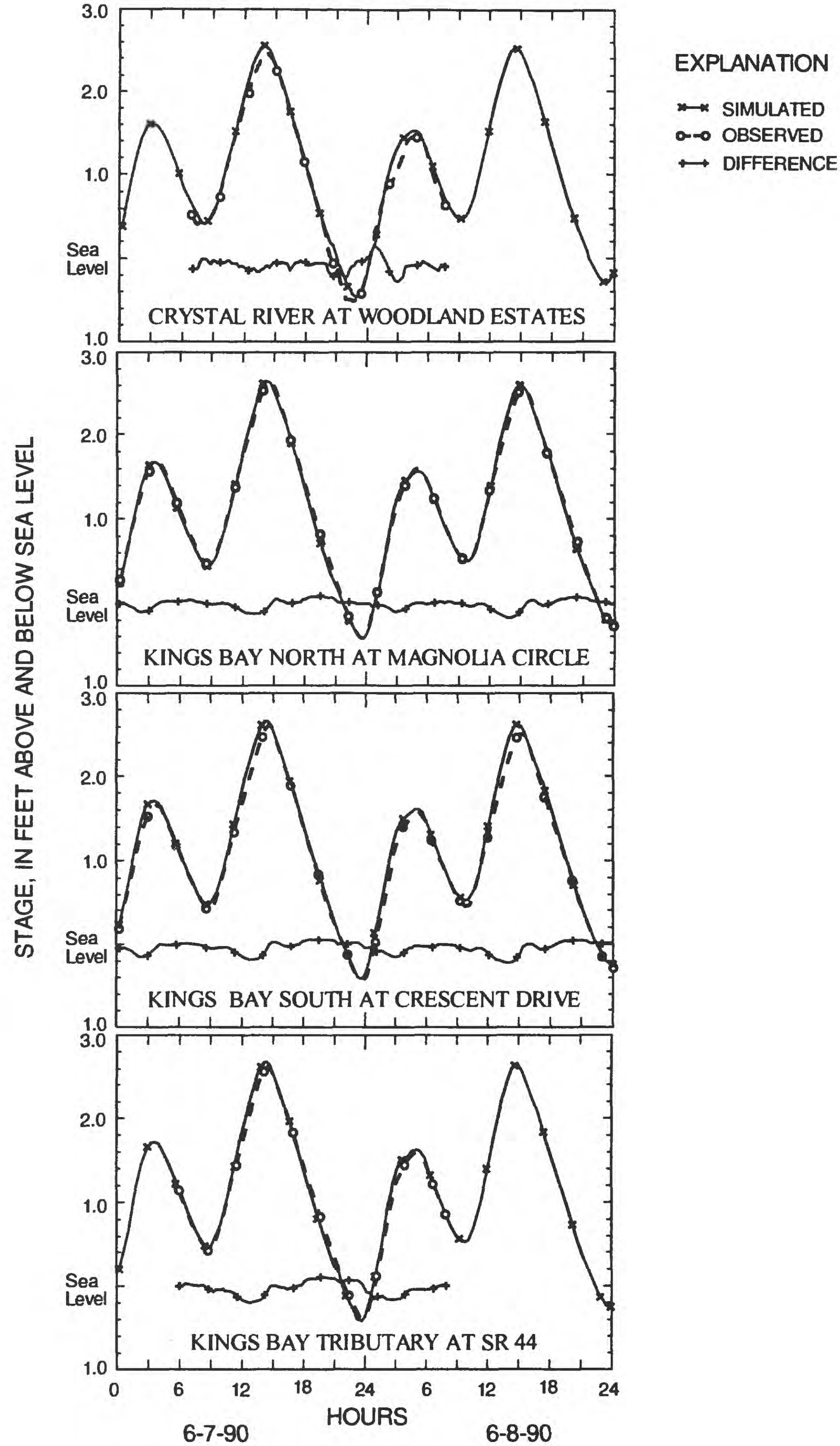



Figure 10. Simulated and observed tidal stage for the calibration period at four measurement sites.

of the range in stage at the measurement sites. Stage is generally the easiest hydrodynamic characteristic to simulate, and the graphical and statistical presentations in figure 10 and table 3 indicate excellent agreement between simulated and observed stage data during the calibration period.

Simulated and observed discharges at three sites for the calibration period are presented in figure 11, and statistical summaries are presented in table 4. Because of the different orders of magnitude of discharge at the three sites, the nominal standard errors provide the most meaningful comparison, ranging from 8 to 14 percent.

Simulated and observed velocity readings were limited because of the previously described malfunctions at two of the four velocity sites. Plots of the east-west components of the simulated and observed velocities for the two submersible velocity meters are presented in figure 12. The plots show that the simulated velocities have the same general shape as the observed velocities, but that individual observed velocities are much more variable than the simulated velocities. Observed velocities at the site north of Buzzard Island (site 12, fig. 3) may have been affected by Hydrilla that grew at the site over the period of deployment, as noted in the previous discussion of data collection.

Table 4. Statistical comparison of simulated and observed discharge for the calibration period

[$ft^3/s$, cubic feet per second]

| Site number[1] | Site name | Standard error[2] ($ft^3/s$) | Nominal error[3] dimensionless |
|---|---|---|---|
| 3 | Hunter Spring Run at Beach Lane at Crystal River (02310743) | 32 | 0.14 |
| 4 | Kings Bay at Kings Bay Drive bridge at Crystal River | 34 | .08 |
| 5 | Crystal River at Woodland Estates at Crystal River | 1,220 | .11 |

[1]Site locations are shown in figure 3.

[2]Standard error $= \frac{\Sigma \left| \text{computed} - \text{measured} \right|}{\text{number of observations}}$

[3]Nominal error $= \frac{\text{standard error}}{\text{range of observations}}$, dimensionless

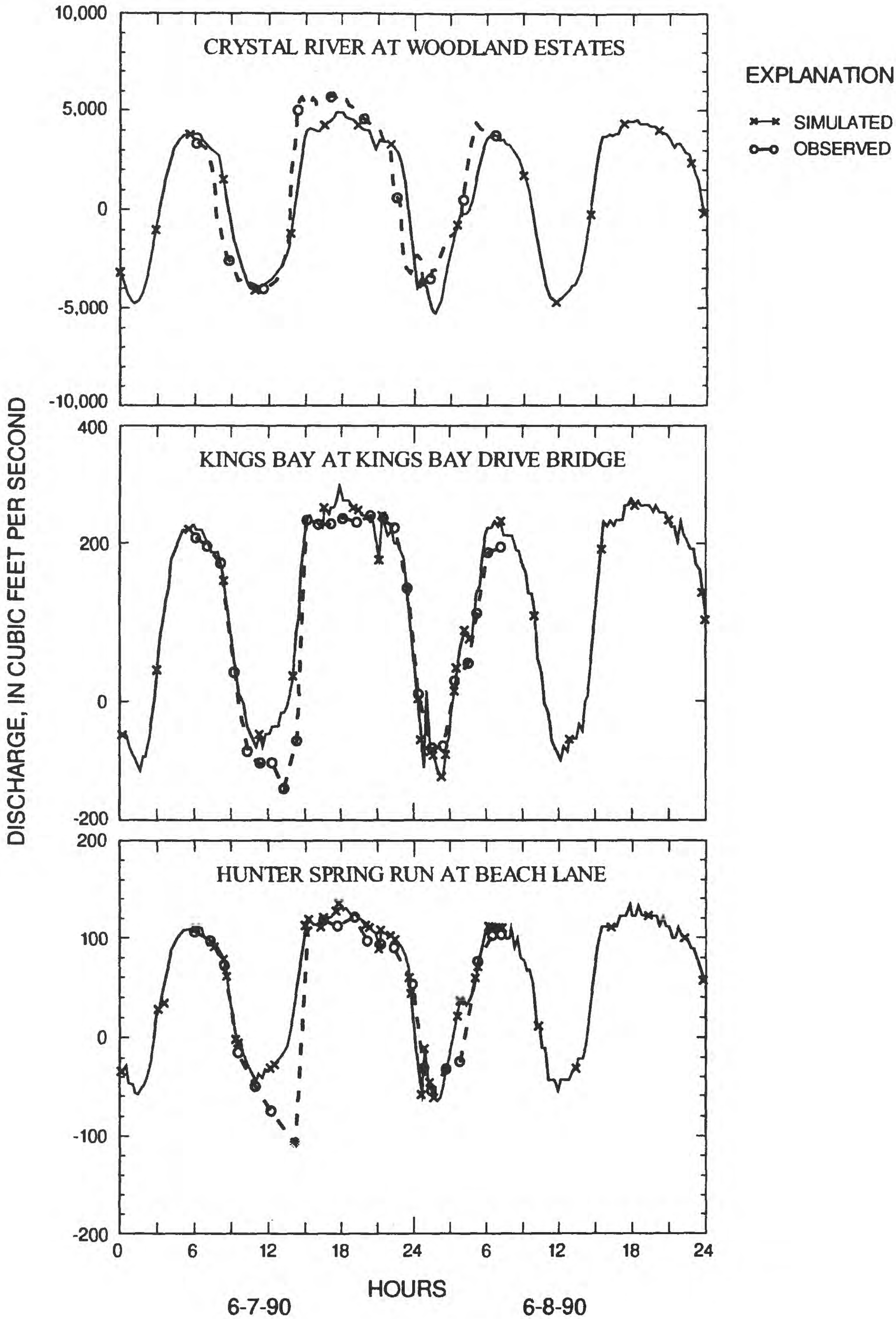



Figure 11. Simulated and observed discharge for the calibration period at three measurement sites.

