Application of Acoustical Methods for Estimating Water Flow and Constituent Loads in Perdido Bay, Florida

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Application of Acoustical Methods for Estimating Water Flow and Constituent Loads in Perdido Bay, Florida

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Abstract

Water flow and quality data were collected from December 1994 to September 1995 to evaluate variations in discharge, water quality, and chemical fluxes (loads) through Perdido Bay, Florida. Data were collected at a cross section parallel to the U.S. Highway 98 bridge. Discharges measured with an acoustic Doppler current profiler (ADCP) and computed from stage-area and velocity ratings varied roughly between $\pm 10,000$ cubic feet per second during a typical tidal cycle. Large reversals in flow direction occurred rapidly (less than 1 hour), and complete reversals (resulting in near peak net-upstream or downstream discharges) occurred within a few hours of slack water. Observations of simultaneous upstream and downstream flow (bidirectional flow) were quite common in the ADCP measurements, with opposing directions of flow occurring predominantly in vertical layers.

Continuous (every 15 minutes) discharge data were computed for the period from August 18, 1995, to September 28, 1995, and filtered daily mean discharge values were computed for the period from August 19 to September 26, 1995. Data were not computed prior to August 18, 1995, either because of missing data or because the velocity rating was poorly defined (because of insufficient data) for the period prior to landfall of hurricane Erin (August 3, 1995). The results of the study indicate that acoustical techniques can yield useful estimates of continuous (instantaneous) discharge in Perdido Bay. Useful estimates of average daily net flow rates can also be obtained, but the accuracy of these estimates will be limited by small rating shifts that introduce bias into the instantaneous values that are used to compute the net flows.

Instantaneous loads of total nitrogen ranged from -180 to 220 grams per second for the samples collected during the study, and instantaneous loads of total phosphorous ranged from -10 to 11 grams per second (negative loads indicate net upstream transport). The chloride concentrations from the water samples collected from Perdido Bay indicated a significant amount of mixing of saltwater and freshwater. Mixing effects could greatly reduce the accuracy of estimates of net loads of nutrients or other substances. The study results indicate that acoustical techniques can yield acceptable estimates of instantaneous loads in Perdido Bay. However, estimates of net loads should be interpreted with great caution and may have unacceptably large errors, especially when saltwater and freshwater concentrations differ greatly.

INTRODUCTION

Estuaries and tidally-affected streams are important natural resources valued for their recreational, economic, ecological, and aesthetic benefits. Pollutant discharges to estuaries and tidally affected streams are regulated to protect their water quality. Effective regulation of these pollutant discharges requires an understanding of tidal variations in flow and chemical flux rates (constituent loads). Until recently, a key limitation in improving our understanding of flow and loading variations in tidally-affected streams and estuaries was the difficulty and large expense associated with successfully measuring continually varying flow in these areas. New technology, employing acoustic techniques, is now available to accurately measure flow and determine average velocities in stream cross sections. This technology has also made it possible to estimate constituent loads in tidal areas with a much greater degree of accuracy.

In 1994, the U.S. Geological Survey (USGS) began a pilot study in cooperation with the Florida Department of Environmental Protection (FDEP) to evaluate the effectiveness of acoustical methods for measuring flows and estimating constituent loads in Perdido Bay. The specific objectives of the study were to determine daily mean discharges in Perdido Bay, vertical and horizontal velocity variations across flow-measuring sections, and estimate constituent loads for selected flow conditions. The purpose of this report is to describe the methods employed in the study, and the results of analyses of water-flow, water-quality, and constituent-loading data. Descriptions of instantaneous and daily mean discharge values (estimated from data collected near the U.S. Highway 98 bridge across Perdido Bay) are presented for the period August 18 through September 28, 1995. Water-quality data and constituent-load estimates at this cross section are presented for selected periods during the spring and summer of 1995. Additional water-quality data collected near the mouths of the Perdido River and Elevenmile Creek during the spring of 1995 are also presented in the report.

DESCRIPTION OF STUDY AREA

Perdido Bay covers an area of approximately 28 square miles along the common border of southwestern Alabama and the western panhandle of Florida, near the city of Pensacola, Florida (fig. 1). Approximately 10 square miles of the bay lie above the U.S. Highway 98 bridge. The average depth of the bay is approximately 7 feet, with deeper parts (10 feet and greater) of the bay occurring near the mouth of the Perdido River and downstream from the U.S. Highway 98 bridge (Livingston, 1992). Depths of approximately 15 feet were also observed near the center of the channel at the U.S. Highway 98 bridge during the study.

Perdido Bay forms the outlet for the Perdido River Basin, which drains an area of 913 square miles. An additional 130 square miles of land contribute runoff to the bay above the U.S. Highway 98 bridge (where most of the data were collected during the study). Several rivers and streams discharge into the bay, the most prominent being the Perdido River and its tributaries, the Blackwater and Styx Rivers and Dyas and Brushy Creeks. Elevenmile Creek and Bayou Marcus are two smaller streams that also discharge to the Perdido Bay upstream of U.S. Highway 98. The average annual runoff to Perdido Bay is approximately 2,000 cubic feet per second, based on a simple extrapolation of average runoff values obtained from gaging stations located on the streams mentioned above.

Average annual precipitation at Pensacola is approximately 63 inches, and ranges from less than 45 to greater than 80 inches during more extreme years. Precipitation is commonly associated with the passage of cold fronts during the winter and intense, convective thunderstorms during the summer. Late winter, early spring, and summer are typically the wettest periods, while the late spring and fall months are typically the driest. Average annual potential evaporation in the area is approximately 47 inches per year (Kohler and others, 1959).

Flow within the bay is affected by tidal fluctuations which are associated with astronomic (sun-moon-earth interaction) and meteorologic forces. Data from tide gages in the bay indicate that the tides are typically diurnal (one high and one low tide per day), although semidiurnal tides (two high and two low tides per day) with small differences between lower low water and higher high water did occur on an approximately 2-week cycle during the study. Although tide tables have not been developed for Perdido Bay, the National Oceanic and Atmospheric Administration (NOAA) tide tables (NOAA, 1994) indicate that average tidal range in Perdido Bay is less than 0.5 foot. In the current study, however, the observed tidal range was approximately 0.8 foot. Strong winds, when aligned with the longitudinal orientation of the bay can also induce water-level changes of up to 0.5 foot (Livingston, 1992; Niedoroda, 1992). However, this orientation (northeast to southwest) roughly parallels the direction with the lowest frequency of strong winds (Livingston, 1992; Niedoroda, 1992).

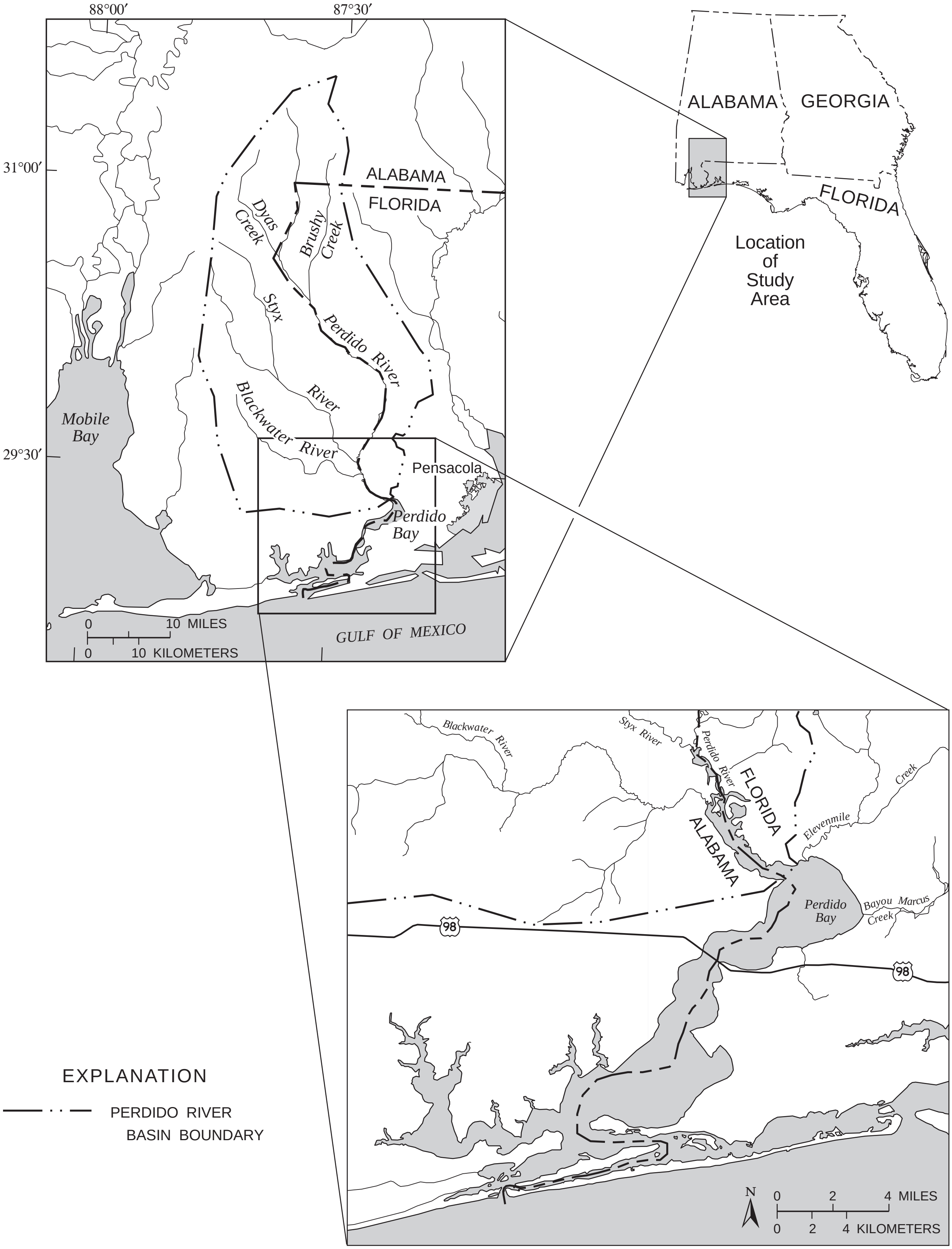

Figure 1. Location of study area.

Various forms of agriculture, including silviculture, are the dominant land use in the northern and western parts of the contributing area to Perdido Bay. Residential, commercial, and industrial land uses occur in the southeastern part of the area, primarily in and around Pensacola. Perdido Bay receives organic carbon, color, and nutrient loads from a large paper mill that discharges effluent to Elevenmile Creek. Effluent from sewage treatment plants is another source of nutrient and organic carbon loadings to the bay.

METHODS OF STUDY

To satisfy the study objectives, three basic data-collection activities were conducted during the study. These include (1) monitoring water-surface elevation (stage) and water velocity on a “continuous” basis (data collected every 15 minutes) at a gaging station established in the boat channel under the center span of the bridge, (2) periodic discharge measurements, and (3) periodic water-quality measurements of nutrients and other chemical constituents and physical properties. Discharge measurements were used to (1) develop equations relating discharge to velocity and water-level data collected at the gaging station, (2) characterize vertical and horizontal variations in water velocity, and (3) compute chemical loads from the water-quality data. The following sections of the report describe the methods used to make discharge measurements and characterize the spatial variability of velocity (velocity field characterization), estimate continuous and daily mean discharge from data collected at the gaging station, and characterize water quality and constituent loads.

Methods Used to Measure Discharge and Characterize Velocity Fields

A boat-mounted broad band acoustic Doppler current profiler (ADCP) was used to measure discharge and evaluate velocity fields at the U.S. Highway 98 cross section. The ADCP uses sound to measure water velocity. An ADCP uses the Doppler effect by bouncing an ultrasonic sound pulse off small particles of sediment and other zooplankton (scatterers) that are present in the water column (Simpson and Oltmann, 1992). The Doppler effect refers to the frequency change of the transmitted sonar signal caused by the relative motion between the ADCP and the scattering material in the water column (RD Instruments, 1992). Since this suspended material is moving at the same velocity as the water, the magnitude of the Doppler effect is directly proportional to the current velocity (RD Instruments, 1992, p. 1-3). By sampling segments of the returning sonar signal in successive time increments, the instrument measures velocities in discrete depth increments in the water column called depth cells (acoustic signals from shallow cells return to the ADCP before signals from deeper cells, thus earlier segments of the signal correspond to shallower data). The area of these depths cells is determined by the ADCP as it measures the elapsed time and velocity of the vessel relative to the stream bottom. The ADCP also measures depth to the bottom as the vessel moves.

