Feasibility of Acoustic Doppler Velocity Meters for the Production of Discharge Records from U.S. Geological Survey Streamflow-Gaging Stations

By Scott E. Morlock, Hieu T. Nguyen, and Jerry H. Ross

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
5957 Lakeside Boulevard
Indianapolis, IN 46278–1996

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
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CONVERSION FACTORS

Multiply	By	To obtain
inch	2.54	centimeter
centimeter (cm)	0.3937	inch
foot (ft)	0.3048	meter
meter (m)	3.281	foot
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pound, avoirdupois (lb)	0.4536	kilogram
kilogram (kg)	2.205	pound, avoirdupois
foot per second (ft/s)	30.48	centimeters per second

Additional abbreviation:

MHz, megahertz

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Abstract

It is feasible to use acoustic Doppler velocity meters (ADVM's) installed at U.S. Geological Survey (USGS) streamflow-gaging stations to compute records of river discharge. ADVM's are small acoustic current meters that use the Doppler principle to measure water velocities in a two-dimensional plane. Records of river discharge can be computed from stage and ADVM velocity data using the "index velocity" method. The ADVM-measured velocities are used as an estimator or "index" of the mean velocity in the channel.

In evaluations of ADVM's for the computation of records of river discharge, the USGS installed ADVM's at three streamflow-gaging stations in Indiana: Kankakee River at Davis, Fall Creek at Millersville, and Iroquois River near Foresman. The ADVM evaluation study period was from June 1999 to February 2001. Discharge records were computed, using ADVM data from each station. Discharge records also were computed using conventional stage-discharge methods of the USGS. The records produced from ADVM and conventional methods were compared with discharge record hydrographs and statistics. Overall, the records compared closely from the Kankakee River and Fall Creek stations. For the Iroquois River station, variable backwater was present and affected the comparison; because the ADVM record compensates for backwater, the ADVM record may be superior to the conventional record. For the three stations, the ADVM records were judged to be of a quality acceptable to USGS standards for publications and near real-time ADVM-computed discharges are served on USGS real-time data World Wide Web pages.

INTRODUCTION

The U.S. Geological Survey (USGS) operates a network of more than 7,200 streamflow-gaging stations in the United States (Wahl and others, 1995) for the production of continuous records of stream and river discharge. The USGS annually publishes the record from each streamflow-gaging station as mean daily discharge values and provides real-time discharge data from more than 4,200 streamflow-gaging stations (Wahl and others, 1995). The availability of near real-time discharge data has become increasingly important to government agencies and private companies who require detailed data quickly for optimal water-management strategies (Mason and Weiger, 1995).

Historically, the USGS has relied on conventional methods to produce discharge records from streamflow-gaging stations. Conventional methods include the measurement and recording of stage ("stage" as used here means the water level of the river or stream referenced to an established datum) by automated sensors and electronic data loggers; the periodic measurement of discharge, using mechanical or acoustic current meters for a range of stages; and the development of a relation called a "stage-discharge rating."

USGS personnel make periodic discharge measurements at streamflow-gaging stations by measuring water depths with a wading rod or sounding weight, measuring velocities with a propeller-type current meter in numerous subsections across a river or stream channel, and integrating the subsection discharges (Rantz and others, 1982, explains the method in detail). Another method of measuring discharge is to use a hydroacoustic device, called an acoustic Doppler current profiler (ADCP), attached to a moving boat (for purposes of this discussion, ADCP is used as a generic term and does not refer to any particular product or model). The ADCP simultaneously measures water velocities, depths, and traverse length to compute discharge as it is moved across the channel (see Morlock, 1994, for more detailed information about ADCP discharge measurements).

For each measurement of discharge, a mean stage for the measurement period is computed. When enough discharge measurements have been made for a wide range of stages, a stage-discharge rating can be developed for a streamflow-gaging station. Discharges then can be computed from the stage data. Stages are recorded on an even interval (commonly 15 or 60 minutes) called a stage "unit value"; each stage unit value yields a computed discharge unit value. The average of the discharge unit values over a 24-hour period is the mean daily discharge. A record of mean daily discharges is called discharge record.

Once a stage-discharge rating is developed, discharge measurements continue to be made to check the validity of the rating. Changes in the hydraulic characteristics of a stream can cause temporary or lasting changes in the stage-discharge rating. These changes are found when discharge measurements depart from the stage-discharge rating by more than a USGS-set percent tolerance that is based on the quality of the discharge measurement. It is standard USGS practice, when one or more measurements reveal a change in the rating, to apply a "stage shift" that temporarily adjusts the rating so that the measurement and rating-computed discharges are within tolerance. The USGS has procedures for determining shifts and correcting a rating (Rantz and others, 1982).

Complex flow conditions at many potential streamflow-gaging stations may negate stable stage-discharge ratings and make the use of conventional methods impractical or impossible. These conditions include flow reversals, backwater effects, hysteresis effects (different stage-discharge relations for rising and falling stages), and channel-roughness changes (such as seasonal vegetation growth, ice cover, and changes in bed forms as in the case of dune migration).

For stations where conventional methods cannot be used, the USGS has installed velocity-measuring instruments, including electromagnetic and mechanical deflection-vane instruments. Instruments that use hydroacoustics (sound propagated in the water) have become prevalent for velocity measurements. The velocity data from these instruments, together with stage data, can be used to produce discharge records from data collected at streamflow-gaging stations. Acoustic velocity meters (AVM's), instruments that use traveltimes of acoustic signals to measure water velocities, were the first hydroacoustic instruments used by the USGS at streamflow-gaging stations. These instruments continue to be used to produce discharge records at streamflow-gaging stations across the United States.

Recently, hydroacoustic instruments called acoustic Doppler velocity meters (ADVM's), developed for river applications, have become available for use at streamflow-gaging stations. ADVM's are small and easy to install and maintain. With the use of ADVM's, it may be possible to produce discharge records from stations where conventional methods cannot be used. ADVM's may not only assist in the production of discharge records from stations where conventional methods work, but they may do so with greater accuracy and efficiency. As of February 2001, an estimated 150 to 200 ADVM's have been purchased by the USGS for installation at streamflow-gaging stations.

Purpose and Scope

The purpose of this report is to describe the feasibility of using ADVM's for the computation of discharge records from USGS streamflow-gaging stations. Two models of ADVM's from two different manufacturers were used in this feasibility study: the SonTek Argonaut-SL and the Nortek EasyQ. It is not the intent of this study to compare the instruments or to recommend an instrument as the better one for the purpose of producing discharge records. It is not meant to imply that these are the only two instruments of this general type that could be used to produce discharge records. These two instruments were included in the study because both were designed specifically for producing discharge records.

The study was performed by installing ADVM’s at three USGS streamflow-gaging stations in Indiana. ADVM data were used to compute records of discharge from each of the streamflow-gaging stations. These records of discharge were compared to the records of discharge computed with conventional methods. The study period was from June 1, 1999, to February 28, 2000.

Physical Setting

ADVM’s were installed at three USGS streamflow-gaging stations in Indiana: Kankakee River at Davis, Fall Creek at Millersville, and Iroquois River near Foresman (fig. 1):

- The Kankakee River at Davis (05515500) is in the Illinois River Basin. The USGS has operated this station since October 1924 (Stewart and others, 1999). The drainage area upstream from the station is 537 mi^2.

- The Iroquois River near Foresman (05524500) is in the Illinois River Basin. The USGS has operated this station since December 1948 (Stewart and others, 1999). The drainage area upstream from the station is 449 mi^2.

- Fall Creek at Millersville (03352500) is in the Wabash River Basin. The USGS has operated this station since October 1929 (Stewart and others, 1999). The drainage area upstream from the station is 298 mi^2. The flow is regulated by an upstream water-supply reservoir.

The Kankakee River and Fall Creek stations were selected as ADVM evaluation stations because the quality of the discharge record produced by conventional USGS methods was judged to be good, which provided a basis for comparison of the discharge record produced with ADVM data.

The Iroquois River station was selected for ADVM installation in an effort to improve the record of discharge. Historically, variable backwater has affected the quality of the record from this station; the cause of the backwater has not been determined. A stable stage-discharge rating can be determined only when rates of change in discharge are stable in relation to rates of change in stage. Backwater is a condition where stage increases are not accompanied by stable changes in discharge—in some cases, discharge may decrease as stage increases. Backwater can be caused by debris, ice jams, control structures, or the confluence of another river downstream from a streamflow-gaging station. For the Iroquois River station, the cause of the backwater has never been determined. The backwater affecting this station is called variable backwater because it only occurs during some periods. Because ADVM-measured velocity data are a more direct measure of discharge than stage data, it was hoped that ADVM data could be used to produce accurate discharge records during variable-backwater periods.

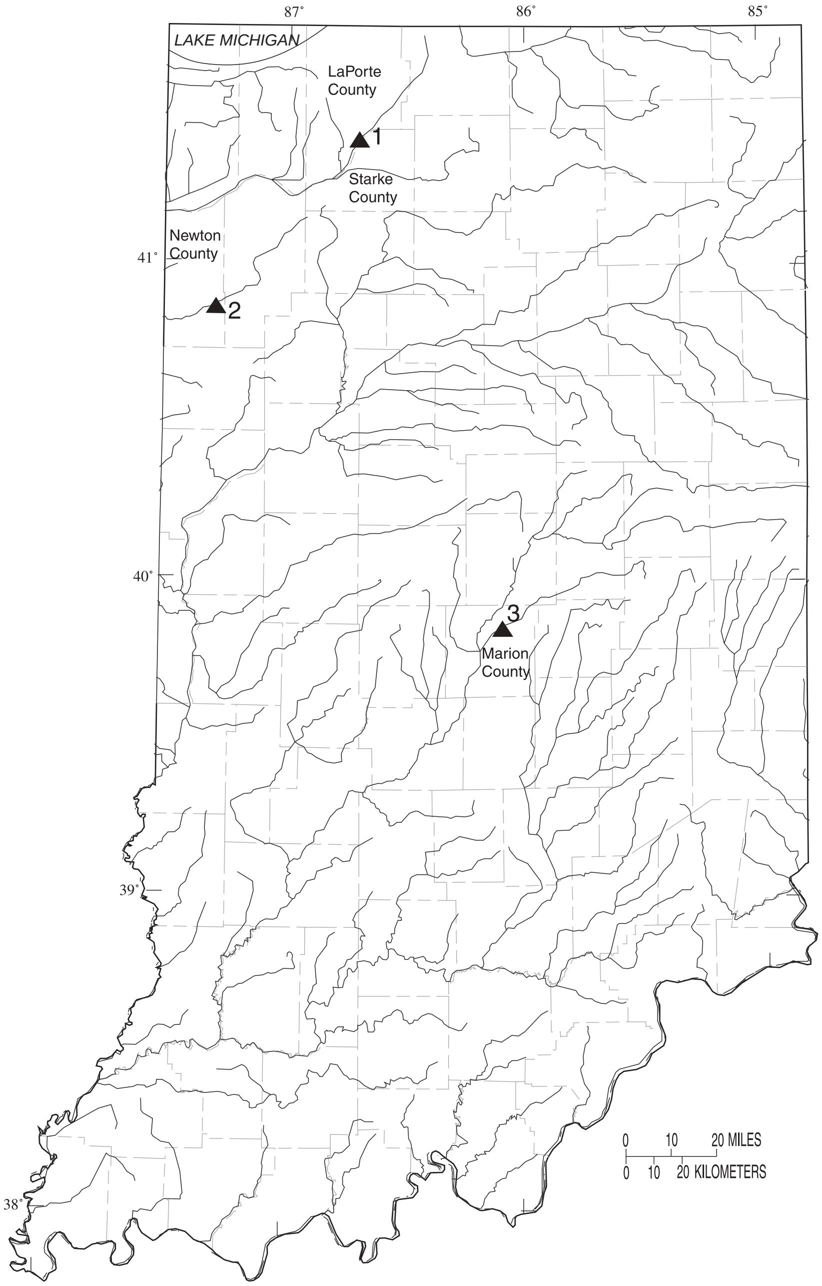
ACOUSTIC DOPPLER VELOCITY METERS

The term “acoustic Doppler velocity meter” is descriptive of how the instrument operates. An ADVM measures water by velocity using the Doppler principle applied to sound (acoustics) transmitted underwater.

Principles of Operation

An ADVM uses a pair of monostatic acoustic transducers set at a known orientation to measure water velocities. “Monostatic” refers to the capability of each transducer to transmit and receive sound (SonTek Corporation, 2000). Each ADVM transducer transmits sound pulses (pings) of a known frequency along a narrow “acoustic beam” (fig. 2). As the pings travel along the acoustic beam, they strike particulate matter (scatterers) suspended in the water. When the pings strike scatterers, some of the sound is reflected along the acoustic beam to the transducer. The returned sound (echo) has a frequency (Doppler) shift proportional to the velocities of the scatterers and water they are traveling in along the acoustic beam.

The two acoustic beams are set at a known angle (beam angle) in a two-dimensional plane that is parallel to the water surface (fig. 2) so if seen from above, they would be in a “V” configuration. From velocities measured along the individual acoustic beams, the ADVM uses trigonometry (because the beam angle is known) to compute velocity in a user-set part (sample volume) of the plane defined by the beams (fig. 2). An ADVM will compute and output a mean velocity for the sample volume; the velocity is



Base from U.S. Geological Survey 1:100,000 digital data, 1983
Albers Equal Area Conic projection,
Standard parallels 29°30' and 45°30', Central meridian -86°

EXPLANATION

▲1 Evaluation-station number	U.S. Geological Survey Site name	U.S. Geological Survey streamflow-gaging-station number
1	Kankakee River at Davis	05515500
2	Iroquois River near Foresman	05524500
3	Fall Creek at Millersville	03352500

Figure 1. Locations of acoustic Doppler velocity meter evaluation sites in Indiana.

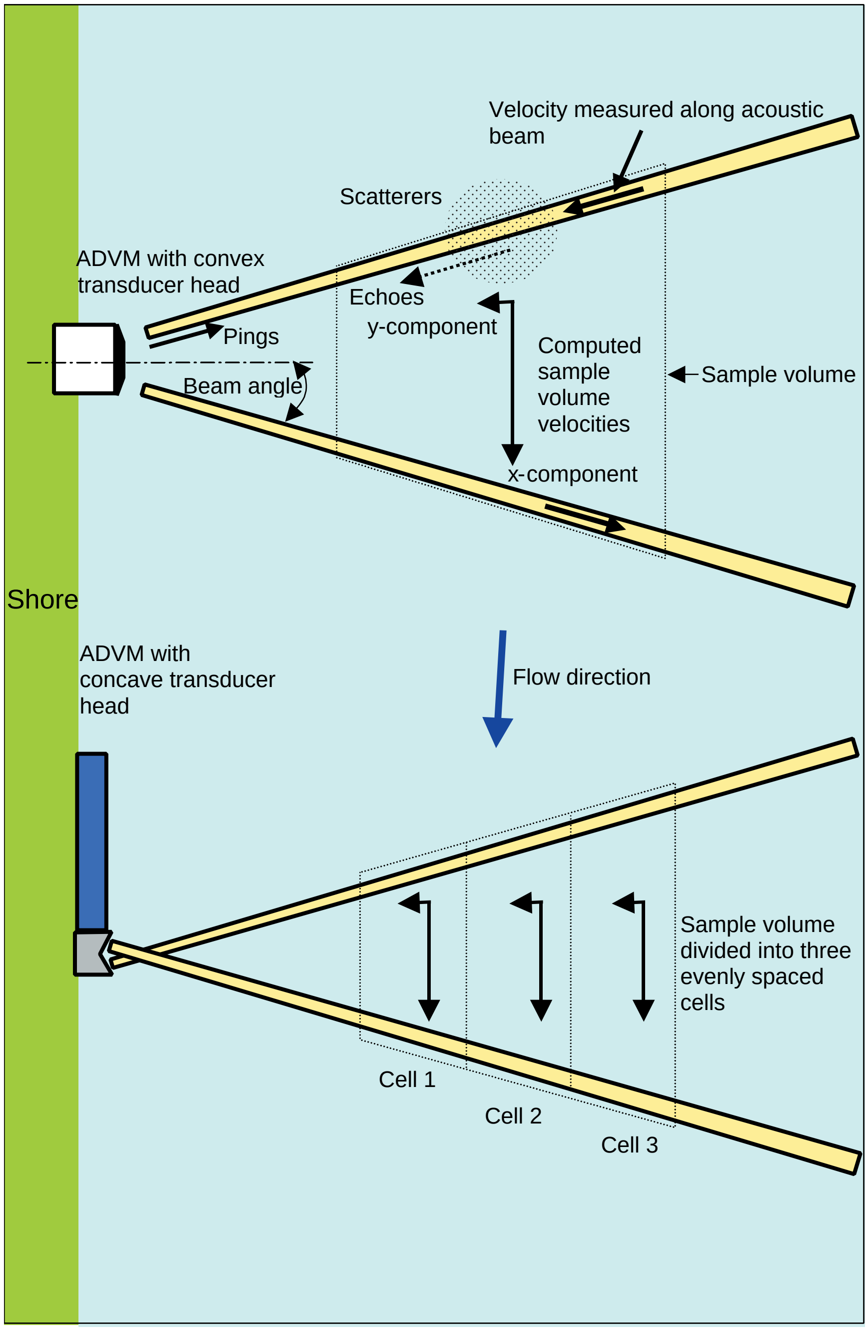


Figure 2. Acoustic Doppler velocity meters (ADVM's).

output in terms of an x-component and a y-component. In a typical installation where the ADVM is mounted on the side of the river, the x-component is the component of velocity parallel to the main flow direction of the river ("along flow") and the y-component of velocity is perpendicular to the main flow direction of the river ("across flow"). The ADVM's sample velocities over a period of time set by the user, the "averaging interval," and report the x- and y-components of the mean velocity sampled during the averaging interval.

An important ADVM parameter is signal strength, which is a measure of the strength of the echoes returned to the ADVM. Signal strength decreases with distance from the ADVM because of sound absorption and spread of the acoustic beams (SonTek Corporation, 2000). The maximum-measurement range of an ADVM is dependent upon the distance at which the signal strength approaches the instrument-noise level. For this discussion, the instrument-noise level may be considered the signal strength of the ADVM measured while the ADVM is out of the water (SonTek Corporation, 2000). ADVM manufacturers sometimes use the terms “signal strength” and “beam amplitude” interchangeably.

Description of Models Used

The Argonaut-SL and EasyQ (fig. 3) are similar in construction and features. Both consist of a transducer head attached to a canister-shaped housing that contains the instrument data-processing electronics. The Argonaut-SL has a convex transducer head, while the EasyQ has a concave transducer head (fig. 2). Both instruments have a watertight cable connector for the attachment of a communications/power cable. Selected specifications for the Argonaut-SL and EasyQ used in this study are given in table 1.

The EasyQ measures and outputs velocities from three separate, consecutive cells within the sample volume (fig. 2). Each cell’s size can range from 0.4 to 2 m (the maximum distance to the beginning of the first cell is 6 to 8 m, giving a maximum range of 16 m). The EasyQ was equipped with an upward-looking transducer designed to measure stage acoustically.

Argonaut-SL’s and EasyQ’s are available with features or options not present in instruments used for this study. For example, the Argonaut-SL is available in different form factors (shapes) and has an upward-looking stage transducer and multi-cell (5 cells) capability, as well a 3.0-MHz-frequency unit intended for smaller rivers and streams. A long-range, 1-MHz EasyQ model is available with 4-m cells. The operating principles and application of instruments discussed in this report generally will be unaffected by these other features or options.

The Argonaut-SL and EasyQ manufacturers provide software used to program their instruments. Programmable parameters include sample-volume size and velocity-sampling interval. The software also is used to perform data-quality and instrument-diagnostic checks.

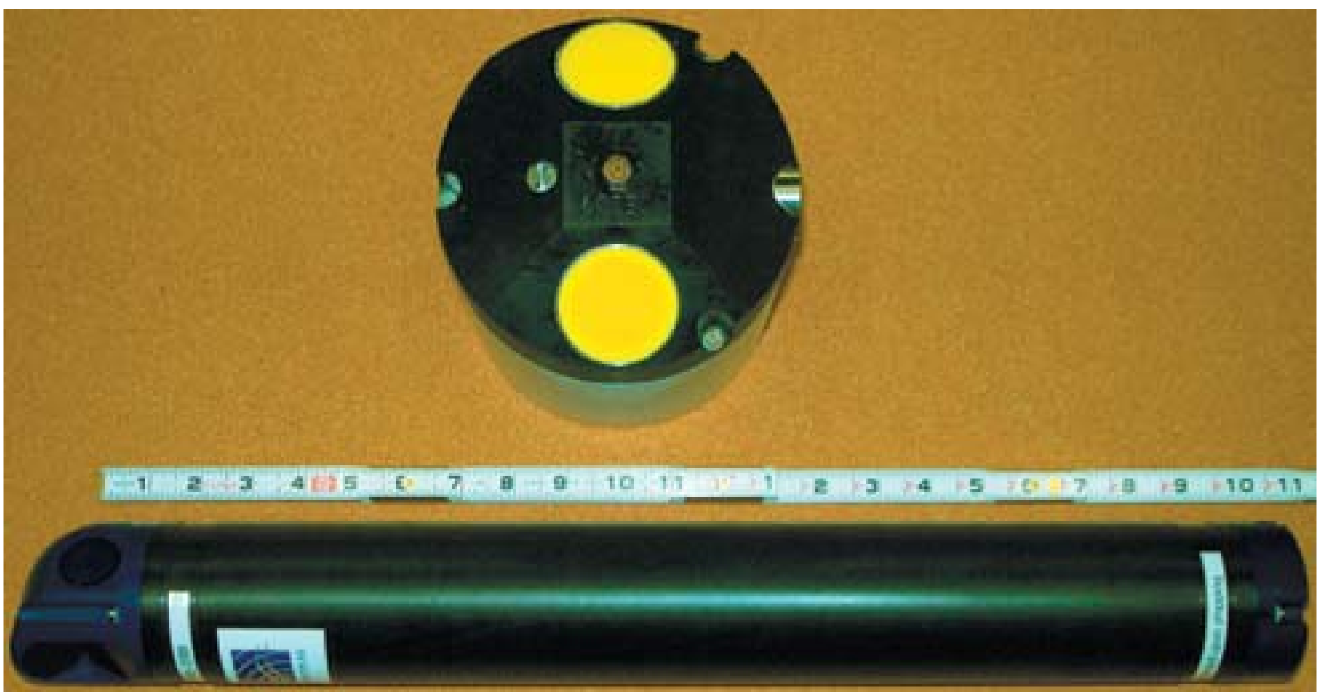


Figure 3. Photographs of Argonaut-SL and EasyQ.

Table 1. Selected specifications for the Argonaut-SL and EasyQ instruments installed at U.S. Geological Survey streamflow-gaging stations in Indiana

[cm, centimeter; kg, kilogram; m, meter; MHz, megahertz]

Feature	Argonaut-SL	EasyQ
Length (cm)	18.0	58.9
Diameter (cm)	15.2	7.5
Weight in air (kg)	2.5	1.7
Transducer beam angle (degrees)	25	25
Sample volume minimum start distance (m)	.5	.2
Sample volume maximum distance (range) (m)	22.0	16.0
Transducer frequency (MHz)	1.5	2.0
Number of cells within sample volume	1	3

The Argonaut-SL and the EasyQ can be interfaced with electronic data loggers (EDL's). The USGS uses EDL's to collect and store parameters from sensors; the parameters then can be retrieved remotely from the EDL's by using various telemetry methods for real-time-data applications. The ADVM can be interfaced with an EDL by using the SDI-12 (serial-digital interface at 1200 baud) communication protocol commonly used by the USGS. To use the SDI-12 protocol, a sensor is connected to a cable that consists of a data wire, power wire, and ground wire. Using the SDI-12 protocol, a number of sensors can be connected to the same EDL through a single communications port. An EDL using the SDI-12 protocol issues a measurement command to the ADVM. The ADVM returns a data string to the EDL that tells the EDL the length of time the ADVM will sample and the number of parameters that will be returned to the EDL after the sampling is complete. After the sampling is complete, the ADVM sends a data string to the EDL containing the sampled parameters.

