U.S. Department of the Interior
U.S. Geological Survey

# Discharge Measurement in Tidally Affected Channels During a Hydrographic Estuarine Survey of Sabine Lake, Texas

A hydrographic survey of Sabine Lake, a broad, shallow estuary lying on the Texas-Louisiana border, was conducted in June 1996 to help address questions relating to potential environmental effects of future water demands in Texas. The use of a variety of new instruments in this study is one means by which automation is improving efficiency and effectiveness of these efforts by increasing the quality and quantity of data collected.

Increasing population and industrial growth in Texas is increasing the demand for water. In response, water planners and managers are considering increased withdrawals from existing reservoirs, development of the few remaining undeveloped freshwater sources, implementation of conservation practices, and transfers of water from water-rich (eastern) to water-poor (western) areas of the State. Each of these approaches, while helping to satisfy the increasing water demand, might also affect the timing and volume of freshwater inflows to Gulf Coast estuaries. Freshwater inflows are critical to the health of Gulf Coast estuaries; they moderate salinity, create salinity gradients from river mouths to the Gulf of Mexico, and provide nutrients to support ecologically and economically important species. Long-term changes in the timing or volume of inflows could change the existing ecological balance of the estuaries.

Recognizing the ecological importance of freshwater inflows to Gulf Coast estuaries, the Texas Legislature directed the Texas Water Development Board (TWDB), the Texas Parks and Wildlife Department (TPWD), and the Texas Natural Resource Conservation Commission to determine the inflows required to maintain "an ecologically sound environment ... that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent" (Texas Water Code 11.147(a)). The TWDB and the U.S. Geological Survey (USGS), with assistance from several other State agencies and universities, collected data in Sabine Lake in June 1996 in support of this directive.

One means of examining the environmental effects of altered freshwater inflows is to compare existing water quality in the estuary to water quality expected to result from alternative water-management scenarios. Flow and water-quality measurements made in the June 1996 study (and past studies in Sabine Lake) will be used to establish existing (baseline) conditions. These same measurements also will serve as a data set by which to calibrate hydrodynamic computer models of Sabine Lake. The resulting models can be used to simulate conditions that would occur under alternative water-management scenarios. For example, in one scenario inflows might be assumed to be reduced in the future in response to larger upstream demand. The output from such a scenario would be compared to baseline conditions to evaluate the scenario's potential environmental effects.

This fact sheet presents data collected by automated stations during June 1996 and describes how the data are used to compute flows in tidally affected channels at Sabine Lake.

## Sabine Lake Study

Sabine Lake, the northernmost estuary in Texas (fig. 1), covers an area of about 259 square kilometers on the Texas-Louisiana border. Water depths in Sabine Lake are typical of shallow estuaries on the Gulf Coast of Texas. Depths at mean low tide vary from about 3 meters (m) in Sabine Lake to 12 m in dredged areas of the rivers and canals. From 1941 through 1987, freshwater inflows from the Sabine Lake drainage basin averaged about 16 billion cubic meters per year, or just over 50 times the volume of the lake, which makes Sabine Lake the least saline estuary in Texas.

During June 1–4, 1996, staff from the TWDB, USGS, TPWD, Texas A&M University-Corpus Christi Conrad Blucher Institute, and Lamar University conducted a 3-day, around-the-clock hydrographic survey of Sabine Lake. Water-velocity and water-quality data were measured at 13 sites, and discharge was measured at 9 of these sites. Tides and meteorological data were measured at several other sites. The flows at each discharge measurement site are tidally affected; that is, flows are subject to tidal forcing in amplitude, direction, and phasing. In addition, flows are influenced by runoff generated within the drainage basin upstream of each site.

For the first time since the TWDB began conducting hydrographic surveys in Texas bays and estuaries, automated stations were used at 3 of the 9 discharge measurement sites (fig. 1): Gulf Intracoastal Waterway (GIW) at State Highway 87, Sabine River, and Black Bayou. Data from the automated stations were used to compute stage-velocity-discharge ratings. Important channel dimensions for the three sites are listed in table 1.