There are limitations to the ADCP technology, however. The ADCP does not measure discharge near the surface, bottom, and at the sides of the transect where the water is too shallow or vessel placement is not possible. Velocities at the surface are not measured due to the submergence of the transducer head beneath the water surface (transducer draft) and due to a “blanking” distance below the transducer which corresponds to electronic and transducer recovery time after signal transmission. For the 1,200 kilohertz ADCP used in this study, the blanking distance is about 0.98 foot (Mike Simpson, U.S. Geological Survey, written commun., 1997). The transducer draft and blanking distance are measured and used by the system software to estimate the surface discharge (by extrapolating a velocity value from the shallowest velocity data measured by the ADCP).

The acoustic wave front from each transducer face consists of a main beam and side lobes. Near the bottom, where side lobe interference causes loss of reception of the main beam acoustic signal, no velocities or discharges can be determined. Again, discharge in this region near the bottom is estimated by the system software by extrapolating a velocity value from the deepest measured velocity data. For the 1,200-kHz system used in this study, the bottom 6 percent of the water column velocities are estimated (Simpson and Oltmann, 1992). Discharge in the near shore segments, where the depth of water is too shallow for the system to operate, is computed by estimating the near shore area (as one half of the depth at the last known vertical velocity sounding multiplied by the distance from that sounding to the shore) and the mean velocity of the near shore area (as mean velocity of the last non-missing vertical velocity sounding multiplied by 0.707).

Estimation of Continuous and Daily-Mean Discharge from Data Collected at the Gaging Station

Continuous stage and water-velocity measurements were made at a gaging station established in the center of the channel beneath the U.S. Highway 98 bridge. These stage and "index" velocity data were collected so that the total area and mean velocity of the cross section at U.S. Highway 98 could be estimated on a continuous basis. Note that the term, index velocity, refers to the velocity measured at the gage, and is generally different from the mean cross-sectional velocity because the velocity measured by the gaging station samples only a small part of the total cross section. The discharge through the cross section is equal to the product of the cross-sectional area and mean velocity of the cross section. Thus, continuous discharge can be estimated from the continuous stage and index velocity data if relations can be developed between stage and cross-sectional area, and between index velocity and mean cross-sectional velocity. The following sections describe procedures used to collect stage and index velocity data, and to develop stage-area and index velocity-mean velocity relations.

Collection of Stage Data and Development of Stage-Area Relation

Stage data were collected using a float-type gage and digital shaft encoder, which were installed in a gage house mounted above a stilling well. Stage data were collected every 15 minutes under routine monitoring operations and at shorter intervals (2 to 5 minutes) when discharge measurements were being made. The gage was installed on the eastern bridge fender near the middle of the U.S. Highway 98 cross section. A vertical staff gage (Rantz and others, 1982) was installed at the downstream end of this fender. This gage was used a reference for correcting stage data that were in error due to vertical movements of the gage house or loss of datum correction information (stored in the encoder) due to lightning strikes. The datums of the staff and float gages were determined using a level and rod, and were used to calculate stage above sea level (using the National Geodetic Vertical Datum of 1929). The stage data should have an error standard deviation of about 0.01 to 0.02 foot, except for periods between April 27 and July 19 and between July 19 and August 16, 1995, when the gage house dropped by 0.30 foot and 0.27 foot, respectively. Concurrent staff-gage and float-gage readings were made at the ends of these two time intervals, and a time-weighted correction was applied to data within these intervals.

Cross-sectional areas were estimated from depth sounding (depth and distance) data from the ADCP discharge measurements. Depth soundings were converted to bottom elevations by subtracting depth observations from the stage observed during a given ADCP measurement. This resulted in a bottom elevation and distance (from right or left bank) data set for each ADCP measurement. A stage-area data set was then created by processing each of the bottom elevation and distance data sets (from individual ADCP measurements) with a channel geometry analysis program (Regan and Schaffranek, 1985). The stage-area data sets from all of the ADCP measurements were then plotted together, and a piecewise-linear equation relating stage and area was developed from the data by graphically fitting a line through the data.

Collection of Water-Velocity Data and Development of Index Velocity-Mean Velocity Relation

The index velocity observations were made by measuring the mean velocity of a portion of the middle of the U.S. Highway 98 cross section (between the two bridge fenders on either side of the boat channel) using an acoustic velocity meter (AVM; Rantz and others, 1982; Laenen, 1985) from December 13, 1994, to September 28, 1995. An AVM installation consists of one or more pairs of sonic transducers and a transceiver that transmits and receives acoustic signals to and from the transducers. At the U.S. Highway 98 gage, one pair of transducers was deployed at an average depth of 3.5 feet. Transducers were separated by a distance of approximately 100 feet and the resulting acoustic path between the two transducers was oriented approximately 60 degrees from the direction of water flow. The AVM measures the difference between the upstream and downstream travel time of acoustic signals (sound moves faster downstream, and the difference in upstream and downstream travel times is inversely proportional to the water velocity), and computes an index velocity (water velocity passing through the acoustic path between the AVM transducers) using the following equation (Laenen, 1985):

$$v_i = \frac{b}{2\cos(\Theta)}\left[\frac{1}{t_{us}} - \frac{1}{t_{ds}}\right] \qquad (1)$$

where v_i is the computed index velocity, b is the length of the acoustic path, Θ is the angle between the acoustic path and water flow direction, and t_{us} and t_{ds} are the respective upstream and downstream travel times for the acoustic signal. Index-velocity data were collected every 15 minutes under routine monitoring operations and at shorter intervals (2 to 5 minutes) when discharge measurements were being made.

Measurements of the mean water velocity of the cross section ($\bar{V}$) were obtained by dividing measured discharge (from the periodic ADCP discharge measurements) by the cross-sectional area at the time of measurement (as determined from the stage-area rating and the mean stage at the time of the ADCP measurement). Linear equations relating index velocity to the mean cross-sectional velocity were then developed by (1) plotting the mean cross-sectional velocities versus the mean of the index velocities measured during a given ADCP measurement, and (2) drawing a best fit line through segments of the v_i versus $\bar{V}$ plot that exhibited a linear relation. This set of linear equations, together, define the relation between the mean cross-section velocity and index velocity (otherwise referred to as the velocity rating).

Computation of Continuous and Filtered Daily-Mean Discharge

Once stage-area and v_i-$\bar{V}$ ratings were developed, discharge estimates were computed using all of the stage and index velocity data. This was accomplished by substituting the continuous stage and index velocity values into the stage-area and v_i-$\bar{V}$ ratings, respectively, and multiplying the resulting cross-sectional area and mean velocity estimates to determine cross-sectional discharge ($\hat{Q}$). Application of this method resulted in a data set with estimates of instantaneous discharge at 15-minute intervals.

Daily mean discharge data were computed by applying a low-pass filter (Godin, 1972) to the instantaneous discharge data set. The discharge data are filtered for two reasons. First, daily-mean discharges computed from unfiltered instantaneous values may be misleading because the daily-mean values will have a cyclic behavior with an amplitude and period that differs from that of the original data. These differences are related to the differences between the period over which the data are averaged and the periods of cyclic components contained in the original data (Lew Delong, U.S. Geological Survey, written commun., June 1993). Filtering is also necessary to evaluate the nontidal component of flow occurring in a tidal reach. For example, Perdido Bay continuously receives large inflows from the Perdido River which results in a net downstream flow of water through the bay. Water also flows in and out of the bay because of tidal currents. Evaluating the magnitude of flow within the bay for periods as short as a few days requires filtering out the tidal flow components. In this study, daily mean filtered discharges were computed from filtered instantaneous discharge values that resulted from applying the Godin filter to the unfiltered instantaneous discharge estimates (which were calculated from stage and index velocity data).

Water Quality and Constituent Loading

Seven water-quality samples were collected in April and September 1995 for analysis of nutrients and other chemical constituents and physical properties. The April samples were collected shortly after a period of seasonal, high flows, while the September samples were collected during a period of average flow. The April and September samples were collected using the equal-discharge method and either a bottle sampler or a point sampler (during vertically-stratified conditions in April). The equal-discharge method was implemented by selecting three to five locations (verticals) in the cross section that were centered in subsections of the cross section that represented equal proportions of the total discharge (for example, if samples were collected at five verticals, each vertical would be located at the center of a subsection containing 20 percent of the total discharge through the cross section). The samples collected at each vertical sampling station were then composited in a churn splitter, which was used to thoroughly mix the samples to obtain a discharge-weighted sample for the cross section. A bottle sampler was used to collect the five samples collected during September 1995. This type of sampler was employed because there were no abrupt changes in temperature or salinity with depth (no thermocline or halocline, respectively), indicating well-mixed conditions during this period. The bottle sampler consisted of an open 1-liter polyethylene bottle which was held in a metal carrier that was suspended by nylon cord. The sampler was deployed by lowering and raising it at a constant rate between the water surface and the bay bottom (samples obtained in this manner were, therefore, depth-integrated samples). A point (Klemmer) sampler was used to collect the two samples on April 28, 1995. This type of sampler was used to collect samples at depths of 3.2 and 8 feet, which was above and below a thermocline and halocline that occurred during this time.

The samples that were collected as described above were analyzed for dissolved chloride, nutrients (nitrogen and phosphorous constituents), dissolved solids, suspended solids, color, turbidity, and specific conductance. These analyses were performed in accordance with methods described in Skougstad and others (1979). Five of these samples were collected during periods when discharge measurements were made using the ADCP. Loading rates were calculated from the nutrient, solids, and chloride analyses by multiplying the reported concentrations of these constituents by the measured discharge and the appropriate conversion factor:

$$L = 0.02832CQ \qquad (2)$$

where L is the loading rate for a given constituent, in grams per second; C is the concentration of a given constituent in milligrams per liter; and Q is the discharge, in cubic feet per second.

Measurements of temperature, specific conductance, dissolved oxygen, and pH were also made at a variety of locations in the U.S. Highway 98 cross section to evaluate spatial variations in these properties. These measurements were made when water-quality samples were collected on April 27 and 28, and September 8. Spatial variations in these properties were evaluated by making measurements at 2- to 3-foot depth increments at 5 vertical sampling stations located at the center of subsections representing 20 percent of the total discharge through the cross section. Measurements at 3-foot depth increments were made at a single vertical location near the gaging station on September 28. Similar measurements were made near the mouths of the Perdido River and Elevenmile Creek on April 28. In addition to these synoptic surveys, temperature data were collected on a “continuous” basis (once every 15 minutes) in the middle of the cross section (adjacent to the stage recorder) at three depths (approximately 2, 6, and 10 feet below the water surface) from July 30, through September 28, 1995.

RESULTS OF STUDY

Stage Observations and Stage-Area Relation

Stage data were collected on a continuous basis (once every 15 minutes) from December 13, 1994 to September 28, 1995. Tidal effects were readily apparent in the continuous stage data, which exhibited a diurnal fluctuation pattern during all periods of a given lunar month, except during periods approximately 7 and 21 days after a spring tide, when a semidiurnal pattern was often apparent (fig. 2). This semidiurnal pattern is evident in figure 2 during September 9-11 and September 23-24. Summary statistics of the continuous stage data are shown in table 1 for the period from August 18 to September 28, 1995. Data prior to this period are not included in table 1 because discharge was not computed prior to August 18 (as described later in the report in the discussion of the velocity rating). Note that the peak measured stage (3.68 feet) during the study occurred prior to this period and was due to storm surge that coincided with the passage of Hurricane Erin during August 3-4, 1995.