The SDI-12 standard allows an EDL to collect up to nine parameters from the Argonaut-SL. The parameters relevant to using an Argonaut-SL for the production of river discharge include the following:

- Velocity x-component: the x-component of the mean velocity measured within the sampling cell (fig. 2).
- Velocity y-component: the y-component of the mean velocity measured within the sampling cell (fig. 2).
- Computed velocity vector: the resultant vector computed from the x- and y-velocity components, using the following formula:

$$V = (Vx^2 + Vy^2)^{1/2} \qquad (1)$$

where,

Vx is the velocity x-component,
Vy is the velocity y-component, and
V is the computed velocity vector.

- Standard deviation: the mean standard deviation of the Argonaut-SL velocity measurement.
- Signal strength: the mean strength of the echoes returning to the Argonaut-SL.
- Temperature: the mean temperature measured by the Argonaut-SL.

The SDI-12 option allows an EDL to collect up to 18 parameters from an EasyQ. The parameters relevant to using an EasyQ for the production of river discharge include the following five**:**

- Velocity x-components for cells 1, 2, and 3: the x-components of the mean velocities measured within each of the three EasyQ cells (fig. 2).

- Velocity y-components for cells 1, 2, and 3: the y-components of the mean velocities measured within each of the three EasyQ cells (fig. 2).

- Amplitudes for cells 1, 2, and 3: the average echo strength within each of the three EasyQ cells.

- Stage: the stage output from the EasyQ upward-looking transducer.

- Pitch and roll: the pitch and roll of the EasyQ computed by the EasyQ on-board tilt sensor.

Installation Considerations

A primary ADVM-installation consideration is avoidance of acoustic-beam signal contamination caused by boundary reflections. Boundaries in a river can include the water surface, river bottom, structures such as bridge piers, and objects such as rocks and logs. The ADVM's described in this report have narrow (about 2-degree) acoustic beams; the beams spread with range from the ADVM and, in a shallow river or stream, may strike the surface or bottom, causing beam contamination and biases in the ADVM velocity measurements. Boundary interference can be prevented with the use of aspect ratio, which provides an estimate of maximum ADVM range and is expressed as range/distance. "Range" is the maximum sample volume range, and "distance" is the distance to the closest boundary (an example using an aspect ratio of 4: an ADVM that is 1 m deep and 2 m from a river bottom should be programmed so that the maximum sample volume range is no greater than 4 m). The aspect ratio indicates that an ADVM will have less range in shallow than in deep rivers and streams. In most conditions, aspect ratios of 8 to 10 will work and, at many stations with high backscatter and smooth bottoms, aspect ratios could be greater than 15 (Craig Huhta, SonTek Corporation., written commun., May 23, 2001).

ADVM signal strength can be used to check for boundary interference within the sample volume. If no boundary interference is present, the signal strength of each beam should peak at the transducer and then gradually decrease with distance from the transducer (fig. 4). Boundary interference will cause the signal strength to increase markedly or "spike" (fig. 4). A spike in the ADVM sample volume means that boundary interference may produce unreliable velocity data. The size of the sample volume would need to be selected so the spike remains outside the sample volume. ADVM manufacturers recommend the end of the sample volume be placed no closer than 10 percent of the total distance from the ADVM to the boundary (for example, if a boundary is discovered at 10 m, the end of the sample volume should be no farther than 9 m). The 10-percent recommendation is designed to minimize a phenomenon known as "sidelobe interference" (SonTek Corporation, 2000).

If no boundary interference is detected within the maximum range of the ADVM, selection of the sample-volume-end distance should be based on the instrument-noise level. The manufacturers recommend that the sample-volume end be programmed so that the beam-signal strengths at the sample-volume end are about five counts above the instrument-noise level (fig. 4). ADVM software will display the signal strengths in units of counts, where one count equals about 0.43 decibel.

The end of the sample volume is selected to prevent boundary interference and to be above the instrument-noise level. The beginning of the sample volume should be selected to minimize turbulence from the structure on which the ADVM is mounted.

If beam-signal strengths drop below the five counts above the instrument-noise level, the Argonaut-SL has a feature that automatically will reduce the end of the sample volume. To ensure accuracy, the user should consider setting the end of the sample volume as specified above so the Argonaut-SL does not reduce the end of the sample volume; a reduction would change the sample-volume size and could change the index-velocity relation.

Another programming consideration is the relation of velocity-measurement errors to the averaging interval. ADVM measurement errors will result from instrument and environmental sources; environmental errors likely will dominate instrument errors. There will be random instrument errors associated with the measurement of velocity using a single ping. Errors are reduced by averaging pings, which increases the averaging interval. Some environmental errors will be

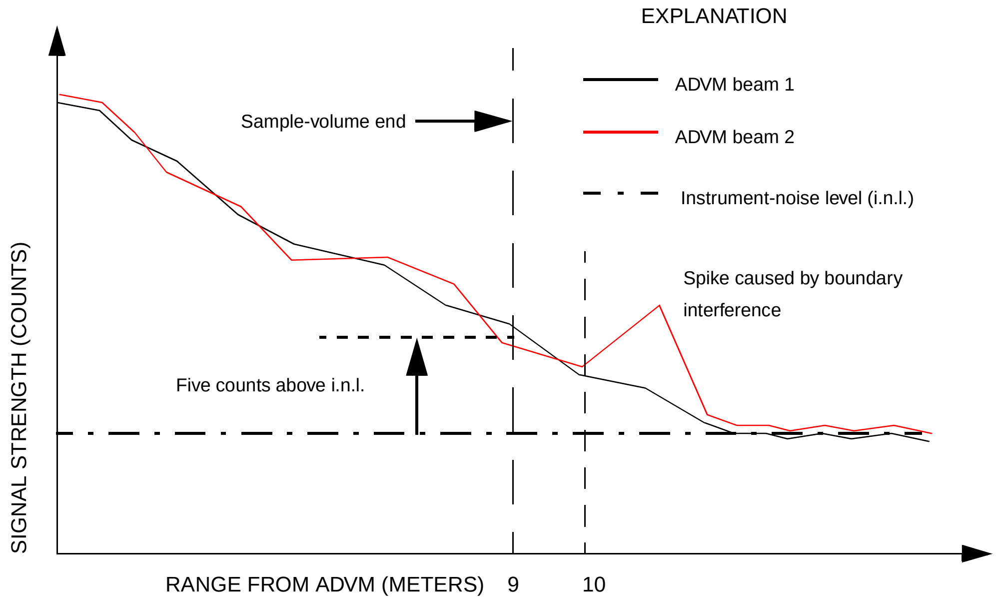


Figure 4. Acoustic Doppler velocity meter (ADVM) signal strength showing selection of ADVM sample-volume end based on a boundary-interference spike and instrument-noise level.

caused by turbulence, the size of turbulent eddies as dictated by channel geometry, and short-term flow pulsations. At stations where river turbulence is pronounced, a longer averaging interval may be needed to attain the level of accuracy a shorter interval would produce at stations with less turbulence. The averaging intervals used at the ADVM stations detailed in this report were arrived at by trial and error; they appear to minimize the measurement errors. In general, the averaging interval for each station will need to be considered individually and some experimentation may be needed to find an optimal interval.

For ADVM installation, it is important to consider flow disturbances caused by structures on which an ADVM is mounted. It is often desirable to mount instruments on the downstream face of a bridge pier, which provides some protection from debris. Mounting to the downstream face of a pier, however, could cause the ADVM to sample within the vortices caused by flow separation from the upstream face of the pier (wake turbulence). The beginning of the sample volume would need to be beyond the wake-turbulence zone. The following equation, derived from Hughes and Brighton (1991), can be used to estimate the extent of the wake-turbulence zone (David Mueller, U.S. Geological Survey, written commun., 2001):

$$b = c(dx)^{0.5}, \qquad (2)$$

where,

- b is the lateral distance from the pier center line to the approximate edge of the wake-turbulence zone,
- d is the width of the pier,
- x is the distance to the upstream face of the pier,
- c is a factor accounting for pier shape: c is 0.62 for circular or round-nosed piers; c is 0.81 for rectangular piers.

For stations with long piers or narrow channels, it may not be practical to set the sample volume totally outside the wake-turbulence zone. If a part of the sample volume is within the zone, it may be necessary to use a longer averaging interval to compensate for the additional turbulence. If possible, the sample volume should be set to be outside the wake-turbulence zone.

Some other installation considerations include the following:

- Protection—The ADVM should be protected from debris and vandalism. Its mount should be durable and rigid, and the instrument should be accessible for maintenance.
- Power—The longer the averaging interval, the greater the power consumption (ADVM manufac-

turers can be consulted concerning computation of power consumption).

- Cable lengths—The maximum recommended cable length for SDI-12 operation is 250 ft (for distances above 250 ft, it may be possible to provide SDI-12 communications using SDI-12 radios).

Theory of Computation of River Discharge

The following approach to the computation of river discharge is based on methods developed by the USGS to produce discharge records from instruments that measure water velocities. These methods were developed mainly for AVM's and now can be applied to ADVM's.

River discharge can be computed, as:

$$Q = \overline{V}A, \tag{3}$$

where,

Q is the discharge in cubic feet per second;

$\overline{V}$ is the mean velocity for a specified channel cross section (mean velocity) in feet per second; and,

A is the channel area for a specified cross section in square feet.

Channel area for a river can be determined by surveying a river cross section. The channel area for a given stage then can be computed from the cross-section survey. Because a range of stage occurs in most rivers, it is necessary to develop a relation between stage and channel area, called a "stage-area rating."

The mean velocity for a river can be computed from the water velocity measured by an ADVM. To compute mean velocities from ADVM-measured velocities, the relation between mean channel and ADVM-measured velocities must be determined.

The method used to relate mean velocity and ADVM-measured velocity is the index velocity method. The instrument measures velocity in a part of the stream and that velocity is used to estimate, or "index," the mean channel velocity. The index velocity method includes the following steps:

1. An ADVM is installed at a streamflow-gaging station. The ADVM is connected to an EDL that begins logging data from the instrument.
2. The channel is surveyed and a stage-area rating is developed.
3. River-discharge measurements are made near the streamflow-gaging station while the ADVM is sampling velocity. Discharge measurements are made using a USGS mechanical current meter or an ADCP.
4. Mean velocity is derived for each individual discharge measurement by dividing the measured discharge from the channel area computed from the stage-area rating.
5. For each discharge measurement, ADVM velocities are averaged for the discharge-measurement period. For purposes of this discussion, "ADVM velocity" refers to the one ADVM velocity parameter to be used as the primary velocity parameter for the computation of discharge. For the Argonaut-SL, the velocity x-component or the computed velocity vector (eq. 1) could be the ADVM velocity. For the EasyQ, any of the velocity x-components from any of the three cells could be the ADVM velocity (alternately, the x-components from two or all three cells could be averaged into a single velocity that would become the ADVM velocity.
6. Each discharge measurement yields a computed mean channel velocity and an average ADVM velocity. These data then can be used to develop a relation to compute mean velocities from ADVM velocities. This relation is called an "index velocity rating." Stage also may be a factor in the development of an index velocity rating.

Various methods can be used to develop an index velocity rating. For example, an index velocity rating could be a single coefficient to relate ADVM to mean velocity, provided the range in stage at the station is negligible (the USGS Indiana District has used a single-coefficient index velocity rating to generate an accurate streamflow record from an AVM-equipped, streamflow-gaging station in northwestern Indiana since 1991). Other ratings could be more complex, particularly at stations with bidirectional flow or a large range of stage. For example, the development and accuracy of complex index velocity ratings for an AVM-equipped USGS streamflow-gaging station on a tide-affected river is described in

Simpson and Bland (1999). For stations with a large range of stage, stage may be a factor in the computation of mean velocities from ADVM velocities. The index velocity rating must be developed individually for each station based on collected data. A detailed discussion of the rating construction for each of the ADVM stations described in this report is given in the section "Index Velocity Ratings."

After a stage-area and index velocity rating are developed, discharges can be computed from a streamflow-gaging station equipped with an ADVM. A discharge can be computed from each ADVM velocity recorded by the station EDL. A measurement of stage also must be recorded with the ADVM so that channel area can be computed. Various USGS stage sensors are described in Rantz (1982).

STUDY METHODS

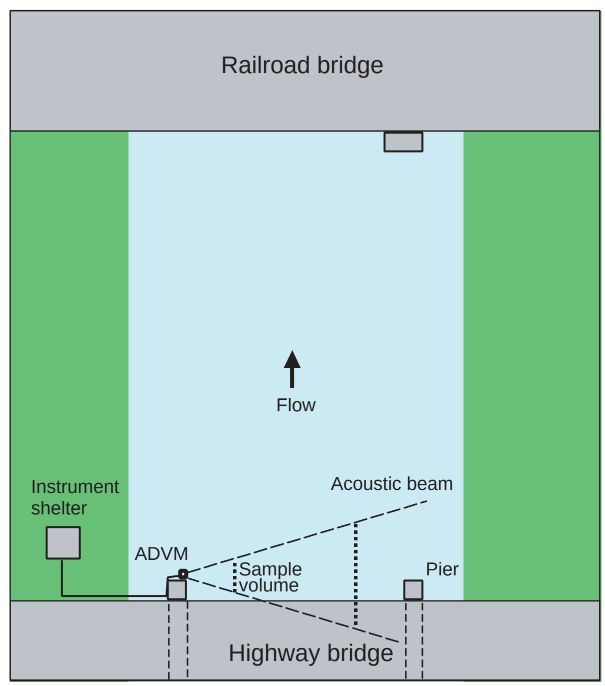
The same approach was used to produce records of streamflow for the three USGS streamflow-gaging stations used for this study, using the ADVM data from each of the stations. Each instrument was installed and interfaced with an EDL; data collection and transmission then began. A channel cross section was surveyed, from which a stage-area rating was produced. Discharge measurements were made, from which an index velocity rating was produced. Stage- and ADVM-velocity data then were used to compute records of discharge.

ADAPS (Automated Data Processing Software) is the USGS computer program used to compute records of discharge. All stage- and ADVM-parameter data logged by the station EDL's were transmitted by telemetry to computers at the USGS Indiana District Office and placed in the ADAPS database. The stage-area and index velocity ratings were entered into ADAPS; the stored stage and velocity data were used to compute discharge.

INSTALLATION OF ACOUSTIC DOPPLER VELOCITY METERS

An Argonaut-SL ADVM was installed at the Kankakee River at Davis streamflow-gaging station in June 1999 and at the Iroquois River near Foresman station in September 1999. An EasyQ was installed at the Fall Creek at Millersville station in March 2000.

The range of expected flows at the Kankakee (fig. 5) and Iroquois River (fig. 7) stations would be contained by the main channel where the ADVM samples velocities. For the Fall Creek station (fig. 6), flows below about 1,600 ft^3/s would be contained in the main channel, but higher flows would spread across a flood plain on both sides of the channel. Selected river characteristics for the three evaluation sites are given in table 2.

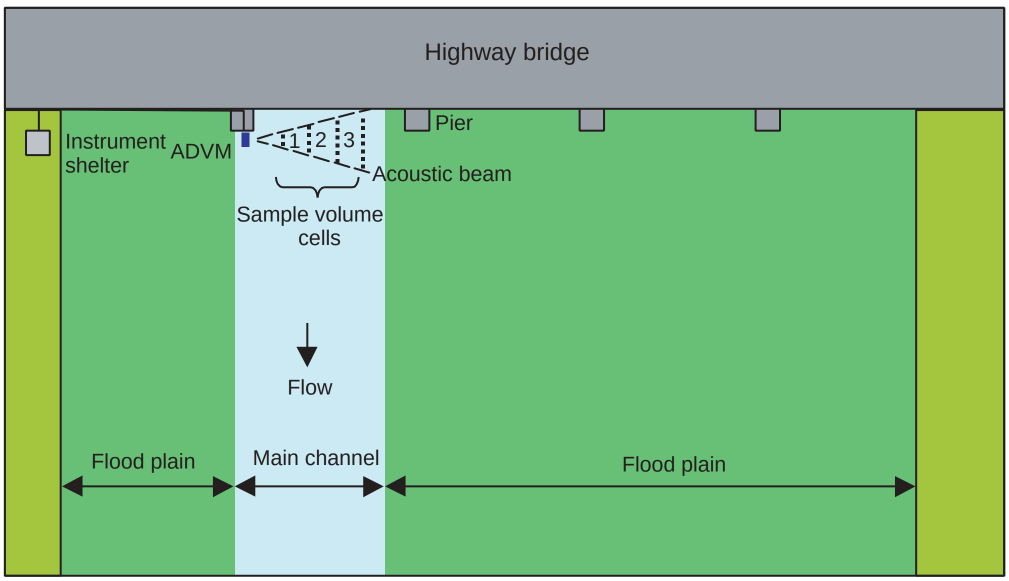


Not to scale

Figure 5. Photograph and site sketch of Kankakee River at Davis, Ind., acoustic Doppler velocity meter (ADVM) evaluation station.

View looking upstream

Highway bridge, downstream face



Not to scale

Figure 6. Photographs and site sketch of Fall Creek at Millersville, Ind., acoustic Doppler velocity meter (ADVM) evaluation station.

A custom mount for the ADVM was constructed and attached to a downstream highway-bridge pier at each of the three stations for protection from downstream-moving debris. ADVM's were mounted at depths of about 1 m (at median flow) for the Kankakee and Iroquois River stations and about 0.5 m at the Fall Creek station. The mounts were built of galvanized steel and aluminum for strength and weather resistance. Each mount was designed so that the ADVM could be pulled up for maintenance. Each ADVM was connected by cable to an EDL in the station instrument shelter. The cable allowed the ADVM to be interfaced for programming and allowed the EDL and ADVM to communicate, using the SDI-12 communications protocol.

Following installation, the ADVM software was used to examine signal strengths for spikes so the sample volume end could be programmed. At each station, the sample volume or cell size was programmed so that no known obstacles were in the sample volume or cell and so that the end of the sample volume was positioned in such a way that signal strengths were at least five counts above the instrument-noise level. The start and end distances for

View, looking upstream

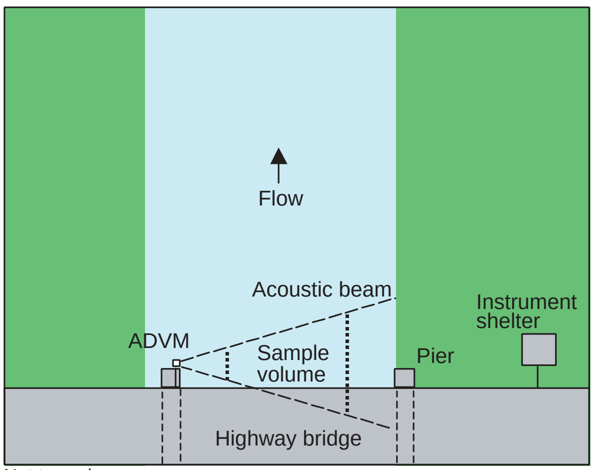


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Figure 7. Photograph and site sketch of Iroquois River near Foresman, Ind., acoustic Doppler velocity meter (ADVM) evaluation station.

the sample volume, as measured from the ADVM transducers, were 2 and 8 m, respectively, for the Kankakee River ADVM and 1 and 8 m, respectively, for the Iroquois River ADVM. For the Fall Creek ADVM (which has a sample volume composed of three cells) the start of the first cell was programmed at a distance of 0.5 m from the ADVM transducers. The cell size was programmed to be 0.75 m; thus the ends of cells 1, 2, and 3 were at 1.25, 2.0, and 2.75 m, respectively, from the ADVM transducers. The start of the sample volumes for the Kankakee and Iroquois River stations were beyond the estimated extent of the bridge-pier wake-turbulence zone (as computed, using eq. 2); for the Fall Creek station, cell 1 lies totally within the estimated extent of the bridge-pier wake-turbulence zone.

After installation, the velocity-averaging interval for the three AVDM’s was programmed at 1 minute. For each of the stations, the EDL was programmed with a sampling interval of 15 minutes—every 15 minutes, the EDL would command the ADVM to sample. Upon completion of the ADVM-averaging interval, the EDL was programmed to log ADVM parameters such as velocities, beam amplitudes, and quality indicators. Thus, an ADVM velocity unit value was the 1-minute average velocity measured by the ADVM logged every 15 minutes.

The velocity-averaging interval was increased from 1 to 10 minutes for the Kankakee River ADVM on August 14, 2000, and for the Iroquois River ADVM on June 26, 2000. The Fall Creek ADVM velocity-averaging interval was increased from 1 to 13 minutes on April 17, 2000—the ADVM velocity unit values were logged on 15-minute intervals, but the velocity-averaging interval was increased to 10 or 13 minutes. This interval increased the time that velocities were being sampled from 7 to 67 percent for the Kankakee and Iroquois River stations and from 7 to 87 percent for the Fall Creek station. Increasing the sampling time lowered random ADVM velocity variations from sample to sample by as much as 100 percent (an example from the Iroquois River station is shown in fig. 8). Because velocity unit-value variations were reduced and velocities were being sampled a greater percentage of the time, velocity and discharge uncertainties from short-time scale fluctuations were reduced.

The EDL’s also logged stage data from separate stage sensors with the ADVM data. The EDL’s at the Kankakee and Iroquois River stations were equipped with a satellite transmitter and were programmed to transmit stage, velocity, and signal strength to the USGS Indiana District Office for processing. The Fall Creek station EDL was equipped for land-line telephone telemetry for automated retrieval by the USGS Indiana District Office of all logged ADVM parameters.

Table 2. Selected river characteristics at three acoustic Doppler velocity meter evaluation sites, Indiana

[ft^3/s, discharge in cubic feet per second; ft, feet]

Characteristic	Acoustic Doppler velocity meter evaluation station		
	Kankakee River at Davis	Fall Creek at Millersville	Iroquois River near Foresman
Mean discharge[a] (ft^3/s)	527	298	410
Median discharge[a] (ft^3/s)	452	127	198
Maximum discharge[a] (ft^3/s)	1,920	10,600	5,930
Discharge range[a] (ft^3/s)	1,766	10,592	5,924
Peak stage (ft)	13.79	13.53	21.0
Stage range[b] (ft)	8.5	13.5	21.0
Channel width[c] (ft)	51	45	78
Mean channel depth[c] (ft)	5.5	1.7	6.0

[a]Applies to mean daily discharges for period of record.

[b]Refers to instantaneous stages for the period of record; the stage range is approximate because of changes in streamflow-gage datum or channel geometry over time.

[c]At location of acoustic Doppler velocity meter measurement section, at median discharge.

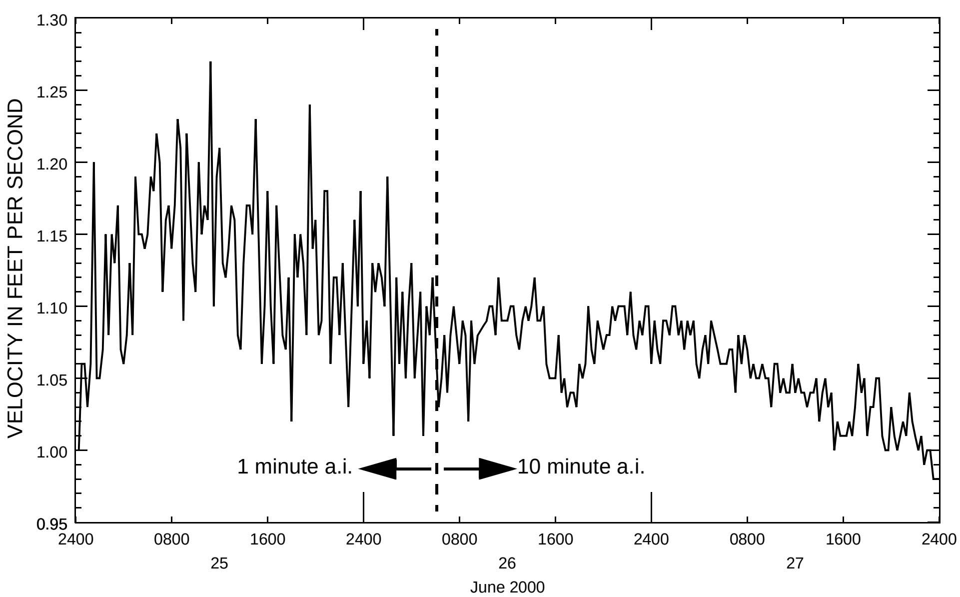

Figure 8. Acoustic Doppler velocity meter (ADVM) velocity unit values showing the effect of increasing the ADVM averaging interval (a.i.) from 1 to 10 minutes, from the Iroquois River near Foresman, Ind., ADVM evaluation station, June 25–27, 2000.

