USE OF ACOUSTIC VELOCITY METHODS AND REMOTE SENSING TECHNIQUES TO MEASURE UNSTEADY FLOW ON THE LOWER YAZOO RIVER IN MISSISSIPPI

D. Phil Turnipseed, Lance M. Cooper, and Angela A. Davis
U.S. Geological Survey, WRD
Pearl, Mississippi

INTRODUCTION

The Yazoo River Basin is Mississippi's largest source of fresh surface-water discharge and an abundant and important natural resource; however, much is unknown of the real-time flow conditions (dynamic channel geometry, velocity distribution and direction, and other hydraulic characteristics) in the complex riverine and backwater-affected reaches in the lower basin. Historically, varied, non-uniform open-channel hydraulic streamflow conditions have made the measurement and computation of streamflow difficult and, in some circumstances, impossible. The computation of continuous streamflow, as well as the design of hydrodynamic flow models, requires adequate understanding of the physical attributes of these complex flow phenomena.

Since 1995, the USGS, in cooperation with the Mississippi Department of Environmental Quality, Office of Land and Water Resources (MDEQ-OLWR), has been actively developing a means of computing real-time continuous streamflow for the lower Yazoo River Basin. In accordance with the National Water Quality Assessment program, the USGS has been collecting many water-quality and biological samples throughout the Yazoo River Basin since January 1996. Measurement of continuous discharge in the lower basin has historically been impractical, especially during periods of high flow on the Mississippi River which can result in bi-directional flow and full flow reversal in the lower Yazoo River Basin reaches.

Extreme rainfall in the upper Ohio River Basin in February and March 1997, in combination with unusually high snow melt in the Mississippi River Basin, resulted in significant flooding on the Mississippi River near Vicksburg, Mississippi, in late March 1997. The flooding recurrence interval at the U.S. Army Corps of Engineers (USACOE) streamgage on the Mississippi River at Vicksburg was about 10 years based on a Log-Pearson Type III distribution analysis by Landers and Wilson (1991). The Mississippi River at this gage rose more than 6 ft (feet) above flood stage and inundated many thousands of acres of land in the lower Yazoo River Basin. This flooding created extremely complex flow conditions in the lower Yazoo River. Drainage control structures for the Steele Bayou and the Little Sunflower River were closed on March 7 and February 9, 1997, respectively, to protect the lower Yazoo River Basin from flooding by the Mississippi River. The Steele Bayou Drainage Control Structure was not reopened until April 11, 1997, and the Little Sunflower River Drainage Control Structure was not reopened until April 15, 1997 (W. Hill, USACOE, oral communication, 1998). Substantial rainfall from the Delta region of the Yazoo River Basin accumulated behind the protected levees during the time that these two drainage control structures were closed, which worsened the flooding conditions in the lower basin.

During high-flow conditions on the Mississippi River, flow at the USGS streamgage at the Yazoo River below Steele Bayou near Long Lake, Mississippi (hereafter referred to as the Yazoo River gage) can be bi-directional or fully reversed and, therefore, cannot be gaged adequately at this location. Recent advances in sonar technology have greatly enhanced the calibration, performance, evaluation, and design of hydrodynamic flow models used to simulate the complex flow in riverine and estuarine systems, and have provided a means of accurately computing real-time continuous streamflow data. Using state-of-the-science signal processing technology known as pulse-to-pulse coherent sonar (RD Instruments 1993), the USGS, in cooperation with the DEQ-OLWR and the Mississippi Department of Transportation (MDOT) has regularly profiled three-dimensional velocities at many locations throughout Mississippi by using an Acoustic Doppler Current Profiler (ADCP) [the use of trade or product names in this report is for identification purposes only and does not constitute endorsement by the USGS]. Velocity measurements made using this technology have compared favorably to measurements obtained by using standard USGS methods of measuring velocity (Rantz et al. 1982). In-situ acoustic technology has also been applied at locations in the state where, until recently, it has been extremely difficult to obtain continuous discharge due to tidal or other unsteady flow conditions. Computation of continuous discharge during floodplain flow on the lower Yazoo River is paramount in the design of hydrodynamic models, the understanding of sediment and nutrient fluxes, and the management of water resources in the lower basin.

Purpose and Scope

This report describes acoustic-signal methodology and remote sensing techniques used to compute discharge during periods of varied, non-uniform flow caused by backwater

from the Mississippi River and presents streamflow data collected by the USGS in 1996-97 for the lower Yazoo River. These data were computed with data collected by using conventional streamgaging methods, an ADCP to measure three-dimensional velocity profiles, and a continuous-recording acoustic velocity meter (AVM). Examples of continuous stage, velocity, and discharge computed with data obtained from the Yazoo River gage are presented for low and medium flows. A separate computation method was developed and is presented for locating discharge at the site during high-flow conditions by using a combination of acoustic sensing instruments, global positioning system (GPS) equipment, and remote sensing technology.

