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Measuring real-time streamflow using emerging technologies: Radar, hydroacoustics, and the probability concept

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Summary Forecasting streamflow during extreme hydrologic events such as floods can be problematic. This is particularly true when flow is unsteady, and river forecasts rely on models that require uniform-flow rating curves to route water from one forecast point to another. As a result, alternative methods for measuring streamflow are needed to properly route flood waves and account for inertial and pressure forces in natural channels dominated by nonuniform-flow conditions such as mild water surface slopes, backwater, tributary inflows, and reservoir operations.

The objective of the demonstration was to use emerging technologies to measure instantaneous streamflow in open channels at two existing US Geological Survey streamflow-gaging stations in Pennsylvania. Surface-water and instream-point velocities were measured using hand-held radar and hydroacoustics. Streamflow was computed using the probability concept, which requires velocity data from a single vertical containing the maximum instream velocity. The percent difference in streamflow at the Susquehanna River at Bloomsburg, PA ranged from 0% to 8% with an average difference of 4% and standard deviation of 8.81 m^3/s. The percent difference in streamflow at Chartiers Creek at Carnegie, PA ranged from 0% to 11% with an average difference of 5% and standard deviation of 0.28 m^3/s. New generation equipment is being tested and developed to advance the use of radar-derived surface-water velocity and instantaneous streamflow to facilitate the collection and transmission of real-time streamflow that can be used to parameterize hydraulic routing models.
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Introduction

Forecasting streamflow during extreme hydrologic events such as floods can be problematic. This is particularly true when flow is nonuniform and river forecasts rely on models that require uniform-flow rating curves to route water from one forecast point to another. For example, during the July 2006 flooding in the Susquehanna and Delaware River basins in Pennsylvania, 11 forecast points exceeded the upper end of the uniform-flow rating curve definition. Flow routing predicted by the National Weather Service (NWS), Middle Atlantic River Forecast Center (MARFC) was compromised, because the stage values associated with the modeled flows or the streamflows associated with the observations could not be accurately forecasted.

MARFC and the US Geological Survey (USGS) partnered to evaluate methods for measuring water velocity and computing instantaneous streamflow dominated by unsteady flow events. The objective of the project was to pilot the use of hand-held radar, hydroacoustics, and computational methods that would support real-time streamflow measurement. The demonstration relied on collecting a single surface-water velocity or multiple point velocities along one vertical at a prescribed location within the channel cross-section. The velocity data was used to compute an instantaneous streamflow using the probability concept developed by Chiu et al. (2005) and Chiu and Tung (2002). The results were then compared to conventional methods for computing streamflow such as acoustic Doppler current profiling (ADCP), acoustic Doppler velocimeters (ADV), and mechanical-current meters.

The demand for developing methods for delivering real-time streamflow will increase as requests for stage-forecasts expand beyond generalized flash-flood warnings to currently-ungaged locations. The instrumentation and methods outlined in this paper offer a solution to these demands. By developing a protocol that uses data collection and computational methods that are accurate and quick, the reliability of flow forecasting is increased and the risk to hydrographers is reduced, where hazardous water bodies or streamflow conditions are encountered.

Study area

Two existing USGS streamflow-gaging stations (stations) (Susquehanna River at Bloomsburg, PA – 01538700 and Chartiers Creek at Carnegie, PA – 03085500) were selected, because they represent a range of hydraulic extremes and drainage basin areas. The Susquehanna River at Bloomsburg drains a relatively large area, has experienced a wide range of streamflow conditions, is hydraulically influenced by in-stream structures used to regulate streamflow and stage, requires measurements be made by boat or at a bridge, and has a relatively wide channel with a stable bed. Fig. 1 illustrates the station location, which is west of Bloomsburg, Columbia County, Pennsylvania and drains an area of 27,300 km^2. It has operated primarily as a stage-only site since January 1994; however, periodic streamflow measurements have been made. From 1995 through 2005, streamflows ranging from 38 to 6315 m^3/s and corresponding gage heights varying from 0.03 to 7.77 m, respectively, were recorded.

In contrast, Chartiers Creek at Carnegie drains a small urban area, is hydrologically flashy, allows measurements to be made by wading or bridge, and has a shallow channel width with steep walls. As illustrated in Fig. 1, the station is south of Pittsburgh, Allegheny County, Pennsylvania and drains an area of 665 km^2. The station is approximately 14.3 km upstream from the confluence of Chartiers Creek and the Ohio River. The Carnegie station has operated continuously since October 1940. Both stage and streamflow data are collected at the station. Based on 74 years of record, minimum and maximum instantaneous flows are 0.45 and 382 m^3/s, respectively.

Methods

The objective of the project was to pilot the use of hand-held radar, hydroacoustics, and computational methods that support real-time streamflow measurement. The demonstration relied on collecting a single surface-water velocity or multiple point velocities along one vertical at a prescribed location within the channel cross-section. The velocity and cross-section data was used to compute an instantaneous streamflow using the probability concept as described by Chiu et al. (2005) and Chiu and Tung (2002). Streamflows were compared to conventional methods such as ADCPs and mechanical-current meters, which are widely accepted as industry standards and served as benchmarks to evaluate the validity of the radar- and hydroacoustically-derived streamflow values (see Table 1).

The principles used to measure surface-water velocities and the state of radar methods and the emerging technologies (radar, hydroacoustics and computational methods) deployed for the demonstration project are described below.

Principles used to measure surface-water velocity and the state of radar methods

The USGS has deployed three types of radars in field tests across the United States (Costa et al., 2006; Plant et al., 2005). They include a continuous-wave (CW) microwave, monostatic UHF Doppler radar, and pulsed Doppler microwave radar. Regardless of the method, each measures surface currents using composite surface scattering. The process is based on the Doppler shift in the transmitted signal that is backscattered from the motion of short waves on the water surface to the transceiver. These short-wave forms act as scatters and are independent of large scale motions of the water surface. Their characteristic length can be estimated using the Bragg resonance condition (Plant et al., 2005):

$$\lambda_b = \lambda / 2 \sin \phi \qquad (1)$$

where λ_b is wavelength of the resonant water wave (the Bragg wave), λ is the wavelength of the radar and ϕ is incidence angle of transmitted wave.