RATING DEVELOPMENT

For each of the three study stations, stage-area and index velocity ratings were created. The stage-area ratings were created so channel area could be computed from stage data; the index velocity ratings were created so mean velocities could be computed from ADVM velocity data.

Stage-Area Ratings

A stage-area rating was developed for each station. The same method was used to create ratings for the three study stations. First, the channel (and surrounding flood plain, if applicable) was surveyed and a surveyed cross section was derived. Next, a standard cross section was developed from the surveyed cross section (the standard cross section approximates the surveyed cross section and has a simpler geometric shape to facilitate computation of channel area from stage). Elevations for the standard cross sections are in terms of stage referenced to the station datums. The creation of stage-area ratings is discussed below for each of the study stations.

Kankakee River at Davis

The stage-area rating was developed by first surveying the channel at the upstream side of a railroad bridge that is about 100 ft downstream from the ADVM. This location was selected because the channel was uniform in depth and geometry. The channel was surveyed with an ADCP deployed from a boat to collect depth data as the boat traversed the channel. The channel was surveyed between the two railroad-bridge piers. The surveyed cross section had an irregular bottom and nearly vertical sides (fig. 9). The standard cross section for this station was rectangular, with a depth of 18 ft and width of 51 ft. Because the standard cross section had nearly vertical sides, a linear equation to relate stage and channel area could be developed. The slope of the equation (stage multiplier) is 50 and the y-intercept is –142.

ADAPS allows stage-area ratings to be created using either equations or tables. The ADAPS equation for stage-area ratings is

$$OUTPUT = A + B(INPUT)^{C} \tag{4}$$

where,

OUTPUT is channel area in square feet,
A is a constant,
B is a multiplier,
INPUT is the unit-value stage in feet, and
C is a power coefficient.

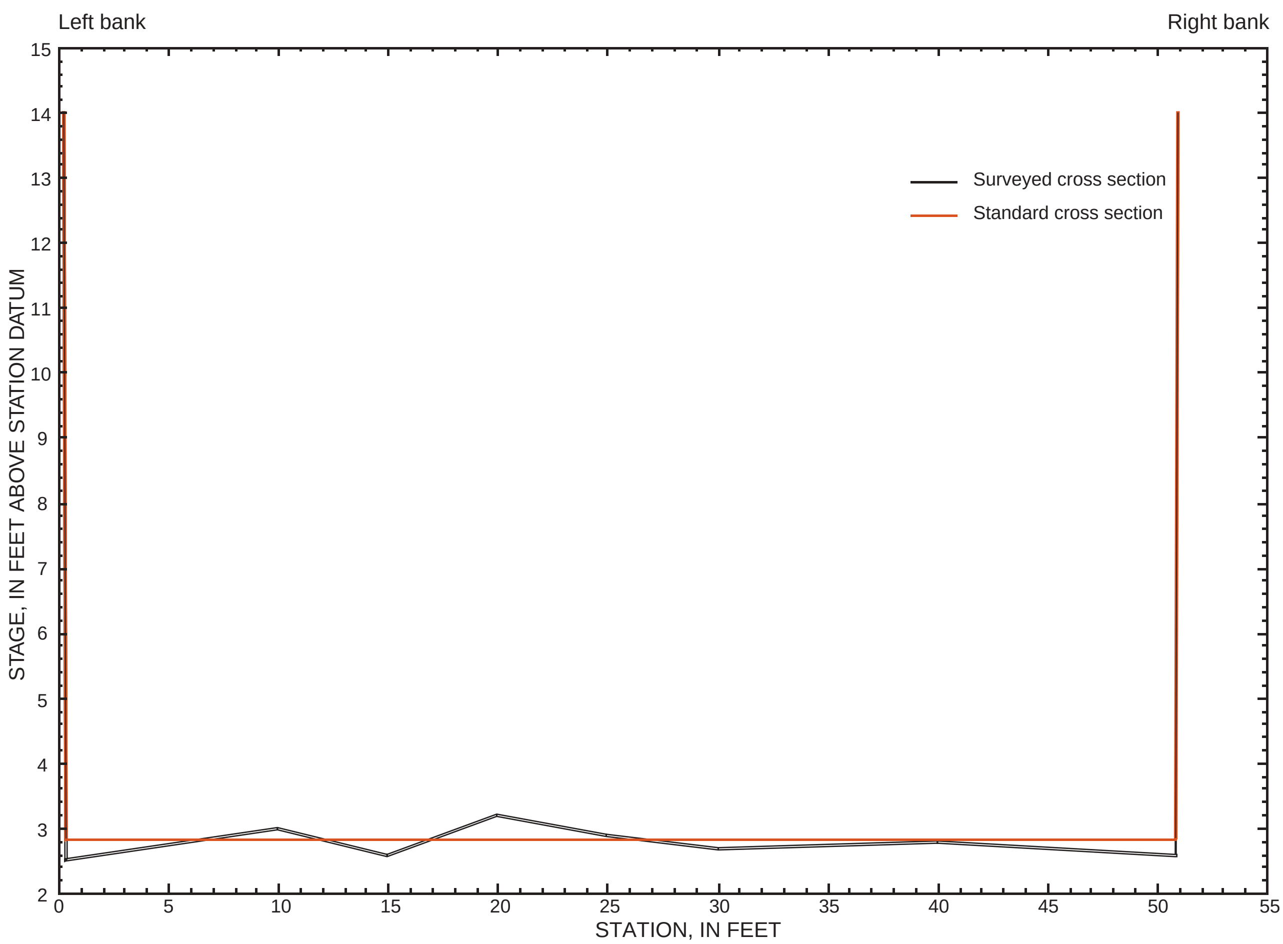

Figure 9. Surveyed and standard cross sections at Kankakee River at Davis, Ind., acoustic Doppler velocity meter evaluation station.

The ADAPS stage-area rating representing the linear stage-area rating for this station is

$$OUTPUT = -142 + 50(INPUT)^1$$

(Note: C = 1 because the rating is a linear equation)

For every stage-unit value, ADAPS outputs the computed-channel area to be used for computation of discharge.

Fall Creek at Millersville

The stage-area rating was developed by first surveying the cross section at the downstream side of the bridge where the ADVM was attached. The cross section consisted of a main channel in which low to medium flows were contained; at higher stages and flows, the water would spread into flood-plain areas on either side of the main channel. The cross-section survey was completed by using a surveyor's level gun to compute elevations and a tagline for distance measurement. The resulting surveyed cross section had an irregular bottom and sloping sides; from this surveyed cross section, the standard cross section was developed (fig. 10).

Because the geometry of the standard cross section was more complex than a rectangular section, a single equation in ADAPS could not be used for a stage-area rating. Instead, the following procedure was used. The standard cross section was divided into rectangular and triangular subsections. For a given stage value, the area of the standard cross section then could be computed by first computing the areas of the appropriate subsections, then summing the subsection areas. This approach was used in a computer spreadsheet program to compute a table of areas from stages for a stage range from 0 to 17.5 ft (table 3). The table of

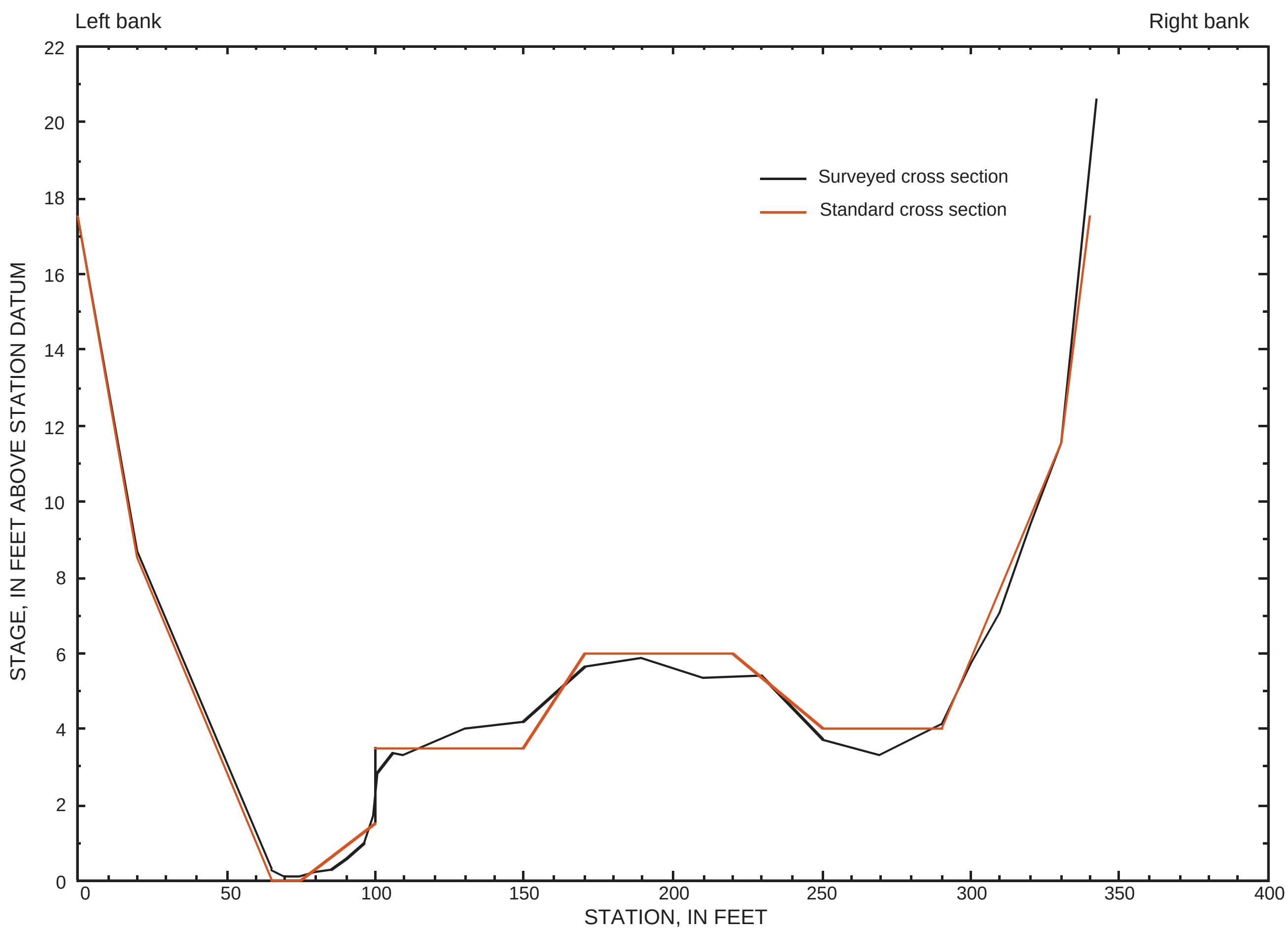

Figure 10. Surveyed and standard cross sections at Fall Creek at Millersville, Ind., acoustic Doppler velocity meter evaluation station.

Table 3. Stages and computed channel areas used to create a tabular stage-area rating for the Fall Creek at Millersville, Ind., acoustic Doppler velocity meter evaluation station

[ft, feet; ft^2, square feet]

Stage (ft)	Channel area (ft^2)	Stage (ft)	Channel area (ft^2)	Stage (ft)	Channel area (ft^2)	Stage (ft)	Channel area (ft^2)
0.00	0	2.00	61.9	5.50	453	11.50	2,175
.50	7.8	2.50	85.4	6.00	558	12.50	2,493
.75	13.7	3.00	110	6.50	693	13.50	2,816
1.00	21.0	3.50	136	7.50	971	14.50	3,142
1.25	29.7	4.00	190	8.50	1,259	15.50	3,472
1.50	39.8	4.50	269	9.50	1,557	16.50	3,806
1.75	50.7	5.00	357	10.50	1,862	17.50	4,144

stages and areas was entered into ADAPS, creating a tabular stage-area rating. For stage values between stages entered in the table, ADAPS performs a linear interpolation to compute channel area. Thus, for any stage value, ADAPS can compute the associated channel area.

Iroquois River near Foresman

The stage-area rating was developed by first surveying the cross section at the downstream side of the bridge where the ADVM was attached. The cross section was a trapezoid in which all flows were contained. The cross-section survey was completed using a steel measurement tape referenced to the low chord of the bridge to measure elevations and a steel tape for distance measurement. The resulting surveyed cross section had an irregular bottom and sloping sides; from this surveyed cross section, the standard cross section was developed (fig. 11). Because the geometry of the standard cross section was more complex than a rectangular section, the same approach described for Fall Creek at Millersville was used to compute a table of areas developed from stages for a stage range of 2 to 24 ft (table 4). The table of stages and areas was entered into ADAPS, creating a tabular stage-area rating. For stage values between stages entered in the table, ADAPS performs a linear interpolation to compute channel area. Thus, for any stage value, ADAPS can compute the associated channel area.

Index Velocity Ratings

An index velocity rating represents the relation between ADVM and mean velocity, so that mean velocities can be computed from the ADVM velocities recorded at a station. The mean velocities computed with the index velocity rating can be multiplied by channel area to compute discharge unit values.

To develop index velocity ratings, concurrent ADVM and mean velocities needed to be collected. The data-collection process included the following steps:

1. Measurements of discharge were made using mechanical, rotating-cup current meters or ADCP’s.
2. For each discharge measurement, the average stage during the measurement period was used to compute channel area at the ADVM standard cross section, using the stage-area rating.
3. The mean velocity in the standard cross section was computed by dividing the measurement discharge by the channel area computed in step 2.
4. ADVM velocity unit values were logged by the EDL during the discharge measurement. When referring to the construction of index velocity ratings, the ADVM velocity becomes the average of ADVM velocity unit values recorded during the discharge-measurement period.

Every measurement of discharge yields a mean velocity and an ADVM velocity. The relation between ADVM velocity and mean velocity can be expected to vary with discharge and possibly also stage. Thus,

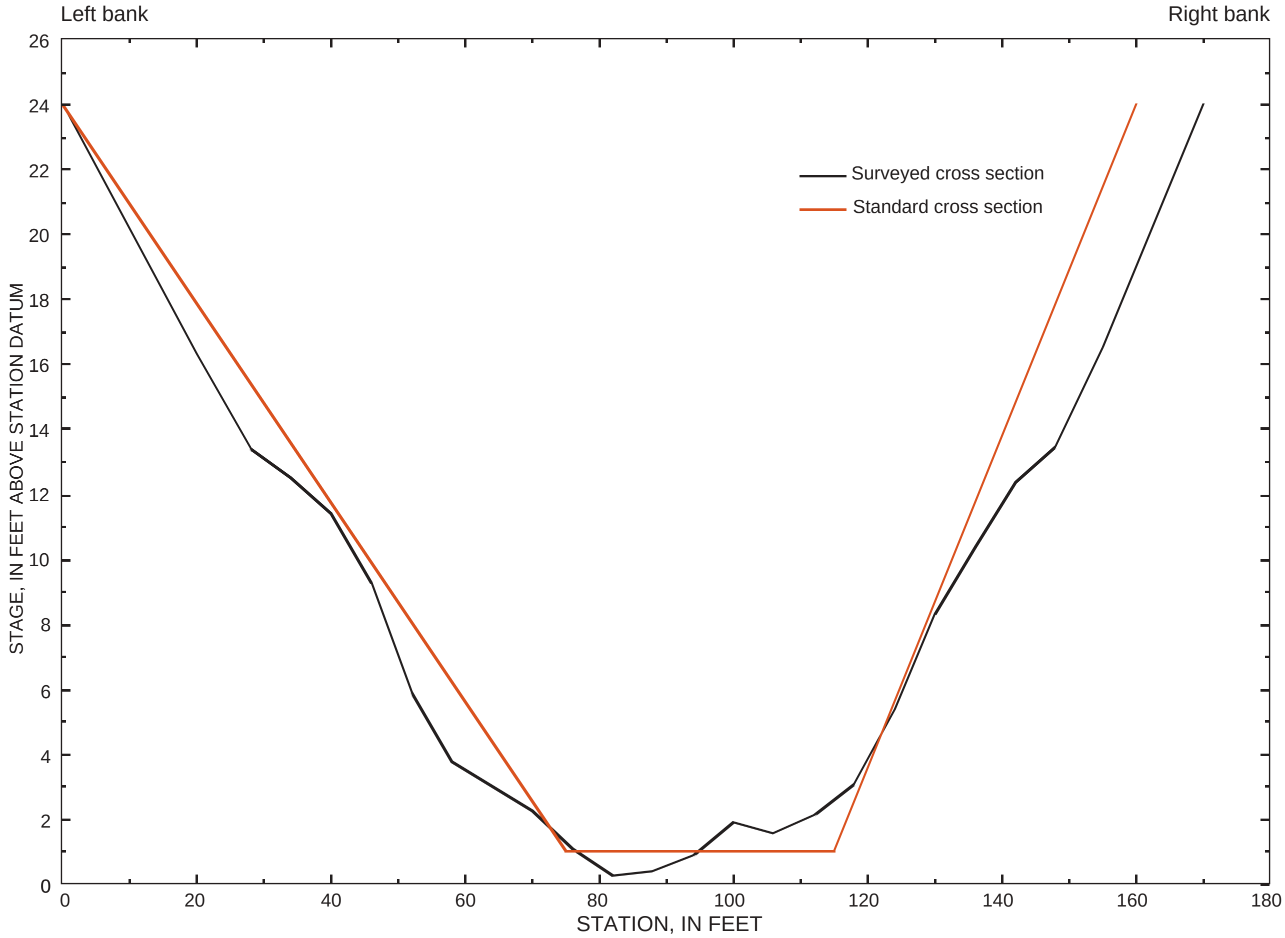

Figure 11. Surveyed and standard cross sections at Iroquois River near Foresman, Ind., acoustic Doppler velocity meter evaluation station.

multiple measurements of discharge for a range of discharges and stages are required to develop an index velocity rating.

Common practice in developing index velocity ratings for AVM's is to plot the mean velocity and AVM-measured velocities from a series of measurements on an x-y plot, where the y-axis represents mean velocity and the x-axis represents AVM velocity. The plot is the start of the analysis of the relation between mean velocity and AVM velocity. The same approach can be used for ADVM's. With the plot and a knowledge of the hydraulics at the station, an index velocity relation is developed. For some stations, the relation may be linear. For others, the relation may best be described as curvilinear or as a compound curve.

The index velocity ratings for the three index-velocity stations were represented by a linear relation. If the relation between mean velocity and ADVM velocity is linear, it can be defined by a linear equation

$$\overline{V} = XV_i + C \qquad (5)$$

where,

$\overline{V}$ is the computed mean channel velocity,

V_i is the index velocity measured by the ADVM,

X is the slope of the line defined in equation 5, commonly called a velocity coefficient, and

C is the y-intercept of the line defined in equation 5, and is commonly referred to as the "constant" of the line.

If mean velocity is found to be equal or nearly equal to ADVM velocity under all flow conditions, equation 5 could be reduced to $\overline{V} = V_i$ (X=1 and C=0). This relation would be possible if the ADVM sample volume covered a large part of the horizontal distance across the channel and if the ADVM sample volume were located at a position in the vertical that represented the mean vertical velocity. This relation occurs at about 60 percent of the total depth of a channel in

Table 4. Stages and computed channel areas used to create a tabular stage-area rating in ADAPS for Iroquois River, Ind., ADVM evaluation station

[ft, feet; ft^2, square feet, --, no data available]

Stage (ft)	Channel area (ft^2)	Stage (ft)	Channel area (ft^2)	Stage (ft)	Channel area (ft^2)
2	43	10	587	18	1,490
3	91	11	680	19	1,628
4	145	12	779	20	1,772
5	205	13	884	21	1,921
6	270	14	994	22	2,076
7	341	15	1,109	23	2,237
8	417	16	1,231	24	2,403
9	499	17	1,358	--	--

many streams and rivers. In most instances, including the installations described in this report, mean velocity would not equal ADVM velocity under all flow conditions because only a fraction of the horizontal channel distance usually is measured and because changing stage affects the relation of ADVM velocity to mean vertical velocity.

If a plot of mean velocity and ADVM velocity indicates a linear relation, various tools are available to derive equation 5. One tool would be to draw a line "by eye" to fit the data points; two points from the line then can be used to compute equation 5. A second tool would be to perform a least-squares linear regression to fit the data.

A linear regression is a method of producing a straight line that can be used to compute a quantity, called the dependent variable ("mean velocity" in this discussion) from a second known quantity, called the independent variable (ADVM velocity). The method takes all of the observations (mean velocity and ADVM velocity) into account and produces a line so that sum of the squares of the departure of mean velocity from the line will be as small as possible. This line is the best fit for the data because it gives computed values of mean velocity that come as near as possible to agreeing with all of the values of observed mean velocity (Ezekial and Fox, 1959).

The linear regression method has advantages over drawing the line by eye. Drawing the line by eye introduces subjectivity in that different persons could have different line fits. The least-squares method of linear regression is a formal, computational method of fitting a line to data, and it eliminates the subjectivity of drawing a line by eye. A linear regression produces tools that can be used to assess how well the equation derived from the linear regression fits the data.

Riggs (1968) gives four assumptions required for linear regressions:

1. The deviations of the dependent variable (mean velocity) about the regression line are normally distributed;
2. Values of the independent variable (ADVM velocity) are known without error;
3. Observed values of the dependent variable (mean velocity) are uncorrelated random events; and
4. Individual variables are homogeneous (for example, all values of the independent variable are ADVM velocity, measured in the same way and in the same units).

Assumption 2 cannot be met perfectly because ADVM measurements of velocity will have errors, including instrument errors and environmental errors. Any instrument that measures a physical quantity will have errors associated with the measurement. For the purposes of creating an index velocity rating, it is assumed that ADVM velocity is known with a level of accuracy sufficient to compute mean channel velocities.

A linear-regression analysis provides three tools that can be used to assess the quality of the fit of the regression-derived equation:

1. Coefficient of determination (r^2)—r^2 indicates what proportion of the variance in the dependent variable can be explained by variation in the indepen-

dent variable. An r^2 of 1 indicates that all of the variance in the dependent variable is explained by the variance of the independent variable. In the case of mean velocity and ADVM velocity, for example, an r^2 of 0.97 indicates that 97 percent of the variation in mean velocity can be explained by the variation of ADVM velocity. Lower values of r^2 may indicate that factors other than ADVM velocity (such as stage) may have a significant effect on the accurate prediction of mean velocity.

2. Standard error of estimate—this parameter is a measure of how nearly the values of the dependent variable computed by the regression line agree with observed values (Ezekial and Fox, 1959). The standard error is in the same units as the dependent variable and can be compared to values of the dependent variable.
3. Residual plots—a residual is the difference between an observed sample of the dependant variable and the value computed by the regression equation. In a residual plot, residuals are plotted on the y-axis with the independent variable on the x-axis. For a valid regression, the plot of residuals should be a random array of points with no discernible pattern. Residual plots can be used to help find regression errors such as nonlinearity, nonconstant variances, and outliers (a residual much larger than the others).

The basic premises for applying equation 5 are (a) that mean velocity can be computed from ADVM velocity; (b) that the changes in mean velocity can be computed by changes in ADVM velocity as defined by the slope of the equation line; and (c) that ADVM velocity is the only parameter to consider when developing an index velocity rating.