Study Area Description

The study area encompasses the lower 17 miles of the Yazoo River in Warren and Issaquena Counties in Mississippi (Figure 1) from just upstream of the U.S. Highway 61 crossing near Redwood, Mississippi, to near the Port of Vicksburg levee. According to the U.S. Engineer Office (1941), the drainage area at the Yazoo River gage (River Mile 9.5), which is upstream of the confluence of the Yazoo River Diversion Canal with the Mississippi River at Vicksburg, is about 13,400 square miles. This location includes all flow in the basin including that from Steele Bayou, Deer Creek, Bogue Phalia, and the Big and Little Sunflower Rivers. Flow from the aforementioned tributaries is controlled by two drainage control structures upstream from River Mile 9.5. The lower basin tributaries are protected from high flows from the Mississippi River by means of the two drainage control structures and a continuous levee located longitudinally along the right (north) bank from the main channel of the Mississippi River to U.S. Highway 61 and beyond. The Loess Bluffs run longitudinally along the left channel bank of the Yazoo River and constrict at a point near the U.S. Highway 61 crossing, forming a natural levee.

STREAMFLOW DATA COLLECTION

Measurement of discharge on the lower Yazoo River began in 1874 (U.S. Engineer Office 1941). In July 1928, the USGS began observing river stage and measuring discharge on the lower Yazoo River near Redwood, Mississippi. Occasional discharge measurements were made at Redwood from 1928 through 1995. Since January 1996, measurements have been made at 1- to 2-week intervals at the Yazoo River below its confluence with Steele Bayou. In October 1996, the USGS, in cooperation with the DEQ-OLWR, and the USACOE Vicksburg District, constructed the Yazoo River gage. This gage provides base data for the computation of sediment and nutrient loads and other water quality and biological data needed for the appropriate management of this important natural resource.

Since October 1996, the USGS has recorded stage, velocity, and other parameters at 1-hour intervals through a Data Collection Platform (DCP) at the Yazoo River gage. Data are transmitted by satellite to the USGS at 4-hour intervals. Stage is measured using a non-submersible transducer attached to a steel-pipe pile cluster near the left (south) bank. The transducer measures water pressure in pounds per square inch at the orifice end in the river, contrasts this to atmospheric pressure at the gage house, and then converts the pressure to feet of water and transmits this value to the DCP where it is recorded. Velocity is measured and transmitted to the DCP using an AVM which receives data from up to four transducers mounted on steel-pipe pile clusters near the left (south) bank near the gage and right (north) bank about 500 ft upstream of the gage. Discharge measurements were made at the site at 1- to 2-week intervals with either an ADCP mounted to a boat or a standard current meter attached to a sounding weight from a boat during low and medium flows.

REMOTE SENSING DATA COLLECTION

On March 22, 1997, the USGS, in cooperation with the U.S. Department of Agriculture Forest Service, the USACOE Vicksburg District, the USACOE Waterways Experiment Station, and the Environmental Protection Agency, Georgia District, Region 4, contracted procurement of aerial photography of the lower reach of the Yazoo River Basin in Mississippi to help determine and document flow conditions during a high-stage event. This photography was obtained during the March 22-23, 1997, peak stage conditions on the Mississippi River near Vicksburg, Mississippi.

The aerial photography was taken at an altitude of 12,000 ft. The flight lines consisted of 26 strips running from north to south with an individual photograph overlap of 60 percent in the forward (north/south) direction and 20 percent in the side (east/west) direction. This overlap assured that the area encompassing the site was completely covered and that photo-interpretation of the photography could be accomplished.

The aerial photography was exposed on black-and-white aerial film using a Jena LMK 15/2323 camera equipped with forward motion compensation. The film was developed at a scale of 1:24000 and processed into black-and-white photographs at a size of 9-in by 9-in, which produced 679 photographs. These photographs were then scanned at a resolution of 600 dots per inch (dpi) with a scale resolution of about 1-meter. After the digital images were created, they were written to compact disk. An additional coverage was produced which consisted of a 1:250,000 USGS digital

raster graphic (DRG), with the flight lines digitized onto it as a separate coverage. This was also written to a compact disk producing a total of 30 compact disks.

METHODS

Analysis of the data collected for this report was accomplished in two steps: 1) Unsteady flow in the channel (for low and medium stage flows less than 91 ft of stage at the Yazoo River gage); 2) Unsteady flow in the floodplain (for high stage flows greater than 91 ft of stage at the Yazoo River gage). Both steps required the use of conventional and unique computational processes to analyze the data.

