Application of Acoustic Velocity Meters For Gaging Discharge of Three Low-Velocity Tidal Streams in the St. Johns River Basin, Northeast Florida

By John V. Sloat *and* W. Scott Gain

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95–4230

Prepared in cooperation with the
St. Johns River Water Management District

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Tallahassee, Florida
1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information
write to:

District Chief
U.S. Geological Survey, WRD
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

Copies of this report may be
purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, Colorado 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
	Flow	
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

<u>Equations for temperature conversion</u> between degrees Celsius (˚C) and degrees Fahrenheit (˚F):

˚C = 5/9 (˚F - 32)
˚F = 9/5 (˚C) + 32

Acronyms and abbreviations used in report

ACM	Acoustic current meter
AVM	Acoustic velocity meter
HIF	Hydrologic Instrumentation Facility
min	minute
SDI-12	Serial Device Interface 12
SJRWMD	St. Johns River Water Management District
SEE	Standard error of the estimate
USGS	U.S. Geological Survey

APPLICATION OF ACOUSTIC VELOCITY METERS FOR GAGING DISCHARGE OF THREE LOW-VELOCITY TIDAL STREAMS IN THE ST. JOHNS RIVER BASIN, NORTHEAST FLORIDA

By John V. Sloat and W. Scott Gain

Abstract

Index-velocity data collected with acoustic velocity meters, stage data, and cross-sectional area data were used to calculate discharge at three low-velocity, tidal streamflow stations in northeast Florida. Discharge at three streamflow stations was computed as the product of the channel cross-sectional area and the mean velocity as determined from an index velocity measured in the stream using an acoustic velocity meter. The tidal streamflow stations used in the study were: Six Mile Creek near Picolata, Fla.; Dunns Creek near Satsuma, Fla.; and the St. Johns River at Buffalo Bluff. Cross-sectional areas at the measurement sections ranged from about 3,000 square feet at Six Mile Creek to about 18,500 square feet at St. Johns River at Buffalo Bluff. Physical characteristics for all three streams were similar except for drainage area. The topography primarily is low-relief, swampy terrain; stream velocities ranged from about -2 to 2 feet per second; and the average change in stage was about 1 foot.

Instantaneous discharge was measured using a portable acoustic current meter at each of the three streams to develop a relation between the mean velocity in the stream and the index velocity measured by the acoustic velocity meter. Using least-squares linear regression, a simple linear relation between mean velocity and index velocity was determined. Index velocity was the only significant linear predictor of mean velocity for Six Mile Creek and St. Johns River at Buffalo Bluff. For Dunns Creek, both index velocity and stage were used to develop a multiple-linear predictor of mean velocity. Stage-area curves for each stream were developed from bathymetric data.

Instantaneous discharge was computed by multiplying results of relations developed for cross-sectional area and mean velocity. Principal sources of error in the estimated discharge are identified as: (1) instrument errors associated with measurement of stage and index velocity, (2) errors in the representation of mean daily stage and index velocity due to natural variability over time and space, and (3) errors in cross-sectional area and mean-velocity ratings based on stage and index velocity. Standard errors for instantaneous discharge for the median cross-sectional area for Six Mile Creek, Dunns Creek, and St. Johns River at Buffalo Bluff were 94, 360, and 1,980 cubic feet per second, respectively. Standard errors for mean daily discharge for the median cross-sectional area for Six Mile Creek, Dunns Creek, and St. Johns River at Buffalo Bluff were 25, 65, and 455 cubic feet per second, respectively. Mean daily discharge at the three sites ranged from about -500 to 1,500 cubic feet per second at Six Mile Creek and Dunns Creek and from about -500 to 15,000 cubic feet per second on the St. Johns River at Buffalo Bluff. For periods of high discharge, the AVM index-velocity method tended to produce estimates accurate within 2 to 6 percent. For periods of moderate discharge, errors in discharge may increase to more than 50 percent.

At low flows, errors as a percentage of discharge increase toward infinity.

INTRODUCTION

Low-velocity tidal streams are common in the low-relief coastal areas of northeast Florida (fig. 1). Gaging of these streams is complicated by unsteady, variable flow conditions. Low-velocity tidal streams commonly have small hydraulic gradients and are susceptible to reverse flow and backwater.

The common stream-gaging practice on upland streams is the development of a discharge rating which relates discharge to gage height. This approach is based on several assumptions: (1) a reasonably stable channel and control, (2) little or no variable backwater conditions, (3) consistent gradient (no reverse flow), and (4) gravity as the principal driving force (rate of change of momentum is not great). These assumptions are not always met in the study area because of tide and backwater conditions that exist in many streams. Under these conditions, the commonly used stage-discharge relation can be very inaccurate.

An alternate approach to compute discharge is to measure a velocity index, relate the index to mean velocity, and multiply that mean velocity by cross-sectional area. An index velocity can be measured either at a point or along a line. Velocity measured along a line is likely to relate better to average stream velocity and is, therefore, a better index of mean velocity than is point velocity. The line velocity can be measured with a relatively high degree of accuracy, regardless of flow direction, by using an acoustic velocity meter (AVM; Laenen and Curtis, 1989). Cross-sectional area is easily determined from field measurements.

To improve the accuracy of discharge record for three gaging sites in the St. Johns River Basin in northeast Florida, the U.S. Geological Survey (USGS), in cooperation with the St. Johns River Water Management District (SJRWMD), instrumented three sites with AVMs during the summer and fall of 1989. Evaluation of historical records indicated that the use of standard mechanical current meters (Price AA) and simple (stage-only) discharge ratings (as described in Rantz and others, 1982) were not applicable at these three sites because of complex streamflow conditions. The decision to instrument these sites with AVMs followed the examination of field and tow-tank data collected at the USGS Hydrologic Instrumentation Facility (HIF; Laenen and Curtis, 1989) which indicated that AVMs could be used to develop accurate and dependable discharge records at low-velocity, tidally affected gaging sites. These sites are part of the basic data-collection network of the USGS.

Purpose and Scope

This report describes the instrumentation and methods applied in the use of AVMs to obtain records of discharge at the three selected sites. Instrumentation used to measure and store stream data are discussed. Procedures used to determine a calculated discharge are described. These include bathymetric surveys of channel cross sections, continuous measurement of an index velocity using an AVM, discharge measurements using a portable acoustic current meter (ACM), development of stage-area curves, statistical estimation of the relation between mean velocity and AVM-measured index velocity, computation of instantaneous discharge, and estimation of error associated with instantaneous and daily mean discharge.

APPLICATION OF ACOUSTIC VELOCITY METERS FOR GAGING DISCHARGE OF LOW-VELOCITY TIDAL STREAMS

The application of AVMs for gaging discharge in low-velocity tidal streams includes several topics directly related to the use of an AVM. These are: (1) principles of the acoustic measurement of a fluid, (2) AVM equipment installation, (3) acoustic path configurations and mean-velocity ratings, and (4) computation of discharge. Each of these topics are discussed in the following sections.

Principles of Acoustic Measurement of Fluid Velocity

The principles of acoustic measurement of fluid velocity were mathematically expressed by Smith and others (1971), and discussed in detail by Laenen and Smith (1983). Principally, an AVM measures an average stream velocity along an acoustic path diagonal to the direction of streamflow. Velocity of the water between two fixed acoustic transducers is determined from the difference in the velocity of sound between two signals propagated downstream and then

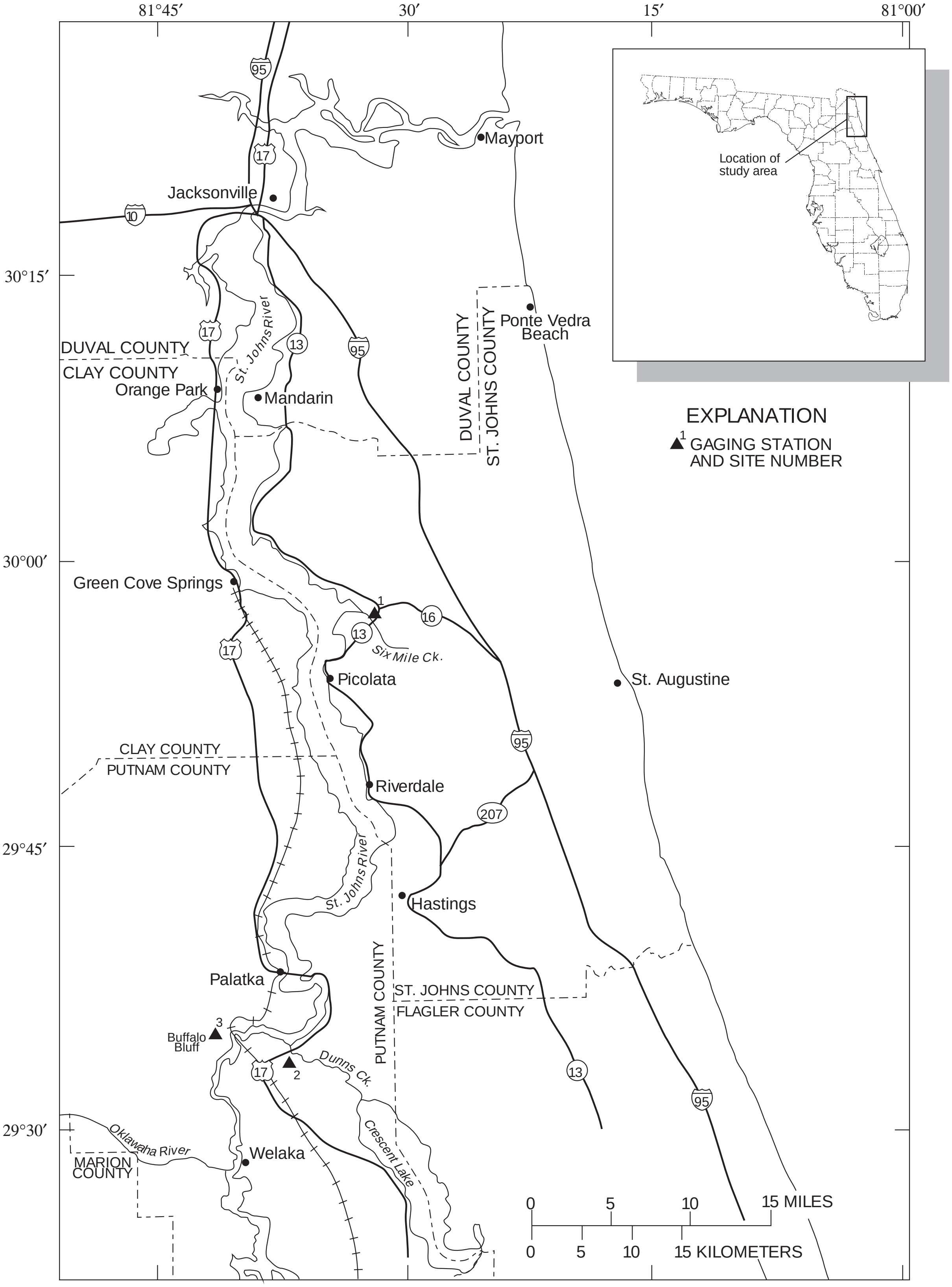

Figure 1. Acoustic velocity meter (AVM) stream-gaging sites.

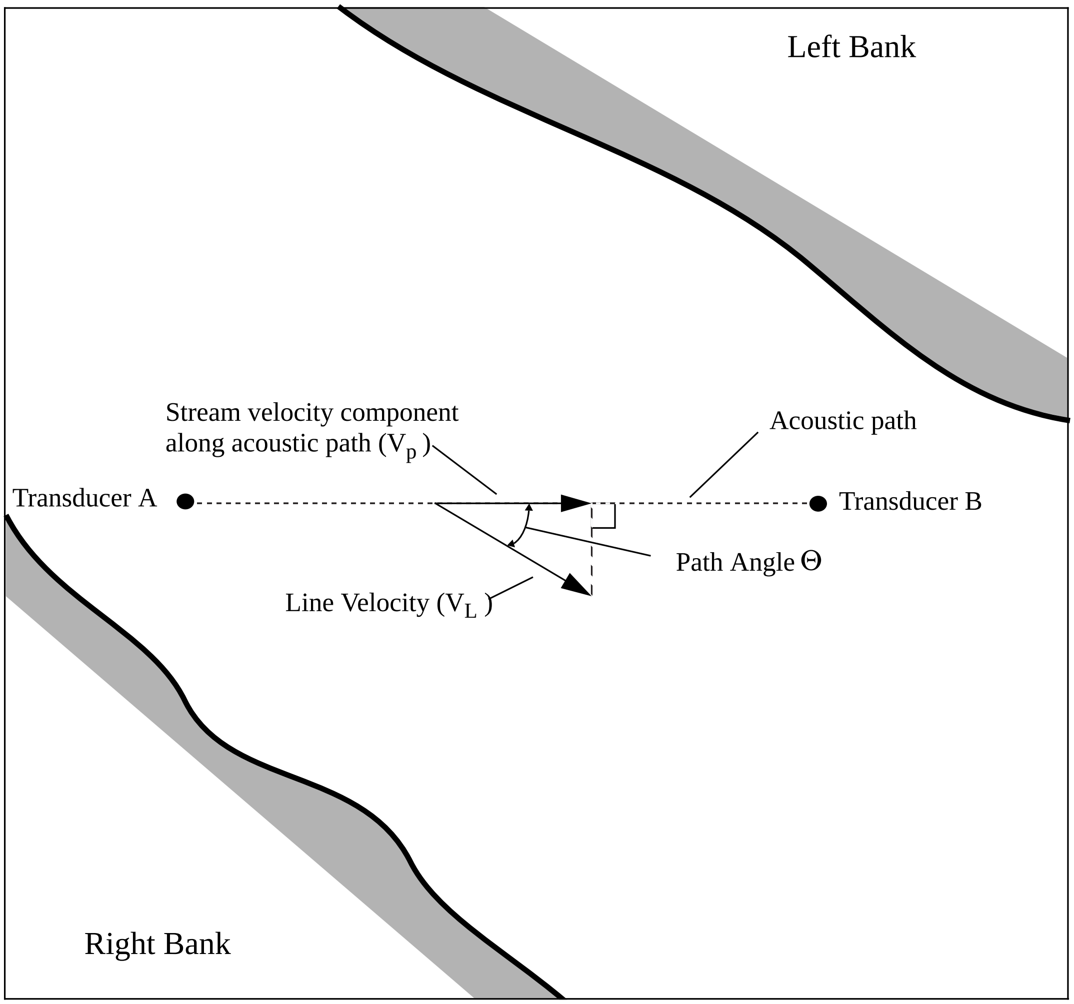

Figure 2. Velocity components and acoustic-path angle for a single-path acoustic velocity meter (AVM) site.

upstream. Velocity vectors and the acoustic path angle typical of a site are shown in figure 2.