Patino and Ockerman (1997) and Patino, Hittle, and Zucker (2001) found that for some AVM stations, stage was a significant parameter in the prediction of mean velocity from AVM-measured velocity. Patino, Hittle, and Zucker give an equation relating both AVM velocity and stage to mean channel velocity that can also be applied to ADVM's:

$$\overline{V} = V_i(X + YH) + C, \qquad (6)$$

where,

$\overline{V}$ is the computed mean velocity,

V_i is the velocity measured by the ADVM,

X is the velocity coefficient,

Y is the stage coefficient,

H is stage, and

C is the constant.

Equation 6 represents a situation where the slope or coefficient that relates ADVM to mean velocity varies with stage. Equation 6 can be arrived at by performing a multiple linear regression, where the dependent variable is mean velocity and the independent variables are V_i and the product of V_i X H.

The tools of assessing the fit of an equation based upon a multiple linear regression are similar to those discussed for a single-parameter linear regression. In the case of a multiple linear regression, r^2 is the coefficient of determination and indicates what proportion of the variance in the dependent variable can be explained by variations in the independent variables. The standard error for a multiple linear regression is a measure of the departure of computed values from the measured values of the independent variable. Two residual plots can be produced from a multiple linear regression, where the departure of computed values from measured values of the dependent variable are plotted separately against each of the independent variables.

Equation 5, the equation for relating mean velocity to ADVM velocity only, may be seen as a form of equation 6: when the *YH* or stage term in equation 6 is zero (stage is not a significant factor in predicting mean velocity from ADVM velocity), equation 6 takes the form of equation 5. Thus, equation 6 can be thought of as a general linear equation for developing an ADVM index velocity rating.

Equation 6 was the basis of index velocity-rating development for the three ADVM evaluation stations. Development of the ratings for each station is described in detail below for each station.

Kankakee River at Davis

Twelve discharge measurements, 623 to 634, were made during the study period (June 1, 1999–February 28, 2001) at the Kankakee River evaluation station (table 5). Eleven of the measurements could be used to construct an index velocity rating (the ADVM velocities were not recorded by the EDL during measurement 624). For the 11 measurements, the mean stages during the measurement periods (referred to as measurement stages hereinafter) ranged from 6.18 to 11.77 ft, whereas measurement discharges

Table 5. Summary of discharge-measurement data from the Kankakee River at Davis, Ind., acoustic Doppler velocity meter evaluation station, June 30, 1999–February 27, 2001

[ft, feet; ft^3/s; cubic feet per second; ft/s, feet per second]

Discharge measurement					
Number	Date	Rated	Stage (ft)	Discharge (ft^3/s)	Mean velocity (ft/s)
623	06/30/99	Poor	7.59	488	2.05
624	09/02/99	Fair	5.92	222	1.44
625	10/04/99	Fair	6.55	317	1.71
626	12/06/99	Good	7.22	404	1.84
627	02/07/00	Fair	6.37	306	1.73
628	02/29/00	Good	8.54	662	2.32
629	04/10/00	Fair	7.20	440	2.02
630	06/19/00	Poor	8.02	644	2.49
631	08/14/00	Fair	6.20	301	1.79
632	10/02/00	Poor	6.18	318	1.90
633	02/05/01	Fair	7.50	502	2.15
634	02/27/01	Good	11.77	1,410	3.16

ranged from 301 to 1,410 ft^3/s. Mean velocities computed from the measurements ranged from 1.71 to 3.16 ft/s.

The Argonaut-SL-computed velocity vector (eq. 1) was selected as the velocity parameter from which to compute discharge and became the ADVM velocity for which index velocity ratings were developed.

Excluding 624, the first four measurements of the study period indicated that the index velocity rating within the range of stages (6.37 to 7.59 ft) and discharges (306 to 488 ft^3/s) of the measurements could be expressed by the equation $\overline{V} = 1.06V_i$. A subsequent measurement with a stage of 8.54 ft and discharge of 662 ft^3/s departed from this equation. The departure was attributed to a change in the relation of mean velocity to ADVM velocity caused by stage change. Further measurements throughout the study period, particularly the last measurement (634), confirmed this assumption; the stage for this measurement, 11.77 ft, was higher than the other measurement stages (the peak stage for the period of record is 12.79 ft).

Each discharge measurement had an associated quality rating of either "good," "fair," or "poor." Discharge measurements made by the USGS are given a rating of excellent, good, fair, or poor by the personnel who made the measurements. A rating of "excellent" means that the measurement would depart no more than 2 percent from the true discharge (a measurement error not greater than 2 percent). A rating of "good" is judged to depart no more than 5 percent from the true discharge; "fair," by 8 percent: and "poor," by more than 8 percent (Sauer and Meyer, 1992). Criteria used to judge the quality of a measurement include measurement technique (for example, how many velocity samples were taken across the channel) and environmental characteristics (such as turbulence). When creating a rating, it is possible to give more importance (weight) to measurements rated "good," followed by "fair," then by "poor." Plots of the data could indicate whether or not the weighting of measurements by quality was necessary for rating development.

A plot of mean and ADVM velocity from the 11 discharge measurements made during the study period (fig. 12) indicated that a line using ADVM velocity for an index velocity rating would not be a good fit of the data. A linear-regression analysis of mean and ADVM velocities from the 11 measurements yielded an r^2 of 0.87, indicating that 13 percent of the variation in mean channel velocities could not be explained by the variation in ADVM velocities. The standard error from the regression was 0.16 ft/s; which is 7.5 percent of the average of the mean velocities (2.11 ft/s) computed from the 11 measurements used in the regression analysis. The data from all discharge measurements were weighted equally in the regression.

It was assumed that, in addition to ADVM velocity, stage was a factor in computing mean velocity. A multiple linear regression was performed with ADVM velocity and the product of stage and ADVM velocity as the independent variables. The data from all discharge measurements were weighted equally in the regression analysis. The regression yields the equation:

$$\overline{V} = V_i(0.521 + 0.073H) + 0.102 \qquad (7)$$

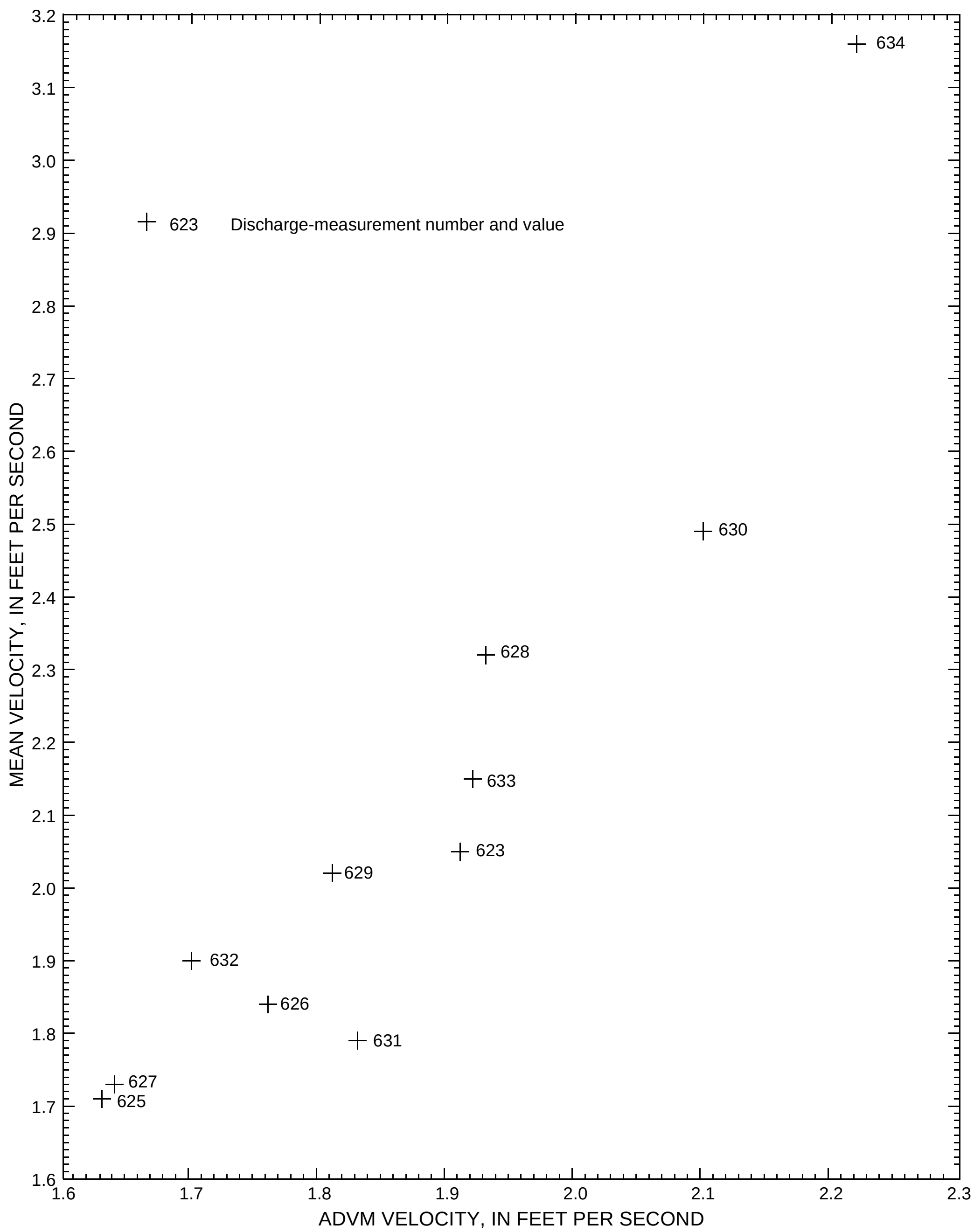

Figure 12. Mean velocity and acoustic Doppler velocity meter (ADVM) velocities from discharge measurements made at the Kankakee River at Davis, Ind., ADVM evaluation station.

The r^2 for the regression was 0.97, and the standard error was 0.08 ft/s, which is 3.8 percent of the average of the mean velocities computed from the 11 measurement used in the regression analysis.

ADAPS has two rating types that can be used for index velocity ratings: the deflection/velocity rating and the stage-velocity factor rating. For either of these options, an equation can be entered that uses the same form as that discussed for the Kankakee River at Davis stage-area rating (eq. 4). In review, equation 4 is given as:

$$\text{OUTPUT} = A + B(\text{INPUT})^C.$$

The input unit value would be velocity for the deflection-velocity rating and stage for the stage-velocity factor rating. The output in both cases would be mean channel velocity. Equation 4 ($\overline{V} = XV_i + C$) can be entered as deflection/velocity rating, with the input as ADVM velocity, A as the constant (C), B as the velocity coefficient (X), and C as 1 because equation 4 is linear.

An equation that computes mean velocity from a single parameter can be entered into ADAPS (equation 7 cannot be entered because as of this writing, ADAPS does not support multiple-parameter equation ratings). It would be possible to compute the mean velocity from equation 7 outside ADAPS, then import the mean channel velocities to ADAPS for discharge computation. This computation would involve writing a custom program to operate on ADVM data outside of ADAPS. Alternatively, it is possible for some EDL's to be programmed to compute mean velocity using equation 7, then store and transmit the computed mean velocity.

A criterion of this study was that ADAPS would be used to produce discharge records from ADVM data. Therefore, ratings were created to approximate equation 6. An approximation of equation 7 is given as

$$V = (0.521 + 0.073H)(V_i + 0.102). \qquad (8)$$

Equation 8 is not mathematically equivalent to equation 7—in equation 7, V_i is multiplied by the quantity ($0.521 + 0.073H$), then the constant 0.102 is added; in equation 8, 0.102 is first added to V_i then this quantity is multiplied by (0.521 + 0.073). Mean velocities computed from the ADVM velocities and stages associated with the 11 discharge measurements using equation 8 are within 0.6 percent of mean velocities computed using equation 7. One exception is measurement 634, where mean velocities departed by 1.2 percent. Because mean velocities computed using equation 8 compare closely with mean velocities computed using equation 7, equation 8 can be represented by equation ratings in ADAPS.

Equation 8 is represented in ADAPS, using a deflection/velocity rating and a stage-velocity factor rating. The quantity ($0.521 + 0.073H$) is represented by a stage-factor correction rating:

$$\text{OUTPUT} = 0.521 + 0.073(\text{INPUT})^1 \qquad (9)$$

where,
INPUT is unit value stage.

The quantity ($V_i + 0.102$) is represented by the deflection/velocity rating

$$\text{OUTPUT} = 0.102 + 1.0(\text{INPUT})^1 \qquad (10)$$

where,
INPUT is unit value ADVM velocity.

ADAPS multiplies the outputs of ratings (9) and (10) to compute mean velocity. For each unit value of stage and ADVM velocity, ADAPS computes and stores a computed mean velocity unit value that (when multiplied by channel area) yields a discharge unit value.

The validity of the index velocity ratings (and stage-area rating) in the range of discharge measurements that produced the rating can be evaluated by comparing discharges computed from the ADVM data, using the ratings (ADVM discharges) to the measured discharges. A factor in the comparison is the quality of the discharge measurement as assessed by the person making the measurement.

Comparison of measured to ADVM discharges for the 11 discharge measurements used to create the ratings is given in table 6. Departures of the measured discharges from ADVM discharges ranged from 0.1 to 8.0 percent. The measured discharges for all measurements (with the exception of 626) were within tolerances, as defined by the quality ratings of each measurement (5, 8, or greater than 8 percent for ratings of "good," "fair," or "poor," respectively), of the respective ADVM discharges. The measured

Table 6. Comparison of discharges computed using an acoustic Doppler velocity meter (ADVM) to measured discharges at the Kankakee River at Davis, Ind., ADVM evaluation station for June 30, 1999–February 27, 2001

[ft^3/s; cubic feet per second; ADVM, acoustic Doppler velocity meter; --, no data available]

Discharge measurement				ADVM-computed	
Number	Date	Rated	Discharge (ft^3/s)	Discharge (ft^3/s)	Discharge departure from measurement discharge (percent)
623	06/30/00	Poor	488	514	5.3
624	09/02/00	Fair	222	--	--
625	10/04/99	Fair	317	321	1.3
626	12/06/99	Good	404	427	5.8
627	02/07/00	Fair	306	303	–.9
628	02/29/00	Good	662	663	.1
629	04/10/00	Fair	440	436	–.9
630	06/19/00	Poor	644	631	–2.0
631	08/14/00	Fair	301	316	5.0
632	10/02/00	Poor	318	293	–8.0
633	02/05/01	Fair	502	503	.3
634	02/27/01	Good	1,410	1,431	1.5

discharge of measurement 626, (rated "good") departed 5.8 percent from the ADVM discharge.

It is standard USGS practice when using conventional stage-area methods to refine or make a temporary adjustment (shift) to a stage-area rating if a discharge measurement rated "good" or "fair" departs by more than 5 or 8 percent, respectively, from the rating discharge; the shift brings the measurement discharge within tolerance of the rating discharge. The departure of a single discharge measurement from the rating may indicate a shift period (Rantz, 1982). Rantz acknowledges that a person who analyzes a rating has the responsibility for explaining the hydraulics that caused the shift detected by a single measurement.

Although measurement 626 departed by more than 5 percent from the ADVM discharge, adjustments to the ratings were not made for the following reasons: (1) the measurement was made prior to August 14, 2000, when the ADVM averaging interval was changed from 1 to 10 minutes to reduce measured-velocity uncertainties, and (2) no reason was found to change the rating—all ADVM parameters, including velocities and quality parameters, were acceptable during the measurement period, and measurement data did not reveal any obvious changes to the channel geometry near the measurement section.

The measurements collectively did not reveal any biases (for example, if all measurement discharges were less than the respective rating-computed discharges). Because all of the measurements were within tolerance of the respective rating discharges (and there were justifications for not adjusting the ratings based on measurement 626), the ratings were judged to be adequate for the production of streamflow within the range of measurements and within the time period of the measurements.

Fall Creek at Millersville

Nine discharge measurements, 1255 to 1263, were made during the study period (March 23, 2000–February 28, 2001) at the Fall Creek evaluation station. Six of the measurements, 1255 to 1260, were used to develop an index velocity rating. For the six measurements, the measurement stages ranged from 1.69 to 3.11 ft (table 7), whereas measurement discharges ranged from 45.8 to 263 ft^3/s. Mean velocities computed from the measurements ranged from 0.95 to 2.27 ft/s.

Table 7. Summary of discharge-measurement data from the Fall Creek at Millersville, Ind., acoustic Doppler velocity meter (ADVM) station, March 30, 2000–August 23, 2000

[ft, feet; ft^3/s; cubic feet per second; ft/s, feet per second]

Discharge measurement					
Number	Date	Rated	Stage (ft)	Discharge (ft^3/s)	Mean velocity (ft/s)
1255	03/30/00	Good	2.27	110	1.47
1256	04/19/00	Good	2.56	164	1.86
1257	06/15/00	Good	3.11	263	2.27
1258	07/27/00	Good	2.02	84.8	1.35
1259	08/22/00	Fair	1.69	45.8	.95
1260	08/23/00	Good	1.81	59.2	1.11

The EasyQ provided an x-velocity component from each of three cells that could potentially be used as ADVM velocities for computation of discharge. Analysis of the velocity unit values from the three cells indicated that cell 3 velocities appeared to be questionable for long periods. For example, many of the cell 3 velocities were negative when all velocity values from the other two cells always were positive (velocities should have always have been positive because the flow in this region always has been observed to be downstream). Because the channel is shallow, it is possible that periodic bending of the beams cause the beams to strike the bottom within cell 3 or that sidelobe interference caused the questionable velocities. Because the velocities from cell 3 were questionable, separate index velocity ratings were developed that used the x-component velocities from cells 1 and 2 for discharge computation.

Plotting ADVM cell 1 and 2 velocities with the mean channel velocities indicated that a well-defined linear relation between ADVM and channel velocities was present within the range of stages and discharges represented by measurements 1255 to 1260 (fig. 13). As a result, the relation between ADVM-measured velocities and mean velocities for both cells could be represented by best fitting a straight line to the data.

A computer statistics program was used to perform two linear regressions, one for cell 1 and one for cell 2. For cell 1, the six mean channel velocities computed from the six discharge measurements were regressed against the corresponding cell velocities. All six measurements were weighted equally in the regression. The equation of the line developed for cell 1 is

$$\overline{V} = 1.22\ V_i + 0.39 \qquad (11)$$

The r^2 for the regression was 0.99 and the standard error was 0.05 ft/s, which is 3.4 percent of the average of the mean channel velocities (1.45 ft/s) computed from the six measurements used in the regression analysis. The r^2 of 0.99 indicated that 99 percent of the variation in mean channel velocities was accounted for in variations of the ADVM velocities. Therefore, it was assumed that within the range of discharge measurements used to produce equation 11, stage was not a factor. The residual plot from the regression analysis did not indicate nonlinearity, nonconstant variances, or large outliers. Equation 11 was found to be an adequate fit of the measurement data and became the index velocity rating for cell 1. Equation 11 is represented in ADAPS as a deflection/velocity rating:

$$\text{OUTPUT} = 0.39 + 1.22(\text{INPUT})^1 \qquad (12)$$

where,

INPUT is unit value ADVM velocity, cell 1.

The equation of the line developed for cell 2 is

$$\overline{V} = 1.40V_i + 0.05. \qquad (13)$$

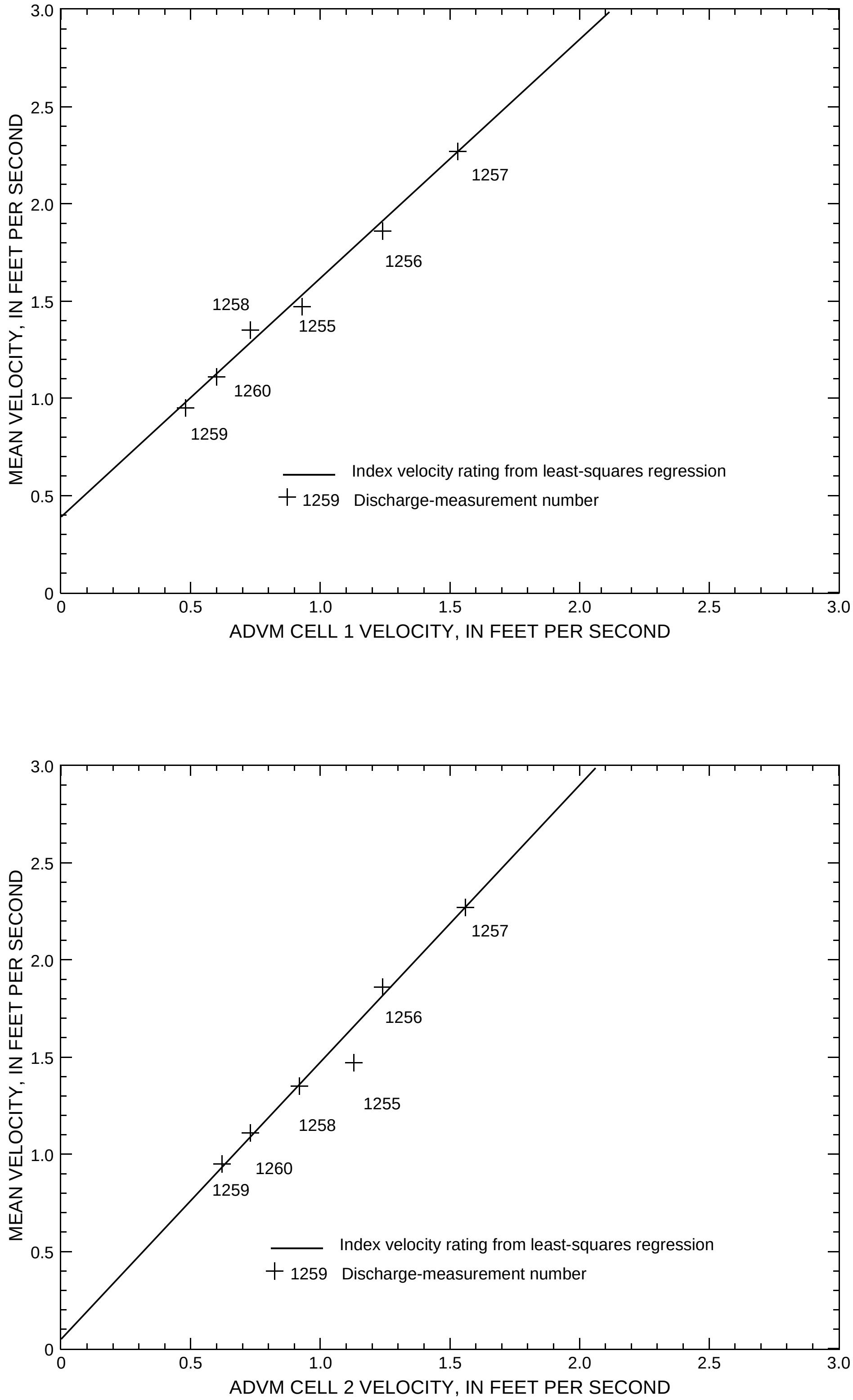

Figure 13. Index velocity ratings for cells 1 and 2 of an acoustic Doppler velocity meter (ADVM) at the ADVM evaluation station Fall Creek at Millersville, Ind.

During measurement 1255, cell 2 velocities were erratic; the maximum and minimum velocities during the period varied by more than 25 percent (the variance was less than 8 percent for cell 1). As a result, this measurement departed below the regression line of equation 13. When the measured discharges and ADVM discharges computed with equation 13 were compared, all of the ADVM discharges were lower than the measured discharges. To eliminate this bias, a new regression analysis was performed with measurements 1256 to 1260. The resulting equation of the line from the analysis is

$$\overline{V} = 1.42V_i + 0.07. \quad (14)$$

Discharges computed with equation 15 did not indicate the negative bias produced by equation 13. The r^2 for the regression was 0.97; the standard error was 0.09 ft/s, which is 6.2 percent of the average of the mean channel velocities (1.45 ft/s) computed from the six measurements used in the regression analysis. The r^2 of 0.97 indicated that 97 percent of the variation in mean channel velocities was accounted for in variations of the ADVM velocities. It was assumed that, within the range of discharge measurements used to produce equation 14, stage was not a significant factor. The residual plot from the regression analysis did not indicate nonlinearity, nonconstant variances, or large outliers. Thus, equation 14 was found to be an adequate fit of the measurement data and became the index velocity rating for cell 2. Equation 14 is represented in ADAPS as a deflection/velocity rating:

$$\text{OUTPUT} = 0.07 + 1.42(\text{INPUT})^1 \quad (15)$$

where,

INPUT is unit value ADVM velocity, cell 2.

