Evaluation of Acoustic Doppler Current Profiler Measurements of River Discharge

By SCOTT E. MORLOCK

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	2.540	centimeter
foot (ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer

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Abstract

Developments in Acoustic Doppler Current Profiler (ADCP) technologies have made these instruments potentially useful for making measurements of discharge in rivers and large streams. Although there have been several laboratory studies and some field experiments, quantitative information on the performance of ADCP's under field conditions is relatively rare but essential to proper assessment of the potential uses and limitations of these instruments. This study was a comparative evaluation of river discharge data and ADCP data collected with conventional methods at 12 selected U.S. Geological Survey streamflow-gaging stations in the continental United States.

ADCP discharge measurements were made at the 12 sites in 1994. Twenty-six of the 31 measurements differed by less than 5 percent from the discharges determined with conventional methods. All 31 ADCP measurements were within 8 percent of the conventional method discharges.

The standard deviations of the ADCP measurements ranged from approximately 1 to 6 percent and were generally higher than the measurement errors predicted by error-propagation analysis of ADCP instrument performance. These error-prediction methods assume that the largest component of ADCP discharge measurement error is instrument related. The larger standard deviations indicate that substantial portions of measurement error may be attributable to sources unrelated to ADCP electronics or signal processing and are functions of the field environment.

INTRODUCTION

The collection of river discharge data is an important aspect of surface-water activities undertaken by the U.S. Geological Survey (USGS). River discharge data is collected at more than 7,200 streamflow-gaging stations throughout the nation (Wahl and others, 1995). These data usually are obtained by mechanical, current-meter measurements of river discharge made from boats at numerous data-collection sites (Rantz and others, 1982). This method can be time consuming, costly, and potentially hazardous.

In 1992, RD Instruments[1] introduced a broadband acoustic Doppler current profiler (hereafter referred to as an acoustic Doppler current profiler or ADCP). This device uses acoustic pulses to measure water velocities and depths. The manufacturer's specifications for these units indicate that they would have sufficient resolution and precision to permit their use in making river discharge measurements in water as shallow as 4 ft. Potential efficiency gains from the use of ADCP's could lead to better records of river discharge obtained at lower costs than conventional methods.

[1]The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Quantitative information on the performance and accuracy of ADCP's in the field environment is rare. In order to develop this information, the USGS undertook field evaluations of ADCP performance and measurement precision by comparing ADCP measurements of river discharge to discharge data obtained by conventional methods. Initially, more than 130 sites were considered as potential evaluation sites; however, because of limitations on funding, time, and logistical constraints, the list was reduced to 12 sites that best met selection criteria. To ensure sampling of a wide variation in flow and channel characteristics, the study sites were selected throughout the continental United States. The evaluations began in April 1994; by July 1994, evaluations had been conducted at nine sites. In November 1994, the evaluations were completed at the remaining three sites.

Purpose and Scope

The purpose of this report is to document evaluations of ADCP discharge measurements at 12 USGS streamflow-gaging sites in the continental United States. The ADCP discharge measurements are evaluated by a comparison with river discharges determined by USGS conventional methods. The evaluation also considered sources of measurement error for the ADCP discharge measurements.

This report is limited to the evaluation of ADCP discharge measurements made on inland rivers under steady-flow conditions. For the 12 evaluation sites, channels at all ADCP discharge measurement sections had average depths of more than 5 ft, and mean velocities of at least 0.7 ft/s. None of the evaluation site rivers was affected by tides or other known sources of variable backwater at the streamflow-gaging station locations, and none was measured during flood conditions.

Location and Characteristics of Evaluation Sites

The evaluation sites cover an extensive geographic area (fig. 1) and sample a wide range of river characteristics (table 1). Channel widths at ADCP discharge measurement sections varied from approximately 140 ft for the Kankakee River at Shelby, Ind., (site 11) to 3,600 ft for the Susquehanna River at Harrisburg, Pa. (site 6). The Clark Fork at St. Regis, Mont., (site 2) had the shallowest channel with a mean depth of approximately 5 ft and a maximum depth of about 7 ft; the deepest channel occurred on the Connecticut River at North Walpole, N.H., (site 9) with a mean channel depth of about 21 ft and a maximum depth of approximately 31 ft. Mean velocities ranged from approximately 0.7 ft/s for the Brazos River near Bryan, Tex., (site 1) to 3.8 ft/s for the Snohomish River near Monroe, Wash., (site 5). Discharges ranged from 768 ft^3/s for the Brazos River (site 1) to 59,800 ft^3/s for the Susquehanna River near Marietta, Pa. (site 7).

Channels ranged from deep, uniform cross sections such as the Connecticut River (fig. 2, site 9) to shallow, irregular channels such as the Susquehanna River at Harrisburg (site 6). Several sites had channels that were deeper on one side—most notably the Oswego River at Oswego, N.Y., (site 8) that had a deep navigation channel.

Other conditions also varied from site to site (table 1). River bottoms at measurement sections ranged from a smooth consistency of sand and silt at the Kankakee River (site 11), to rocky bottoms at the Kootenai River (site 3). Turbidity was not measured at any site; however, site observations indicated that a range of turbidities was encountered. For example, the water was clear on the Kootenai River, whereas water at the Brazos River site appeared muddy. Flow conditions at most sites were steady and uniform across the channel. A notable exception was the Oswego River site, where flow was turbulent with heavy waves and eddying on one side of the channel.

EXPLANATION

▲1 EVALUATION SITE

EVALUATION SITE NUMBER	STREAMFLOW-GAGING STATION NAME	STREAMFLOW-GAGING STATION NUMBER
1	Brazos River at State Highway 21 near Bryan, Texas	08108700
2	Clark Fork at St. Regis, Montana	12354500
3	Kootenai River below Libby Dam near Libby, Montana	12301933
4	Willamette River at Salem, Oregon	14191000
5	Snohomish River near Monroe, Washington	12150800
6	Susquehanna River at Harrisburg, Pennsylvania	01570500
7	Susquehanna River at Marietta, Pennsylvania	01576000
8	Oswego River at Lock 7, Oswego, New York	04249000
9	Connecticut River at North Walpole, New Hampshire	01154500
10	St. Joseph River at Elkhart, Indiana	04101000
11	Kankakee River at Shelby, Indiana	05518000
12	Illinois River at Marseilles, Illinois	05543500

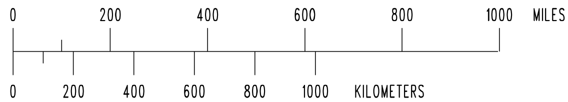
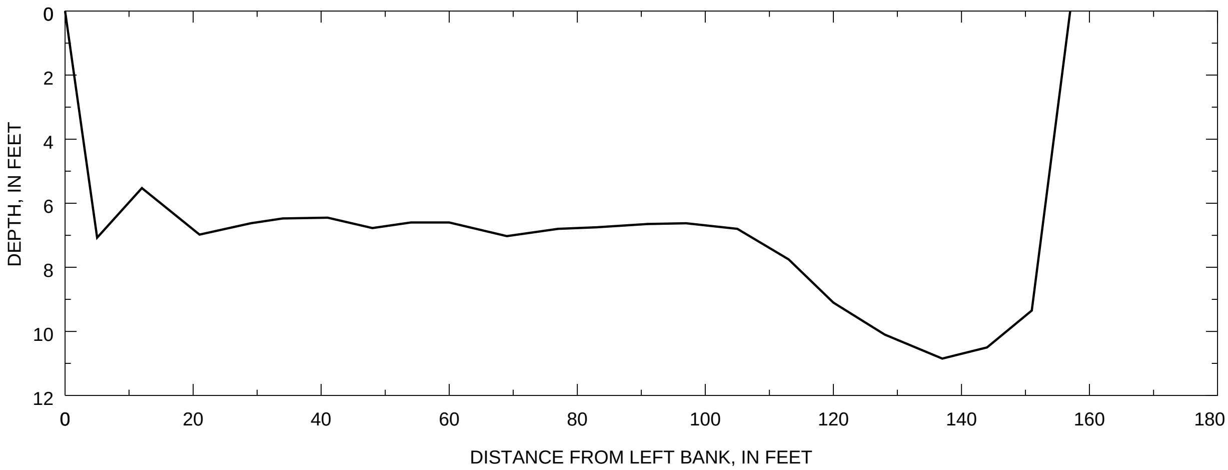
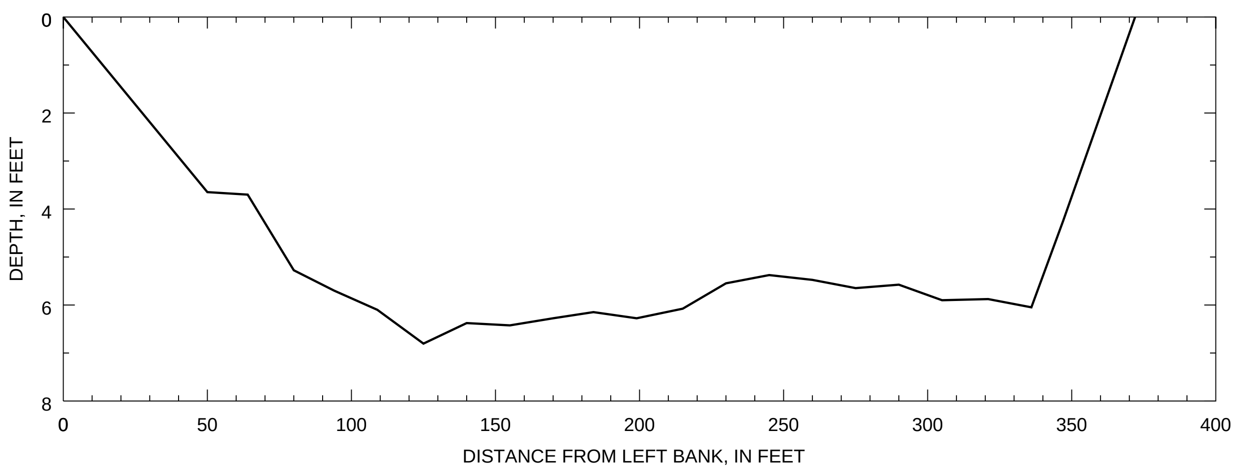


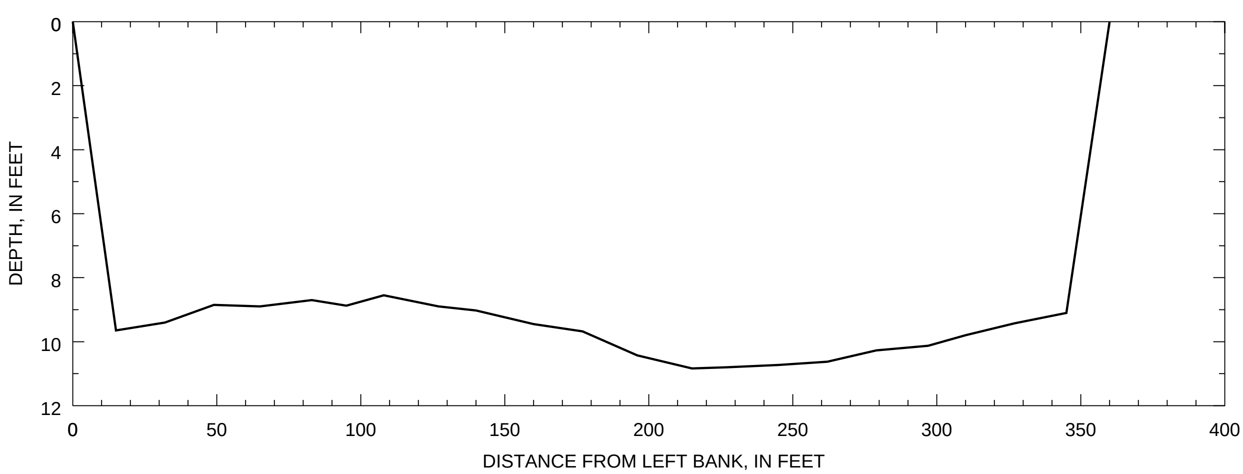
Figure 1. Map showing location of acoustic Doppler current profiler sites in the conterminous United States of America. States with measurement sites are outlined with a bold line.