The stage-area rating that was developed from the ADCP depth soundings is shown in figure 3. These data are grouped by measurement trip in figure 3, which makes it possible to evaluate changes in the stage-area relation that may have occurred between trips. The data shown in figure 3 show two distinct “bands,” with one band of data corresponding to the ADCP measurements made in April and July and another corresponding to the measurements made September. The cross-sectional areas in September were approximately 3,600 to 4,400 square feet greater than those in April and July, possibly a result of scour in the U.S. Highway 98 section of Perdido Bay after Hurricane Erin. Differences were also evident between the early and late September measurements. The areas from the September 8-9 measurement period were generally 1,600 to 1,800 square feet greater in area than the September 26-28 data, although the significance of this difference is questionable because most of the September 8-9 stage-area data were within the range of variation of the September 26-28 data. Accordingly, the early and late September data were lumped together and an equation describing the stage-area relation was developed by graphically fitting a line through the data (fig. 3). This relation was applied to stage data

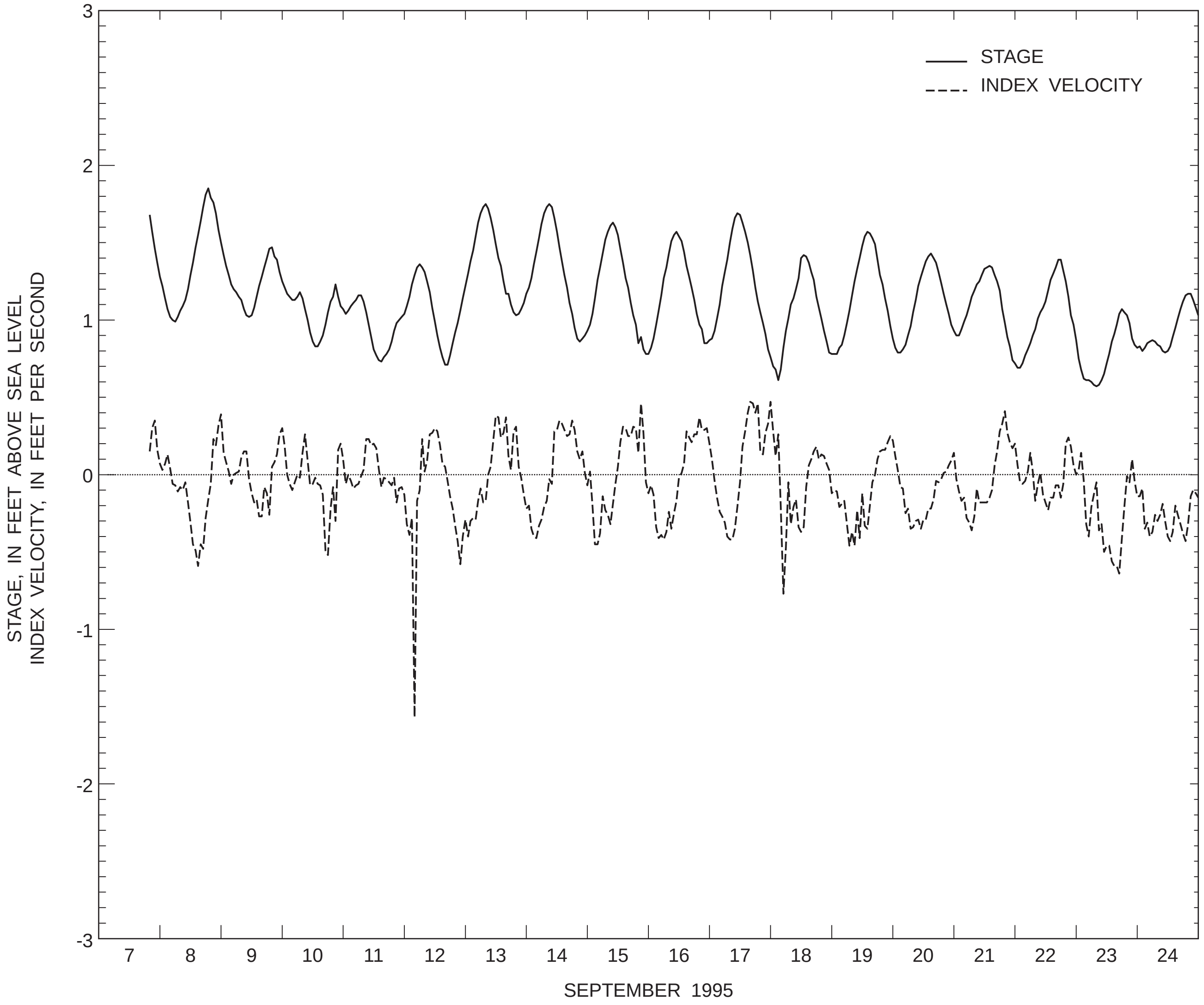

Figure 2. Stage and index velocity at Perdido Bay at U.S. Highway 98 near Pensacola, Florida, during September 7-24, 1995.

Table 1. Summary statistics of continuous stage, area, velocity, and discharge data, August 18-September 28, 1995

[Negative values indicate velocities or discharge in the upstream direction. ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Variable	Mean	Standard deviation	Maximum	Minimum	90th percentile	75th percentile	Median	25th percentile	10th percentile	Number of observations
Stage, in ft	1.14	0.28	1.85	0.32	1.55	1.35	1.11	0.92	0.79	3,828
Area, in ft^2	38,300	1,100	41,000	35,300	39,900	39,100	38,200	37,500	37,000	3,828
Index velocity, v_i, in ft/s	-0.06	0.25	1.49	-1.7	0.29	0.10	-0.08	-0.23	-0.38	3,814
Mean cross section velocity, $\overline{V}$, in ft/s	0.05	0.28	1.40	-0.62	0.42	0.26	0.12	-0.25	-0.29	3,814
Computed discharge, $\hat{Q}$, in ft^3/s	2,000	10,800	54,600	-24,200	16,000	10,100	4,500	-9,700	-11,200	3,814

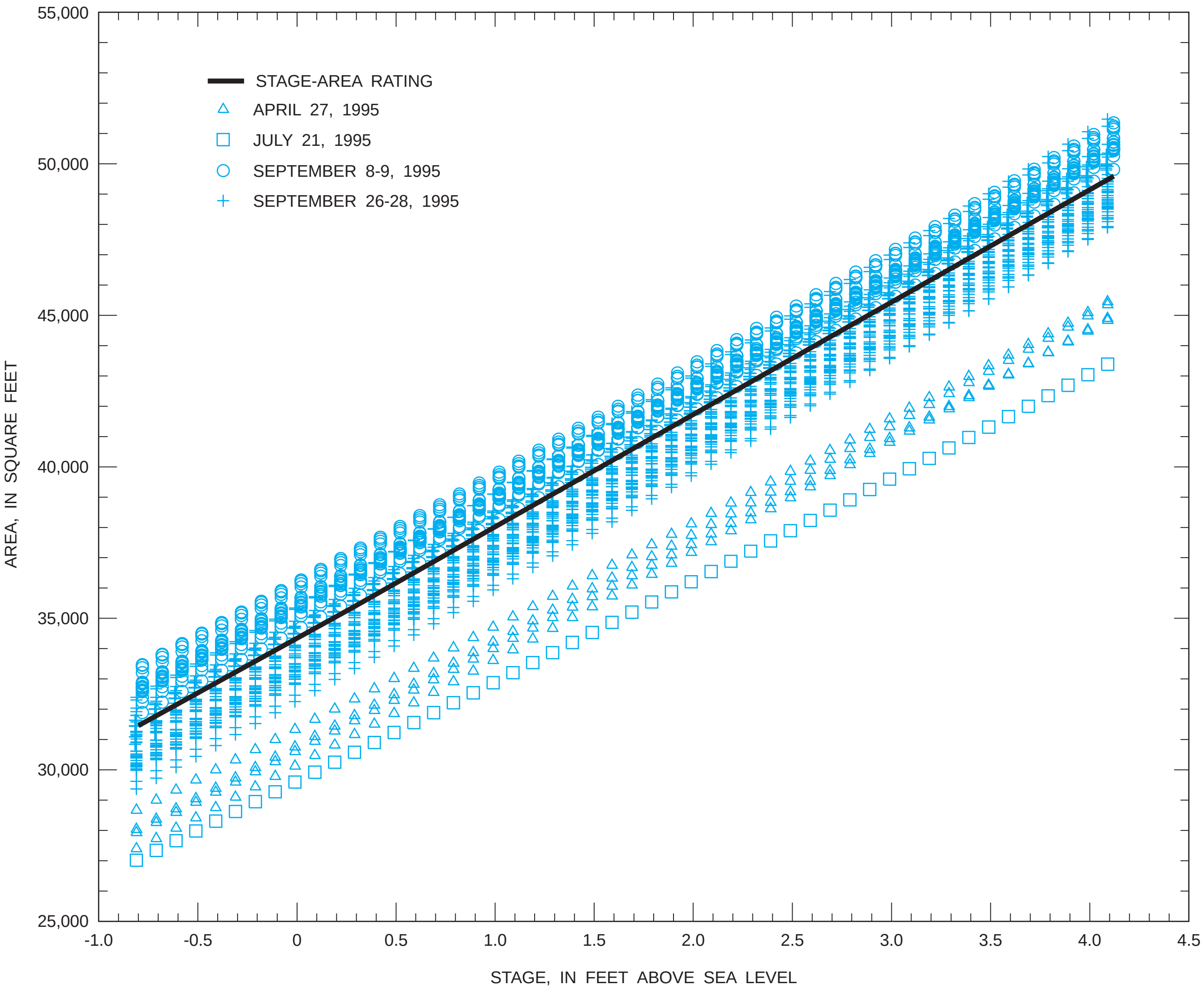

Figure 3. Stage-area rating.

collected after the passage of Hurricane Erin. A similar procedure was used to fit a stage-area relation from the April and July ADCP data and applied to the prehuricane period. Summary statistics describing the cross-sectional areas that were estimated from the continuous stage data are shown for the period of August 18 to September 28, 1995, in table 1. As seen in the table, cross-sectional areas ranged from 35,300 to 41,000 square feet.

Discharge Measurements

Discharge measurements were made with the ADCP during four periods, April 27-28, July 21, September 7-8, and September 27-28 (table 2). Collection of these data was necessary for developing a velocity rating, evaluating spatial and temporal flow variations, and computing loads for selected constituents. Changes in the magnitude, direction, and spatial patterns of flow are discussed in this section. In the following discussion, positive values of net flow are referred to as net-downstream flow (toward the Gulf of Mexico). Conversely, negative values of net flow are referred to as net-upstream flow or flow in a direction opposing the natural flow of freshwater in the Perdido River, which is toward the Gulf of Mexico.

Several patterns were evident in the measured cross-sectional velocity profiles made with the ADCP. First, bidirectional (simultaneous downstream and upstream) flow is quite common. No periods of static flow were seen for the whole cross section; rather net flow reversals occurred as upstream and downstream flow regions equaled each other in magnitude.