**Table 1.** Channel dimensions of sites where ratings were developed

| Site name | Width (meters) | Maximum depth (meters) | Cross-sectional area (square meters) |
|---|---|---|---|
| GIW at State Highway 87 | 189.0 | 5.8 | 929.0 |
| Sabine River | 283.5 | 9.1 | 1,551.5 |
| Black Bayou | 54.9 | 3.9 | 160.7 |

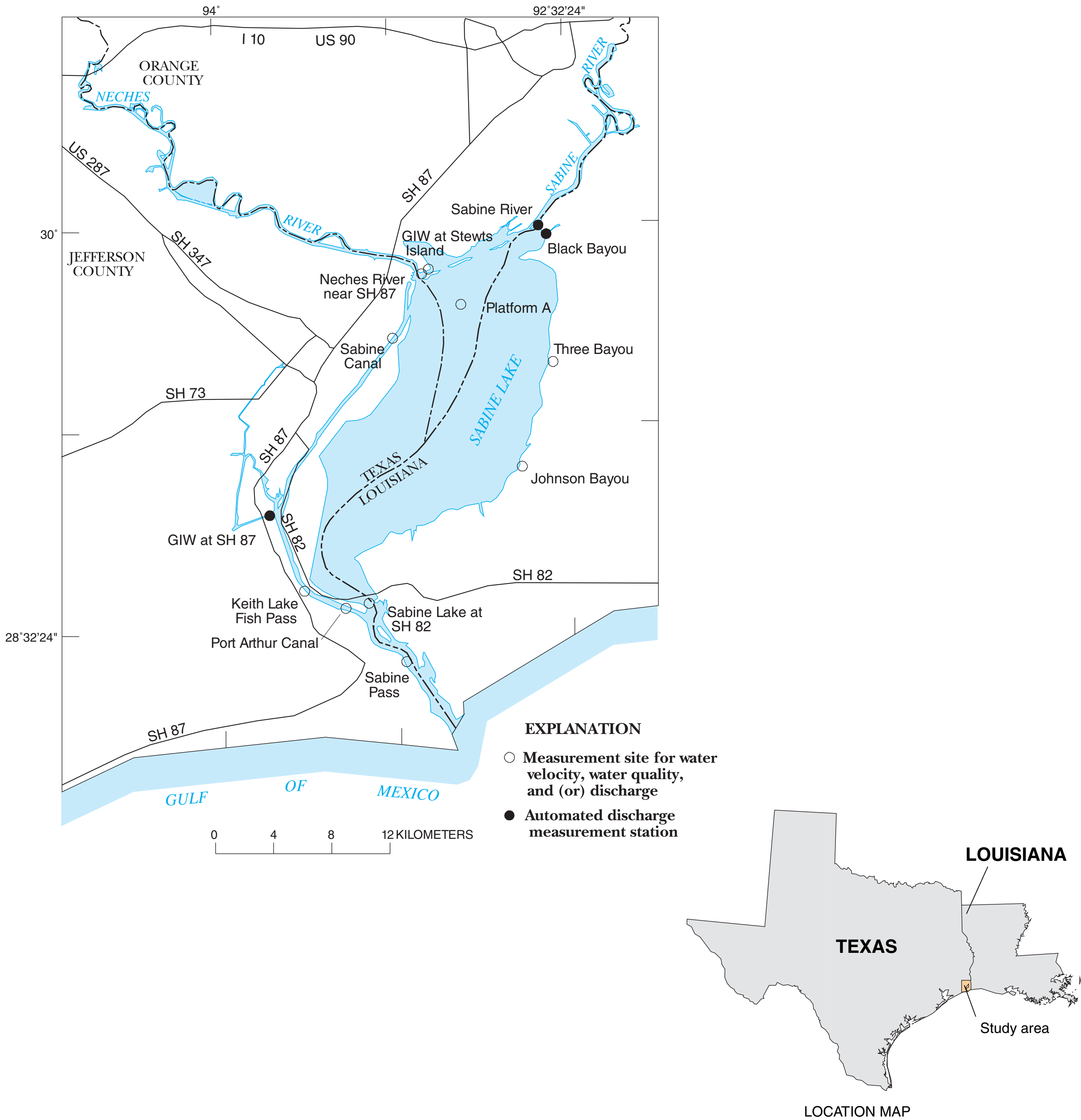


**Figure 1.** Measurement sites, Sabine Lake, Texas.

## Discharge Measurement in Tidally Affected Channels

Until recently, discharge measurements in tidally affected channels were extremely difficult. Velocity meters typically measure the velocity at a single point, but the velocity must be known at many depths and locations across the channel to compute an accurate discharge. Such discharge measurements are very labor intensive and are rarely performed in rapidly changing tidal environments because of the time and manpower required to complete a single measurement. The vessel-mounted broadb and acoustic Doppler current profiler (ADCP), which is capable of measuring the discharge in a channel more efficiently than conventional instruments, was introduced in the late 1980s. The ADCP uses acoustic signals to measure water velocity at multiple depths and multiple locations, as well as depth and boat position, as the vessel travels across the channel. The device then integrates these readings into a single discharge measurement. A typical discharge measurement can be completed in several minutes.

The TWDB and USGS have used ADCPs in hydrographic surveys since 1993 to measure discharge hourly at major locations of interest. These discharge measurements still are labor intensive because a measurement crew must be stationed continually near the measurement location. Sites to be measured by a single ADCP must be geographically close enough that travel times between sites allow hourly measurements. Consequently, the number of discharge measurement sites is limited by the number of crews and instruments available, and historically, discharge measurements have been desired at more sites than can be measured manually during a hydrographic survey.