Site 1, Brazos River near Bryan, Tex.

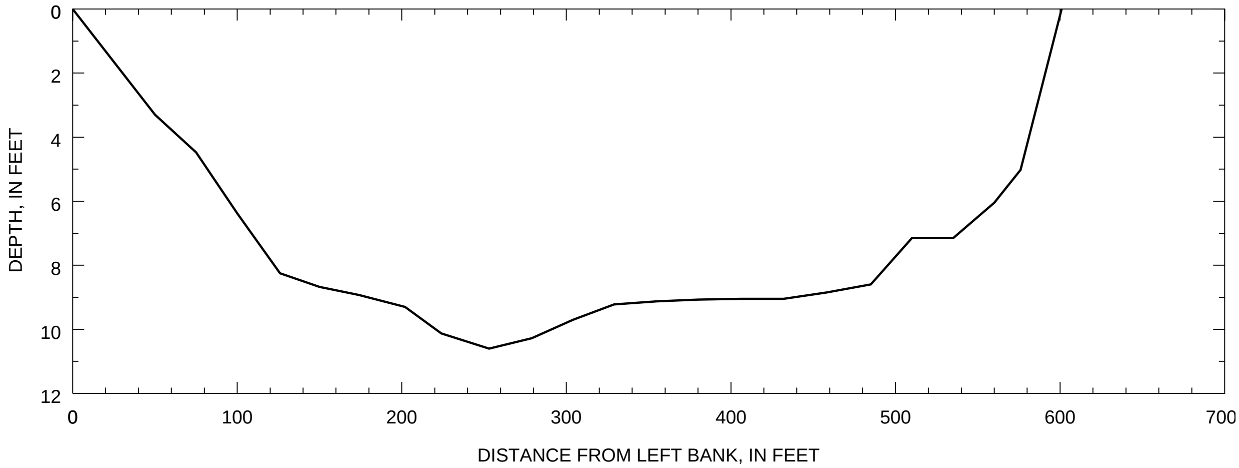


Site 2, Clark Fork at St. Regis, Mont.

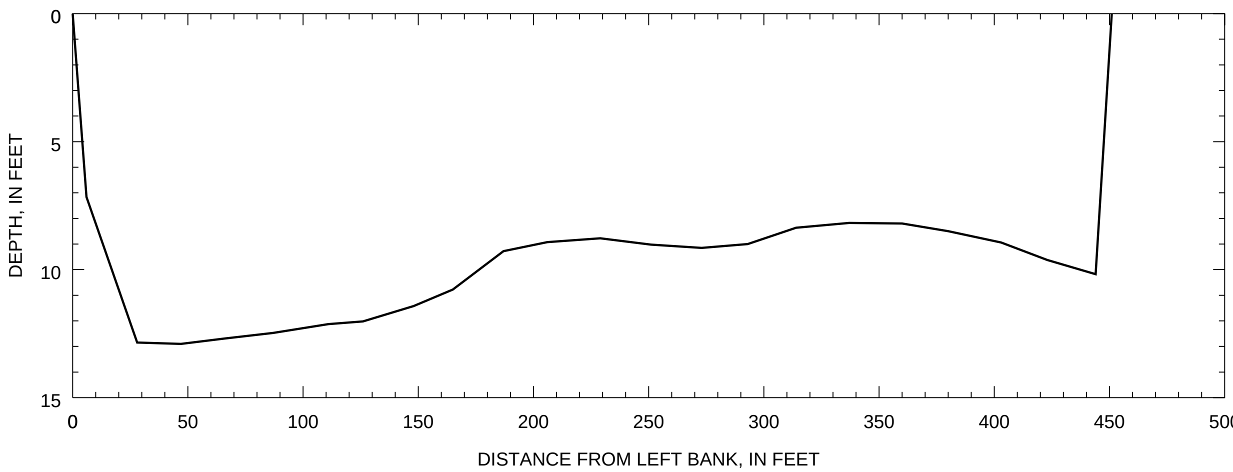


Site 3, Kootenai River below Libby Dam, near Libby Mont.

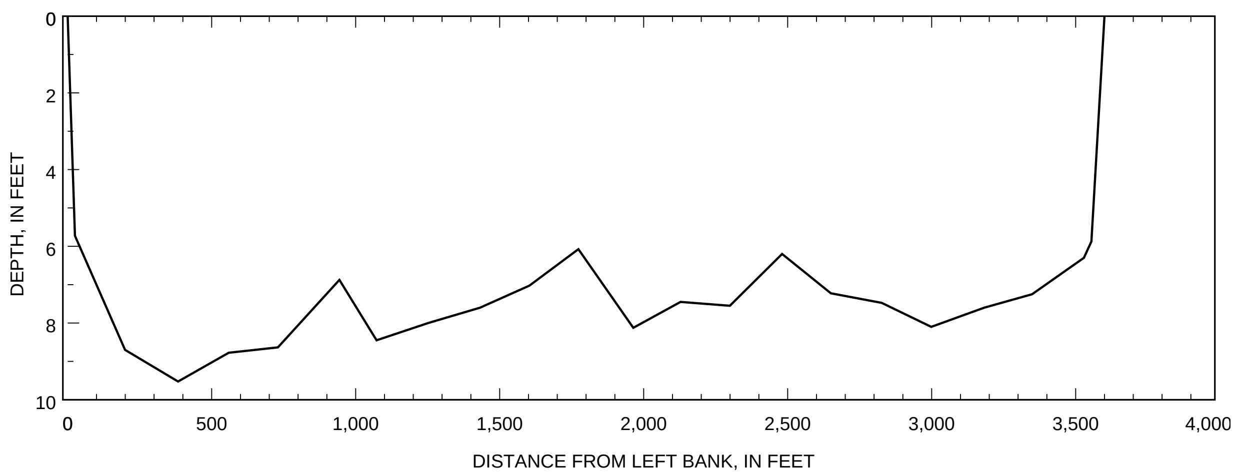
Figure 2. Channel cross sections at evaluation sites.



Site 4, Willamette River at Salem, Oreg.

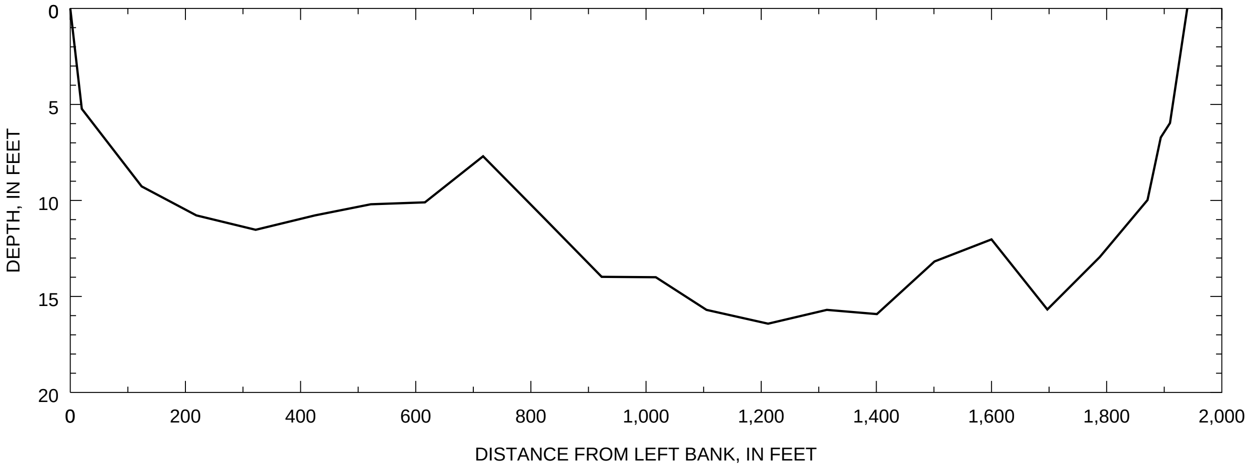


Site 5, Snohomish River near Monroe, Wash.

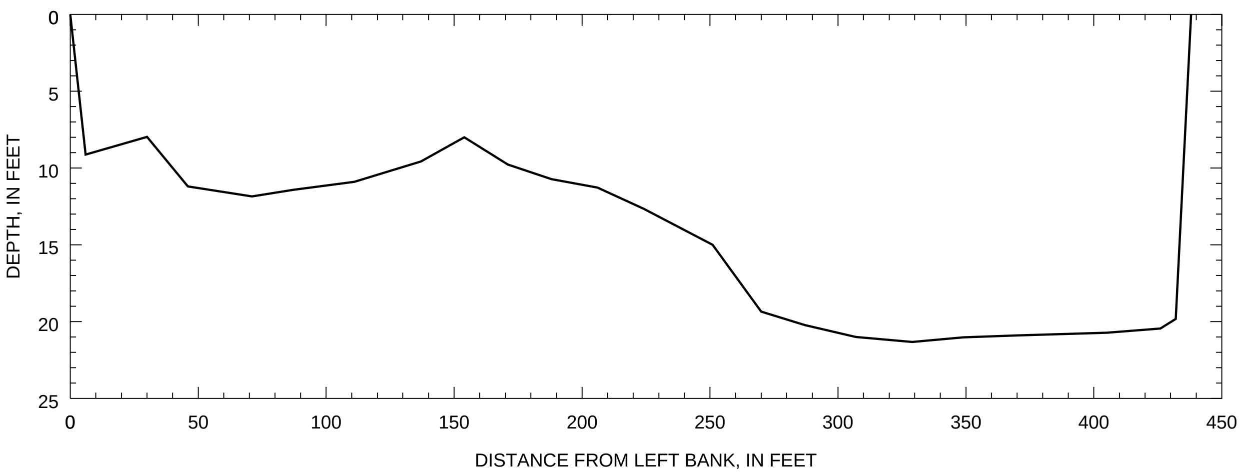


Site 6, Susquehanna River at Harrisburg, Pa.