Table 2: Discharge measurements made with the acoustic Doppler current profiler at U.S. Highway 98

[Negative discharge values indicate net upstream flow]

Date	Time	Discharge, in cubic feet per second
04/27/95	1804	9,700
04/27/95	2007	3,400
04/27/95	2037	3,900
04/27/95	2322	-1,600
07/21/95	0246	-3,700
09/07/95	1532	-13,800
09/07/95	1555	-14,900
09/07/95	1613	15,200
09/07/95	1634	15,700
09/07/95	1656	17,400
09/07/95	1738	13,400
09/07/95	1805	11,300
09/08/95	0753	-11,000
09/08/95	0812	-12,300
09/08/95	0831	-10,900
09/08/95	0850	-12,000
09/08/95	0945	-11,600
09/08/95	1008	-13,400
09/08/95	1032	-12,800
09/08/95	1054	-13,200
09/08/95	1116	-11,600
09/08/95	1312	-11,200
09/08/95	1331	-8,900
09/08/95	1352	-5,500
09/08/95	1413	-2,300
09/26/95	1925	-9,000
09/26/95	1952	-10,900
09/26/95	2016	-9,900
09/26/95	2043	-9,100
09/27/95	0803	12,800
09/27/95	0828	12,800
09/27/95	0847	12,400
09/27/95	0908	9,800
09/27/95	0937	11,300
09/27/95	1026	9,000
09/27/95	1044	5,600
09/27/95	1104	3,200
09/27/95	1245	600
09/27/95	1315	-500
09/27/95	1453	-9,100
09/27/95	1511	-10,000
09/27/95	1545	-9,000
09/27/95	1611	-9,000
09/27/95	1627	-9,000
09/27/95	1644	-8,300
09/27/95	1702	-8,500
09/27/95	1720	-9,000
09/27/95	1738	-8,400
09/27/95	1922	-10,500
09/27/95	1941	-9,800
09/27/95	1922	-11,300
09/27/95	2052	-13,100
09/27/95	2134	-12,400
09/27/95	2151	-11,800
09/27/95	2216	-10,400
09/27/95	2234	-11,200
09/27/95	2322	-10,400
09/28/95	0804	12,800
09/28/95	0826	12,400
09/28/95	0857	12,500
09/28/95	0939	11,300
09/28/95	1010	10,000
09/28/95	1033	9,300
09/28/95	1051	9,500
09/28/95	1112	9,100
09/28/95	1139	7,700
09/28/95	1200	9,600
09/28/95	1219	8,400
09/28/95	1257	6,800
09/28/95	1323	4,600
09/28/95	1341	5,600
09/28/95	1404	3,600

During high- or low-tide conditions, bidirectional flow still occurred even as the volume of water in the measured cross section was at a maximum or minimum, respectively. The actual reversal of net discharge through the measured cross section occurred after the tidal extremes. This is illustrated in figure 4 where the upper cross section shows the velocity profile at low tide at 1904 hours on April 27, 1995, when the discharge was approximately 9,700 cubic feet per second downstream. During this period, a relatively high downstream flow region existed in the upper part of the water column and a relataively low upstream flow region surrounded by a near static flow region occurred deeper in the water column in the eastern half of the cross section. The lower cross section in figure 4 shows the velocity profile during rising tide 4.5 hours later at 2330 hours. Discharge has reversed and is

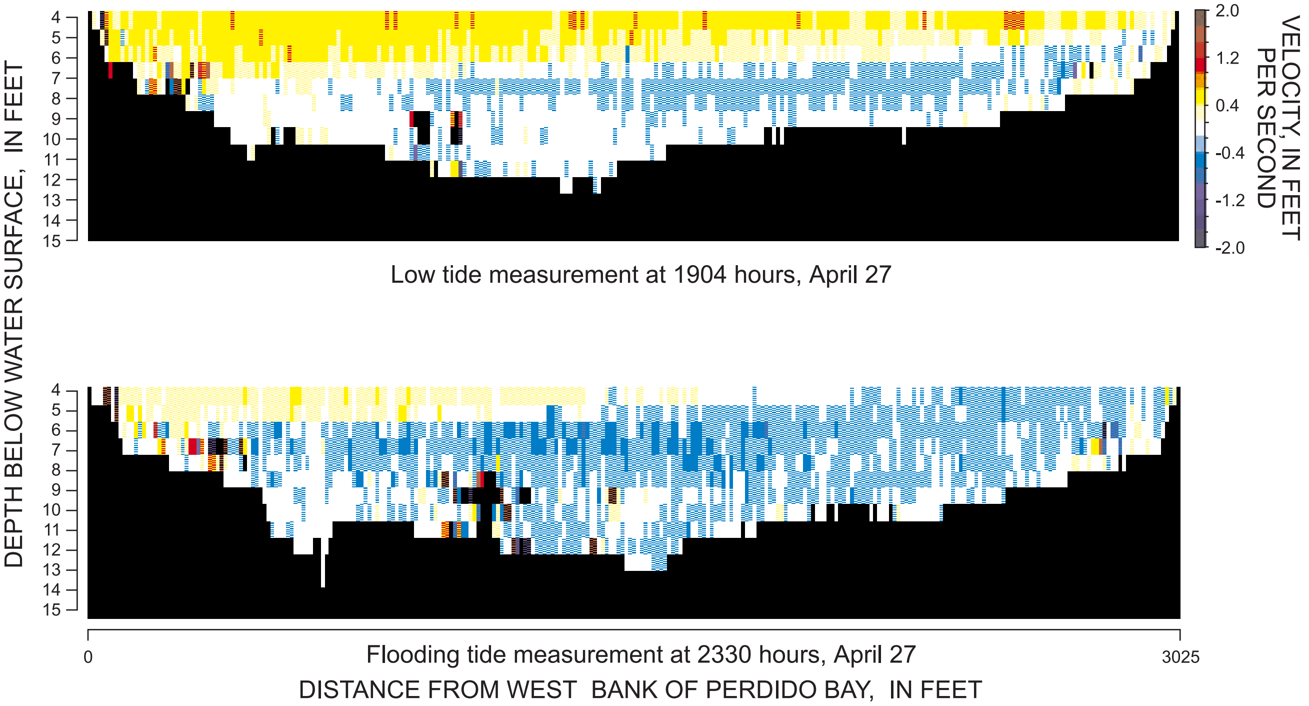

Figure 4. Flow fields determined from discharge measurements made on April 27, 1995.

approximately 1,600 cubic feet per second upstream. At that time, the lower depth upstream flow region had grown in both size and extent whereas the downstream flow region had decreased extensively.

Second, the net flow reversals occur quickly. For example, the data collected on September 27 indicate a change from a net-downstream flow of 620 cubic feet per second to a net-upstream flow of 510 cubic feet per second occurring within 30 minutes. Changes from net flows of several thousand cubic feet per second probably occurred over slightly longer periods.

Finally, while the spatial patterns of flow (velocity or flow fields) can be highly variable and complex, there was a similar pattern seen in both the April and September ADCP measurements. Much of the flow in the section often concentrated in cells of relatively high flow. During ebbing conditions, downstream flow typically occurs in the shallower water depths of the cross section with mixed (upstream and downstream) flow occurring deeper in the section (fig. 5, top profile). During flooding conditions (fig. 5, bottom profile), upstream flow generally occurs at greater depths, middle channel, with mixed (bidirectional) or slow flow in shallower depths.

Acoustical Velocity Meter Velocity Measurements and Index Velocity-Cross Section Velocity Rating

Tidal effects were apparent in the continuous v_i data, exhibiting a pattern that was similar to the pattern in stage data. Maximum downstream and upstream index velocities generally occurred midway through the ebbing and flooding tides, and stagnant values occurred near high and low tides (fig. 2). Summary statistics for the continuous v_i data are shown in table 1. No longer-term (study-period time scale) trends were evident in the data.

The velocity rating (V versus v_i) and the data points that were used to fit the rating are shown in figure 6. This velocity rating was developed from the previously described stage-area ratings and the AVM measured index velocities and ADCP discharge data collected during September 1995. The rating is comprised of three linear segments corresponding to $v_i < -0.14$ foot per second, $-0.14 \le v_i < -0.12$ foot per second, and $v_i \ge -0.12$ foot per second. Analysis of figure 6 indicates that most of the data points used to fit the lower, middle, and upper segments of the rating are within plus or minus 0.05, 0.17, and 0.04 foot per second of the rating, respectively. The larger

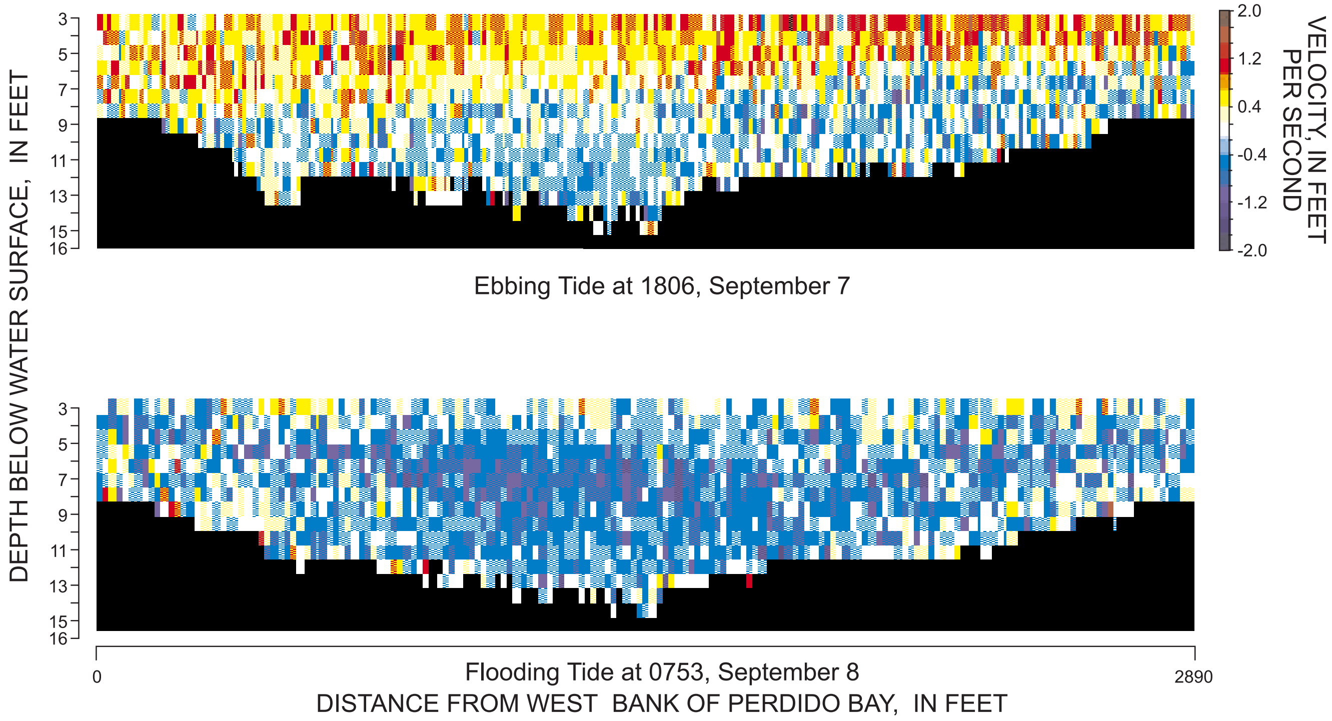

Figure 5. Flow fields determined from discharge measurements made on September 7-8, 1995.

scatter around the middle segment of the rating is due to the steep slope of this segment. This steep slope represents an abrupt shift in the velocity rating associated with conditions near slack (low) tide as the tidal current reverses from ebbing to flooding flow. Because of this abrupt transition, discharge values calculated during these conditions can have large errors. This is evident in the ADCP measurements made shortly after low tide on September 27. Differences between calculated and measured discharges for three measurements made during this period ranged from approximately -7,600 to 12,800 cubic feet per second. The summary statistics of the continuous v_i data indicate that less than 2 percent of the v_i data fell within the range of values that correspond to the middle, “high-error,” segment of the rating curve. The velocity rating shown in figure 6 was used to compute mean cross-sectional velocities ($\bar{V}$) from the continuous index velocity values collected by the AVM. Summary statistics of these computed $\bar{V}$ values are shown in table 1.

Data collected prior to August were not included in table 1 because the velocity rating was not applicable to all of the index-velocity measurements collected during the study. The cross-sectional velocity and index-velocity data collected during the periods when ADCP measurements were made in April and July did not fit the velocity rating described above (fig. 6). This indicates that a shift in the velocity rating may have occurred at some time prior to September 1995. One possible explanation for such a shift is that changes may have occurred during Hurricane Erin, which struck Pensacola on August 3, 1995, and produced a storm surge of approximately 2.5 feet in Perdido Bay. Unfortunately, the prehurricane ADCP data are insufficient to quantify possible shifts in the velocity rating or develop a prehurricane velocity rating (equipment problems prevented more ADCP data from being collected during the April and July trips). As described previously, differences between the pre- and posthurricane stage-area relations suggest that significant scouring of the U.S. Highway 98 cross section may have occurred due to the hurricane. Such changes could result in shifts in the velocity rating by changing the relative depth (depth divided by total depth) at which the AVM transducers are suspended. Because insufficient data were available to define a prehurricane velocity rating, discharge estimates were not computed from the continuous stage and index velocity data for the prehurricane period.