Depending on the radars wavelength, the Bragg wave (the wavelength of the short waves responsible for the Doppler shift) can be estimated using Eq. (1). For example, K-band radar with a frequency of 24 GHz translates to a 1.25 cm

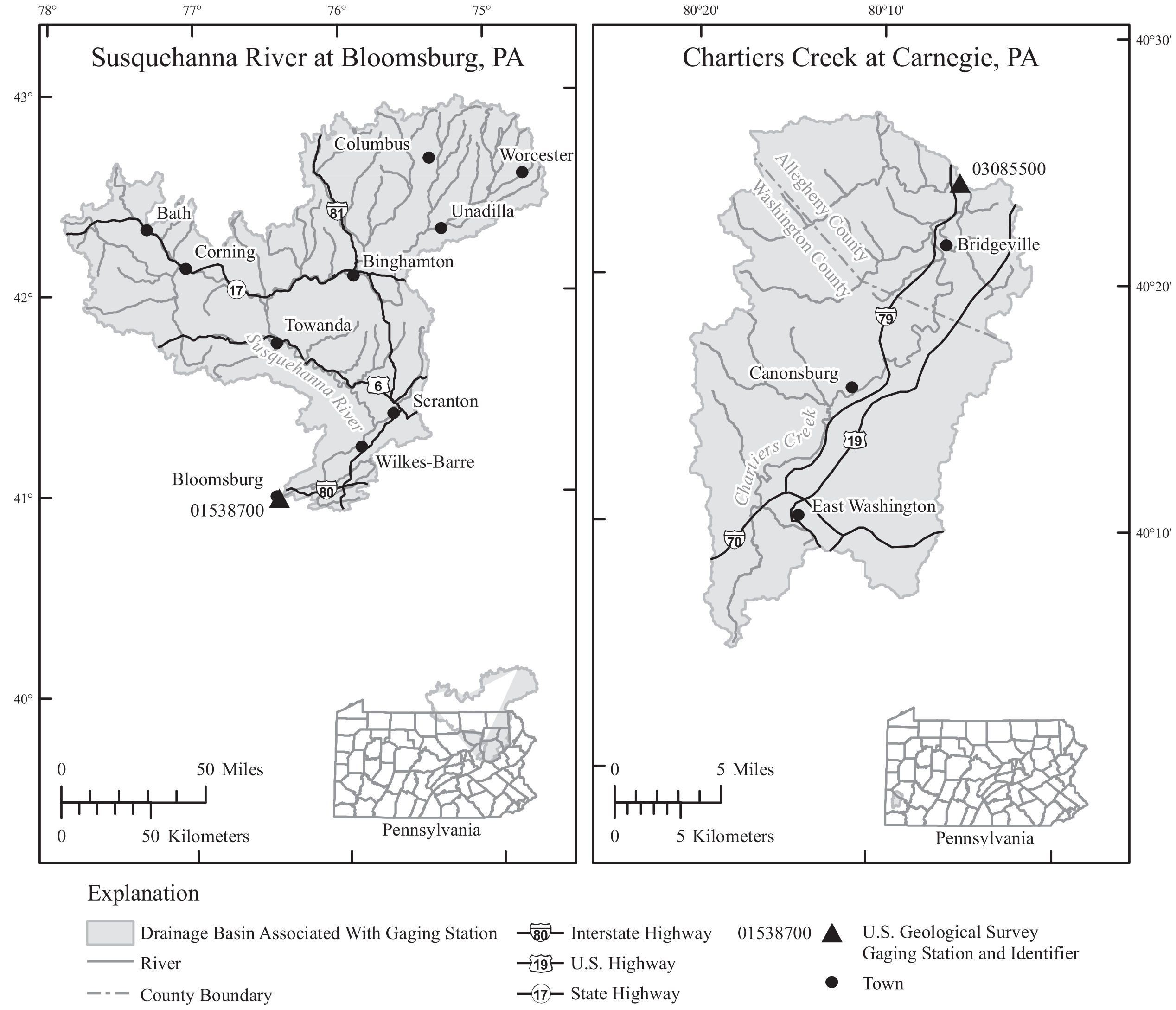


Figure 1 Site location maps illustrating the US Geological Survey gaging stations Susquehanna River at Bloomsburg, PA and Chartiers Creek at Carnegie, PA used for the demonstration project.

Table 1 Conventional and emerging technologies for measuring velocity and computing streamflow at US

Measurement methods	Computation methods
Conventional	
ADCP	$\sum Q$ for each ensemble
Mechanical current meter and ADV	Midsection method
Rating curve	Stage-discharge relation
Emerging technologies	
Hand-held radar and hydroacoustics	Probability concept

Geological Survey gaging stations Susquehanna River at Bloomsburg, PA and Chartiers Creek at Carnegie, PA.

wavelength. Given Eq. (1) and an incidence angle of 45 degrees, a Bragg wave of approximately 0.9 cm is needed for backscatter. Both the microwave and UHF Dopplers rely on Bragg scattering; therefore, some degree of surface roughness is needed to measure velocities. The roughness can be generated by turbulent boils, wind, or rain (Costa et al., 2006). These scatterers are used with Eq. (2) to compute the Doppler shift, which is normally displayed by two sharp peaks or Bragg lines that represent the advancing and receding Bragg waves. If the transmitted signal is coherent, the complete velocity spectrum can be measured with no phase discontinuities (signal does not make sudden, large jumps while the time series is being collected). As a result, a Doppler spectrum of the received signal can be obtained by removing the frequency of the transmitted signal from the received signal and the surface velocity can be computed

$$f_\mathrm{d} = (v_\mathrm{h} \pm c)/\lambda_\mathrm{b} \tag{2}$$

where, f_d is Doppler frequency shift, v_h is the surface velocity in the direction of transmission and c is phase speed, which has a value of 23 cm/s near λ_b of 1.7 cm.