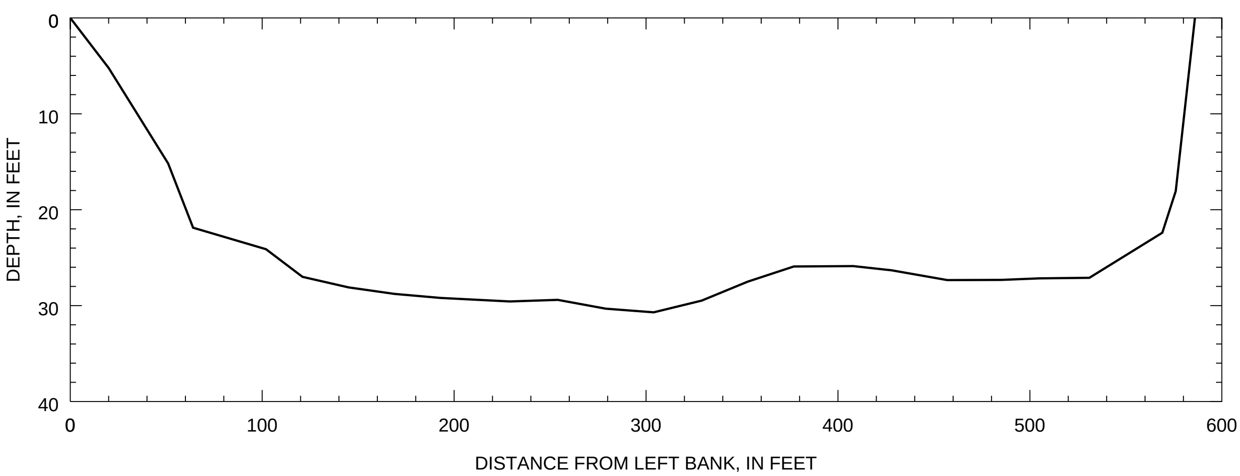
Figure 2. Channel cross sections at evaluation sites.



Site 7, Susquehanna River at Marietta, Pa.

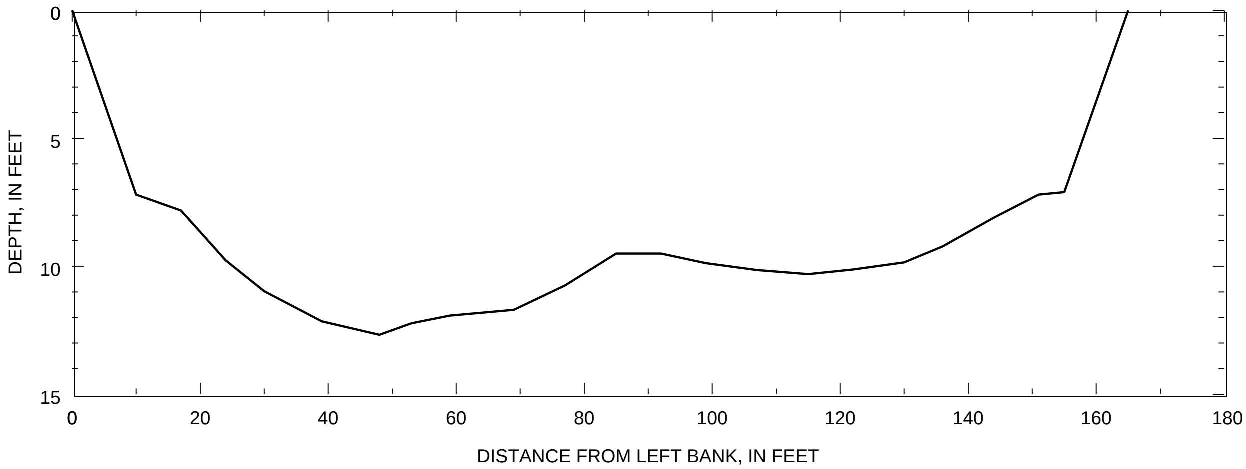


Site 8, Oswego River at Lock 7, Oswego, N.Y.

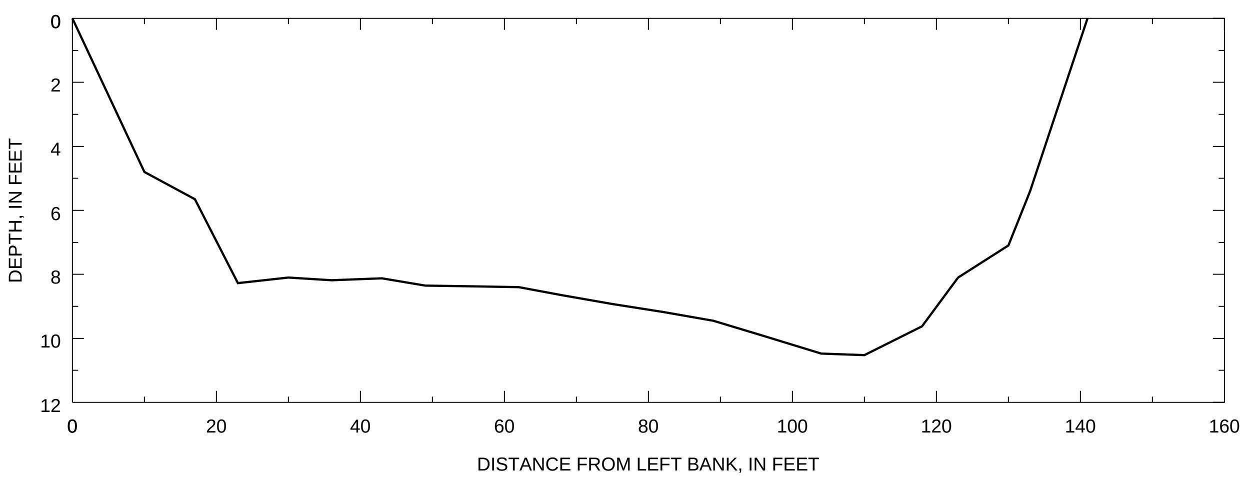


Site 9, Connecticut River at North Walpole, N.H.

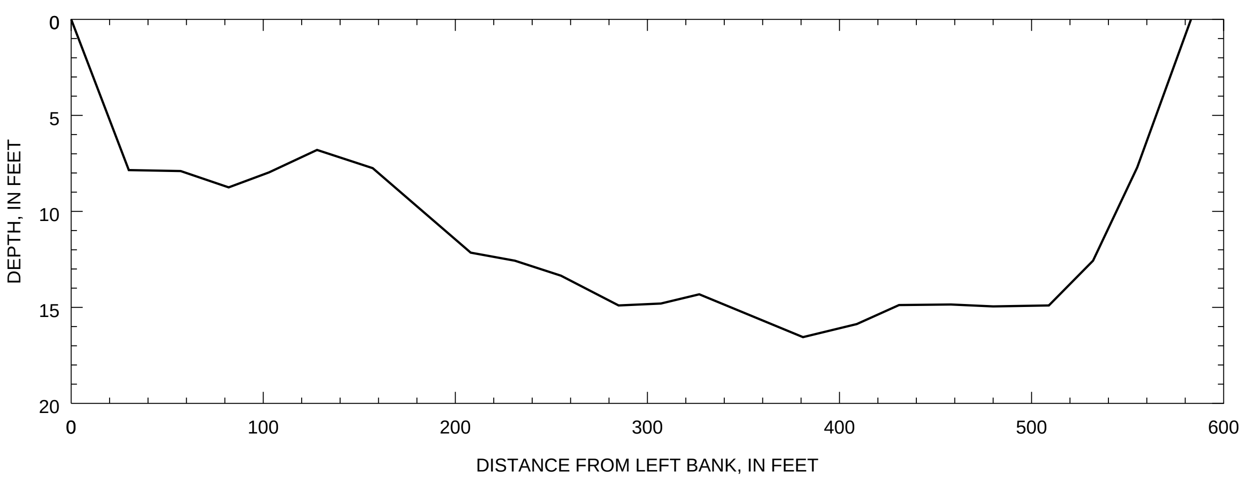
Figure 2. Channel cross sections at evaluation sites.



Site 10, St. Joseph River at Elkhart, Ind.



Site 11, Kankakee River at Shelby, Ind.



Site 12, Illinois River at Marseilles, Ill.

Figure 2. Channel cross sections at evaluation sites.

Table 1. Selected characteristics of channel sections at evaluation sites

[ADCP, acoustic Doppler current profiler; ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

ADCP evaluation site number (fig. 1)	Site name	Width (ft)	Mean depth (ft)	Maximum depth (ft)	Area (ft^2)	Mean velocity (ft/s)	Discharge (ft^3/s)	Observations of river conditions
1	Brazos River at State Highway 21 near Bryan, Tex.	160	7	11	1,110	0.7	758	Muddy water, uniform flow, sand bottom
2	Clark Fork at St. Regis, Mont.	370	5	7	1,850	2.4	4,380	Clear water, uniform flow, rock and gravel bottom
3	Kootenai River below Libby Dam near Libby, Mont.	360	9	11	3,320	1.2	3,860	Clear water, uniform flow, rock and gravel bottom
4	Willamette River at Salem, Oreg.	600	8	11	4,540	3.1	13,900	Uniform flow
5	Snohomish River near Monroe, Wash.	450	10	13	4,490	3.8	16,300	Uniform flow
6	Susquehanna River at Harrisburg, Pa.	3,600	8	10	27,100	2.0	55,400	Uniform flow; irregular, wide, and shallow channel section
7	Susquehanna River at Marietta, Pa.	1,940	12	16	23,200	2.6	59,800	Uniform flow, irregular channel section
8	Oswego River at Lock 7, Oswego, N.Y.	440	15	21	6,400	2.4	16,500	Turbulent flow with eddies on sides of channel, irregular channel section
9	Connecticut River at North Walpole, N.H.	590	25	31	14,700	1.2	16,400	Uniform flow; regular, deep channel section located in a reservoir pool
10	St. Joseph River at Elkhart, Ind.	165	10	13	1,540	1.7	2,570	Uniform flow and gravel bottom
11	Kankakee River at Shelby, Ind.	140	8	11	1,100	2.1	2,320	Muddy water, uniform flow, regular channel section, sand bottom
12	Illinois River at Marseilles, Ill.	580	12	17	6,700	1.8	12,600	Uniform flow

Measurement sections at the Kootenai River (site 3), St. Joseph River (site 10), and the Illinois River (site 12) were located below and in proximity to a lock system or dam. At the Connecticut River (site 9), the ADCP measurement section was located above a dam and in a reservoir pool.

Acknowledgments

The author thanks the numerous USGS personnel who assisted with the evaluations. Jerry Dean and James Dubuisson of Lockheed Stennis Operations constructed a mount for the ADCP's that worked for all evaluation sites. Thadd Pratt of the U.S. Army Corps of Engineers and several USGS personnel reviewed ADCP data. James R. Marsden, Michael Metcalf, Christopher Humphries, and James Rodgers of RD Instruments are thanked for their ADCP advice and technical support.

DESCRIPTION OF ACOUSTIC DOPPLER CURRENT PROFILER

The main external components of an ADCP are a transducer assembly and a pressure case. The transducer assembly consists of four transducers that operate at a fixed, ultrasonic frequency, typically 300, 600, or 1200 kilohertz (kHz). The transducers are horizontally spaced 90 degrees apart on the transducer assembly; all transducers have the same fixed angle from the vertical, referred to as a "beam angle," that is typically 20 or 30 degrees. The transducer assembly may have a convex or concave configuration. The pressure case is attached to the transducer assembly and contains most of the instrument electronics (fig. 3).

When an ADCP is deployed from a moving boat, it is connected by cable to a power source and to a portable microcomputer. The computer is used to program the instrument, monitor its operation, and collect and store the data.