ADAPS uses ratings 12 and 15 to compute mean velocity for cells 1 and 2, respectively. Thus, for each stage unit value and ADVM cell 1 and 2 velocity, ADAPS computes and stores a computed mean velocity unit value that, when multiplied by channel area, yields a discharge unit value for each cell. The validity of the index velocity ratings (and stage-area rating) in the range of discharge measurements that produced the rating was evaluated by comparing computed discharges to measurement discharges.

Comparison of computed to measured discharges for cells 1 and 2 for the six discharge measurements used to create the ratings is given in table 8. Also in table 8 are comparisons of computed to measured discharges for three discharge measurements (1261 to 1263) made after the ratings discussed previously were developed.

For cell 1, departures of measured discharge from ADVM discharges for measurements 1255 to 1260 ranged from less than 0.6 to 5.7 percent. Measurements 1255 to 1260 were used to create the rating, whereas measurements 1261 to 1263 were made after development of the rating. Except for numbers 1258 and 1263, the measured discharges for all measurements were within tolerances as defined by the quality ratings of each measurement (5, 8, or greater than 8 percent for ratings of “good,” “fair,” or “poor,” respectively) of the respective ADVM discharges. Measurement 1258, rated “good,” departed by 5.1 percent and measurement 1263, rated “good,” departed by 5.7 percent.

Although measurement 1258 and 1263 departed by more than 5 percent from the ADVM discharges, adjustments to the ratings were not made for the following reasons. (1) These measurements were rated “good” by the person who made the measurement, but the particular measurement section used is rocky and turbulent and the rating of measurement quality is somewhat subjective—the measurements could have been rated “fair,” in which case they would have been within tolerance (8 percent) of the respective ADVM discharges. (2) No reason to change the rating was found—all ADVM parameters, including velocities and quality parameters, were acceptable during the measurement period, and the measurement did not reveal any obvious changes to the channel geometry near the measurement section.

The measurements collectively did not reveal any biases (for example, if all measurement discharges were less than the respective rating-computed discharges). Because all measurements were within tolerance of the respective rating discharges and there were justifications for not adjusting the ratings based on measurements 1258 and 1263, the rating was judged to be adequate for the computation of streamflow records within the range of measurements and within the time period of the measurements.

For cell 2, departures of the measured from ADVM discharges for measurements 1256 to 1263 ranged from 0.0 to –32.9 percent. Excluding 1255 and

Table 8. Comparison of discharges computed using an acoustic Doppler velocity meter (ADVM) to measured discharges from the Fall Creek at Millersville, Ind., ADVM evaluation station, March 30, 2000–January 24, 2001

[ft^3/s; cubic feet per second; ADVM, acoustic Doppler velocity meter]

Discharge measurement				ADVM computed			
				Discharge (ft^3/s)		Departure from measurement discharge (percent)	
Number	Date	Rated	Discharge (ft^3/s)	Cell 1	Cell 2	Cell 1	Cell 2
1255	03/30/00	Good	110	114	125	3.7	13.9
1256	04/19/00	Good	164	168	161	2.3	–1.6
1257	06/15/00	Good	263	261	265	–.6	.7
1258	07/27/00	Good	84.8	80.4	86.5	–5.1	2.0
1259	08/22/00	Fair	45.8	47.0	45.8	2.7	0
1260	08/23/00	Good	59.2	59.8	59.0	1.1	–.3
1261	10/16/00	Good	134	137	123	2.2	–8.2
1262	12/13/00	Fair	356	354	342	–.6	–3.9
1263	01/24/01	Good	158	167	106	5.7	–32.9

with the exception of 1261 and 1263, the measured discharges were within tolerances of the respective ADVM discharges. Measurements 1261 and 1263 were made after the creation of the index velocity rating for cell 2. The measurement 1261 discharge, rated "good," departed by 8.2 percent from the ADVM discharge. Though measurement 1261 departed by more than 5 percent from the ADVM discharge, adjustments to the ratings were not made because no reason to change the rating was found. All ADVM parameters, including velocities and quality parameters appeared to be of good quality during the measurement period, and the measurement did not reveal any changes to the channel geometry near the measurement section.

Measurement 1263, made on January 24, 2001, and rated "good," departed by –32.9 percent from the ADVM discharge. The –32.9 percent departure of measurement 1263 was the result of a bias in cell 2 velocities that occurred from December 18, 2000, to February 9, 2001. The bias likely was caused by an obstruction in cell 2; the bias and measures implemented to compensate for the bias are discussed in the section "Computation of the Records." Because of the bias, the departure of measurement 1263 from the ADVM discharge is explainable and does not invalidate the rating. Because measurement 1261 was the only other measurement that departed outside the tolerance assigned by the measurement-quality rating and because measurement 1261 was made after creation of the rating, the rating was not adjusted. A continued trend in departures would justify a rating adjustment. Measurement 1262, made after 1261, was within tolerance of the rating.

The offset from equation 11 (that became the cell 1 index velocity rating) is 0.39, compared to the offset from equation 14 (that became the cell 2 index velocity rating) of 0.07. The offset for cell 1 is large compared to that for cell 2 and implies that when the ADVM measures zero velocity, some flow still is present in the channel. This larger offset could be a result of the proximity of cell 1 to the bridge pier—friction from the pier would slow down the water velocity in the pier's vicinity. Cell 2 is farther from the pier and therefore would not be affected to the extent of cell 1.

Iroquois River near Foresman

Eighteen discharge measurements, 521 to 544, were made during the study period (October 1, 2000–February 28, 2001) at the Iroquois River evaluation station. Fourteen of the measurements, 521 to 536, were used to construct an index velocity rating. Measurement 523 was not used to construct the rating because the river was ice covered when the measurement was made; measurement 527 was not used because pertinent measurement data were not available at the time the rating was created. For the 14 measurements, stages ranged from 4.23 to 12.24 ft (table 9), whereas measurement discharges ranged from 25.3 to 988 ft^3/s. Mean channel velocities computed from the measurements ranged from 0.27 to 1.48 ft/s. The Argonaut-SL x-component of velocity was used for development of the index velocity rating.

Plotting ADVM and mean velocities indicated that a well-defined linear relation between ADVM-measured velocities and mean velocities is present within the range of stages and discharges represented by measurements 521 to 536 (fig. 14). As a result, the relation between ADVM-measured velocities and mean velocities could be represented by fitting a straight line to the data.

A linear regression was performed in which the 14 mean channel velocities computed from the 14 discharge measurements were regressed against the corresponding cell velocities. All measurements were weighted equally in the analysis. The equation of the line is

$$\bar{V} = 0.97V_i - 0.10. \tag{16}$$

The r^2 for the regression was 0.98, and the standard error was 0.05 ft/s, which is 5.9 percent of the average of the mean velocities (0.85 ft/s) computed from the 14 measurements used in the regression analysis. The r^2 of 0.98 indicated that 98 percent of the variation in mean velocities was accounted for in variations of the ADVM velocities. Therefore it was assumed that, within the range of discharge measurements used to produce equation 16, stage was not a factor. The residual plot from the regression analysis did not indicate nonlinearity, nonconstant variances, or large outliers. Equation 16 was found to be an adequate fit of the measurement data and became the index velocity rating for cell 1. Equation 16 is represented in ADAPS as a deflection/velocity rating:

$$\text{OUTPUT} = -0.10 + 0.97(\text{INPUT})^1 \tag{17}$$

where,

INPUT is unit value ADVM velocity.

Table 9. Summary of discharge-measurement data from the Iroquois River near Foresman, Ind., ADVM evaluation station, October 15, 1999–June 26, 2001

[ft, feet; ft^3/s; cubic feet per second; ft/s, feet per second; --, no data available]

Discharge measurement					
Number	Date	Rated	Stage (ft)	Discharge (ft^3/s)	Mean velocity (ft/s)
521	10/15/99	Fair	4.23	25.3	0.27
522	12/16/99	Poor	5.50	94.9	.51
523	02/02/00	Fair	4.84	39.5	--
524	03/01/00	Good	8.20	318	.88
525	04/06/00	Fair	5.75	112	.63
526	04/24/00	Good	10.71	566	.88
527	05/09/00	--	6.96	203	--
528	05/10/00	Fair	10.76	717	1.31
529	05/10/00	Fair	10.92	742	1.25
530	05/11/00	Fair	11.02	698	1.15
531	05/11/00	Fair	11.00	720	1.14
532	05/11/00	Fair	10.93	645	1.10
533	05/11/00	Fair	10.87	644	1.09
534	06/07/00	Good	8.30	349	.94
535	06/21/00	Fair	11.52	988	1.48
536	06/26/00	Fair	12.24	773	1.10

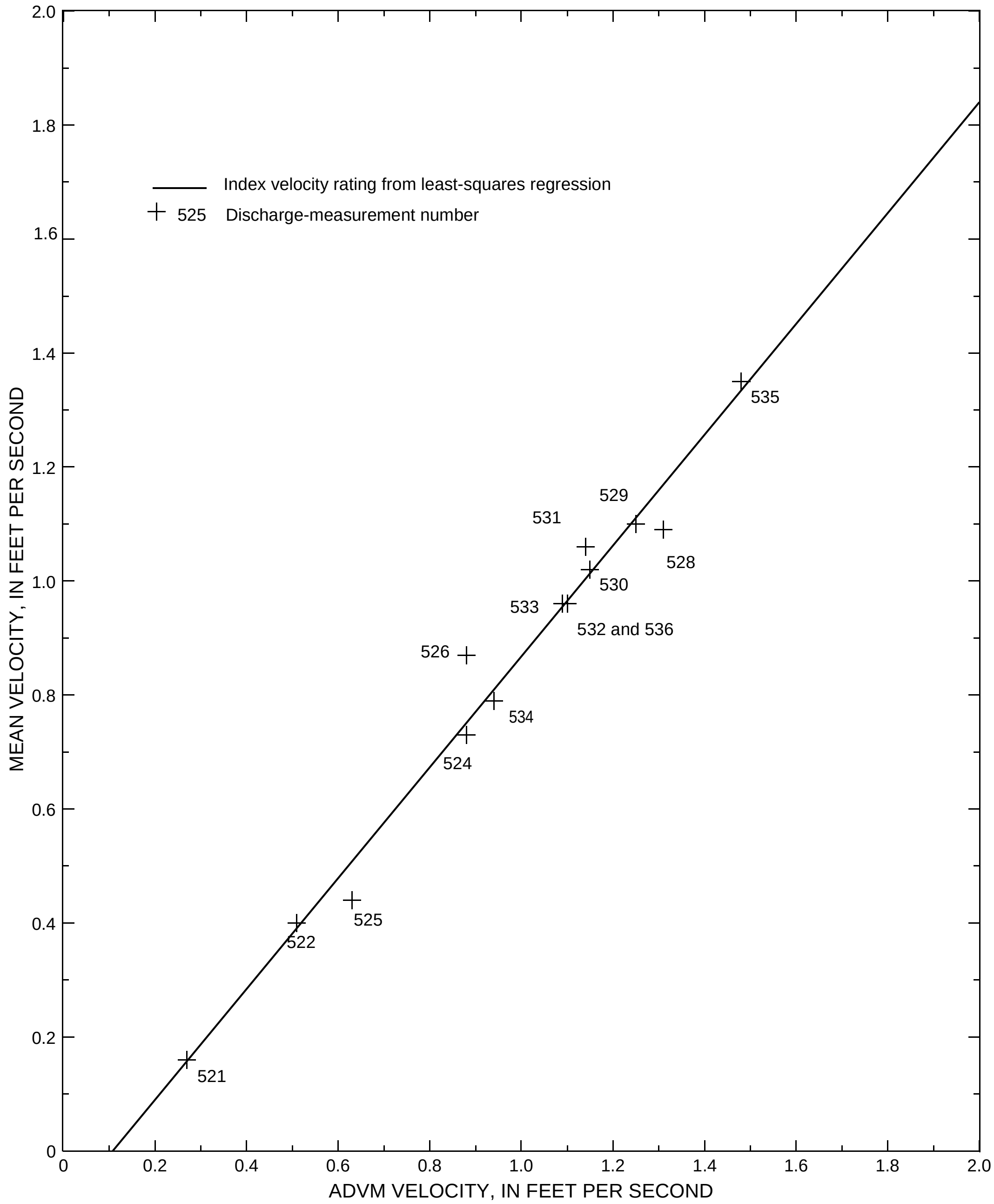

Figure 14. Index velocity rating for an acoustic Doppler velocity meter (ADVM) at the ADVM evaluation station Iroquois River near Foresman, Ind.

The output of rating 17 is mean velocity. Thus, for each ADVM velocity unit value, ADAPS computes and stores a computed mean velocity unit value that, when multiplied by channel area, yields a discharge unit value. The validity of the index velocity rating (and stage-area rating) in the range of discharge measurements that produced the rating was evaluated by comparing measured discharges to ADVM discharges.

Computed discharges and measured discharges for the 14 discharge measurements used to develop the ratings are compared in table 10. Also, measured discharges and ADVM discharges for four discharge measurements (537 to 540) made after the ratings discussed above were created are compared in table 10. Except for measurements 521, 525, and 526, all 18 discharge measurements were within tolerance of the ADVM discharges (table 10).

Table 10. Comparison of discharges computed from acoustic Doppler velocity meter (ADVM) to measured discharges from the Iroquois River near Foresman, Ind., ADVM evaluation station, October 15, 1999–February 12, 2001

[ft^3/s; cubic feet per second; ADVM, acoustic Doppler velocity meter; --, data not available]

Discharge measurement				ADVM computed	
Number	Date	Rated	Value (ft^3/s)	Discharge (ft^3/s)	Discharge departure from measurement discharge (percent)
521	10/15/99	Fair	25.3	23.0	–9.1
522	12/26/99	Poor	94.9	92.7	–2.3
523	02/02/00	Fair	39.5	--	--
524	03/01/00	Good	318	324	1.9
525	04/06/00	Fair	112	129	15.2
526	04/24/00	Good	566	494	–12.7
527	05/09/00	--	203	--	--
528	05/10/00	Fair	717	768	7.1
529	05/10/00	Fair	742	749	.9
530	05/11/00	Fair	698	694	–.6
531	05/11/00	Fair	720	684	–5.0
532	05/11/00	Fair	645	648	.5
533	05/11/00	Fair	644	649	.8
534	06/07/00	Good	349	357	2.3
535	06/21/00	Fair	988	972	–1.6
536	06/26/00	Fair	773	774	.1
537	07/12/00	Fair	1,300	1,290	–.8
538	10/13/00	Fair	36.0	37.0	2.8
539	11/15/00	Fair	121	112	–7.4
540	02/12/01	Fair	2,090	2,090	–4.3

Though measurements 521, 525, and 526 departed by more than the tolerance from the ADVM discharges, adjustments to the ratings were not made for the following reasons: (1) the measurements were made prior to June 26, 2000, when the ADVM averaging interval was changed from 1 to 10 minutes to reduce measured-velocity uncertainties; (2) no reason to change the rating was found—all ADVM parameters, including velocities and quality parameters, were acceptable during the measurement period, and the measurement did not reveal any obvious changes to the channel geometry near the measurement section.

The measurements collectively did not indicate any bias. Because all of the measurements (except 521, 525, and 526) were within tolerance of the respective ADVM discharges, and there were justifications for not adjusting the rating based on the those three measurements, the rating was judged to be adequate for the computation of discharge records within the range of measurements and within the time period of the measurements.

Ratings Applications and Limitations

Each of the ratings developed for these stations is based upon the linear relation described by equation 6. The validity of using linear equations to define the ratings was confirmed by line-fit plots and other analysis tools. In addition to application of these tools, it is necessary to examine if an index velocity rating also reflects hydraulic conditions at the station.

In the case of Kankakee River index velocity ratings, stage and ADVM velocity are parameters.

Stage is a parameter in the index velocity rating because the relation of mean to ADVM velocity changes with stage. Two velocity profiles were collected on different days within the ADVM sample volume, using an ADCP (fig. 15). The ADCP was held stationary and collected velocity data for about 1 minute; the velocity data that form each profile were averaged over the 1-minute sampling period. One profile was collected at a stage of 6.20 ft, and the second was made at a stage of 11.77 ft. The ADVM is fixed at a stage of about 4 ft. The mean velocity for the lower stage profile occurs at a depth of about 3.5 ft and the higher stage profile occurs at a depth of about 6.0 ft. This result illustrates that the ratio of ADVM-measured velocity to mean velocity changes as stage changes; from discharge measurements made on the days the profiles were collected, the ratios of mean to ADVM-measured velocities were 0.96 and 1.42, respectively, for the lower and higher stage scenarios.

Because the shapes of the lower and higher stage profiles are similar, the assumption that the effect of stage may be expressed as part of a linear equation is also reasonable. Within the range of discharge measurements used to develop the rating, the channel geometry for the Kankakee River station is constant—all flows are confined to the rectangular channel. A substantial change in channel geometry for certain flow conditions (such as when the flow spills over the channel into a flood plain) almost certainly causes a departure of the index velocity rating from a linear form. Because this change in channel geometry does not occur at the Kankakee River station, the assumption of linearity in the index velocity rating is supported further.

In the case of Iroquois River index velocity rating, ADVM velocity is the only parameter. The assumption that stage is not a necessary parameter for the Iroquois River station within the range of discharge measurements used to create the rating also can be made by examining a velocity profile from the station. The previously discussed higher stage profile from the Kankakee River and a higher stage profile collected from the Iroquois River station are compared in figure 15. The Iroquois River profile has less curvature than the Kankakee River profile; the velocity varies by no more than 0.15 ft/s (the mean channel velocity is about 2.3 ft/s) from a stage of 13.99 to 5.79 ft. The reason is that the Kankakee River channel bottom is rougher (composed of rock and gravel) than the Iroquois River channel bottom (composed of silt). Increased channel roughness causes the curvature of the velocity profile to increase (Chow, 1959). Because of the smooth bottom, the lack of curvature of much of the velocity profile at the Iroquois River station can mean that the relation of mean velocity to ADVM velocity will remain relatively constant regardless of changing stage; this result supports the assumption that stage is not a factor in the creation of an index velocity rating. The assumption of the linear relation between mean velocity and ADVM velocity is supported by the fact that the channel geometry remains constant over the range of discharges used to create the index velocity rating.

ADVM velocity is the only parameter for the Fall Creek at Millersville index velocity rating. Because of the shallow depth during discharge measurements, velocity profiles were not collected during the study period. Because the stream has a rocky bottom, however, velocity profiles likely would resemble those from the Kankakee River, indicating that stage also likely would be a factor. Stage is not a factor for the rating created from the range of discharge measurements because the total range of stage represented by the rating is 1.46 ft. This range means that the position change in the vertical of mean velocity to ADVM velocity is not great enough to alter the relation between mean and ADVM velocity.

The linearity of the ratings represented in this study does not indicate that all index velocity ratings for all stations would be linear. For many stations, a curvilinear rating (or a rating represented by various curves) would be more appropriate. To produce accurate discharge records, a rating should represent the hydraulics at the station and be confirmable by comparisons of rating-computed discharges to measured discharges. Thus, ratings must be developed on a case-by-case basis.

The range of measurement discharges and stages used to develop the index velocity ratings for each of the stations is less than the range of discharges and stages that historically have occurred at the stations. For example, the range of measured discharges for Kankakee River at Davis was 301 to 1,410 ft^3/s, or 1,109 ft^3/s (table 6). The range of mean daily discharges for the period of record is 1,766 ft^3/s; thus, the range of discharges from measurements used to construct the index velocity rating is about 62 percent of the historical range of mean daily discharges at the station. For Fall Creek at Millersville and Iroquois River near Foresman, the range of

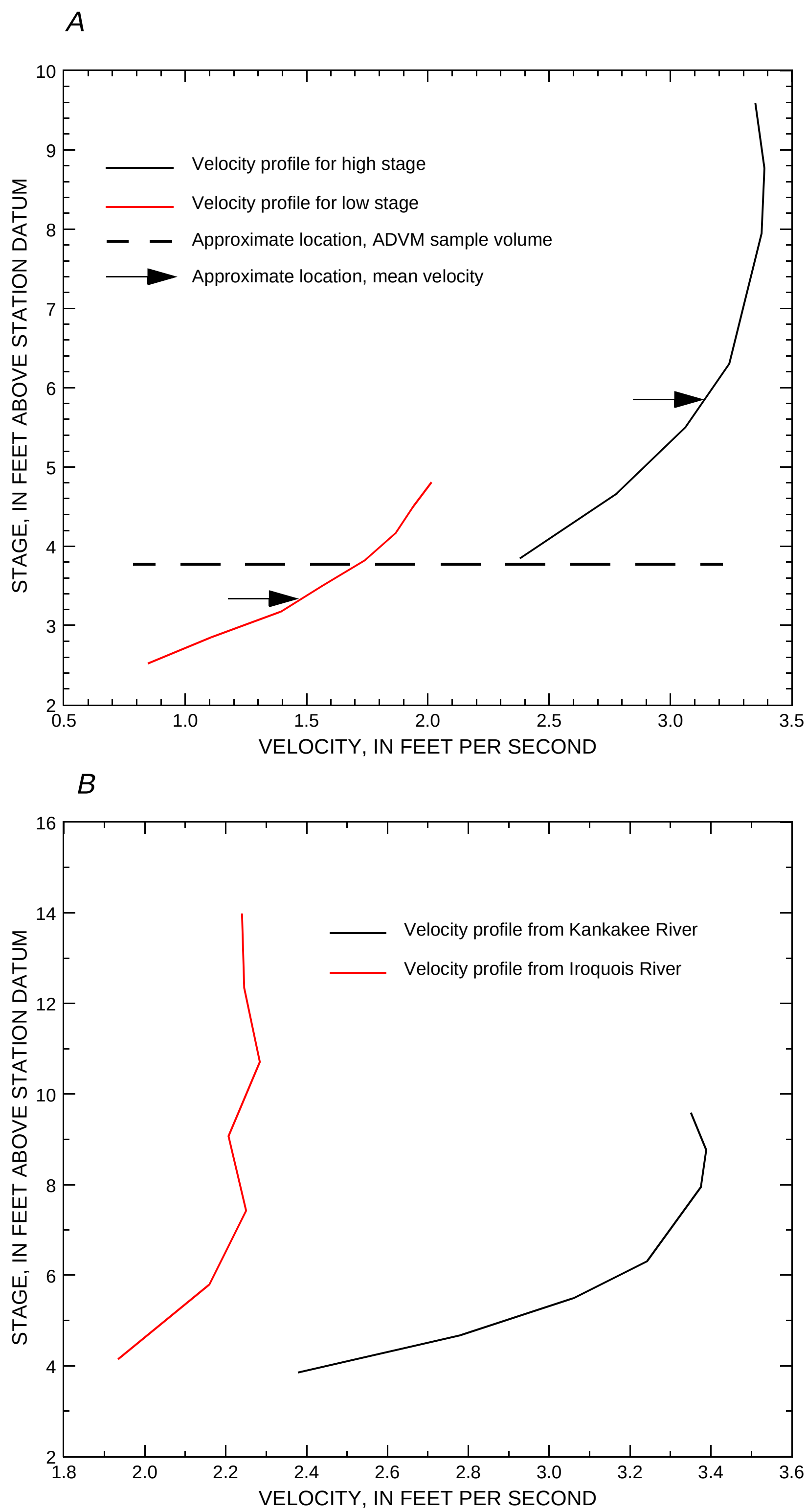

Figure 15. Velocity profiles from (*A*) the Kankakee River at Davis, Ind., acoustic Doppler velocity meter (ADVM) evaluation station, for profiles collected at high and low stages, and (*B*) the Iroquois River near Foresman, Ind., and Kankakee River at Davis, Ind., ADVM evaluation station.

measurement discharges used to construct the index velocity ratings was 2 and 38 percent, respectively, of the historical range of mean daily discharges at the stations. This result means that the index velocity ratings described in this report will be used to compute discharge records for discharge values outside the range of each rating.