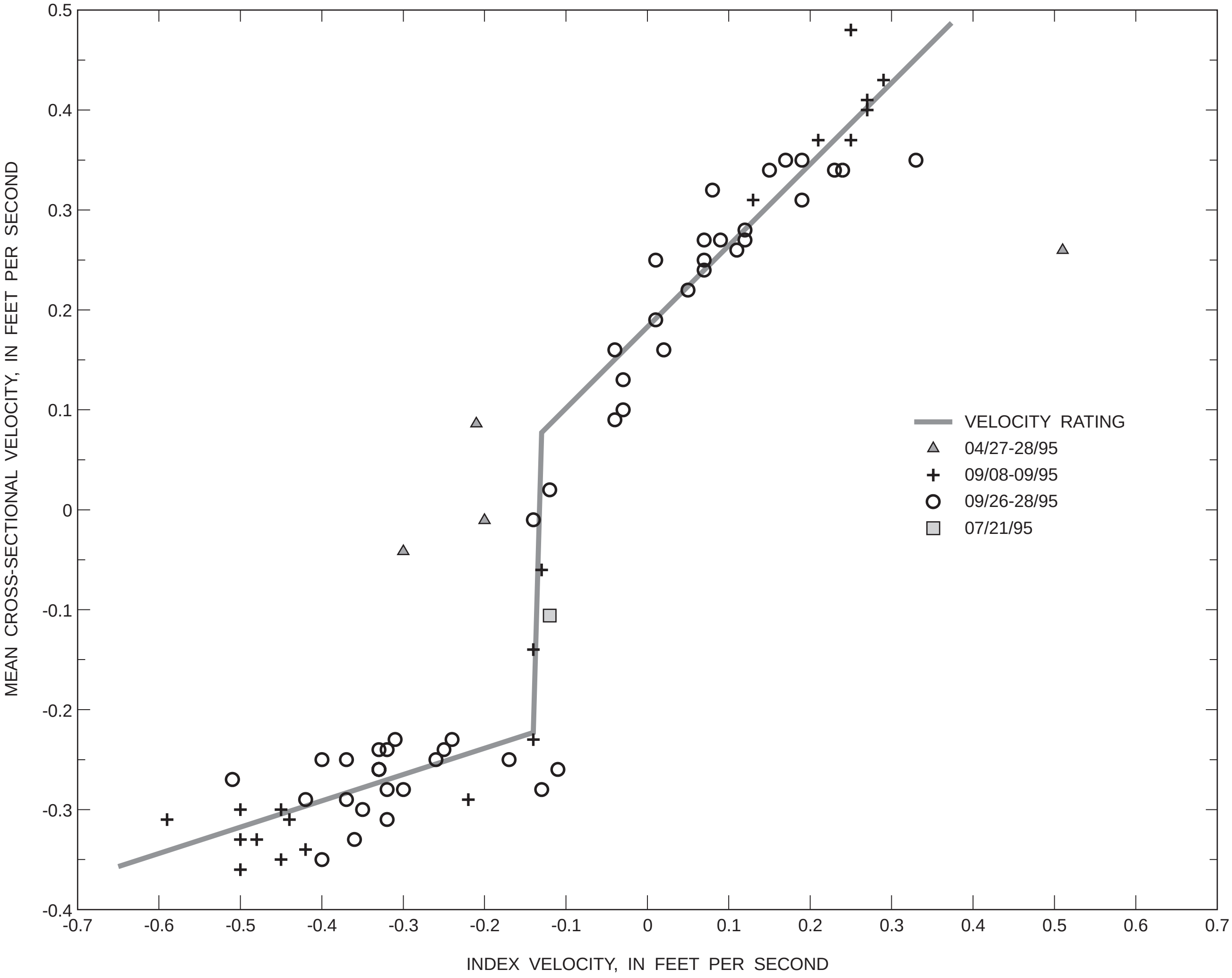

Figure 6. Relation between mean cross-section velocity and index (Acoustic Velocity Meter) velocity in Perdido Bay at U.S. Highway 98 near Pensacola, Florida.

Continuous Discharge Estimates and Net-Downstream Flows

Continuous discharge estimates were computed for the period from August 18 to September 28, 1995, using the continuous stage and index-velocity, and the stage-area and velocity ratings described previously. These data were then processed with a low-pass filter to eliminate the tidal components from the discharge data. These data were subsequently averaged to obtain daily mean discharge values that represent net downstream flows. Data were not computed prior to August 18, 1995, either because of missing data or because the velocity rating was poorly defined for the period prior to landfall of hurricane Erin (August 4, 1995). This section presents the results of these computations and describes the temporal variability, errors, and limitations associated with the continuous and filtered daily mean discharge estimates.

As previously mentioned in the methods section, continuous discharge estimates were computed by substituting the continuous stage and index velocity values into the stage-area and v_i - $\bar{V}$ ratings, respectively, and multiplying the resulting cross-sectional area and mean velocity estimates to determine cross-sectional discharge ($\hat{Q}$). The resulting $\hat{Q}$ data show a pattern of daily fluctuations that are similar to that seen in the index-velocity data (figs. 2 and 7), although the peaks are flatter and the between-peak

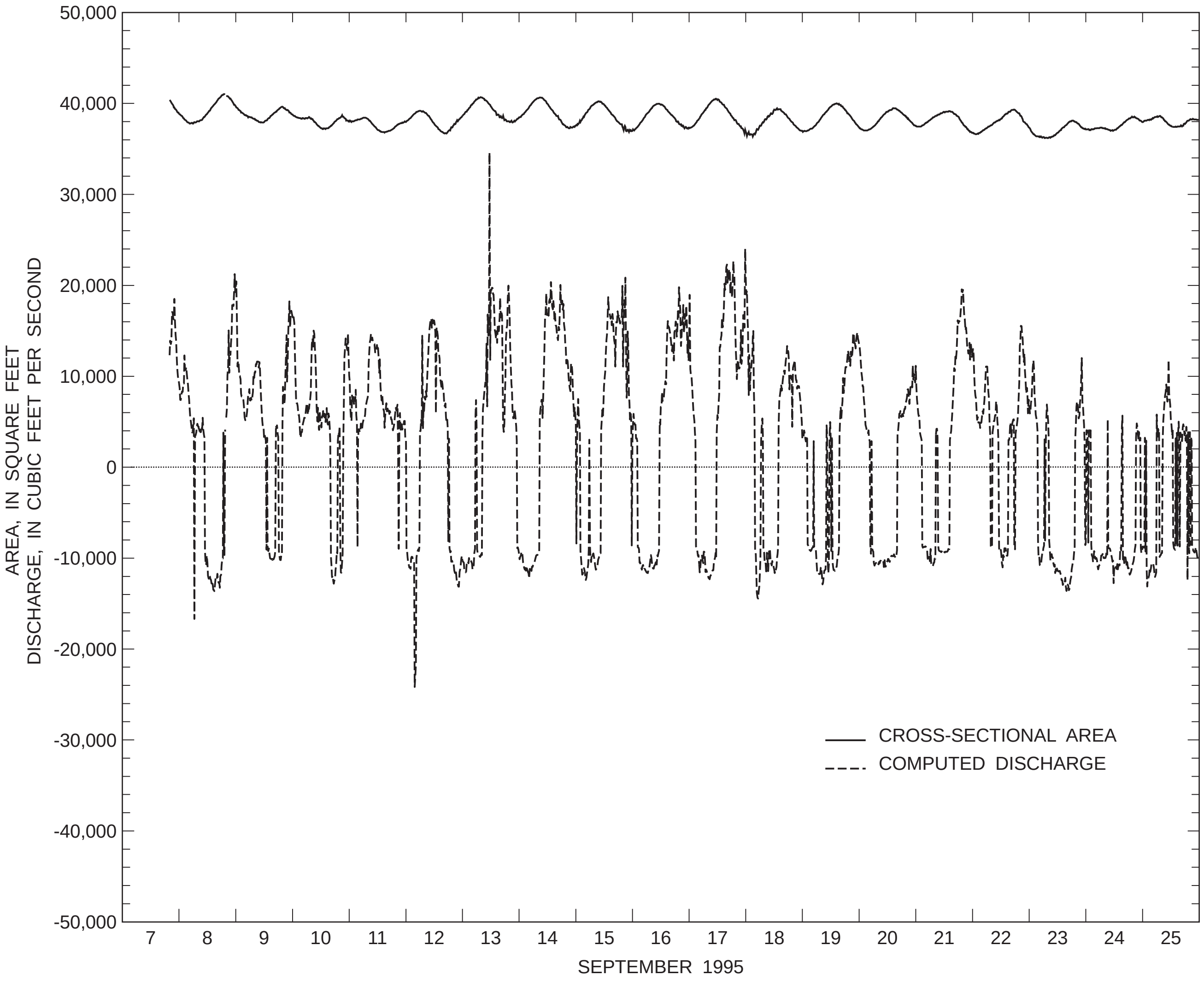

Figure 7. Cross-sectional area and computed discharge in Perdido Bay at U.S. Highway 98 near Pensacola, Florida.

transitions (between net-upstream and downstream flow) steeper for the $\hat{Q}$ hydrograph. This pattern arises because the computed $\hat{Q}$ values are more sensitive to variations in index velocity (and less sensitive to variations in stage) and because of the nonlinear shape of the velocity rating (the velocity rating is much steeper for slack water conditions), as shown in figure 3. Summary statistics describing the distribution of $\hat{Q}$ values computed from the continuous stage and index-velocity data are presented in table 1.

The accuracy of the continuous discharge estimates (computed from individual stage and index-velocity observations at the U.S. Highway 98 gage) was assessed by evaluating the differences between the ADCP measured discharge values and corresponding discharge estimates computed from the stage and index-velocity data collected at the time of the ADCP discharge measurements. Most of these “residual differences” were within a range of plus or minus 2,000 cubic feet per second. The upper and lower quartile values of the residuals were 1,100 and -780 cubic feet per second, respectively, and the 90th and 10th percentiles were -2,100 and 1,600 cubic feet per second, respectively. Additionally, no obvious bias was evident in plots of these residuals. These data suggest that the errors in the continuous discharge estimates for the posthurricane period were generally less than plus or minus 2,000 cubic feet per second, which is equivalent to approximately 20 percent of the typical flow rates during ebbing or flooding conditions. The errors associated with the continuous discharge estimates during slack water conditions can be much larger; however, the periods during which errors of this magnitude are likely to occur are limited because of the brevity of slack water periods.

Filtered daily mean discharge values (Q_f) were computed for the period from August 18 to September 26, 1995. The filtered daily mean discharge values were compared to runoff from upstream gages as a check on the reasonableness of the discharge values computed at the U.S. Highway 98 gage. In this comparison, runoff to Perdido Bay upstream of U.S. Highway 98 (Q_{us}) was estimated by adding the daily mean streamflows from the Perdido River at Barrineau Park, Florida (station number 02376500) and the Styx River near Elsanor, Alabama (station number 02377570) and multiplying the result by 1.775, which is the ratio of the combined drainage areas of these two stations and the approximate drainage area to the Perdido Bay upstream from U.S. Highway 98. These estimated daily mean discharges to Perdido Bay upstream of U.S. Highway 98 were then averaged over the period for which filtered daily mean discharge values were available from the U.S. Highway 98 gage (August 17, 1995, and later). This average discharge to Perdido Bay (exptrapolated from upstream gages) was approximately 1,600 cubic feet per second, which compares favorably to the average of the filtered daily mean discharges at the U.S. Highway 98 gage, 1,590 cubic feet per second.