Unsteady flow in the channel

Chow (1959) documented that discharge (Q) in cubic feet per second for steady or unsteady open-channel flow in a given channel section can be expressed as:

$$VA = Q \quad (1)$$

where, for the purposes of this report, V is the mean velocity in feet per second, and A is the cross-sectional flow area in square feet normal to the direction of the flow. The law of continuity for unsteady flow requires consideration of time. To compute continuous discharge at the Yazoo River gage during periods of low and medium flow, when unsteady flow conditions existed as a result of backwater effects from the Mississippi River on stage and velocity, a relation was developed between the velocity continuously measured by the AVM and the average velocity computed from the ratio of measured discharge to area. Acoustic transmitting and receiving transducers were placed at an elevation of about 45 ft above sea level on the downstream side of two steel-pipe pile clusters located on the left (south) bank near the gage and the right (north) bank about 500 ft upstream of the gage. Transducers are devices that convert electrical signals to sound and vice versa. An AVM measures travel time of sound through water using a differential travel time. The differential travel time is determined by making two successive measurements on a given path in each direction. The forward direction is measured by logging the travel time of sound from the upstream to the downstream transducer; the reverse direction measurement is the travel time of the sound from the downstream to the upstream transducer. Therefore, the arrival time of the sound signal from the forward direction measurement will be shortened in proportion to the water velocity. When the velocity is zero, the forward and reverse travel times are equal. The AVM in use at this gage senses both positive and negative directions of flow. The relation can be best defined as:

$$TF = L/(C + v\cos A) \quad (2)$$
$$TR = L/(C - v\cos A) \quad (3)$$

where:

TF is travel time in the forward (downstream) direction, in seconds;
TR is travel time in the reverse (upstream) direction, in seconds;
L is the path length between the two transducers, in ft;
C is the speed of sound, in feet per second;
v is the velocity of the water along the path, in feet per second; and
cos A is the cosine of the path angle from the direction of flow.

Solving both equations for the speed of sound results in the following equation:

$$L/TF - v\cos A = L/TR + v\cos A \quad (4)$$

The equation is further simplified by solving for v:

$$v = L/2\cos A(1/TF - 1/TR) \quad (5)$$

The speed of sound can be altered by temperature, pressure, and salinity; therefore the elimination of the speed of sound in equation 4 simplifies the computation of an instantaneous point velocity and eliminates the need to measure other variables to account for changes in the speed of sound. Compensation was also made for signal delays due to cable length, transducer characteristics, and electronic hardware within the AVM. The transducers measure instantaneous point velocity and transmit this value to the AVM which in turn transmits the data to a data logger on 1-hour intervals. Discharge measurements by conventional methods (Rantz et al. 1982) and by an ADCP were used to develop a relation between the instantaneous point velocity measured by the AVM and average velocity computed from these discharge measurements. The ADCP has four transducers that transmit pulses of sound into the water. The transducers then measure the return sound as it is echoed from small ambient particles floating with the water currents. Using the Doppler principle, the ADCP converts the returned sound into components of water-current velocity. The ADCP measures both the speed and direction of the water currents at multiple locations in the water column. It is beyond the scope of this report to detail all the vector mechanics involved in how the ADCP computes its position through time. Comparison of nearly simultaneous discharge measurements by personnel of the USGS have shown that the ADCP can measure discharge within 5 percent of the measurement obtained using a standard current meter (Morlock 1996). Comparison of the typical curves of equal velocity in a natural, irregular channel cross section from Chow (1959) and a cross section showing similar velocity

curves generated from ADCP data at the Pascagoula River at Graham Ferry, Mississippi, on October 11, 1994, show good correlation between theoretically generated open-channel velocity distribution and actual field measurements of velocity distribution measured with and ADCP (Turnipseed and Storm 1995).

A relation for the Yazoo River gage was developed between average velocity computed by dividing the measured discharge by the area and instantaneous point velocity measured by the AVM (Figure 2a). Discharge measurements made at 1- and 2-week intervals from October 1996 through February 1998 at the Yazoo River gage were used to develop this relation between average velocity across the measured channel-bed cross section and the instantaneous point velocity measured at an elevation of about 45 ft above sea level by the AVM transducers. This equation may be expressed as:

$$V = 0.356 + 0.633v \quad (6)$$

where V is the average velocity for the cross section, 0.356 is the y-offset, in ft, 0.633 is a dimensionless slope coefficient, and v is an instantaneous point velocity measured by the AVM, in feet per second. Because average velocity is inversely proportional to area for a given constant discharge, if area changes, then velocity also changes. Given this and the unsteady nature of streamflow affected by backwater from the Mississippi River at the gage, slope and offset may change over time. For the purposes of this report, equation 6 is assumed to be valid for flow conditions during the period of the study (October 1996 through October 1997).

To compute average velocity from measured discharge, a stage/area relation was developed using a fathomed cross section surveyed on May 29, 1996, and area was computed at 1-ft elevation intervals to develop a stage/area relation for stages up to 91 ft above sea level (Figure 2b). To compute discharge during periods of backwater affected flow, the velocity relation (eq. 6) was used to compute mean velocity from instantaneous point velocity which was then multiplied by the area determined from the stage/area curve. The product of these two variables is an instantaneous discharge. Stages above 91 ft cannot be adequately computed by using the existing gage because of significant floodplain flows.

