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Computation of Discharge Using the Index-Velocity Method in Tidally Affected Areas

Scientific Investigations Report 2005-5004

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

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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
square foot (ft^2)	929.0	square centimeter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	2.54	centimeter
inch per hour (in/hr)	2.54	centimeter per hour

ABBREVIATIONS

ADVM	acoustic Doppler velocity meter
Bay	San Francisco Bay
bins	range gated sample volume
Delta	Sacramento–San Joaquin River Delta
GPS	geographic positioning system
<	less than
PST	Pacific Standard Time
UVM	ultrasonic velocity meter
$\overline{V}$	mean velocity
V_i	index velocity
V_p	water velocity along the acoustic path

ORGANIZATIONS

USGS	U.S. Geological Survey

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Computation of Discharge Using the Index-Velocity Method in Tidally Affected Areas

By Catherine A. Ruhl and Michael R. Simpson

Abstract

Computation of a discharge time-series in a tidally affected area is a two-step process. First, the cross-sectional area is computed on the basis of measured water levels and the mean cross-sectional velocity is computed on the basis of the measured index velocity. Then discharge is calculated as the product of the area and mean velocity. Daily mean discharge is computed as the daily average of the low-pass filtered discharge. The Sacramento-San Joaquin River Delta and San Francisco Bay, California, is an area that is strongly influenced by the tides, and therefore is used as an example of how this methodology is used.

Introduction

The U.S. Geological Survey (USGS) has operated a network of flow-monitoring stations in the Sacramento–San Joaquin River Delta (Delta) since 1987. Additionally, equipment may be deployed to intensively study specific areas for short (3-to 9-month) periods. Tides from the Pacific Ocean enter the San Francisco Bay (Bay) and Delta system through the Golden Gate and cause twice-daily variations in stage and velocity throughout the region. Because water level cannot be uniquely related to discharge in tidally affected areas, standard stream-gaging techniques cannot be used in the Bay and Delta (Smoot and Novak, 1969). To overcome these challenges, a wide range of acoustic instrumentation has been used successfully to measure discharge. Instrumentation currently in use by the USGS include: ultrasonic velocity meters (UVM) and acoustic Doppler velocity meters (ADVM).

Purpose and Scope

This report describes the index-velocity method for computing discharge in tidal environments and goes on to describe an approach for determining daily discharge by using a tidal filter. The main body of the report summarizes the techniques; appendices at the end of the report cover the detailed procedures and calculations. In addition, a section identifying some potential mistakes has been included to assist those who develop calibration relations to identify possible explanations for anomalous data.

Acknowledgements

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Principles of Operation

Ultrasonic Velocity Meters

UVMs work on a "time of travel" principle. The UVM system is comprised of two acoustic transducers that are aimed at each other and are mounted at the same depth diagonally across a channel (*fig. 1A*). Both transducers are connected to a central processing unit by underwater cables. To measure the water velocity, an acoustic pulse is transmitted between the transducers in both directions: first an acoustic pulse travels from A to B then a pulse travels from B to A (*fig. 1A*). An acoustic signal that has a component traveling in the same direction as the water (from A to B, *fig. 1A*) will arrive earlier than an acoustic signal that is traveling against the water velocity (from B to A, *fig. 1A*). The water velocity along the acoustic path (V_p) is proportional to the difference in time it takes the acoustic signal to travel between the two transducers (ADS Corporation, 2003). Index velocity (V_i) is determined by measuring the difference in time required for an acoustic signal to travel between the two transducers and a knowledge of transducer configuration (specifically the distance between transducers and the angle of the acoustic path, with respect to the principal streamflow direction) (*fig. 1A*). A UVM system can have more than one acoustic path; for example, there can be multiple paths in the vertical with pairs of transducers mounted at different elevations in the water column; or a "cross-path" configuration with pairs of transducers mounted so that their acoustic paths create an "X" pattern across the channel.

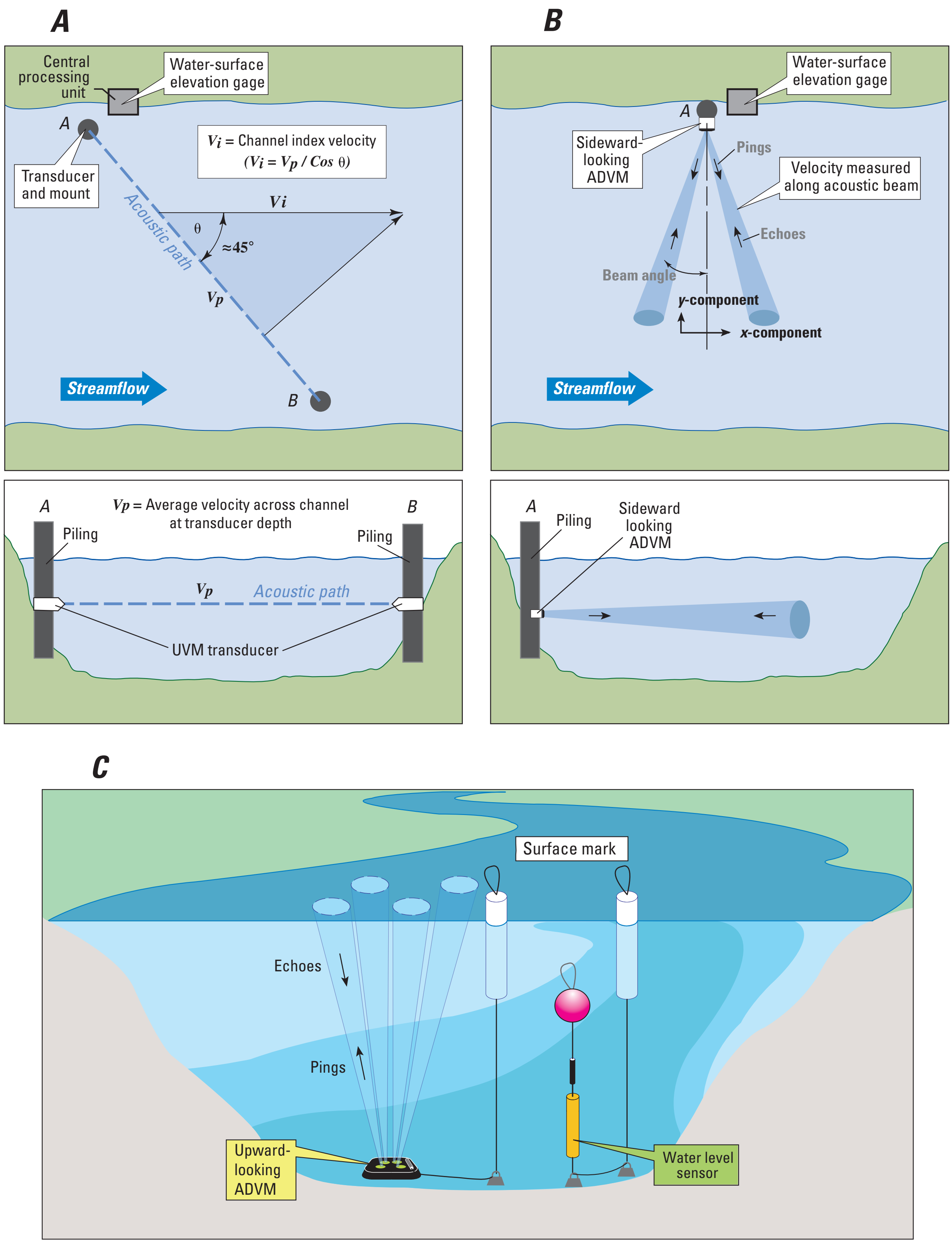

Figure 1. Schematic of standard acoustic stream-gaging stations. (*A*) ultrasonic velocity meter; (*B*) horizontal acoustic Doppler velocity meter; and (*C*) upward-looking acoustic Doppler velocity meter.

Acoustic Doppler Velocity Meters

ADVMs utilize monostatic transducers, or transducers that both send and receive an acoustic pulse. An acoustic pulse of a known frequency is sent out into the water column along the acoustic beam. A fraction of that acoustic pulse is reflected by small particles in the water, returning to the transducer at a frequency that has been shifted due to the Doppler effect. The index velocity (V_i) is the water velocity within the acoustic beam and is determined on the basis of the change in the transmitted acoustic frequency and the geometric configuration of the transducers (SonTek Corporation, 2000) (*figs. 1B, C*).

There are three general classifications for ADVMs: point velocity, single bin, and profiler. Each system uses the Doppler shifts of sound waves reflected off of particles moving with the water, however, implementation varies among systems.

Point Velocity

Point velocity ADVMs use converging beams to measure velocity in a small sample volume. These ADVMs are used both in the laboratory and in the field to measure point velocities but generally are not used for index-velocity measurements.

Single Bin

Single bin ADVMs use divergent beams to sample larger sections of the velocity field. The sample volume can be manipulated by range gating the received signal, or programming the start distance and end distance of the acoustic beam over some portion of the instrument range. The measured velocity is proportional to the magnitude of the Doppler frequency shift and is spatially averaged over the sample volume. The sample volume can vary from the maximum instrument range to a few centimeters. Single bin ADVMs are used primarily for index velocity measurements and can be mounted in downward-looking, upward-looking, and sideward-looking configurations.

Profiler

ADVM profilers use diverging beams for velocity measurement, but contain sophisticated, high-speed, signal processing software that can calculate multiple velocities from numerous range-gated sample volumes (bins) along the beam path. Both the size and number of these bins can be controlled from the ADVM firmware and usually are spaced evenly along the main beam axis. ADVM profilers can be used to measure index velocities using upward-looking, downward-looking, and side-looking configurations. With bottom-tracking software or satellite geographic positioning system (GPS) integration, they also can be mounted on mobile, downward-looking platforms to gather velocity profiles or to collect moving-boat discharge measurements (Simpson, 2001).

Methods

Discharge is a function of both area and velocity. The equation used to calculate discharge is:

$$Q = A\overline{V} \qquad \text{(eq. 1)}$$

where

- Q is discharge;
- A is the cross-sectional area (area); and
- $\overline{V}$ is the cross-sectionally averaged velocity (mean velocity) (Munson and others, 1990).

Because direct measurement of the area and mean velocity is difficult, easily measured parameters are used as surrogates. Calibration relations are used to calculate the area and the mean velocity using the stage and index velocity measurements collected at the gage location.

Calculating Area on the Basis of Stage

Stage or water level is recorded as a time-series at the gage location (*fig. 1*). Stage can be measured using various techniques (Barron, 1963; Rantz and others, 1982; Kennedy, 1988; Latkovitch and Leavesley, 1992). Techniques currently used at long-term stations in the Sacramento-San Joaquin Delta include upward looking acoustic beams, bubble-gage sensors, and stilling wells equipped with a float tape and shaft encoder. Water-level records for the short-term sites can be obtained either through internally logging probes associated with the instrument packages (*fig. 1C*), or a stage record from a nearby gaging station. The measured stage is related to cross-sectional area based on detailed channel surveys. At long-term stations, these relations are confirmed approximately every 3 years, or whenever rating discrepancies are identified.

The stage versus cross-sectional area relation is determined from a detailed channel survey. Channel surveys can be conducted using a variety of techniques such as sounding weights, fathometers, or downward-looking ADVM profilers to capture the submerged features, and standard surveying techniques to characterize the bank profile (*fig. 2*). Water levels change rapidly in the Bay and Delta area: reaching 11.5 inches per hour (in/hr) at the Golden Gate; 7.3 in/hr near the confluence of the Sacramento and San Joaquin Rivers; and 0.5 in/hr near the upstream Delta boundaries on the Sacramento and San Joaquin Rivers (Tidelog, 2004). Due to rapidly varying water levels in tidally affected environments, close synchronization between the time of the bank surveys, bathymetric surveys, and water-level measurements at the gage must be maintained so that survey data can be related directly to stage. At short-term monitoring stations the approach is similar, though the bank elevations often are estimated rather than surveyed.

The final relation between stage and area is developed for the expected stage range at the gage location. There are a number of approaches that can be used to develop this relation including the Channel Geometry Analysis Program (Regan

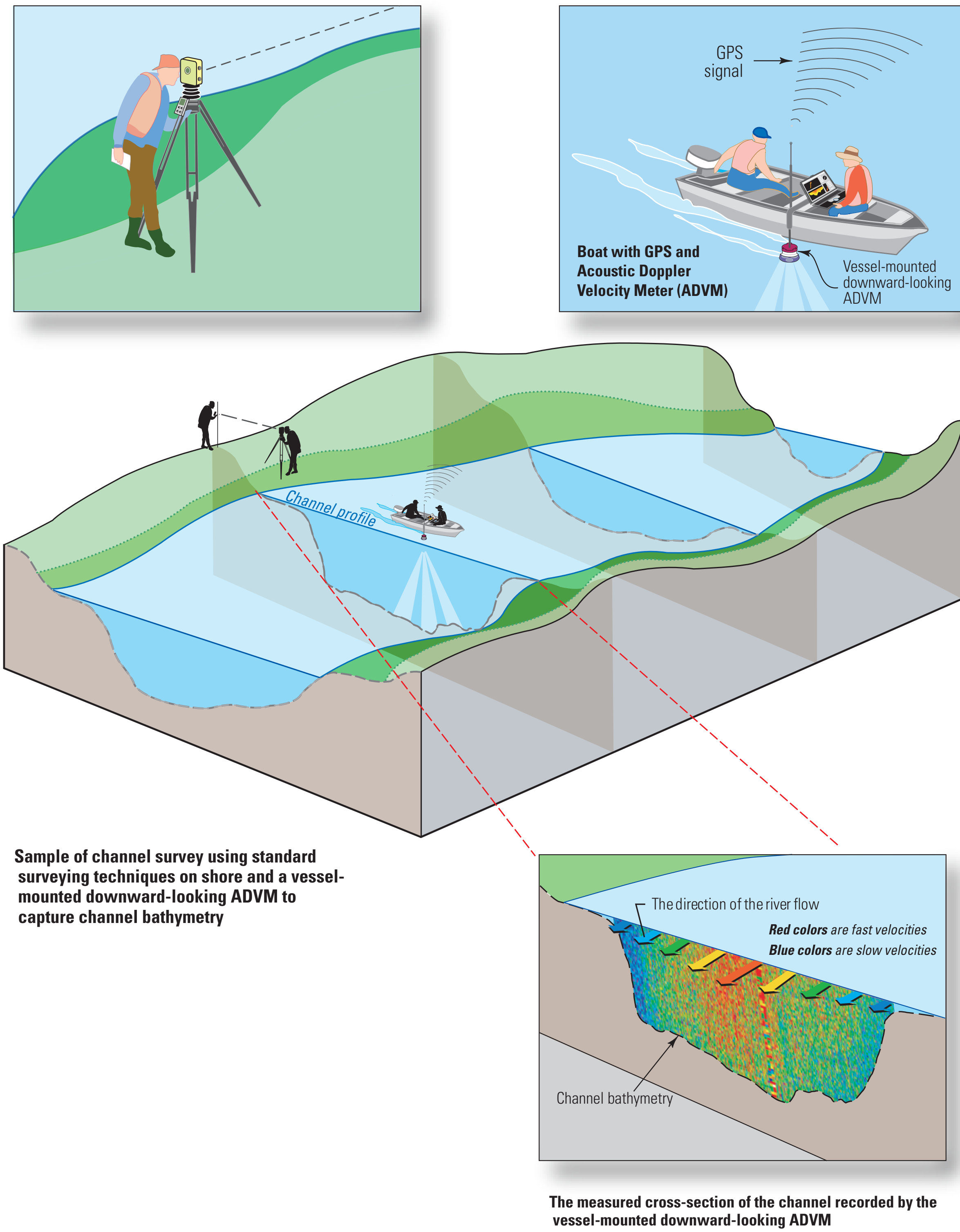

Figure 2. Schematic of bathymetry and channel-bank survey field method.

and Schaffranek, 1985) or AreaComp.exe (Rehmel, 2002). In general, a quadratic equation is sufficient to characterize the channel area (Rantz and others, 1982). The details of how the stage versus area relation is determined are contained in *Appendix A*.