Filtered mean daily flow values should be more accurate than the continuous data because the random error of such estimates is inversely proportional to the number of instantaneous discharge estimates used to calculate the average. The improvement in accuracy resulting from averaging is limited, however, because the continuous estimates are still subject to a variable (with time) bias that occurs due to subtle shifts in the rating curve. For example, a shift as small as 0.01 foot per second in the velocity rating would result in a bias of approximately 400 cubic feet per second, which is approximately 20 percent of the mean daily filtered value during the posthurricane period. This type of error is not reduced when daily average values are computed from instantaneous values, and detection and elimination of bias as small as this is probably not possible. Determination of the probable magnitude of these “random” shifts would require more ADCP measurement trips than were possible in this study. Such an exercise would yield valuable insight into the accuracy with which daily average flow rates could be estimated from AVM-equipped gages in tidal environments in which the magnitude of net flows is small in comparison to gross tidal inflows and outflows. The reader is referred to a report by Sloat and Gain (1995) for further discussion of the errors associated with instantaneous and average flow estimates obtained from continuous AVM data. The report by Sloat and Gain also describes the deployment of multiple AVM paths. Such an approach could yield more accurate discharge estimates in future AVM deployments in Perdido Bay because of the bidirectional nature of flow in the bay and the large width of the bay cross section.

The results described above indicate that the usefulness of the discharge estimates obtained in Perdido Bay using an AVM depends on the intended application of the data and is limited by the accuracy of the data. For example, the data are not very useful for estimating total inflow or outflow (for periods of a day or longer) because the errors associated with these estimates are much larger than the estimates themselves (the uncertainty of the sum of the individual instantaneous estimates is proportional to the number of estimates in the summation). However, the AVM data are useful for estimating instantaneous flow rates if errors on the order of 20 percent are acceptable. Data with this level of accuracy could be quite useful for calibrating or verifying a hydraulic model of Perdido Bay over periods of time that would be impractical for continuous measurement with an ADCP. Similarly, estimates of mean daily values may also be useful if errors on the order of 20 percent are acceptable.

Water Quality and Constituent Loads

Spatial Surveys of Temperature, Specific Conductance, Dissolved Oxygen, and pH

As described in the methods section, surveys of temperature, specific conductance, dissolved oxygen, and pH were conducted on April 27-28, and on September 8, 1995, (during water-quality sample collection) to evaluate the spatial variability of water quality during these periods. The results of these surveys are illustrated in the boxplots shown in figures 8-11. The plots were constructed by grouping measurements made at the same depth but at several different vertical sampling stations. The boxplots of the temperature and specific conductance data illustrate the abrupt thermoclines (fig. 8) and haloclines (fig. 9) present during the April surveys, as well as the absence of a strong halocline and a reversing (decreasing from surface to the middle depths, then increasing with depth towards the bottom) trend in the temperature profile during the

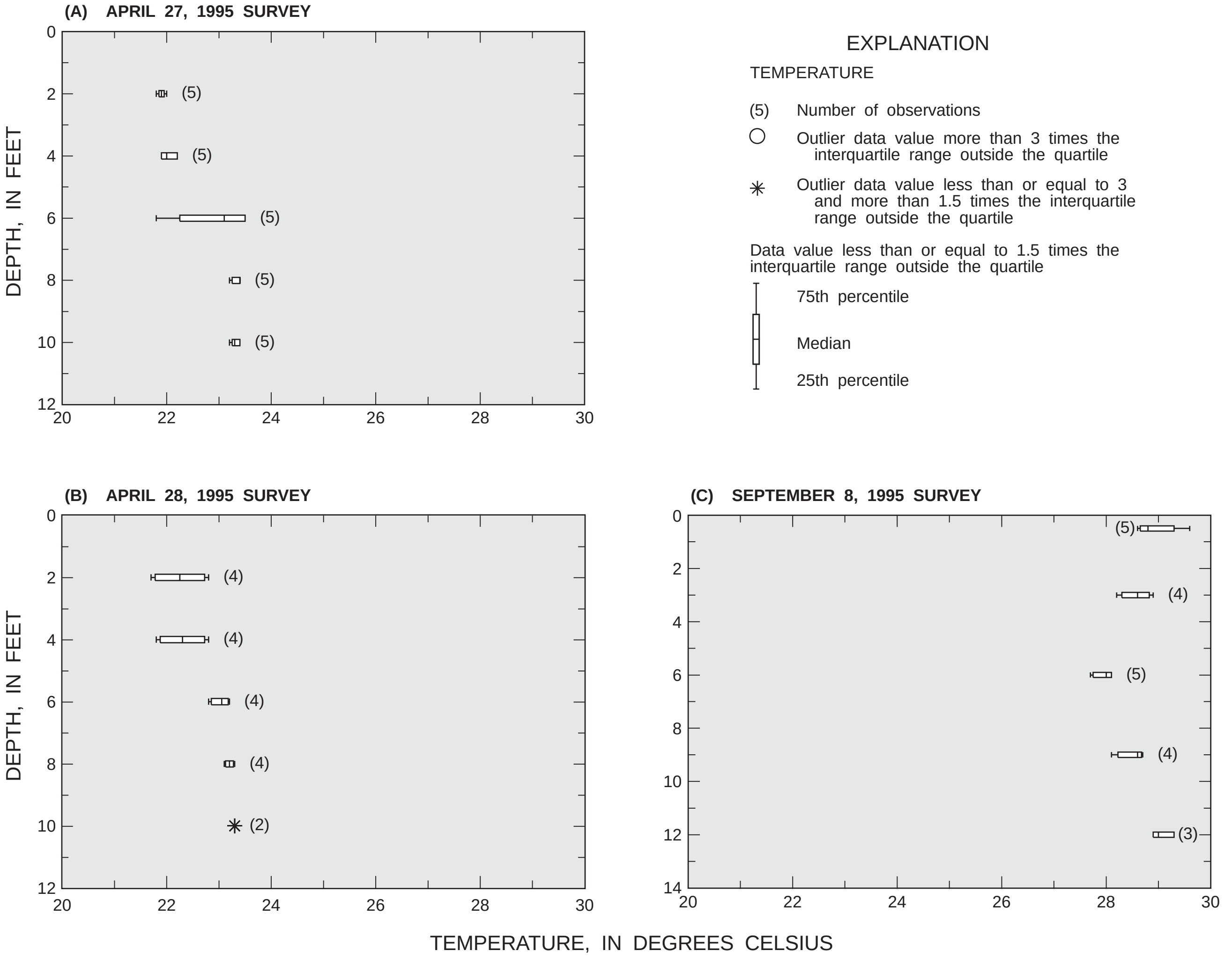

Figure 8. Temperature observations from April and September surveys of Perdido Bay at U.S. Highway 98.

September survey. Data collected from the surveys in both months indicate that horizontal variations in temperature and specific conductance were generally small when compared to variations with depth. Measurements of temperature and specific conductance were made on September 28, 1995, at a single vertical sampling station near the gage. The conductance profile on this date was similar to that of the September 8 survey (conductance increased with depth but a strong halocline was not evident). The temperature measured on September 28 increased with depth, although the magnitude of the difference between near surface and near bottom measurements ranged from 0.3 to 1.1 °C from the early morning survey to the late morning survey, respectively. Measurements of temperature, specific conductance, dissolved oxygen, and pH were also made at selected vertical sampling stations near the mouths of the Perdido River and Elevenmile Creek (fig. 1) on April 28 and are presented in the tables 3-5.

Relations between water depth and dissolved oxygen and pH were also evident in the April 27-28, and September 8 cross-sectional surveys (figs. 10 and 11). Dissolved oxygen concentrations generally increased with depth in the April surveys, although the differences in median concentrations were less significant because the horizontal variability of concentrations was generally greater (approaching or exceeding the range of concentrations from the water surface to bay bottom) at depths greater than or equal to 6 feet. Dissolved oxygen concentrations measured in the April surveys ranged from less than 6 to greater than 10 milligrams per liter (fig. 10), which was equivalent to dissolved oxygen saturation levels of 70 to 140 percent under the observed temperature and

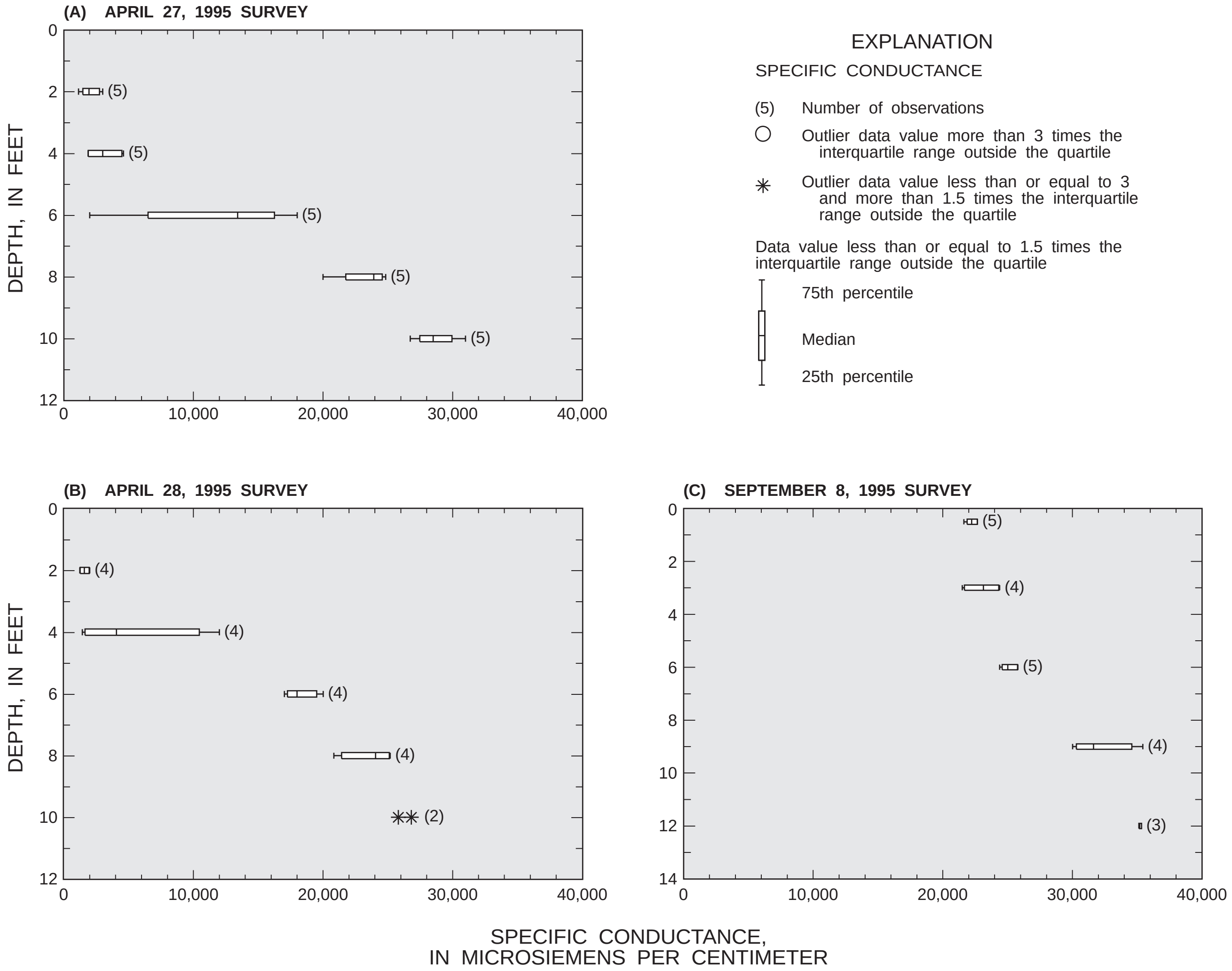

Figure 9. Specific conductance observations from April and September surveys of Perdido Bay at U.S. Highway 98.

salinity conditions. Dissolved oxygen concentrations ranged from less than 2 to greater than 8 milligrams per liter during the September 8 survey (fig. 10). Differences between dissolved oxygen concentrations at the various depth intervals were also more distinct in the September 8 survey because the concentration ranges at individual depth intervals were much smaller than the overall concentration range (from water surface to the bay bottom).