Unsteady flow in the floodplain

Discharge during unsteady flow conditions in the floodplain was located and computed using existing acoustic doppler methods and remote sensing technology. As previously stated, during March and April 1997, the Mississippi River experienced a flood of about a 10-year recurrence interval which caused significant backwater at the Yazoo River gage. River levels rose more than 7 ft above the left (south) bank at the gage. Streamflow at this stage could not be adequately computed at the existing gage and was, therefore, determined by using the following five steps:

1) Determination of flow direction. To compute discharge during floodplain flow, a determination of flow direction in this region was necessary not only for the March 1997 flood, but also for future reference. During the over-flight, ground crews were deployed in boats with Global Positioning System (GPS) equipment and compasses to obtain flow direction at selected locations in the lower reaches.

2) Formation of photo-mosaic of the lower Yazoo River Basin. Error is inherent in all maps and is often introduced into photographs because of inconsistency in the plane's path caused by unexpected changes in aircraft elevation, altitude, or tilt changes. Radial error is also introduced to photographs by curvature of the camera lens. Most gross errors in the aerial photography were rectified using a remote sensing software application on a personal computer.

Creating a photo-mosaic of the photographs to produce a single coverage of the study area for entry into a geographic information system (GIS) involved geo-referencing the photographs to known ground-control points. Geo-referencing of the aerial photography was resolved by using a remote sensing software application on a personal computer. Each digital photograph was displayed on-screen along with a 1:24,000 digital raster graphic (DRG) of the study area. Points were picked from the photographs and correlated to known ground-control points (that is, roadways, powerlines, buildings and other cultural features) locatable on the DRG. At least three ground-control points are required to reference each photograph but as many points as possible were used to maximize accuracy. The points were then recalculated to coincide with the points on the DRG thus creating a geo-rectified image. The photographs were then prepared for assembly into the final photo-mosaic. First the border, incorporating the flight information, was removed from each photograph. This was accomplished through a process known as photo-subsetting. By selecting the part of the photograph lying inside the border, it was then possible to crop the image and remove the border. After this process was completed on all the photographs in the study area, the images were ready to be pieced together into a photo-mosaic. This was accomplished by opening all the images into a single view, setting a user-defined percentage of side and top overlap for each photo, and then allowing the software to process the final photo-mosaic image.

The aerial photographs comprising the photo-mosaic image of the study area have a RMS (root mean square) error of between 0.03 and 13 pixels. The high RMS error in some of

the aerial photographs was due to the lack of good geographic control points. Many of the aerial photographs are of flooded or forested lands of the Delta with very few cultural features identifiable for use as good ground-control points.

3) Spectral classification of land and water. Land and water separation in the photo-mosaic of the study area was achieved through the performance of a supervised classification in ERDAS Imagine to help determine the areal extent of flooding. Classification is the process of grouping pixels (separate rasterized picture elements which, in this imagery, represent about 1 square meter of the basin) of similar characteristics by color in a signature editor. A supervised classification allows the analyst to determine the patterns in the image using information such as aerial photographs and digital images (ERDAS 1997). Patterns are indicated in an AOI (area of interest) layer by drawing small polygons around pixels with similar characteristics. Areas of the photo-mosaic that were interpreted as water were enclosed in polygons and labeled with a blue-green color in the signature editor. Similarly, the areas interpreted as land were labeled with an automatically assigned gray-scale color. More than one hundred polygons in the AOI layer separated the land and water areas of the photo-mosaic. The large number of polygons in both the areas of land and water were due to varying pixel characteristics between individual photographs within the photo-mosaic. A statistical analysis subsequent to grouping of the patterns set by the analyst in the AOI layer results in a final classified image. As a result of this procedure, the 136 classes were reduced to 24 classes.

The photography was exposed on black-and-white panchromatic film. During flooding of the lower Yazoo River Basin, a region of low slopes and relief, water depths in many flooded areas were very shallow, and the water was clouded with high sediment loads. The classified image resulted in a separation of land and water with a 50-percent accuracy.

4) Determination of flow location. During the March 1997 flood in the Lower Yazoo River Basin, crews were deployed at less than 1-week intervals to measure discharge and determine flow conditions at predetermined locations. In all, 60 separate discharge measurement transects were made with an ADCP to help address flow magnitude, location, and direction. Measurement transects were made at the following locations:

1. Channel cross sections at the Yazoo River gage;
2. Channel cross sections from the Steele Bayou Drainage Control Structure to the top of the left (south) bank;
3. Floodplain cross sections along Long Lake Road from the top of the left (south) bank to the Vicksburg Port levee;
4. Channel and floodplain cross sections at the U.S. Highway 61 crossing of the Yazoo River.

Measurements from these four locations were used to compute continuous discharge in the lower Yazoo River Basin during stages greater than 91 ft at the Yazoo River gage. Measuring consecutively at these locations also helped determine when flow returned to within the channel banks and, therefore, when the AVM gage data could be used to compute continuous discharge for the river.