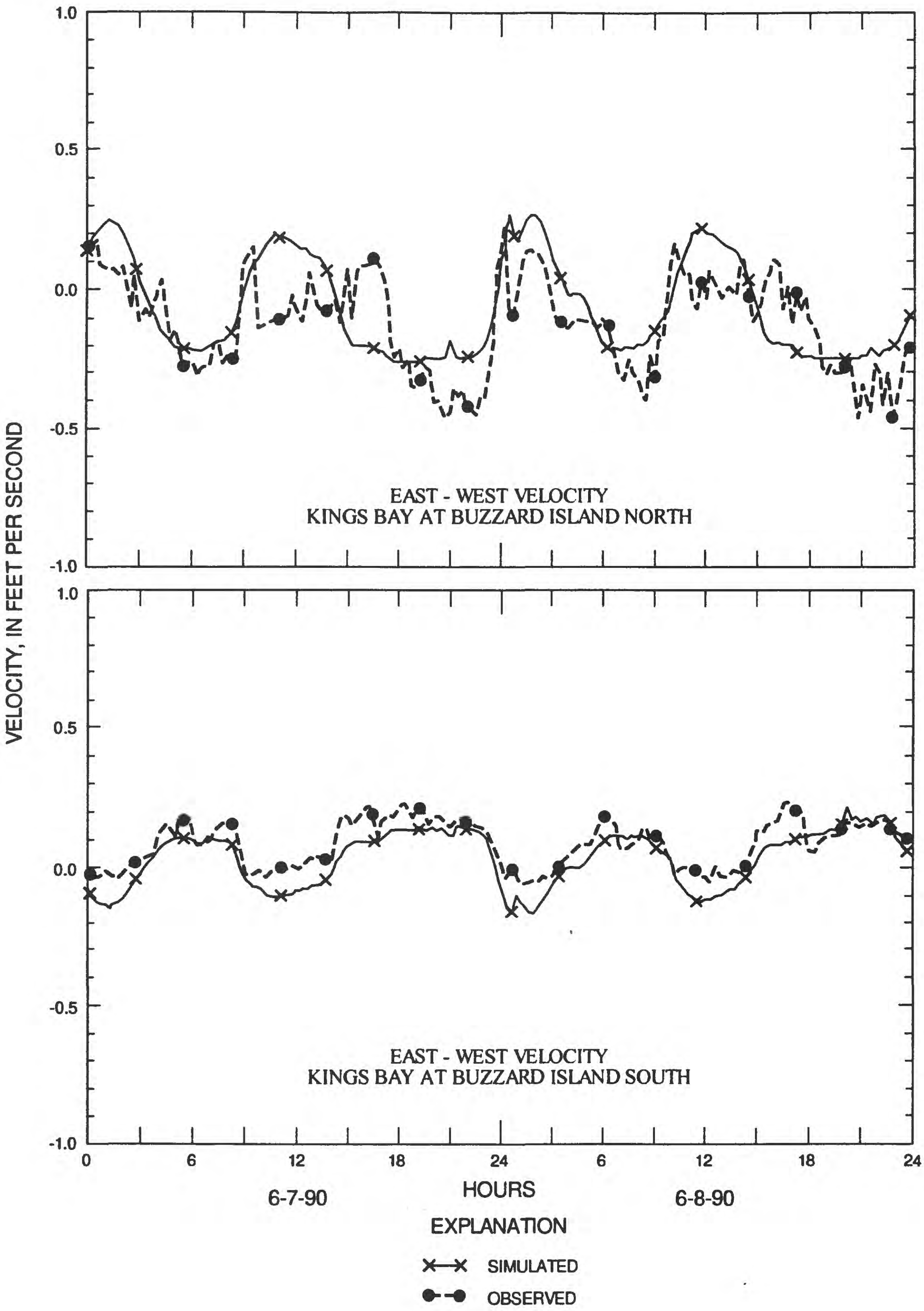



Figure 12. Simulated and observed velocity for the calibration period at two measurement sites.

Generally, salinity is considered the most difficult characteristic to simulate accurately with a hydrodynamic model. Observed and simulated salinities at four sites are shown in figure 13. Simulated and observed salinities were most closely matched at Crystal River at Woodland Estates (site 5, fig. 3), where the water is a mixture of waters of varying salinities from throughout the bay. At Kings Bay Drive bridge and the sites east and west of Buzzard Island, the differences between observed and simulated values are less than 0.5 ppt for most of the calibration period, and the water is virtually fresh.

Tidal stage at two tidal-stage measurements sites and velocity at two velocity measurement sites for the verification period are presented in figures 14 and 15, respectively. The ability of the model to simulate stage and velocity at the measurement sites for the verification period is about the same as for the calibration period.

## TIDAL-FLOW AND CIRCULATION CHARACTERISTICS

Tidal-flow and circulation characteristics of Kings Bay and Crystal River were evaluated by simulating three different hydrologic conditions--low inflow, typical inflow, and low inflow with reduced bottom friction. The low inflow conditions during the tidal-cycle measurements in June 1990 were simulated by distributing the discharge of 735 $ft^3/s$ among the springs as previously discussed. The typical inflow is 975 $ft^3/s$ (Yobbi and Knochenmus, 1989), and the discharges used for the low-inflow simulation were increased by a factor of 1.3 for the typical inflow simulation. Low-friction conditions with no Hydrilla were simulated for low spring inflow by replacing the spatially varying Manning's roughness coefficient with a constant value of 0.024 in an attempt to represent a sandy bottom covered by eel grass, which was historically characteristic of Kings Bay. Hydrilla, which can grow from mud-line up to the water surface, was assumed to affect the flow characteristics only by changing the friction coefficient. The direct effect of the physical presence of Hydrilla, which could, for example, reduce the effective flow depth, was not considered. With the exception of spring inflow and bottom friction, the physical and hydrologic conditions for the three application simulations were identical. The application simulations were performed for the same 5-day time period and with the same tidal-boundary

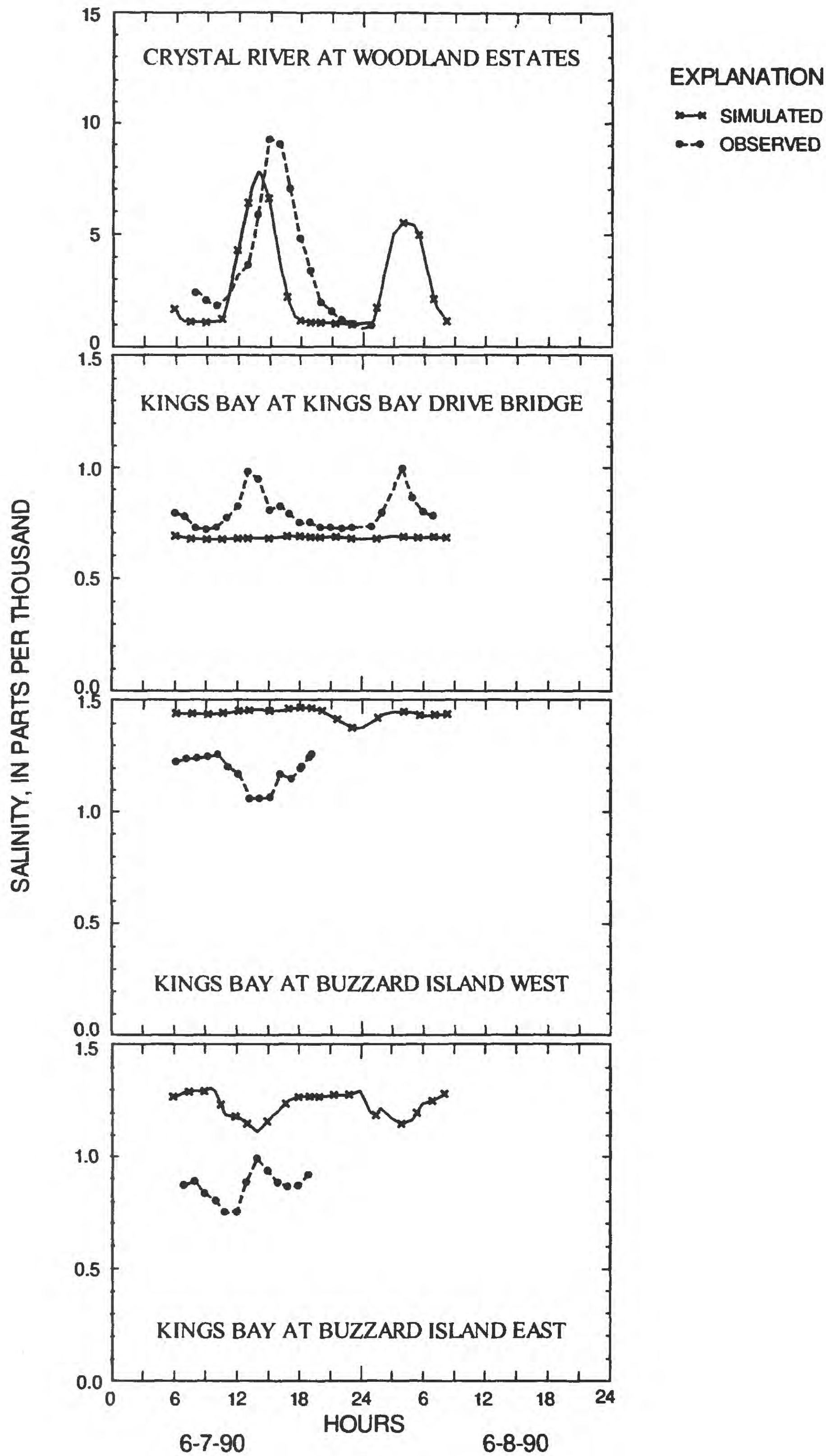



Figure 13. Simulated and observed salinity for the calibration period at four measurement sites.

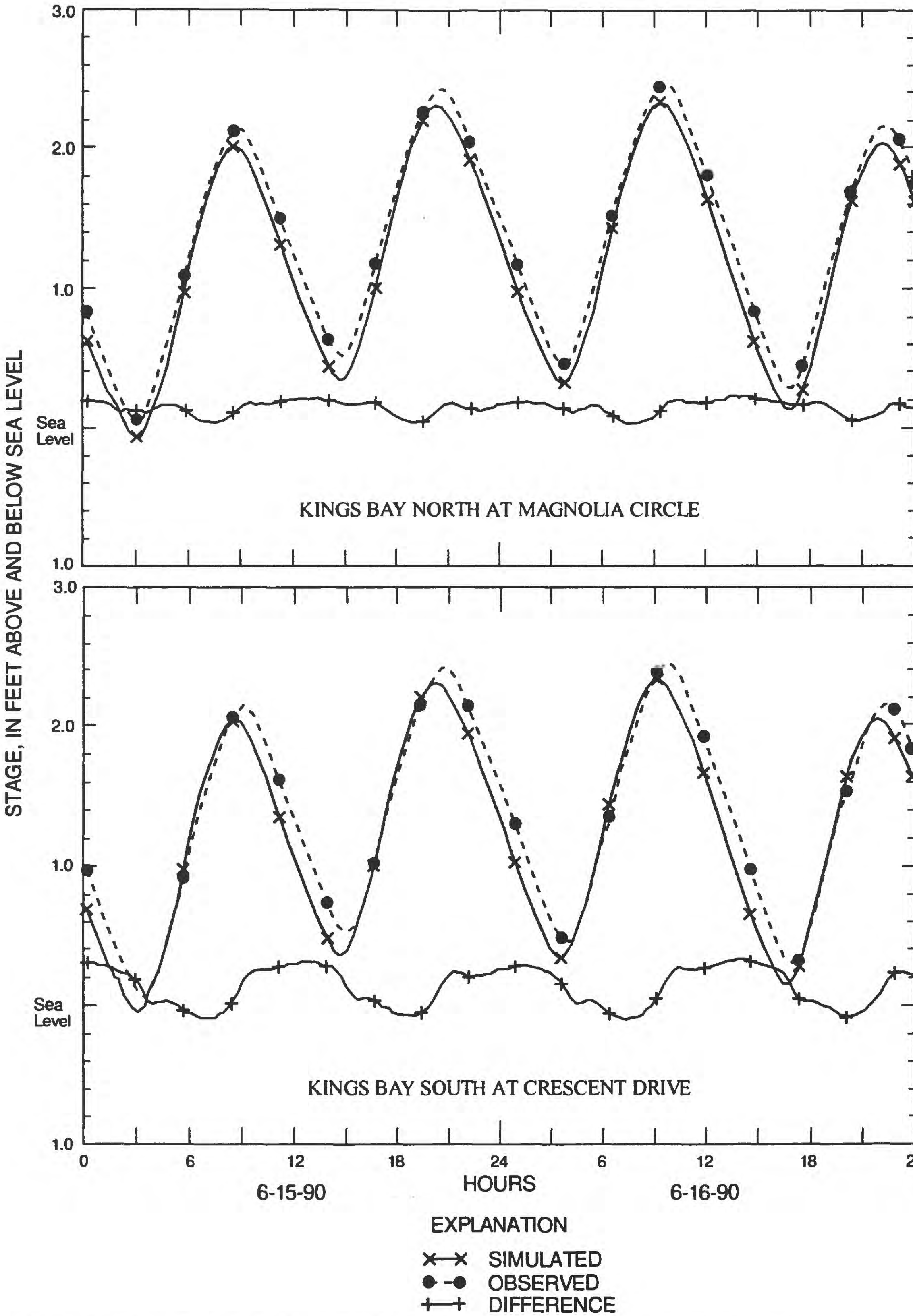



Figure 14. Simulated and observed tidal stage for the verification period at two measurement sites.