Calculating Mean Velocity on the Basis of the Index Velocity

The index velocity is recorded as a time-series at the gage location (*fig. 1*). Over the last several decades, many advances have been made in the field of hydroacoustics and now a variety of instruments are available to measure index velocities (Rantz and others, 1982; Morlock and others, 2002). Examples of equipment that are currently in use at long-term monitoring stations in the Sacramento-San Joaquin Delta include UVMs and sideward-looking ADVMs (both single-bin and profiling). Short-term deployments use internally logging, upward-looking ADVMs and are calibrated in the same manner as the long-term stations.

The collection of discharge measurements using acoustic techniques has improved significantly and now is employed frequently (Morlock and others, 2002). The specifics of how individual discharge measurements are collected are described in detail in Simpson and Oltmann (1993), Morlock (1994), and Simpson (2001). In tidally affected environments, it is important to collect discharge measurements that adequately characterize the high frequency variability of the tides as well as the seasonal variability associated with the annual hydrologic cycle (Simpson and Bland, 1999). Tidal variability is captured by collecting between 50–120 discharge measurements over a 12- to 13-hour period; the seasonal variability is captured by collecting a smaller set of data (10–20 measurements) periodically during periods of hydrologic interest (most often high-flow events). At many locations in the Delta, the influence of the rivers is minimal compared to the influence of the tides. Periodic discharge measurements must be collected over the life of the station to ensure that the calibration relation is stable. Changes in transducer alignment and channel geometry can change the rating.

The mean velocity during each transect is calculated by dividing the discharge, measured using a boat-mounted downward-looking ADVM profiler, by the channel area, calculated based on the water level measured at the gage. The time of the measurement is taken as the mid-point of the duration of the discharge measurement. If a water-level reading was not recorded at that time, the values are interpolated linearly to get an estimate of the area at the time the transect was conducted.

The index velocity measured at the gage is related directly to the mean velocity. If the recorded index velocity is an average over a time interval, the time must be shifted to the midpoint of the interval to ensure proper synchronization with the boat measurements. The relation between the index velocity and mean velocity is developed by identifying the index velocity measured at the time of the midpoint of each transect. If the transect occurred between two data points recorded at the gaging station, the resulting index velocity is calculated based on linear interpolation to ensure that all values are on the same time-base. The final relation is based on a least-squares regression between the index velocity and mean velocity.

A wide range of relations have been developed in the Bay and Delta region (*fig. 3*) most of which are linear (*fig. 3A*). However, more complex ratings also are possible. In this system, we have documented several higher-order polynomial ratings (*fig. 3B*); loop ratings that are indicative of ebb-flood asymmetries in the current structures at the measurement location causing a different relation between the flood-to-ebb transition versus the ebb-to-flood transition (*fig. 3C*); and occasionally we have found a bimodal relation (*fig. 3D*). A sample calculation of the mean velocity based on the index velocity, is given in *Appendix B*.

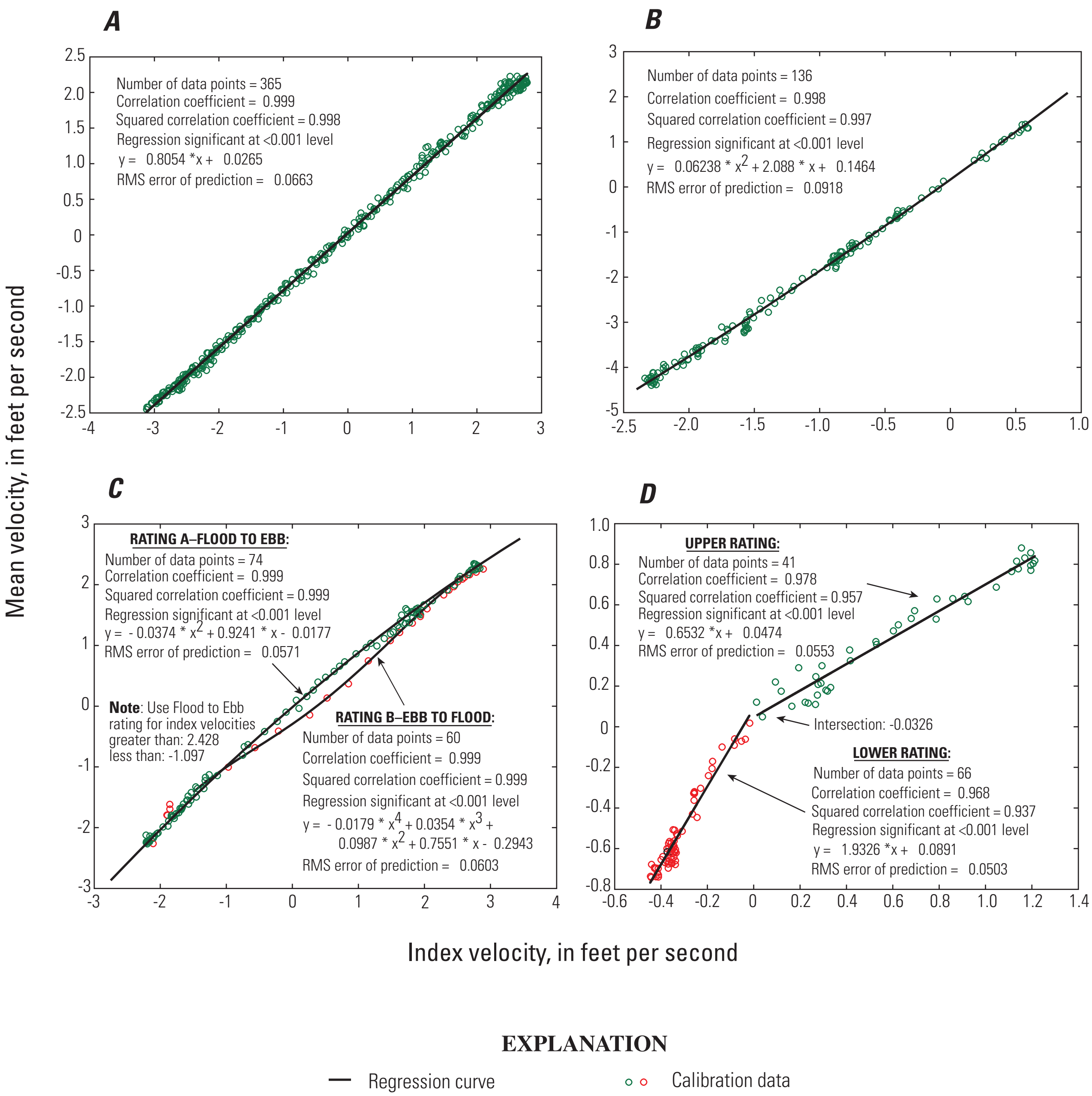

Figure 3. Examples of index velocity versus mean velocity ratings. (*A*) simple linear rating; (*B*) quadratic rating; (*C*) loop rating; and (D) bi-modal rating.

Calculating Discharge

Once the cross-sectional area is calculated from the stage time-series data and the mean velocity is calculated from the index velocity time-series data, discharge can be calculated (*fig. 4A*, blue line). Discharge is the product of these two values: $Q = A\overline{V}$ (eq. 1). A sample discharge time-series based on a linear velocity calibration is given in *Appendix C*. In addition, *Appendix C* presents the methodology for calculating discharge at locations that have more complex loop and bimodal velocity ratings.

Calculating Daily Flow

Calculating daily discharge in a tidally influenced environment cannot be accomplished simply by averaging all of the values collected during that 24-hour period. Simple averaging causes cyclical variations, or aliasing, in the data that are spurious and are a function of the averaging scheme, not the data. Therefore, a low-pass filter is used to remove frequencies that have periods less than 30 hours. The most energetic variations removed in this process are the astronomical tides (typically with periods at or around 12 and 24 hours); however, other variations (meteorological, hydrologic, or operational) that have periods less than 30 hours also are removed. A number of filters are available including the Godin filter (Godin, 1972), a Fourier transform filter (Walters and Heston, 1982; Burau and others, 1993), or a Butterworth filter (Roberts and Roberts, 1978). All of these filters are used by the San Francisco Bay/Delta Hydrodynamics Program for a variety of purposes, however, published daily discharge values are calculated using a Butterworth filter with a 30-hour stop period and a 40-hour pass period (*fig. 4A*, red line; and *fig. 4B*, red line).

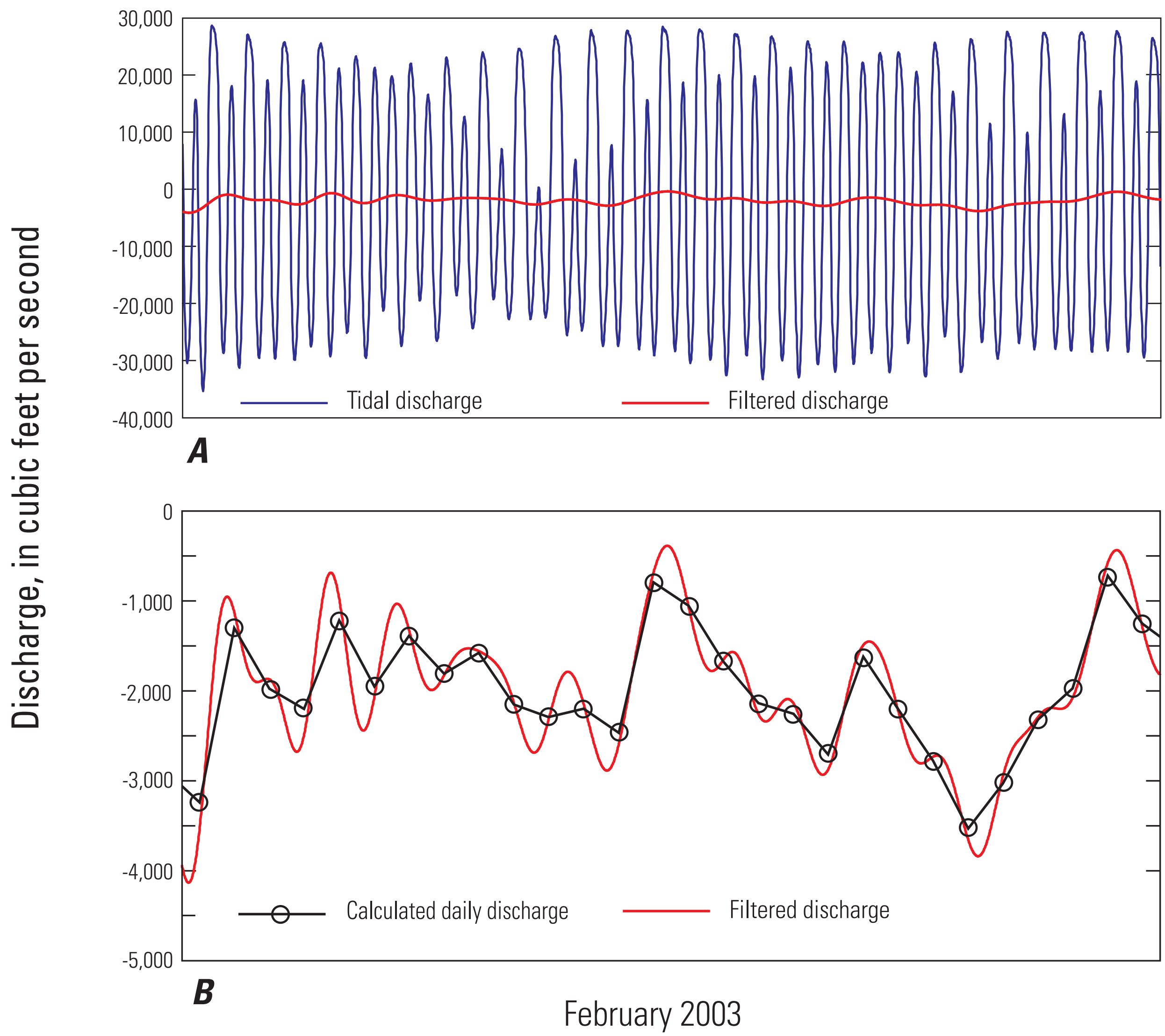

Figure 4. Example of discharge record. (*A*) tidal discharge, and filtered discharge; and (*B*) filtered discharge, and daily average discharge.

Note that tidal variations with periods greater than 30 hours, such as spring/neap cycle effects, will remain in the resulting tidally averaged data (Roberts and Roberts, 1978). In addition, approximately 2 days of filtered data at the beginning and end of the time-series or adjacent to any gap in the time-series are erroneous due to filter ringing and are not used. The daily discharge is calculated as the 24-hour daily average of the tidally filtered data (*fig. 4B*, black line with open circles). A sample calculation of daily discharge time-series is given in *Appendix D*.

Importance of High-Quality Data

Collecting high-quality data is important in any system. It is particularly critical in tidal systems where the tidally averaged flows are desired. Often tidally averaged flows are several orders of magnitude smaller than the tidal flows; therefore, a relatively small bias in the tidal flows can become a substantial error in the tidally averaged data. Clock synchronization, channel-bottom movement, boat positioning, discharge measurement duration (too fast or too slow), configuration file settings, and equipment positioning all can affect the resulting data. Attention to detail is critical in minimizing problems during data collection. A summary of how different types of problems are manifest in the final calibration data sets is given in *Appendix E*.