5) Continuous-discharge computations during floodplain flow. Linear interpolation between ADCP discharge measurements made from March 11 through April 17, 1997, in the lower Yazoo River Basin was used to compute daily mean discharges at the Yazoo River gage during the period (stage greater than 91 ft) when flow in the channel at the gage was not representative of flows for the basin. Discharge measurements made during this period were assumed to have represented flow in the channel and the floodplain (table 1) in the lower reach of the Yazoo River.

RESULTS

Continuous streamflow data, as well as data for other channel characteristics, have been collected, processed, and computed since October 1995 for the USGS continuous recording streamgage at the Yazoo River below Steele Bayou near Long Lake, Mississippi. Analyses of the data provide continuous stage/discharge information through time at the gage.

During a high stage event on the Mississippi River, aerial photography was obtained of the lower Yazoo River Basin. This photography was digitized onto compact discs, assembled into a photo-mosaic, entered into a GIS, and spectrally classified into land and water classes. This land and water GIS coverage was overlain with surface-water flow direction vectors collected in the field with GPS equipment during and after the over-flight. ADCP discharge measurement transects of the lower Yazoo River Basin during peak stages on the Mississippi River at Vicksburg, Mississippi, were also overlaid onto the land and water coverage (Figure 3). The GIS processing of digitized and assembled black-and-white aerial photography, which includes spectrally classified land and water, flow direction at select locations during a significant flooding event on the Mississippi River and the lower Yazoo River Basin provides reference to flow characteristics in the basin during the March 1997 flood, as well as permanent documentation for future studies of the area.

Channel-bed cross sections in the vicinity of the gage were surveyed every 1 to 2 weeks by using data measured by an ADCP. A channel-bed cross section near river mile 10 was

used to develop a stage/area relation for use in computing discharge at the Yazoo River gage during low and medium flows affected by backwater from the Mississippi River. A relation between average velocity, computed from measured discharge, and the instantaneous velocity, measured by an AVM, was developed. Discharge was measured for unsteady flow conditions at the gage by using an ADCP and conventional velocity-measuring instruments.

Two methods were used to compute continuous discharge. The product of an average velocity for the entire channel cross section (derived from the relation between average velocity and point velocity) and a cross-sectional area was used to compute discharge for stages less than 91 ft. Discharges computed for stages less than 91 ft represent low and medium flow periods affected by backwater from the Mississippi River (Figure 4a). During the March 1997 flooding of the lower Yazoo River Basin, 60 ADCP discharge measurements were made in the lower basin to help determine flow location and direction and for use in the computation of continuous discharge for the Yazoo River gage. A linear interpolation between discharge measurements was used during this period of unsteady flow to compute continuous discharge at the gage for stages greater than 91 ft (Figure 4b).

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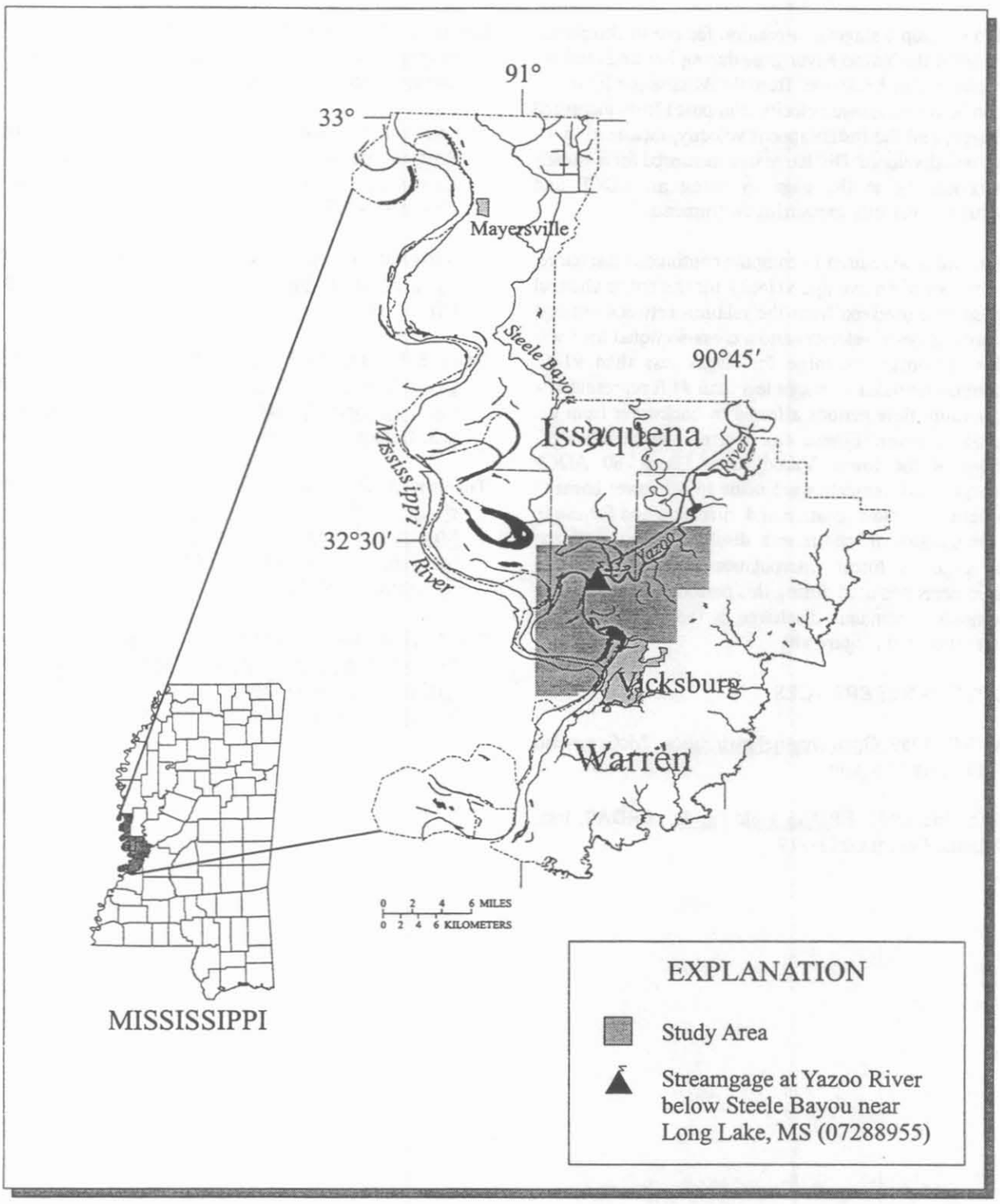