## Computation of Discharge Using Ratings

At many sites, velocity and stage measurements in a channel can be related to ADCP-measured discharges through regression analysis. Such regression analysis develops a velocity-stage-discharge relation, commonly called a rating, from which the discharge in a channel can be computed using a single velocity and stage measurement. Automated velocity meters, stage sensors, and data recorders to measure and record velocity and stage can be housed in data-collection stations so that velocity, stage, and discharge measurements from which the rating is developed do not have to be taken during the hydrographic survey. The burden on ADCP resources is thus reduced during the survey, and the ADCPs can be used at locations where ratings cannot be developed. Additionally, because the data-collection stations operate unattended, personnel and resources can be directed to other locations to make manual measurements.

Until recently, instruments for measuring velocity were operated manually. Measurements typically were read from an instrument and recorded in a field book, and the data were transcribed in the office for analysis. Manual data collection occasionally led to measurement error in the form of missing data or operator-related instrument failure. Scarce resources also constrained the number of measurements. Many of these limitations are being overcome with the advent of electronic dataloggers. Automated data collection, while more complex technically, removes many of the difficulties of manual data collection by (1) ensuring that the measurements are collected at regular, shorter time intervals; (2) eliminating subjectivity in reading meters; (3) eliminating errors when recording or transcribing data; (4) allowing data collection during adverse conditions; and (5) reducing costs by reducing personnel requirements.

### *Automated Instrumentation*

At each of the three sites where discharge ratings were desired, automated stations were deployed which housed stage sensors and velocity meters. Stage was measured with submersible pressure transducers. Two types of velocity meters were used at the automated stations—acoustic velocity meters (AVM) and acoustic point-velocity meters (APVM). An AVM was used in the GIW at State Highway 87 site, and APVMs were used at the Sabine River and Black Bayou sites.