The stream-velocity component parallel to the acoustic path when the signal is traveling from point A to point B (fig. 2) is:

$$V_{pd} = \frac{D}{t_{AB}} - c, \qquad (1)$$

where V_{pd} is the downstream integrated water velocity vector along the acoustic path from point A to point B,

c is the propagation rate of sound in still water,

D is the distance from point A to point B, and

t_{AB} is the traveltime of acoustic signal from point A to point B.

Similarly, the stream velocity parallel to the acoustic path when the signal is traveling upstream from point B to point A is:

$$V_{pu} = c - \frac{D}{t_{BA}}, \qquad (2)$$

where V_{pu} is the upstream integrated water-velocity vector along the acoustic path from point B to point A (upstream), and

t_{BA} is the traveltime of acoustic signal from point B to point A.

Equations 1 and 2 are based on the velocity of sound in still water (c), which varies with the conductance and temperature of water. However, path velocity is computed as the average of upstream and downstream velocities, and c cancels when equations 1 and 2 are summed:

$$V_p = \frac{D}{2}\left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}}\right), \tag{3}$$

where V_p is the average path velocity along the acoustic path.

Equation 3 defines the velocity parallel to the acoustic path. To determine the vector component of velocity in the direction of flow (index velocity), the cosine of the angle between the acoustic path and the direction of flow must be considered as:

$$V_L = (V_p) / ((\cos\Theta), \tag{4}$$

where V_L is the average stream velocity component across the acoustic path (index velocity) in the direction of streamflow; and

Θ is the acute angle between the acoustic path and the direction of streamflow.

Equipment Installation

Typically, an AVM site is instrumented with water velocity and stage-measuring devices and a data recorder. An index velocity is measured using the AVM, acoustic transducers, and cabling. Stage is measured using one of several standard USGS stage measurement sensors, such as a float and counterweight, tape, and shaft-encoder. Output from the measuring devices is recorded by either an electronic datalogger or telemetered (by satellite or phone modem) to an off-site database. Power is supplied to all equipment by a 12-volt battery (fig. 3).

The AVM contains a software program to: (1) activate acoustic transducers, (2) compute average velocities from one or more acoustic paths, (3) report speed of sound and signal gain for signal quality, and (4) report possible errors within the system. Instrument settings must be made for several parameters within the program. Depending on the AVM model used, these parameters usually include internal timing delays, speed of sound in water, acoustic-path lengths, and path angles. Discussion of each parameter in an AVM software program is beyond the scope of this report; however, documentation is usually provided by the manufacturer.

The acoustic transducer serves two functions which are: (1) convert an electrical pulse to a sonic pulse (transmit), and (2) convert a sonic pulse to an electrical pulse (receive). The acoustic transducer is excited by an electrical pulse (sending pulse) transmitted by the AVM. The transducer converts the electrical pulse into a sonic pulse which is propagated across the stream. The sonic pulse is then received by another acoustic transducer that converts the sonic pulse back into an electrical pulse, which is then transmitted to the AVM (receiving pulse). The elapsed time between the sending and the receiving pulses is measured by the AVM. This process is applied in succession for both upstream and downstream directions of signal propagation, and the index velocity is computed using the method previously described in this report.

Typically, the AVM is installed using prefabricated transducer mounts, cables, and acoustic transducers. The AVM is mounted in the gage house and electrically grounded. Prefabricated transducer mounts are attached to pre-driven pilings in the stream and cables are run from the AVM to transducers on each piling. The two acoustic transducers, after being wired, are lowered to predetermined depths, and aligned with one-another across the stream (corresponding to the acoustic path).

Transducers are manually aligned in the field for maximum signal strength. First, the transducer face is vertically leveled (this is done above the water surface). Second, each transducer is lowered to a similar depth, and third, the transducers are rotated left or right until the signal strength is maximized. To avoid misalignment, transducers should be aligned when velocities are sufficient to overcome density gradients that may cause signal bending in the stream during periods of low-flow.

Lengths of cable located above the water surface should be protected by grounded-metal conduit (as recommended by the USGS HIF). Cable lengths below the water surface are weighted down by tying short lengths of heavy chain to the cable at 15- to 20-ft intervals. Care must be taken to avoid sharp bends in the cable which can eventually weaken it and possibly cause signal failure.

Acoustic Path Configurations and Computational Approaches

The arrangement of acoustic paths at an AVM gaging installation affects effort required to maintain

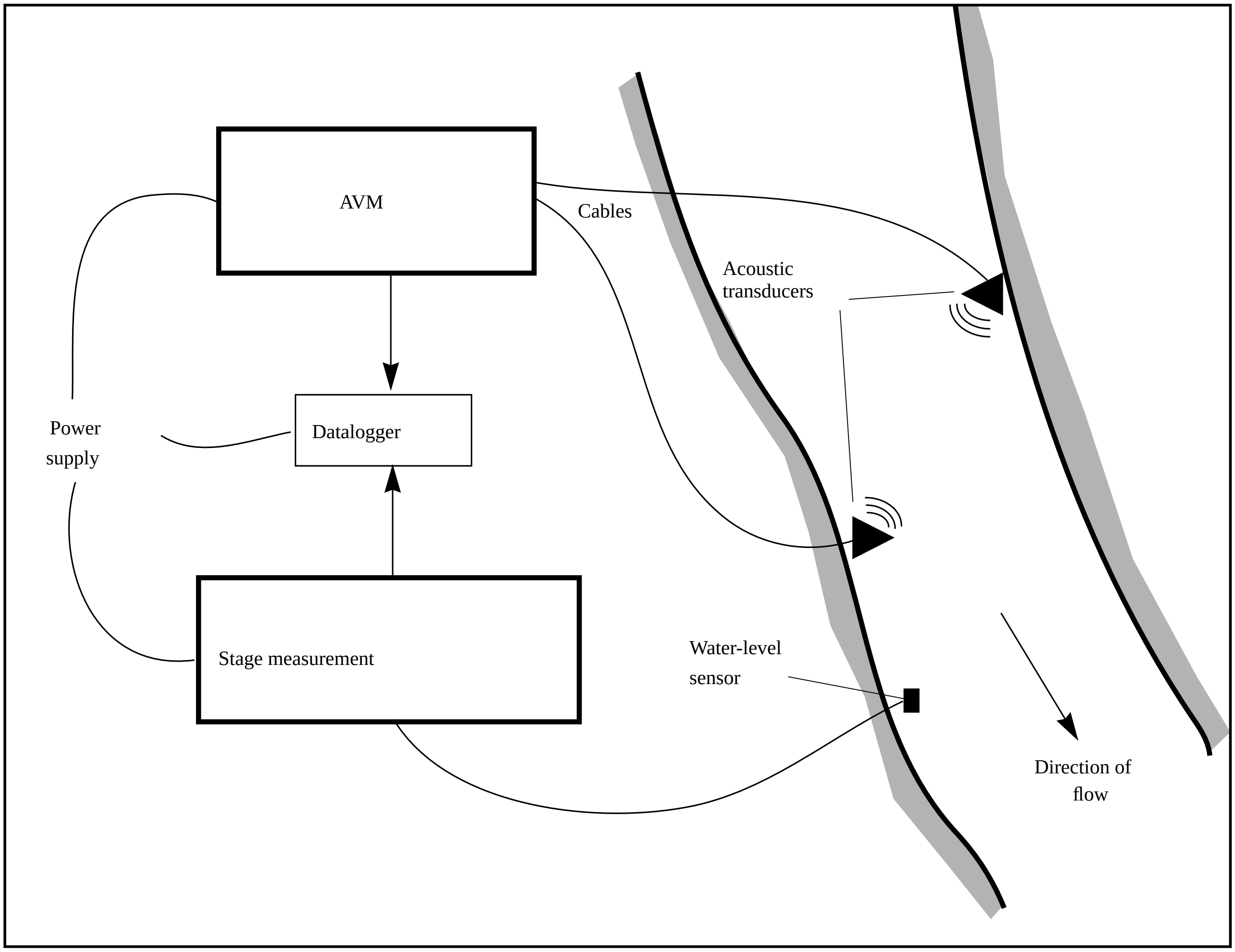

Figure 3. Device configuration for acoustic velocity meter (AVM) stream-gaging site.

the installation, and the way in which ratings are constructed and applied. Acoustic path configurations fall into four general types: (1) single paths, (2) multiple paths with simple redundancy, (3) multiple paths with cross orientation, and (4) multiple paths with incremental subsections. A general schematic of each of these configurations is shown in figure 4. The single path configuration is the simplest arrangement and requires the least effort to maintain and to rate. However, single paths may be insufficient in length to span the entire width of a stream, may poorly represent mean velocities where the angles of flow in relation to the acoustic path vary over time and space, and may lack the corroboration of alternative velocity data from other paths.

Multiple-path configurations with simple redundancy add reliability to the system but require more work in the field and only marginally improve the representativeness of measured index velocities. Where multiple paths are oriented at cross angles to one another, index velocities can be averaged for the multiple paths to account for variations in flow angle. This increases the representativeness of measured index velocities, but requires that all paths operate correctly at all times, adding a considerable level of difficulty to station operations and computations.

The use of multiple paths in incremental subsections is an extension of single and cross path configurations and generally is limited to wide cross sections. As with the cross-path configuration, the sectional configuration requires that all paths be in operation to compute discharge.

The rating procedure for an AVM streamflow station depends on the path configuration and the

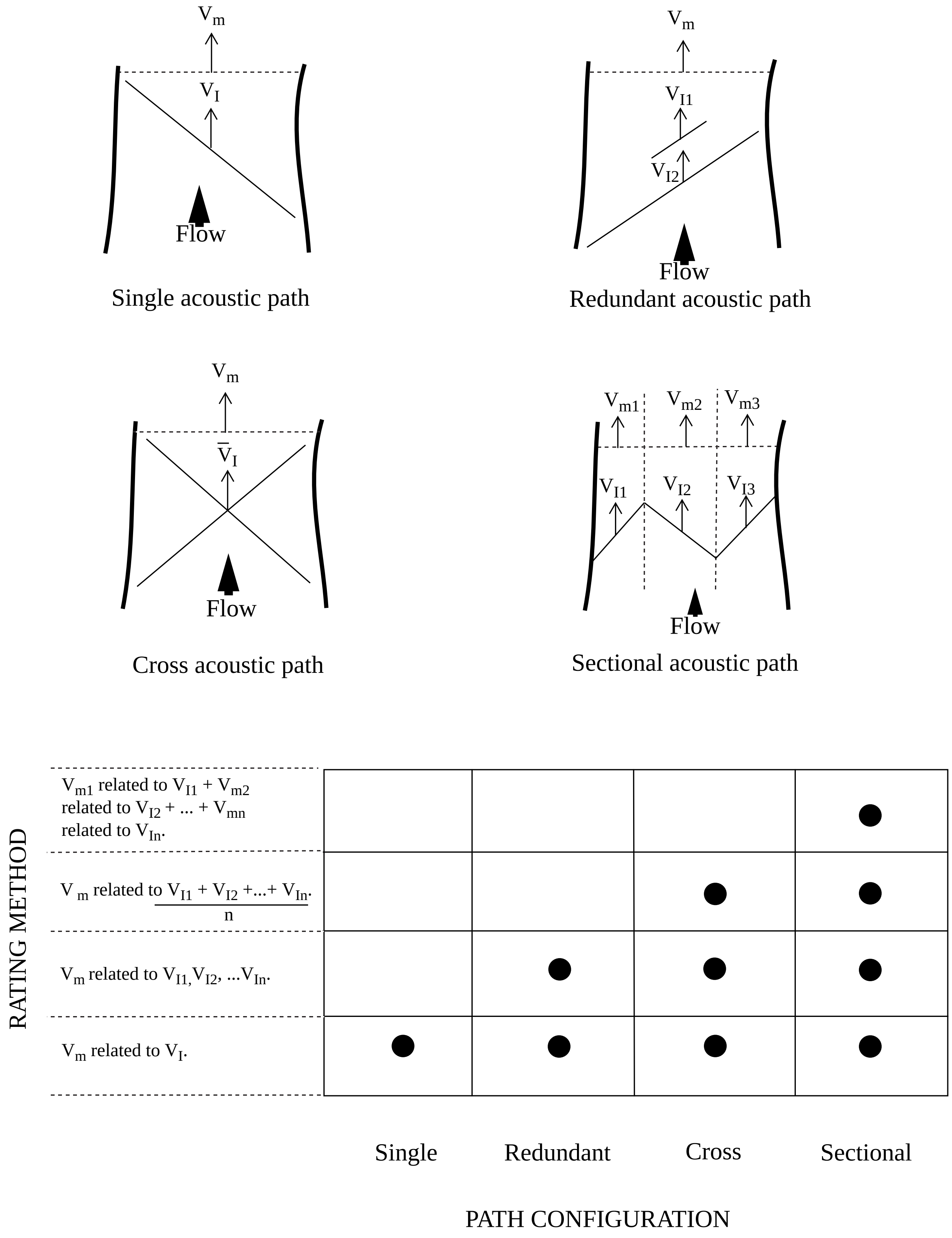

Figure 4. Path configurations and velocity rating methods for acoustic velocity meter (AVM) gaging sites.

quality of the data from each path. The single path system requires a single rating of mean velocity against index velocity. Discharge measurements to determine mean channel velocity can be made along the acoustic path or any other path traversing the entire stream and corrected for the angularity of flow. It is not necessary that the single acoustic path traverse the entire width of the stream or be coincident with the measurement cross section to provide a representative index of mean channel velocities as long as variations in velocity in the horizontal and vertical axis are consistent.