Due to diffraction effects, microwave beamwidths are generally on the order of several degrees (Plant et al., 2005). As a result, depending on the incidence angle and water gap, the area illuminated by the microwave may range from decimeters to meters in each dimension. This footprint ensures that only Bragg waves traveling toward or away from the antenna are effective scatterers. The spectra are analyzed by fitting the noise level to an inverse frequency function, dividing the received signal by the noise level, and applying an algorithm to determine the frequency (f_c) midway between the Bragg lines (Plant et al., 2005). The surface velocity (v_h) in the direction of the horizontal look of the antenna is computed using Eq. (3)

$$V_h = \lambda \times f_c/2\sin\phi \tag{3}$$

Errors in measuring surface-water velocities can be attributed to variations in the mean current, which are produced by highly turbulent conditions (low surface-water velocity coupled with high winds), surfaces waves that exceed the Bragg wavelength, or drift currents. The effect of turbulence and excessive Bragg wavelengths cause Bragg waves to advect at a various speeds and result in a broadening of the Doppler shift making it difficult to discriminate between the advancing and receding waves (Plant et al., 2005). In severe cases, the broadening tends to smear the Bragg lines and result in suspect surface-water velocity estimates. Drift currents are problematic and occur when wind blows across the water surface. The shear creates motion at the water surface, which may be in a direction different from that of bulk flow. Because microwaves measure velocities at water depths of approximately $0.044\lambda_b$, quantifying the magnitude of drift is important. Plant et al. (2005) estimated that for $\lambda_b = 1.7$ cm, the water velocity at a depth of 0.075 cm will be measured by the microwave rather than at the water surface. Assuming the wind drift layer has not decayed, the drift creates an error in the measured velocity of the instrument. In general the magnitude of the drift velocity is estimated to be approximately 2% of the wind speed measured at a height of 10 m above the water surface. For example, a wind speed of 10 m/s produces a drift velocity of 20 cm/s. Assuming the microwave measurement follows a logarithmic decay, the drift velocity at the effective measurement depth is approximately 11 cm/s. This error must be accounted for and is incurred in the surface-water velocity measurement only if the wind blows exactly along the direction, which the antenna is pointing (Plant et al., 2005). Regardless, microwaves offer an advantage over ADCPs and ADVs in that they are capable of measuring water velocities very near the surface.

The CW microwave is generally fixed to a bridge or held by hand over the water surface. It is characterized by a coherent frequency of 24 GHz, which is equivalent to the hand-held radar described below. Although the transceiver is inexpensive and operates with minimum power (5 milliwatts), it is a direct conversion receiver (homodyne), and unwanted signals or noises are filtered. As a result during low wind and flow conditions, sufficient surface roughness may not exist to produce sufficient backscatter above background noise levels; therefore the CW microwave may not be capable of producing reliable surface-water velocity estimates (Plant et al., 2005). However, the signal level depends on the water-surface conditions encountered, as well as receiver design. The signal can only be detected if it is above the noise; therefore, the lower the noise level, the smaller the surface roughness needed for measuring. Additionally, the sign of v_h (Eq. (3)) cannot be determined without knowing the flow direction apriori (Plant et al., 2005).

UHF Doppler radar is a high-frequency radar that broadcasts at 350 MHz. CODAR Ocean Sensors developed a unit (RiverSonde; the use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the USGS) that is monostatic (same antenna used for transmitting and receiving) and relies on Bragg scattering. The radar makes three basic measurements including (1) the Doppler frequency, (2) the distance or range of the scattering patch, and (3) the direction of arrival of the radar echoes (Costa et al., 2006). The radial component of the flow velocity can be mapped as a function of position on the water surface, where the received signal is processed to determine the Doppler shift and direction in each frequency bin producing the Doppler shift. As with the CW microwave, the Bragg scattering process is highly selective relative to wavelength and direction. The only significant energy returned to the radar originates from water waves having approximately one-half the radar wavelength. The signal that is returned represents an average over the scattering patch (Costa et al., 2006). Assuming a 350 MHz frequency, Bragg wavelengths of approximately 50 cm are needed for effective scatterers. Because scattering at longer wavelengths is less prone to high-order wave—wave interactions, approaching and receding Bragg lines at high frequencies such as UHF are easily distinguished from each other when compared to microwave frequencies. In addition, advective effects of longer waves are less and yield very narrow Bragg lines; however, when the antenna beamwidth is broad, Bragg waves traveling away from the antenna looking upstream yield similar Doppler shifts to Bragg waves advancing toward the antenna looking downstream. These effects are difficult to separate, and supplemental processing is needed to discriminate between advancing and receding waves that may have overlapped.

A pulsed Doppler microwave radar (RiverRad) was developed by the Applied Physics Laboratory at the University of Washington. The radar is a coherent, X-band unit that emits bursts of 10 GHz microwaves across the entire water surface from two antennae originating on the riverbank. RiverRad transmits with four different pulse widths to yield resolutions of 3.75, 7.5, 15, and 30 m. The maximum ranges it can reach at these resolutions are 0.5, 1, 2, and 4 km, respectively (Plant et al., 2005). Average surface-water velocities are measured in a series of bins, whose location is measured by time gating and size varies with beam width in the azimuth direction. Velocity vectors are determined from one antenna pointing 23° upstream and one directed 23° downstream of the cross-channel direction.

Emerging technologies deployed for the demonstration project

The parameters needed to compute instantaneous streamflow are water velocity, cross-sectional area, and a method of computation. For this effort, water velocity was measured using hand-held radar and hydroacoustics such as ADCPs and ADVs. Cross-sectional areas had been previously established through stage-area ratings; however, channel profiles were characterized at the time of site visits using

ADCPs or conventional surveys using a wading rod or bridge rig and measuring the channel width, water depth, and river stage. Horizontal control and vertical elevations were recorded using a total-station survey relative to the gage datum. The probability concept was then used to compute an instantaneous streamflow using the water velocity and cross-sectional area recorded at each station.

Hand-held radar

Hand-held radar is one of a variety of radar methods being developed and evaluated by the USGS for measuring streamflow without entering or touching the water; it was selected for this effort because of its inexpensive cost and ease of use.