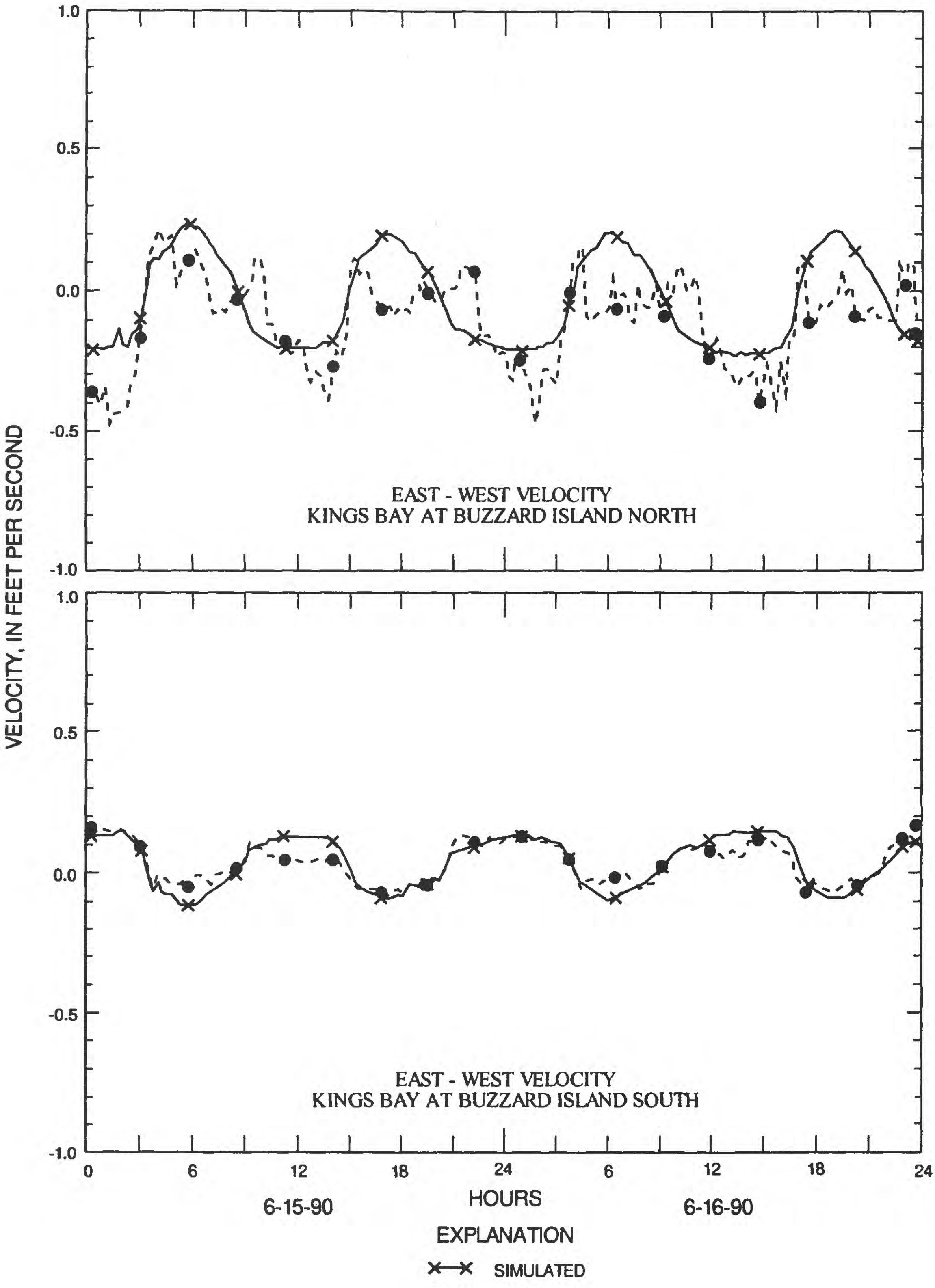



Figure 15. Simulated and observed velocity for the verification period at two measurement sites.

conditions as used for the calibration simulation. The application simulations included Lagrangian particles to determine the circulation patterns and several conservative constituents to determine the flushing characteristics of Kings Bay.

## Lagrangian Particle Analysis

One of the objectives of this study was to use the model results to describe the tidal-flow and circulation characteristics of Kings Bay. Tidal motion is the immediately apparent water motion in an estuary, but the tidal motion masks the net water motion, which is typically much smaller than the tidal motion (Cheng and Casulli, 1982). The net water motion is often called the residual circulation or nontidal circulation. Residual circulation drives long-term transport in an estuary, which is an important factor for determining the water quality and ecological health of an estuary (Cheng and Casulli, 1982). Residual circulation can be calculated with either the Eulerian or the Lagrangian approach.

The Eulerian approach determines a nontidal average velocity at the model grid points by averaging the simulated velocities over a period of time that is longer than the tidal periods of interest (Goodwin, 1987). The result is an Eulerian average or residual velocity for which oscillatory tidal fluctuations are removed. An Eulerian residual velocity is current-meter data that are averaged over a period of time. Eulerian residual velocities are a useful method for comparing measured velocities to simulated velocities (Cheng and Casulli, 1982).

The Lagrangian approach tracks a fluid particle as water velocity moves it through an estuary. Simulated Lagrangian particle tracks or residual velocities are not the same as measured or simulated Eulerian residual velocities (Cheng and Casulli, 1982; Ridderinkhof and Zimmerman, 1990). Eulerian analysis can determine only residual velocities at fixed points, whereas Lagrangian analysis is based upon a reference frame that moves at the same rate as the water velocity. Lagrangian particle tracks represent the transport process of advection, or transport by the water velocity, but do not represent the transport process of dispersion (Schoellhamer and Jobson, 1986). The displacement of water mass and constituents in the water is a Lagrangian phenomenon, so Lagrangian particle analysis was used to present the simulation results.

Lagrangian particles were added to each of the three 5-day application simulations. Particles were injected at 10 sites (fig. 16) every hour during the second day of the application simulations. A total of 240 particles were injected during each application simulation. The particles were transported in the model domain based upon the simulated water velocities.

The track of an example particle (144) injected at site 4 (fig. 16) during the low inflow simulation at 1500 hours on June 7, 1990, is shown in figure 17. The line connects the hourly particle positions and represents the particle track. Symbols are plotted along the track at 24-hour intervals after injection. The southeastern symbol is at the injection site and the western symbol is at the location where the particle exited through Crystal River. The particle was injected during an ebbtide, was moved seaward and landward by the tides as it generally moved to the northwest, and exited the model domain through Crystal River.

Several particle tracks are presented to convey the major circulation features of the estuary. The particle track can cross over land, as shown in figure 16, a result of connecting hourly positions, but the simulated particle does not actually move over land. Velocity information was not available for areas outside the model domain, so the particle position could not be determined once the model boundary was reached. The tracks that are presented were terminated when the particle reached the model boundary (fig. 8).

Limitations of the model and of particle injection need to be considered when interpreting Lagrangian particle tracks. The particle tracks are only as accurate as the simulated depth-averaged velocities. If the simulated depth-averaged velocities are inaccurate or if depth averaging is not appropriate, the particle tracks will not be accurate. At shorelines, the model prohibits flow perpendicular to the shoreline (cross-shore flow) and permits only tangential (or longshore) flow. Thus, particles that are close to a shoreline may tend to travel parallel to the shoreline for an unreasonably long period of time. Finally, Lagrangian particle tracks are sensitive to the time of injection and initial position (Ridderinkhof and Zimmerman, 1990).

## Low-Inflow Conditions During June 1990

Most of the injected particles remained in Kings Bay and Crystal River less than 96 hours for the low-inflow conditions. Of the 240 particles that were injected during the second day of simulation time, 212 exited the model

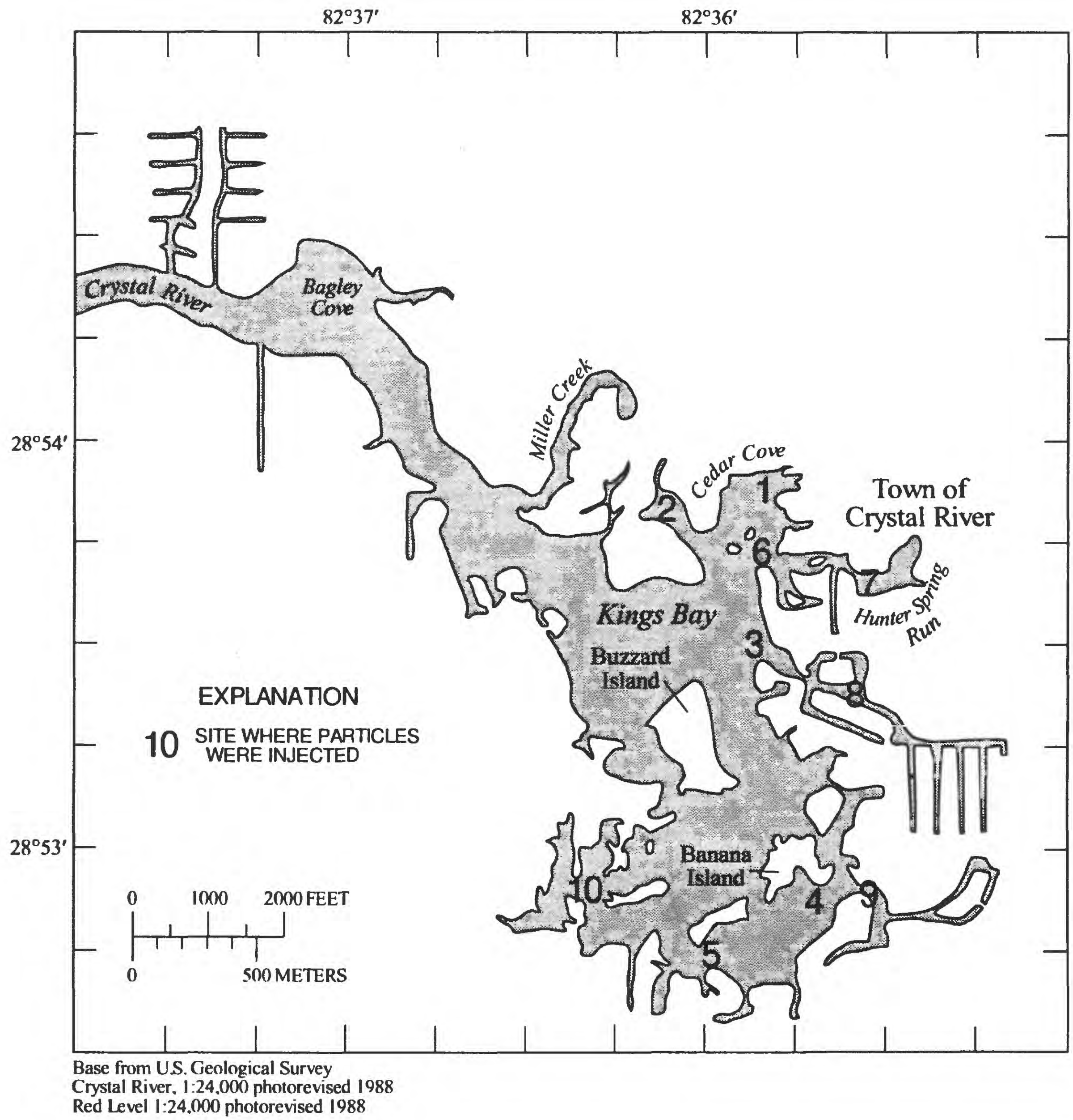



Figure 16. Location of particle injection sites.