A multiple-path system with redundancy requires that two or more ratings be developed, one for each path relating mean velocities to index velocity. To compute discharge, it is necessary to select one or another path or to average the paths depending on the quality of the records for each acoustic path. This process adds a level of complexity to the computational process. Computation with a cross-path system further requires that a rating be developed to relate mean channel velocity to the mean of two or more index velocities. And a sectional configuration requires that ratings be developed for the flow components in each subsection of the stream channel.

The choice of a rating method reflects not only the acoustic path configuration but also the quality of the ratings and the reliability of the velocity data. Cross and sectional multiple-path configurations can be rated for average and sectional velocities or reduced to simple single or multiple-path redundant ratings. For multiple path configurations, the rating method applied should minimize the uncertainty in computed velocities. Because of complexities in collecting continuous index velocity data on multiple paths, single-path ratings have often proven to be the most practical approach.

Development of Curves of Relation

Discharge of a stream is computed as the product of the mean velocity and the channel cross-sectional area:

$$Q = A\,V_M, \qquad (5)$$

where Q is discharge, in cubic feet per second,

A is cross-sectional area, in square feet, and

V_M is mean velocity, in feet per second.

Under the complex streamflow conditions that exist when tidal or backwater conditions are present, it is necessary to develop simple relations for area and mean velocity in terms of measurable variables. In equation 5 the cross-sectional area of the stream can be expressed as a function of stage, and the mean velocity can be expressed in terms of specific stream variables including stage, index velocity, and rate of change of stage and index velocity. Statistical methods can be used to determine which stream variables are significant for estimating mean velocity.

Rating tables can be developed for relations between stage and cross-sectional area. Least-squares multiple linear regression, a useful technique for estimating the relation between a response variable and multiple independent variables, can be used for deriving relations between mean velocity and measured stream variables (stage and AVM-measured index velocity and rate of change of stage and velocity). Additionally, the residuals (unexplained error) from the resulting regression equation can be evaluated to determine if a significant relation exists between the response (mean velocity) and independent variable(s) and if the response variable is adequately estimated. Least-squares multiple linear regression and the analysis of residuals are described by Draper and Smith (1982).

DESCRIPTION OF SITES AND SUITABILITY OF SITES FOR AVM MEASUREMENT

Reconnaissance was done on three low-velocity tidal streams to determine overall suitability for measurement using AVM equipment and to determine specific locations where measuring could best be accomplished. Acoustic phenomena of reflection, refraction, and attenuation (related to measurement with AVM equipment, described by Laenen, 1985) were taken into consideration in the selection process, as well as the logistical constraints of access, construction, ownership, and safety. Site-identification numbers are listed in table 1 and locations are shown in figure 1.

Physical characteristics for all three streams are similar except for drainage area: the topography primarily is low-relief, swampy terrain; stream velocities range from about -2 to 2 ft/s, and the average daily change in stage is about 1 ft.

Table 1. Site-identification numbers for acoustic velocity meter (AVM) stream-gaging sites

Map number	Station name	Station number	Latitude	Longitude
			(degrees, minutes, seconds)	
1	Six Mile Creek near Picolata, Fla.	02245328	29˚57’04”	81˚32’37”
2	Dunns Creek near Satsuma, Fla.	02244440	29˚34’39”	81˚37’35”
3	St. Johns River at Buffalo Bluff near Satsuma, Fla.	02244040	29˚35’46”	81˚41’00”

The location, length, and depth below the water surface of the acoustic path(s) were assigned for each site to minimize spurious fluctuations in the acoustic signal. Paths were located in channel cross sections free of turbulent effects from flow obstructions that could cause unpredictable fluctuations in horizontal and vertical velocity profiles. Path depths and lengths were assigned based on minimum clearance distances (to water surface and streambed), and maximum stream-density gradients (temperature and conductivity in vertical and horizontal profiles). Clearance distances were assigned so that acoustic signals reflected from the water surface or streambed would not interfere with the direct path signal. Density gradients were measured and path lengths determined to minimize signal fluctuations caused by refraction (bending of the acoustic signal). Locations, acoustic path configurations, and channel cross sections for the three AVM sites are described in the following sections.

For each site, the AVMs were activated at 15-min intervals. Once activated, the AVM measures index velocity every 2 seconds for a duration of 40 seconds. The average velocity during the 40-second period, corresponding system diagnostics, and stage are then recorded by an electronic datalogger.

Six Mile Creek

Six Mile Creek is a tributary of the St. Johns River in St. Johns County, Fla. The AVM stream-gaging site is 1.0 mi upstream from the mouth, just below the County Road 13 bridge (fig. 1).

The site has a single acoustic path (fig. 5). A cross section of the channel along the acoustic path (fig. 6) shows the depth of the acoustic transducers relative to the lowest water-surface elevation measured during the study.

The AVM produced reliable velocity data when the flow was well mixed. Further, discharge measurements made at the site indicated that a single path was adequate for the estimation of the mean stream velocity. However, occasionally steep thermal gradients (greater than 1°C/meter depth) would occur in the top 5 to 6 ft of the stream during mid-morning to early afternoon, caused by the combination of low velocities in the stream and warm ambient air temperature. The thermal gradients caused the acoustic signals propagated across the stream by the AVM to become erratic, which resulted in erratic velocity measurements and occasional signal loss for periods up to about 6 hours. In an effort to minimize these effects on the acoustic signal, a second (redundant) acoustic path with a shorter path length (60 ft) was installed under a bridge at a depth about 2 ft below the original acoustic path (fig. 7). Velocity data collected from the shorter path indicated that the acoustic path was not affected by the thermal gradients.

Dunns Creek

Dunns Creek is a tributary of the St. Johns River in Putnam County, Fla. The AVM stream-gaging site is 0.8 mi upstream from the mouth, just below the U.S. Highway 17 bridge (fig. 1).

The two acoustic paths at the site are at similar depth (fig. 8). A cross section along each acoustic path (fig. 9) shows the depth of the acoustic path relative to the lowest water-surface elevation measured during the study.

The AVMs performed well because flow at the site was always well mixed, reducing the possibility of signal loss from density gradients in the stream. Data losses at the site primarily were caused by equipment failure—broken cables, loss of power, lightning strikes, vandalism, and weak acoustic transducers. Equipment failures were most common on acoustic path 1, thus rating measurements collected from acoustic path 2 were more numerous. By using path 2 data instead of the combined data for paths 1 and 2, a more accurate mean-velocity rating was obtained for the site.

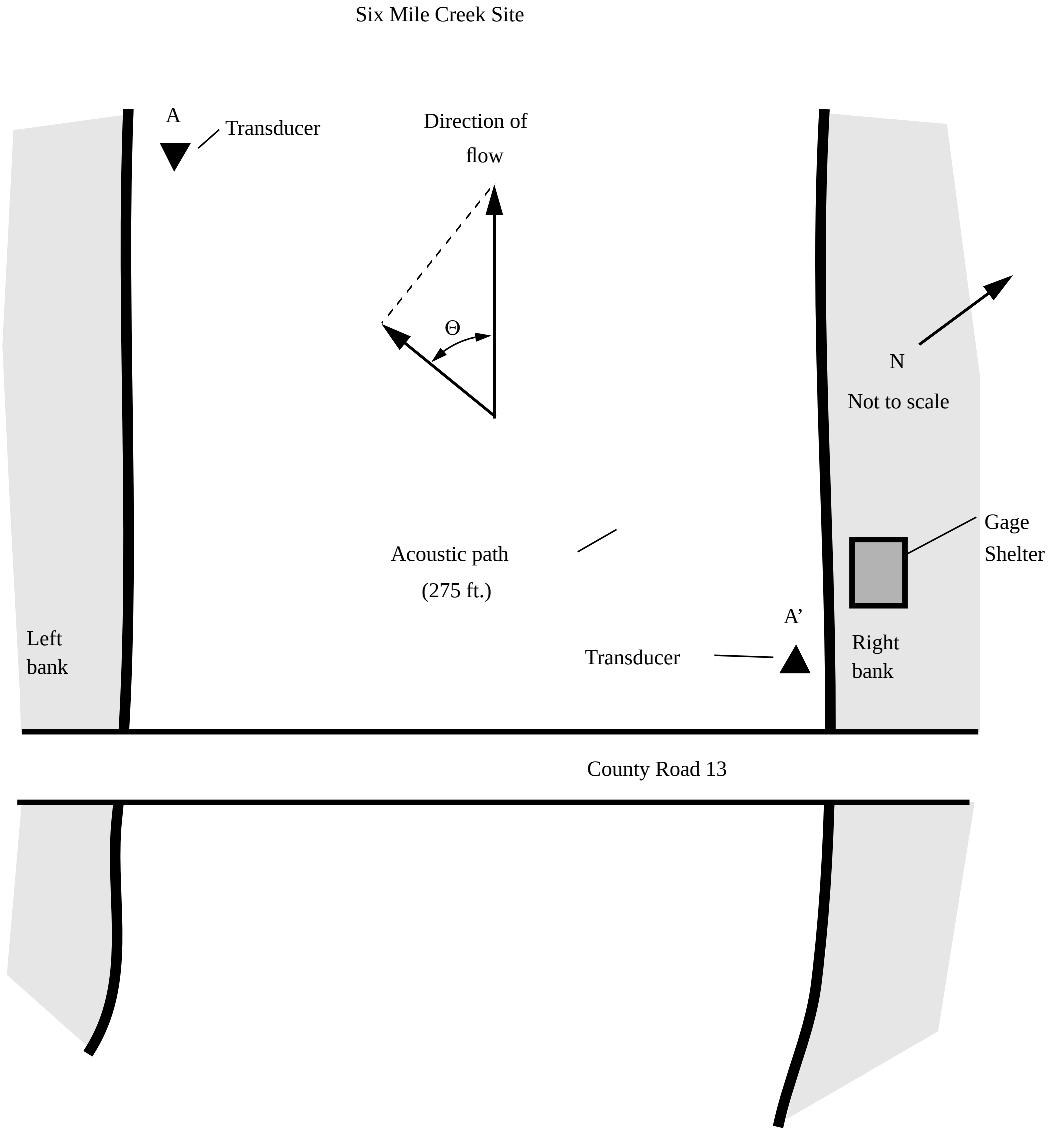

Figure 5. Acoustic velocity meter (AVM) configuration on Six Mile Creek.

St. Johns River at Buffalo Bluff

The AVM stream-gaging site on the St. Johns River at Buffalo Bluff is located 89 mi upstream from its mouth at the Atlantic Ocean, just above a railroad bridge crossing the river in Putnam County, Fla. (fig. 1).

Originally, the site had three acoustic paths that together crossed 80 percent of the river width (fig. 10). Cross sections of the channel along each acoustic path (fig. 11) show the depth of each acoustic path relative to the lowest water-surface elevation measured during the study.

When the AVMs were operating properly they produced reliable velocity data. However, several problems with the installation resulted in frequent periods of missing record that made the computation of discharge difficult and time consuming. The primary cause of missing record was equipment failure.

Equipment failures, similar in nature to those described for Dunns Creek, occurred more frequently at Buffalo Bluff. Two predominant causes of the high rate of equipment failure were the location of the two gage houses for the AVM equipment (mounted on the piers of a railroad bridge) and the location of the upstream transducer piling (used to mount acoustic

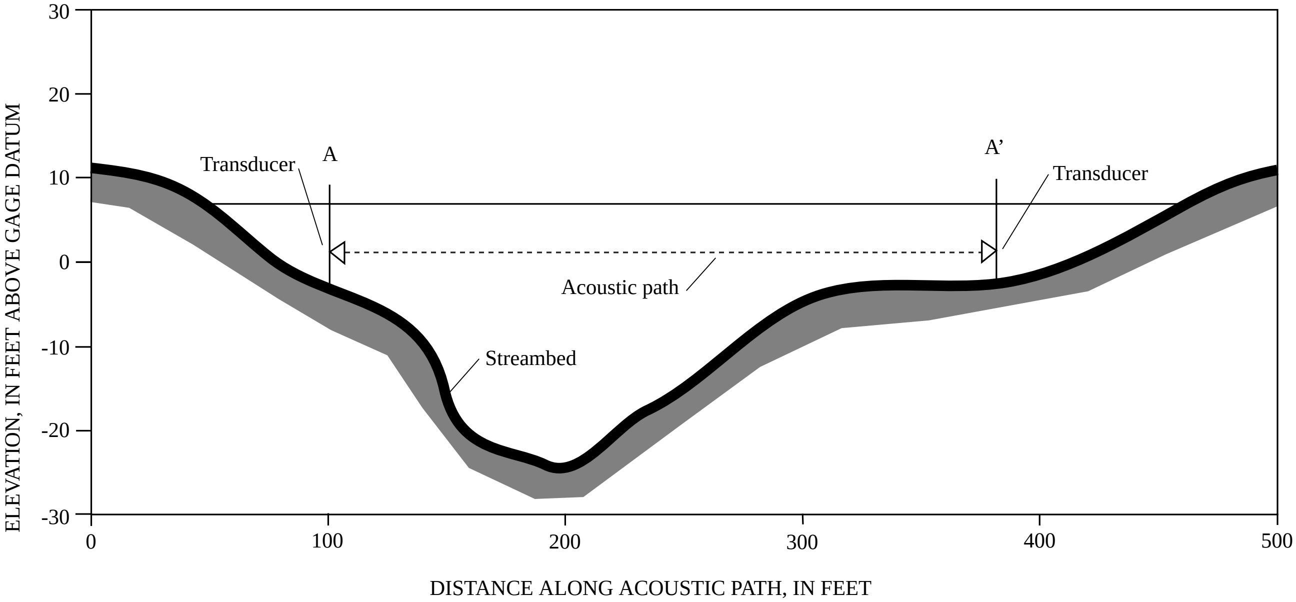

Figure 6. Oblique cross section of Six Mile Creek channel at the gaging station.

transducers) for paths 1 and 2 (fig. 10). Rail cars crossing the bridge several times a day caused considerable vibration in the equipment which tended to loosen AVM electrical connections and to bend metal electrical conduit that was installed to protect the AVM transducer cables (causing cable breaks). The upstream transducers for acoustic paths 1 and 2 were mounted in the river on a piling close to the shipping channel. On several occasions, large barges passing the site collided with the transducer piling and caused transducer misalignment. The collisions also damaged the transducer mounts and caused cable breaks.