Summary

The index-velocity method used by the U.S. Geological Survey for calibrating flow-monitoring stations in tidally influenced environments is described. Discharge is computed as a three step process: (1) calculating the cross-sectional area based on a stage time-series; (2) calculating the mean cross-sectional velocity based on a measured index velocity time series, and (3) calculating discharge as the product of the area and mean velocity: Q=VA. A daily mean discharge value is computed based on a daily average of the low-pass filtered discharge.

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Appendix A. Sample Computation of the Cross-Sectional Area Relation

Introduction

This appendix describes the standard procedure used to compute the cross-sectional area. In this example, standard survey techniques were used to characterize the riverbanks and a downward-looking vessel-mounted ADVM was used to collect bathymetry data. The cross section is presented in *figure A1*. This is an example of one approach for collecting and processing the data—-this information may be collected and analyzed using a variety of techniques.

The cross-sectional area is a function of the stage. In tidal systems, water levels vary significantly over short periods of time; therefore, it is important to accurately document the time of the channel survey to ensure that all data can be corrected to the same vertical datum and related to the concurrently recorded gaging-station data.

Establishing the stage-versus-area relation is a four-step process: (1) channel-bank survey; (2) bathymetry survey; (3) synthesis-of-field data; and (4) determination of stage-versus-area relation.

Step 1. Channel-Bank Survey

Standard surveying techniques are used to measure the elevations of the channel banks from the crest of the river bank to the water's edge. Both horizontal location and vertical elevation information must be recorded during the field survey. It is critical to document the time that elevations at the water's edge are measured; this allows the application of an accurate correction to the survey elevation data ensuring that all of the information used to develop the relation has the same vertical datum.

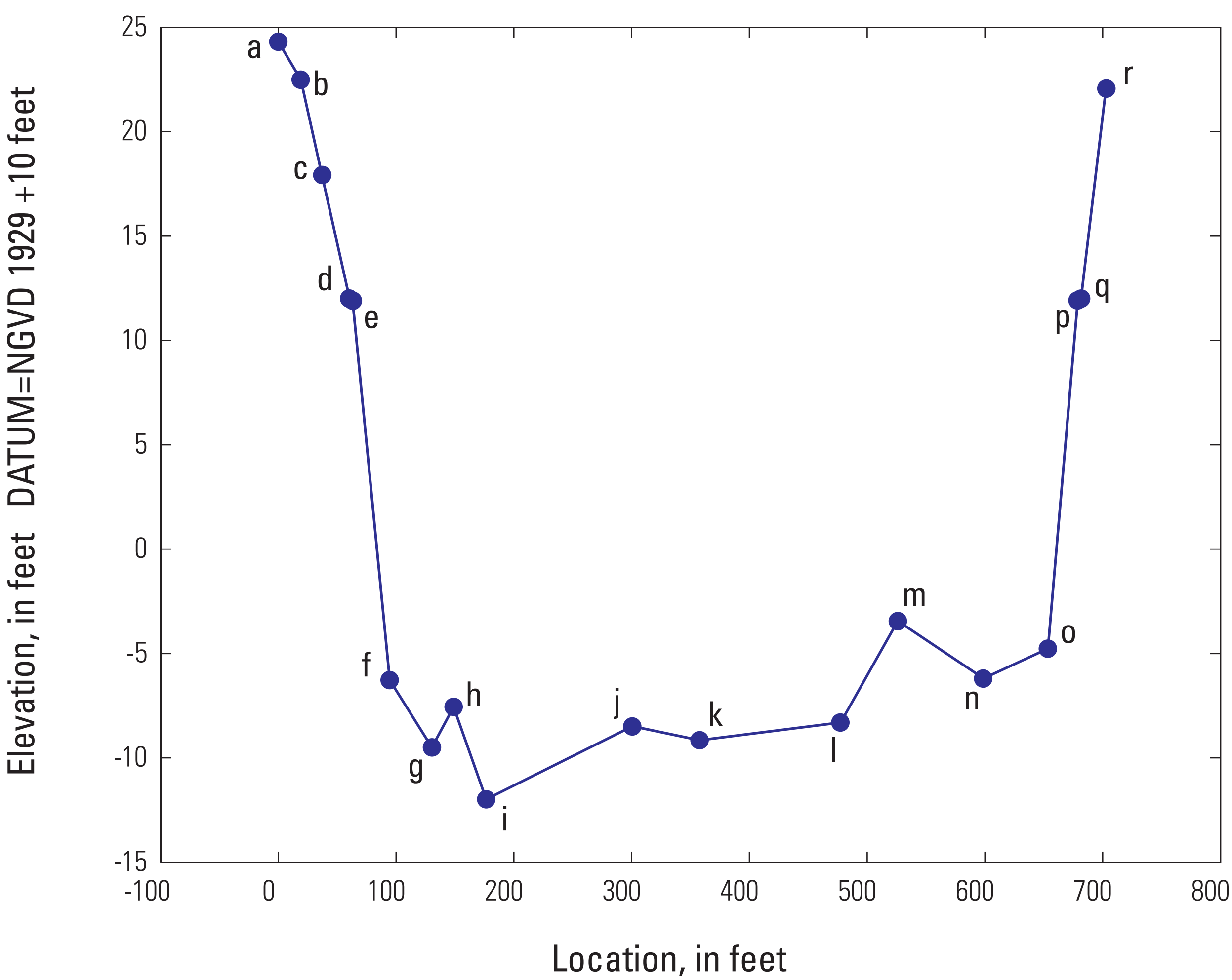


Figure A1. Measured channel cross section. Standard survey techniques used on the channel banks, and a vessel-mounted downward-looking acoustic Doppler velocity meter used in the submerged portion of the channel.

of the vertical elevation data so that the datum is consistent between the stage gage and the survey data.

Summaries of the field notes associated with the channel-bank survey and the stage data recorded at the gaging station are presented in *tables A1* and *A2*. For the purposes of the channel-bank survey, the data recording interval was set to a 1-minute interval rather than the standard 15-minute interval.

Table A1. Summary of field notes collected during channel-bank survey. [All units in feet]

Label on figure A1	Horizontal location	Vertical elevation	Field notes
a	−19	14.41	
b	0	12.60	
c	18	8.02	
e	44	2.00	time = 1441
p	660	2.04	time = 1447
r	684	12.20	

Table A2. Summary of stage data recorded at gaging station

Time	Stage (in feet)	Comments
1438	11.85	
1439	11.86	
1440	11.87	
1441	11.88	Left bank water's edge elevation collected
1442	11.89	
1443	11.90	
1444	11.91	
1445	11.92	
1446	11.93	
1447	11.94	Right bank water's edge elevation collected
1448	11.95	
1449	11.96	

Horizontal Location Correction

The horizontal location correction is used to zero the cross section at the crest of either the left or right bank, depending on where the channel bank survey is started. The horizontal location measurements collected in the field all are relative to the initial position of the surveying instrument. In this particular case, the horizontal location correction is +19 feet (ft) to account for the placement of the instrument 19 ft from the crest of the left bank (*table A3*).

Table A3. Summary of field data and horizontal location corrections [All units in feet]

Label on figure A1	Horizontal location	Corrected horizontal location	Vertical elevation	Field notes	Remarks
a	−19	0	14.41		(1) Location correction is +19 feet to account for the initial placement of the surveying equipment.
b	0	19	12.60		
c	18	37	8.02		
e	44	63	2.00	time = 1441	
p	660	679	2.04	time = 1447	
r	684	703	12.2		

Vertical Elevation Correction

A vertical elevation correction is necessary if the channel-bank survey is not referenced to the same vertical datum as the stage gage. Discrepancies between the measured elevation at the water's edge (positions "e" and "p" on *fig. A1*) and the concurrently recorded stage also may occur due to hydrodynamic processes causing lateral variations in water level. For the purposes of developing the stage-versus-cross-sectional area relation, we assume that the water surface is level across the channel and that the measured stage at the gaging station is an accurate reflection of the elevation of the entire water surface. The correction applied to the measured elevations is calculated as follows:

$$H_{corr} = \frac{[(stg_{t_1} - H_{t_1}) + (stg_{t_2} - H_{t_2})]}{2} \quad \text{(eq. 2)}$$

where

H_{corr} is applied to each of the measured elevations to ensure that the measured elevations are directly related to the datum at the gaging station;

stg is the stage recorded at the gaging station at the time the elevation at the water's edge is measured by the survey crew; and

H is the elevation measured by the survey crew at the water's edge.

The subscripts refer to the time that the measurements were collected so they can be related to the values recorded at the gaging station.

In this example, the calculation is determined as follows:

$$H_{corr} = \frac{[(stg_{1441} - H_{1441}) + (stg_{1447} - H_{1447})]}{2} =$$

$$\frac{[(11.88 - 2.00) + (11.94 - 2.04)]}{2} = 9.89 \quad \text{(eq. 3)}$$

Therefore, 9.89 ft is added to each surveyed elevation (*table A4*).

Table A4. Summary of field data and location and elevation corrections [All units in feet]

Label on figure A1	Horizontal location (feet)	Corrected horizontal location (feet) (1)	Vertical elevation (feet)	Corrected vertical elevation (feet) (2)	Field notes (3)	Remarks
a	−19	0	14.41	24.30		(1) Location correction is +19 feet to account for the initial placement of the surveying equipment.
b	0	19	12.60	22.49		
c	18	37	8.02	17.91		
e	44	63	2.00	11.89	time = 1441 stage = 11.88 feet	(2) Elevation is corrected +9.89 feet to reflect the elevation at the water's edge recorded by the stage gage.
p	660	679	2.04	11.93	time = 1447 stage = 11.94 feet	
r	684	703	12.2	22.09		(3) Stage data taken from *table A2*

Channel-Bank Survey Correction Summary

The corrected channel-bank survey data (*table A5*) is used with the bathymetry survey data to compute the area relation.

Table A5. Summary of corrected channel-bank survey data [All units in feet]

Label on figure A1	Corrected horizontal location (1)	Corrected elevation (2)	Remarks
a	0	24.30	(1) Location correction is +19 feet to account for the initial placement of the surveying equipment.
b	19	22.49	
c	37	17.91	
e	63	11.89	(2) Elevation is corrected +9.89 feet to reflect the elevation at the water's edge recorded by the stage gage.
p	679	11.93	
r	703	22.09	

Step 2. Bathymetry Survey

For the purposes of illustration, this example uses the mean beam depth output from a downward-looking, vessel-mounted, ADVM profiling system. A fathometer or a sounding weight also can be used to obtain bathymetry data along the cross-section. The time of the bathymetry survey must be recorded so that an accurate correction can be applied to make sure all of the data are referenced to the same vertical datum.

Similar to the channel-bank survey, both the horizontal location and the vertical elevation must be corrected. The horizontal location is corrected so that the zero horizontal location of the bathymetry survey is the water's edge, allowing for a user-defined measured edge distance. The horizontal location must be shifted a second time when the bank-survey and bathymetry-survey data are synthesized (Appendix A, Step 3). The vertical elevation is corrected so the bathymetric survey and the stage gage use a consistent vertical datum.

A summary of the bathymetry field data and the stage data recorded at the gaging station are presented in *tables A6* and *A7*. In this case, the bathymetry survey was conducted at 1525 PST, approximately 2 hours after the channel-bank survey (Appendix A, Step 1) and the stage rose nearly 0.1 ft in that time. For the purpose of illustration, 10 points across the cross-section were used to characterize the bathymetry (*fig. A1*). The entire ADVM data file can be processed using AreaComp.exe (Rehmel, 2002); however, a subset is presented here to highlight the procedure. Because the downward-looking ADVM profiler cannot measure all the way to the water's edge, the operator must record the edge distance that is necessary in the analysis. The distance from the downward-looking ADVM profiler to the shore should be measured using an accurate technique such as a laser range finder.

Table A6. Summary of field notes associated with bathymetry survey [All units in feet]

Label on figure A1	Horizontal location	Water depth	Field notes
d	−34	0	Left bank edge distance: 34 feet
f	0	18.27	
g	35.87	21.49	
h	54.30	19.55	
i	82.01	23.98	
j	206.08	20.48	
k	263.16	21.15	Mid-time of transect=1525 PST
l	383.01	20.30	
m	431.59	15.43	
n	504.45	18.19	
o	559.10	16.76	
q	587.1	0	Right bank edge distance: 28 feet
Channel width = 587.1 feet + 34 feet= 621.1 feet			

Table A7. Summary of stage data recorded at gaging station

Time	Stage (feet)	Remarks
1520	11.95	
1521	11.96	
1522	11.97	
1523	11.97	
1524	11.98	
1525	11.99	Bathymetry survey conducted
1526	11.99	
1527	12.00	
1528	12.01	
1529	12.02	
1530	12.02	
1531	12.03	

Horizontal Location Correction

The initial horizontal-location correction “zeros” the bathymetry survey at water’s edge of either the left or right bank, depending on the starting point of the survey. A second horizontal location correction must be applied when the channel bank survey data and the bathymetry survey data are synthesized (Appendix A, Step 3). The horizontal location measurements all are relative to the position of the ADVM profiler at the start of the transect. In this case, the horizontal location correction was +34 ft because the ADVM profiler was located 34 ft from the left bank water’s edge as recorded by the operator in the field notes (*table A8*, remarks column).

Table A8. Summary of field data and location corrections
[All units in feet]

Label on figure A1	Horizontal location	Corrected horizontal location (1)	Water depth	Remarks
d	−34	0	0	(1) Location corrected by +34 feet to adjust for the initial edge estimate. A second correction will be applied later when these data are synthesized with the channel-bank survey.
f	0	34	18.27	
g	35.87	69.87	21.49	
h	54.30	88.30	19.55	
i	82.01	116.01	23.98	
j	206.08	240.08	20.48	
k	263.16	297.16	21.15	
l	383.01	417.01	20.30	
m	431.59	465.59	15.43	
n	504.45	538.45	18.19	
o	559.10	593.10	16.76	
q	587.10	621.10	0	

Vertical Elevation Correction

An elevation correction is necessary because the bathymetry data are measured relative to the water’s surface. The correction is based on the (1) stage recorded at the mid-point of the bathymetry survey and (2) a conversion from depth to elevation.

$$H = stg_{MP} - D \qquad \text{(eq. 4)}$$

where

H is the corrected elevation;
stg_{MP} is the stage recorded at the gaging station at the mid-point of the bathymetry survey; and
D is the depth at each location recorded during the bathymetry survey.

In this example, stg_{MP} is 11.99 ft (*table A7*). The correction results are summarized in *table A9*.