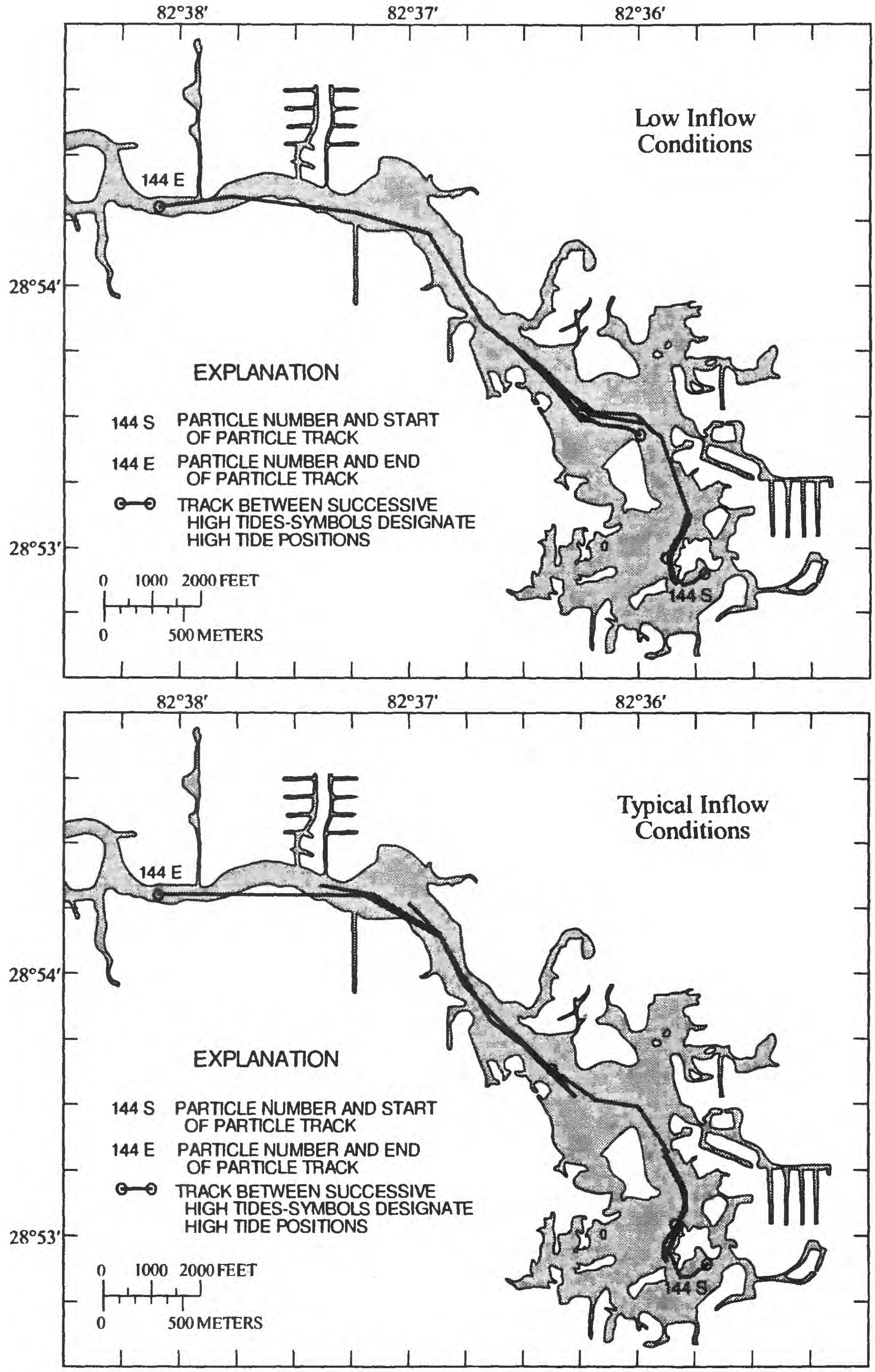



Figure 17. Tracks for particle 144 for low- and typical-inflow conditions.

domain by the end of the fifth day of simulation time. The remaining particles were close to shorelines and seemed to be trapped because the velocity component perpendicular to shorelines was zero. The average residence time of the particles that exited was about 59 hours (table 5). The particles were transported out of the model domain by a seaward residual current caused by the spring discharge.

Table 5. Particle residence times in Kings Bay and Crystal River for three different hydrologic conditions

| Particle number | Low inflow (hours) | Typical inflow (hours) | Low inflow and lower friction (hours) |
|---|---|---|---|
| 144 | 57 | 54 | 57 |
| 148 | 31 | 29 | 31 |
| 175 | 76 | 51 | 76 |
| Mean of all that exited | 59 | 50 | 56 |

Particles injected relatively far from the mouth of Crystal River exited the model domain by the end of the fifth day of simulation time. After injection, particle 144 (fig. 17) moved to the northwest into Crystal River with some modulation by the tides, and exited the model 57 hours after injection (table 5). Particle 148 (fig. 18) was injected at high tide (simulation time 1500 hours on June 7), entered Crystal River before the next low tide, returned no farther landward than the center of Kings Bay during succeeding high tides, and exited the model domain 31 hours after injection. Particle 175 (fig. 19) was injected at peak ebbflow (simulation time 1800 hours on June 7), moved toward the mouth of Crystal River with some modulation by the tides, and exited the model domain 76 hours after injection.

Particles usually exited the model domain within 24 hours of entering Crystal River. Particles 144 (fig. 17), 148 (fig. 18), and 175 (fig. 19) are examples of particles that remained in Crystal River less than 24 hours. The symbols in figures 17 through 19 indicate the injection site, the particle positions at 24-hour intervals after injection, and the exit point. Injected particles that remained in Crystal River longer than 24 hours were trapped along the shoreline of the river; thus, water in Crystal River is rapidly (less than 24 hours) transported to the Gulf of Mexico.

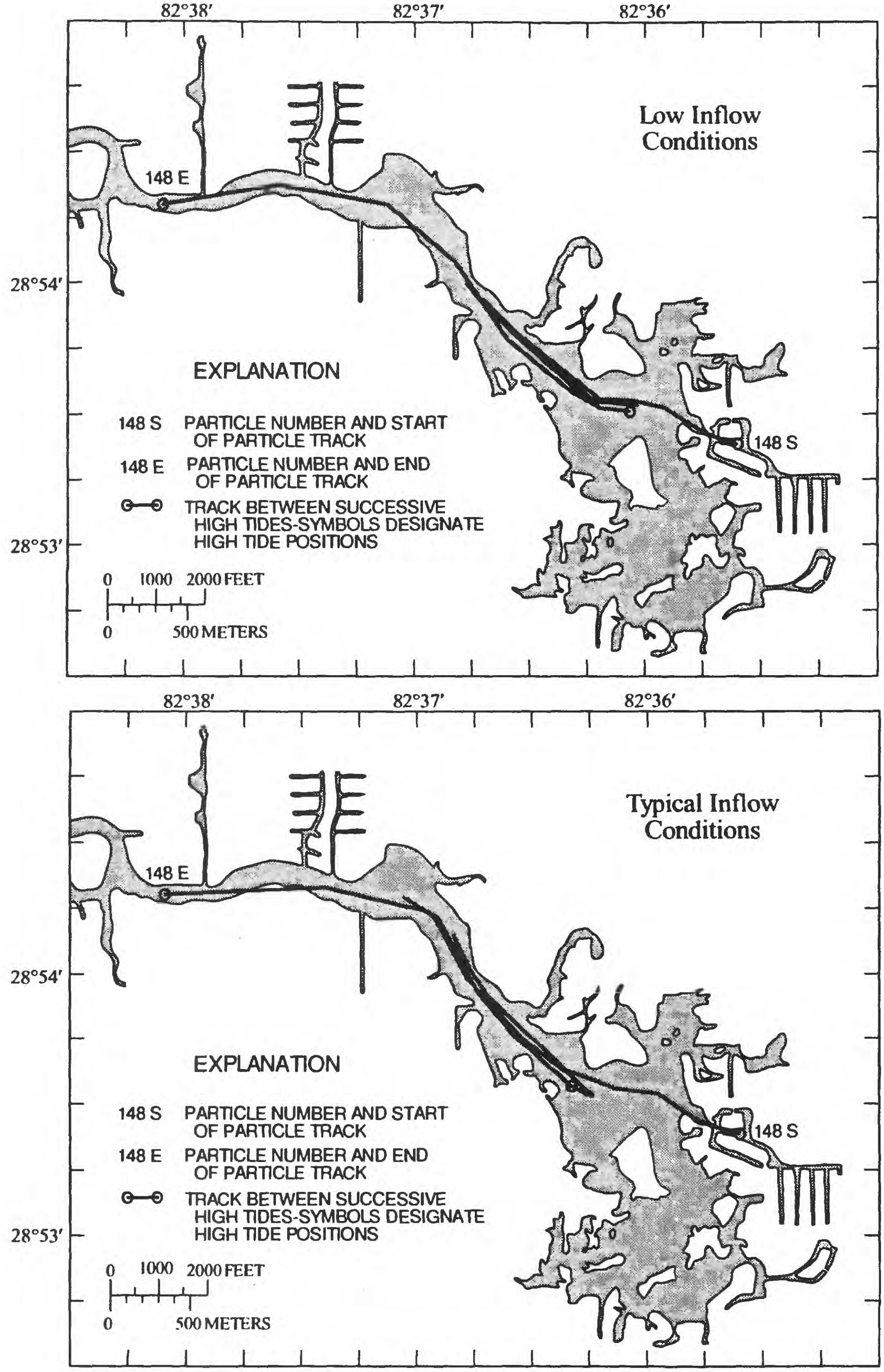



Figure 18. Tracks for particle 148 for low- and typical-inflow conditions.