The sectional configuration of the initial installation of the AVMs at the site was based on the best information available at the time and on the general philosophy that acoustical paths should span as much of the river as possible. This philosophy assumes that the AVM can be used directly to measure discharge if sufficient horizontal coverage and well-defined vertical-velocity profiles exist at the site (Smith, 1969). When all the acoustic paths were functioning properly, total discharge was computed by simple algebraic summation of partial discharge computed through each of the three acoustic path subsections. However, when one or two of the acoustic paths were not functioning or were producing unreliable data, alternative velocity ratings, based on a relation between acoustic paths, were used to estimate flow for the missing subsection. Routine computation of discharge by algebraic summation frequently was not possible because of the number of paths and the high frequency of AVM failure on any of the paths.

In an effort to improve the reliability of data and simplify the computation of discharge, the acoustic path configuration at Buffalo Bluff was changed. Acoustic paths 1 and 2 were removed and a shorter acoustic path was installed under the railroad bridge (fig. 12). The acoustic path is approximately 60 ft in length at an elevation similar to acoustic path 3. A redundant mean-velocity rating method has been adopted; each acoustic path is rated to mean velocity in the entire cross section; discharge is rated to each individual path; and the multi-paths serve as redundant data. Since the change in the acoustic path configuration, data losses have been reduced significantly and accuracies of new index-velocity ratings are consistent to previous velocity ratings.

INSTRUMENTATION, MEASUREMENT, AND COMPUTATION OF DISCHARGE AT THE THREE AVM STREAMFLOW SITES

Several successive steps were necessary to compute discharge record at the AVM streamflow sites. The first step was the installation of the AVM equipment, a stage-measurement device, and a data-collection device. The second step was to obtain

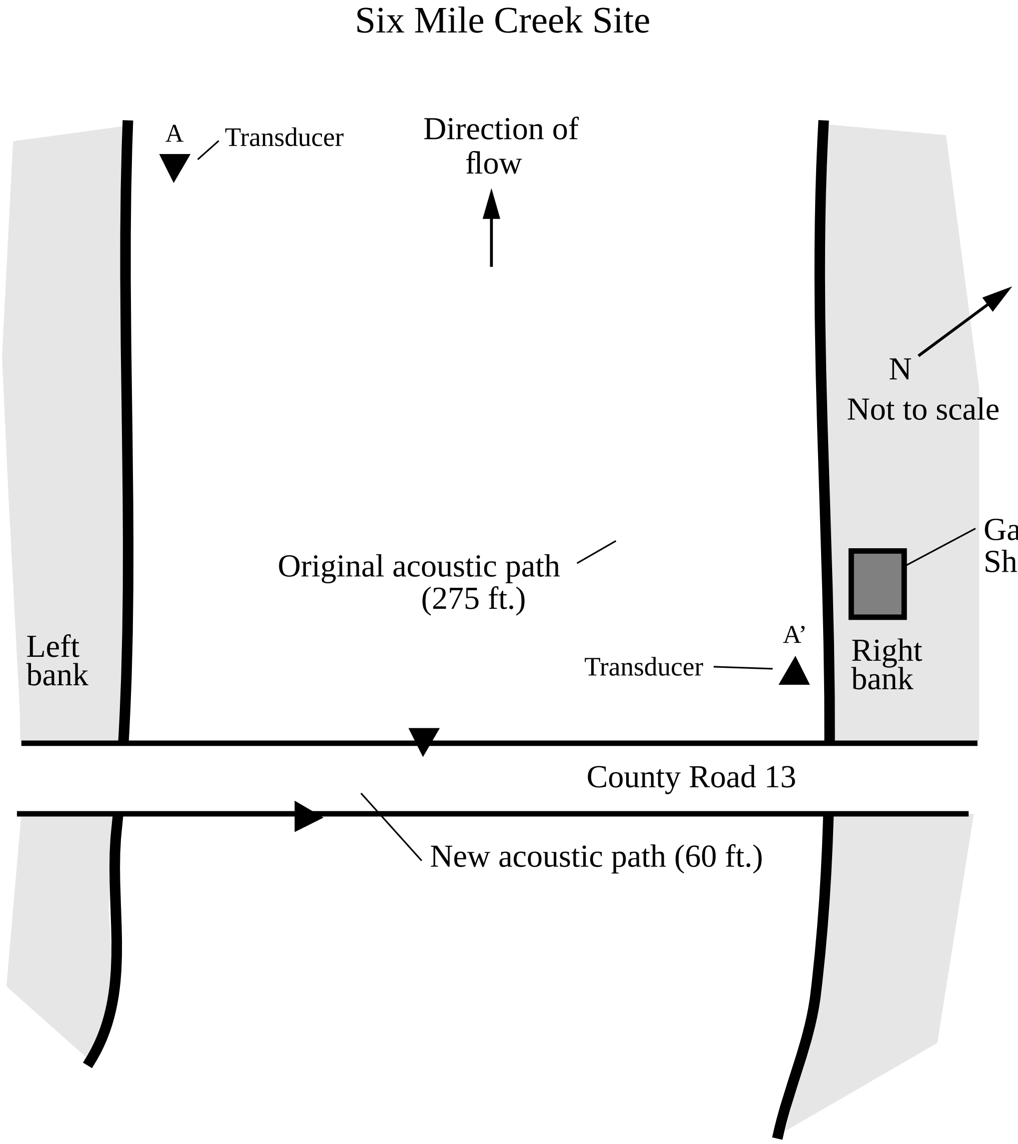

Figure 7. New acoustic velocity meter (AVM) redundant-path configuration on Six Mile Creek.

measurements of discharge and cross-sectional area. The third step was to develop relations between stage and area and between mean velocity and AVM index velocity. These steps are described in the following sections.

Equipment Installation

The AVM sites were instrumented with velocity and stage measuring devices and a datalogger for recording. Water velocity is measured using an Accusonic model 7300 AVM, acoustic transducers, and cabling; stage is measured using a float and counterweight, tape, and a shaft encoder. A datalogger (using Serial-Digital-Interface-12 (SDI-12) protocol) is used to record output from the measuring devices and a 12-volt battery is used to supply power to all equipment.

Discharge Measurements

Discharge was measured at each AVM site to determine mean velocity using a portable Neil-Brown acoustic current meter (ACM). The portable ACM is a vector-averaging (current magnitude and direction)

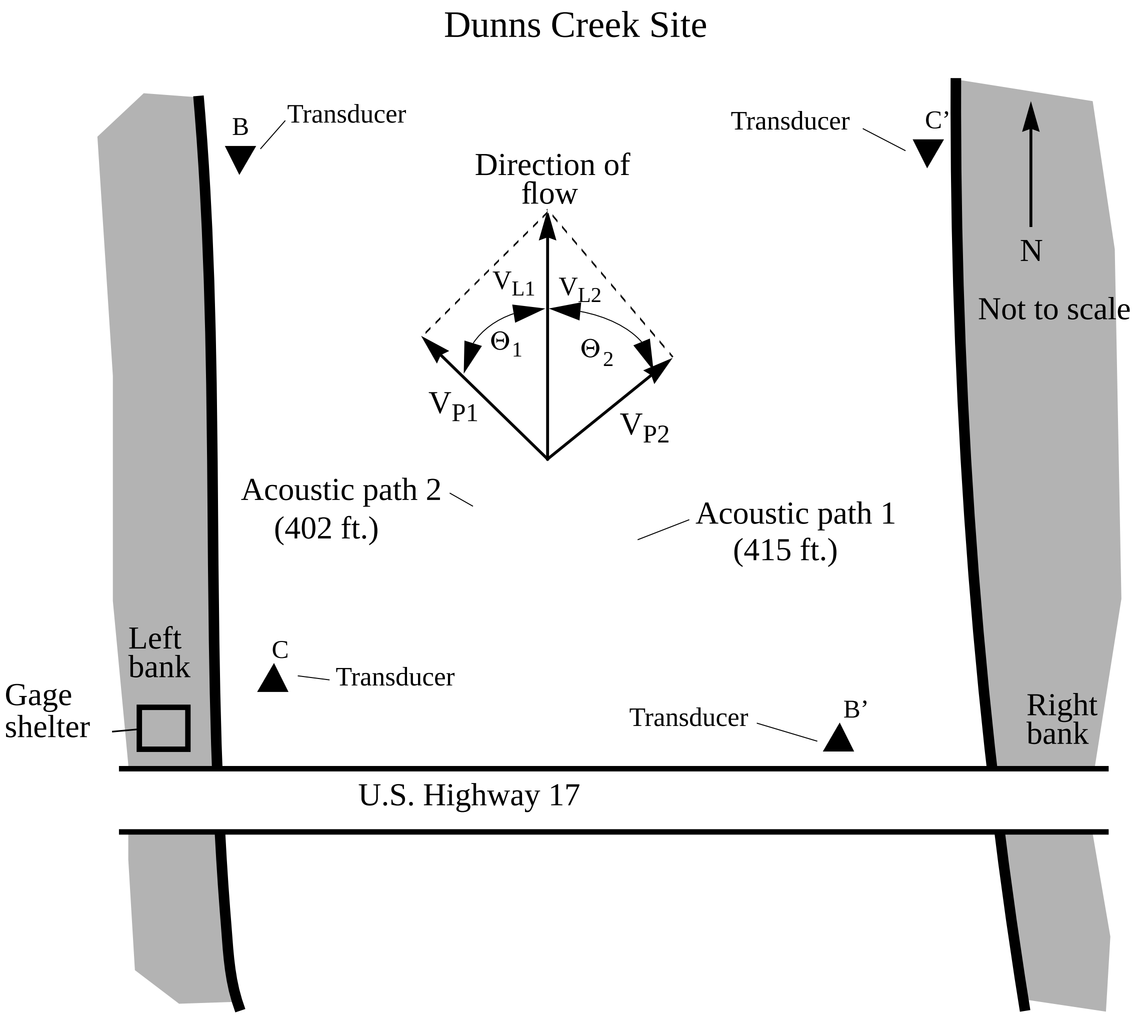

Figure 8. Acoustic velocity meter (AVM) stream-gaging site on Dunns Creek.

current meter that can measure point velocities as low as 0.03 ft/s. It also contains an internal magnetometer compass that provides a magnetic-heading reference for the measured current data.

The ACM was used to measure discharge because of the limitations of the more common mechanical, low-velocity Price current meter (type AA). The recommended minimum velocity of the Price meter is 0.2 ft/s (Rantz and others, 1982, v. 1, p. 86). Also, the use of conventional mechanical current meters such as the Price meter require that the operator visually observe the direction of streamflow. However, when the measurement depth increases and visibility decreases, the meter is no longer visible and the operator cannot observe the meter and the direction of streamflow. In tidal streams, where flow is bi-directional and velocities are low, accurate flow measurements with conventional mechanical meters are often unobtainable.

Because of rapidly changing stage and velocity, the duration of each discharge measurement had to be decreased. This was done by reducing the number of measurement sections from a USGS standard minimum of 25 to a minimum of 18 and by reducing the averaging interval for each point velocity from a USGS standard measurement of 40 seconds to 20 seconds. This procedure follows recommendations presented by Rantz and others, 1982, v. 1, p. 174. During each discharge measurement, ancillary data such as AVM-measured index velocity, system diagnostics, and stage were recorded at 5-min intervals using an electronic datalogger. The AVM-measured velocity and stage were then averaged for the duration of the discharge measurement.

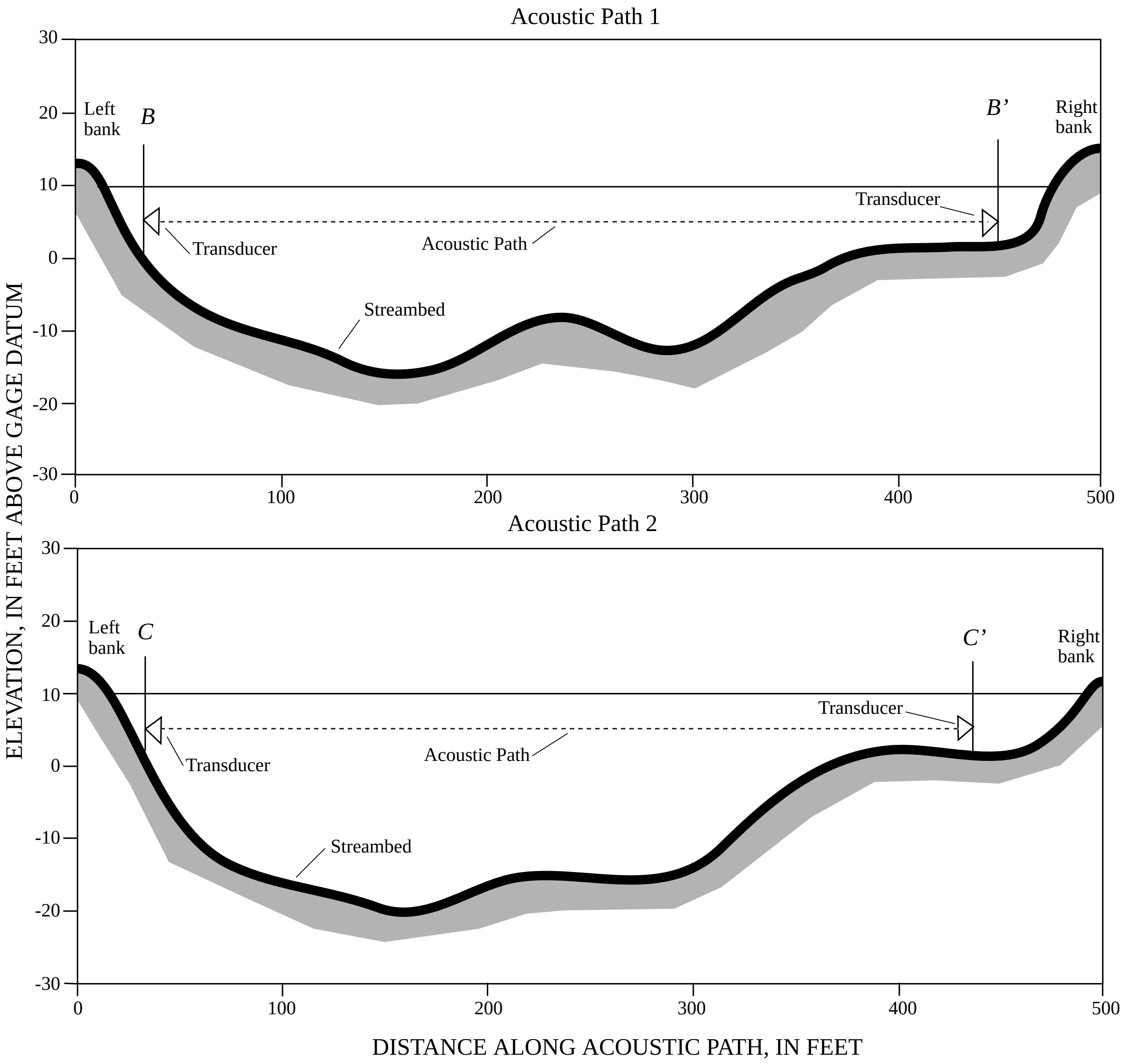

Figure 9. Oblique cross sections of Dunns Creek channel at the gaging station.