Surface-water velocities were measured using a Decatur surface-velocity radar (SVR™) gun. As with the CW microwave, UHF Doppler radar, and pulsed Doppler microwave radar, the unit operates by transmitting microwave energy (radio waves) at a point of interest (the *y*-axis) on the water surface. When the beam strikes the water surface, a portion of the beam's energy is returned to the unit. The difference in the frequency between the transmitted and reflected signal is proportional to the speed of the water surface (Decatur Electronics, 2001). The distinction between the hand-held unit and its counterparts is the manner in which the signals are processed. The unit computes the surface-water velocity using the magnitude shift in the transmitted and received signal rather than Bragg scattering. The hand-held radar is not capable of storing or transmitting the data to a data collection platform; however, it includes a tilt sensor that compensates for the cosine error (pitch) when the unit is pointed towards the water surface at an angle of 45° or less. In addition, the unit can account for the cosine error (yaw) when the unit is pointed at the water surface from the waters edge. For the demonstration project all measurements were made using a pitch of 45° and yaw of 0°. The configuration of the hand-held radar relative to a channel is illustrated in Fig. 2.

Hydroacoustics

Two hydroacoustic methods were used to either collect velocity data or corroborate the instantaneous streamflow measured at a given site. For example, an ADCP was used at Bloomsburg to verify the computed streamflows; whereas, an ADV was used at Bloomsburg and Carnegie for data collection and corroboration.

Acoustic doppler current profiler. At Bloomsburg a boat-towed RD Instruments 600 kHz Workhorse Rio Grande ADCP was used; shallow water depths at Carnegie precluded the use of an ADCP. The unit was mounted to the starboard side of the boat and towed from one channel bank to the other to measure water velocity and compute streamflow. It was operated using a bottom-track mode and in water depths greater than 0.91 m and water velocities greater than 0.15 m/s. ADCPs transmit sound bursts into the water and measure the reflected signal from particles suspended

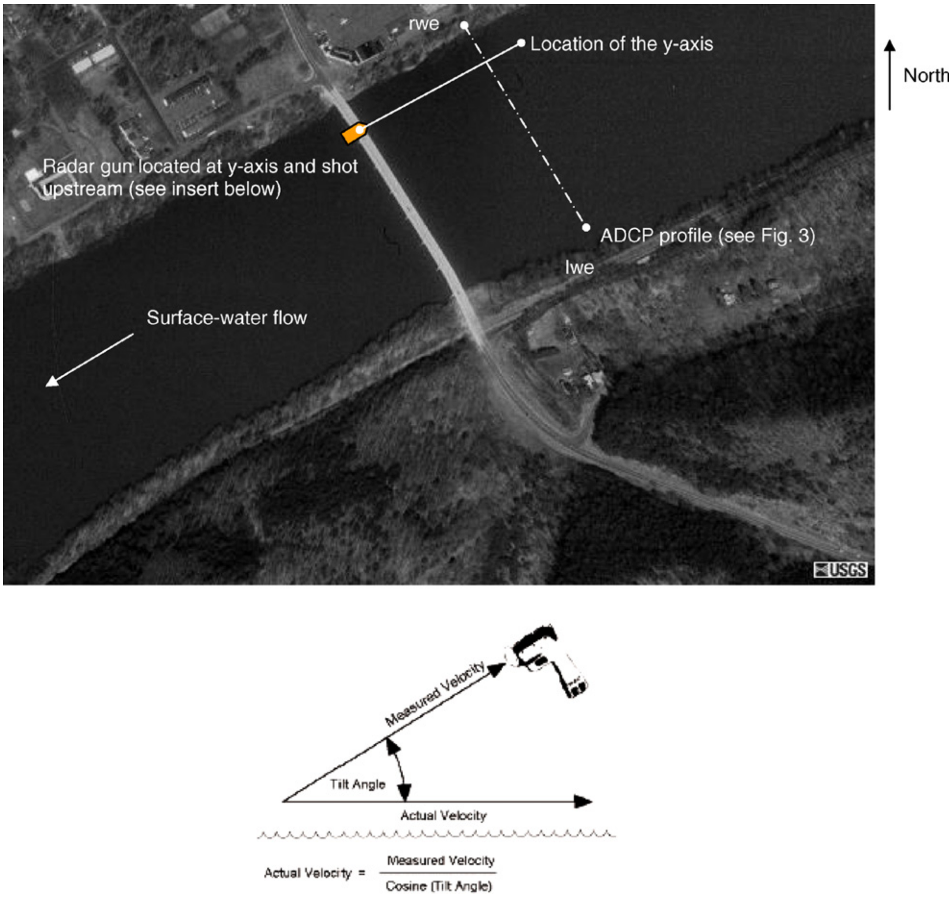
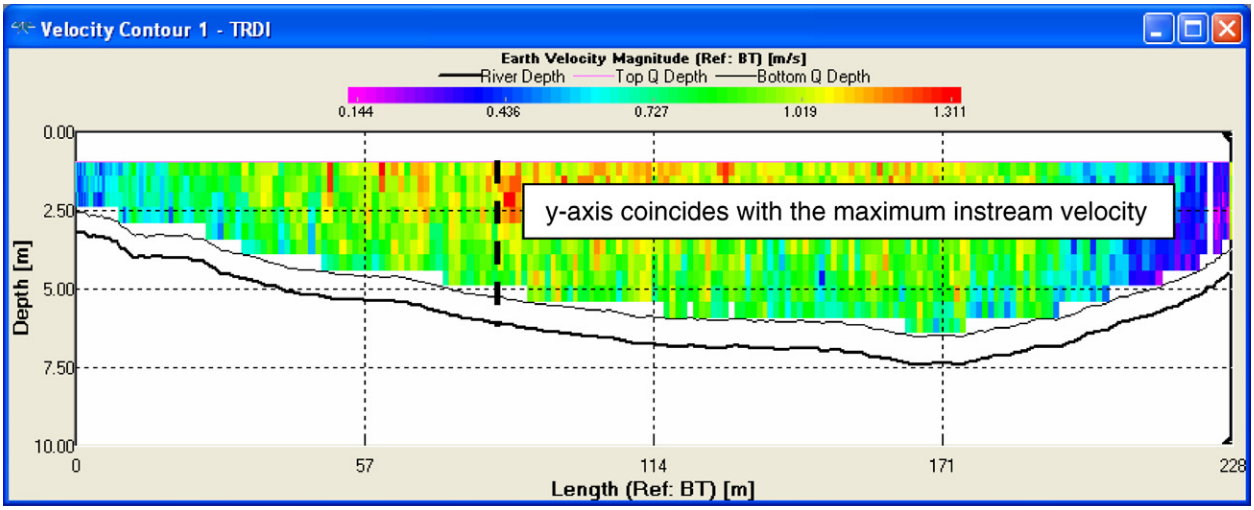