Table A9. Summary of field data and elevation corrections [All units in feet]

Label on figure A1	Horizontal location	Corrected horizontal location (1)	Water depth	Corrected vertical elevation (2)	Remarks
d	−34.00	0	0	11.99	(1) Location corrected by +34 feet to adjust for the initial edge estimate. An additional correction is necessary to synthesize these data with the channel-bank survey. (2) Elevation corrected by 11.99 feet to account for the stage recorded at the gaging station at the mid-point of the bathymetry survey.
f	0	34.00	18.27	−6.28	
g	35.87	69.87	21.49	−9.50	
h	54.30	88.30	19.55	−7.56	
i	82.01	116.01	23.98	−11.99	
j	206.08	240.08	20.48	−8.49	
k	263.16	297.16	21.15	−9.16	
l	383.01	417.01	20.30	−8.31	
m	431.59	465.59	15.43	−3.44	
n	504.45	538.45	18.19	−6.20	
o	559.10	593.10	16.76	−4.77	
q	587.10	621.10	0	11.99	

Bathymetry Survey Correction Summary

The corrected bathymetry-survey data (*table A10*) is used with the channel-bank survey data to develop the cross-sectional area relation.

Table A10. Summary of corrected bathymetry survey data
[All units in feet]

Label on figure A1	Corrected horizontal location (1)	Corrected vertical elevation (2)	Remarks
d	0	11.99	(1) Location corrected by +34 feet to adjust for the initial edge estimate. An additional correction is necessary to synthesize these data with the channel-bank survey. (2) Elevation corrected by 11.99 feet to account for the stage recorded at the gaging station at the mid-point of the bathymetry survey.
f	34.00	−6.28	
g	69.87	−9.50	
h	88.30	−7.56	
i	116.01	−11.99	
j	240.08	−8.49	
k	297.16	−9.16	
l	417.01	−8.31	
m	465.59	−3.44	
n	538.45	−6.20	
o	593.10	−4.77	
q	621.10	11.99	

Step 3. Synthesis of Field Data

The vertical corrections are assumed to have been applied (Appendix A, Step 2) to combine the bank survey with the bathymetry survey. However, the horizontal position of the bathymetry survey must be shifted again so that the "centerlines" of the two channel surveys are aligned. In this example, the width of the water surface was measured at 616 ft during the channel-bank survey and at 621 ft during the bathymetric survey based on the edge measurements and the "distance made good" recorded by the profiling ADVM. Instrument precision and changing water elevation both contribute to this discrepancy. The centerline of the bathymetric survey is placed at the centerline of the gap between the two bank surveys.

$$L_{corr} = \frac{[(L_{WE_2} - L_{WE_1}) - (W_b)]}{2} + L_{WE_1} \quad \text{(eq. 5)}$$

where

L_{corr} is the correction that will be applied to the bathymetry survey location data;.

L_{we1} and L_{we2} are the horizontal locations at the water's edge as measured during the bank survey; and

W_b is the width of the submerged portion of the channel, as measured during the bathymetric survey.

In this example the calculation is as follows:

$$L_{corr} = \frac{[(L_{WE_2} - L_{WE_1}) - (W_b)]}{2} + L_{WE_1} = \frac{[(679 - 63) - (621)]}{2} + 63 = 60.5 \quad \text{(eq. 6)}$$

The results are summarized in *table A11*. In this example, there is some overlap between the channel-bank survey and the bathymetry survey near the water's edge due to the changing tide.

Table A11. Summary of synthesized field data [All units in feet]

Label on Figure A1	Location	Finalized location	Elevation	Remarks
a	0	0	24.30	The location of the bathymetry survey data was corrected by +60.5 feet to place the bathymetry survey in the middle of the bank survey. Only the bathymetry data were corrected (shown in the shaded grey portion of the table)
b	19	19	22.49	
c	37	37	17.91	
e	63	63	11.89	
d	0	60.50	11.99	
f	34	94.50	−6.28	
g	69.87	130.37	−9.50	
h	88.30	148.80	−7.56	
i	116.01	176.51	−11.99	
j	240.08	300.58	−8.49	
k	297.16	357.66	−9.16	
l	417.01	477.51	−8.31	
m	465.59	526.09	−3.44	
n	538.45	598.95	−6.20	
o	593.10	653.60	−4.77	
q	621.10	681.60	11.99	
p	679	679	11.93	
r	703	703	22.09	

Step 4. Calculating the Stage-Versus-Area Relation

In order to establish the relation between cross-sectional area and stage, a table that establishes the area over the entire range of expected stage values is developed. This table can be developed manually or by a number of different software products. For the purposes of this example, the elevation and location data in *table A11* are used as input into AreaComp.exe (Rehmel, 2002) (*fig. A2*). By selecting the “Create Stage Area Rating” button at the bottom of the screen, a table with the range of expected stage values specified in the form (in this case from 5 to 20 ft with an interval of 0.01 ft) and the associated cross-sectional areas were calculated. These results were exported and simple least-squares regression analysis was performed to develop a quadratic equation describing the relation between stage and cross-sectional area. In this case, the resulting relation was:

$$A = 2.75(S)^2 + 557.6(S) + 4715 \qquad \text{(eq. 7)}$$

where

A is the cross-sectional area, in square feet; and
S is the stage recorded at the gaging station, in feet.

In this case, the difference between the table results and the quadratic equation estimate is less than 0.1 percent. Other systems, such as the USGS automated data-processing system (ADAPS) use table look-up functions rather than equations.

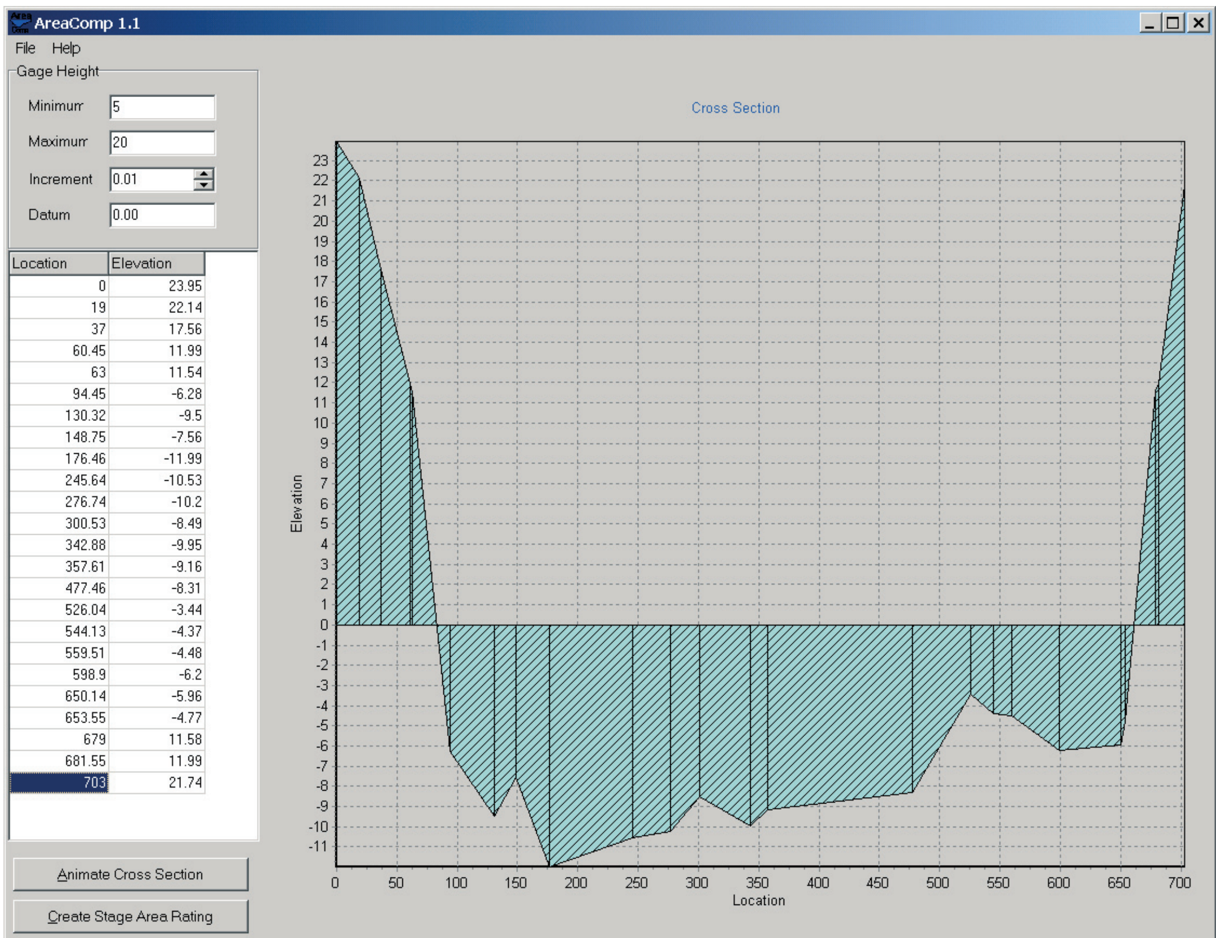


Figure A2. Screen capture of channel cross section from AreaComp.exe. The expected tidal range is summarized on the upper left of the figure; tabular location and elevation data are summarized on the left of the figure; and graphical representation is presented on the right of the figure.

Appendix B. Sample Computation of the Mean Velocity

Introduction

This appendix describes the standard procedure used to compute the mean velocity from the index velocity. In this example, a downward-looking, vessel-mounted ADVM profiler was used to collect discharge measurements over a full tidal cycle. These data were combined with additional data collected over the life of the station to establish the final relation. Relations are finalized when the full range of expected flows have been measured and are stable over time.

One of the most important aspects of establishing the mean-velocity relation is ensuring that the discharge measurements and the gaging-station index velocity and stage measurements are well synchronized. In highly dynamic systems, timing that is off by as few as 5 minutes can cause erroneous ratings.

Establishing the index velocity-versus-mean-velocity relation is a three-step process: (1) collection of discharge measurements; (2) synthesis of field and gage data to compute the mean velocity; and (3) computation of the relation between the mean velocity and the index velocity.

Step 1. Collection of Discharge Measurements

In this step, the discharge measurements are organized for use in the calibration process. This section does not address the mechanics of collecting discharge measurements (see Simpson and Oltmann, 1993; Simpson, 2001; and OSW Technical Memoranda, 2002, for details). A table summarizing the results of each ADVM transect is generated once the data have been processed (*table B1*).

All of the data presented in the table below are values that are extracted from the ASCII summary files generated by the ADVM profiler software for each transect. The data in *table B1* only are a subset of the dataset used in the rating process and are presented to exemplify the procedure. Discharge measurements were collected over a 13-hour period and cover the full range of tidal conditions that regularly occur at this station. Spring and neap tides are not specifically targeted unless there are site-specific conditions that suggest that specific tidal conditions are critical to developing the calibration. These data will be combined with other discharge measurements collected at other times to develop the final calibration.

Table B1. Summary of selected downward-looking vessel-mounted acoustic Doppler velocity meter discharge measurements

Transect number	Date	Start Time	End Time	Duration (in seconds)	Discharge (in cubic feet per second)
1	6/26/2003	5:18:11	5:25:57	465	24967
2	6/26/2003	5:26:19	5:32:03	344	24701
3	6/26/2003	5:32:26	5:40:53	507	24462
4	6/26/2003	5:41:10	5:46:46	337	24267
5	6/26/2003	6:05:20	6:12:17	418	24173
6	6/26/2003	6:12:33	6:19:02	389	24359
7	6/26/2003	6:19:23	6:27:07	464	24052
36	6/26/2003	10:21:31	10:29:57	505	6898
37	6/26/2003	10:30:09	10:36:01	351	4929
38	6/26/2003	10:39:50	10:48:35	524	1326
58	6/26/2003	13:51:53	13:58:12	378	–25012
59	6/26/2003	14:29:17	14:33:52	275	–22675
60	6/26/2003	14:34:05	14:40:15	371	–22966
78	6/26/2003	17:02:26	17:09:18	412	–3264
79	6/26/2003	17:09:31	17:15:57	386	–1957
80	6/26/2003	17:16:08	17:23:06	418	–666
81	6/26/2003	17:23:16	17:29:50	394	597
82	6/26/2003	17:30:02	17:36:52	410	1758
83	6/26/2003	17:37:02	17:42:19	317	3093
89	6/26/2003	18:18:26	18:24:51	385	9045
90	6/26/2003	18:25:02	18:31:33	391	9322
91	6/26/2003	18:31:52	18:39:46	474	9552

Step 2. Synthesis of Field and Gage Data to Compute the Mean Velocity

The mean velocity is calculated by dividing the ADVM-measured discharge by the area calculated by the cross-sectional area relation (*Appendix A*) at the time of the discharge measurement. First, the transect time for each measured discharge is established as the mid-point of the transect time (*table B2*, column 3). The stage measured at the gaging station (*table B2*, column 5) is computed by linearly interpolating between the nearest two recorded data points. The cross-sectional area (*table B2*, column 6) is calculated using the equation developed in Appendix A based on the stage measurement (*table B2*, column 5). The index velocity (*table B2*, column 7) is taken to be the index velocity measured at the time of the discharge measurement by linearly interpolating between the two nearest recorded data points. Finally, the mean-velocity (*table B2*, column 8) is calculated by dividing the measured discharge (*table B2*, column 4) by the calculated area (*table B2*, column 6).

Step 3. Computation of the Relation between the Mean Velocity and the Index Velocity

The mean velocity is correlated to the index velocity using least-squares regression: relating the index velocity measured at the gaging station at the time of the transect (*table B2*, column 7) to the mean velocity calculated from the ADVM discharge measurement (*table B2*, column 8). Numerous software packages are available that can assist in developing this relation. In this example, a linear relation was established (*fig. B1*) between the index velocity and the mean velocity. There are cases where more complicated calibrations (*fig. 3B–D*) have been developed due to local hydrodynamic features at the station. In this example the resulting relation was:

$$\overline{V} = 0.8054(V_i) + 0.0265 \quad \text{(eq. 8)}$$

where

$\overline{V}$ is the mean velocity; and

V_i is the index velocity.