Additionally, system diagnostics were checked to ensure the integrity of the AVM-measured index-velocity data.

Stage-Area Relation

A stage-area relation was developed for each study site (fig. 13). The cross-sectional area was computed as a function of stage using a bathymetric survey of the channel (measured using a fathometer) and various values of stage (as measured on the outside staff gage). Cross-sectional areas were computed for values of stage ranging between minimum and maximum values expected at the site. Rating tables were then developed relating stage to area.

Mean-Velocity Rating

Regression equations were developed relating mean velocity computed from discharge measurements to the corresponding AVM index velocity measured by the AVM. The mean velocity and AVM index-velocity data used in the regression analysis were collected during periods of seasonal high and low flow and during several tidal cycles. The analysis

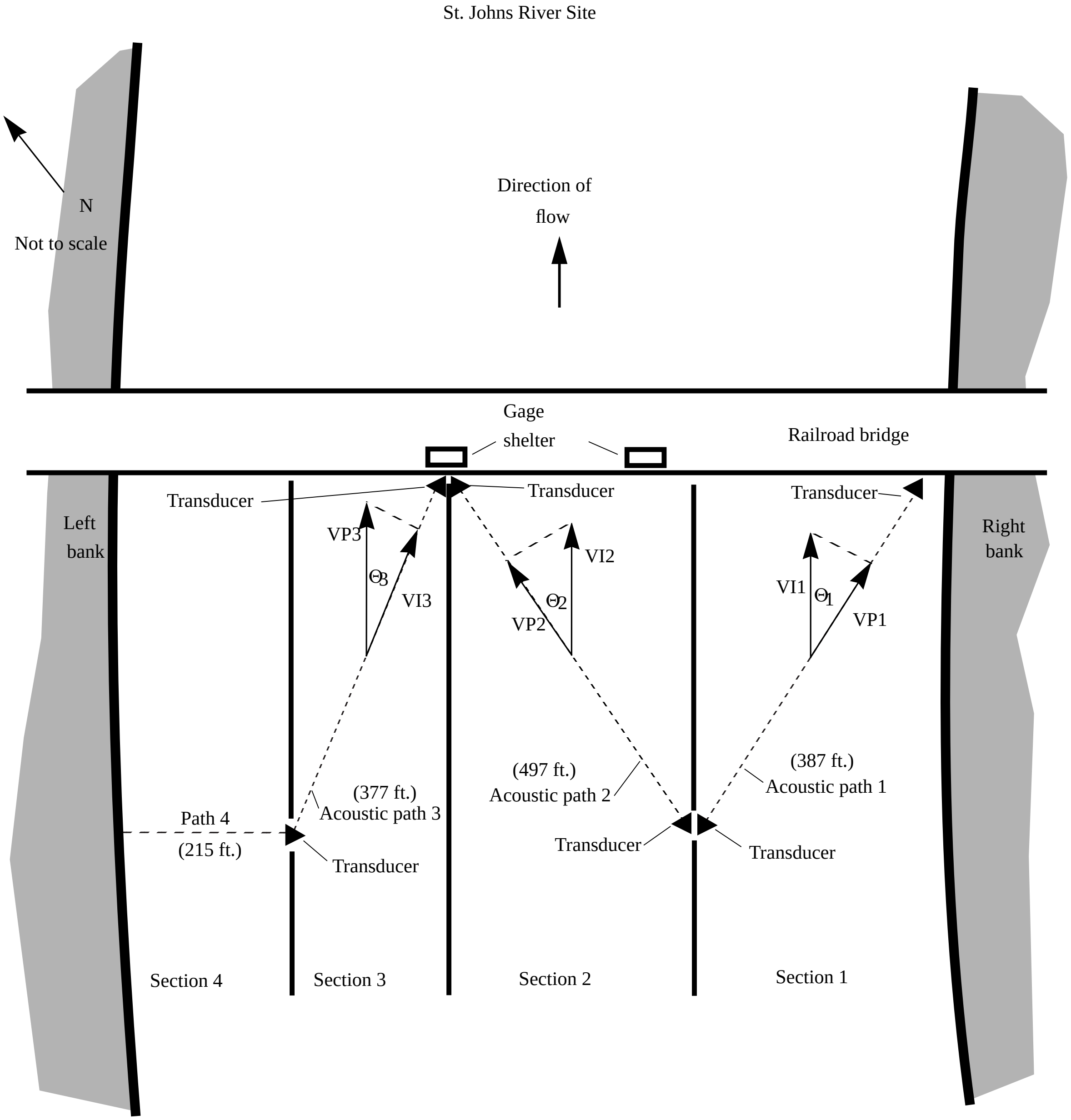

Figure 10. Acoustic velocity meter (AVM) multi-sectional configuration on the St. Johns River at Buffalo Bluff.

required several assumptions about errors calculated from the regression: errors must be independent over time (not serially correlated), normally distributed, and of equal variance over the range of velocities. Residual plots for each regression generally confirm these assumptions.

Regression equations initially were developed using several mathematical combinations of stage, AVM index velocity, the product of stage and index velocity, and the rate of change of stage and AVM index velocity as independent variables. With the exception of Dunns Creek (path 2), AVM index velocity was the only significant linear predictor of stream velocity. The general form of the resulting regression equation for mean velocity for each study site is:

$$V_M = a \times V_I + b, \tag{6}$$

where V_M is mean velocity in feet per second,
V_I is index velocity measured from the AVM, in feet per second, and a,b are constants.

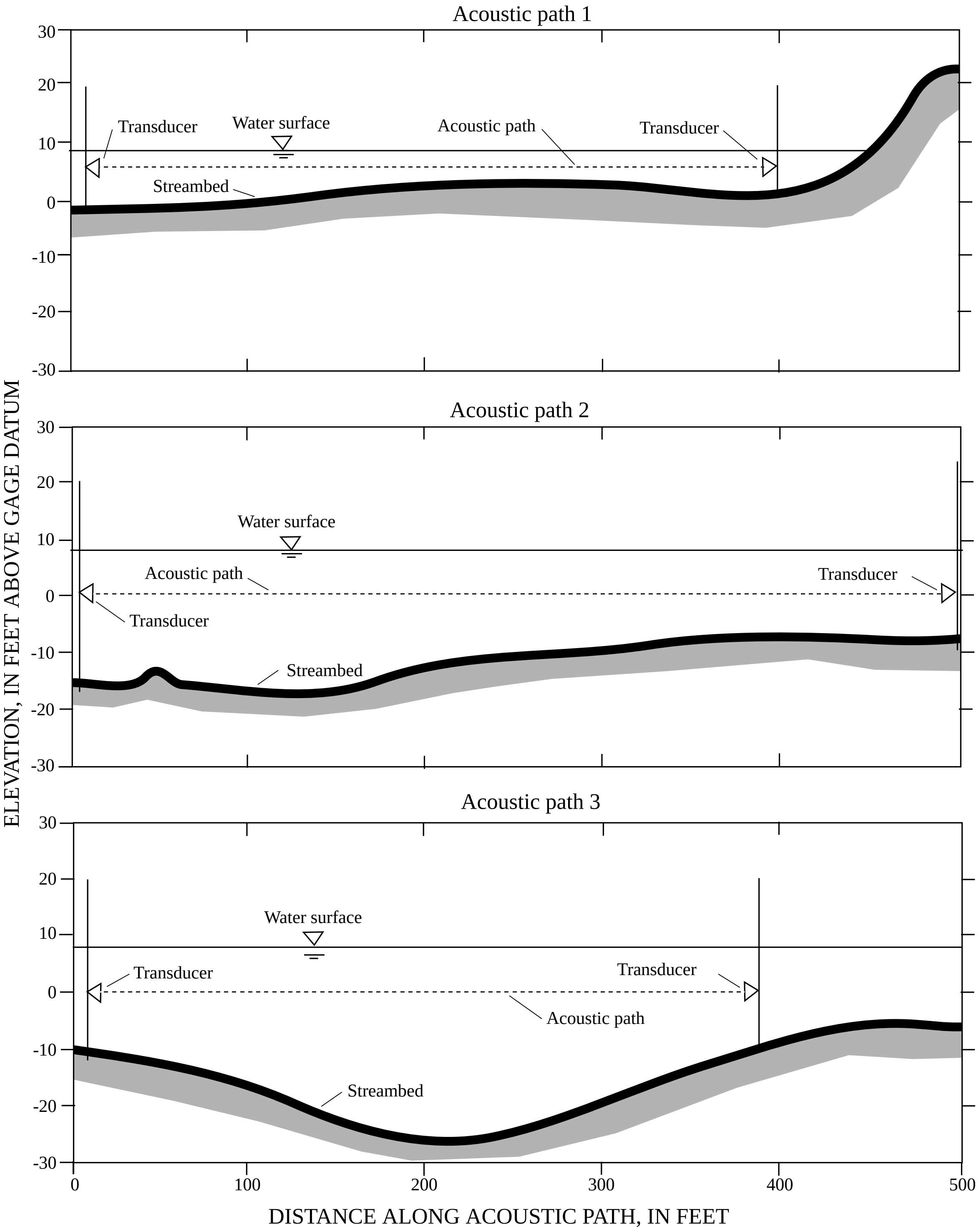

Figure 11. Oblique cross sections of St. Johns River at Buffalo Bluff channel at the gaging station.

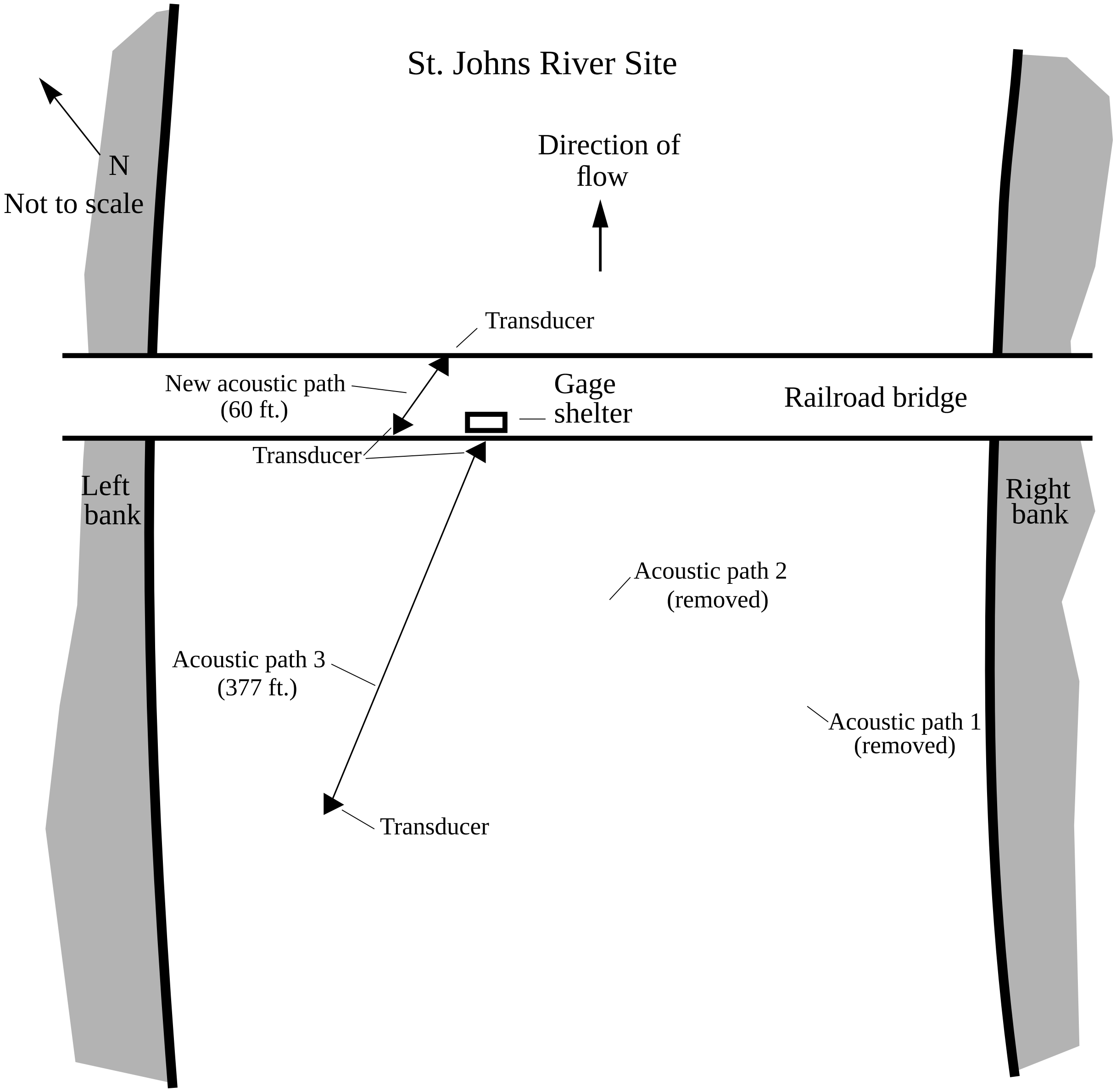

Figure 12. Acoustic velocity meter (AVM) multi-redundant configuration on the St. Johns River at Buffalo Bluff.