Figure 2 Hand-held radar configuration oriented upstream at the *y*-axis used to measure the surface-water velocity at the Susquehanna River at Bloomsburg, PA.



y-axis coincides with the maximum instream velocity

Figure 3 Typical acoustic Doppler current profile illustrating the *y*-axis and maximum instream velocity used to compute real-time streamflow (m, meters; m/s, meters per second; BT, bottom track measures the speed and direction of the bottom motion relative to the ADCP; Top Q, top layer discharge; Bottom Q, bottom layer discharge).

in the water column. The frequency shift between the transmitted and reflected sound (Doppler shift) is used to compute the particle velocity, which is assumed to be moving at the same rate as the water. It should be noted that because the ADCP is towed the unit must compensate for the relative movement of the boat by tracking the river bottom and measuring the boat speed and direction. Protocols previously established by the USGS for ADCP use were adopted for this program.

The ADCP relies on software to compute streamflow. For each ensemble generated by the ADCP, a sub-discharge is computed based on the velocity of the vessel and depth of each ADCP beam. This information is then used to compute a total streamflow for the cross-section (RD Instruments, 2003). A typical channel-cross section illustrating the velocity distribution and channel geometry recorded by the ADCP is illustrated in Fig. 3.

Acoustic doppler velocimeter. For wading measurements at Carnegie and Bloomsburg, top-setting rods were equipped with an ADV (SonTek FlowTracker, a single-point, Doppler current meter). For bridge measurements, mechanical-current meters (Price type AA) were used with bridge cranes.

The ADV uses two acoustic receivers and one transmitter to generate a pulse of sound at a known frequency. As the pulse passes through the sample volume, the acoustic energy is reflected by suspended matter and returned to the receivers. The Doppler shift is proportional to the water velocity. The unit is capable of measuring flow velocities ranging from 0.0009 to 4.88 m/s and can be used in water depths as shallow as 2.54 cm. The ADV also was used to collect multiple point velocities along the vertical containing the maximum, instream-channel velocity (the *y*-axis) during wading or from an anchored boat. Point velocities along the *y*-axis were collected from near the channel bottom and at prescribed intervals to depths just below the water surface.

Streamflow was computed using the midsection method described by Rantz (1982). Channel subsections were spaced so that no subsection contained more than 10% of the total streamflow. Ideally measurements should not contain more than 5% of the total streamflow in a subsection. As a result, wading and bridge measurement had between 20 and 30 subsections. Subsections were close together in portions of the cross section where the depths and velocities were greatest. Velocity measurements were recorded along each vertical using the two-point method, which relies on the point velocities reported at 0.2 and 0.8 times the water depth (0.2*D* and 0.8*D*) to generate a mean-vertical velocity. This mean velocity was then multiplied by the width of each subsection (the distance between the preceding and following verticals and divided by two) and the channel depth along the measured vertical to yield a sub-discharge. The sub-discharges are then summed to determine the streamflow.

The Probability Concept

Probability-based solutions offer advantages in that they (1) require less field time because either a single-point velocity on the water surface or multiple-point velocities along a single vertical are needed to compute an instantaneous streamflow, (2) facilitate real-time velocity and streamflow measurements, when coupled with the proper instrumentation and (3) apply to unsteady flow conditions (such as looped ratings and flood flows) at the time of measurement.

The probability concept is based on an alternative velocity-distribution equation developed by Chiu (1989), who continues to pioneer work in this area of study. By measuring the surface velocity using radar and relying on probability-based solutions to compute the mean-channel velocity, unsteady streamflow can be estimated (Chiu and Tung, 2002). The method requires the *y*-axis be established at the cross-section of interest, and all velocity measurements (surface water and vertical points) be collected at this particular location. Additionally it prescribes that the ratio of the mean-channel velocity (u_{avg}) to maximum velocity (u_{max}) is unique for the cross-section of interest.

To derive the mean-channel velocity and compute streamflow, the following steps were used.

1. Review the historical record to identify the location of the *y*-axis, which is the vertical where the maximum velocity is recorded.
2. Measure the (i) surface-water velocity or (ii) multiple point velocities at the *y*-axis.
3. Determine the water depth (*D*) at the *y*-axis.
4. Determine the depth (*h*) of u_{max} below the water surface at the *y*-axis.
5. Determine the cross-sectional area of the channel.
6. Determine Φ using Eq. (4), (5) and compute streamflow using Eq. (6)

$$\frac{u}{u_{\max}} = \frac{1}{M} \ln\left[1 + (e^M - 1)\frac{y}{D-h}\exp\left(1 - \frac{y}{D-h}\right)\right], \quad \text{if } h > 0 \tag{4}$$

$$u_{\max} = (u_D M) \div \ln\left[1 + (e^M - 1)\frac{1}{1-\frac{h}{D}}\exp\left(1 - \frac{1}{1-\frac{h}{D}}\right)\right] \tag{5}$$

$$Q = u_{\text{avg}} \times A = \Phi \times u_{\max} \times A \tag{6}$$

where $\Phi = u_{\text{avg}}/u_{\max} = (e^M/e^M - 1) - 1/M$, *A* is the area of the channel section, *D* is water depth at the *y*-axis, *h* is the depth of $u_{\max}$ below the water surface; if $h > 0$, then $u_{\max}$ occurs below the water surface, *M* is the parameter relating the mean and maximum water velocities, u_{avg} is the mean cross-sectional water velocity, $u_{\max}$ is maximum water velocity, *u* is water velocity along the *y*-axis as a function of *y*, u_d is surface-water velocity at the *y*-axis, *y* is the distance from the channel bed on the *y*-axis and y_{axis} is that vertical within the channel section, in which the maximum channel velocity occurs.