An AVM measures the velocity of water by means of an acoustic signal that moves faster downstream than upstream. Velocity is measured along an acoustic path between two transponders that are set diagonal to the direction of streamflow. The difference in the time required by the acoustic signal to travel between the transponders in the upstream and downstream directions is directly proportional to the mean velocity of the water along the acoustic path between the transponders.

An APVM measures the velocity of water at a single point by means of a Doppler phase shift technique. Acoustic signals are transmitted and received within a small sampling volume and a phase shift of the received acoustic signal is induced by the water velocity in the sampling volume. This phase shift is used to compute the water velocity in the sampling volume.

Neither an AVM nor an APVM will provide a completely accurate index of the overall flow conditions in a channel. Complex flow conditions can occur in tidally affected channels, such as when eddy flows near one bank move opposite to the primary direction of flow in the channel. Bidirectional flow also can be caused by density differences through the water column. The velocity provided by the AVM is the mean water velocity along the acoustic path between the transponders. How representative this velocity is of the overall mean channel velocity varies with the depth at which the transponders are placed, the distance between the transponders, and the stability of the horizontal and vertical flow regimes. The wider the distance between the transponders, the greater the likelihood that the primary flow characteristics of the channel are captured in the mean velocity measured between the transponders. Point-velocity measurements provide a water-velocity measurement at only one point in the channel, so the accuracy of velocity-discharge ratings also can be affected by complex flow conditions. Both AVMs and point-velocity meters need to be placed to reflect as much as possible the overall conditions in the channel in order to provide an accurate index of flow.

### *Rating Method*

A series of ADCP discharge measurements were made before and after the survey over a range of flow conditions at the three sites, and the corresponding velocity meter and stage readings were recorded. Generally, three ADCP discharge measurements were made for each flow condition, and at least two velocity and stage readings were recorded during the time the three ADCP measurements were made. From these data, regression models of the following form were developed for each rated site:

$$Q = B_1 + B_2 V + B_3 S,$$

where Q is estimated discharge, $B_1$, $B_2$, and $B_3$ are regression coefficients, V is measured velocity, and S is measured stage normalized by subtracting the mean stage measured during the survey. The resulting regression equations and diagnostic statistics are shown in table 2. For the GIW site, positive discharges reflect water flowing to the southwest. For the Sabine River and Black Bayou sites, positive discharges reflect water flowing into the estuary system; negative discharges reflect water flowing out of the estuary system.