The relation between mean velocity and AVM-measured index velocity for each AVM stream-gaging site is shown in figure 14. Mean velocities were computed by dividing measured discharges by the cross-sectional area from the stage-area rating for the average stage during the discharge measurement. The data indicate that measured mean velocity is a simple linear function of AVM index velocity, even during periods of negative (upstream) flow. Generally, the data are evenly distributed about the regression equation throughout the range of measured values.

The standard error estimate for the regressions ranged from 0.040 to 0.068 ft/s and is fairly uniform over the range of velocities. Regression equations for each study site, along with the standard errors, are listed in table 2.

A plot of the residuals of the regression of mean velocity and stage for the rating at Dunns Creek is shown in figure 15. This was the only site for which stage was also a significant predictive variable for mean cross-sectional velocity. The first plot (A) in figure 15 shows the residuals (from the regression of mean velocity to AVM-measured index velocity) before stage was added to the regression equation. The downward trend in residuals with stage indicates that stage is a useful predictor of a portion of the total

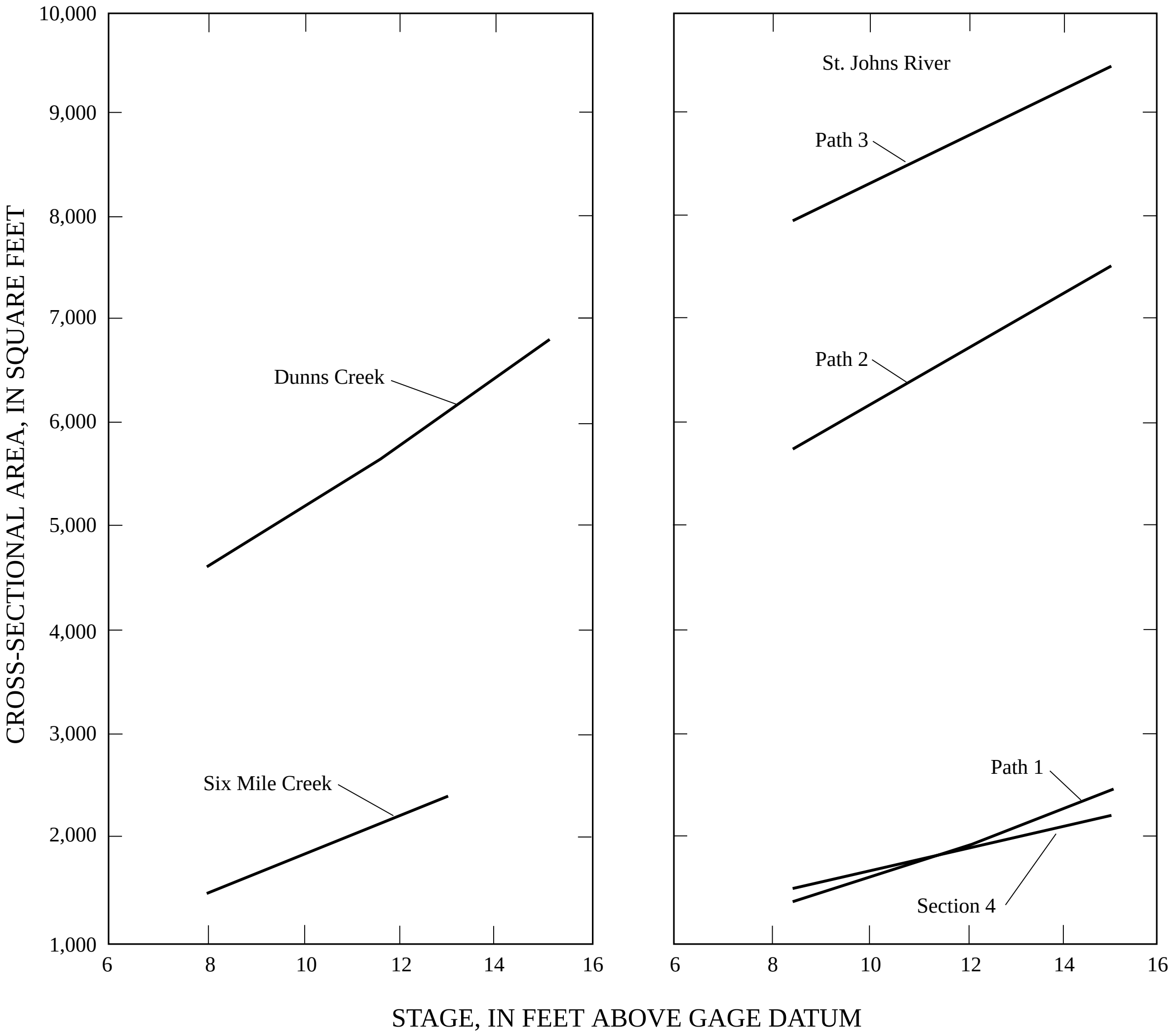

Figure 13. Relation between stage and cross-sectional area for acoustic velocity meter (AVM) stream-gaging sites.

variation in observed velocities. The second plot (B) in figure 15 shows the residuals after stage has been added as an independent variable in the regression equation. The same comparison for the other two streams (not shown) indicated no significant trends in the residuals with stage.

Estimation of Error

Uncertainty in estimates of instantaneous and mean daily discharge is produced by random and systematic errors. Three principal sources of error in the estimated discharge can be identified: (1) instrumental errors associated with measurement of area and index velocity, (2) biases in the representation of mean daily stage and velocity due to natural variability in these over time and space, and (3) errors in cross-sectional area and mean-velocity ratings based on stage and index velocity. In practice, instrumental errors in stage and velocity measurements tend to be small and appear to be randomly distributed. Errors in sample representation tend to be periodic and may induce bias in discharge computations over short periods of time, but increasing the number of observations and the length of the computational period tend to improve representation. The errors in cross-sectional area ratings generally are relatively small because stage and cross-sectional area are relatively easy to measure and verify on a consistent basis. The largest single source of error remaining in discharge computations is uncertainty in the mean-velocity rating.

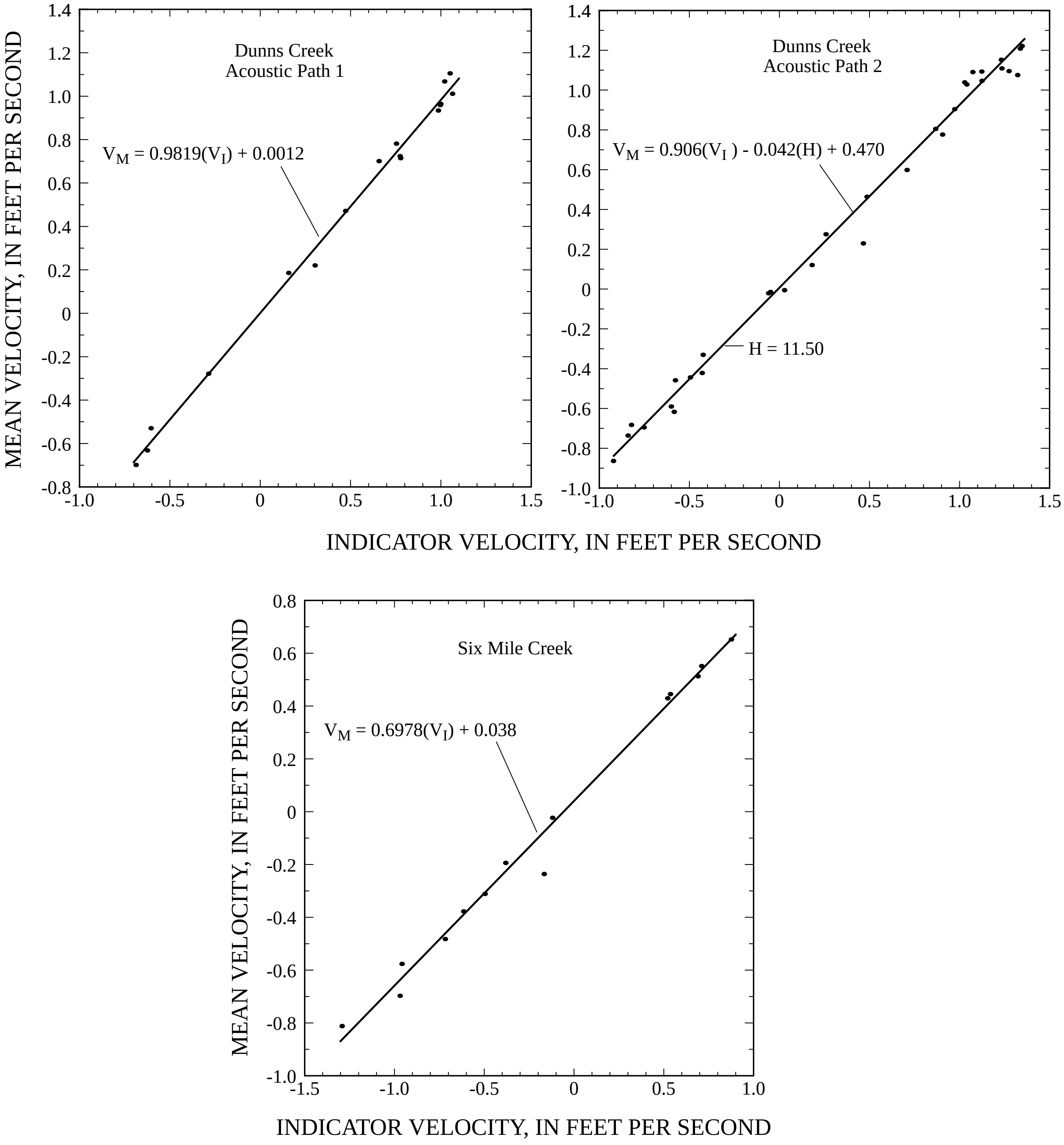

Figure 14. Relation of mean velocity in steam to acoustic velocity meter (AVM)-measured index velocity for AVM steam-gaging sites. (V_I, AVM-measured index velocity, in feet per second; H, stage, in feet above gage datum.)

Smith (1969) identified both random and systematic errors associated with discharge measurements and the velocity ratings developed from these measurements. Although random error in an empirical rating can be reduced by increasing the number of velocity measurements used, the rating itself remains a single estimate of the true velocity relation and thus its uncertainty produces a systematic error in the discharge computation process which cannot be reduced unless a whole new experimental setup (rating) is tested. Biases produced by systematic error are not easily separated from random error. However, where errors in area ratings are small, uncertainty in discharge computations can be estimated mathematically as something less than the standard error of regression for the mean velocity ratings.

Errors in instantaneous discharges as the result of errors in the velocity rating can be estimated for

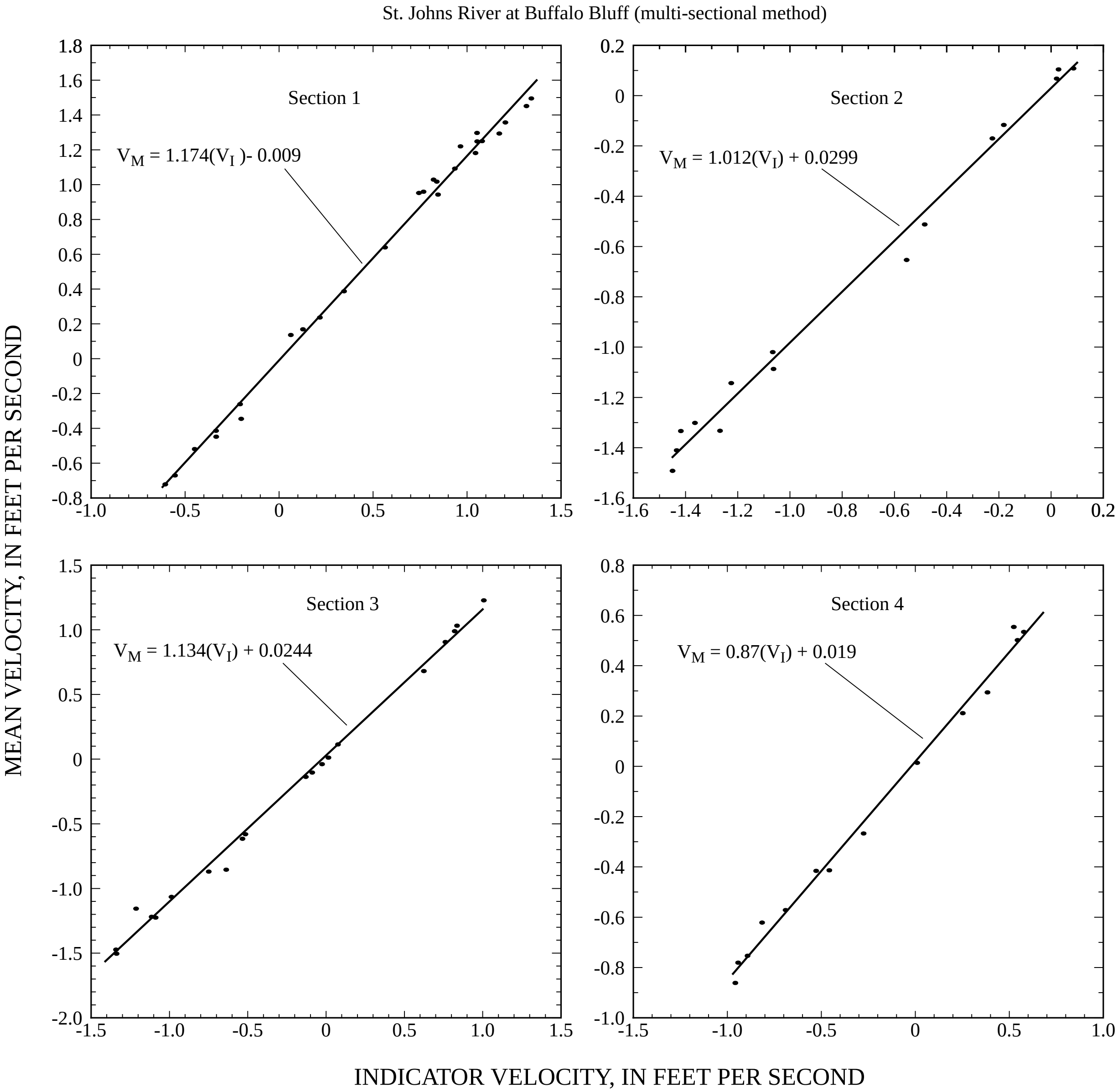

Figure 14. Relation of mean velocity in steam to acoustic velocity meter (AVM)-measured index velocity for AVM steam-gaging sites. (V_I, AVM-measured index velocity, in feet per second; H, stage, in feet above gage datum.)—Continued