Operational Principles

The ADCP measures velocity magnitude and direction using the Doppler shift of acoustic energy reflected by material suspended in the water column. The ADCP transmits pairs of short acoustic pulses along a narrow beam from each of the four transducers. As the pulses travel through the water column, they strike suspended sediment and organic particles (referred to as "scatterers") that reflect some of the acoustic energy back to the ADCP. The ADCP receives and records the reflected pulses. The reflected pulses are separated by time differences into successive, uniformly spaced volumes called "depth cells." The frequency shift (known as the "Doppler effect") and the time-lag change between successive reflected pulses are proportional to the velocity of the scatterers relative to the ADCP. The ADCP computes a velocity component along each beam; because the beams are positioned orthogonally to one another and at a known angle from the vertical (usually 20 or 30 degrees), trigonometric relations are used to compute three-dimensional water-velocity vectors for each depth cell. Thus, the ADCP produces vertical velocity profiles composed of water speeds and directions at regularly spaced intervals.

ADCP discharge measurements are made from moving boats; therefore, the boat velocities must be subtracted from the ADCP measured water velocities. ADCP's can compute the boat speed and direction using "bottom tracking" (RD Instruments, 1989). The channel bottom is tracked by measuring the Doppler shift of acoustic pulses reflected from the bottom to measure boat speed; direction is determined with the ADCP on-board compass. If the channel bottom is stationary, this technique accurately measures the velocity and direction of the boat. The bottom-track echoes also are used to estimate the depth of the river (Oberg, 1994).

ADCP discharge measurements are made by moving the ADCP across the channel while it collects vertical-velocity profile and channel-depth

Figure 3. Typical acoustic Doppler current profiler. Photograph courtesy of RD instruments.

data. The ADCP transmits acoustic pulses into the water column. The groups of pulses include water-profiling pulses and bottom-tracking pulses. A group of pulses containing an operator-set number of water-profiling pulses (or water pings) interspersed with an operator-set number of bottom-tracking pulses (or bottom pings) is an “ensemble”; a single ensemble may be compared to a single vertical from a conventional discharge measurement (Oberg, 1994).

A single crossing of the stream from one side to the other is referred to as a “transect.” Each transect normally contains many ensembles. When depth and water velocities are known for each ensemble, an ADCP can compute the discharge for each ensemble. The discharge from all transect ensembles are summed, yielding a computation of river discharge for the entire transect. ADCP operational parameters (such as depth-cell length, number of water and bottom pings per ensemble, and time between pings) are set by the instrument user. The settings for these parameters are governed by river conditions (such as depth and water speed) and also by the frequency and physical configuration of the ADCP unit (RD Instruments, 1989).

Operational Limitations

ADCP’s are subject to operational limitations that directly influence the quality of discharge measurements. One of these limitations is the inability of an ADCP to collect data from all areas of river channels. Unmeasurable subsections are encountered in the making of almost all ADCP discharge measurements. Unmeasurable areas include a top, bottom, and side or edge subsections (fig. 4). (Hereafter, subareas of channels measured and not measured by an ADCP will be referred to as “subsections.”)

The inability of an ADCP to collect data from the top subsection is the result of three factors: transducer draft, blanking distance, and lag. “Transducer draft” refers to the distance that the transducers are submerged. The transducers must be fully submerged during the discharge measurement, and the ADCP cannot measure the portion of the water column above the transducers. “Blanking distance” refers to a zone directly below the transducers in which echoes cannot be received by the transducers because of their physical properties. “Lag” is the distance between successive portions of the pings transmitted by an ADCP. The sum of the transducer draft, blanking distance, and lag is the length of the top portion of the water column that cannot be profiled by the ADCP.

Water velocities also cannot be measured near the streambed (bottom subsection) because of side-lobe interference. Side-lobe interference results from the striking of the channel bottom by side-lobe energy from each of the four acoustic beams. The reflections of the side-lobe energy from the channel bottom are strong and overwhelm echoes from scatterers near the channel bottom. The thickness of the bottom subsection is typically about 6 percent of the distance from the channel bottom to the ADCP for transducers with 20-degree beam angles.

Another unmeasured subsection is the edge subsection. In many instances, depths are too shallow near river edges for the ADCP to measure. In the case of a channel with a vertical bank, an ADCP signal often will strike the bank and return a false bottom echo, leading to estimation of less depth near the bank than is actually present. When the ADCP begins to underestimate the actual depth, data collection should stop, leaving the portion of the channel near the wall (the edge subsection) unmeasured.

The ADCP data-collection and processing software approximates the discharge in the unmeasured subsections by extrapolating water-velocity data from the measured subsection (fig. 4) and multiplying this velocity by the unmeasured subsection area. Velocities for the top and bottom subsections are estimated by extending the measured vertical-velocity profile through the unmeasured subsections. Two extrapolation schemes are available for extending the vertical-

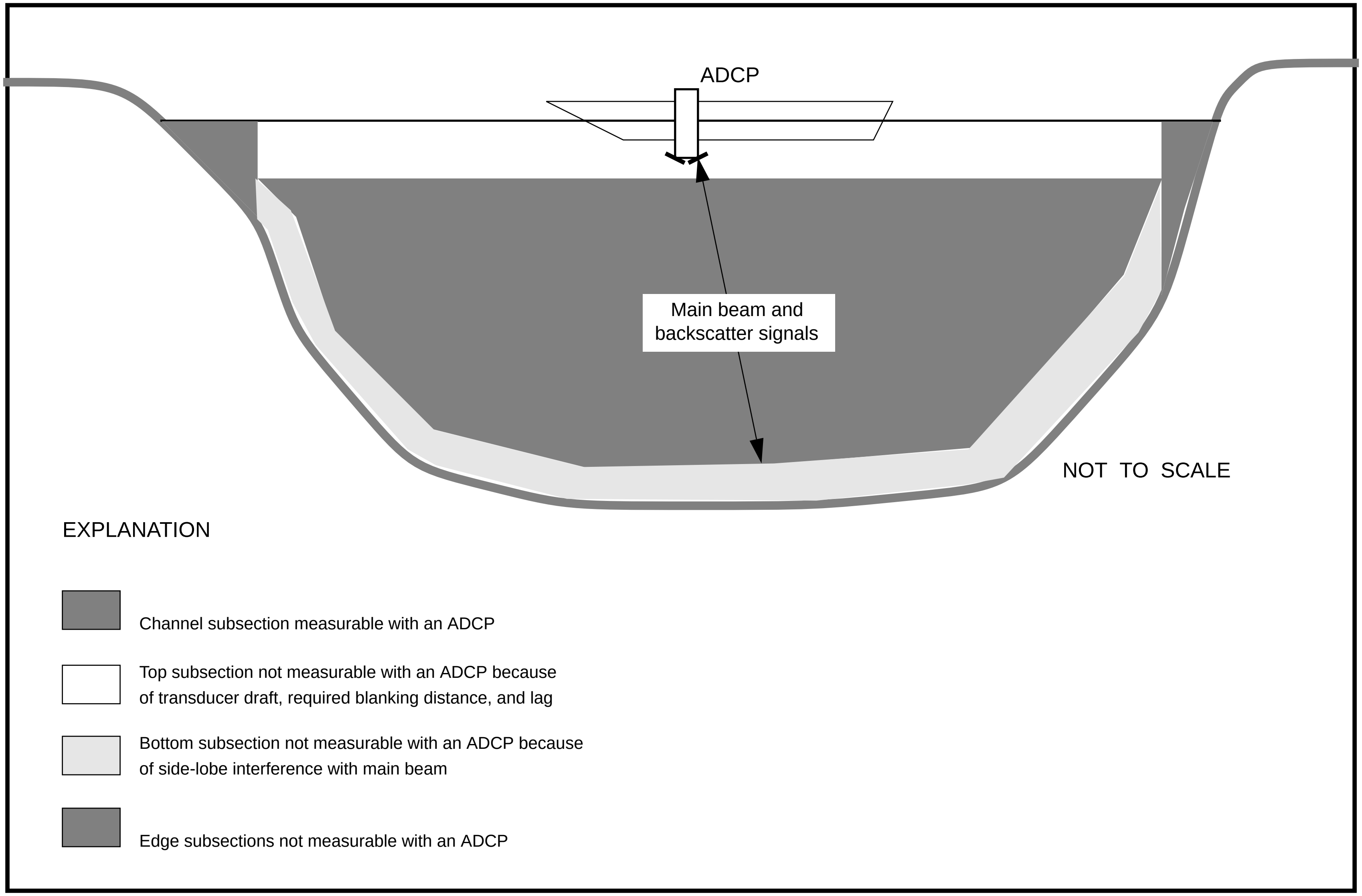


Figure 4. Sketch showing the subsections of a river channel not measured by an acoustic Doppler current profiler (ADCP).

velocity profile: a constant-extrapolation scheme and a power-law extrapolation scheme. If the constant-extrapolation scheme is used, the last depth-cell velocity on the top of the measured subsection is extended through the top subsection to the water surface. Similarly, the constant-extrapolation scheme, if used for bottom subsection, will extend the bottom depth-cell velocity to the channel bottom. The power-law extrapolation scheme fits a power curve to the depth-cell velocities in the measured subsection and extends the curve through the top or bottom subsections (RD Instruments, 1989). The exponent of the power curve is set by the user. Chen (1989, 1991) presents the power law for vertical-velocity profiles and suggests an exponent of 1/6 for the power curve (Oberg, 1994). Typically, the power-law extrapolation with a 1/6 power-curve exponent is used for the bottom subsection, and either the power-law or constant extrapolation is used for the top subsection.

The ADCP software computes discharge in the edge subsections by estimating the mean velocity and area of the subsections. For most natural channels, the edge subsections are assumed to be triangular; the area is computed by multiplying the depth from the last measured ADCP subsection by the distance to edge-of-water (estimated and entered by the user), then dividing by two. The estimated velocity of a triangular edge subsection is computed by multiplying the mean velocity magnitude of the last measured ADCP subsection by 0.707 (Simpson and Oltman, 1993, p. 9). For a channel with vertical edge walls, the edge sections would have a rectangular area; the mean velocity of an edge subsection with a vertical edge would be estimated by multiplying the last measured ADCP subsection mean velocity by 0.91 (as recommended in Rantz and others, 1982, p. 82) when estimating velocities near vertical walls.

Other operational limitations also can affect discharge measurements. Boat speed can significantly affect the precision of ADCP discharge measurements. As boat speed increases, measurement precision decreases. For measurements on slow-moving streams in particular, boats must cross the stream very slowly to minimize measurement error (Michael Simpson, U.S. Geological Survey, written commun., 1994). Pitching and rolling of an ADCP during a discharge measurement, such as when waves are present, also may affect measurement error. ADCP's have a pitch and roll indicator that can be activated during data collection to compensate for pitch and roll.

MEASUREMENT OF RIVER DISHARGE AT EVALUATION SITES

ADCP river discharge measurements were made at 12 evaluation sites. For comparison purposes, USGS conventional measurement methods also were used to determine discharge at the 12 sites.

Acoustic Doppler Current Profiler Measurements

The ADCP units were mounted on boats to collect the discharge-data collection (fig. 5). Discharge measurements were attempted with either a 1200- or a 600-kHz frequency ADCP, or both, at all evaluation sites. The 1200-and 600-kHz units were used in the evaluations because these are the types of ADCP's most commonly used by the USGS. ADCP's used at the evaluation sites had 20-degree transducer-beam angles. Pitch and roll compensation was active on all units.

ADCP data-collection parameters are set by the instrument operator with the use of a configuration file. These files are created on the microcomputer using the ADCP software or a text-editor program and then are downloaded to the ADCP. Selected ADCP-configuration parameters for each of the evaluation sites are given in table 2. Selected configuration files used are included in appendix 1. More detailed information on configuration files may be found in RD Instruments (1993).