Results

The measured-water velocities and computed streamflow for the Bloomsburg and Carnegie stations are presented below. Channel characteristics and field measurements are summarized in Table 2.

Velocity measurements

Surface-water velocity measurements using hand-held radar at Bloomsburg ranged from 0.61 to 0.70 m/s; the near-surface, ADV-derived velocity was 0.72 m/s. Hand-held radar was used from the bridge deck; the point measured on the water surface coincided with the *y*-axis and was approximately 30.5 m upstream of the bridge (Fig. 2). Surface-water velocity measurements using the hand-held radar unit at Carnegie ranged from 0.76 to 0.79 m/s; the near-surface, ADV-derived velocity was 0.79 m/s. Because Carnegie was wadable, the hand-held radar was used in two modes to measure surface-water velocity at the *y*-axis: (1) in-channel, standing approximately 3.05 m downstream of the waded cross-section and (2) from the bridge deck 30.5 m upstream of that same cross section. Because of the channel geometry and bed composition, well-defined riffles provided sufficient roughness for return energy to be recognized by the antenna.

Environmental factors may influence the quality of the surface-water velocity recorded by the hand-held radar. During low-flow conditions when surface-water velocities approached 0.30—0.61 m/s and the surface was pool-like, the unit recorded spurious values. This observation may be related to the quality of the return energy received by the antenna. To verify the validity of these velocities, ''near-surface'' velocity measurements at both stations were collected using an ADV by submerging the unit immediately below the water surface. It should be noted that the ADV sampling depth is limited to approximately 2.54 cm and does not provide an exact measure of the surface-water velocity. The ADV was also used to collect discrete velocities along the *y*-axis as a function of depth to assist with computing instantaneous streamflow. Fig. 4 and Fig. 5 illustrate the ADV-derived velocity distribution along the *y*-axis at Bloomsburg and Carnegie, respectively. In general $u_{\max}$ was measured below the water surface at both stations. A summary of the velocity measurements are presented in Table 2.

There was concern regarding the effects of wind drift and the maximum distance over which the return energy could be measured by the radar transceiver. As stated previously, wind moving across the water surface may create wave forms, which result in a motion different from the main direction of surface-water currents. During high flows this effect is minimal; however, during low flows or under pooled conditions, wind could introduce significant errors in the surface-velocity measurement. Additionally precipitation (such as rain or snow) passing in front of the instrument may influence velocity measurements. In slow water (0.30—0.61 m/s) the vertical velocity component produced by precipitation may be substantial resulting in errors (Decatur Electronics, 2001). Based on the site conditions observed at Carnegie (no wind or precipitation), the hand-held radar provided reliable results at a distance of at least 42.7 m along the hypotenuse from the target; however, the surface-water roughness at Bloomsburg was less, and the wind velocity was more dominant than that observed at Carnegie. These factors may have contributed to the variability in the measured surface-water velocity recorded by the hand-held radar at Bloomsburg. The low end of the

Table 2 Channel characteristics and water velocity measurements measured at US Geological Survey gaging stations Susquehanna river at Bloomsburg, PA and Chartiers Creek at Carnegie, PA

Station	Drainage area (km^2)	Width (m)	Hydraulic depth (m)	Area (m^2)	Near-surface water velocity using ADV (m/s)	Surface water velocity using hand-held radar (m/s)	Percent difference (%)
Chartiers Creek at Carnegie PA	665	27.4	0.43	12.1	0.79	0.76—0.79	4—0
Susquehanna River at Bloomsburg, PA	27,300	324	1.58	513	0.72	0.61—0.70	15—2

km^2, square kilometers; m, meters; m^2, square meters; m/s, meters per second; %, percent difference.

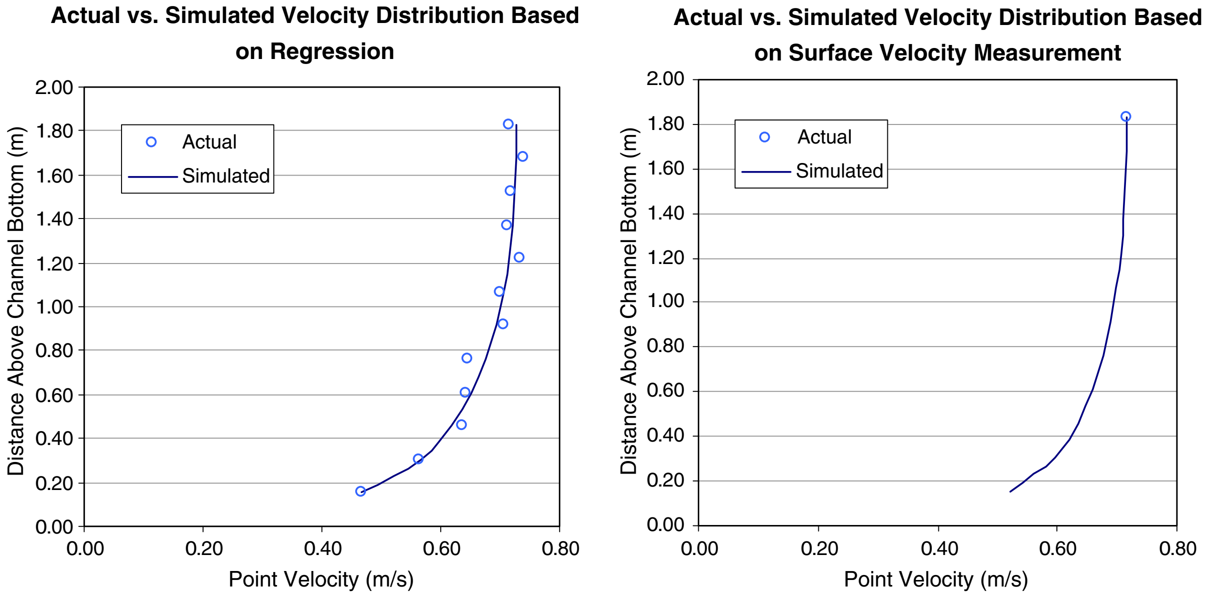


Figure 4 Actual versus simulated point velocities measured as a function of depth on the vertical that coincides with the *y*-axis at Susquehanna River at Bloomsburg, PA (m, meters; m/s, meters per second).