Based on analysis tools and comparison of measured discharge and rating discharges, the ratings for all three stations appear to be valid within the range of measurements made during the study period; this result does not mean the ratings will remain valid outside the range of stages and discharges of the measurements that were used to develop the ratings. For the ratings to remain valid, the relations defined by the ratings must remain stable. Each station must be examined for assumptions to be made about the validity of the ratings beyond the range of the measurements used to develop the ratings.

For Kankakee River at Davis, the measurements appear valid for 62 percent of the historical flow range. Because the range of flows would be confined to the channel at the ADVM measurement section, it is reasonable to expect the ratings to remain valid outside the range of measurements.

The Iroquois River rating may remain valid outside the measurements used to create it. The range of flows would be confined to the channel, so it is reasonable to assume that the change in mean channel velocity would remain linear with the change in ADVM-measured velocity. This assumption was tested by measurement 540, made after creation of the rating and with a greater discharge (2,090 ft^3/s) than the maximum measurement used to create the rating (988 ft^3/s). The measurement was within tolerance of the rating discharges. While it is reasonable to assume that the ratings for Kankakee River at Davis and Iroquois River near Foresman will remain stable outside the range of measurements used to create the rating, the only way to confirm this assumption is to continue to make discharge measurements outside the range of the ratings.

For Fall Creek, the rating would not be expected to remain valid for all stage and discharge ranges. The ratings for cells 1 and 2 assume a linear relation between mean velocity and ADVM velocity; as previously discussed, these relations appear valid within the range of discharge measurements used to create the ratings. The linear relation between mean velocity and ADVM velocity may remain linear when most of the discharge is contained within the main channel—field experience indicates that most of the discharge is contained within the main channel below a stage of about 6 ft and discharge of about 1,600 ft^3/s. Above 6 ft, flows will begin to occur in the flood plain (fig. 6) and the relation between mean velocity and ADVM velocity is likely to depart from the linear relation defined by the index velocity ratings described in this report. Flows in the flood plain mean that a small change in stage represents a larger change in area than an equivalent stage change with flow confined to the channel, equating to a larger change in channel area and a lower change in mean velocity. The ADVM still would be measuring in the main channel, so the relation of change in mean velocity to ADVM velocity likely would depart from the relation seen in the main channel.

During the period of record, mean daily discharges from the Fall Creek station were below 1,600 ft^3/s about 97 percent of the time; therefore, flows usually are confined to the channel (where the index velocity rating is valid). Peak discharges are important; it will be necessary to make discharge measurements at flows above 1,600 ft^3/s to define the rating so that higher flows may be accurately computed. Because the rating shape likely would depart from a straight line above about 1,600 ft^3/s, a rating to reflect the departure would be a compound rating consisting of the current linear relation for flows restricted to the channel and the relation(s) defined by measurements for higher flows. At present, such a rating cannot be entered into ADAPS, so the rating would be implemented as a table in ADAPS. The table would consist of inputs (ADVM velocities) and corresponding outputs (mean velocities). Table values would be computed outside ADAPS, using the appropriate relation for the flow condition.

For a rating to continue to be valid at a station, factors that could invalidate the rating must not occur. Factors that could adversely affect the validity of an index velocity rating include (but are not limited to) the following:

1. Changes in the channel geometry at the ADVM standard cross-section location—could be caused by scouring and filling of the riverbed by floods or dredging.
2. Overbank or flood-plain flows, as discussed previously for Fall Creek—might invalidate a rating

for flows confined to the channel when overflow occurs.

3. ADVM velocity-measurement errors—an object such as a submerged log within the ADVM sampling volume would tend to bias the ADVM velocity low. ADVM malfunctions, such as a temperature sensor failure, could result in velocity biases.
4. Weed growth in the channel—would bias the ADVM velocities low if the weeds are in the sampling volume.
5. Ice cover—could change the vertical velocity distribution and effective channel area.
6. Density gradients in the water, such as temperature gradients—exist because of variations in physical constituents such as water temperature. The speed of sound in water is affected by gradients that have the effect of bending an acoustic beam as it travels through the water (Laenen, 1985). If an ADVM ray bends, the position of the sample volume could change and thus change the relation between ADVM velocity and mean velocity. In a worst-case scenario, one or both beams could be bent enough to touch the water surface or riverbed, biasing the measured velocities.

Ultimately, it is only possible to confirm the continued validity of an index velocity rating by continuing to make measurements of discharge. Accurate discharge records depend upon the accuracy of the mean velocity produced from the index velocity rating.

ACOUSTIC DOPPLER VELOCITY METER DISCHARGE RECORDS

Records for discharge were produced from each of the three ADVM evaluation stations. These records could be compared to conventional records and evaluated.

Computation of the Records

The same records-computation procedures were used for the three evaluation stations. First, unit value stages and ADVM velocities were analyzed for obvious errors, called "spikes," using plots of the unit values. Spikes occurred infrequently and were of short duration—usually there was no more than one spike on any day a spike occurred. In these instances a spike manually was edited so that the spike conformed to the values that preceded and followed.

The quality of all unit value velocity data was examined by analyzing

- Beam amplitudes—for sudden, unexplained changes. Most of the time, beam amplitudes would increase with and decrease with discharge because suspended-sediment concentrations would increase and decrease with discharge (increasing suspended-sediment concentrations represent an increase in backscatter and therefore cause the return strength from the ADVM beams to increase).

- Velocity standard deviation—collected from the Argonauts; in general, the standard deviation remained low and constant throughout the study period.

- x- and y-velocity components—for accurate discharges to be computed from ADVM velocities, the mean river flow direction should not change significantly. Because an ADVM outputs both x- (downstream) and y- (across-stream) velocity components, flow-direction changes can be assessed. If the river flow direction remains constant, the y-components of velocity should remain small relative to the x-components of velocity (y-components were small in comparison to x-components at the three evaluation stations).

- Velocity output from multiple cells—of the Fall Creek at Millersville ADVM were compared over time. Comparison of velocities from adjacent cells is a valuable diagnostic tool.

There was only one period at one station of the three with a persistent data-quality problem. The problem affected the velocity and the computed discharge from cell 2 of the Fall Creek ADVM. Measurement 1263, made January 24, 2001, departed by –32.9 percent from the discharge computed from cell 2 (table 8). From December 18, 2000, to February 9, 2001, cell 2 velocities departed from cell 1 velocities. On average, cell 2 and cell 1 velocities were within 0.03 ft/s; during the period in question, cell 2 velocities were as much as 0.8 ft/s lower than cell 1 velocities (fig. 16). This departure in velocities was accompanied by an increase in cell 2 beam amplitudes. Normally, cell 2 beam amplitudes are lower than cell 1 (cell 2 is farther away from the ADVM than cell 1, and the beam amplitudes are less than those from cell 1); during the period in question, beam amplitudes were greater from cell 2 than from cell 1 (fig. 16). It is likely that an object or objects, such as tree branches, became stationary in cell 2. A stationary object in cell 2 would bias measured velocities low and increase beam amplitudes. The departures of cell 2 velocities from cell 1 velocities were about 0.35 ft/s, on average, through January 5; then these gradually began to increase to about 0.62 ft/s on February 2. The 0.62-ft/s departure remained constant from February 2 to February 9. On February 9, during a flow increase, velocities and beam amplitudes rapidly normalized. It is likely that debris in cell 2 caused the velocity departures, and that the area of cell 2 affected by debris grew in volume from January 5 through February 2 and then remained constant. The flow rise on February 9 then apparently moved the debris completely out of cell 2.

The low-velocity bias that affected cell 2 velocities caused the discharges computed from cell 2 to depart from those from cell 1 by more than 60 percent, on average, from December 18, 2000, to February 9, 2001. To compensate, a velocity shift was applied to the cell 2 velocities for this period. The concept of velocity shift is similar to that of a stage shift used to compute discharges, using conventional stage-discharge methods. The velocity shift was implemented in ADAPS in a manner similar to application of stage shift in ADAPS. The magnitude of the velocity shift was computed by adding to cell 2 the mean departures of cell 2 from cell 1: +0.35 held constant to January 5, then steadily increased (prorated) to +0.65 on February 2, and held at +0.65 until February 9 when the shift was prorated to zero during the flow rise. After application of the shift, the discharges computed from cell 2 were within 2 percent, on average, of those computed from cell 1.

After the analysis of unit-value data was complete, and any necessary processing such as the editing of spikes and the velocity-shift application was completed, ADAPS was used to produce the discharge record. To compute the discharge record from unit values, ADAPS would

1. Compute channel-area unit values from stage-unit values, using the stage-area rating.
2. Compute mean velocity unit values from ADVM velocity unit values, using the index velocity rating(s) (for the cell 2 velocities from the Fall Creek ADVM during the velocity-shift period, ADAPS added the appropriate shift value to the unit-value velocity before computing mean velocity from the rating).
3. Compute unit-value discharges, using equation 2 ($Q = \overline{V}A$) by multiplying unit-value mean velocities by channel areas.
4. Computing mean daily discharge by averaging the computed unit value discharges for a 24-hour period.

The ADAPS discharge record was evaluated by a comparison to the conventional discharge record. Wahl, Thomas, and Hirsch (1995) outline the general process for producing discharge records using conventional methods.

Following a measurement, a preliminary evaluation is made of the degree to which the stage-discharge relation has changed on the basis of measurements made up to that time—provisional discharges are determined, assuming that the most recent measurements define the channel condition. This process is repeated following each measurement. With each measurement, however, more measurements are available to evaluate the stage-discharge relation. This process may lead to changes in the provisional discharges that had been computed for previous months. At the end of the year, all measurements are available for review. The entire set of measurements are used to reevaluate the rating conditions for the year. Final decisions are made about the stage-discharge relation that were in effect during the year, and the record is refined or recomputed as necessary. This record then is passed through a rigorous review process and, once approved, the data are considered final and are placed in the archives and published.

Relevant USGS standards and practices (Rantz, 1982) were used to compute the conventional record. The conventional and ADVM records were computed independently of one another and by different personnel; the ADVM and conventional records then were compared.

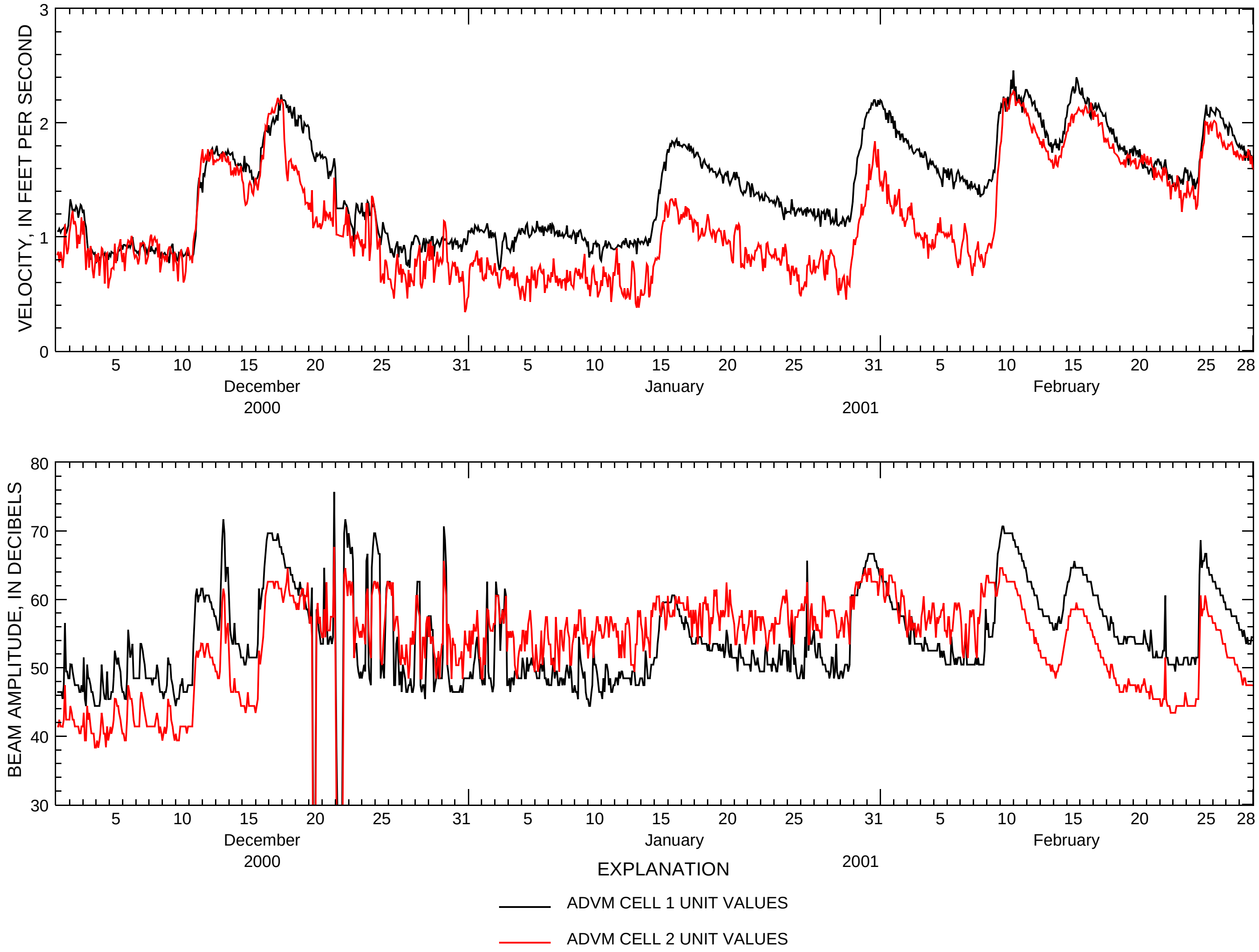

Figure 16. Acoustic Doppler velocity meter (ADVM) cell 1 and 2 velocity unit values and beam-amplitude unit values from the ADVM evaluation site Fall Creek at Millersville, Ind., December 1, 2000–February 28, 2001 (Note: beam-amplitude scale is approximate).

Comparison of the Records

The ADVM and conventional records were compared qualitatively, using hydrographs. In the context of this discussion, a hydrograph is a time series of the mean daily discharges and is a valuable tool in the analysis of the discharge record. For instance, a hydrograph, in conjunction with weather data, can indicate whether an increase in discharge is legitimate (caused by rainfall) or is the result of a physical factor (such as a debris jam downstream from the gage; this would cause an increase in stage without a true increase in discharge). Hydrographs of the conventional and ADVM-produced records were compared for the three evaluation stations. The records for each evaluation station also were compared quantitatively; that is, the differences in mean daily discharges between conventional and ADVM-produced records were examined using statistics.

When using conventional methods, it is sometimes necessary to estimate the record for certain periods. Equipment malfunctions can cause data loss or the storage of incorrect data; periods in which malfunctions occur must be estimated. Ice is another reason to estimate record. When ice partially or totally covers a river, the stage-discharge rating becomes invalid. The method of estimation during such a period is to graphically compare the hydrograph to one or more stations with similar characteristics (Rantz, 1982, explains the procedure in detail). Periods in which the record was estimated are not included in the comparisons between ADVM and conventional records in order to eliminate the subjectivity associated with discharge estimates.

The ADVM and conventional mean daily discharge hydrographs for the study period from Kankakee River at Davis are shown in figure 17. Within the period, 561 mean daily discharges (days in which discharges were not estimated) were available for comparison. Generally, the conventional hydrographs and ADVM hydrographs compare closely—high- and low-flow periods correspond, and larger peaks are supported by precipitation data. Some periods of noticeable departure can be seen in the hydrographs: in June and August of 1999, ADVM discharges were approximately 8 to 12 percent higher than the corresponding conventional discharges; from September through December 2000, conventional discharges were approximately 8 to 14 percent higher than the ADVM discharges. The reasons for these departures are not known.

The conventional and ADVM records compare closely. For the 561 nonestimated data days within the study period, the average of mean daily discharges was 426 and 427 ft^3/s, for the conventional and ADVM records, respectively. The average difference between conventional and ADVM discharges was 1.08 ft^3/s and the standard deviation of the difference was 30.1 ft^3/s. The maximum percent difference between conventional and ADVM discharges was 21.1. Ninety-eight percent of the ADVM discharges were within 15 percent of the conventional discharges; 86 percent were within 10 percent of the conventional discharges; and 51 percent were within 5 percent of the conventional discharges.

The ADVM and conventional hydrographs for the study period from Fall Creek at Millersville ADVM cells 1 and 2 are shown in figures 18 and 19, respectively. Within the study period, 322 mean daily discharges (days in which discharges were not estimated) were available for comparison. Generally, the conventional and ADVM hydrographs compared closely for both cells—high- and low-flow periods correspond and larger peaks are supported by precipitation data. For cell 1, there were short periods of departure from the conventional discharges where ADVM discharges were 5 to 10 percent greater than the conventional discharges; generally, these departure periods occurred within the 70- to 200-ft^3/s range and on the recession of flow peaks. During peak discharges in June and October, ADVM discharges were on average about 10 percent lower than conventional discharges. For cell 2, discharges compared closely on these same peaks. For this reason, it is speculated that bridge-pier turbulence may have affected cell 1 velocities during higher flows. Because cell 2 is farther away from the pier, the effect of turbulence would be lessened for cell 2. For the rest of the study period, cell 2 discharges compared closely to conventional discharges; there were short periods of departure during the period November 2000 to January 2001.

The conventional and ADVM cell 1 and 2 records compare closely. For the 322 nonestimated data days within the study period, the average of mean daily discharges was 242 ft^3/s for the conventional record and 242 ft^3/s for the records from both cells. The average difference between conventional and ADVM discharges was 1.51 and 1.79 ft^3/s for cells 1 and 2, respectively, and the standard deviation of the

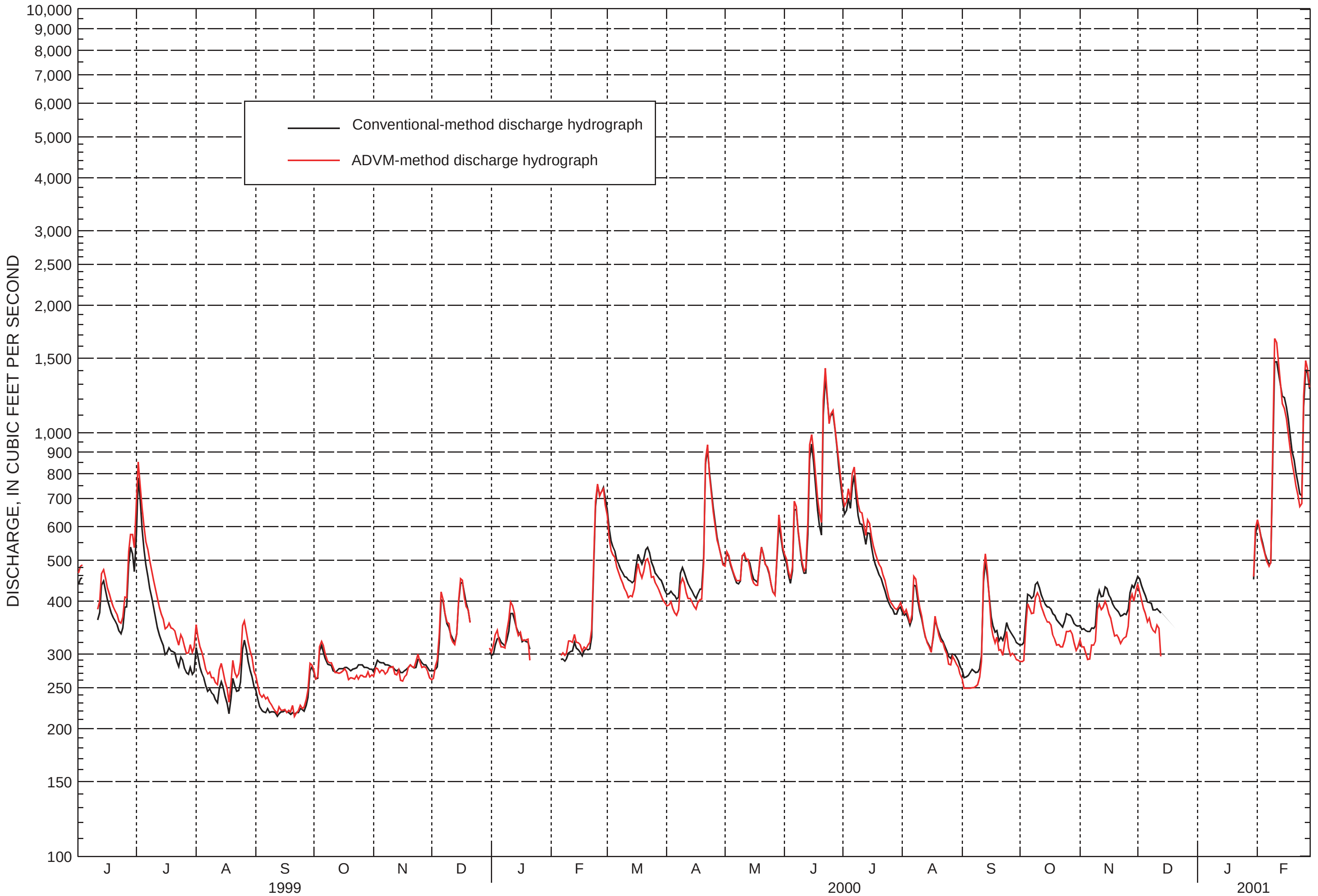

Figure 17. Comparison of mean-daily discharge hydrographs produced by conventional method and acoustic Doppler velocity meter (ADVM) methods from the Kankakee River at Davis, Ind., ADVM evaluation station, June 1, 1999–February 28, 2001 (Note: breaks in graph represent periods of missing data).

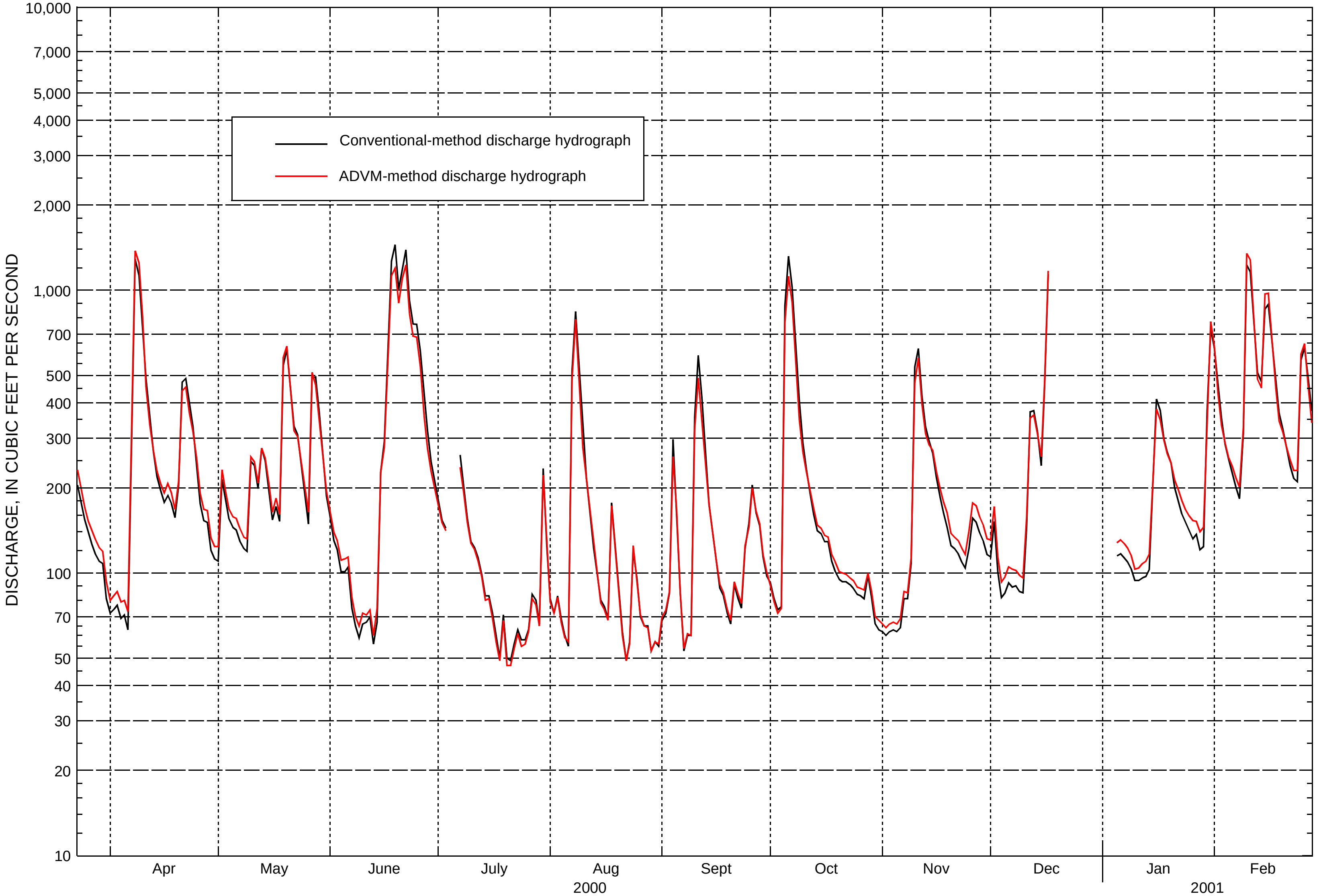

Figure 18. Comparison of mean-daily discharge hydrographs produced by conventional method and acoustic Doppler velocity meter (ADVM) methods, using ADVM cell 1, from the Fall Creek at Millersville, Ind., ADVM evaluation station, March 23, 2000–February 28, 2001 (Note: breaks in graph represent periods of missing data).