Table B2. Summary of transect data and gaging station data

Transect number	Date	Time	Discharge (in cubic feet per second)	Stage (in feet)	Area (in square feet)	Index velocity (in feet per second)	Mean velocity (in feet per second)
1	6/26/2003	5:22	24967	11.60	11553	2.688	2.161
2	6/26/2003	5:29	24701	11.53	11510	2.713	2.146
3	6/26/2003	5:37	24462	11.46	11466	2.733	2.133
4	6/26/2003	5:44	24267	11.40	11429	2.719	2.123
5	6/26/2003	6:09	24173	11.18	11293	2.779	2.141
6	6/26/2003	6:16	24359	11.12	11256	2.767	2.164
7	6/26/2003	6:23	24052	11.05	11212	2.763	2.145
36	6/26/2003	10:26	6898	10.09	10621	0.925	0.649
37	6/26/2003	10:33	4929	10.15	10658	0.654	0.462
38	6/26/2003	10:44	1326	10.25	10719	0.248	0.124
58	6/26/2003	13:55	−25012	11.59	11547	−2.572	−2.166
59	6/26/2003	14:32	−22675	11.79	11671	−2.349	−1.943
60	6/26/2003	14:37	−22966	11.81	11684	−2.315	−1.966
78	6/26/2003	17:06	−3264	11.90	11740	−0.355	−0.278
79	6/26/2003	17:13	−1957	11.87	11721	−0.231	−0.167
80	6/26/2003	17:20	−666	11.84	11702	−0.103	−0.057
81	6/26/2003	17:27	597	11.82	11690	−0.001	0.051
82	6/26/2003	17:33	1758	11.80	11678	0.182	0.151
83	6/26/2003	17:40	3093	11.78	11665	0.275	0.265
89	6/26/2003	18:22	9045	11.65	11584	0.940	0.781
90	6/26/2003	18:28	9322	11.63	11572	1.023	0.806
91	6/26/2003	18:36	9552	11.62	11566	1.114	0.826

In this example, the mean and index velocity is strongly linearly correlated as indicated by an r-squared value of 0.998 and a root-mean-squared error of prediction of 0.0663. Because the tidal stage range (2 ft) at this station is small, compared to the channel depth (25 ft), the effect of water depth on the index-velocity measurement is minimal. However, if the range in stage at a particular location is large, stage may be included as a regression variable as part of a multiple regression analysis to increase the statistical significance of the resultant equation. There also are other ways to include stage in the mean velocity calculation (Simpson and Bland, 1999).

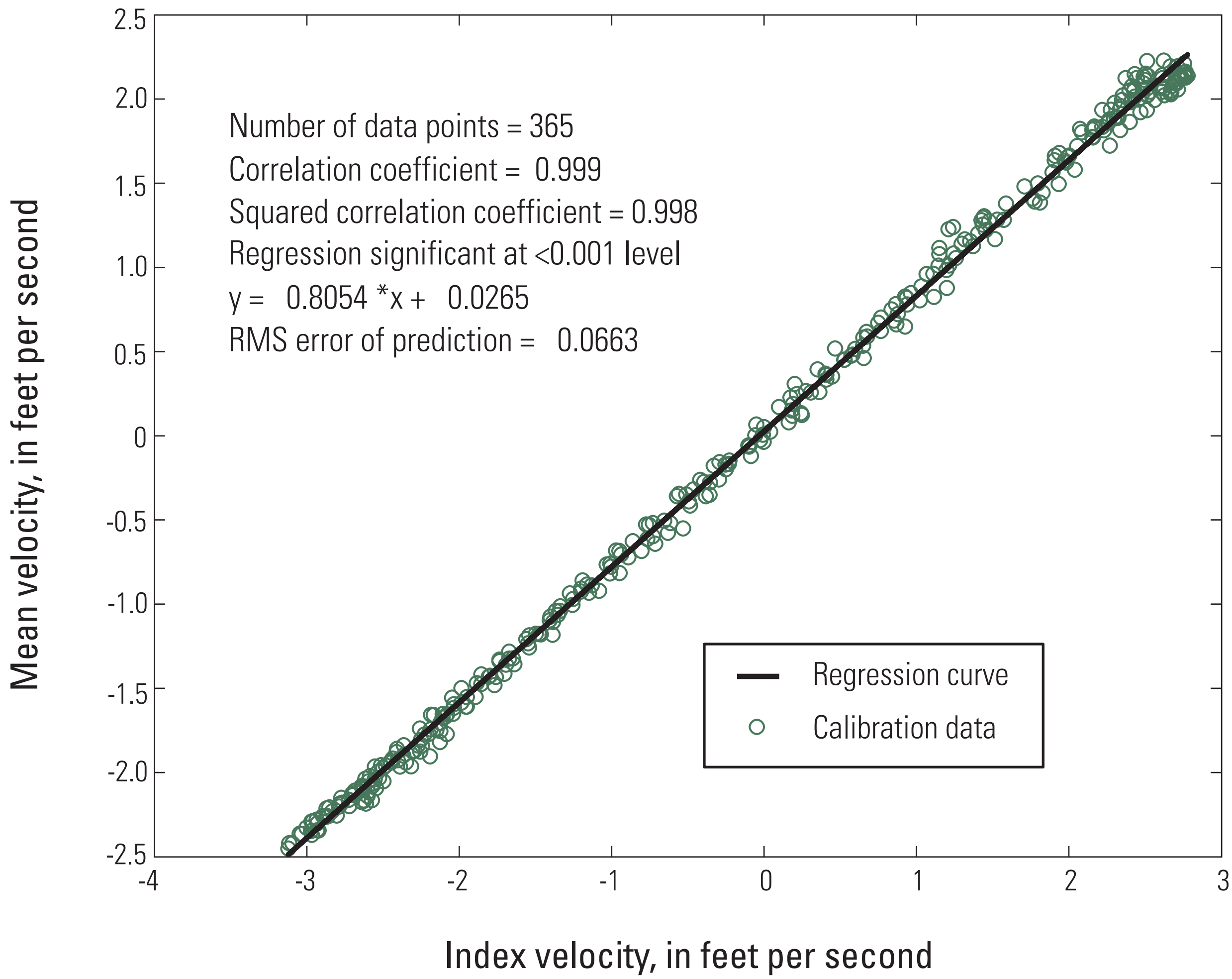


Figure B1. Relation between index velocity and mean velocity.

Appendix C. Sample Discharge Calculation

Introduction

This appendix describes the standard procedure used to determine the discharge at an index-velocity station. Discharge calculations are straight-forward when the index velocity relation is either a simple linear relation (*fig. 3A*) or a higher-order polynomial relation (*fig. 3B*). A sample calculation is presented below using a linear relation. Once the area relation (*Appendix A*) and mean velocity relation (*Appendix B*) are established, the discharge calculation follows from equation 1. In the event that a more complex rating is necessary, such as a loop rating or a bimodal rating, then more sophisticated programming is required (discussed at the end of this appendix).

Computing discharge is a two-step procedure: (1) assemble stage and index-velocity data collected at the gaging station, and (2) calculate results.

Step 1. Assemble Stage and Index-Velocity Data Collected at the Gaging Station

Assemble the quality-reviewed stage and index-velocity data collected at the gaging station (*table C1*). Ensure that the two time-series sample the same points in time. A brief, 4-hour period is presented in tabular format (*table C1*) as an example, the graphical presentation of discharge contains 1 month of data (*fig. C1*).

Step 2. Calculate Discharge

Linear or Polynomial Rating

Using the stage-versus-area relation,

$$A = 2.75(S)^2 + 557.6(S) + 4715 \qquad \text{(eq. 7)},$$

and the index-velocity-versus-mean-velocity relation,

$$\overline{V} = 0.8054(V_i) + 0.0265 \qquad \text{(eq. 8)}$$

discharge readily can be calculated based on equation 1 (*table C1*).

Using the same procedure and equations, a 1-month data record has been processed and presented graphically (*fig. C1*). These data also will be used in Appendix D to show the procedure for calculating daily discharge values.

Table C1. Tabular summary of recorded gaging station data and calculations

Date and time	Stage (in feet)	Area (in square feet)	Index velocity (in feet per second)	Mean velocity (in feet per second)	Discharge (in cubic feet per second)
2003/01/11 10:00	13.22	12567	−2.778	−2.2109	−27784
2003/01/11 10:15	13.29	12611	−2.686	−2.1368	−26947
2003/01/11 10:30	13.34	12643	−2.578	−2.0498	−25916
2003/01/11 10:45	13.38	12668	−2.439	−1.9379	−24549
2003/01/11 11:00	13.41	12687	−2.273	−1.8042	−22890
2003/01/11 11:15	13.41	12687	−2.084	−1.6520	−20959
2003/01/11 11:30	13.40	12681	−1.878	−1.4860	−18844
2003/01/11 11:45	13.36	12655	−1.617	−1.2758	−16145
2003/01/11 12:00	13.31	12624	−1.334	−1.0479	−13229
2003/01/11 12:15	13.24	12580	−1.031	−0.8039	−10113
2003/01/11 12:30	13.16	12529	−0.704	−0.5405	−6772
2003/01/11 12:45	13.06	12466	−0.334	−0.2425	−3023
2003/01/11 13:00	12.95	12397	0.093	0.1014	1257
2003/01/11 13:15	12.84	12328	0.546	0.4662	5747
2003/01/11 13:30	12.72	12253	0.976	0.8126	9957
2003/01/11 13:45	12.59	12171	1.438	1.1847	14419

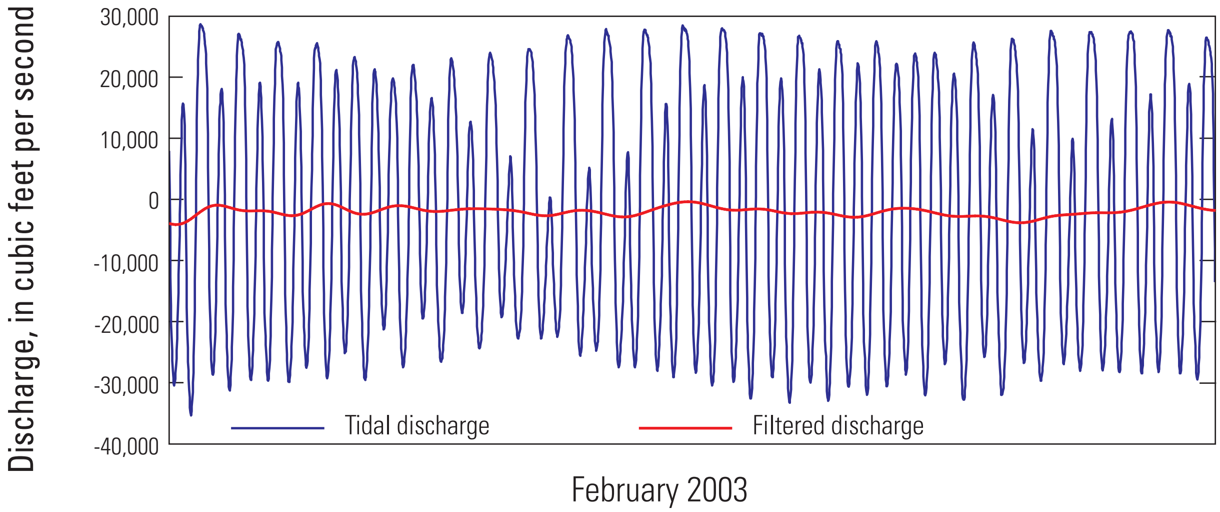


Figure C1. Discharge calculated as a result of the stage versus cross-sectional area relation (see Appendix A) and the index velocity versus mean velocity relation (see Appendix B).

Loop Rating

In the event that a loop rating is necessary, the discharge calculations become more involved. A loop rating actually is two mean velocity ratings that have been developed for the same tidally affected channel: a flood-to-ebb relation (*fig. C2*, rating A) and an ebb-to-flood relation (*fig. C2*, rating B).

Computing discharge from a loop rating is complex because the computational algorithm must change between ratings based on the tidal phase. In general, as velocities increase from maximum flood (negative) to maximum ebb (positive), rating A is used to compute discharge; as velocities decrease from maximum ebb to maximum flood, rating B is used. At points beyond the transition points where ratings A and B intersect, a single relation is used: in this example rating A, is used at the extremes (*fig. C3*).

In the event that the flows reverse before the transition point between ratings is reached, the algorithm becomes significantly more complex. Although there are many ways to transition between the two ratings, the approach presented here is a time-stepped percentage calculation. A total of 10 data points are used to transition between the two rating curves. The transition begins 5 points before the local maximum velocity and ends after the time-stepped percentage algorithms have stepped through 10 data points. At the beginning of the transition, 100 percent of rating A is used and 0 percent of rating B is used; at the next point, 90 percent of rating A and 10 percent of rating B is used, and so on until at the tenth and final point used in the transition 0 percent of rating A

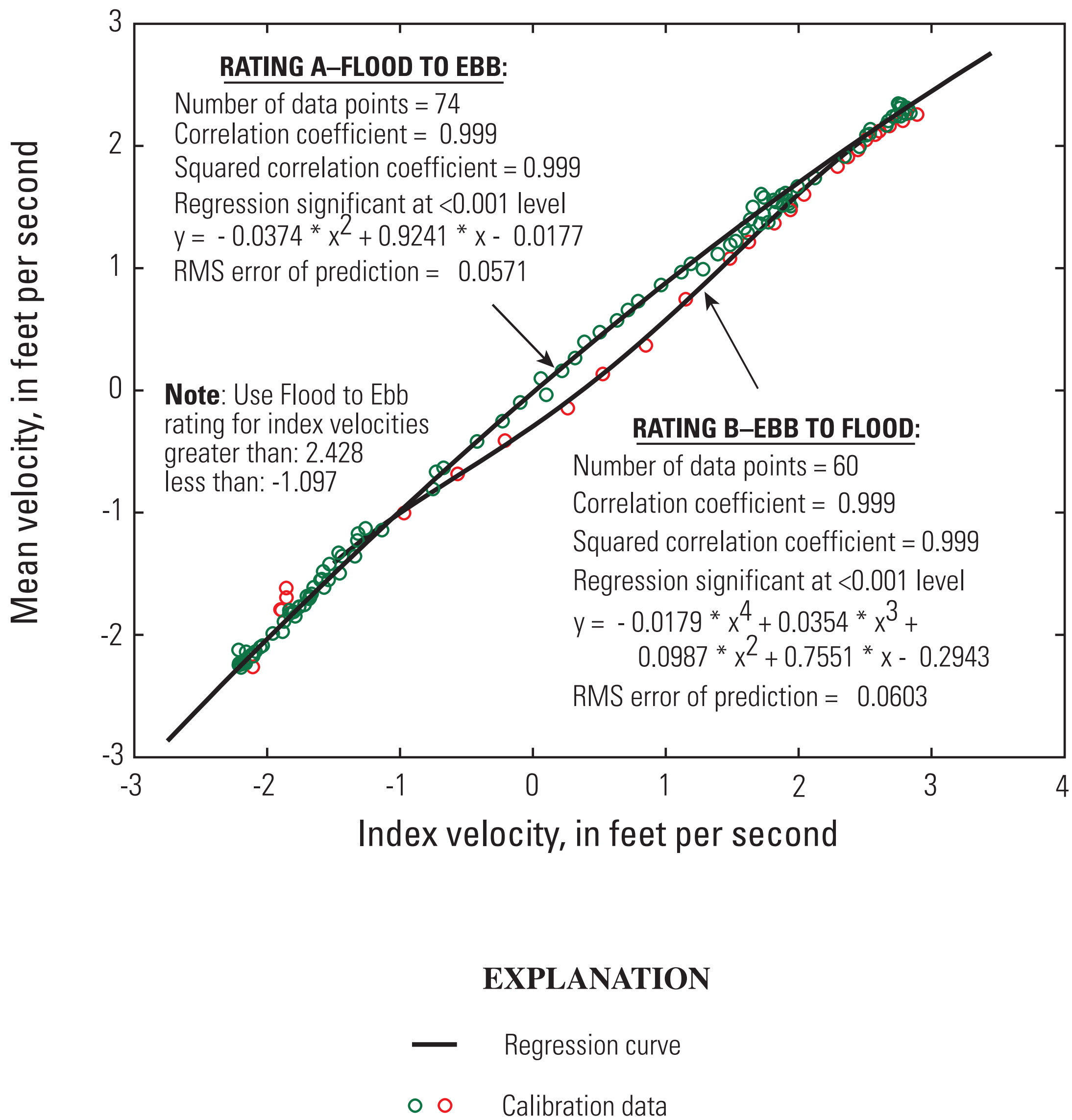


Figure C2. Sample loop rating. Asymmetries in the flow distributions in the channel between flood flows and ebb flows cause a loop rating. These ratings are very difficult to implement and can often be reduced or eliminated by selecting a different gage location or different hydroacoustic instrumentation.