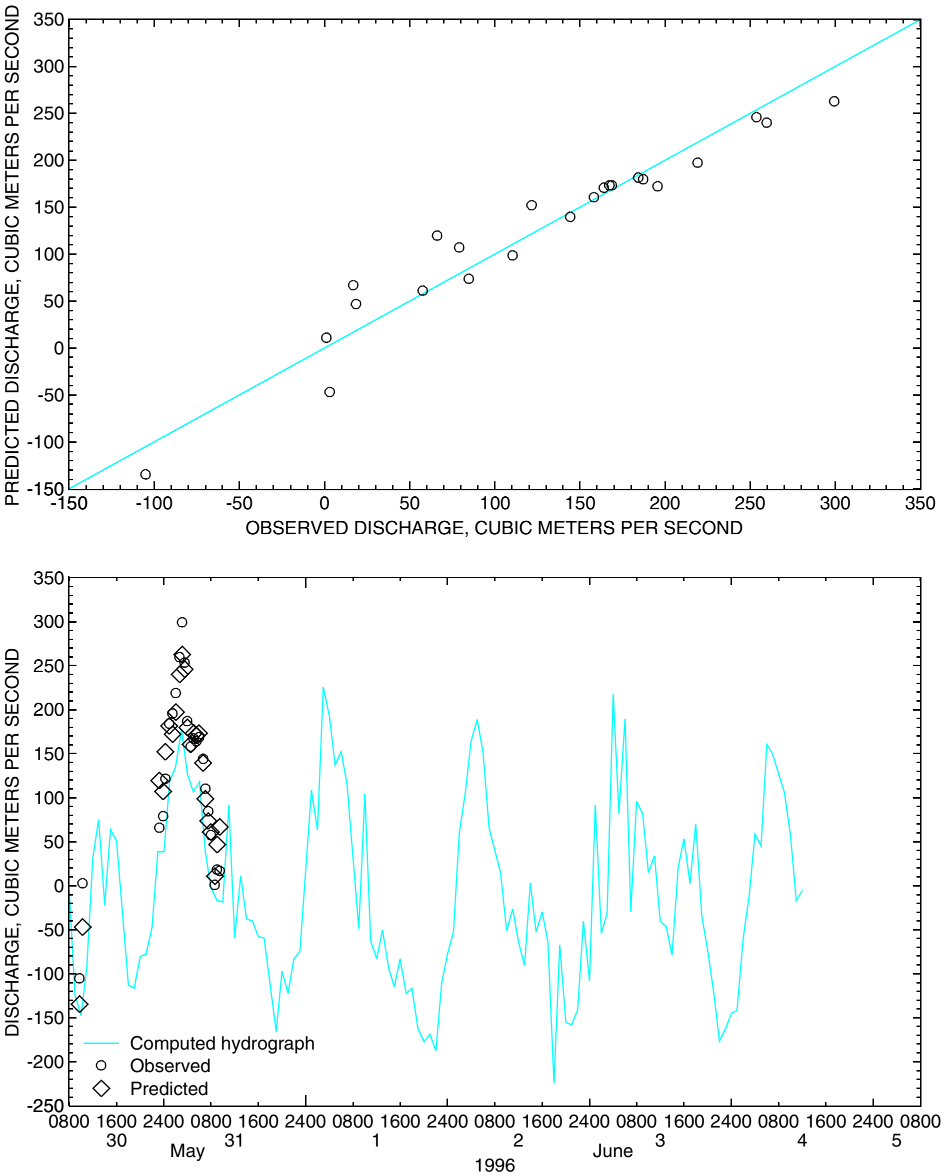


**Figure 2.** Predicted versus observed discharges, and hydrograph computed from regression for the Gulf Intracoastal Waterway at State Highway 87.

### Gulf Intracoastal Waterway at State Highway 87

The AVM velocity and stage were recorded automatically at 2-minute intervals while the ADCP measurements were made. The three ADCP measurements from each flow condition were averaged, and the mean ADCP-measured discharge was regressed against the mean velocity that was recorded while the ADCP measurements were made; a total of 23 data points were available to develop the rating. Discharge ranged from -105.1 to 299.3 cubic meters per second ($m^3/s$), velocity ranged from -59.7 to 85.0 centimeters per second (cm/s), and normalized stage ranged from -0.21 to 0.132 m. Equipment and personnel constraints limited the range of flows measured. Only one negative flow was measured. Consequently, this rating is not considered accurate for negative flows.

### Sabine River

The APVM velocity and stage were recorded automatically at 5-minute intervals while the ADCP measurements were made. The three ADCP measurements from each flow condition were averaged, and the mean ADCP-measured discharge was regressed against the mean velocity; a total of nine data points were available to develop the rating. Discharge ranged from -461.4 to 634.6 $m^3/s$, velocity ranged from -14.0 to 34.7 cm/s, and normalized stage ranged from -0.11 to 0.09 m.