each site as the product of instantaneous cross-sectional area (fig. 13) and the standard error estimate (SEE) from the mean-velocity regression (table 2). Errors in discharge are not expressed here in percentages as is commonly done, but instead are shown in units of velocity (ft/s) or discharge (ft^3/s). The ratings in figure 14 show that the variance of residuals around the regression line are fairly uniform over the range of index velocity (V_I). Expressing the standard error of discharge estimates as a percentage of the total discharge tends to overestimate the accuracy of discharge estimates at low flows and underestimate accuracies at high flows. For example, a daily mean discharge of 50 ft^3/s at Dunns Creek may be 100 percent in error, whereas a daily mean discharge of 1,500 ft^3/s may be only 3 percent in error.

Computed instantaneous discharge errors are shown as a function of cross-sectional area for each study site (fig. 16). Standard errors in discharge for the median cross-sectional areas for Six Mile Creek, Dunns Creek, and St. Johns River are 94, 360, and 1,980 ft^3/s, respectively (fig. 16). Over the range of

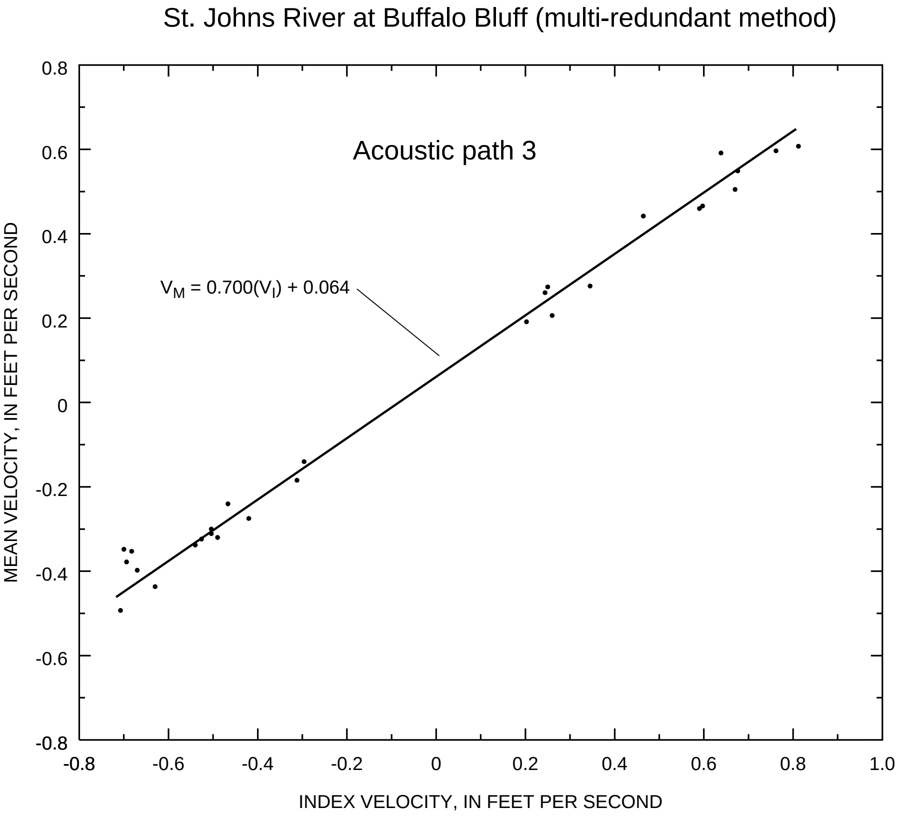

Figure 14. Relation of mean velocity in steam to acoustic velocity meter (AVM)-measured index velocity for AVM steam-gaging sites. (V_I, AVM-measured index velocity, in feet per second; H, stage, in feet above gage datum.)—Continued

measured cross-sectional areas, errors for instantaneous discharges range from 66 to 115 ft^3/s for Six Mile Creek, 271 to 408 ft^3/s for Dunns Creek, and 1,820 to 2,300 ft^3/s for St. Johns River (fig. 16).

Errors in mean discharges may be somewhat less than those in instantaneous discharges because of the central tendency of the mean. In the absence of substantial errors in area ratings, the standard error of mean daily discharges can be estimated as the product of the daily mean cross-sectional area and the standard error of the estimated value from the mean velocity-index velocity relation. This also assumes that mean velocity is linearly related to index velocity and that cross-sectional area is not covariant with index velocity (which is generally true in Florida). The equation for the standard error of an estimated value is expressed in the following equation:

$$SE(\hat{y}(x)) = \sqrt{\frac{1}{n} + \left(\frac{(x-\bar{x})}{sx}\right)^2}(SEE), \qquad (7)$$

where x is the independent variable used in mean-velocity rating,
SE(y(x)) is the standard error estimate of mean velocity from the regression equation at any value of the variable x,
n is the number of data points (discharge measurements),
x is the mean of x values in the discharge measurements,
sx is the standard deviation of x values in the discharge measurements, and
SEE is the standard error estimate.

The estimated value of velocity from equation 6 represents a mean V_M for a given V_I. The standard error of this estimated mean velocity is at a minimum at the mean of the observations of index velocity input to the regression analysis. This error increases for index velocities above and below the mean.

Table 2.--Regression equations for the estimation of mean velocity at acoustic velocity meter (AVM) stream-gaging sites

[All equations are for mean velocity in the stream, in feet per second. R^2, correlation coefficient; ft/s, feet per second; AP, acoustic path; V_M, mean velocity, in feet per second; V_I, AVM-measured index velocity, in feet per second; --, no data]

Path number (shown in figs. 5, 8, and 10),	Number of discharge measurements	Mean velocity range	Mean V_M	Equation	R^2	Standard error of estimate (ft/s)	Standard error of the mean (ft/s)
Six Mile Creek (single path method)							
AP 1	14	-0.48 – 0.65	0.010	$V_M = 0.6978\ V_I + 0.0380$	0.99	0.057	0.015
Dunns Creek (redundant path method)							
AP 1	17	-.69 – -1.01	.447	$V_M=0.982V_I + 0.001$	.99	.047	.011
AP 2	32	-.92 – 1.35	.358	$V_M = 0.906\ V_I - 0.042H + 0.47$	.99	.063	.011
St. Johns River at Buffalo Bluff (sectional method)							
Section 1							
AP 1	27	-.60 – 1.34	.592	$V_M = 1.174\ V_I - 0.0090$	.99	.055	.011
Section 2							
AP 2	16	-1.49 – .11	-.753	$V_M = 1.012\ V_I + 0.0299$	.99	.060	.015
Section 3							
AP 3	20	-1.47 – 1.23	-.294	$V_M = 1.134\ V_I + 0.0244$	.99	.068	.015
Section 4							
AP 4	14	-.86 – .50	-.183	$V_M = 0.8701\ V_I + 0.0190$	.99	.043	.011
St. Johns River at Buffalo Bluff (redundant method)							
AP 3	29	-.71 – +.81	-0.076	$V_M = 0.700V_I + 0.064$	.99	.040	.007
AP 4	--	--	--	--	--	--	--

The standard error of mean daily velocities near the mean of the input data set can be simplified from equation 7 to:

$$SE(\hat{y}(x)) = \frac{SEE}{\sqrt{n}}\ . \qquad (8)$$

Standard errors at the mean value of V_I were computed for each site using equation 8 and are included in table 2. These errors represent a minimum uncertainty for computed mean velocities given the random error incorporated into the determination of a velocity rating. The actual standard error for a given computed daily mean velocity is probably somewhat greater than this but less than the standard error of computed instantaneous velocities (standard error of regression). As noted previously, random errors in instrument readings and random variations in the representativeness of AVM path velocities within a streamflow cross section can be reduced by averaging multiple instrument readings into a single daily value. No amount of sampling replication and averaging, however, can reduce the systematic error in the rating. This error remains a bias in all computed velocities (and discharges) based on the rating.

The instrumental precision of the AVM can exceed the accuracy of the index velocity rating and give the appearance of greater accuracy in computed discharges than is justified. For example, the data-plotted instantaneous discharges for Dunns Creek (fig. 17) show sufficient continuity over time to discern changes and patterns within a range of discharges well below the indicated standard error of ±300 to 400 ft^3/s. The absence of noticeable random scatter around the cyclic pattern of discharges would seem to indicate a high degree of precision. The scatter of observations around the rating line for Dunns Creek (fig. 14) and the standard error of regression for the rating, however, indicate somewhat lesser conformity

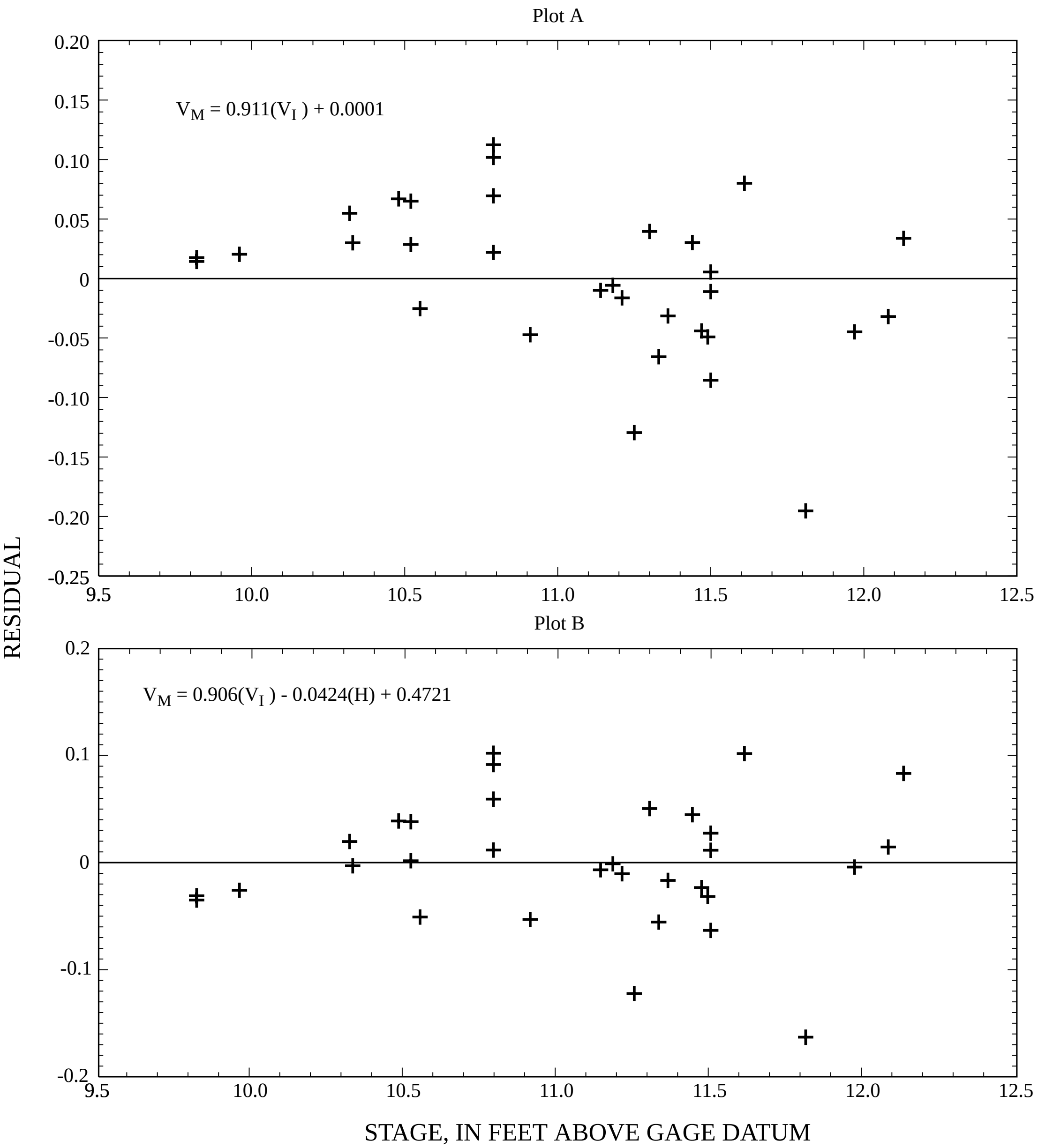

Figure 15. Residuals from regression of mean velocity to stage with and without stage as an independent variable for Dunns Creek Path 2. (V_I, AVM-measured index velocity, in feet per second; H, stage, in feet above gage datum.)

between measured and computed instantaneous velocities than is indicated between successive computed discharge.