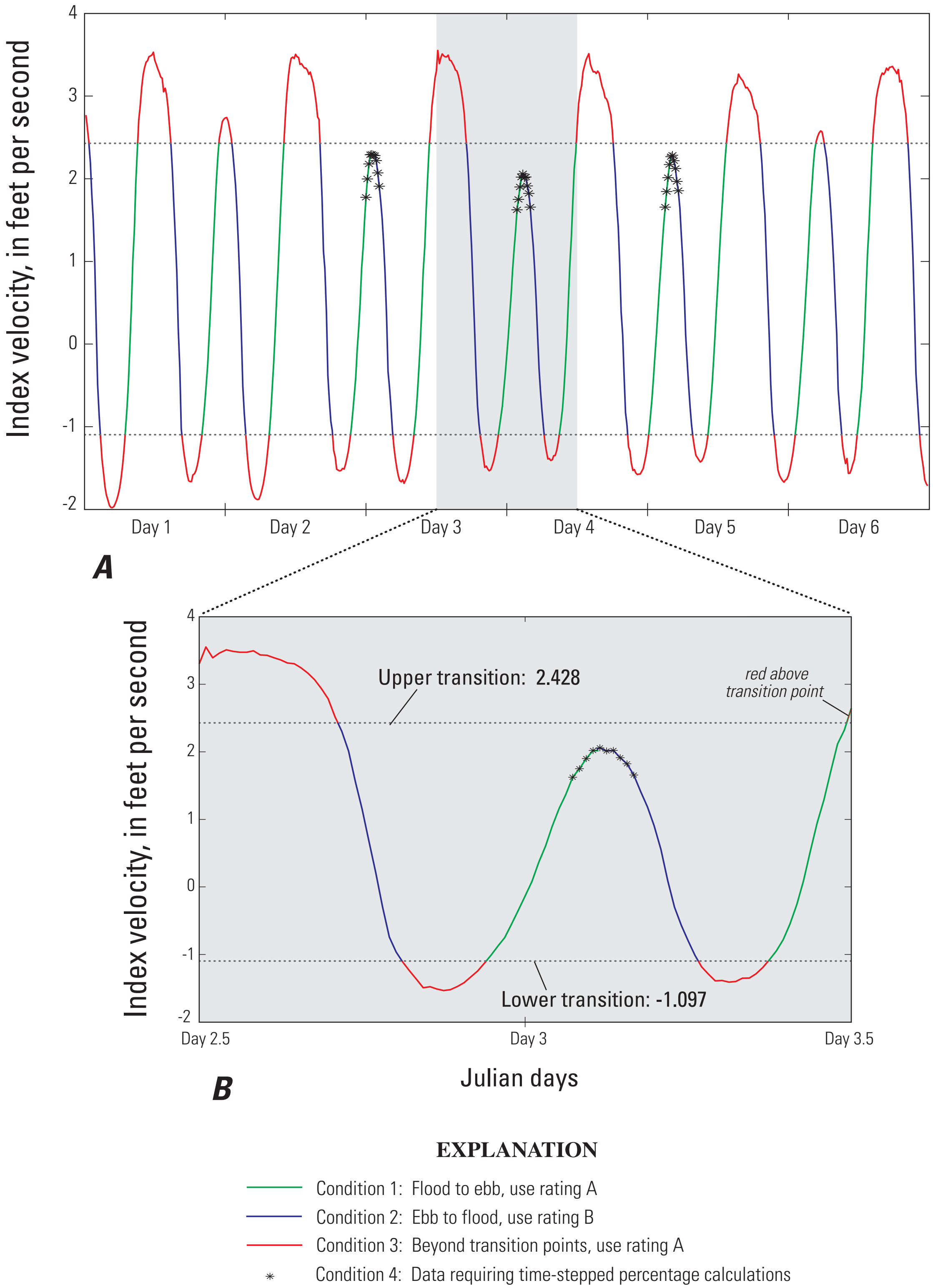


Figure C3. Implementation of loop rating. Data are broken down into four categories: (1) flood to ebb conditions; (2) ebb to flood conditions; (3) beyond transition-point conditions; and (4) data requiring the time-stepped percentage calculation. Each of these categories utilizes a specific index-velocity versus mean-velocity relation. (A) a 6-day period to show when the time-stepped percentage calculation is necessary (black asterisks); and (B) a 24-hour period to show in greater detail how the time-stepped percentage calculation is implemented.

and 100 percent of rating B is used (*fig. C3B*). Once the mean velocity is calculated, the discharge record is determined using equation 1.

Given the complexity and ambiguity in the discharge calculation using a loop-rating, they should be avoided, where possible, by using equipment that can sample a large fraction of the width of the channel, or place the station in locations that are less geometrically complex (for example, away from bends or junctions).

Bimodal Rating

In the event that a bimodal rating is necessary (*fig. C4*), the discharge calculations are more complicated than the standard polynomial relations. In order to calculate discharge, the measured index velocity first is compared to the intersection point. If the measured index velocity is greater than the rating intersection point, then the upper index velocity rating is applied; if the measured index velocity is less than the rating intersection point, then the lower rating is applied. Once the mean velocity has been calculated, equation 1 is used to calculate the discharge.

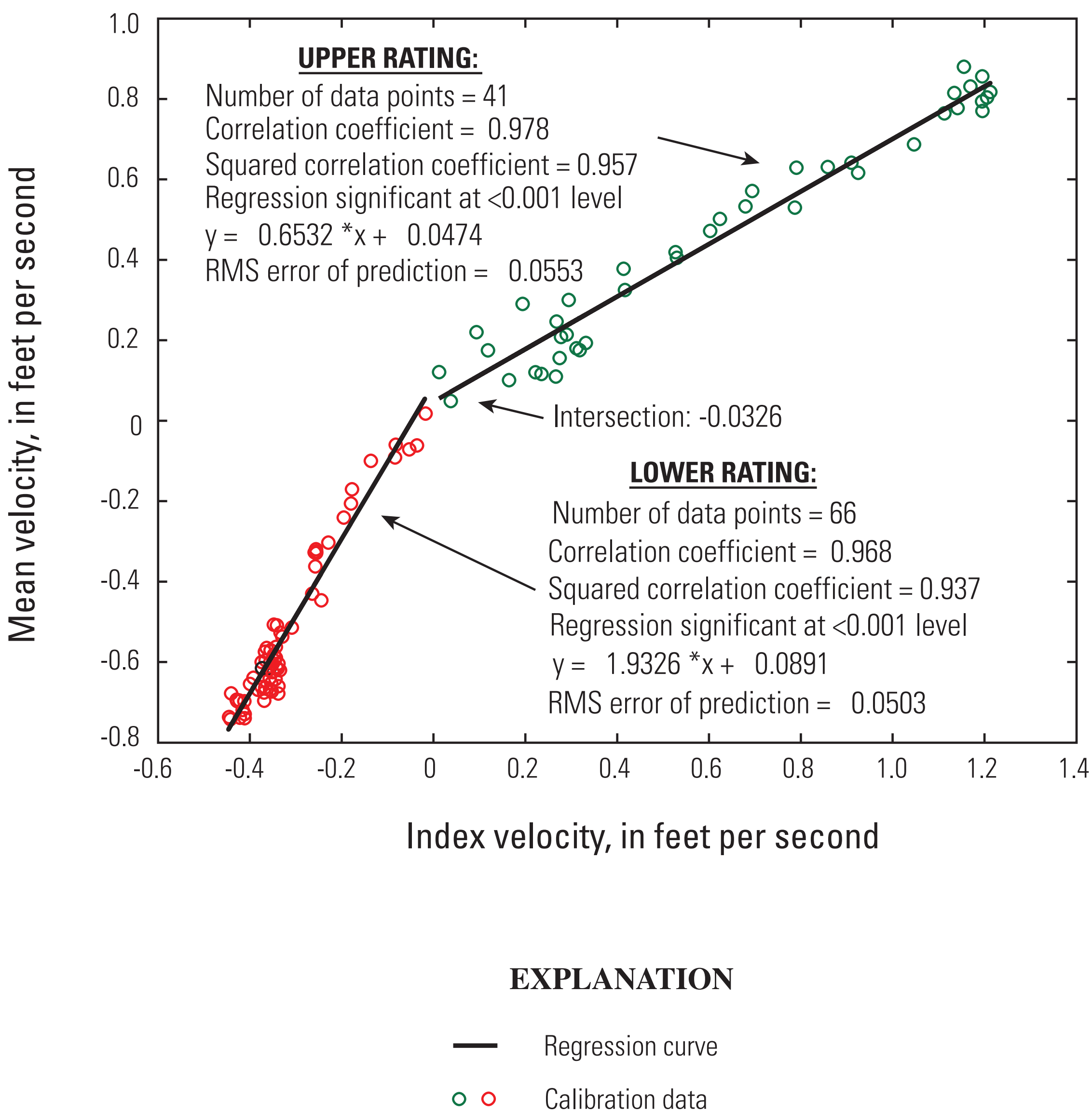


Figure C4. Sample bi-modal rating.

Appendix D. Calculation of Daily Discharge

Introduction

This appendix describes the standard procedure used to determine the daily discharge at an index velocity station. This is a two-step process: (1) apply a low-pass Butterworth filter (Roberts and Roberts, 1978); and (2) calculate the daily average of the filtered values.

Step 1. Apply a Low-Pass Butterworth Filter

Once the tidal time-series of discharge has been calculated [*fig. D1A* (blue line)], a low-pass Butterworth filter (Roberts and Roberts, 1978) is applied to the data to remove the high-frequency tidal signals [*fig. D1A* (red line) and *fig. D1B* (red line)]. A stopband period of 30 hours and a passband period of 40 hours are used: signals with periods less than 30 hours are not transmitted to the filtered data; signals with periods greater than 40 hours are transmitted to the filtered data with minimal loss; and signals that fall in the transition between the stopband and the passband are damped, but some fraction of them are transmitted to the filtered data. Filter ringing causes erroneous data at the beginning and end of a continuous data set; therefore, 2 days of data at the beginning and end of the time series and on either side of a data gap are rejected as part of this process.

Step 2. Calculate the Daily Average of the Filtered Values

Once the tidal time-series of filtered discharge has been calculated (Appendix D, step 1), the daily discharge is calculated as the daily-average of the filtered discharge data over the 24-hour period (*fig. D1B*, black line with open circles). In the event that the tidally averaged discharge data are incomplete for a particular day, a daily average is not calculated.

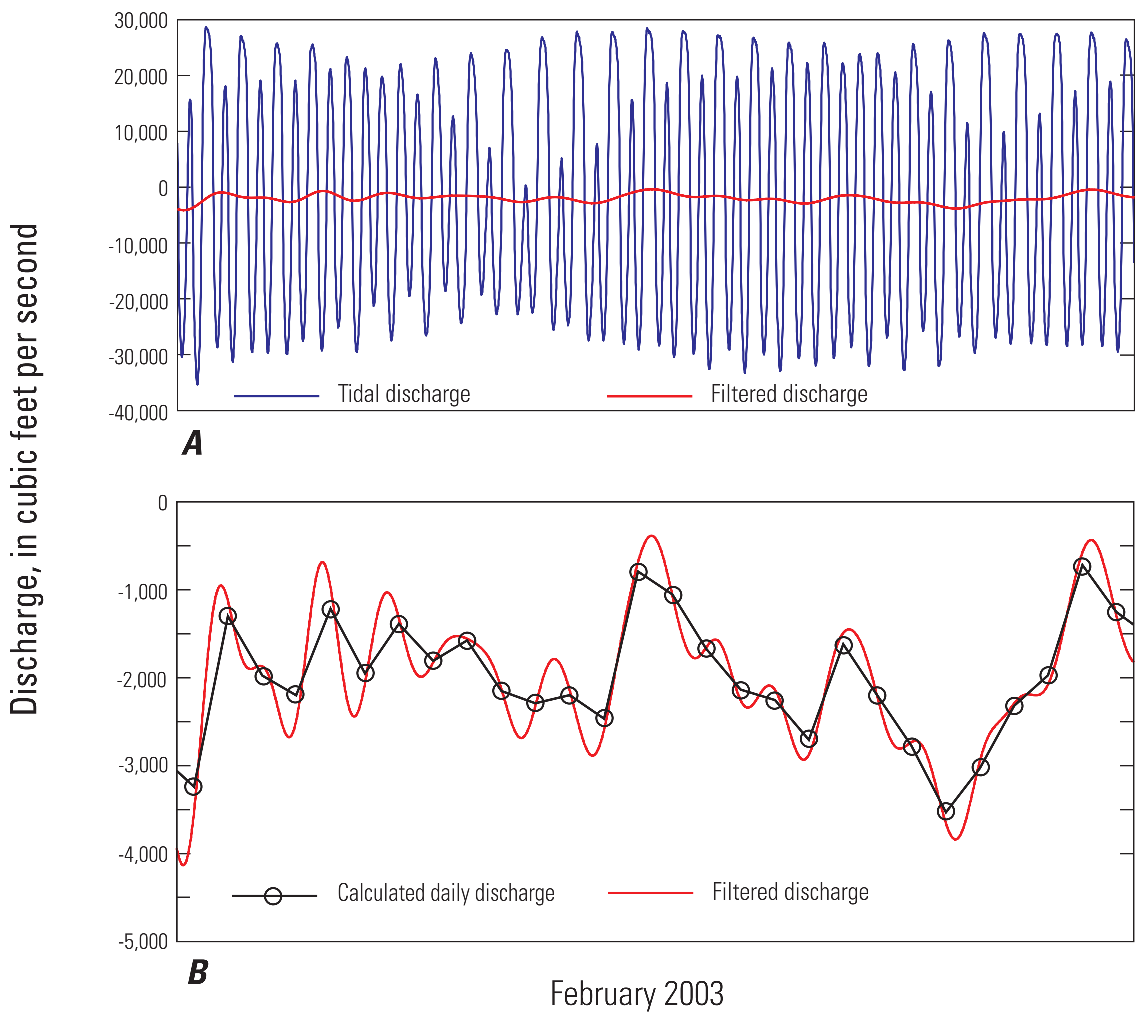


Figure D1. Example of discharge record. (A) tidal discharge, and filtered discharge; and (B) filtered discharge, and daily average discharge.