### Black Bayou

The APVM velocity and stage were recorded manually before and after each set of three ADCP measurements because of an equipment limitation. The flow conditions changed more rapidly at this site than the other two sites, and several minutes elapsed between the manual readings and the ADCP measurements. The velocity and stage recorded before the set of three ADCP measurements generally were different than those recorded after, indicating that the hydraulic conditions were changing during the discharge measurements. The third (final) ADCP discharge measurement was regressed

**Table 2.** Regression coefficients and diagnostic statistics for discharge ratings

[equation: $Q = B_1 + B_2V + B_3S$, where Q is estimated discharge in cubic meters per second; V is measured velocity in centimeters per second; and S is stage in meters above (+) or below (-) the mean stage measured during the hydrographic survey; p-value, attained significance level; $R^2$, coefficient of determination (variability in the measured discharges explained by the equation); RMSE, root mean square error (square root of the mean of the squares of the regression residuals) in cubic meters per second; n/a, not applicable. Stage not in regression because identical discharges were recorded for two different stages (loop rating).]

| Site name | $B_1$ (p-value) | $B_2$ (p-value) | $B_3$ (p-value) | $R^2$ | RMSE |
|---|---|---|---|---|---|
| GIW at State Highway 87 | +29.37 (0.001) | 2.74 (<0.001) | n/a | 0.93 | 26.4 |
| Sabine River | -153.4 (0.003) | 21.97 (<0.001) | n/a | .96 | 91.3 |
| Black Bayou | -1.72 (0.734) | 1.20 (0.010) | -256.2 (0.029) | .98 | 5.6 |