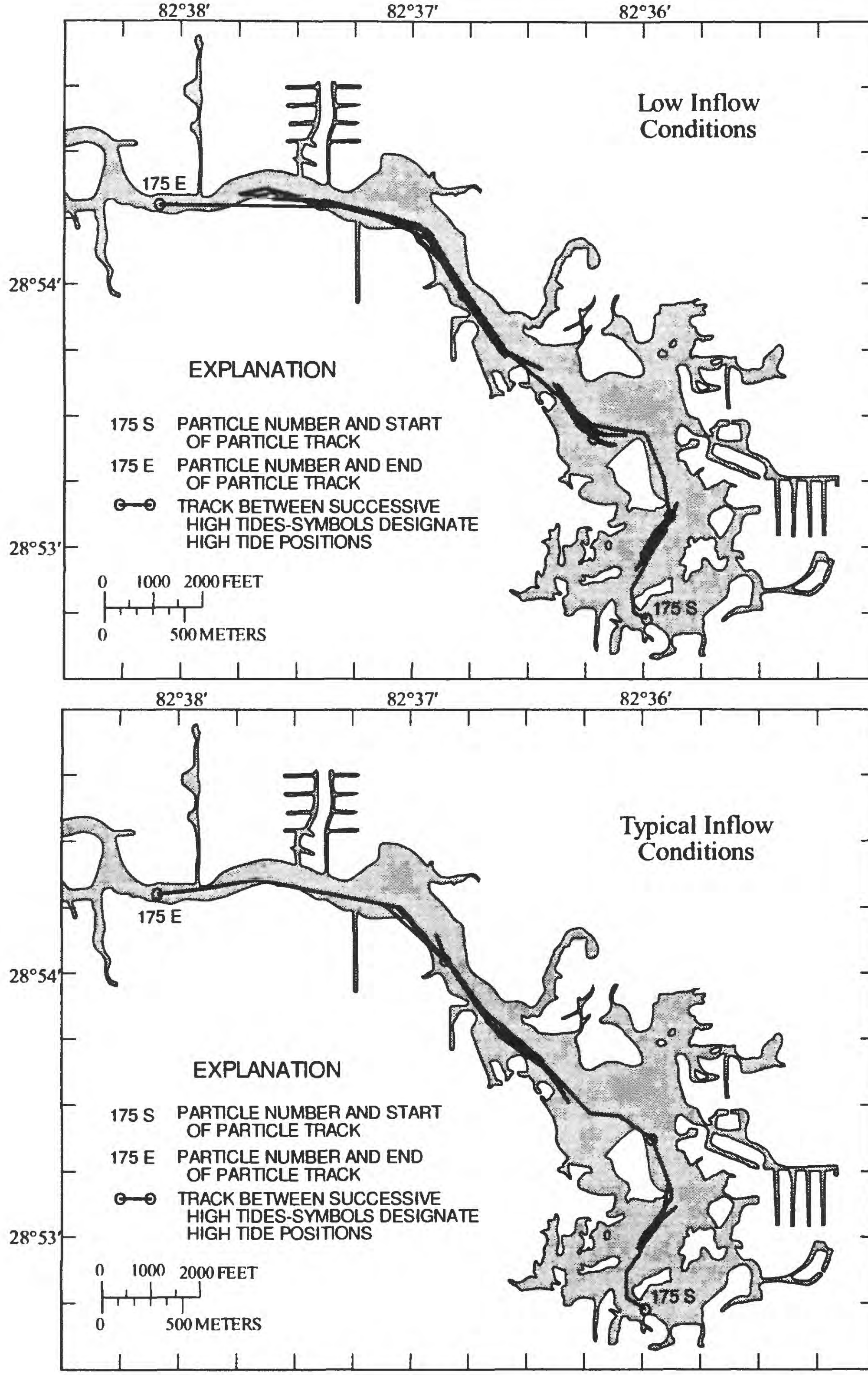



Figure 19. Tracks for particle 175 for low- and typical-inflow conditions.

Spring discharge creates a residual flow toward the Gulf of Mexico in all parts of Kings Bay and the tides modulate the particle tracks. For low-inflow conditions, 212 of 240 particles that were injected during the second day of simulation time exited the model domain by the end of the fifth day of simulation time; the average residence time was 59 hours. The particle tracks proceeded toward Crystal River and the Gulf of Mexico with modulation by the tides. Particles injected south of Buzzard Island moved north along the eastern side of the island and usually exited the model within 24 hours of entering Crystal River.

## Differences Due to Typical Inflow Conditions

Most of the injected particles had smaller residence times in Kings Bay and Crystal River for typical inflow conditions than for low-inflow conditions. Of the 240 particles that were injected during the second day of simulation time, 218 exited the model domain by the end of the fifth day of simulation time. The average residence time of the particles that exited was 50 hours (table 5). The particles were transported more rapidly to the model boundary by a larger seaward residual current caused by the larger simulated spring discharge.

Particle tracks for typical inflow conditions are similar to the tracks for low-inflow conditions. The tracks for particles 144, 148, and 175 during typical inflow conditions are shown on figures 17, 18, and 19, respectively, below the particle tracks for low inflow conditions. Similar to low-inflow conditions, typical inflow created a residual flow toward the Gulf of Mexico in all parts of Kings Bay, and tides modulated the particle tracks. Particles injected south of Buzzard Island for typical inflow conditions moved north along the eastern side of the island and usually exited the model domain within 24 hours of entering Crystal River.

The larger spring discharge for typical inflow conditions increased the seaward residual flow. The position of particle 144 at 24 and 48 hours after injection was more seaward for typical inflow conditions than for low-inflow conditions (fig. 17). Particle 144 exited the model domain 54 hours after injection for typical inflow conditions, whereas it exited 57 hours after injection for low-inflow conditions (table 5). Particle 148 (fig. 18) and particle 175 (fig. 19) also were more seaward and exited more rapidly for typical inflow conditions because of the increased spring discharge.

## Differences Due to Lower Bottom Friction with no Hydrilla Verticillata

Simulation results for low-inflow conditions did not change as a result of uniformly reducing roughness coefficients to reflect the lower bottom friction that would exist if Hydrilla were not present. Of the 240 particles that were injected during the second day of simulation time, 212 exited the model domain by the end of the fifth day of simulation time. The remaining particles were close to shorelines and seemed to be trapped because the velocity component perpendicular to shorelines is zero. The average residence time of the particles that exited was 56 hours (table 5). The particle tracks for lower bottom friction and low inflow are not shown because they are virtually the same as those shown for low inflow in figures 17 through 19. The residence times of particles 144, 148, and 175 were virtually the same for the two low-inflow conditions; therefore, lower bottom friction does not significantly affect the circulation or residence times of Kings Bay.

# FLUSHING CHARACTERISTICS

Simulation of conservative constituent motion in the estuary was considered necessary to satisfy the study objective of determining flushing characteristics. A conservative constituent does not decay with time or react with other constituents, so the transport of a conservative constituent is determined by the processes of advection and dispersion. Advection is the movement of a constituent with the mean water velocity, and dispersion is the tendency of a constituent to spread due to water velocity fluctuations about the mean velocity. In the previous section, the residual circulation was determined by studying the advective characteristics of discrete Lagrangian water particles. Simulation of conservative constituents is better suited for determining flushing characteristics than non-conservative constituents because the conservative constituents can be injected uniformly in a subarea of the estuary instead of at discrete points. The process of dispersion is included in the constituent transport equation (eq. 5).

Each simulation included four independent conservative constituents. One constituent was salinity, which was used to determine water density (eq. 9) and baroclinic effects. The other three constituents, called layers in the model documentation, were conservative dyes originating from three different locations in the bay. The first layer consisted of dye originating at grid points where spring discharge was input and was used to determine the rate at which Kings Bay would be flushed by water from the springs. The second layer simulated dye from the Crystal River sewage-treatment plant and was used to determine how discharge from the plant is flushed from the estuary. The third layer was dye originating in the southeastern corner of the bay and was used to determine the flushing characteristics of a part of the estuary relatively far from the Gulf of Mexico.

Each constituent, or layer, had different initial concentrations and spring discharge concentrations. For some of the layers, initial concentrations throughout most of the bay were set at 10.0 units (which can be interpreted as a mass per unit volume, such as milligrams per liter or parts per thousand), and injected dye was given a concentration of 0.0 unit. For other layers, initial concentrations in the bay were set at 0.0 unit, and injected dye was 10.0 units. To reduce the possibility of numerical instability caused by discontinuous dye distribution, several rows or columns of model cells were assigned initial concentrations so that the distribution gradually changed from 10.0 to 0.0 units.

During the simulations, the concentrations of water entering the model domain from the western model boundary in Crystal River were specified. When water was leaving the model domain at the Crystal River boundary, the model stored the concentrations of the exiting water at each grid cell. The concentrations for up to 300 minutes of simulation time were stored, and concentrations of water that exited more than 300 minutes prior to the current simulation time were discarded. When water reentered the model domain, the concentration of the incoming water was determined by reversing the order of the stored concentrations at each grid cell. This approach returns water to the model domain during approximately the first 300 minutes of a floodtide with the same concentration it had when it left the model domain during the preceding ebbtide. After about 300 minutes, a concentration of 10.0 units was assumed at the inflow open boundary for the salinity layer, and a concentration of 0.0 unit was assumed for the other dye layers.

The dye concentration in Kings Bay probably was not sensitive to the open boundary dye concentration because the floodtide did not advect particles from the open boundary into Kings Bay. Particle 175, for example, was near the open boundary at a low tide for low-inflow conditions (fig. 19). During the following floodtide, the particle traveled upstream only as far as Miller Creek and did not enter Kings Bay; thus, dye introduced at the open boundary was not advected into Kings Bay during floodtide. The simulated dye concentrations in Kings Bay probably were more sensitive to the distribution of spring discharges.

The total mass and average cell concentration were computed every hour of simulation time for each constituent in each of 8 subareas (fig. 20) of the model grid and for the entire bay (subareas 1 through 8). Simulation results are presented as time series of the average concentration in the entire bay or selected subareas. Average concentrations were computed as the sum of the concentrations in individual cells divided by the total number of cells in the subarea.

## Low-Inflow Conditions During June 1990

The first layer of dye originating from spring vents was used to determine the rate at which Kings Bay would be flushed by water from the springs. The initial dye concentration throughout most of the bay was set at 10.0 units, and the concentration of dye from the spring discharges was equal to 0.0 unit. Thus, the reduction in dye mass with time as the simulation progressed indicated the flushing rate of the bay by the springs. Within 94 hours, more than 95 percent of the 10.0-unit background concentration of the bay was flushed out by the 0.0-unit concentration discharge being injected from the springs (fig. 21). The average concentration of dye throughout Kings Bay decreased exponentially with some modulation. The exponential decrease was caused by flushing from the spring discharge, and the modulation was caused by advection of dye between Kings Bay and Crystal River as a result of floodtides and ebbtides.

Dye from the sewage-treatment plant was used to determine how discharge from the plant is flushed from the estuary. The initial concentrations throughout the bay were set to 0.0 unit. The spring discharge concentrations were also set equal to 0.0 unit. Two discharge sources that represent the canal system that conveys the sewage-treatment plant discharge to Cedar Cove were set equal to 10.0 units. The dye injected in this manner produced concentrations that had nearly reached equilibrium by the end of the 5-day (120-hour) simulation period (fig. 22). The average concentration throughout the bay increased asymptotically with some tidal modulation.