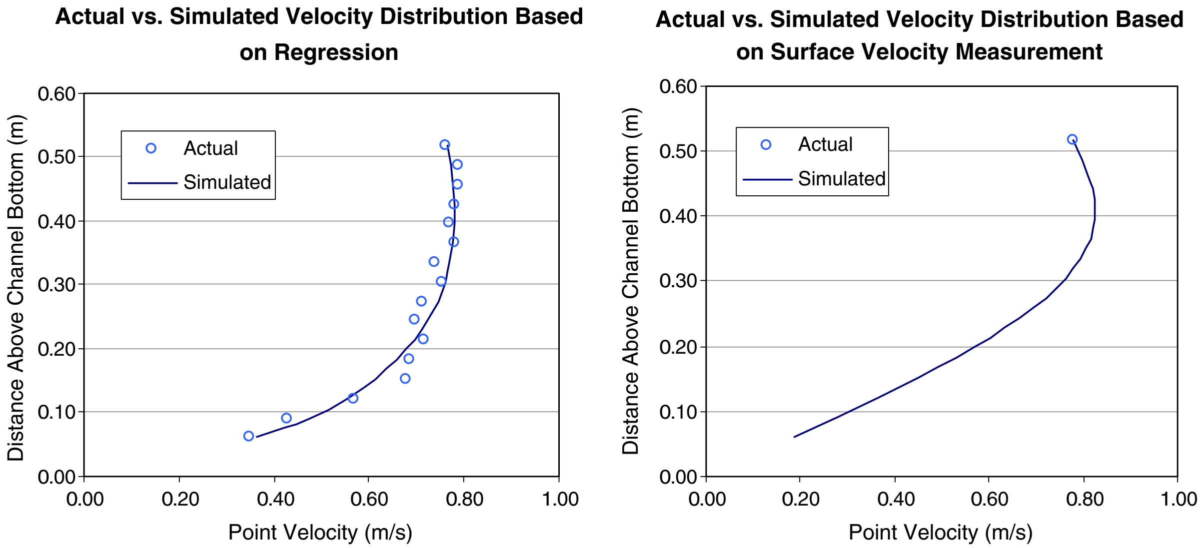


Figure 5 Actual versus simulated point velocities measured as a function of depth on the vertical that coincides with the *y*-axis at Chartiers Creek at Carnegie, PA (m, meters; m/s, meters per second).

surface-water velocities recorded at Bloomsburg (0.61 m/s), which were used to generate the probability-based streamflow, may impart a bias.

Streamflow measurements

Instantaneous streamflow was computed using the velocity data and cross-sectional areas acquired from the hand-held radar and hydroacoustics. The instantaneous streamflow was then compared to conventional methods such as ADCPs and stage-discharge ratings, which were established for each site. This process involves measuring the discharge and stage during a variety of streamflow conditions including extreme events. Initial measurements are made as often as practical with a frequency necessary to define the station rating for a range of stage (Rantz, 1982). Measurements are then made at periodic intervals (generally monthly to bimonthly) to verify the rating and to define temporary shifts due to changing stream-channel conditions. If these changes are permanent, a rating change is applied. The gage height is generally recorded using a wire weight or transducer, and the streamflow is measured using ADCPs or mechanical-current meters. After the rating has been established, the recorded gage height is used in conjunction with the established stage-discharge ratings at each station to determine the streamflow.

As previously indicated, probability-based solutions require (1) a single surface-water velocity or a velocity profile

Table 3 Variables used to compute instantaneous streamflow estimates at US Geological Survey gaging stations Susquehanna River at Bloomsburg, PA and Chartiers Creek at Carnegie, PA

Station	$u_{\max}$ measured (m/s)	$u_{\max}$ derived (m/s)	Φ (dim)	D (m)
Chartiers Creek at Carnegie PA	0.79	0.78	0.58	0.52
Susquehanna River at Bloomsburg, PA	0.74	0.73	0.78	1.83

$u_{\max}$, maximum water velocity; m/s, meters per second; m, meters; $\Phi = u_{\text{avg}}/u_{\max}$; u_{avg}, mean cross-sectional water velocity; D, water depth at the y-axis.

at the y-axis, (2) magnitude and depth of $u_{\max}$ at the y-axis, (3) water depth at the y-axis, and (4) cross-sectional area. Historical USGS Discharge Measurement Notes (Form 9-275) were reviewed to confirm the location of the y-axis by selecting that vertical, which exhibits the greatest 0.2 D point velocity. Additionally the location and magnitude of the maximum surface-water velocity was determined for each channel section using the hand-held radar. The variables for each station are presented in Table 3.

At Bloomsburg the ratio of $u_{\text{avg}}/u_{\max}$ was approximately 0.78, which was determined using both the surface-water velocity and vertical-velocity profile. For data collected during the period of record, the channel width ranged from 302 to 368 m for various streamflows with the y-axis occurring at bridge stationing 1010. The maximum-surface velocity measured during the site visit was recorded at station 1000, suggesting the location of the y-axis is relatively stable. Based on the record the standard deviation of the y-axis location is ±22.6 m. This finding is consistent with Chiu and Chen (1999) and Fulton (1999), who reported similar observations at other stations where historical records were available. The maximum velocity was measured to be 0.74 m/s at a depth of 0.15 m below the water surface. The water depth at the y-axis was approximately 1.83 m. Streamflow based on the emerging technologies ranged from 282 to 292 m^3/s, the ADCP was 287 m^3/s; the mechanical-current meter was 306 m^3/s; and rating curve was 299 m^3/s. Percent differences between the emerging technologies and conventional methods ranged from 0% to 8%; the average percent difference was 4% and the standard deviation was 8.81 m^3/s.