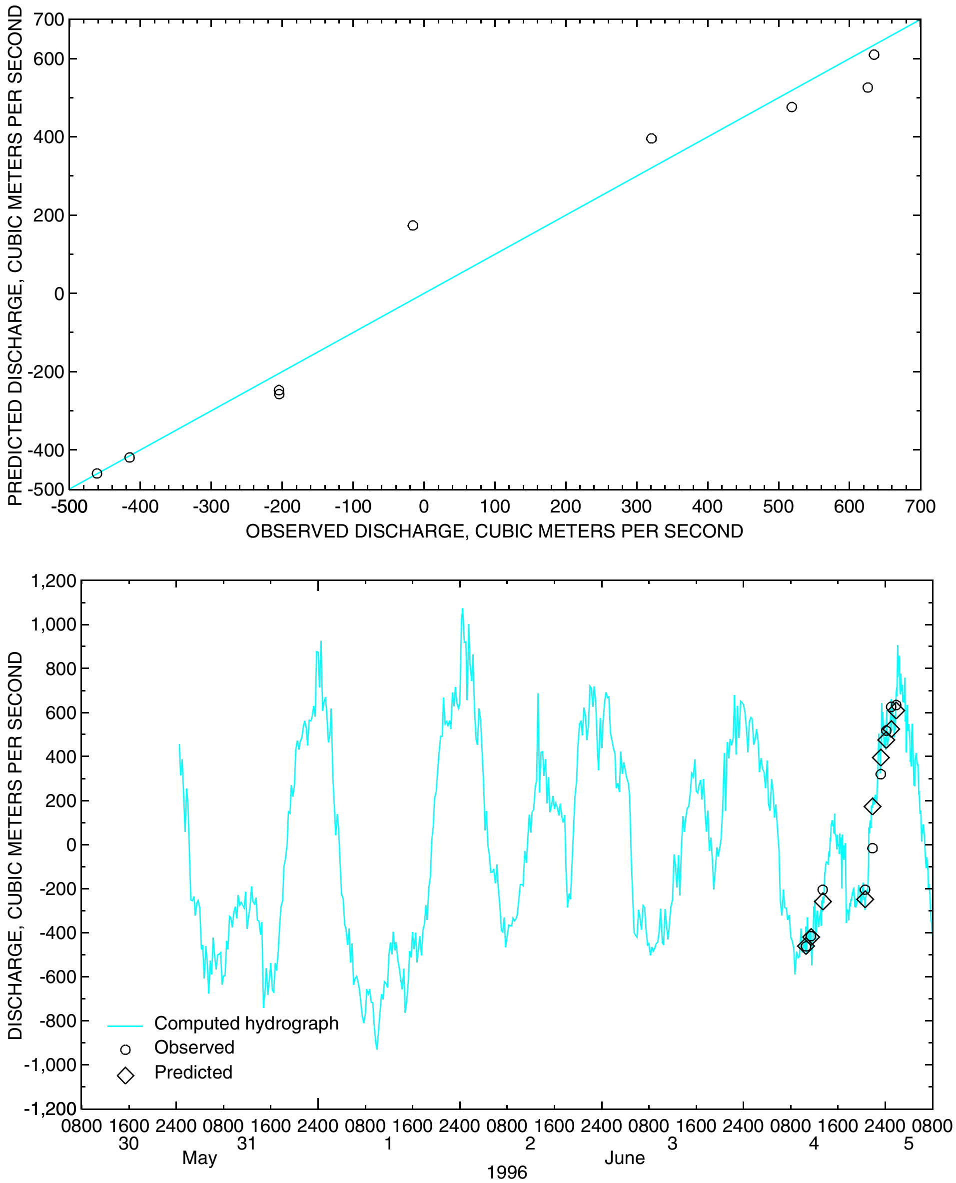


**Figure 3.** Predicted versus observed discharges, and hydrograph computed from regression for the Sabine River.

against the final velocity and stage readings because that set of discharge and velocity/stage measurements occurred closer in time than the earlier measurements. A total of nine data points were available to develop the rating. Discharge ranged from 31.7 to 54.2 $m^3$/s, velocity ranged from -22.5 to 19.6 cm/s, and normalized stage ranged from -0.13 to 0.04 m.

### *Rating Results*

Graphs of stage versus discharge for the GIW and Sabine River sites indicated loop ratings (identical discharges for two different stages), but an insufficient number of measurements were made to define the looping characteristics sufficiently to include stage in the regressions. Bidirectional flow commonly occurs at small discharges (when the tide changes direction); thus, small discharges computed from the ratings are imprecise for all three sites. At larger, sustained flows, however, bidirectional flow does not occur, and the velocities provide accurate indices of the overall flow conditions. None of the sets of rating measurements cover the entire range of velocities or stages measured during the hydrographic survey. However, the ratings are linear over the range of the measured data, and the accuracy of the discharges computed by extrapolating the ratings to the range of velocities and stages measured during the hydrographic survey are considered sufficient for model calibration and testing.

Graphs of the predicted versus observed discharges and the discharge hydrographs computed using the regression relations are shown in figures 2–4. The observed and predicted discharges also are shown on the hydrographs. The predicted and observed discharges do not plot directly on the computed hydrographs in most cases because of the methods used to collect and process the data. For the GIW and Sabine River sites, each observed discharge is the mean of three ADCP measurements and represents the average discharge over the time period required to make the measurements (typically about 10 minutes). Additionally, the velocities and stages used to develop the regression relations are the mean values measured during the time required to complete the ADCP measurements, whereas the velocities and stages used to compute the hydrographs are instantaneous values. For Black Bayou, there was a time lag of several minutes between the start of the third ADCP measurement and the time at which the stage and velocity were recorded manually, and flow conditions were observed to change somewhat during the ADCP measurements. Additionally, for all three sites, the velocity and stage readings used to compute the discharge hydrographs are those recorded at the beginning of each hour. The time period shown on the hydrograph plots includes the 3-day hydrographic survey as well as the time period over which rating data were collected.

## Summary

Discharges during a hydrographic survey of Sabine Lake were computed at three sites using velocity and stage measured with automated stations, and ratings developed by regressing discharge against velocity and stage. The automated velocities, particularly point velocities, do not provide accurate indices of overall channel conditions at the small discharges commonly encountered when the tide changes directions; the ratings presented here are not precise at small discharges. However, the ratings provide acceptable accuracy at the medium and large discharges used for model calibration. The