Figure 1. Location of study area in lower Yazoo River Basin, in Mississippi.

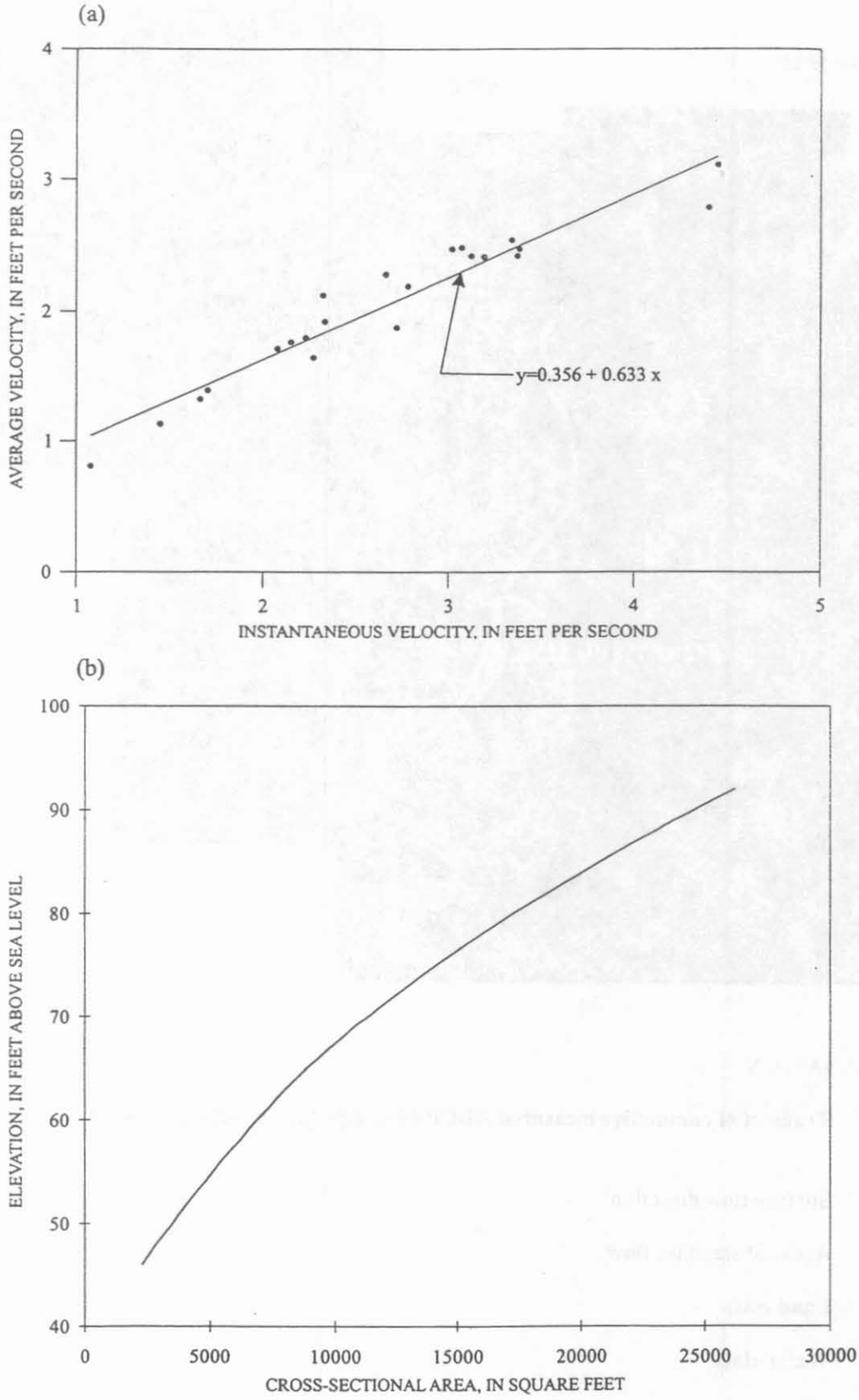

Figure 2. Average velocity/instantaneous velocity relation(a) and, stage/area relation (b) used to compute discharge at Yazoo River below Steele Bayou near Long Lake, MS (07288955).