Measured pH values ranged from 6.5 to 8.1 in the April surveys and generally increased with depth, although this pattern was less distinct in the April 28 data because of greater horizontal variability in the shallower (less than 6 feet deep) data (fig. 11). A distinct pattern of decreasing pH with increasing depth was evident in the September survey data, with pH values ranging from 7.5 to 8.0 (fig. 11).

Analyses of Synoptic Water-Quality Samples

Seven water samples were collected in April and September 1995 and the results of the analyses of these samples are shown in table 6. Two samples were collected concurrently on April 28: one above the halocline (at a depth of 1 meter), and one below the halocline (at a depth of 2.5 meters). The remaining samples, which were collected in September, were a composite of depth-integrated samples collected at several vertical sampling stations along the U.S. Highway 98 cross section. The April 28 samples were collected on an ebbing tide, approximately 6 hours after high tide. The September 8 sample was collected approximately 2 hours before a high tide. Samples were collected within 2 hours of low and high tides and on flooding and ebbing tides on September 27-28.

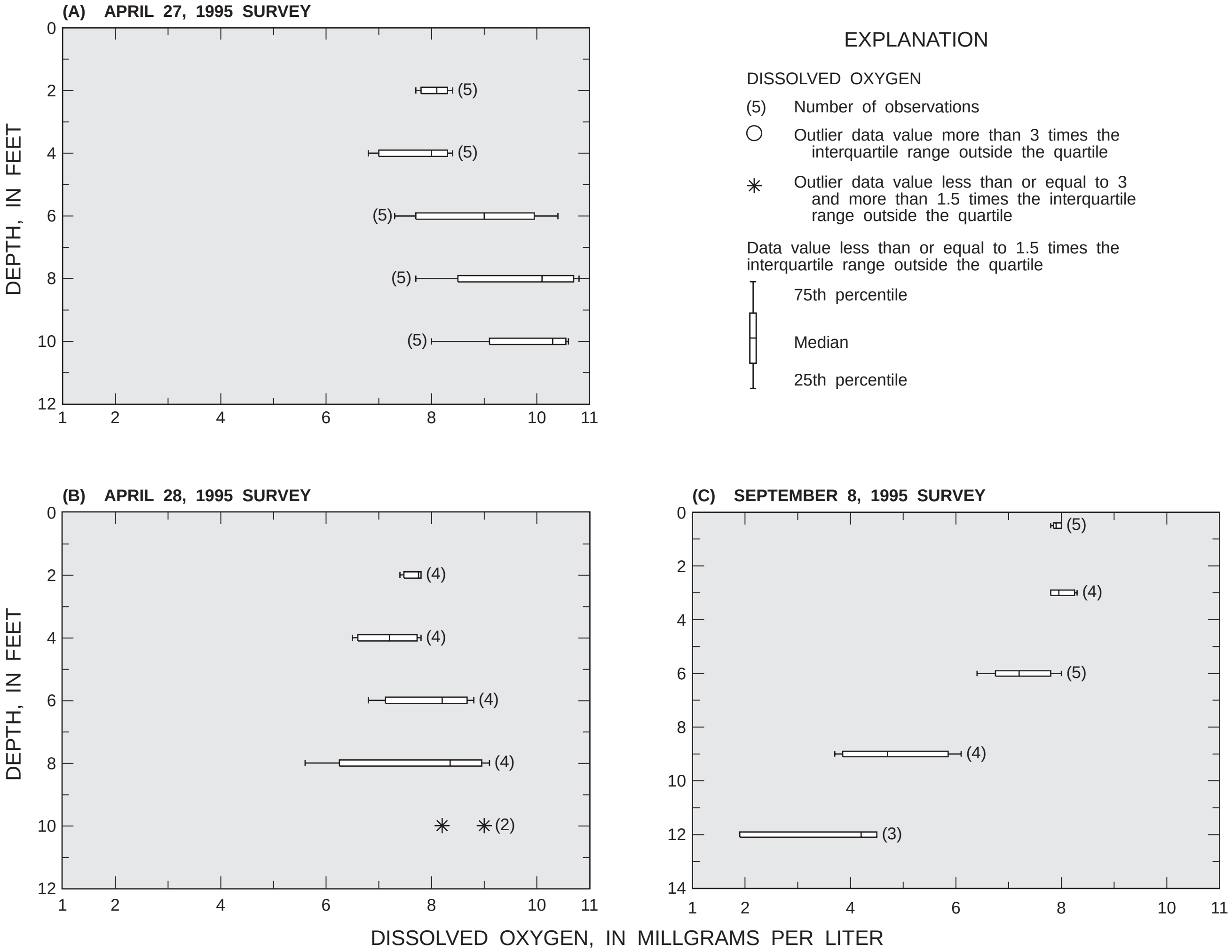

Figure 10. Dissolved oxygen oxygen observations from April and September surveys of Perdido Bay at U.S. Highway 98.

The largest differences in the water-quality data occurred in the conductance, chloride, solids, and color values. Specific conductance values were lower for the April samples (ranging from approximately 1,600 to 9,400 microsiemens per centimeter) than the September samples (which ranged from approximately 27,000 to 29,000 microsiemens per centimeter). Chloride and solids concentrations showed a similar pattern with significantly higher concentrations occurring in the September samples. Color values exhibited the opposite pattern, with significantly higher values occurring in the April samples. The chloride and solids concentrations from the shallow and deep samples collected on April 28 are consistent with poor mixing of shallow, fresher water with deeper, more saline water at the time of sample collection.

Table 3. Temperature, specific conductance, dissolved oxygen, and pH on April 28, 1995, approximately 1,000 feet from mouth of Elevenmile Creek, 10 feet from center of channel

[Latitude: 30°27’34” Longitude: 87°22’45”; bottom depth, 7.5 feet; time of observation approximately 1500 hours]

Depth, in feet	Temperature, in degrees Celsius	Dissolved oxygen, in milligrams per liter	Specific conductance, in microsiemens per centimeter	pH
1	23.7	3.6	590	7.1
3	21.3	3.0	630	7.1
5	20.4	3.0	690	7.1
7	20.4	3.7	700	7.1

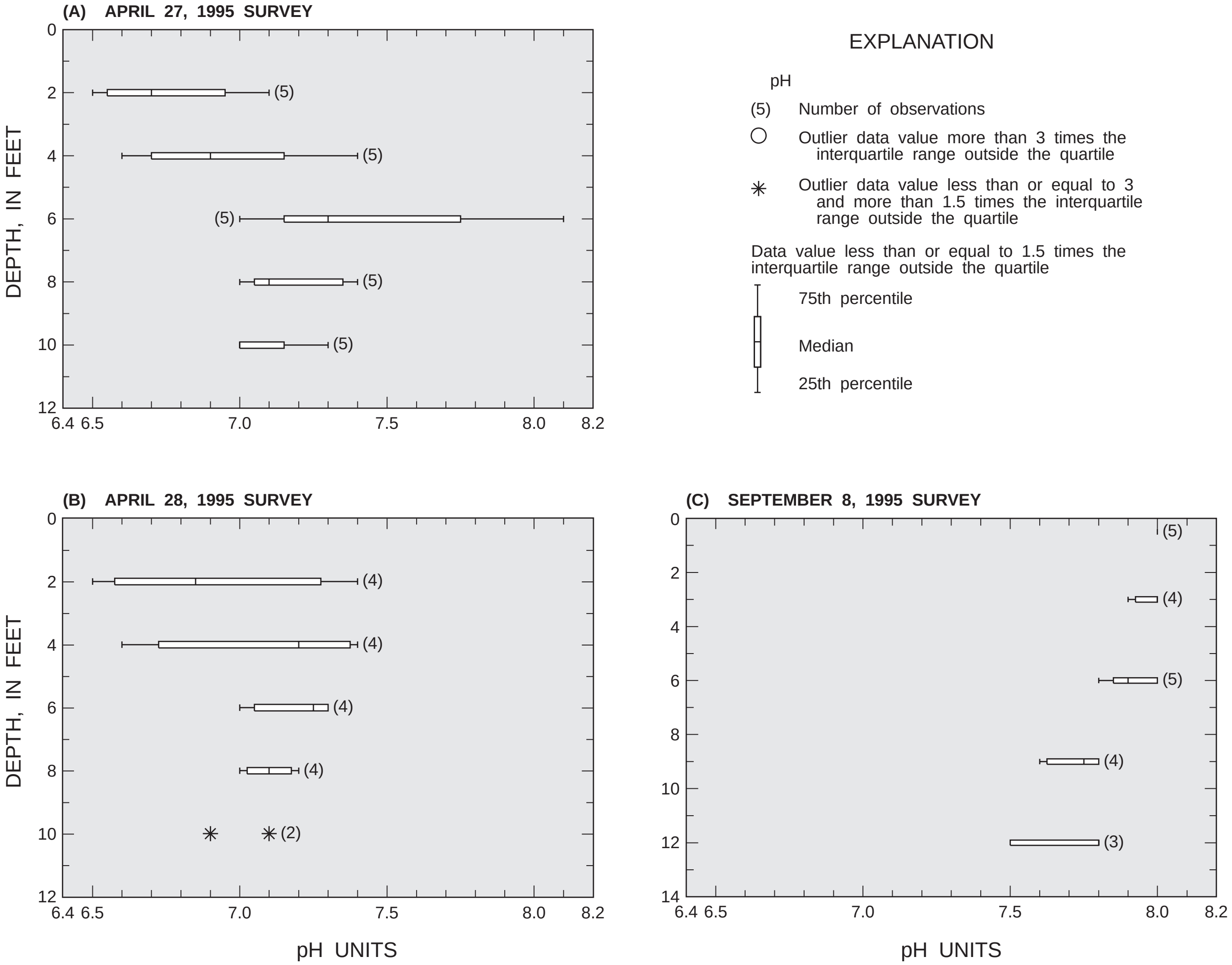

Figure 11. pH observations from April and September surveys of Perdido Bay at U.S. Highway 98.

Table 4. Temperature, specific conductance, dissolved oxygen, and pH on April 28, 1995, approximately 1,000 feet from mouth of Elevenmile Creek, in center of channel

[Latitude: 30°27’34” Longitude: 87°22’45”; bottom depth, 10.3 feet; time of observation approximately 1400 hours]

Depth, in feet	Temperature, in degrees Celsius	Dissolved oxygen, in milligrams per liter	Specific conductance, in microsiemens per centimeter	pH
1	23.8	3.9	480	7.1
2	22.7	3.9	530	7.1
4	20.4	2.2	690	7.1
6	20.4	2.2	720	7.0
8	20.4	1.9	720	7.0
10	20.3	2.4	880	7.0

Table 5. Temperature, specific conductance, dissolved oxygen, and pH on April 28, 1995, at mouth of Perdido River

[Latitude: 30°27’02” Longitude: 87°23’45”; bottom depth, 16 feet; time of observation approximately 1530 hours; -----, missing value]

Depth, in feet	Temperature, in degrees Celsius	Dissolved oxygen, in milligrams per liter	Specific conductance, in microsiemens per centimeter	pH
1	22.0	6.5	110	5.6
6	21.7	6.3	120	5.7
7.5	19.6	6.9	300	5.4
8	-----	6.6	2,500	5.4
9	20.3	4.8	3,700	6.7
12	21.4	6.7	19,400	6.6
15	22.0	7.0	20,900	6.5

The concentrations of the various nitrogen and phosphorous constituents that were analyzed showed little variability among the samples (table 6). Total nitrogen values ranged from approximately 0.2 to 0.7 milligrams per liter, with the bulk (70 to 100 percent) of the total nitrogen occurring as organic nitrogen. Detectable nitrate plus nitrite nitrogen concentrations were only present in the April 28 samples. The most significant difference (with respect to nitrogen constituents) between the shallow and deep samples from April 28 were the ammonia values; the ammonia concentration in the deeper sample was four times higher than the concentration in the shallower sample. Concentrations of phosphorous constituents were also low or below reporting limits in the samples collected (table 6).

Estimates of Constituent Loads

As described previously, loads were calculated for periods when synoptic water quality samples and ADCP discharge data were collected concurrently. The results of the constituent load calculations and discharge values at the time of sample collection are shown in table 7. The magnitude of measured discharges during sample collections ranged from approximately -9,100 to 12,000 cubic feet per second. The direction of net flow was downstream (positive flow) during the ebbing conditions on September 28 (tables 3 and 4), as expected. The direction of net flow was upstream (negative flow) during the four measurements that were made during flooding tides or near the high and low tides (tables 3 and 4).