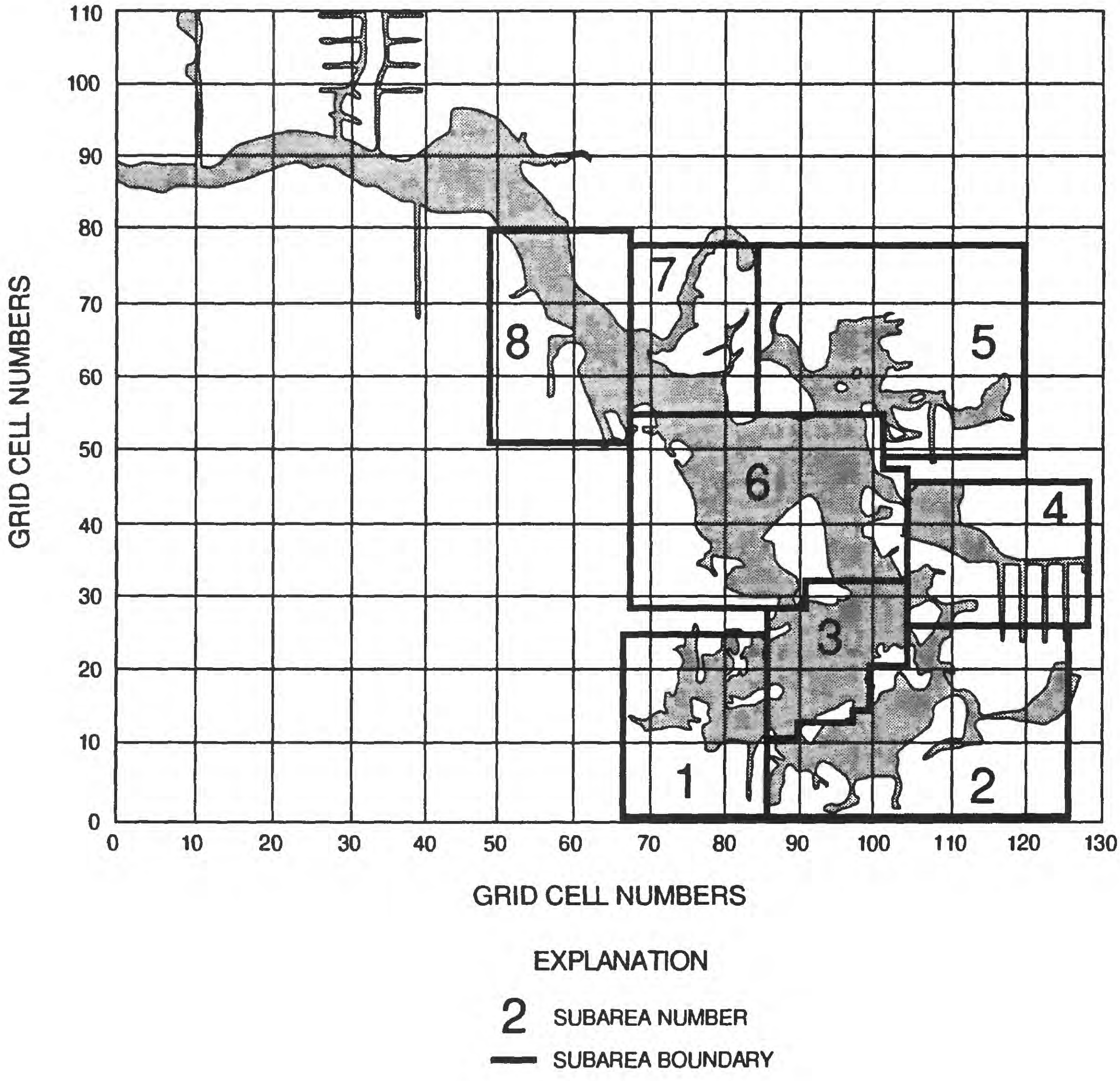



Figure 20. Subarea boundaries for simulated dye injections.

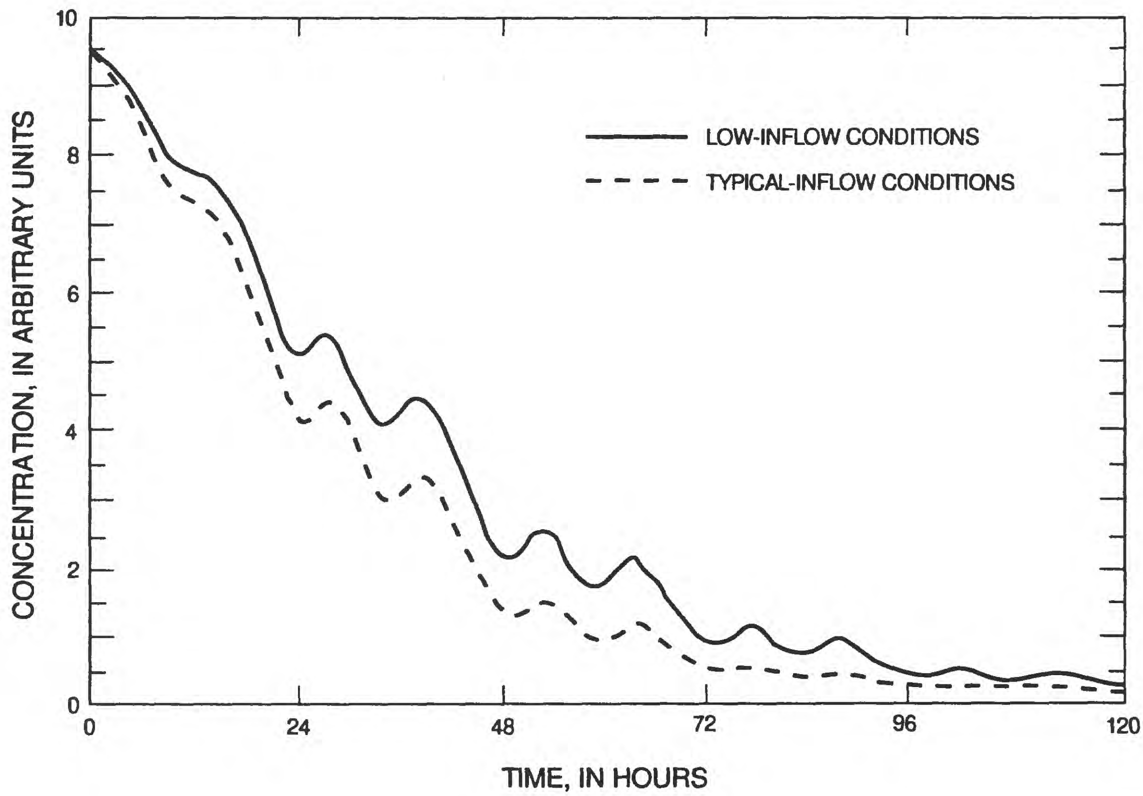



Figure 21. Average concentrations of dye in Kings Bay that resulted from dye originating in spring vents during low- and typical-inflow conditions.

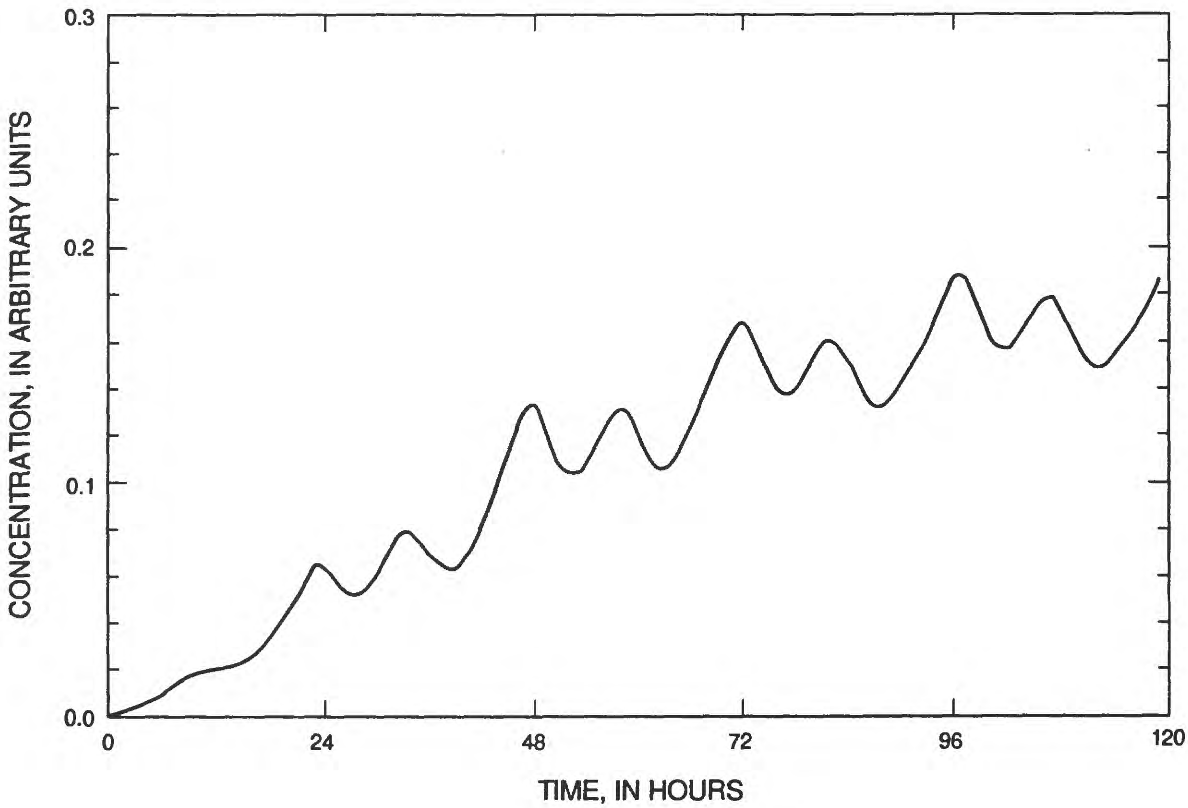



Figure 22. Average concentrations of dye in Kings Bay that resulted from dye originating from the sewage-treatment plant during low-inflow conditions.

The tidal variation of the distribution of dye originating from the sewage-treatment plant is shown in figures 23 and 24. At the last simulation high tide (1600 hours June 10), concentrations of injected dye east and west of Buzzard Island (fig. 23) were relatively low (less than 0.05 unit), and this dye was transported south from Crystal River during the preceding floodtide. The 1.0-unit contour was in northern Cedar Cove. At the last simulation low tide (2400 hours June 10), the 0.05-unit contour was in northern Kings Bay (fig. 24), and at least part of the 1.0-unit contour line moved south of Cedar Cove.

The dye originating in subarea 2 (fig. 20) in the southeastern corner of the model grid was used to determine the flushing characteristics of parts of the estuary relatively far from the Gulf of Mexico. The initial concentrations were set to 10.0 units where the dye originated and 0.0 unit elsewhere. The spring discharge concentration was 0.0 unit.

Although subarea 2 is relatively far from Crystal River and the Gulf of Mexico, 95 percent of the dye injected in that area was flushed from the area within 48 hours. The time series of average dye concentrations in subareas 2, 3, 6, and 8 (fig. 25) indicate that the dye moved north from the southeastern corner of Kings Bay to Crystal River. The concentration in the southeastern corner of the bay (subarea 2) decreased rapidly at the start of the simulation as dye moved north of Banana Island into subarea 3. Near the end of the first day of simulation, dye reached along Buzzard Island into the central part of Kings Bay (subarea 6) and also was present in Crystal River (subarea 8). After 48 hours, the concentration was greater in Crystal River than in the other subareas and was decreasing with time in all four subareas. The dye was being moved seaward by the residual flow from the springs, and the relatively low concentrations throughout subarea 2 indicate that all of the southeastern corner of the bay was being flushed by spring discharge. The tidal modulation of the dye concentrations also is apparent from figure 25.