The high degree of continuity in computed instantaneous discharges suggests that errors are not random over time. If errors in computed discharge are defined as the difference between the computed and true discharge time-series data (both of which appear to be smooth and periodic within the limits of measurement), then the time series of errors must also be smooth and periodic. From this it follows that errors in computed discharge must be correlated, and thus biased, within a given period of time which can be represented as the average correlation length of the error time series. The periodicity of tidal flow reversals in this system would suggest a possible error correlation length similar in duration to the tide. By extension, the standard error of discharges for averaging intervals of less than several tidal cycles (such as daily averages), will tend to be greater than the minimum calculated using equation 8, and may tend toward the greater standard error of instantaneous observations represented by the standard error of regression. Over averaging intervals of many correlation lengths (such as months or years), the standard error of the mean may approach that computed from equation 8.

Though the standard errors of estimated velocity are small (between 0.01 and 0.015 ft/s), errors in mean daily discharge can be large due to large cross-sectional areas. Examples of standard errors in computed mean daily discharges (for mean daily values computed near the mean) of V_I are shown as a function of cross-sectional area for each study site in figure 16. Errors in discharge for the median cross-sectional area for Six Mile Creek, Dunns Creek, and St. Johns River at Buffalo Bluff (sectional method) during the study period are 25, 65, and 455 ft^3/s, respectively (fig. 16).

Though the use of AVMs in tidally affected streams can produce reliable estimates of high discharge, the accuracy of the method applied at low, net daily flows can be very poor. Mean daily discharge at the three AVM sites ranged from about -500 to +1000 ft^3/s at Six Mile and Dunns Creeks and from -500 to +15,000 ft^3/s on the St. Johns River at Buffalo Bluff. For periods of high discharge, the AVM index-velocity method tends to produce estimates accurate within 2 to 6 percent. For periods of moderate discharge, errors in discharge estimates may increase to more than 50 percent. At low flows, errors in percentage of discharge increase toward infinity.

SUMMARY

Three tidally affected streams in northeast Florida were selected for application of acoustic velocity meters (AVMs). Gaging of low-velocity tidal streams is complicated by unsteady, variable flow conditions. Development of a simple relation between stage and discharge is not possible because of tidal and backwater conditions in these streams. AVMs can be used under these conditions to compute discharge by multiplying cross-sectional area by mean velocity, estimated using index velocity measured by the AVM.

Physical characteristics for all three low-velocity tidal streams are similar except for drainage area. The topography for all three sites primarily is low-relief, swampy terrain. During a typical tidal cycle, stream velocities range from -2 to 2 feet per second and the average variation in stage is about 1 foot. Two of the gaging sites, Six Mile Creek and Dunns Creek, are tributaries of the St. Johns River, each located about 0.8 to 1.0 mile upstream from the mouth. The third gaging site is located on the St. Johns River at Buffalo Bluff about 89 miles upstream from its mouth at the Atlantic Ocean. Cross-sectional areas at the measurement section ranged from about 2,500 square feet at Six Mile Creek to 18,500 square feet at St. Johns River at Buffalo Bluff.

The three stream-gaging sites were instrumented to measure index velocity (using an AVM), corresponding system diagnostics, and stage (using a shaft encoder). Measurements were made at 15-minute intervals and recorded using a datalogger. To determine mean velocity, discharge was measured at each site using a portable acoustic current meter and standard U.S. Geological Survey stream-gaging techniques. The acoustic current meter was used rather than the low-velocity Price type AA current meter because it more accurately measures velocity magnitude and direction vectors.

Stage-area curves for each stream were developed using bathymetric data. Least-squares multiple linear regression was used to estimate mean velocity as a function of the AVM-measured index velocity. Results of the regression analysis for Six Mile Creek and the St. Johns River study site indicate that a simple linear relation exists between mean velocity and AVM-measured index velocity. Results of the regression analysis for the Dunns Creek study site indicate that a multiple-linear relation exists between mean velocity and AVM-measured index velocity and stage.

Instantaneous discharge was computed by multiplying results of relations developed for cross-sectional area and mean velocity. Principal sources of error in the estimated discharge are identified as: (1) instrument errors associated with measurement of stage and index velocity, (2) errors in the representation of mean daily stage and index velocity due to natural variability over time and space, and (3) errors in cross-sectional area and mean-velocity ratings based on stage and index velocity. Errors in discharge are not expressed in percentages as is commonly done, but instead are shown in absolute units of velocity and discharge. Standard errors for instantaneous discharge for the median cross-sectional area for Six Mile Creek, Dunns Creek, and St. Johns River at Buffalo Bluff were 94, 360, and 1,980 cubic feet per second, respectively. Standard errors for mean daily discharge for the median cross-sectional area for Six Mile Creek, Dunns Creek, and St. Johns River at Buffalo Bluff were 25, 65, and 455 cubic feet per second, respectively. Mean daily

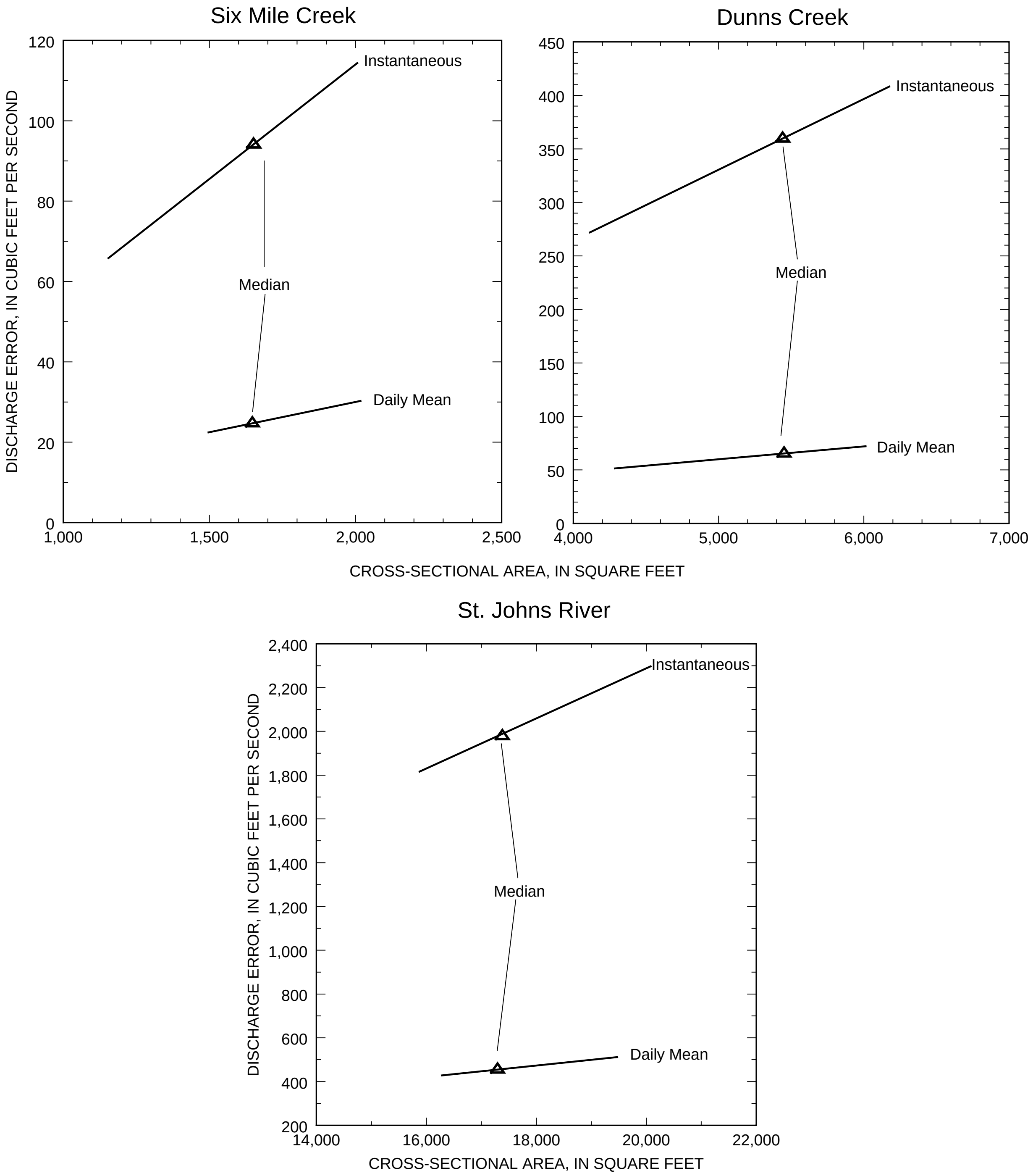

Figure 16. Relation of discharge error as a function of cross-sectional area for acoustic velocity meter (AVM) stream-gaging sites.

discharge at the three sites ranged from about -500 to 1,500 cubic feet per second at Six Mile Creek and Dunns Creek and from about -500 to 15,000 cubic feet per second on the St. Johns River at Buffalo Bluff. For periods of high discharge, the AVM index-velocity method tended to produce estimates accurate within 2 to 6 percent. For periods of moderate discharge, errors in discharge may increase to more than 50 percent. At low flows, errors as a percentage of discharge increase toward infinity.

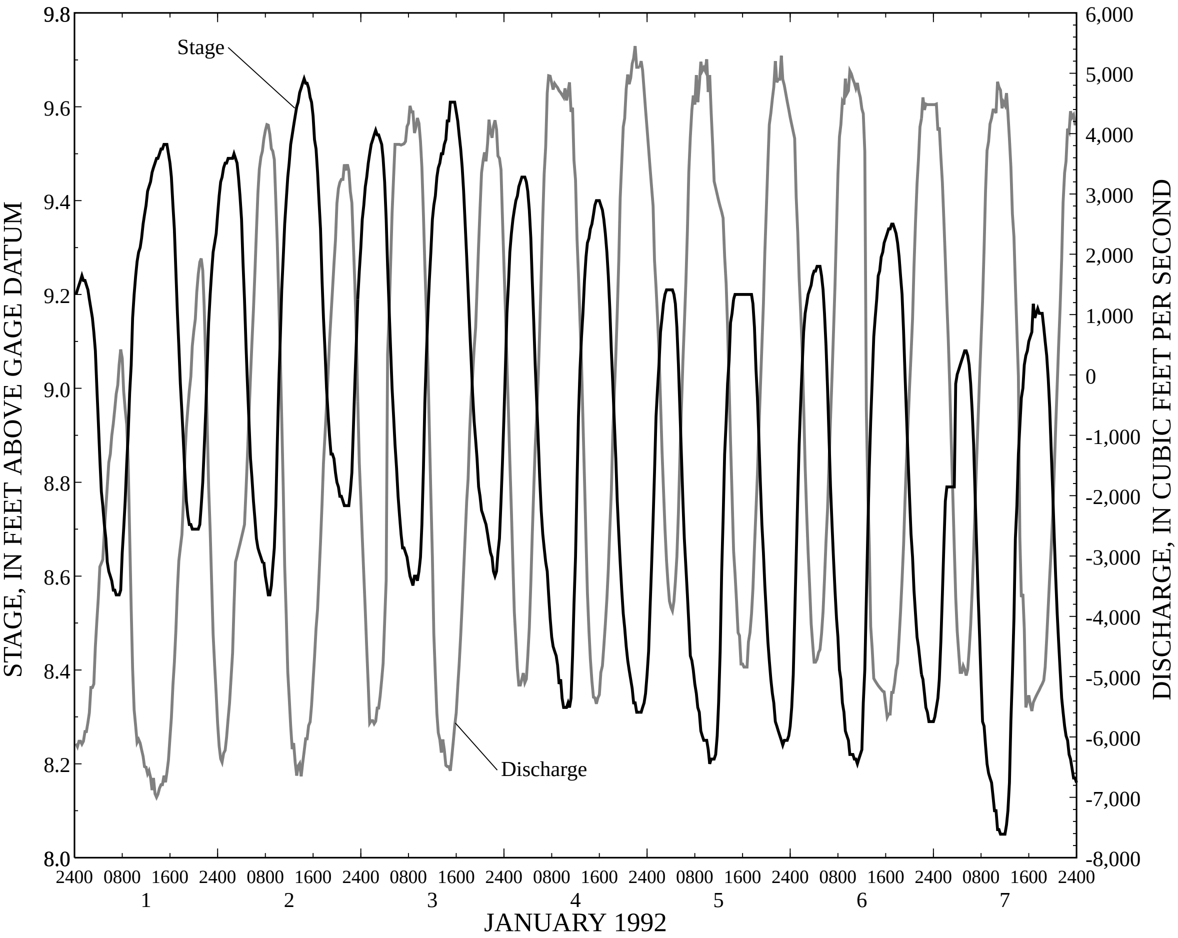

Figure 17. Instantaneous stage and discharge for a 7-day period at Dunns Creek.

Selected References

Chow, V.T., 1959, Open channel hydraulics: New York, McGraw-Hill, p. 523–535.

Draper, N.R., and Smith, Harry, 1982, Applied regression analysis: New York, John Wiley & Sons, p. 141–210.

Laenen, Antonius, 1985, Acoustic velocity meter systems: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. 17, 38 p.

Laenen, Antonius, and Curtis, Jr., R.E., 1989, Accuracy of acoustic velocity metering systems for measurement of low velocity in open channels: U.S. Geological Survey Water-Resources Investigations Report 89–4090, p. 15.

Laenen, Antonius, and Smith, Winchell, 1983, Acoustic systems for the measurement of streamflow: U.S. Geological Survey Water-Supply Paper 2213, 26 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: v. 1: Measurement of stage and discharge, p. 174–5, and v. 2: Computation of discharge: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Smith, Winchell, 1969, Feasibility study of the use of the acoustic velocity meter for measurement of net outflow from the Sacramento-San Joaquin Delta in California: U.SW. Geological Survey Water-Supply Paper 1977, 54 p.

Smith, Winchell, Hubbard, L.L., and Laenen, Antonius, 1971, The acoustic streamflow measuring system on the Columbia River at The Dalles, Oregon: U.S. Geological Survey Open-File Report, 60 p.