Figure 5. Boat equipped for ADCP measurements.

Table 2. Selected acoustic Doppler current profiler configuration parameters for data collection at evaluation sites

[ADCP, acoustic Doppler current profiler; kHz, kilohertz; cm, centimeters; ms, milliseconds]

ADCP evaluation site number (fig. 1)	Site name	ADCP frequency (kHz)	Depth-cell length (cm)	Number of depth cells	Pings per ensemble		Time between pings (ms)	Blank after transmit (cm)
					Water	Bottom		
1	Brazos River at State Highway 21 near Bryan, Tex.	1200	25	24	4	3	5	40
2	Clark Fork at St. Regis, Mont.	1200	25	16	4	3	0	40
3	Kootenai River below Libby Dam near Libby, Mont.	1200	25	24	4	3	0	40
3	Kootenai River below Libby Dam near Libby, Mont.	600	50	12	4	3	0	50
4	Willamette River at Salem, Oreg.	1200	25	24	4	3	0	40
5	Snohomish River near Monroe, Wash.	1200	25	28	4	3	0	40
5	Snohomish River near Monroe, Wash.	600	50	14	4	3	0	50
6	Susquehanna River at Harrisburg, Pa.	1200	25	24	4	3	0	40
7	Susquehanna River at Marietta, Pa.	1200	50	12	4	3	0	40
7	Susquehanna River at Marietta, Pa.	600	50	12	4	3	0	50
8	Oswego River at Lock 7, Oswego, N.Y.	600	50	16	4	3	0	50
9	Connecticut River at North Walpole, N.H.	1200	50	35	4	3	0	50
9	Connecticut River at North Walpole, N.H.	600	50	35	4	3	0	50
9	St. Joseph River at Elkhart, Ind.	1200	25	22	4	3	9	50
10	St. Joseph River at Elkhart, Ind.	600	35	22	4	1	9	50
10	Kankakee River at Shelby, Ind.	600	35	22	4	1	9	50
11	Illinois River at Marseilles, Ill.	1200	25	40	5	4	0	50

An ADCP is operated by setting a mode parameter for water profiling and bottom tracking. The user-set mode parameters control the ADCP ping scheme. Water and bottom modes 1, 2, 4, and 5 were available at the time of the evaluation effort; mode 4 was used for all evaluation efforts because this is an accepted mode for river discharge measurements on rivers with depths greater than 5 ft and velocities greater than 0.4 ft/s. A detailed description of ADCP modes may be found in RD Instruments (1993).

After an ADCP's operational status was determined and the proper configuration file loaded, the collection of discharge data began. Data were collected at each site by completing a series of transects with each instrument. One transect is a single crossing of the stream channel from one side to the other; a single transect will yield one value of total stream discharge. At least six transects were run for each ADCP used at an evaluation site. At most sites, two series of at least six transects were completed for each ADCP unit used. The transects were run in alternating directions across the stream. The transects were started and ended near the stream edges, close to the point at which the water was deep enough for the ADCP to begin velocity profiling. Channel markers were placed at transect start and end points for most sites so that the unmeasured edge-subsection distances could be estimated. Edge-subsection distances were estimated by measurement with a steel tape or by distance marks on a steel tag line; in some cases, distances were estimated visually with the boat length as a reference. At least 35 ensembles were collected for all successful transects. All discharge data were collected and stored on the microcomputer.

Discharge-extrapolation schemes for unmeasured subsections were chosen on the basis of analysis of the vertical-velocity distributions in the measured channel subsections. The power-law extrapolation scheme with a 1/6 exponent was used for the unmeasured top and bottom subsections for all transects, with the exception of those from the Illinois River (site 12). At this site, the constant-extrapolation scheme was used for the unmeasured top subsection, and the power-law extrapolation scheme with a 1/6 exponent was used for the unmeasured bottom subsection.

Unmeasured edge-subsection discharges were estimated with the ADCP software; the triangular-area edge-subsection assumption and velocity multiplier used for natural channels was applied to all transects from all evaluation sites except for the Oswego River (site 8). This site had vertical edge walls; therefore, rectangular edge subsection areas were assumed.

After completion of the measurements, all transects were processed and analyzed. The first step in data processing was to check all transects for obvious data-quality problems. Transects with data-quality problems (such as those that were not complete because of inadvertent termination of data collection or those containing many ensembles with no velocities) were not used. About one-third of the measurements had some transect data-quality problems. These problems eliminated all data collected from the 600-kHz ADCP for four evaluation sites: the Brazos River (site 1), Clark Fork (site 2), Susquehanna River at Marietta (site 7), and Willamette River (site 4). The water depths at three of these sites were such that 25-cm depth cells were used for data collection with the 600-kHz unit. The smallest manufacturer-recommended depth-cell size for mode-4 operation of 600-kHz ADCP's is 50 cm. The 25-cm depth-cell sizes produced unrealistic velocities in many of the depth cells. The Willamette River was deep enough to use 50-cm depth cells with the 600-kHz unit; however, 25-cm depth cells erroneously were used to calculate invalid depth-cell velocities. As a result, the data collected with the Willamette River 600-kHz ADCP were eliminated from the evaluation process. Depth cells of 35 cm were used for 600-kHz measurements at the Kankakee River (site 11) and St. Joseph River (site 10). The 35-cm depth cells were also smaller than the recommended 50-cm depth cells; however, unrealistic velocities were not present in any depth cells. As a result, the 600-kHz ADCP discharge measurements that were made using 35-cm depth cells were used for the evaluations.

The quality of ADCP data from the evaluation sites was evaluated with regard to two criteria, “backscatter intensity” and “pulse-to-pulse correlation.” Backscatter intensity is a parameter measured by ADCP’s and refers to the intensity of echoes returning from particles in the water. Backscatter intensity was sufficient at all sites for water-velocity computation. A pulse-to-pulse correlation-coefficient measures the correlation between echoes from the dual pings that an ADCP transmits. The pulse-to-pulse-correlation coefficient was within acceptable bounds for the evaluation-site data.

The discharge values from individual transects within a transect series were averaged to yield a transect-series mean discharge. No less than four and no more than six transects were used to compute the transect-series mean discharge. For this report, a transect-series mean discharge is considered to be a single measurement of river discharge, referred to as an “ADCP discharge measurement.”

At least one ADCP discharge measurement was completed at all evaluation sites. Data collection was attempted with the 1200- and 600-kHz units at 9 of the 12 evaluation sites. The 1200-kHz unit could not be used at the Oswego River site because the unit failed before measurements could be made. The 1200-kHz ADCP was not used at the Kankakee River because there was an urgent need elsewhere for the 1200-kHz unit. The 600-kHz unit was not used at the Illinois River site because the unit was being used for another project during this period.

A total of 31 ADCP discharge measurements (table 3) were computed for evaluation purposes; 18 measurements were from a 1200-kHz ADCP, and 13 measurements were from a 600-kHz ADCP.

Conventional Measurements

To provide comparative information useful for evaluating the ADCP measurements, river discharge at all evaluation sites also was determined using conventional methods. Conventional methods generally involve the use of pre-established stage/discharge relations or ratings. Historically, a rating is constructed by making measurements of river discharge and plotting the discharge value against the stage of the stream at the time of the measurement. This method involves measuring width, depth, and velocity at a number of vertical sections across a stream. Depths are measured by sounding with heavy weights, and velocity is measured with rotating-cup current meters. As water flows past the meter, the meter cups rotate at speeds proportional to current velocity. The product of depth, width, and velocity is the discharge.

The conventional river discharge data used for evaluating the ADCP measurements were computed by applying the discharge rating to the stage of the river at the time of the ADCP measurement. At 7 of the 12 evaluation sites, supplemental information was obtained by making conventional current-meter measurements on the same day as the ADCP measurement. At two sites, the Brazos River (site 1) and the Snohomish River (site 5), the current-meter measured discharge differed from the rating discharge by more than 5 percent. Adjustments using methods described in detail by Rantz and others (1982) were made to the ratings at these two sites to cause them to agree more closely with the current-meter measurement (table 4).

Table 3. Acoustic Doppler current profiler measurement data for evaluation sites

[ADCP, acoustic Doppler current profiler; kHz, kilohertz; ft^3/s, cubic feet per second]

ADCP evaluation measurement number	Site name	ADCP frequency (kHz)	Number of transects averaged to compute measurement	Measurement discharge (ft^3/s)
1	Brazos River at State Highway 21, near Bryan, Tex.	1200	6	758
2	Brazos River at State Highway 21, near Bryan, Tex.	1200	6	745
3	Clark Fork at St. Regis, Mont.	1200	6	4,290
4	Clark Fork at St. Regis, Mont.	1200	5	4,380
5	Kootenai River below Libby Dam near Libby, Mont.	1200	4	3,860
6	Kootenai River below Libby Dam near Libby, Mont.	1200	4	3,880
7	Kootenai River below Libby Dam near Libby, Mont.	600	6	3,780
8	Kootenai River below Libby Dam near Libby, Mont.	600	6	3,800
9	Willamette River at Salem, Oreg.	1200	6	13,900
10	Willamette River at Salem, Oreg.	1200	6	14,200
11	Snohomish River near Monroe, Wash.	1200	5	16,300
12	Snohomish River near Monroe, Wash.	1200	4	16,100
13	Snohomish River near Monroe, Wash.	600	6	16,800
14	Snohomish River near Monroe, Wash.	600	6	16,600
15	Susquehanna River at Harrisburg, Pa.	1200	4	55,400
16	Susquehanna River at Marietta, Pa.	1200	6	59,400
17	Susquehanna River at Marietta, Pa.	600	6	59,800
18	Oswego River at Lock 7, Oswego, N.Y.	600	6	16,500
19	Oswego River at Lock 7, Oswego, N.Y.	600	6	16,500
20	Connecticut River at North Walpole, N.H.	1200	6	16,400
21	Connecticut River at North Walpole, N.H.	1200	6	16,600
22	Connecticut River at North Walpole, N.H.	600	6	16,100
23	Connecticut River at North Walpole, N.H.	600	6	16,300
24	St. Joseph River at Elkhart, Ind.	1200	6	2,570
25	St. Joseph River at Elkhart, Ind.	1200	6	2,580
26	St. Joseph River at Elkhart, Ind.	600	4	2,600
27	St. Joseph River at Elkhart, Ind.	600	5	2,560
28	Kankakee River at Shelby, Ind.	600	6	2,280
29	Kankakee River at Shelby, Ind.	600	5	2,320
30	Illinois River at Marseilles, Ill.	1200	6	12,600
31	Illinois River at Marseilles, Ill.	1200	4	12,500

Table 4. Conventional discharge data and discharge-rating adjustments

[ADCP, acoustic Doppler current profiler; ft^3/s, cubic feet per second; --, no data available

ADCP evaluation site number (fig. 1)	Site name	Stream-gaging station rating discharge (ft^3/s)	Conventional current-meter discharge (ft^3/s)	Difference, current meter from rating discharge, in percent	Temporary adjustment to rating discharge[1] (ft^3/s)
1	Brazos River at State Highway 21 near Bryan, Tex.	671	768	14.5	97
2	Clark Fork at St. Regis, Mont.	4,480	4,490	0.3	--
3	Kootenai River below Libby Dam near Libby, Mont.	3,930	3,870	-1.5	--
4	Willamette River at Salem, Oreg.	14,100	--	--	--
5	Snohomish River near Monroe, Wash.	15,600	16,700	5.7	1,100
6	Susquehanna River at Harrisburg, Pa.	53,200	52,500	-1.3	--
7	Susquehanna River at Marietta, Pa.	59,800	--	--	--
8	Oswego River at Lock 7, Oswego, N.Y.	15,400	16,000	3.9	--
9	Connecticut River at North Walpole, N.H.	17,700	17,200	-2.8	--
10	St. Joseph River at Elkhart, Ind.	2,570	--	--	--
11	Kankakee River at Shelby, Ind.	2,340	--	--	--
12	Illinois River at Marseilles, Ill.	12,200	--	--	--

[1]Adjustment to the rating discharge was made because the conventional current meter measurement departed more than 5 percent from the rating discharge; the adjustment equals the difference between the rating and current meter discharges.