Ninety-five percent of dye injected from the springs was transported out of the model domain through Crystal River during the 5-day low inflow simulation because of residual flow from the springs. Dye originating from the sewage treatment plant was transported as far south as Buzzard Island at high tide and into the central part of Kings Bay at low tide. Simulation results indicate that all of the open waters of Kings Bay, including the southeastern corner, were flushed by the spring discharge.

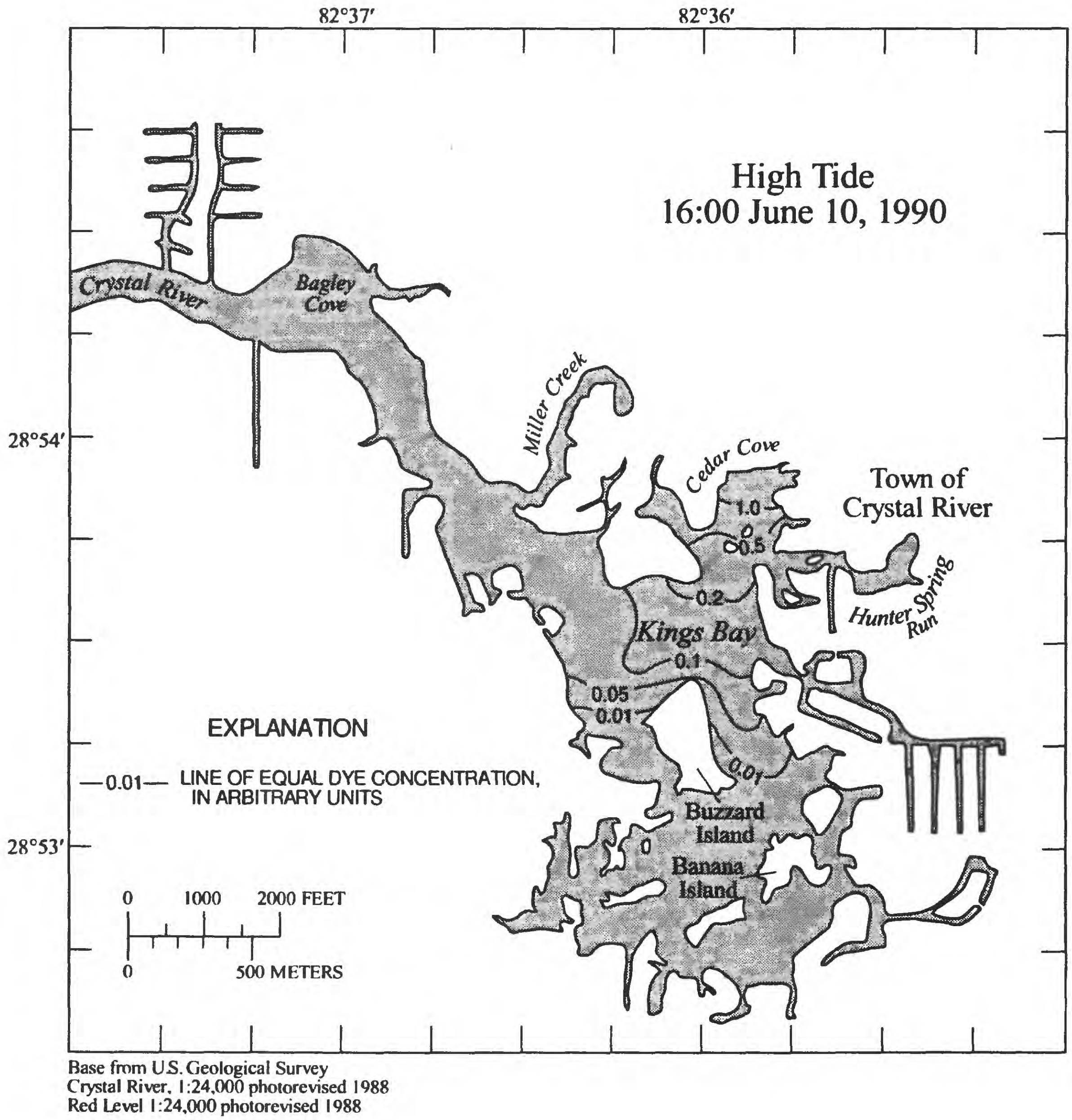



Figure 23. Distribution of dye originating from the sewage-treatment plant during high tide.

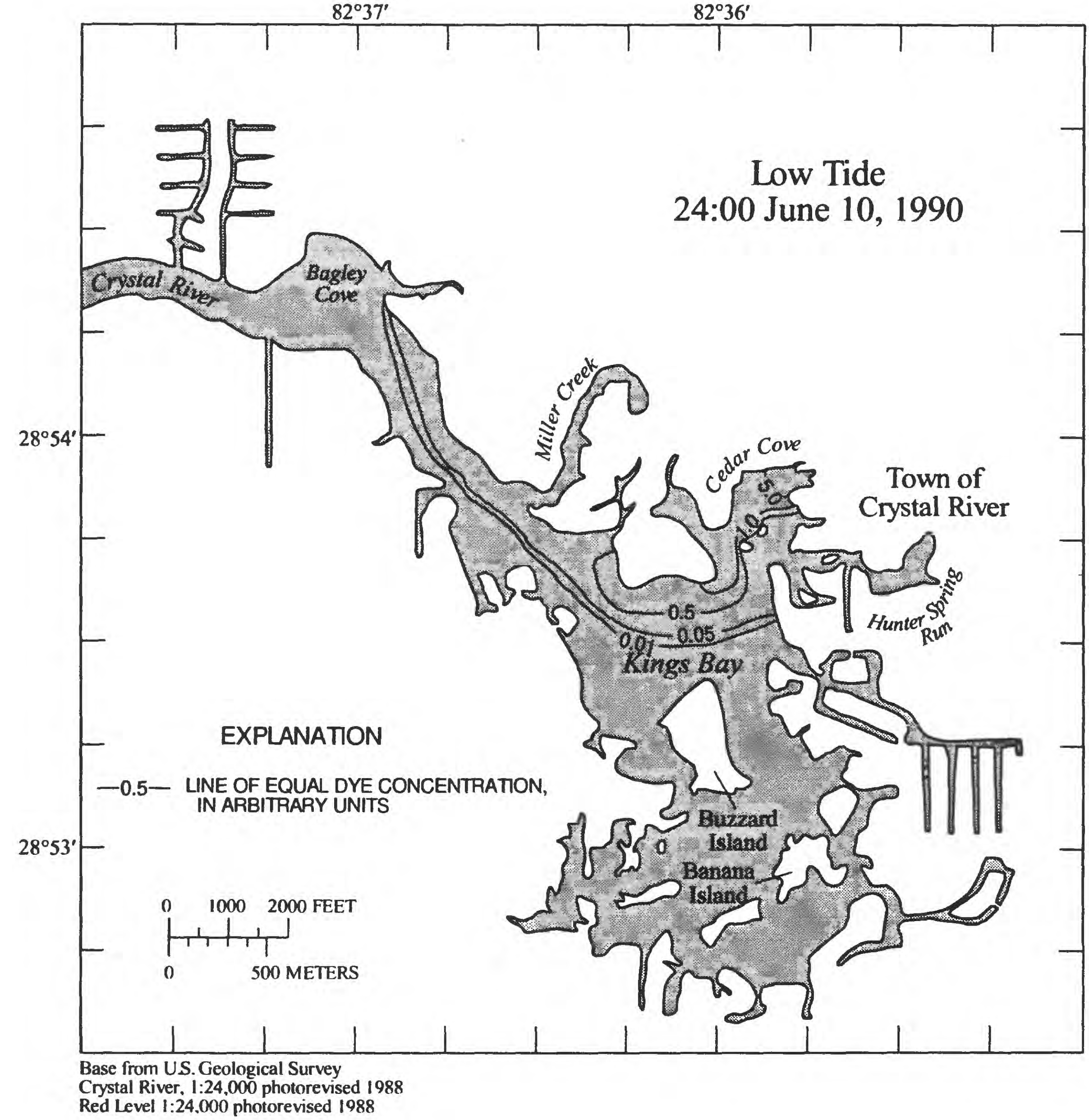



Figure 24. Distribution of dye originating from the sewage-treatment plant during low tide.

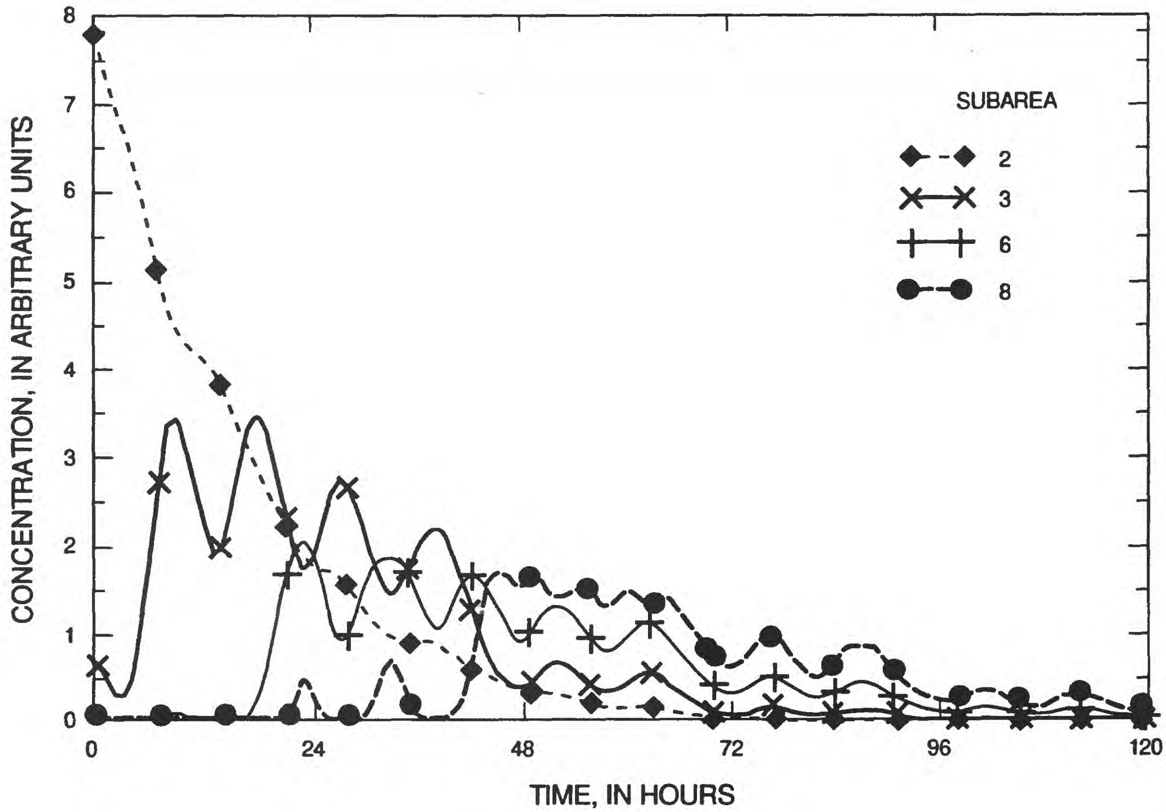



Figure 25. Average concentrations of dye in subareas 2, 3, 6, and 8 that resulted from dye originating in subarea 2 during low-inflow conditions.