Appendix E. High-Quality Data and Examples of Common Mistakes

Introduction

This section describes the importance of collecting high-quality data and provides examples of potential problems that may arise during data collection and data processing and how these problems affect the resulting calibrations and discharge calculations. The USGS Office of Surface Water (OSW) has released a number of policy and technical guidance memoranda to ensure that data are collected consistently throughout the USGS (U.S. Geological Survey Office of Surface Water, 2002a,b). The issues discussed in this section are not meant to be an exhaustive list of the potential problems, but rather a selection of some of the common mistakes that we have encountered in our data analysis. These examples are meant to show how these problems can affect the final discharge calculations. The following scenarios will be discussed: data synchronization, channel-bottom movement, index-velocity transducer alignment, and configuration files and general boat operation.

Data Synchronization

Making sure the clocks at the gaging station and the vessel-mounted ADVM profiler used to collect direct discharge measurements are synchronized is critical. Even small errors (5 minutes or less) can cause significant errors in the final discharge calculations (*table E1*).

The percent errors are consistently greater on the daily flow calculations because the daily flows typically are orders of magnitude smaller than the tidal flows. Therefore, small errors in the tidal flows can create significant errors in the resulting daily flow calculations. Timing errors cause spurious flood-ebb asymmetry in the calibration that does not exist (*fig. E1*).

Table E1. Comparison of differences between calculated flow data with a 5-minute synchronization offset.

	Maximum flow difference (in cubic feet per second)	Minimum flow difference (in cubic feet per second)	Average flow difference (in cubic feet per second)	Average percent flow difference (in percent)
Station 1				
Tidal Flows	225	−100	60	1.6
Daily Flows	110	42	60	3.1
Station 2				
Tidal Flows	12200	−3080	3400	4.0
Daily Flows	11000	1070	3370	10.5
Station 3				
Tidal Flows	4570	−2390	360	4.3
Daily Flows	780	−200	370	15.7
Station 4				
Tidal Flows	14260	−13710	230	5.4
Daily Flows	3400	−1260	270	7.5

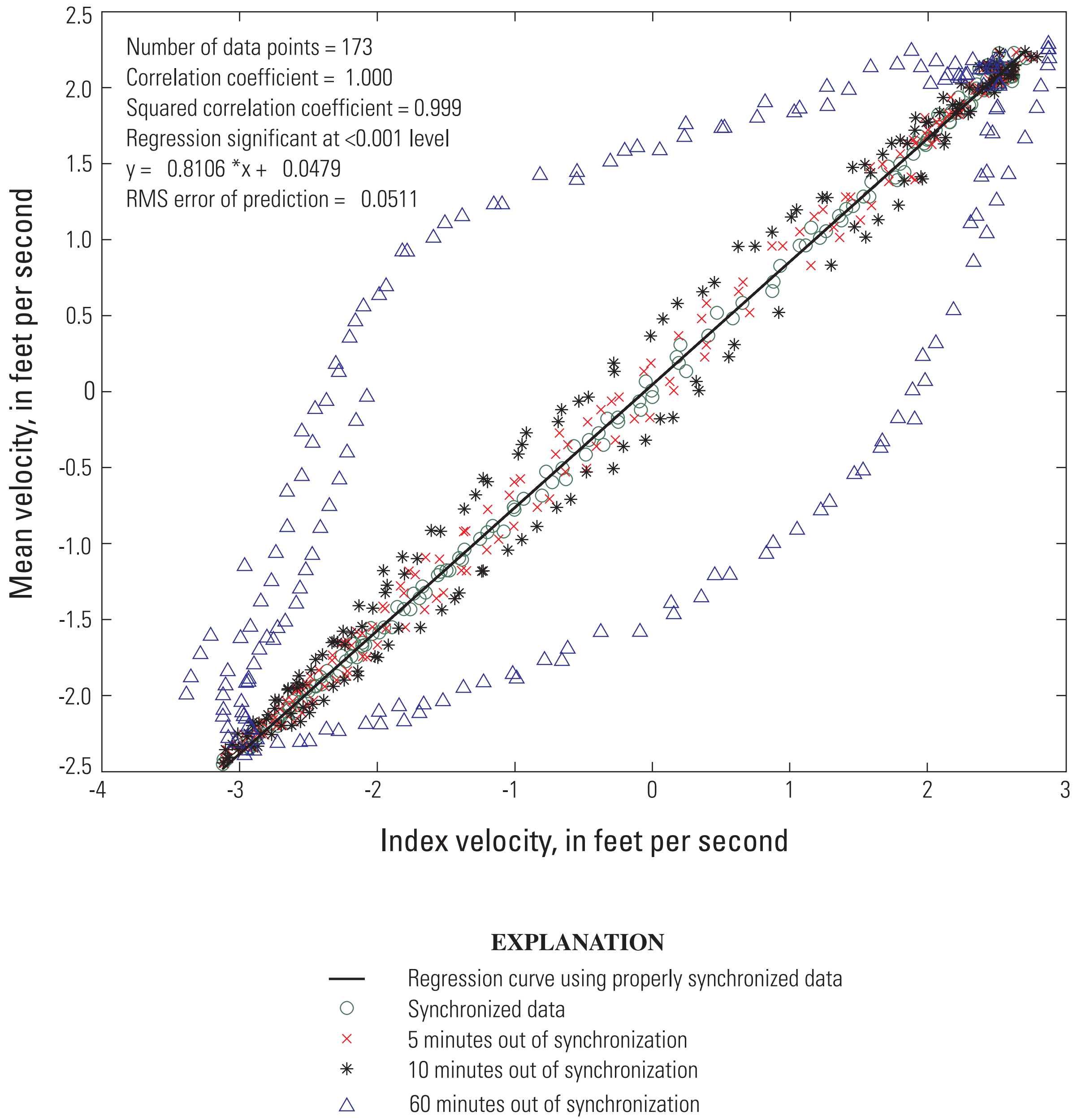


Figure E1. Comparison of index-velocity versus mean-velocity relations when synchronization problems exist.

Channel-Bottom Movement

Channel-bottom movement can contribute significant error in the discharge measurements using ADVM systems if a GPS system is not used. When taking discharge measurements, the ADVM profiler can use a “bottom tracking” mode to subtract the boat velocity from the measured velocities. When the bed sediments are moving, the bottom tracking algorithm will compute an erroneous boat velocity that then is used to erroneously correct the measured velocity for movement of the boat. Therefore, it is essential to confirm that the channel bottom is stable when using the “bottom-tracking” mode. The ADVM bottom-tracking algorithm tends to underestimate the discharge under conditions when there is significant bed movement (*fig. E2*). In this example, bottom-movement caused an 8.8-percent underestimation of the channel velocity. Channel bottom movement is well-documented and can happen under a wide variety of flow conditions. A 10-minute anchored boat test should be conducted whenever velocities exceed 1 ft/s or if bottom movement is suspected (Lipscomb, 1995; Simpson, 2001; U.S. Geological Survey Office of Surface Water, 2002b; Rehmel and others, 2003).

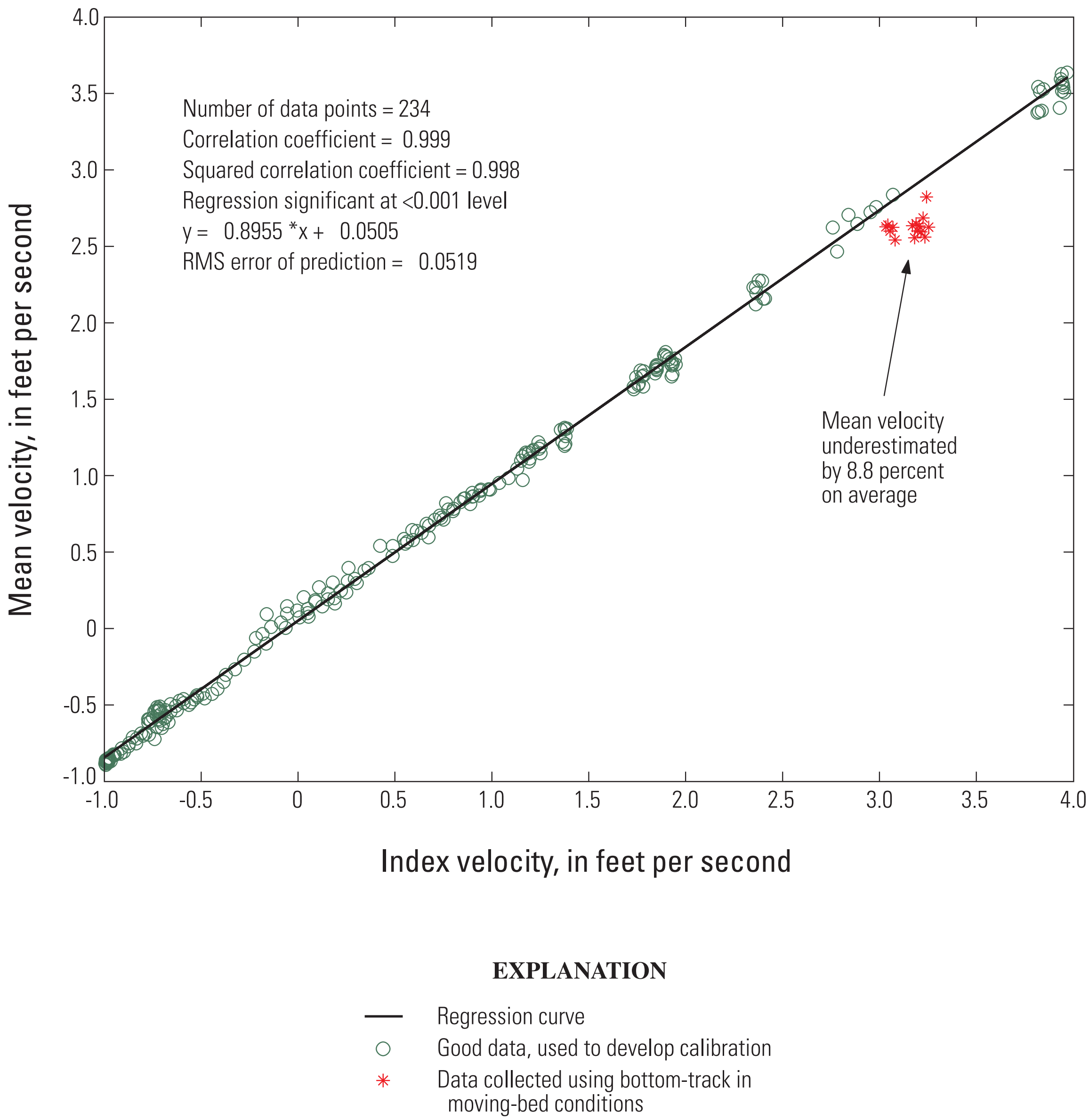


Figure E2. Impacts of using bottom-track in moving-bed conditions on the resulting index velocity versus mean velocity relation.

Index-Velocity Transducer Alignment

The orientation of the UVM or ADVM index-velocity transducers should be kept constant. A change in transducer orientation results in a change in the water volume sampled and, thus, causes a change in the relation between the index velocity and mean velocity. At a site with a sideward-looking ADVM, a rotation of approximately 5 degrees caused a shift of 4.7 percent between the predicted-mean velocity and the measured-mean velocity (*fig. E3*). The differences were greater at lower flows (V_i < 2.0 ft/sec), with a discrepancy of 7 percent. This slight rotation in the ADVM unit caused an over-estimation of the discharge at this location until the problem was identified and corrected. In general, the effect of changes in transducer orientation is site-specific and depends on the local lateral velocity structure, which, in turn, depends on the local geometry.

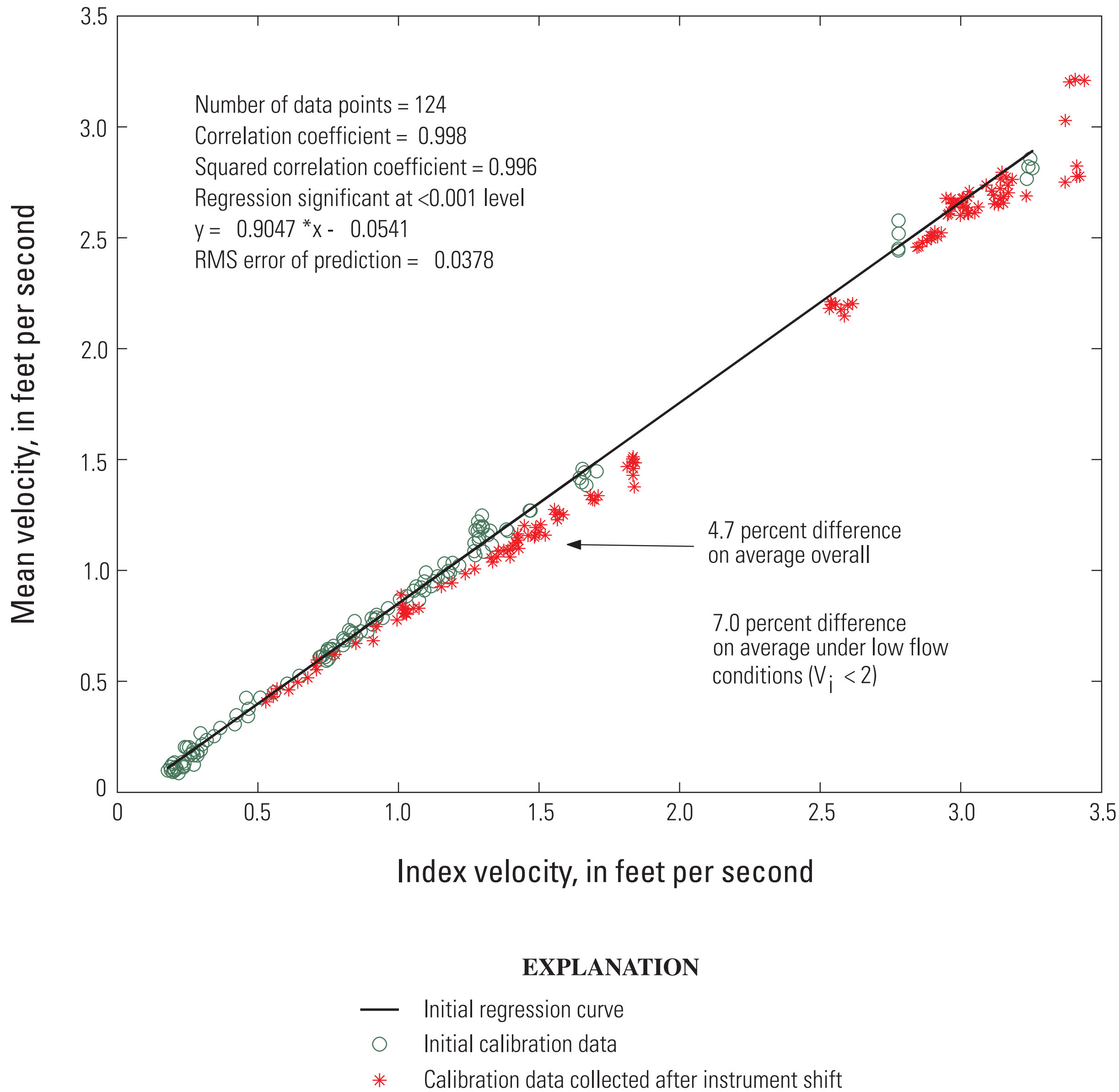


Figure E3. Impacts of misaligned instrumentation on the resulting index velocity versus mean-velocity relation.