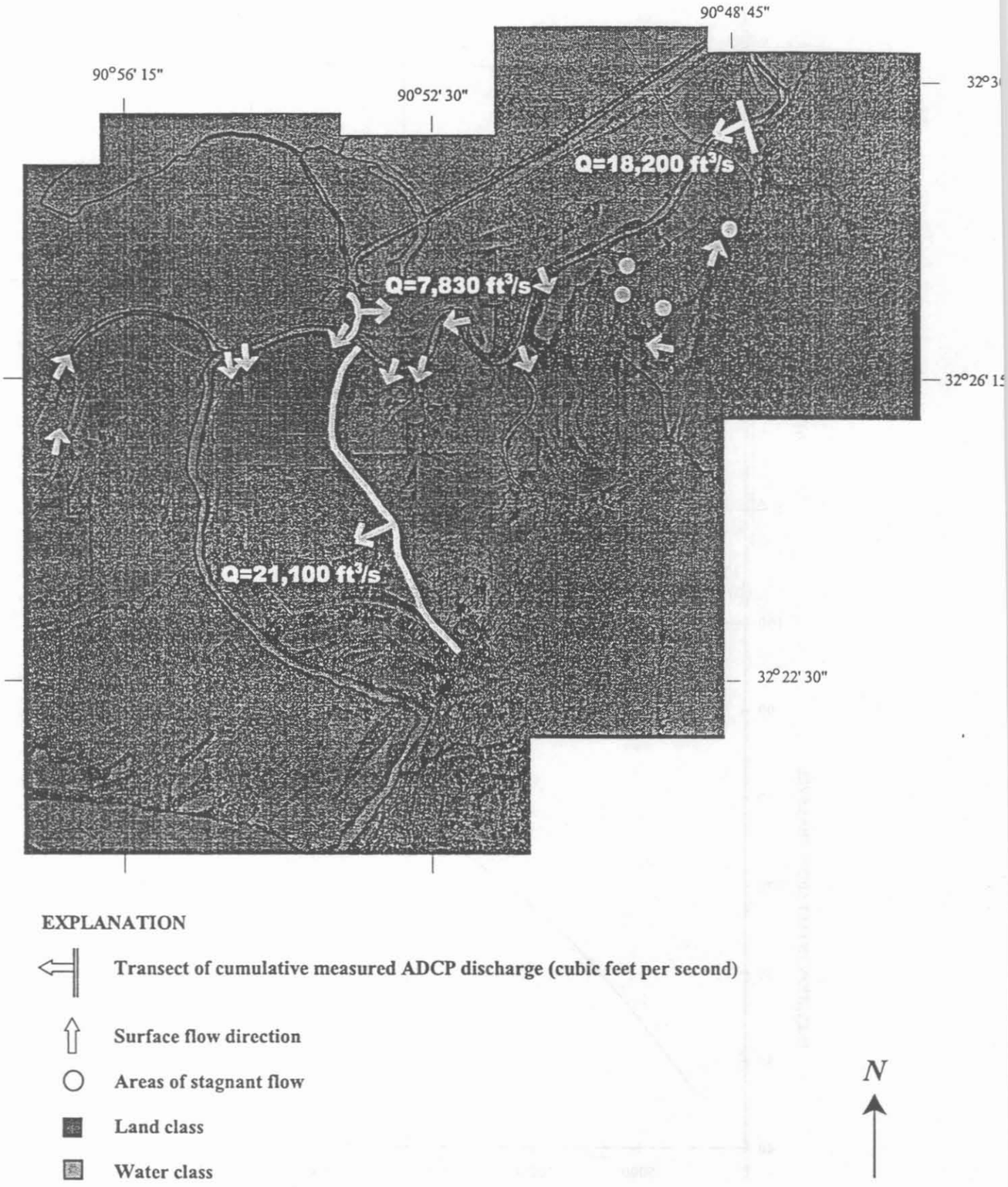

Figure 3. Spectral classification of land and water overlaid with flow direction and ADCP measured discharge transects in cubic feet per second at selected locations in the lower Yazoo River Basin, Mississippi on March 23-24, 1997.