EVALUATION OF ACOUSTIC DOPPLER CURRENT PROFILER RIVER DISCHARGE MEASUREMENTS

ADCP discharge measurements from the 12 stream sites were evaluated by comparing the measurements with discharges determined by conventional methods and by error analysis of ADCP discharge measurements.

Comparison of Profiler Discharge Measurements and Conventional Discharge Measurements

The 31 ADCP discharge measurements from the 12 evaluation sites were compared to discharges determined from conventional methods. Twenty-five of the ADCP discharge measurements were within 5 percent of the adjusted rating discharges (table 5). Six ADCP discharge measurements differed by more than 5 percent from the rating discharges. The greatest difference from the rating discharge was 7.9 percent (table 5).

ADCP discharge measurements differed by more than 5 percent from the rating discharges at the Oswego River and Connecticut River sites. For the Oswego River, the two ADCP discharge measurements differed by 7.1 percent from the rating discharge; for the Connecticut River, the difference from the rating discharge of the four ADCP discharge measurements ranged from 6.7 to 7.9 percent. At the Oswego River, the conventional current-meter discharge measurement differed by 4.0 percent from the rating discharge. At the Connecticut River, the conventional current-meter discharge measurement differed by 2.8 percent from the rating discharge. It is standard practice to not make an adjustment to a discharge rating unless a conventional current-meter measurement differs by more than 5 percent from the rating discharge (Rantz and others, 1982). If, however, adjustments were made to the rating discharges for the Oswego and Connecticut Rivers, ADCP discharge measurements 18 and 19 made at the Oswego River would be within 3.1 percent of the adjusted rating discharges for the measurements; ADCP discharge measurements 20, 21, and 22 made at the Connecticut River would be within 5 percent of the adjusted rating discharges for the measurements. ADCP discharge measurement 23 from the Connecticut River would differ by 5.2 percent from the adjusted rating discharge for the measurement.

Analysis of Profiler Measurement Error

ADCP discharge measurement error has a number of possible sources, including velocity-measurement error, errors in discharge extrapolation through unmeasured subsections, and natural velocity fluctuations in the river or stream (Marsden, 1994). An indication of the ADCP discharge measurement error is the standard deviation of the ADCP discharge measurement. The standard deviation of an ADCP discharge measurement is the standard deviation of the series of transect discharges that compose the measurement.

Each ADCP discharge measurement is the sum of the mean discharges from the measured and unmeasured (top, bottom, and edge) channel subsections. Therefore, a standard deviation can be computed for discharge in each subsection; this standard deviation indicates the measurement error of discharge for each subsection, as well as the relative contribution of each subsection to the ADCP discharge measurement error.

Standard deviations of discharge were computed for each subsection in the 31 ADCP measurements (table 6). The standard deviations of discharge are hereafter referred to as “standard deviations,” and the discharge in a subsection is referred to as “subsection discharge.” Standard deviations in the measured subsections ranged from about 1 to 7 percent of the corresponding

Table 5. Comparison of acoustic Doppler current profiler discharge measurements and rating discharges

[ADCP, acoustic Doppler current profiler; ft^3/s, cubic feet per second]

ADCP evaluation measurement number	Site name	Discharge determined from: ADCP measurement (ft^3/s)	Discharge determined from: Station rating[1] (ft^3/s)	Difference, ADCP measurement from station rating discharge, in percent
1	Brazos River at State Highway 21 near Bryan, Tex.	758	768	-1.3
2	Brazos River at State Highway 21 near Bryan, Tex.	745	768	-3.0
3	Clark Fork at St. Regis, Mont.	4,290	4,480	-4.2
4	Clark Fork at St. Regis, Mont.	4,380	4,480	-2.2
5	Kootenai River below Libby Dam near Libby, Mont.	3,860	3,930	-1.8
6	Kootenai River below Libby Dam near Libby, Mont.	3,880	3,930	-1.3
7	Kootenai River below Libby Dam near Libby, Mont.	3,780	3,930	-3.8
8	Kootenai River below Libby Dam near Libby, Mont.	3,800	3,930	-3.3
9	Willamette River at Salem, Oreg.	13,900	14,100	-1.4
10	Willamette River at Salem, Oreg.	14,200	14,100	0.7
11	Snohomish River near Monroe, Wash.	16,300	16,000	1.9
12	Snohomish River near Monroe, Wash.	16,100	16,000	0.6
13	Snohomish River near Monroe, Wash.	16,800	16,700	0.6
14	Snohomish River near Monroe, Wash.	16,600	16,600	0
15	Susquehanna River at Harrisburg, Pa.	55,400	53,400	3.7
16	Susquehanna River at Marietta, Pa.	59,400	59,800	-0.7
17	Susquehanna River at Marietta, Pa.	59,800	59,800	0
18	Oswego River at Lock 7, Oswego, N.Y.	16,500	15,400	7.1
19	Oswego River at Lock 7, Oswego, N.Y.	16,500	15,400	7.1
20	Connecticut River at North Walpole, N.H.	16,400	17,800	-7.9
21	Connecticut River at North Walpole, N.H.	16,600	17,800	-6.7
22	Connecticut River at North Walpole, N.H.	16,100	17,400	-7.5
23	Connecticut River at North Walpole, N.H.	16,300	17,600	-7.4
24	St. Joseph River at Elkhart, Ind.	2,570	2,570	0
25	St. Joseph River at Elkhart, Ind.	2,580	2,570	0.4
26	St. Joseph River at Elkhart, Ind.	2,600	2,570	1.2
27	St. Joseph River at Elkhart, Ind.	2,560	2,570	-0.4
28	Kankakee River at Shelby, Ind.	2,280	2,340	-2.6
29	Kankakee River at Shelby, Ind.	2,320	2,340	-0.8
30	Illinois River at Marseilles, Ill.	12,600	12,200	3.3
31	Illinois River at Marseilles, Ill.	12,500	12,200	2.5

[1]Station rating refers to the stage discharge relation for each streamflow-gaging station.

Table 6. Discharges and standard deviations of discharges for acoustic Doppler current profiler discharge measurements and measurement subsections

[ADCP, acoustic Doppler current profiler; kHz, kilohertz; for each measurement, the mean is in the first row and the standard deviation is in the second row in parentheses ( ) ; top, measured, bottom, left, and right refer to ADCP measurement-channel subsection; see figure 4 for relative locations of these subsections]

ADCP evaluation measurement number	Site name	ADCP frequency (kHz)	Discharge (cubic feet per second)					
			Top	Measured	Bottom	Left	Right	Total
1	Brazos River at State Highway 21, near Bryan, Tex.	1200	416	217	97	11	17	758
			(28)	(16)	(9)	(4)	(9)	(49)
2	Brazos River at State Highway 21, near Bryan, Tex.	1200	405	230	93	8	9	745
			(22)	(11)	(9)	(2)	(5)	(37)
3	Clark Fork at St. Regis, Mont.	1200	2,350	1,100	674	110	50	4,290
			(41)	(52)	(13)	(28)	(22)	(90)
4	Clark Fork at St. Regis, Mont.	1200	2,370	1,170	667	118	51	4,380
			(54)	(82)	(15)	(35)	(6)	(148)
5	Kootenai River below Libby Dam near Libby, Mont.	1200	1,810	1,410	584	34	29	3,860
			(45)	(22)	(20)	(6)	(7)	(36)
6	Kootenai River below Libby Dam near Libby, Mont.	1200	1,830	1,400	579	34	38	3,880
			(40)	(43)	(46)	(10)	(10)	(78)
7	Kootenai River below Libby Dam near Libby, Mont.	600	2,120	942	616	56	50	3,780
			(36)	(10)	(30)	(19)	(8)	(61)
8	Kootenai River below Libby Dam near Libby, Mont.	600	2,150	958	605	45	45	3,800
			(40)	(24)	(18)	(8)	(8)	(62)
9	Willamette River at Salem, Oreg.	1200	5,380	6,580	1,610	208	118	13,900
			(158)	(200)	(90)	(106)	(47)	(312)
10	Willamette River at Salem, Oreg.	1200	5,070	7,510	1,460	122	61	14,200
			(44)	(60)	(52)	(39)	(17)	(112)
11	Snohomish River near Monroe, Wash.	1200	5,210	9,370	1,670	42	36	16,300
			(128)	(284)	(32)	(22)	(24)	(277)
12	Snohomish River near Monroe, Wash.	1200	5,160	9,200	1,610	37	50	16,100
			(52)	(170)	(32)	(6)	(11)	(206)
13	Snohomish River near Monroe, Wash.	600	7,800	5,850	3,060	29	35	16,800
			(133)	(174)	(140)	(18)	(24)	(244)
14	Snohomish River near Monroe, Wash.	600	7,740	5,820	3,020	26	23	16,600
			(146)	(168)	(125)	(15)	(15)	(195)
15	Susquehanna River at Harrisburg, Pa.	1200	22,600	25,700	6,870	75	123	55,400
			(589)	(356)	(190)	(17)	(42)	(644)

Table 6. Discharges and standard deviations of discharges for acoustic Doppler current profiler discharge measurements and measurement subsections—Continued