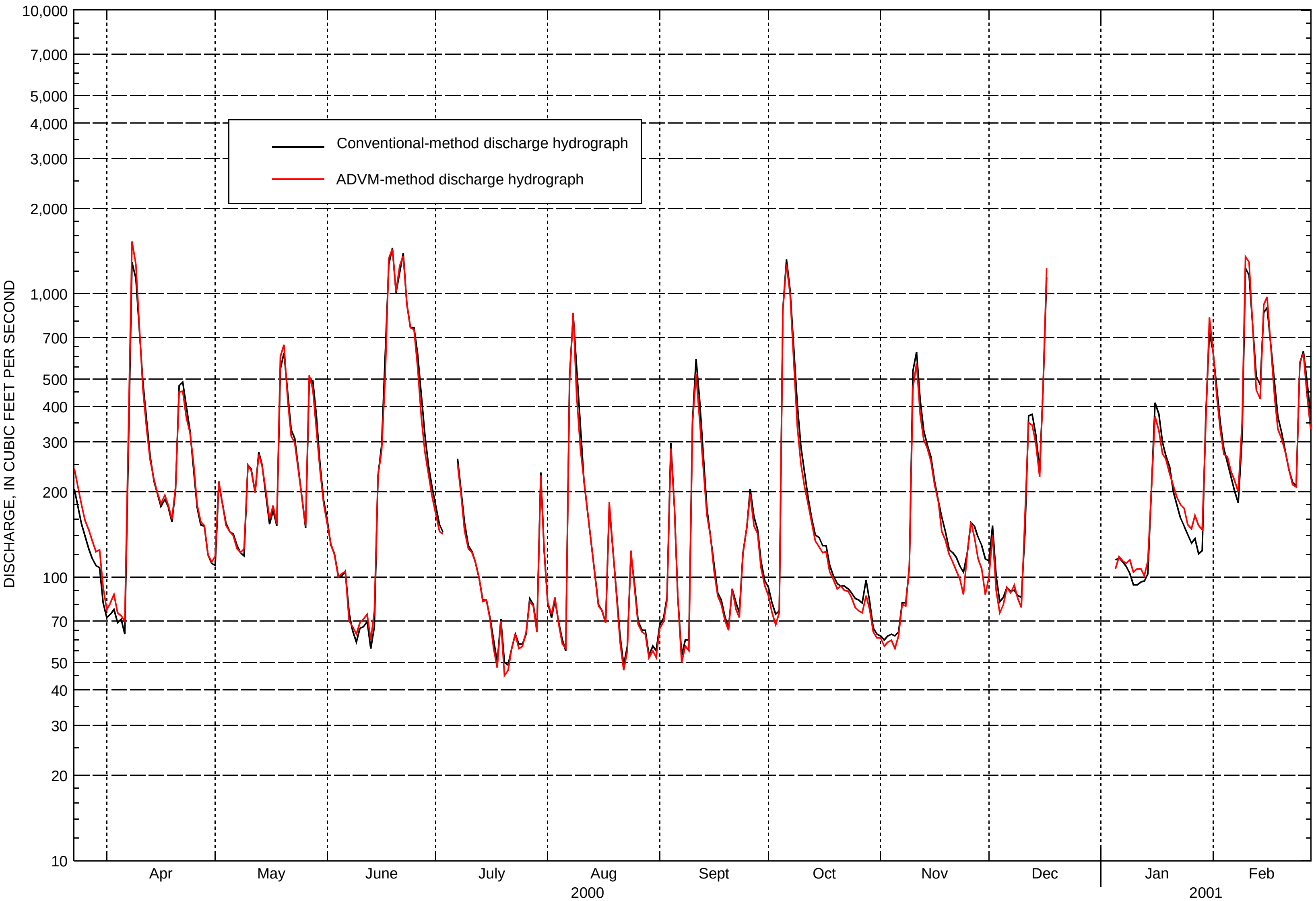

Figure 19. Comparison of mean-daily discharge hydrographs produced by conventional method and acoustic Doppler velocity meter (ADVM) methods, using ADVM cell 2, from the Fall Creek at Millersville, Ind., ADVM evaluation station, March 23, 2000–February 28, 2001 (Note: breaks in graph represent periods of missing data).

difference was 35.4 and 29.8 ft^3/s for cells 1 and 2, respectively. The maximum percent difference between conventional and ADVM discharges was 19.8 and 25.6 for cells 1 and 2, respectively. For cell 1, 97 percent of the ADVM discharges were within 15 percent of the conventional discharges; 74 percent were within 10 percent of the conventional discharges; and 42 percent were within 5 percent of the conventional discharges. For cell 2, 94 percent of the ADVM discharges were within 15 percent of the conventional discharges; 82 percent were within 10 percent of the conventional discharges; and 57 percent were within 5 percent of the conventional discharges.

The ADVM and conventional hydrographs for the study period from the Iroquois River near Foresman are shown in figure 20. Within the period, 387 mean daily discharges (days in which discharges were not estimated) were available for comparison. There was more departure in the hydrographs for this station than in the other two study stations. Historically, variable backwater has been noted at this station. Variable backwater particularly is evident during some high-discharge periods, such as June 25–July 17, 2000. The effect of backwater is illustrated in a graph of unit-value stages and ADVM velocities for April 15 to July 31, 2000 (fig. 21). From April 15 to June 24, the relation between stage and ADVM velocity appears stable (thus, the relation between stage and discharge would remain stable); velocities increase with stage, and the patterns of peak velocity to stage are consistent. Starting with a secondary peak on June 25, a change is visible in the relation between stage and velocities. During the June 25 peak, velocities were lower than velocities during smaller peaks prior to June 25. For the two large peaks July 2 to 19, velocities are considerably lower than velocities that occurred on earlier peaks with lower stages. Analysis of unit-value stages and velocities for other periods reveal that some backwater likely is present at times during low-discharge periods as well.

During the entire study period, the average of mean daily discharges compares closely: for the 387 nonestimated days within the study period, the averages of mean daily discharges were 242 and 237 ft^3/s for the conventional and ADVM records, respectively. The average difference between conventional and ADVM discharges was 5.41 ft^3/s, and the standard deviation of the difference was 51.8 ft^3/s. Other statistics reflect departures in the conventional and ADVM discharges. The maximum percent difference between conventional and ADVM discharges was 49.0. Sixty-nine percent of the ADVM discharges were within 15 percent of the conventional discharges; 56 percent of the ADVM discharges were within 10 percent of the conventional discharges; and 34 percent were within 5 percent of the conventional discharges.

Evaluation of the Records

The USGS has the following accuracy ratings for discharge records: “excellent” means that about 95 percent of the daily discharges are within 5 percent of their true values; “good,” within 10 percent; and “fair,” within 15 percent (Kennedy, 1983). Records that do not meet any of these criteria are rated “poor” (note that accuracy ratings for discharge measurements differ from accuracy ratings assigned to individual discharge measurements). Assuming that the discharge record produced by conventional methods represents the true discharge record, then the Kankakee River at Davis and Fall Creek at Millersville ADVM records (cell 1 and 2) could be called “fair” because about 95 percent of the ADVM discharges were within 15 percent of the conventional discharges for the study period. The conventional record, however, cannot be said to represent the true discharge record because of error sources in this method, including:

- Errors in the discharge measurements used to create the stage-discharge rating;
- Errors in the stage-discharge rating (such as regions that are not well defined by discharge measurements); and
- Errors in the applications of stage shifts—whereas there are standard procedures of the application of shifts (Rantz, 1982, and Kennedy, 1983), there is subjectivity in shift application. The person producing the record must use personal judgment as to shift periods, magnitudes, and shapes (in this study, no shifts were needed for the Kankakee River conventional record as all discharge measurements were within tolerance of the stage-discharge rating; for Fall Creek at Millersville, four periods of shift application were required to bring the stage-discharge rating within tolerance of discharge measurements).

Because the index velocity ratings were proven valid within the range of discharge measurements used

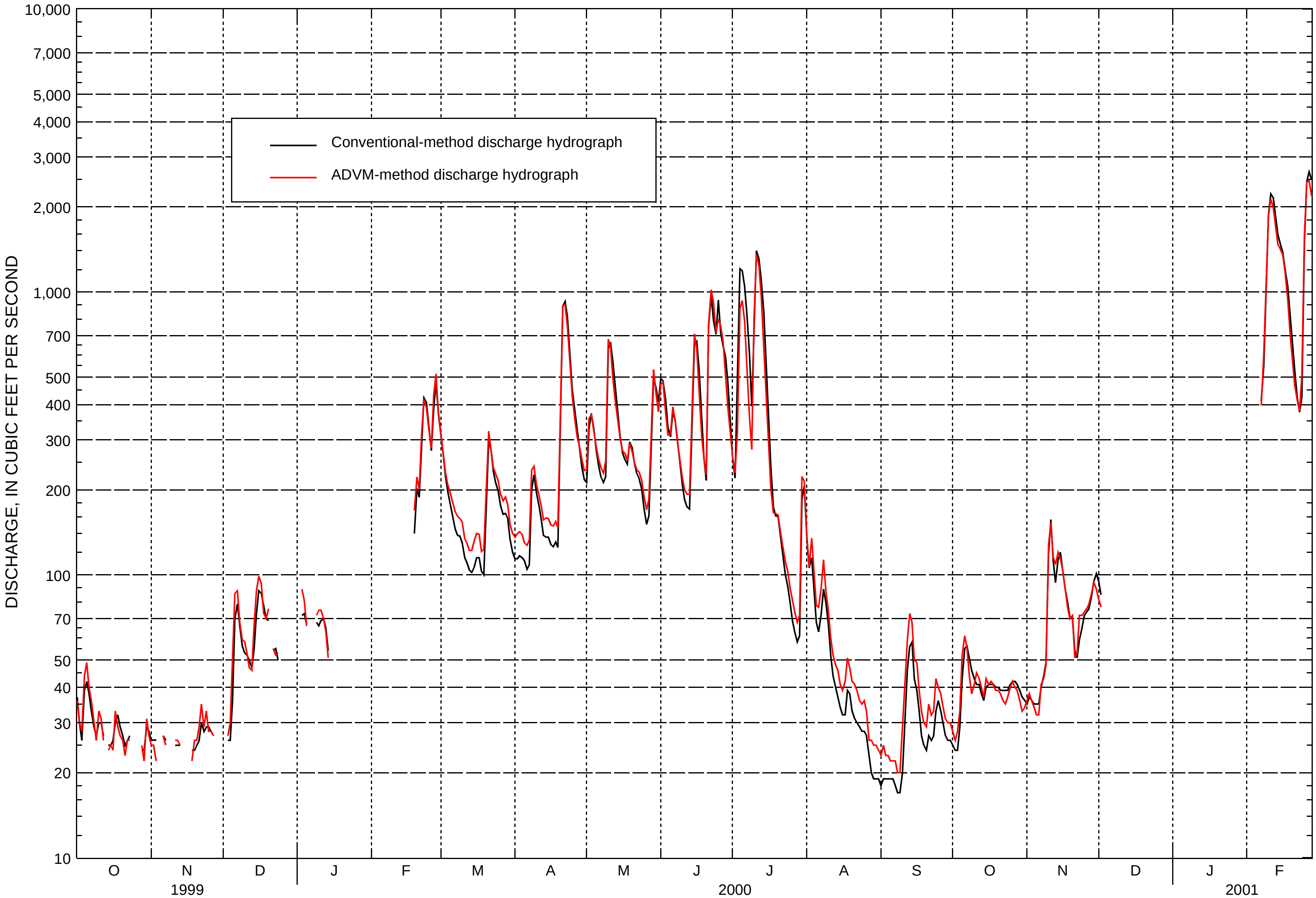

Figure 20. Comparison of mean-daily discharge hydrographs produced by conventional method and acoustic Doppler velocity meter (ADVM) methods from the Iroquois River near Foresman, Ind., ADVM evaluation station, October 1, 1999–February 28, 2001 (Note: breaks in graph represent periods of missing data).

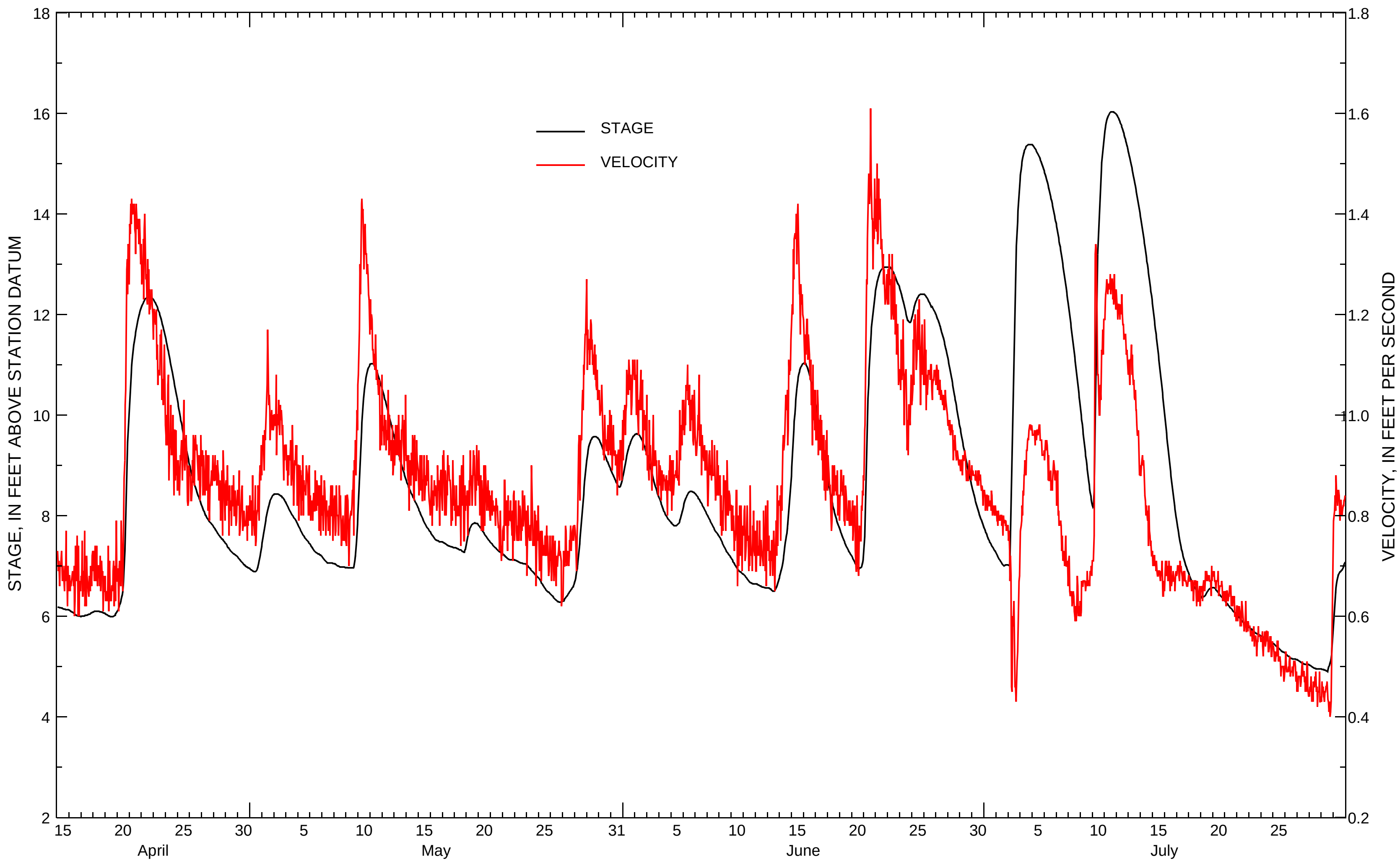

Figure 21. Stage and acoustic Doppler velocity meter (ADVM) measured velocity unit values from the Iroquois River near Foresman, Ind., ADVM evaluation station, April 15–July 31, 2000.

to create the ratings and because the quality of ADVM data was good, a rating of “good” was given to parts, if not all, of the record from the Kankakee and Fall Creek stations.

For the Iroquois River near Foresman station, the conventional and ADVM records depart more than the other two stations do. This station has a history of variable backwater and discharge-record quality problems that have been documented by the hydrographers who analyzed the record. Historically, extensive shift periods had to be used to produce the conventional record; it is likely that the quality of the ADVM record exceeds that of the conventional record. The velocity that the ADVM record is based on will compensate for backwater effects because velocities are a more direct index of discharge than are stages where backwater is present.

The ADVM record was compared to the conventional record to assess the ADVM record based on a record produced by long-standing USGS methods. The conventional and ADVM records from the Kankakee River and Fall Creek stations compare closely. Additionally, discharge measurements made through the study period confirm the validity of the stage-area and index velocity ratings. Thus the ADVM record from these stations for the study period can be rated “good.” For the Iroquois River station, the comparison between conventional and ADVM records was not as close as the other two stations; there is evidence to support the conclusion that the ADVM record may be more accurate than the conventional record. Also, discharge measurements during the study period confirm the validity of the rating. Thus the ADVM record from the Iroquois River near Foresman can be rated “good.”

The quality of the ADVM record meets USGS publication standards. The ADVM records for Kankakee River at Davis and Iroquois River near Foresman were published in Stewart and others (2000); the record from the three stations were published in 2001. Real-time unit value discharges computed from ADVM data are served on the Indiana District Real-Time Surface-Water-Data Retrieval World Wide Web pages for the three evaluation stations (fig. 22).

Instrument reliability is an important factor in the feasibility of using ADVM’s for the production of discharge records. For the stations and study periods documented in this report, no ADVM malfunctions caused lost or missing records and the ADVM’s required no special maintenance. Light coatings of silt and biological growth on the ADVM transducers did not appear to reduce the quality of the ADVM data. Little, if any, maintenance was required to keep the ADVM’s operational.

The comparison of ADVM discharge records with conventional records for the study stations was one tool used to assess the quality of the ADVM record. At other stations, such a comparison may not be possible (for example, stations where a stage-discharge relation is not present, such as in estuarine rivers or bidirectional flow stations). If an ADVM is to be installed at a new USGS streamflow-gaging station, it would be important to produce discharge record from the ADVM as soon as possible and to avoid producing redundant conventional records. To make ADVM use practical, there must be ways of assessing the accuracy of the ADVM record. Ultimately, the accuracy of an ADVM discharge record produced by an ADVM will depend primarily on:

1. Accuracy of the stage-area and index velocity ratings,
2. Stability of the stage-area and index velocity ratings,
3. Accuracy of stage measurements, and
4. Accuracy of ADVM velocity measurements.

The accuracy of the index velocity ratings is dependent upon the accuracy of the discharge measurements used to create the ratings and also upon whether the number of measurements made adequately defines the ratings. The accuracy of the stage-area curve should be acceptable if cross-section data were collected with care and if the stage-area relation remains stable, provided the channel geometry does not change significantly. If index velocity ratings can be represented by mathematical models such as linear equations, plots and various statistical tools can be used to gage the accuracy of the model. Ultimately, the only way to continue to assess the validity of the stage-area and index velocity ratings is by continued measurements of discharge.

USGS policy states that stage should be measured with an accuracy of 0.01 ft or 0.2 percent of the effective stage being measured, whichever is less restrictive (U.S. Geological Survey, 1992). This policy was designed to support computation of discharge from stage-discharge relations. For ADVM’s, stage accuracy is important because errors in stage will produce errors in computation of channel areas,

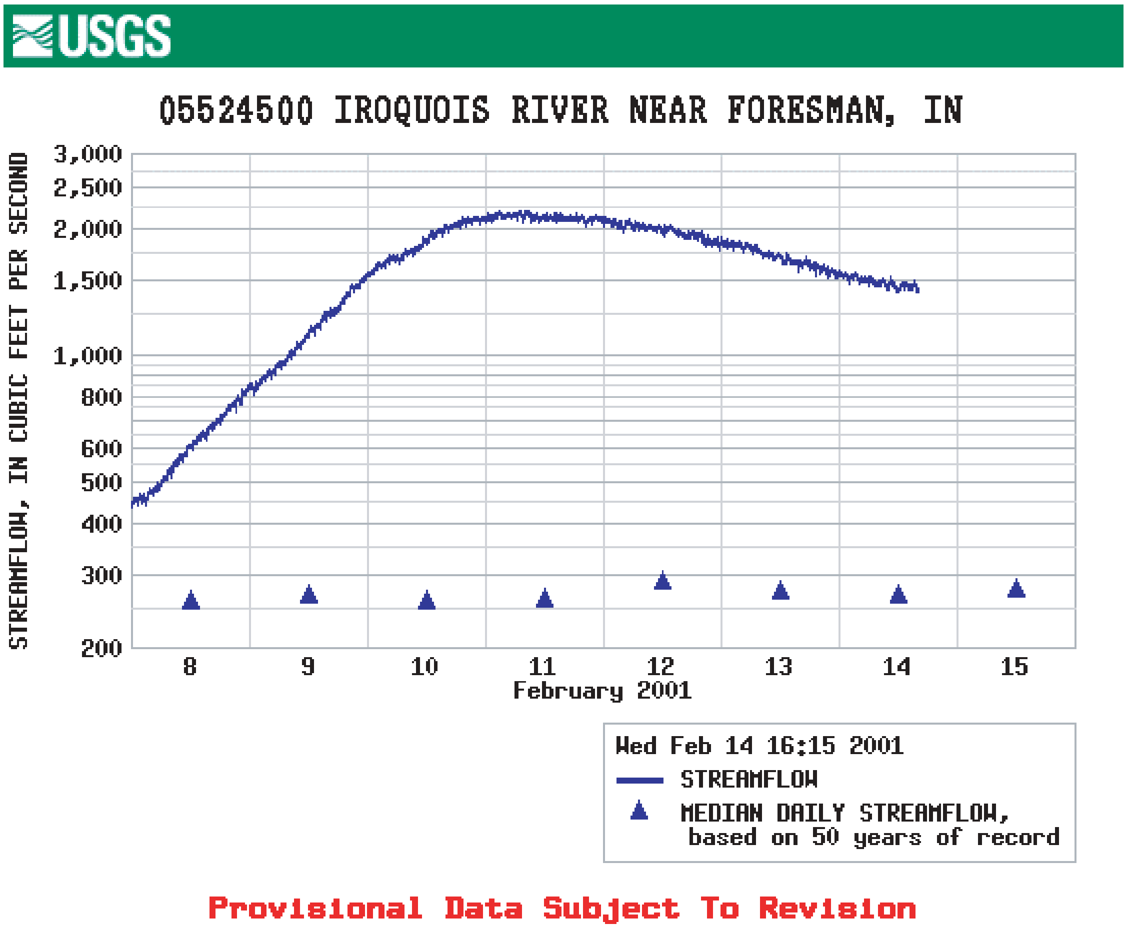

Figure 22. Example of near real-time discharge hydrograph from Iroquois River near Foresman, Ind., served on the World Wide Web.

producing discharge errors proportional to channel-area errors ($Q = VA$). For example, at median flow, a 0.05-ft error in stage would cause a 0.6-, 1.0-, and 3.3-percent error in channel area and discharge at the Kankakee River, Iroquois River, and Fall Creek evaluation stations, respectively. A greater discharge error would occur at Fall Creek because of channel geometry. Rivers or streams that are shallow and wide are more sensitive to area and discharge errors caused by stage errors.