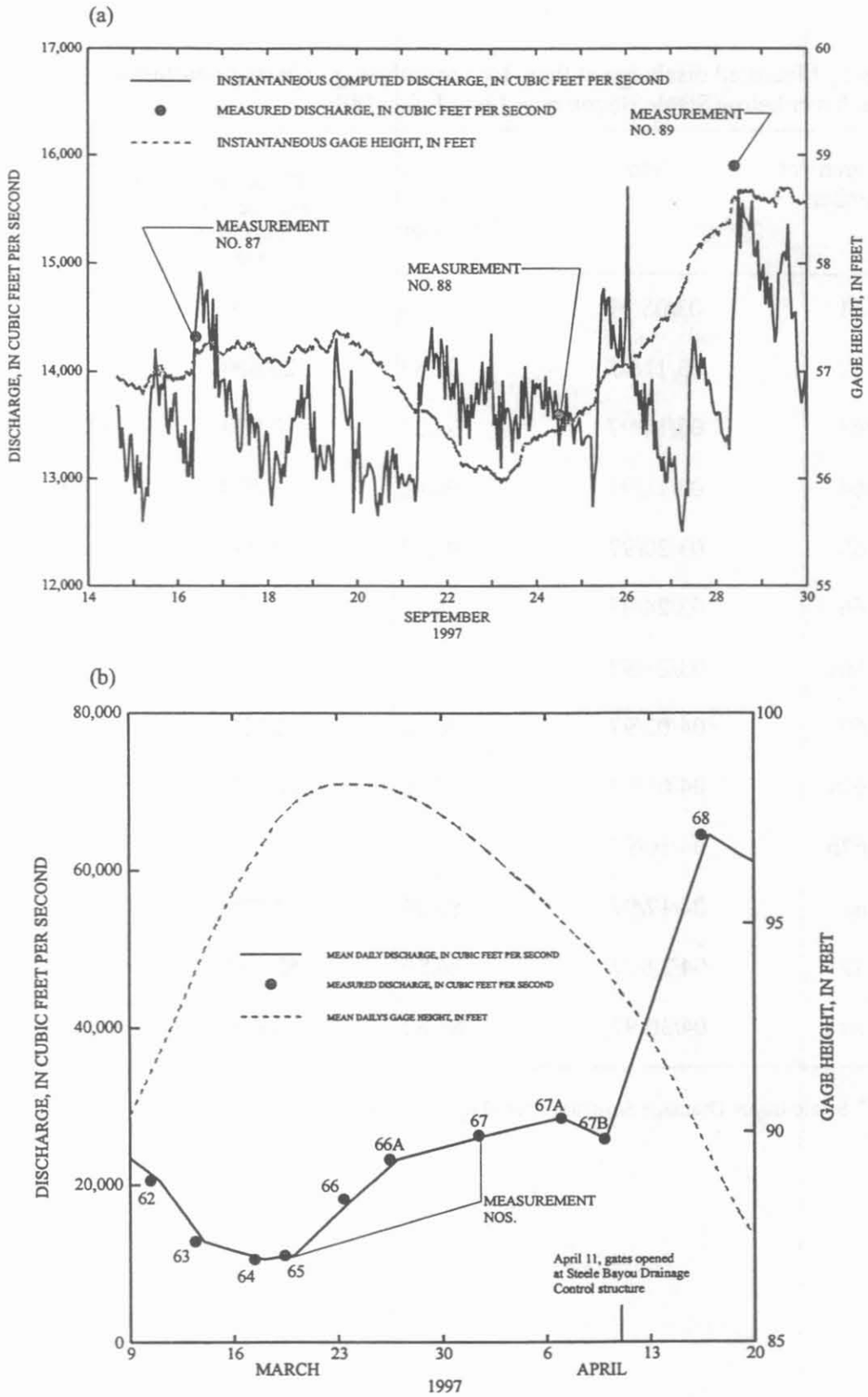

Figure 4. Instantaneous computed stage and discharge from September 15 through 30, 1997 (a) and computed daily mean stage and discharge for March 10 through April 20, 1997 (b) for the Yazoo River below Steele Bayou near Long Lake, MS (07288955).

Table 1. Measured discharge at three locations during high stage unsteady flow near the Yazoo River below Steele Bayou near Long Lake, MS.

Measurement number	Date	Water Surface Elevation (ft)	Discharge		
			Channel near gage including Right (north) floodplain	Left (south) floodplain	U.S. Highway 61 bridge
61	03/05/97	86.88	29,100	-	-
62	03/11/97	91.83	20,600	-	-
63	03/14/97	94.31	8,590	4236	-
64	03/18/97	96.88	-6,570	17,100	-
65	03/20/97	97.82	-8,230	19,300	-
66	03/24/97	98.29	-7,830	21,500	18,200
66a	03/27/97	-	-	-	23,200
67	04/02/97	96.78	5,929	-	26,200
67a	04/07/97	95.06	16,500	-	28,400
67b	04/10/97	-	-	-	25,700
68	04/17/97	89.22	64,500*	-	28,600
69	04/22/97	86.80	58,600	-	-
70	04/30/97	84.82	44,900	-	-

* Steele Bayou Drainage Structure opened April 11, 1997.