ADCP evaluation measurement number	Site name	ADCP frequency (kHz)	Discharge (cubic feet per second)					
			Top	Measured	Bottom	Left	Right	Total
16	Susquehanna River at Marietta, Pa.	1200	14,400 (235)	39,800 (322)	5,080 (74)	53 (22)	101 (18)	59,400 (578)
17	Susquehanna River at Marietta, Pa.	600	20,400 (288)	30,700 (464)	8,590 (289)	56 (18)	85 (27)	59,800 (950)
18	Oswego River at Lock 7, Oswego, N.Y.	600	6,400 (212)	7,700 (487)	2,400 (90)	81 (18)	-135 (26)	16,500 (692)
19	Oswego River at Lock 7, Oswego, N.Y.	600	6,500 (208)	7,500 (207)	2,500 (165)	81 (11)	-125 (32)	16,500 (413)
20	Connecticut River at North Walpole, N.H.	1200	2,890 (61)	11,940 (129)	1,410 (52)	38 (16)	42 (12)	16,400 (211)
21	Connecticut River at North Walpole, N.H.	1200	2,900 (26)	12,000 (185)	1,420 (24)	40 (12)	40 (11)	16,600 (235)
22	Connecticut River at North Walpole, N.H.	600	3,000 (45)	11,600 (219)	1,300 (30)	60 (17)	46 (21)	16,100 (286)
23	Connecticut River at North Walpole, N.H.	600	3,030 (68)	11,700 (302)	1,310 (28)	83 (16)	66 (21)	16,300 (387)
24	St. Joseph River at Elkhart, Ind.	1200	1,120 (17)	1,140 (24)	268 (7)	22 (5)	18 (5)	2,570 (19)
25	St. Joseph River at Elkhart, Ind.	1200	1,110 (19)	1,140 (22)	271 (7)	27 (12)	24 (9)	2,580 (23)
26	St. Joseph River at Elkhart, Ind.	600	1,080 (25)	1,100 (31)	368 (7)	29 (5)	17 (2)	2,600 (57)
27	St. Joseph River at Elkhart, Ind.	600	1,060 (26)	1,100 (35)	363 (15)	21 (9)	19 (5)	2,560 (41)
28	Kankakee River at Shelby, Ind.	600	1,020 (28)	853 (26)	355 (7)	19 (6)	29 (12)	2,280 (65)
29	Kankakee River at Shelby, Ind.	600	1,070 (37)	884 (27)	317 (25)	21 (5)	24 (14)	2,320 (61)
30	Illinois River at Marseilles, Ill.	1200	3,670 (90)	7,700 (173)	1,050 (27)	62 (19)	71 (7)	12,600 (200)
31	Illinois River at Marseilles, Ill.	1200	3,690 (70)	7,570 (228)	1,080 (62)	66 (17)	83 (16)	12,500 (302)

measured subsection discharges (percentages are computed from the magnitudes of standard deviations and discharges for the ADCP discharge measurements and subsections given in table 6). When computed as percentages of the total discharge of each corresponding ADCP discharge measurement, the standard deviations in the measured subsections were generally less than 2 percent. Standard deviations in the top subsections ranged from approximately 1 to 7 percent of the corresponding top-subsection discharges and ranged from less than 1 to about 4 percent of the total discharge of each corresponding ADCP discharge measurement. Standard deviations in the bottom subsection ranged from approximately 1 to 9 percent of the corresponding bottom-subsection discharges and generally were less than 1 percent of the total discharge of each corresponding ADCP discharge measurement. The standard deviations in the left and right edge subsections ranged from approximately 10 to nearly 70 percent of the corresponding edge-subsection discharges, but were less than 1 percent of the total discharge for each corresponding ADCP discharge measurement.

The top and measured subsections generally had the lowest standard deviations when computed as a percentage of the respective subsection discharges, but they generally had the highest standard deviations when computed as a percentage of total discharge of each corresponding ADCP discharge measurement. The reason for the highest standard deviations is that the largest percentage of total discharge occurred in the top and measured subsections for all ADCP discharge measurements. The standard deviations of the bottom-subsection discharges (expressed as a percentage of total discharge of each corresponding ADCP discharge measurement) generally were less than those for the top and measured subsections; a lesser portion of the total flow occurred in the bottom subsection for all ADCP measurements. Standard deviations of the edge subsections generally were high when computed as percentages of the corresponding edge-subsection discharges, but they were low when taken as percentages of the total discharge of each corresponding ADCP discharge measurement.

The standard deviations of the total discharges of the ADCP discharge measurements ranged from about 1 to 4 percent of the corresponding total discharges, with the exception of the two Brazos River measurements that had standard deviations of 5 and 6.5 percent of the corresponding total discharges. The mean boat speed for the Brazos River site was more than 2 ft/s, while channel velocities were about 1 ft/s. The manufacturer recommends that the boat speed be kept equal to or less than the channel-water velocities (James R. Marsden, RD Instruments, oral commun., 1994). The higher measured standard deviations from the Brazos River data demonstrate the effect of the higher-than-recommended boat speeds used in data collection. The frequency of the ADCP used to make the measurements, 1200- or 600-kHz, did not have a significant effect on measurement standard deviation. An exception is the St. Joseph River, where the standard deviations were higher for the data collected with the 600-kHz unit. The standard deviations were higher because 35-cm depth cells were used for the 600-kHz measurements at this site, rather than the recommended 50-cm depth cells.

Sources of errors in the measured subsections include ADCP instrument error and flow variations in the river. Because the discharges in the top and bottom subsections are extrapolated from the measured subsections, discharge errors in the top and bottom subsections could be expected to be the same magnitude as those for the measured subsections. The standard deviations in the top and bottom subsections appear to support this assumption.

Discharges of the edge subsections had high standard deviations when taken as percentages of the subsection discharges. These standard deviations indicate that substantial errors had occurred, affecting the discharge extrapolation for the edge subsections. Analysis of the data and on-site observations indicate that a likely source of this error is velocity error in the ADCP ensembles collected close to shore. This velocity error probably was caused by sudden changes in boat speed and direction. The speed and direction changes were common at the start and end of transects in near-shore areas, particularly when stream velocities were high in those areas. These errors could have been minimized in the processing of discharge data by averaging a series of ensembles close to the edge subsections. This ensemble-averaging technique was not used in the processing of the evaluation measurements because of the small percentages of flow in the edge subsections. Error also could have been introduced by incorrectly estimating the distance from the last collected ensemble to the shore.

ADCP instrument error in the measured subsection and the expected error in the extrapolated top, bottom, and edge subsections can be estimated by formulas that use ADCP-configuration parameters, subsection areas, and the average boat speed used for the measurement (boat speed is not a factor in the edge-subsection error formula) (Marsden, 1994). The total measurement error then can be estimated by summing computed subsection error and an error factor which accounts for non-instrument errors such as temporal flow variance or turbulence. The non-instrument error factor is estimated to be approximately equal to the error computed for the top subsection (Marsden, 1994). The total measurement error was estimated by these methods for each of the ADCP discharge measurements. The estimated measurement errors are compared to the standard deviations of the ADCP discharge measurements for 17 of the evaluation measurements in table 7. The formulas for the error-estimate computations are given in appendix 2.

For several measurements, the estimated measurement errors and standard deviations are close. Generally, the standard deviations are higher than the estimated errors; the standard deviation for a measurement made at the Oswego River site is as much as four times higher than the estimated error. The estimated measurement-error computations assume that ADCP instrument and unmeasured subsection-extrapolation errors are the main sources of measurement error. Therefore, the higher standard deviation indicates that a significant portion of the measurement error was contributed by sources other than ADCP instrument or extrapolation error, such as temporal flow variations and turbulence (Marsden, 1994).

The difference between the standard deviation of an ADCP discharge measurement and estimated measurement error may be indicative of temporal flow-variability error or other non-instrument-related error. The differences between the estimated measurement errors and standard deviations for the 31 ADCP discharge measurements are small when computed as a percentage of the total discharge of each corresponding ADCP discharge measurement; for most of the sites, this difference was 1 percent or less. The greatest difference was for an Oswego River measurement; the difference between standard deviation and estimated measurement error expressed as a percentage of total discharge was approximately 3 percent. Site observations and data analysis indicate the Oswego River had heavy turbulence at the ADCP discharge measurement section, with reverse flow along one side.

The standard deviations for four ADCP discharge measurements were lower than the estimated measurement errors. The formulas used to estimate discharge error are designed to be conservative; therefore, under ideal flow conditions, the standard deviation could be lower than the error estimate (James R. Marsden, RD Instruments, oral commun., 1995).

All measurements were based on the mean of a series of six or less transect discharges. For 10 of the ADCP discharge measurements, 1 or more of the transects in the measurement-transect series were not used in the computation of mean discharge because of data-quality problems. Had six or more transects been used to compute mean discharges, the measurement-standard deviations may have increased or decreased.

Table 7. Comparison of acoustic Doppler current profiler measurement discharge standard deviations and estimated errors

[ADCP, acoustic Doppler current profiler; kHz, kilohertz; ft^3/s, cubic feet per second]

Site name	ADCP frequency (kHz)	ADCP measurement			
		Number	Discharge (ft^3/s)	Standard deviation (ft^3/s)	Estimated error (ft^3/s)
Brazos River at State Highway 21 near Bryan, Tex.	1200	1	758	49	60
Clark Fork at St. Regis, Mont.	1200	3	4,290	90	64
Kootenai River below Libby Dam near Libby, Mont.	1200	6	3,860	78	91
Kootenai River below Libby Dam near Libby, Mont.	600	8	3,800	62	92
Willamette River at Salem, Oreg.	1200	9	14,200	112	113
Snohomish River near Monroe, Wash.	1200	11	16,300	227	99
Snohomish River near Monroe, Wash.	600	13	16,800	244	91
Susquehanna River at Harrisburg, Pa.	1200	15	55,400	644	327
Susquehanna River at Marietta, Pa.	1200	16	59,400	578	290
Susquehanna River at Marietta, Pa.	600	17	59,800	950	278
Oswego River at Lock 7, Oswego, N.Y.	600	18	16,200	692	160
Connecticut River at North Walpole, N.H.	1200	20	16,400	211	96
Connecticut River at North Walpole, N.H.	600	23	16,100	387	240
St. Joseph River at Elkhart, Ind.	1200	24	2,570	19	48
St. Joseph River at Elkhart, Ind.	600	26	2,600	57	63
Kankakee River at Shelby, Ind.	600	28	2,280	65	38
Illinois River at Marseilles, Ill.	1200	30	12,600	200	115

POSSIBLE FUTURE WORK

The ADCP discharge data documented in the report were collected from river sections with mean velocities greater than 0.7 ft/s and mean depths greater than 5 ft. Further evaluation of ADCP-collected data, particularly data from shallow, slow streams, would be beneficial for USGS offices that may use ADCP's for data collection at sites that have a wide range of flow conditions. Such efforts could evaluate ADCP data collected with other operating modes (such as mode 5, which is designed for use in slow, shallow water) from sites with conditions that differ from most inland rivers, such as tide effects and changing salinity gradients.

The development of acoustic moving-boat, flow-measuring devices similar to ADCP's (but of different models and manufacturers) also would necessitate evaluation efforts for potential use by the USGS.

SUMMARY AND CONCLUSIONS

Acoustic Doppler current profilers (ADCP's) are hydroacoustic instruments that can be used to make river discharge measurements from moving boats. Thirty-one measurements of river discharge were made with ADCP's at 12 USGS streamflow-gaging stations to evaluate the performance of ADCP's in field conditions. Data were collected with a 1200-kHz ADCP at five sites, with a 600-kHz unit at two sites, and with a 600- and a 1200-kHz unit at five sites.

The ADCP discharge measurements were compared to conventional method discharges computed for the period over which the ADCP discharge measurements were made. Twenty-five ADCP discharge measurements were within 5 percent of the conventional discharges computed from the streamflow-gaging-station rating discharges. Six ADCP discharge measurements differed by more than 5 percent from the respective rating discharges; the maximum departure was 7.6 percent. These six measurements were collected at two of the evaluation sites.

ADCP discharge measurement error was indicated by the standard deviations of the ADCP discharge measurements. The standard deviations ranged from about 1 to 7 percent of the measurement discharges. The estimated error of each ADCP discharge measurement also was computed from formulas derived by the manufacturer of ADCP's. The computations of estimated measurement error assume that ADCP instrument- and unmeasured subsection-extrapolation errors are the main source of measurement error. The standard deviations for most ADCP discharge measurements were higher than the estimated measurement errors, indicating that significant components of measurement error were not related to the instruments; errors of this nature include temporal variations of flow. As a result, measurement precision can be affected greatly by selection of a measurement location; making ADCP measurements at locations where flow variations are minimized can improve measurement precision. Measurement precision also can be affected by instrument- and boat-operation factors.