Stage sensors used at the Kankakee and Iroquois River stations were incremental shaft encoders in stilling wells that met USGS stage-accuracy requirements. For the Fall Creek station, an incremental shaft encoder was used as the primary stage sensor ("primary" refers to a stage sensor that produces the stage used in discharge-record computation) until September 30, 2000. From October 1, 2000, to February 28, 2001, the stage from the EasyQ upward-looking transducer was used as the primary stage sensor. Throughout the study period, the EasyQ stage was within, on average, 0.01 ft of the encoder stage and was used as the primary stage sensor for the period. The stage from the EasyQ was used as the primary stage sensor for part of the study period, but the absolute accuracy has not been assessed formally by the USGS. The same is true of the upward-looking stage transducer available with newer models of the Argonaut-SL.

Errors in discharge computation are directly proportional to velocity-measurement errors ($Q = VA$). The manufacturers of the Argonaut-SL and the EasyQ claim velocity accuracies of 1 percent of the measured velocity ±0.5 centimeters per second (0.016 ft/s). This accuracy has not been assessed formally by the USGS. Because the ADVM velocity data were used to produce acceptable records of discharge for the three study stations, it is assumed that the ADVM velocity-measurement accuracy was sufficient for computation of mean daily discharges acceptable to the USGS. Mean channel velocities from the three study stations ranged from about 0.2 ft/s at the Iroquois River station to about 3.5 ft/s at the Kankakee River station. Velocity accuracies may not be sufficient to produce accurate discharge records under all conditions. At some stations, such as those in estuaries, mean velocities may be significantly lower than the range of mean velocities observed at the three study sites (velocity uncertainties would be a larger percentage of the mean velocities and, thus, discharges at low-velocity stations).

Because factors 1 to 4 are station dependent and because all stations will have different characteristics, the best assessment of discharge-record accuracy will be the continued comparison of discharges computed from the ADVM data to discharges measured in the field.

USE OF ACOUSTIC DOPPLER VELOCITY METERS FOR THE PRODUCTION OF DISCHARGE RECORDS

Whereas the scope of this study was limited to three streamflow-gaging stations located in Indiana, the study revealed some implications and issues that may have a wider application.

Ice-Affected Periods

During ice-affected periods, a stage-discharge rating often is not reliable; the ice will cause stages to rise without a corresponding rise in discharge. During such periods, the discharge record must be estimated; the estimation is aided if one or more discharge measurements were made during the period. Otherwise, comparisons with the hydrographs of other stations in conjunction with weather data must be used to estimate the record. Estimated records during ice periods are subjective and usually are rated “poor.”

ADVM’s may allow for less-subjective estimates of discharge during ice-affected periods. An ADVM discharge was computed during a discharge measurement (523) made at the Iroquois River station when the river was totally ice covered. The measurement yielded a discharge of 39.5 ft^3/s. The ADVM-computed discharge during the measurement period was 51.0 ft^3/s, a difference of 29 percent. Measurement notes indicated the average ice thickness was 0.5 ft, and when holes were chopped in the ice to make the measurement, the water level came to the top of the ice. This result means that the river was under pressure and that the channel area used to compute ADVM discharge was based on a stage that was about 0.5 ft high. When the channel area was recomputed manually for a 0.5-ft lower stage, the ADVM discharge for the measurement period was recomputed at 42.6 ft^3/s, 7.8 percent higher than the measurement discharge. Because of the rough underside of the ice, the velocity profile usually is different than when the surface is free of ice. Rantz and others (1982) recommend that for velocities sampled at 60 percent of the distance from bottom of ice to streambed, a coefficient of 0.92 be applied to estimate the mean velocity. Because the ADVM measured velocity at about 60 percent of the depth under the ice during the measurement period, the ADVM-computed velocity was adjusted by multiplication of 0.92. This yielded a recomputed ADVM discharge of 39.2 ft^3/s, which is within 1 percent of the measured discharge.

A more rigorous approach to estimates of discharge during ice-affected periods is explained by Wang (2000). Flow-distribution models for deriving station-specific equations are used to compute discharges from AVM velocities during periods of channel ice cover. In this approach, bed-roughness and ice-roughness parameters are estimated from velocity profiles collected at a station. A hydraulic parameter is determined from cross-section area and locations of the AVM transducers. A “beta” coefficient is computed from the roughness and hydraulic parameters. AVM velocity multiplied by the beta coefficient yields discharge for a particular stage. The beta coefficient can be expressed as a function of stage through a regression analysis. Thus, discharge becomes a function of stage and AVM velocity. Discharges computed from this method compared closely to discharge measurements made at AVM stations in Canada during ice periods (Wang, 2000). Discharges computed from Wang’s methods, although developed for AVM stations, can be applied directly to ADVM’s as well.

Whether using a simple coefficient or Wang’s approach, the stage of the bottom of the ice needs to be known. One way to estimate the stage of the bottom of the ice is to use an ADVM equipped with an upward-looking stage transducer. For the Iroquois River near Foresman, the thickness of the ice was estimated, using the discharge-measurement data and temperature records, for the ice-affected period. The Fall Creek at Millersville ADVM was equipped with an upward-looking transducer and measured the stage of the ice bottom during the ice-affected period December 18, 2000, to January 4, 2001, thus computing channel area and discharge based on this stage. No discharge measurements were made during this period to confirm the discharge. The records for the ice-affected periods from the three stations were rated “poor.”

Multi-Cell Capabilities

The EasyQ three-cell feature provided a quality-assurance tool for comparison of velocity and amplitude data from the cells. Noticeable departures in velocities and beam amplitudes can identify problems in one cell, whereas periods with no departures can add confidence to the ADVM record. Each cell can be rated separately to produce discharge, and if one cell appears to produce a better record, it can be used as the “primary cell.” For Fall Creek at Millersville, for example, cell 2 may do better at high flows because it is farther from the bridge pier, and it may be less affected by bridge-pier turbulence. The multi-cell capability allowed the discovery of the velocity bias in cell 2 for a period at the Fall Creek at Millersville station and allowed the computation of velocity shifts to compensate for the errors caused by the velocity bias. The Argonaut-SL’s used at the study stations did not have the multi-cell feature.

Multiple cells can have disadvantages: velocity instrument “noise” would be higher than for a single, larger cell, and there are more data parameters to log, store, and analyze. The multi-cell feature may not be applicable at all stations but can be considered as a valuable quality-assurance tool.

Velocity Shifts

If the stage-area and index velocity ratings remain stable and the velocity measurements remain unbiased, shifts should not need to be applied to produce ADVM discharge records. As demonstrated for cell 2 of the Fall Creek ADVM, it is possible to use velocity shifts to compensate for discharge-computation errors induced by velocity-measurement biases. It might be possible to compensate for changes in the stage-area rating caused by channel-geometry changes by using a stage shift. ADAPS will use the shifted stage to compute channel area. If the channel geometry changes, the index velocity rating also will likely become invalid because the station hydraulic characteristics will change. In this case, new stage-area and index velocity ratings likely will be required. It may be difficult to produce accurate ADVM discharge records if such changes are frequent.

Real-Time Discharge Data

When supplying near real-time discharge data, as the USGS provides on the World Wide Web for many stations, ADVM—as opposed to conventional-method discharges—may be advantageous. If a station has stable channel and hydraulic characteristics and the ADVM ratings are reliable, the real-time discharge data should be accurate. For many stations measured with conventional methods, discharge measurements indicate that shifts need to be applied in periods for which real-time data were provided; the post-measurement computed discharges will be different than the real-time values. Periods of shifting were required to produce the discharge record, using conventional methods, for the Fall Creek and Iroquois River study stations; no shifts were required for the Fall Creek cell 1 and Iroquois River ADVM-produced discharge records during the study period.

Upland Rivers and Streams

The USGS has used hydroacoustic instruments like AVM’s at streamflow stations where the relation between stage and discharge is unstable (Laenen, 1985). ADVM’s can be valuable at new streamflow-gaging stations under similar conditions. The Kankakee River and Fall Creek stations described in this report may be classified as small- to medium-sized upland rivers that do not appear to be subject to stage-discharge instabilities. Stage-discharge methods have produced accurate discharge records at such stations, so this method primarily has been used in the USGS. It may be advantageous for the USGS to install ADVM’s at such stations. ADVM’s can offer the advantages of more reliable real-time discharge and more accurate estimates of the discharge record during ice-affected periods.

Rating of Acoustic Doppler Velocity Meter Discharge Records

In judging the accuracy of the record, various factors can be considered. The accuracy of the ADVM ratings can be determined with analysis tools such as those discussed in this report and by studying the departures of discharge measurements from ADVM discharges. Particular caution should be exercised for discharge records that are outside the range of discharge measurements used to define the index velocity rating(s). If the hydraulics at a station indicate that the rating likely will change at a certain stage and(or) discharge thresholds, then it would be prudent to reduce (downrate) records that exceed those thresholds. For example, the record from Fall Creek at Millersville might be rated as follows: “record good except for discharges above 1,600 ft^3/s, which are poor” (because at discharges above 1,600-ft^3/s, flows in the flood plain will likely cause a departure from the linear index velocity rating). It is important to base ADVM ratings upon the knowledge of conditions at a station in order to make informed decisions concerning rating of the record.

Questionable ADVM data, such as the velocity biases seen at the Fall Creek station, are cause to downrate the quality of a discharge record. It is important to continue to use all diagnostic tools available to assess the quality of the ADVM records. This includes study of recorded ADVM parameters and on-station checks. It would be prudent to perform a beam-amplitude check every time an ADVM station is visited and to note any unusual results.

POTENTIAL FUTURE STUDIES

It would be beneficial to quantify accuracies of ADVM’s in a laboratory setting as well as in the field. Informal laboratory testing of the ADVM’s used in this study is described in the Appendix. As the ADVM models used in this study are upgraded with new features, it would be beneficial to test the new features in the laboratory and field. Testing of instruments from other manufacturers as they become available would be beneficial.

Other beneficial potential future studies could include

- Ice-period studies—further studies could identify problems and suggest methods for evaluation of ADVM records during ice periods. Such studies might produce recommended methods (for example, the application of coefficients to the ADVM velocities).

- Bidirectional flow studies—studies of ADVM stations with different flow regimes, such as very slow and(or) bidirectional flow, would be useful, particularly documentation concerning rating development and discharge-record quality.

- Nonlinear rating-development studies—studies that document nonlinear rating development and assessment would be beneficial for those with ADVM stations that cannot be accurately modeled with linear ratings.

SUMMARY AND CONCLUSIONS

The purpose of this study was to describe the feasibility of using velocity data collected by acoustic Doppler velocity meters (ADVM’s) for the computation of discharge records from three USGS streamflow-gaging stations. Two models of ADVM’s (the SonTek Argonaut-SL and Nortek EasyQ) from two different manufacturers were used.

ADVM’s were installed at three USGS streamflow-gaging stations in Indiana: the Kankakee River at Davis, Fall Creek at Millersville, and Iroquois River near Foresman. The Kankakee River and Fall Creek stations were selected for the installation because the quality of the discharge record produced by conventional USGS methods was judged to be “good,” thus providing a basis for comparison of the discharge record produced with ADVM data (the USGS has the following accuracy ratings for discharge records: “excellent” means that about 95 percent of the daily discharges are within 5 percent of their true values; “good,” within 10 percent; and “fair,” within 15 percent—records that do not meet any of these criteria are rated “poor”). The Iroquois River station was selected for ADVM installation in an effort to improve the record of discharge; historically, variable backwater has affected the quality of the record from this station.

Stage-area and index velocity ratings were created for each of the three study stations. The stage-area ratings were created so that channel area could be computed from stage data; the index velocity ratings were created so that mean velocities could be computed from ADVM velocity data. Stage-area ratings were created on the basis of surveyed channel cross sections: the Kankakee River cross section was rectangular; the Fall Creek cross section included a broad flood plain, and the Iroquois River cross section was trapezoidal. The Kankakee River stage-area rating was represented as a linear equation in ADAPS, whereas the Iroquois River and Fall Creek ratings were tabular ratings.

Stage, mean velocity, and ADVM velocity data from discharge measurements were used to develop index velocity ratings for the three stations, based on linear models: the Kankakee River rating used stage and ADVM-measured velocities as significant parameters for computation of mean velocities, whereas the Fall Creek and Iroquois River ratings used ADVM-measured velocities only for computation of mean velocity. The validity of the ratings was confirmed by analysis of coefficients of determination, standard errors, and residual plots from the linear regressions used to create the ratings and by comparisons of discharges computed from the ratings to measured discharges. Based on hydraulic features at the stations, Kankakee and Iroquois River ratings may remain valid outside the range of the discharge measurements used to create the ratings; the Fall Creek ratings likely will not remain valid above discharges where significant flows in the flood-plain area begins.

Stage and water-velocity data from the ADVM's were used to compute a continuous record of discharge from each of the streamflow-gaging stations. These records of discharge were compared to the records of discharge computed by using conventional USGS methods. ADVM records for the Kankakee River and Fall Creek at Millersville stations compared closely to the conventional records.

For the Kankakee River, the average of mean daily discharges were 426 and 427 ft^3/s for the conventional and ADVM records, respectively, during the study period. Ninety-eight percent of the ADVM discharges were within 15 percent of the conventional discharges; 86 percent were within 10 percent of the conventional discharges; and 51 percent were within 5 percent of the conventional discharges.

For Fall Creek at Millersville, the average of mean daily discharges was 242 ft^3/s for the conventional record and 242 ft^3/s for the records from cells 1 and 2. The maximum percent difference between conventional and ADVM discharges was 19.8 and 25.6 for cells 1 and 2, respectively. For cell 1, 97 percent of the ADVM discharges were within 15 percent of the conventional discharges; 74 percent were within 10 percent of the conventional discharges; and 42 percent were within 5 percent of the conventional discharges. For cell 2, 94 percent of the ADVM discharges were within 15 percent of the conventional discharges; 82 percent were within 10 percent of the conventional discharges; and 57 percent were within 5 percent of the conventional discharges.

For the Iroquois River near Foresman, the average of mean daily discharges were 242 and 237 ft^3/s for the conventional and ADVM records, respectively. Sixty-nine percent of the ADVM discharges were within 15 percent of the conventional discharges; 56 percent of the ADVM discharges were within 10 percent of the conventional discharges; and 34 percent were within 5 percent of the conventional discharges. Because of the presence of variable backwater at the Iroquois River station and the ability of the ADVM data to compensate for this backwater, the discharge record from the ADVM is probably more accurate than the conventional discharge record.

The scope of this study was limited to three streamflow-gaging stations in Indiana, but the study did reveal some issues that may have application beyond these stations. ADVM's may be able to provide discharge estimations during ice-affected periods that are less subjective than estimations with conventional methods. The multiple-cell ADVM feature provides a valuable tool for data-quality assessment. ADVM-generated discharge data are valuable for real-time-data dissemination. ADVM installation on upland rivers could be useful even though conventional methods have been predominant for such rivers. When judging the quality of discharge records produced from ADVM data, factors to consider include the range of validity of index velocity ratings and the quality of stage and ADVM velocity data.

In conclusion, this study has shown that it is feasible to use ADVM's installed at streamflow-gaging stations to produce records of discharge of acceptable quality for publication and distribution. This statement, however, does not imply that ADVM's can be used at all stations. Rivers at some stations will be too shallow or will have hydraulic and other physical characteristics that make ADVM use impractical. Conditions at candidate stations need to be assessed individually to see if ADVM use will be feasible.

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APPENDIX

LABORATORY EVALUATIONS

Informal laboratory testing has been performed on both the EasyQ and Argonaut-SL at the USGS Office of Surface Water Hydraulics Laboratory, Stennis Space Center, Miss. To perform tests on ADVM velocity-measurement ability, a tow-tank facility was used. The tow tank is a concrete channel with a 12-ft by 12-ft cross section and a length of 450 ft; an electric tow cart moves along tracks atop the tow tank (fig. 23) at a selectable speed from 0.05 to 16 ft/s. A data-acquisition system is used to monitor elapsed time and distance traveled to determine the cart speed. The ADVM's were tested by attaching them to the tow cart so that they were suspended in the tow tank. The tow cart with the attached ADVM was run across the tow tank at known speeds.

ADVM stage-measurement tests were performed using a large cylindrical holding tank (deep tank) measuring 33 ft in diameter and 37 ft deep (fig. 23). A catwalk across the tank allowed the ADVM's to be lowered to different depths, and a steel tape attached to the mount holding the ADVM and marked in 0.01-ft intervals was used to measure instrument depth position.

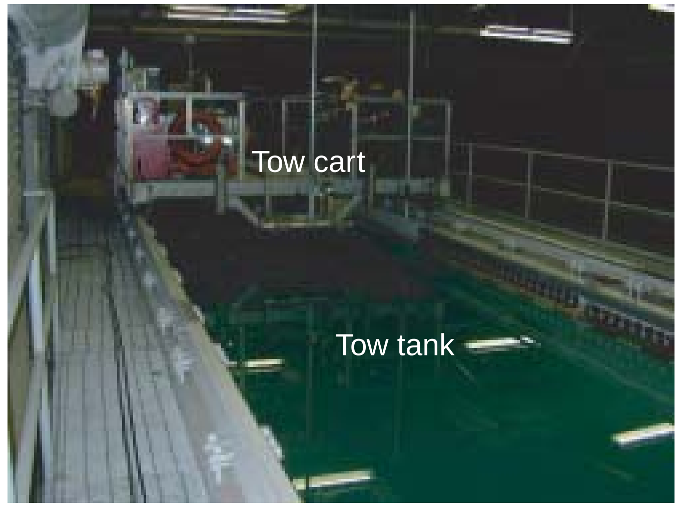
A test was performed on the EasyQ, July 26–29, 1999. The EasyQ stage-measurement capability was tested in depths from about 1 to 12 ft. The stage uncertainty associated with the test was estimated to be 0.02 ft; some of the uncertainty likely was because of observed movement of the EasyQ mount. Ideally, the top of an EasyQ stage transducer should be perfectly level so it is parallel with the water surface. From the tests, it appeared that angles of about 3 degrees off-level could be tolerated. Forty-five tow-tank tests were performed for a range of speeds from about 0.1 to 15 ft/s. The velocity-measurement uncertainty was estimated at 0.09 ft/s; much of the uncertainty was attributed to internal velocity waves in the tank that would affect low-speed runs. Had the low-speed runs been discounted in the data analysis, the velocity uncertainty would have been less. Gordon (1999) details the procedures and results of this test. A second test on the EasyQ stage-measurement capability was done in the deep tank on October 23 and November 20, 2000. A data-quality parameter associated with EasyQ stage indicated that there was a problem with the quality of stage data collected both days, and the cause of the problem could not be determined; no conclusions could be drawn from the tests.

A test was performed on the velocity-measurement capabilities of the Argonaut-SL August 21–25, 2000. The Argonaut-SL was tested at various pitch, roll, and yaw angles and for speeds ranging from about 0.05 to 2.2 ft/s (Craig Huhta, SonTek Corporation, written commun., August 25, 2000). Linear regressions of cart speed and ADVM-measured velocities were performed for the various tests, and the deviations of the slopes (from 1.0) and offsets (from 0.0) of the regression lines were used as estimators of velocity uncertainties. In summary, for test runs with the Argonaut in a normal orientation (pitch, roll, and yaw angles negligible), the velocity uncertainty was within about 1 percent of measured velocities for runs above 0.10 ft/s. Runs below 0.10 ft/s were not included in the analysis because of internal velocity waves, as noted for the EasyQ tests. On one set of runs, with a roll angle of 10 degrees, and another set of runs, with a pitch angle of 15 degrees, the velocity uncertainties were about 3 percent of the measured velocities. The cause of the greater uncertainties for these runs was not discovered; the tests were repeated and did not show this bias. Tests of the Argonaut-SL stage-measurement capabilities were performed in the deep tank on October 23 and November 20, 2000. Fifteen tests at Argonaut depths of about 5 to 32 ft were performed. The stage uncertainty from the tests was estimated to be within 0.03 ft. Six more tests were carried out at depths of about 2, 5, and 15 ft while waves were being generated in the deep tank. The stage uncertainty for these tests was estimated to be 0.01 ft.

The laboratory tests performed on the ADVM's did not confirm or reject ADVM manufacturer accuracy specifications, but some conclusions could be drawn from the tests: (1) the tests indicate that the instruments have the potential to meet accuracy requirements for many discharge-computation applications; (2) although absolute stage accuracies were not established, the first EasyQ test produced estimated stage uncertainties of 0.02 ft, which agreed with estimated accuracies from the Fall Creek ADVM field evaluation (the laboratory tests indicated that Argonaut-SL stage uncertainties are similar); and (3) the laboratory tests were valuable in that they performed the function of providing base-line data and suggested new approaches for further testing.

Further testing would be beneficial for two reasons. First, the velocity tests and subsequent analysis were not consistent. The EasyQ was tested over a range of velocities from about 0.1 to 15 ft/s, whereas the Argonaut-SL range was about 0.05 to 3 ft/s. The Argonaut was tested at various yaw, pitch, and roll angles, and the EasyQ was tested at a single orientation (yaw, pitch, and roll angles were zero). Because the tests were informal and took place at different times, consistency was not a goal. Second, in the test process, some problems were noted that could adversely affect the test results, such as the presence of tow-tank internal currents noted by Gordon (1999). Another problem with tow-tank testing is that at high speeds, the velocity-sampling interval is very short, which can increase measured velocity errors.

The laboratory ADVM-velocity tests suggest that future velocity testing might be conducted in a large flume in addition to tow-tank testing. The problem with internal tow-tank currents biasing low-velocity tests would be eliminated, and a consistent averaging interval could be used for all velocity tests (velocity averaging is dependent on tow-cart speed in tow-tank testing). A problem with flume testing is in determining the reference velocity for comparison. For further stage tests, to reduce uncertainties related to the movements of catwalk-suspended mounts, it may be advisable to suspend the instruments from a frame that is independent of the catwalk structure.



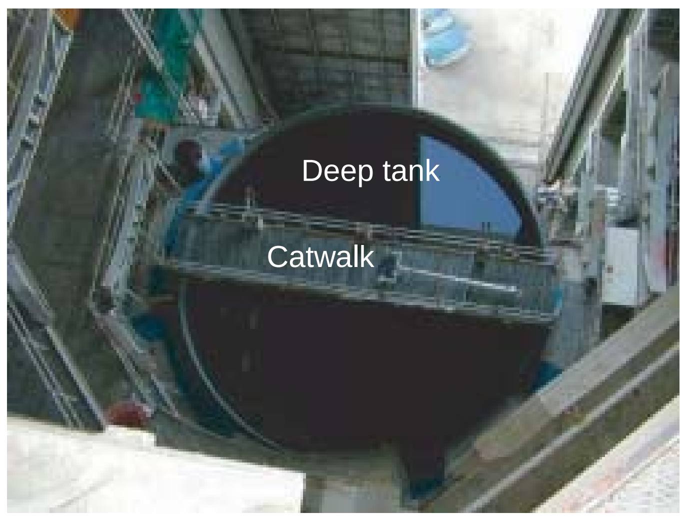


Figure 23. Photographs of tow tank and tow cart (top) and deep tank (bottom) at the U.S. Geological Survey Hydraulics Laboratory, Stennis Space Center, Mississippi.