Discharge Measurement Configuration Files and General Boat Operation

There are many other aspects of data acquisition that can affect the quality of the calibration. Examples include: boat speed; boat pitch and roll; and the configuration of the downward-looking vessel mounted ADVM profiler, including transducer depth, channel depth, edge estimation, etc.

Boat speed can affect the calibration in several ways. Making discharge measurements when the boat speed is too fast leads to decreased precision in the form of an increase in variability between successive measurements. If the boat speed is too slow, the tide can change the velocities across the channel sufficiently during the period of the discharge measurement to cause a poor correlation between the measured mean velocity and the index velocity (*fig. E4*). Most discharge measurements are being collected in 4 to 5 minutes in a channel approximately 600 ft wide, with tidal flows of approximately 12,000 ft^3/s. In this example, the discharge measurement (*fig. E4*, red asterisk) took 11 minutes to complete. Because tidal conditions change very rapidly at this location, the resulting mean velocity was 55 percent below the predicted mean velocity.

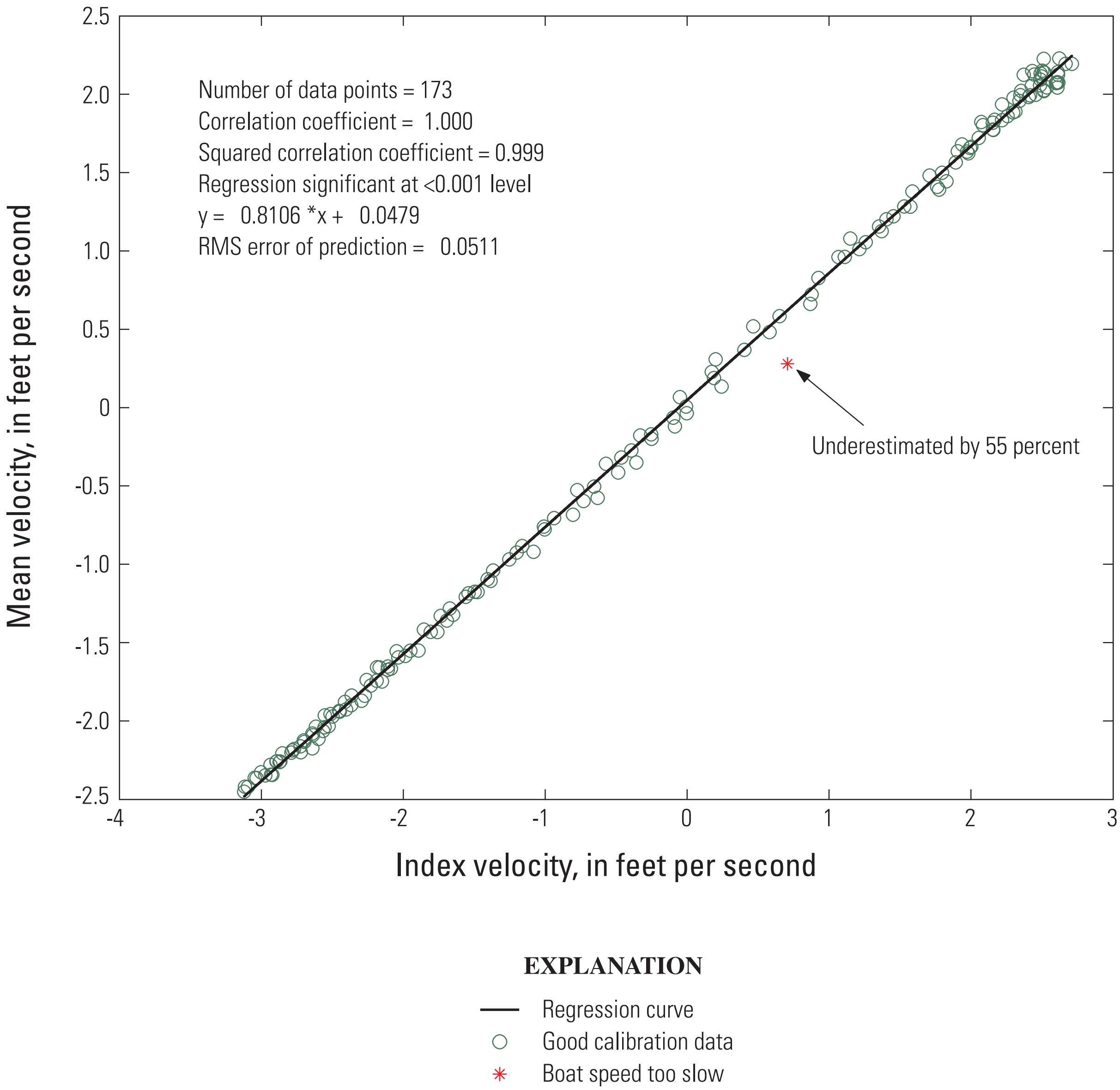


Figure E4. Impacts of improper boat speed on the resulting index-velocity versus mean-velocity relation.

In a different situation, the discharge measurements collected resulted in a poor correlation with the index velocity data (*fig. E5*). A retrospective analysis of this situation showed that the boat speed was too fast; the estimated channel depth was approximately five times greater than the actual channel depth; the transducer depth was held constant, even though the boat loading was changed and the crew moved about the boat; and edge estimates were made without using a range finder. In a wide and shallow channel, the effects of erroneous transducer depth are much greater than in a narrow and deep channel. “Eyeball” estimates of edge distances tend to underestimate the distance to shore, are highly variable, and can be a significant source of error if the estimated areas are large compared to the total cross-sectional volume (Simpson, 2001).

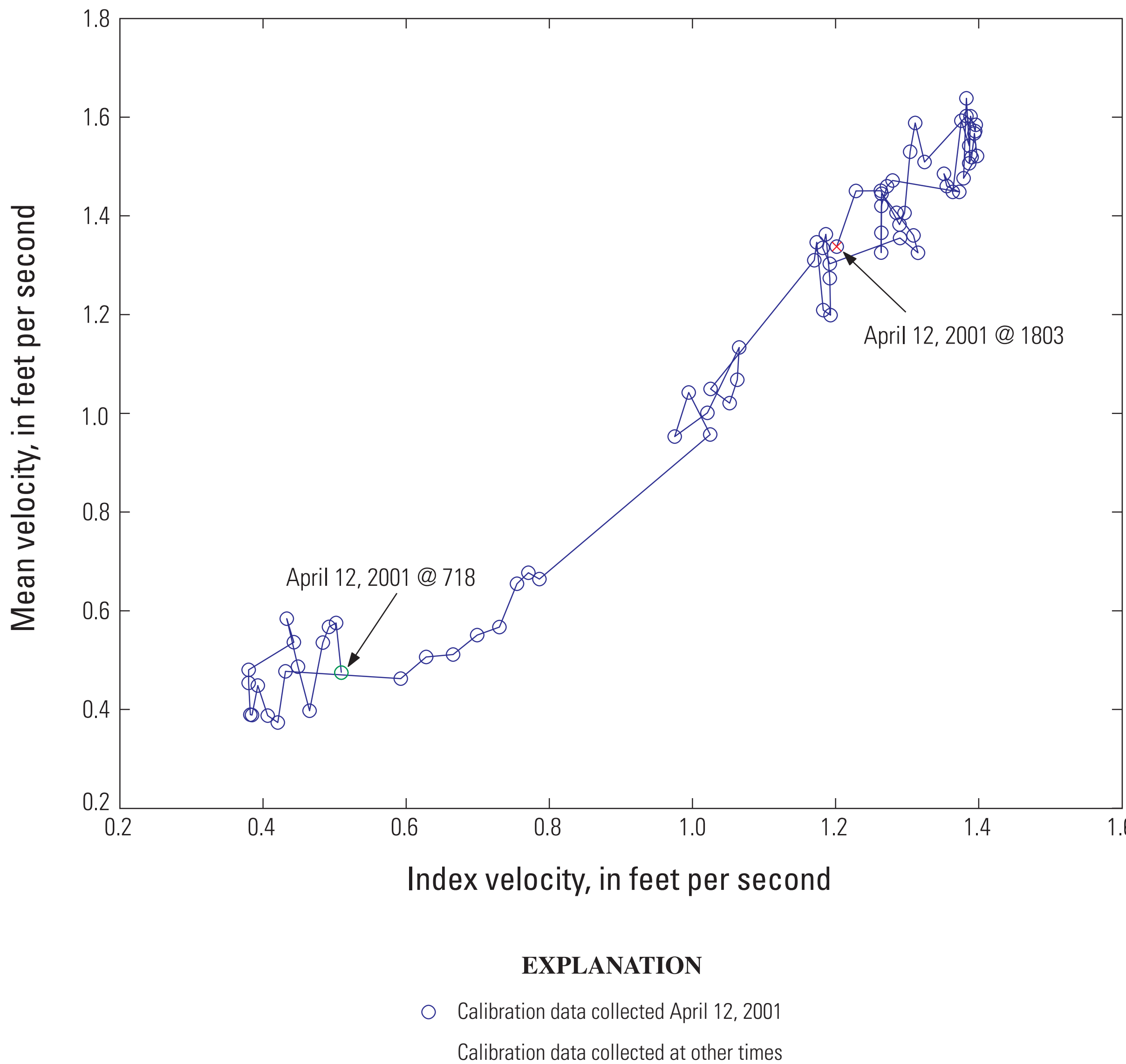
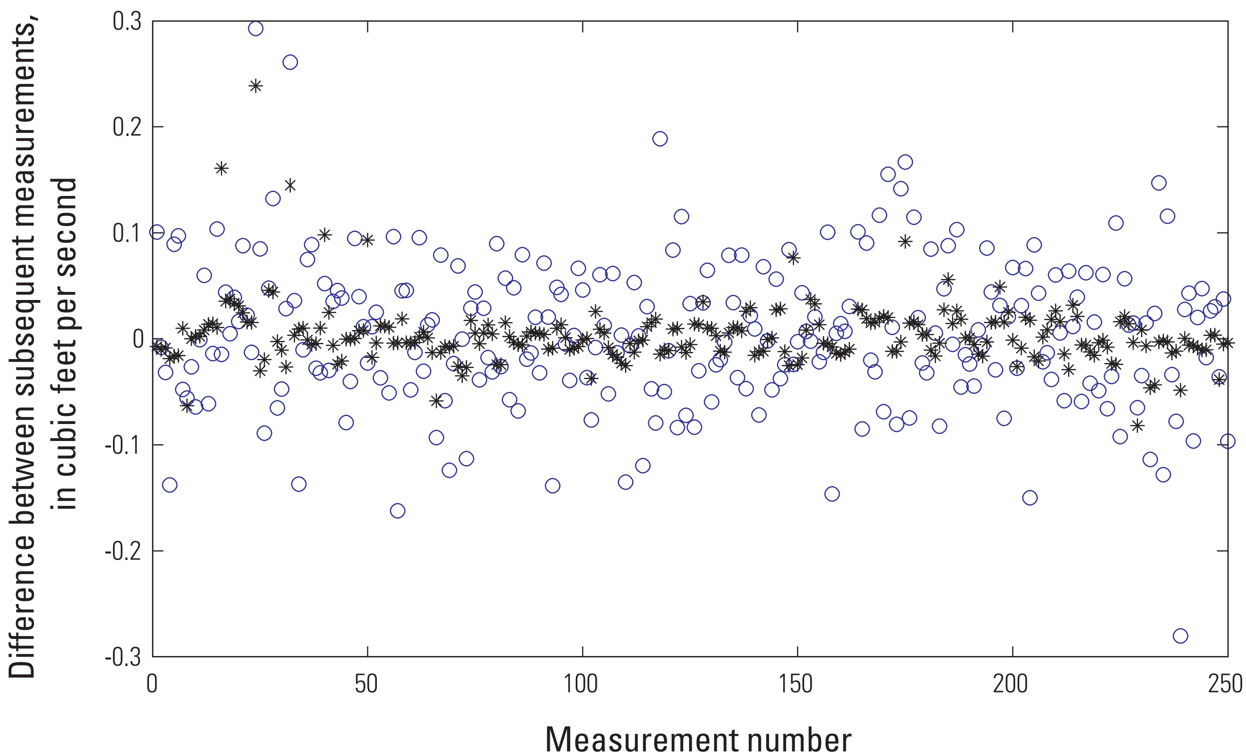


Figure E5. Impacts of poor vessel-mounted downward-looking acoustic Doppler velocity meter configuration and poor boat operation techniques on the resulting index velocity versus mean velocity relation.

It is difficult to identify a single issue that caused problems in the above example; however, the standard deviation between the mean velocity data is approximately double the standard deviation between the index velocity data (*fig. E6*). Some variability is expected because of changing field conditions, but the high variability in this calibration suggests that greater attention to detail in the field was necessary.



EXPLANATION

○ Measured mean velocity: Standard deviation = 0.102
∗ Recorded index velocity: Standard deviation = 0.052

Figure E6. Comparison of the difference between subsequent velocity measurements as recorded by the index velocity instrumentation and the vessel-mounted downward-looking acoustic Doppler velocity meter.