The evaluation of ADCP discharge measurements documented in this report indicates that ADCP's can be used successfully for data collection under a variety of field conditions. Use of these instruments is feasible to collect discharge data from river sites similar to many of those described in this report.

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APPENDIXES

APPENDIX 1. SELECTED ACOUSTIC DOPPLER CURRENT PROFILER (ADCP) CONFIGURATION FILES USED AT EVALUATION SITES

The following is a mode 4 configuration file for a 1200 kilohertz (kHz) ADCP, used at the Snohomish River, near Monroe, Wash., evaluation site.

```
BEGIN RDI CONFIGURATION FILE

COMMUNICATIONS
{
ADCP         ( ON   COM1 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
ENSOUT       ( OFF  COM2 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
NAV          ( OFF  COM3 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
REFOUT       ( OFF  COM4 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
EXTERNAL     ( OFF  COM4 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]

ENSEMBLE OUT
{
ENS CHOICE   ( N N N N N N N N )  [ Vel Corr Int %Gd Status Leader BTrack Nav ]
ENS OPTIONS  (BOTTOM   1   8   1   8 )  [ Ref First Last Start End ]
}

ADCP HARDWARE
{
Firmware        ( 4.12 )
Angle           (      20 )
Frequency       (    1200 )
System          (    BEAM )
Mode            (       4 )
Orientation     (    DOWN )
Pattern         ( CONCAVE )
}

DIRECT COMMANDS
{
WS25
WF40
BX100
WN028
WD111100000
WP00004
BP003
WM4
TP000005
ES0
EZ1111101
}

RECORDING
{
Deployment ( SNH4 )
Drive 1    (   C  )
Drive 2    (   C  )
```

```
ADCP       ( YES )
Average    (  NO )
Navigation (  NO )
}

CALIBRATION
{
ADCP depth                  (    0.20 m      )
Heading / Magnetic offset  (   0.00      0.00 deg )
Transducer misalignment    (    0.00 deg    )
Intensity scale            (    0.43 dB/cts )
Absorption                 (   0.440 dB/m   )
Salinity                   (     0.0 ppt    )
Speed of sound correction  (     YES        )
Pitch & roll compensation  (     YES        )
Tilt Misalignment          (    0.00 deg    )
Pitch_Offset               (    0.000 deg    )
Roll_Offset                (    0.000 deg    )
Top discharge estimate     (     POWER      )
Bottom discharge estimate  (     POWER      )
Power curve exponent       (      0.1667   )
}

PROCESSING
{
Average every ( 500.00 s )
Depth sounder (  NO )
Refout_info (   1   8  30.00  1.000 0      1) [bins:1st last, limit, weight,
               format, delaysec]
External_formats  ( N N N N )  [ HDT HDG RDID RDIE ]
External_decode   ( N N N N ) [ heading pitch roll temp ]
}

GRAPHICS
{
Units        ( English )
Velocity Reference (   BOTTOM   )
East_Velocity      (   -5.0    5.0  ft/s )
North_Velocity     (   -5.0    5.0  ft/s )
Vert_Velocity      (   -0.5    0.5  ft/s )
Error_Velocity     (   -0.3    0.3  ft/s )
Depth              (      1     16   bin )
Intensity          (     60     90     dB)
Discharge          (    -35     35 ft3/s )
East_Track         (   -158    214    ft )
North_Track        (    -34    338    ft )
Ship track         (  9 bin    3.0  ft/s )
Proj_Velocity      (   -5.0    5.0  ft/s )
Proj_Angle         (    0.0  deg from N )
Bad_Below_Bottom   (  YES  )
Line1              (SNOHOMISH RIVER 1200kHZ MODE4                     )
Line2              ( 4 water, 3 bottom pings                          )
}
```

```
HISTORY
{
SOFTWARE        ( BB-TRANSECT )
Version         ( 2.65 )
}

END RDI CONFIGURATION FILE
```

The following is a mode 4 configuration file for a 600 kilohertz (kHz) ADCP, used at the Snohomish River, near Monroe, Wash., evaluation site.

```
BEGIN RDI CONFIGURATION FILE

COMMUNICATIONS
{
ADCP          ( ON   COM1 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
ENSOUT        ( OFF  COM2 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
NAV           ( OFF  COM3 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
REFOUT        ( OFF  COM4 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
EXTERNAL      ( OFF  COM4 9600 N 8 1 ) [ Port Baud Parity Databits Stopbits ]
}

ENSEMBLE OUT
{
ENS CHOICE   ( N N N N N N N N )  [ Vel Corr Int %Gd Status Leader BTrack Nav ]
ENS OPTIONS  (BOTTOM   1   8   1   8 )  [ Ref First Last Start End ]
}

ADCP HARDWARE
{
Firmware        ( 4.12 )
Angle           (     20 )
Frequency       (    600 )
System          (   BEAM )
Mode            (      4 )
Orientation     (   DOWN )
Pattern         (  CONVEX )
}

DIRECT COMMANDS
{
WS25
WF50
BX100
WN014
WD111100000
WP00004
BP003
WM4
WE0450
ES0
EZ1111101
}
```

```
RECORDING
{
Deployment ( SNL4 )
Drive 1    (   C  )
Drive 2    (   C  )
ADCP       ( YES )
Average    (  NO )
Navigation (  NO )
}

CALIBRATION
{
ADCP depth                 (    0.25 m      )
Heading / Magnetic offset  (   0.00      0.00 deg )
Transducer misalignment    (    0.00 deg    )
Intensity scale            (    0.43 dB/cts )
Absorption                 (   0.440 dB/m   )
Salinity                   (     0.0 ppt    )
Speed of sound correction  (     YES        )
Pitch & roll compensation  (     YES        )
Tilt Misalignment          (    0.00 deg    )
Pitch_Offset               (    0.000 deg    )
Roll_Offset                (    0.000 deg    )
Top discharge estimate     (     POWER      )
Bottom discharge estimate  (     POWER      )
Power curve exponent       (      0.1667   )
}

PROCESSING
{
Average every ( 500.00 s )
Depth sounder (  NO )
Refout_info (   1   8  30.00  1.000 0      1) [bins:1st last, limit, weight,
               format, delaysec]
External_formats  ( N N N N )  [ HDT HDG RDID RDIE ]
External_decode   ( N N N N ) [ heading pitch roll temp ]
}

GRAPHICS
{
Units        ( English )
Velocity Reference (   BOTTOM   )
East_Velocity      (   -5.0    5.0  ft/s )
North_Velocity     (   -5.0    5.0  ft/s )
Vert_Velocity      (   -0.5    0.5  ft/s )
Error_Velocity     (   -0.3    0.3  ft/s )
Depth              (      1     12   bin )
Intensity          (     60     90 counts)
Discharge          (    -35     35 ft3/s )
East_Track         (   -350    406    ft )
North_Track        (   -417    338    ft )
Ship track         (  9 bin    3.0  ft/s )
Proj_Velocity      (   -5.0    5.0  ft/s )
```

```
Proj_Angle          (     0.0  deg from N )
Bad_Below_Bottom    (   YES  )
Line1               (SNOHOMISH RIVER  600kHZ MODE4                    )
Line2               ( 4 water, 3 bottom pings                         )
}

HISTORY
{
SOFTWARE        ( BB-TRANSECT )
Version         ( 2.65 )
}

END RDI CONFIGURATION FILE
```

APPENDIX 2. FORMULAS FOR ACOUSTIC DOPPLER CURRENT PROFILER (ADCP) DISCHARGE MEASUREMENT ERROR ESTIMATION (from Marsden, 1993; James R. Marsden, RD Instruments, written commun., 1994)

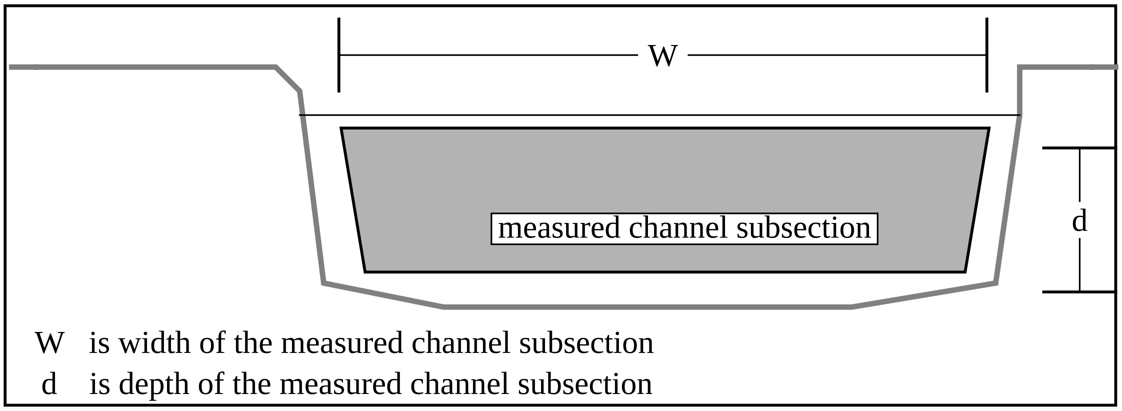

Figure 1
Channel subsection measured with an ADCP

The ADCP instrument error for the measured channel subsection is given as:

$$\Delta Q_{ADCP} = \sigma_v \sqrt{Whdv_b t}$$

where v_b is the average velocity of the boat,

σ_v is the single ping standard deviation of the ADCP,

h is the length of one depth cell,

t is the time for an individual ping.

The expected error in the top subsection extrapolated discharge is given as:

$$\Delta Q_{top} = \sigma_v l \sqrt{Wv_b t}$$

for Mode 4:

$$l = d_{ADCP} + d_{blank} + 1.5h$$

where l is the thickness of the top subsection,

d_{ADCP} is the ADCP transducer depth,

d_{blank} is the blanking distance.

Similarly, the expected error in the bottom subsection extrapolated discharge is give as:

$$\Delta Q_{bottom} = \sigma_v b \sqrt{W v_b t}$$

to compute b, use the greater of:

$$b = h$$

or

$$b = 0.06\,(d_{mean} - d_{ADCP})$$

where b is the thickness of the bottom subsection,

d_{mean} is the mean channel depth.

Formulas for the top and bottom subsections are for constant extrapolations of the vertical velocity profiles. These estimates can be used for power-law extrapolations; they would most likely be conservative because the power-law scheme uses more depth cells for the extrapolation.

The error predicted for the discharge extrapolated for one edge subsection is given as:

$$\Delta Q_{edge} = \sigma_v \frac{0.707 L d_m}{2} \sqrt{\frac{h}{d w_p}}$$

where L is the distance from shore to the nearest vertical ADCP section,

d_m is the actual depth of the vertical section nearest the shore,

w_p is the number of pings in the vertical section.

The vertical section may be one ADCP ensemble or the average of a number of ensembles.

For a vertical wall, the 0.707 factor would change to 0.91.

Discharge measurement errors such as turbulence and shear conditions are not accounted for by the above estimates. These errors can be estimated by equating them to the top subsection discharge error estimate, ΔQ_{top}.

The total estimated discharge measurement error is then:

$$\Delta Q = \Delta Q_{ADCP} + 2\Delta Q_{top} + \Delta Q_{bottom} + \Delta Q_{edge1} + \Delta Q_{edge2}$$