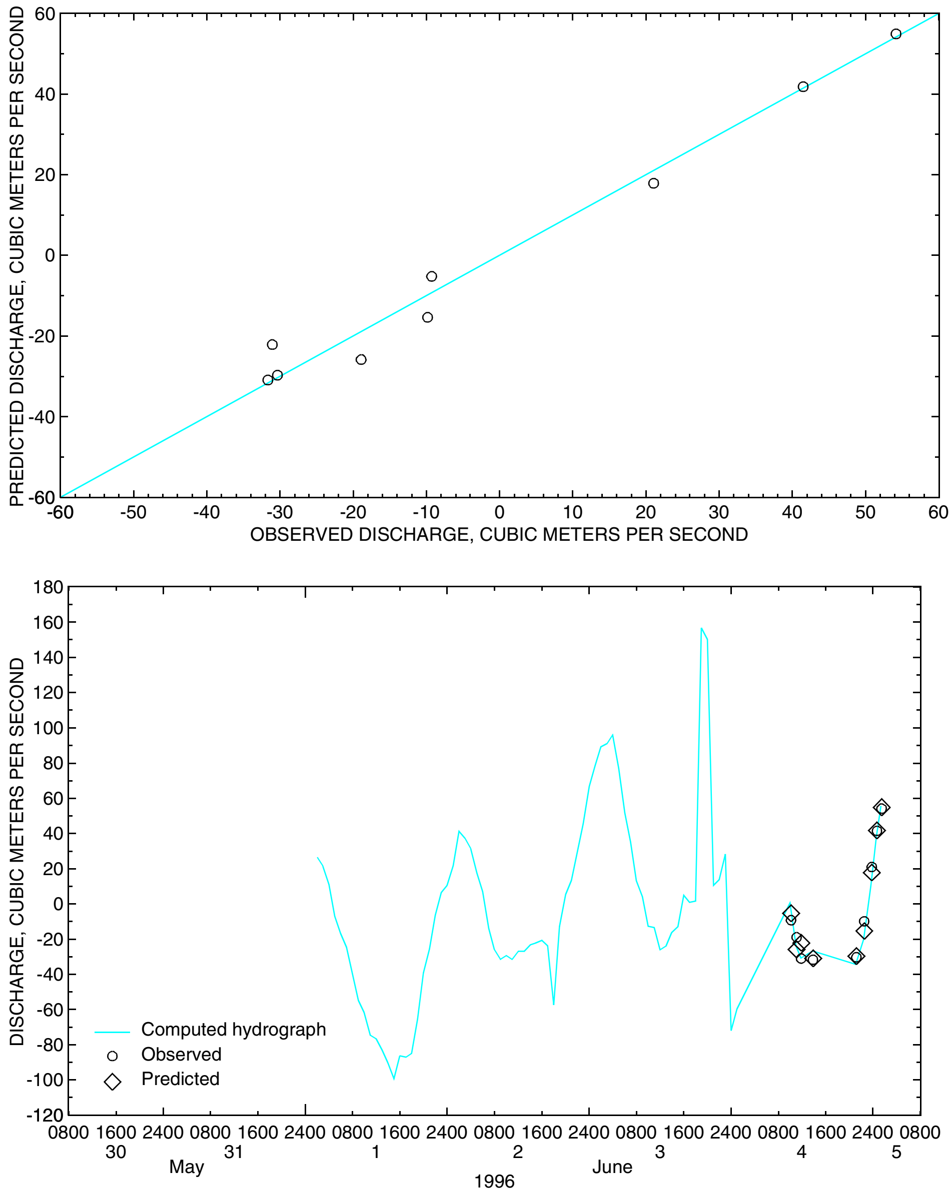


**Figure 4.** Predicted versus observed discharges, and hydrograph computed from regression for Black Bayou.

use of stations with automated instrumentation optimized personnel resources and allowed manual measurements of velocity and water quality to be made at additional locations where installation of automated instrumentation was not feasible.

Based upon these promising results, the use of automated instrumentation will be expanded during future hydrographic surveys to further reduce labor requirements and to provide higher-quality data than can be obtained manually.

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