The chloride and solids loads were the largest fluxes among the chemical constituents that were evaluated because chloride and solids concentrations were two to four orders of magnitude larger than the nutrient concentrations. The estimates of chloride loads ranged from -3,000 to 3,300 kilograms per second, and total solids and suspended solids ranged from -5,600 to 6,700 and -41 to 84 kilograms per second, respectively. Note that negative flows indicate that the net transport of a chemical constituent is upstream.

The computed loads of nitrogen and phosphorous constituents were much smaller than those of chloride and solids. Total nitrogen loads ranged from -180 to 220 grams per second. The bulk of this load was represented by organic nitrogen, with roughly equal proportions of dissolved and undissolved organic nitrogen loads for all but the September 8 sample. Total organic plus ammonia nitrogen loads, less their dissolved ammonia component, ranged from approximately -170 to 220 grams per second. In contrast, none of the total nitrate plus nitrite or dissolved ammonia loads exceeded 6 grams per second. Total phosphorous loads ranged from -10 to 11 grams per second. The loading rates in table 4 suggest that at least half of the phosphorous load in the September 27-28 samples was comprised of phosphorous in a form other than orthophosphate.

It should be noted that the loads described above are instantaneous loads and are therefore not necessarily representative of net downstream or upstream loads that occur over longer time intervals. For example, even if the concentration of a given substance is constant during a day, the load might vary over four orders of magnitude over the course of a tide cycle as the discharge changes from 10,000 cubic feet per second in the upstream direction during a flooding tide to 10,000 cubic feet per second in the downstream direction during an ebbing tide. One approach that is commonly used to estimate net loads is to estimate instantaneous loads continuously (for example, every 15 minutes) and filter these loads to remove tidal effects (Stoker and others, 1996). This results in instantaneous net loads that are independent of the loads caused by the tidal movement of water. Continuous estimates of instantaneous loads are typically obtained by developing a relation between concurrent measurements of discharge and load, which is then applied to the unfiltered continuous discharge estimates. Average (net) loads over periods of a day or longer could be computed by averaging the filtered instantaneous loads. An alternative approach for estimating these average loads would be to multiply chemical concentrations by daily mean filtered discharge values. This approach might be suitable if concentrations are approximately constant during a given day.

Application of either of the above approaches for computing net loads over periods of a day or longer may yield estimates of questionable accuracy in a system like Perdido Bay, where gross tidal inflows and outflows are much larger than the net flows (inflows minus outflows). Under these conditions, chemical concentrations may be greatly affected by the mixing of saltwater and freshwater. For example, the chloride concentrations observed in the September samples ranged from 9,200 to 10,000 milligrams per liter, which is several orders of magnitude larger than

Table 6. Water quality data from synoptic water quality samples

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter, total and suspended solids represent residue after evaporating at 105 °C]

Sample Date	Sample time	Approximate tidal condition	Chloride, dissolved, in mg/L	Color, in platinum-cobalt units	Total solids, in mg/L	Suspended solids, in mg/L	Specific conductance, in µS/cm	Turbidity, in nephelomtric turbidity units	Nitrogen, total, in mg/L	Ammonia + organic nitrogen, dissolved, in mg/L	Ammonia + organic nitrogen, total, in mg/L	Organic nitrogen, dissolved, in mg/L	Ammonia nitrogen, dissolved, in mg/L	Nitrate + nitrite nitrogen, dissolved, in mg/L	Nitrate + nitrite nitrogen, total, in mg/L	Nitrite nitrogen, dissolved, in mg/L	Phosphorous, dissolved, in mg/L	Phosphorous, total in mg/L	Ortho phosphorous, in mg/L
04/28/95	1245-1315[1]	Ebbing	440	100	970	70	1,590	10	0.54	0.30	0.44	0.28	0.02	0.10	0.10	<0.01	<0.02	<0.02	0.01
04/28/95	1245-1315[2]	Ebbing	2,800	60	6,200	18	9,430	8.0	0.59	0.31	0.51	0.23	0.08	0.08	0.08	<0.01	<0.02	<0.02	0.01
09/08/95	1315-1400	1 hour before high	9,200	30	17,000	74	26,600	1.8	0.22	0.23	0.22	0.21	0.02	<0.02	<0.02	0.01	<0.02	<0.02	0.01
09/27/95	1520-1540	2 hours after low	9,200	20	18,000	48	27,000	3.8	0.67	0.25	0.67	0.24	0.01	<0.02	<0.02	<0.01	<0.02	0.04	<0.01
09/27/95	0942-1012	Flooding	9,900	20	19,000	100	28,700	3.0	0.59	0.26	0.59	0.25	0.01	<0.02	<0.02	<0.01	<0.02	0.02	<0.01
09/28/95	0022-0044	3 hours before high	10,000	20	19,000	140	28,700	4.0	0.61	0.24	0.61	0.22	0.02	<0.02	<0.02	0.01	<0.02	0.02	0.01
09/28/95	0927-0956	Ebbing	9,500	15	19,000	240	28,400	3.8	0.63	0.27	0.63	0.26	0.01	<0.02	<0.02	<0.01	<0.02	0.03	<0.01

[1] Sample collected above halocline at depth of 1 meter.
[2] Sample collected below halocline at depth of 2.5 meters.

Table 7. Loads computed from the product of net-discharge and constituent concentrations

[Positive load values indicate net-seaward loads and negative load values indicate net-landward loads; kg/s, kilograms per second; g/s, grams per second]

Sample date	Sample time	Discharge, in cubic feet per second	Chloride, dissolved, in kg/s	Solids, total, in kg/s	Suspended solids, in kg/s	Nitrogen, total, in g/s	Ammonia + organic nitrogen, dissolved, in g/s	Ammonia + organic nitrogen, total, in g/s	Organic nitrogen, dissolved, in g/s	Ammonia nitrogen, dissolved, in g/s	Nitrate + nitrite nitrogen, dissolved, in g/s	Nitrate + nitrite nitrogen, total, in g/s	Nitrite nitrogen, dissolved, in g/s	Phosphorous, dissolved, in g/s	Phosphorous, total in g/s	Ortho phosphorous, in g/s
09/08/95	1215-1300	-11,400	-3,000	-5,500	-24	-71	-71	-71	-68	-6	<-6	<-6	-3	<-6	<-6	3
09/27/95	1420-1440	-9,100	-2,400	-4,600	-12	-170	-65	-170	-62	-3	<-5	<-5	<-3	<-5	-10	<-3
09/27/95	1942-2012	-9,800	-2,700	-5,200	-28	-160	-72	-160	-69	-3	<-6	<-6	<-3	<-6	-6	<-3
09/27/95	2322-2344	-10,400	-2,900	-5,600	-41	-180	-71	-180	-65	-6	<-6	<-6	-3	<-6	-6	-3
09/28/95	0827-0856	12,400	3,300	6,700	84	220	95	220	91	4	<7	<7	<4	<7	11	<4

chloride concentrations in upstream runoff. If we assume that chloride concentrations were fairly constant during the period August 18 though September 28, 1995, (when continuous discharge data are available), and that mixing is insignificant, then equation 2 could be used to estimate net loads of chloride during this period by multiplying the average of the filtered daily mean discharges in this period (1,600 cubic feet per second) and the average chloride concentration observed in the early and late September samples (9,600 milligrams per liter). This results in an estimated net load of approximately 440 kilograms per second. This number is probably 3 orders of magnitude larger than the actual net loading rate that occurred in late August and September because the terrestrial loads that were input to Perdido Bay during and shortly before this period were probably on the order of 100-1,000 milligrams per second. A similar calculation for net solids loads would also yield unreasonably large values. These large errors are the result of differences in the volume-weighted concentrations in the incoming and outgoing tidal flows. Errors of this magnitude occur with concentration differences as small as 1 percent, even if the more sophisticated approach of averaging instantaneous filtered loads is employed.

Estimates of net loads of nutrients are also affected by mixing, although these effects are less obvious because differences between saltwater and freshwater concentrations of nutrients are much smaller than corresponding differences in chloride or solids concentrations. For example, multiplying the average of the filtered daily mean discharges from late August through September (1,600 cubic feet per second) and the average total nitrogen concentration observed in the early and late September samples (0.54 milligrams per liter) results in a net load of approximately 24 grams per second, which is within the range of plausible net loads from terrestrial sources. However, small differences between nutrient concentrations in saltwater and freshwater can affect the significance of this estimate. For example, if the average daily tidal inflow rate were 10,000 cubic feet per second and tidal outflow rate (tidal inflow plus terrestrial runoff) were 11,400 cubic feet per second, then a concentration difference of only 0.05 milligram per liter in the inflowing (saltier) and outflowing (fresher) water could result in an error of 70 percent in the above estimate of net nitrogen load. This hypothetical error is certainly plausible for this example, which assumed that nitrogen concentrations were stable during the late August-September period. The magnitude of this error is also plausible (and probably conservative) even if more sophisticated approaches are employed, such as computing continuous loads from continuous, discharge-weighted samples. The errors associated with the more commonly used technique of estimating and filtering continuous loads should be considerably larger than this, because continuous nutrient concentrations are typically estimated from discharge-concentration relations (as opposed to using measured concentrations from continuous discharge-weighted samples). The above results indicate that acoustical techniques can yield acceptable estimates of instantaneous loads in Perdido Bay; however, estimates of net loads should be interpreted with great caution and may have unacceptably large errors, especially when saltwater and freshwater concentrations differ greatly.

SUMMARY

Water flow and quality data were collected from December 1994 to September 1995 to evaluate variations in discharge, water quality, and chemical fluxes (loads) through Perdido Bay, Florida. Data were collected at a cross section parallel to the U.S. Highway 98 bridge. Discharges measured with an acoustic Doppler current profiler (ADCP) and computed from stage-area and velocity ratings varied roughly between $\pm 10,000$ cubic feet per second during a typical tidal cycle. Large reversals in flow direction occurred rapidly (less than 1 hour) and complete reversals, resulting in near peak net-upstream or downstream discharges, occurred within a few hours of slack water. Observations of simultaneous upstream and downstream flow (bidirectional flow) were quite common in the ADCP measurements, with opposing directions of flow occurring predominately in vertical layers. The observed flow fields were complex and changed over time, with flow often concentrated in cells of strong flow that strengthened and weakened through a tide cycle. Instantaneous discharge values were computed at 15-minute intervals and filtered daily values were computed for the period from August 18 to September 28, 1995. Data were not computed prior to August 18, 1995, either because of missing data or because the velocity rating was poorly defined (due to insufficient data) for the period prior to the passage of Hurricane Erin (August 3-4, 1995). The results of the study indicate that acoustical techniques can yield useful estimates of continuous (instantaneous) discharge in Perdido Bay. Useful estimates of average daily net flow rates can also be obtained, but the accuracy of these estimates will be limited by small rating shifts that introduce bias into the instantaneous values that are used to compute the net flows.

Concentrations of total nitrogen ranged from 0.22 to 0.67 milligram per liter, with organic nitrogen representing the bulk of total nitrogen. Concentrations of phosphorous constituents were low (less than 0.04 milligram per liter) or below detection limits in the samples collected. Distinct thermoclines and haloclines were observed during sample collection on April 28, but were absent during sample collections in early and late September. Instantaneous loads of total nitrogen ranged from -180 to 220 grams per second for the sample collected during the study, and instantaneous loads of total phosphorous ranged from -10 to 11 grams per second. The chloride concentrations from the water samples collected from Perdido Bay indicated a significant amount of mixing of saltwater and freshwater. Mixing effects could greatly reduce the accuracy of estimates of net loads of nutrients or other substances. The study results indicate that acoustical techniques can yield acceptable estimates of instantaneous loads in Perdido Bay; however, estimates of net loads should be interpreted with great caution as they may have unacceptably large errors, especially when saltwater and freshwater concentrations differ greatly.

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