## Differences Due to Typical Inflow Conditions

When spring discharges were increased by 30 percent to represent typical inflow conditions, 95 percent of the dye injected from the spring vents was flushed from the bay in 71 hours (fig. 21). Because it had taken 94 hours to flush the same volume of dye from the system during low-inflow conditions, a 30-percent increase in spring discharge decreased the flushing time by 25 percent. The average concentration of dye in Kings Bay also decreased more rapidly for typical inflow conditions than for low-inflow conditions because of increased flushing as a result of increased spring discharge. The mean, minimum, and maximum cell concentration differences between low and typical inflow conditions also indicate that concentrations are lower for typical inflow conditions (fig. 26). A positive difference indicates that the concentration is greater for typical inflow, and a negative difference indicates that the concentration is greater for low inflow. The average cell concentration for typical inflow is about 1.0 unit less than for low inflow on June 7-8, 1990. The spatial dye distribution patterns were about the same for the two inflow conditions, but the typical inflow concentrations were less.

## Differences Due to Lower Bottom Friction with No Hydrilla Verticillata

The model simulation with lower friction did not significantly affect the flushing of Kings Bay. Lower friction had virtually no effect on the average concentration of dye that resulted from dye originating from spring vents. The time series of concentration for lower friction is virtually identical to the low inflow condition time series shown in figure 21. The mean cell concentration differences between low inflow and low inflow with lower friction also indicate that concentrations are virtually identical (fig. 27). A positive difference indicates that the concentration is greater for lower friction. All of the maximum and minimum differences in cell concentrations are within about 2 units, and the mean concentration difference is virtually 0.0 unit. Therefore, the estimated change in the bottom friction that can result from removal of Hydrilla does not seem to significantly affect the flushing of Kings Bay, based upon the results of the model simulation.

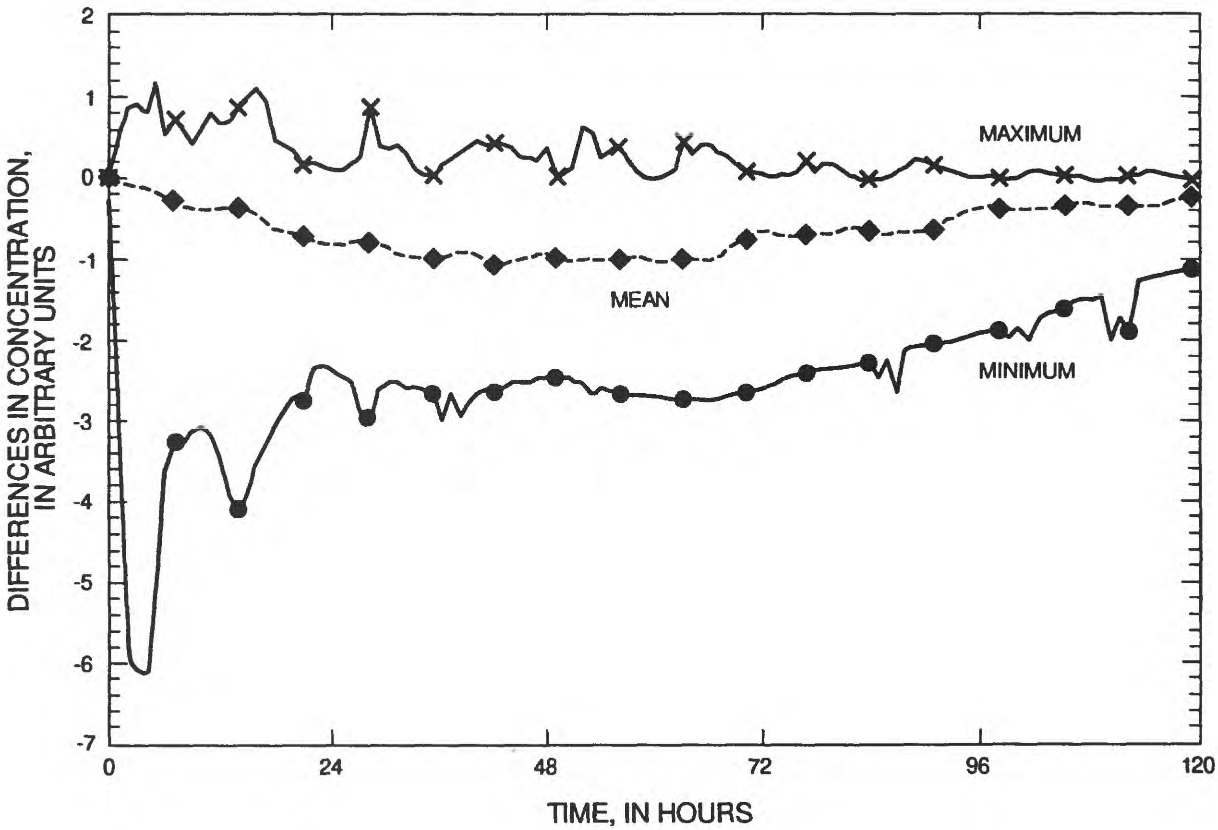



Figure 26. Differences in average cell dye concentrations in Kings Bay for low- and typical-inflow conditions.

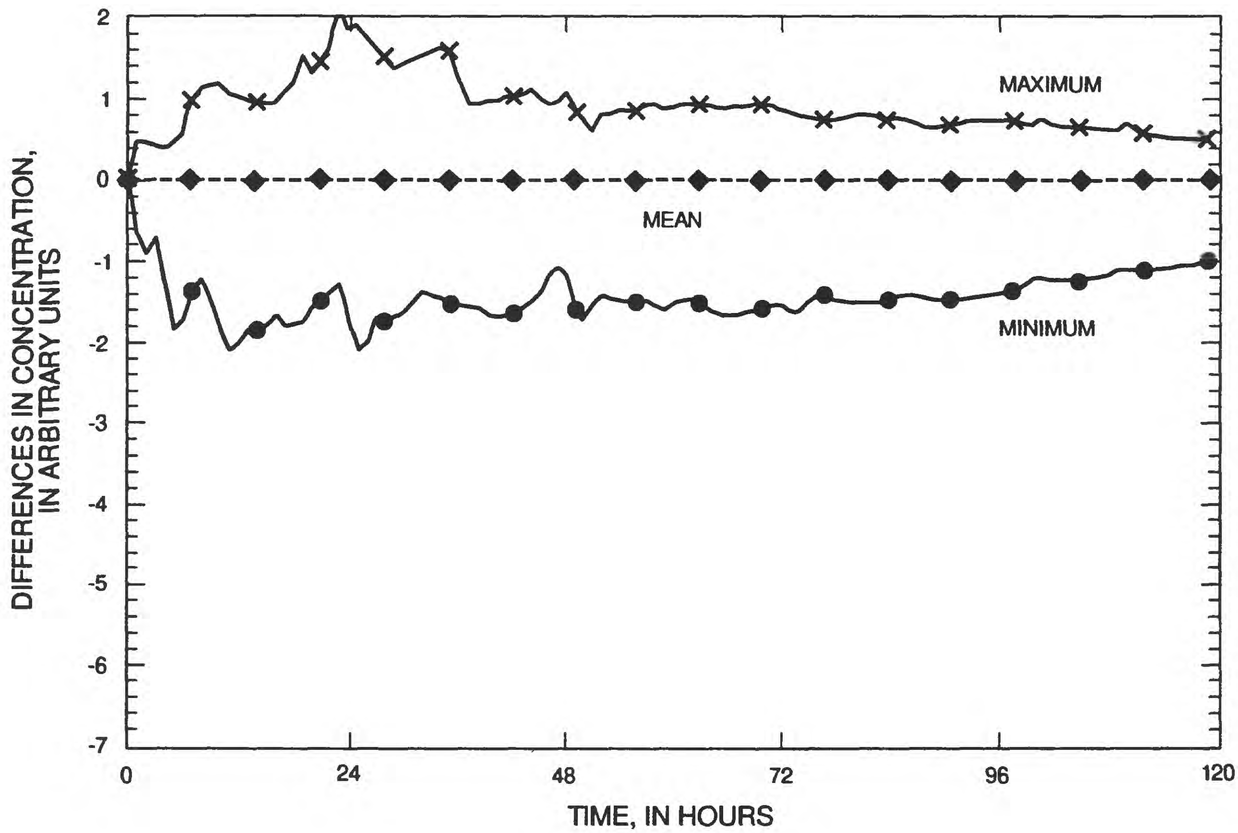



Figure 27. Differences in average cell dye concentrations in Kings Bay for low-inflow conditions and low inflow with reduced friction.

## SUMMARY AND CONCLUSIONS

Kings Bay is a spring-fed estuary in Citrus County on the west coast of peninsular Florida. The waters of Kings Bay have historically served as a major recreational attraction. Since 1960, however, the native vegetation in the bay has been displaced by Hydrilla verticillata, and, more recently, Lyngbya woolei has also appeared. To understand any hydrologic factors that could have contributed to the appearance of nuisance vegetation or cause changes in water quality, the interacting hydrodynamic characteristics of Kings Bay, the springs, Crystal River, and the Gulf of Mexico need to be defined.

Field measurements of tidal stage, velocity, and discharge data were made throughout Kings Bay during June 1990. A two-dimensional hydrodynamic model was calibrated and verified with this field data and was used to study the tidal-flow, circulation, and flushing characteristics of Kings Bay and to evaluate the effect of such water motion on the distribution of dissolved constituents. The model was used to simulate the response of the bay during low-inflow conditions (net flow of 735 $ft^3/s$), typical inflow conditions (net flow of 975 $ft^3/s$), and low-inflow conditions with the reduced bottom roughness characteristic of reduced vegetation.

The circulation characteristics of Kings Bay were determined by simulating Lagrangian particles that were transported with the simulated water velocity. Spring discharge transported the particles from Kings Bay into Crystal River and out of the model domain. Tidal effects added an oscillatory component to the particle paths. The mean particle residence time was 59 hours for low-inflow conditions, 50 hours for typical inflow conditions, and 56 hours for low-inflow conditions with reduced bottom friction. Thus, spring discharge has a greater effect on particle residence time than does bottom friction. Circulation patterns were virtually identical for the three simulated hydrologic conditions.

Simulations of conservative dye constituents were used to determine the flushing characteristics of Kings Bay for the three hydrodynamic conditions. The average concentration of dye initially injected in Kings Bay decreased asymptotically due to spring discharge, and the tide caused some oscillation in the average dye concentration. Ninety-five percent of the dye initially injected from the springs exited Kings Bay and Crystal River in 94 hours for low inflow, 71 hours for typical inflow, and 94 hours for low inflow with reduced bottom friction. Results of model simulation indicate that all of the open waters of Kings Bay are flushed by the spring discharge. Reduced bottom friction has little effect on flushing.

Circulation and flushing characteristics in Kings Bay are primarily determined by discharge from numerous springs located throughout the bay. Tides modulate water level, water velocity, and advective transport, but spring discharge is the most significant factor affecting residual circulation and flushing.

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