At Carnegie the ratio of $u_{\text{avg}}/u_{\max}$ was approximately 0.58 based on multiple-point velocities recorded along the y-axis (at a distance of 20.1 m from the left edge of water). It should be noted that when taking a wading measurement, the location of the y-axis should be spatially referenced using an arbitrary (bridge stationing) or a georeferenced system (latitude and longitude). The maximum velocity measured was 0.79 m/s and occurred at a depth of .05 m below the water surface. The water depth at the y-axis was approximately 0.52 m. Streamflow based on the emerging technologies ranged from 5.47 to 5.92 m^3/s; the mechanical current-meter was 5.95 m^3/s; and the rating curve was 5.35 m^3/s. Percent differences in streamflow between emerging technologies and conventional methods ranged from 0% to 11%; the average percent difference was 5% and the standard deviation was 0.28 m^3/s.

The streamflows computed using conventional and probability-based solutions are summarized in Table 4. The velocity distribution at the y-axis was recorded at Bloomsburg (Fig. 4) and Carnegie (Fig. 5) and computed using (1) multiple point velocities and (2) a single surface-water velocity. Actual velocity measurements are represented by the open circles; whereas, the theoretical distribution is represented by the solid lines. It should be emphasized that all velocity measurements were made at the y-axis, which coincides with the maximum velocity within the channel.

Radar and hydroacoustics accuracy

Accuracy of the SVR™ gun measurements was evaluated by investigators at the USGS Hydrologic Instrumentation Facility (HIF) Testing Section and reported by Fulford (written commun., 2003). Test results provided by the HIF indicate that the SVR™ guns have the following accuracy:

- Velocity accuracy at 0°, ±0.03 m/s.
- Vertical angle accuracy, ±4°.

The estimated range of velocity error (in m/s) was estimated using Eq. (5):

$$\text{error}_{\text{estimated}} = V_{\text{reading}}\left[\frac{\cos\alpha}{\cos(\alpha \pm 4^\circ)} - 1\right] \pm \frac{0.1}{\cos(\alpha \pm 4^\circ)}, \qquad (7)$$

where V_{reading} is the average velocity measurement recorded by the SVR™ gun and α is the vertical angle, which the gun is held. It should be noted that the vertical angle is automatically corrected by a tilt-sensing device in the SVR™. Given a velocity of approximately 0.76 m/s and a tilt of 45°, the estimated range of error is +0.09 to −0.09 m/s. It should be noted that the manufacturer of the SVR™ gun suggests a minimum surface-water velocity of 0.03 m/s and a maximum surface-water velocity of 13.7 m/s can be measured with an accuracy of ±0.03 m/s. Prior to operation, the velocity reading was verified using a 1098 Hz tuning fork, which is equivalent to a reading of 6.8 m/s on the guns display.

The accuracy of the ADV was established through tow-tank tests conducted at the USGS Hydraulics Laboratory at the HIF. The unit was tested at eight tow-cart speeds ranging from 0.03 to 0.91 m/s. The mean percent difference from actual for the range of velocities tested was approximately −2.5%. The ADV specifications indicate it does not require further calibration beyond what is provided by the factory.

Conclusions and recommendations

Based on the results of the demonstration project program at two stations in Pennsylvania, a hand-held radar gun coupled with the probability concept is capable of providing accurate and defensible measures of surface-water velocity and instantaneous streamflow. When compared to conventional methods such as an ADCP, mechanical current-meter measurements, and rating curves, the emerging technologies provide agreement, and the field time needed

Table 4 Instantaneous streamflow computed using conventional and emerging technologies and the percent difference at US geological survey gaging stations Susquehanna river at Bloomsburg, PA and Chartiers Creek at Carnegie, PA

Station	Conventional methods and instantaneous streamflow (m^3/s)		Emerging technologies and instantaneous streamflow (m^3/s)		
			Multiple point velocities along a single vertical	Single surface water velocity using ADV	Single surface water velocity using hand-held radar
			5.47 m^3/s	5.92 m^3/s	5.81 m^3/s
Chartiers Creek at Carnegie PA	Mechanical current meter	5.95	8%	0%	2%
	Rating curve	5.35	2%	11%	8%
			292 m^3/s	288 m^3/s	282 m^3/s
Susquehanna River at Bloomsburg, PA	ADCP	287	2%	0%	2%
	Mechanical current meter	306	4%	6%	8%
	Rating curve	299	2%	4%	6%

m^3/s, cubic meters per second; %, percent difference.

to measure and compute the streamflow is significantly reduced. The ratio u_{avg}/u_{max} at Bloomsburg and Carnegie appear to be extremely stable and invariant to changes in streamflow and stage and are applicable over the entire range of streamflow reported at the stations. The location of the y-axis within a channel cross-section generally coincides with the maximum surface-water velocity. At Bloomsburg, historical data suggest the position of the y-axis is stable over a wide range of flow conditions.

The instrumentation and analytical methods presented in this paper offer a proof-of-concept demonstration that provides instantaneous streamflow, which can be input into hydraulic routing models. Because the ratio u_{avg}/u_{max} is invariant to changes in streamflow, velocity, stage, channel geometry, bed form and material, slope, and alignment; it is resilient and capable of yielding accurate streamflow estimates in excess of those values limited by the traditional uniform-rating curves. As a result, radar-derived streamflow and velocity would provide the feedback needed to make the appropriate model adjustments and provide accurate stage forecasts. The method also offers the advantage of providing a measure of the mean-channel velocity and streamflow during hydrologic extremes in both gaged and ungaged settings; as a result, they are ideal for real-time reporting and facilitate forecasts by providing a continuity check. By developing procedures that account for these variable flow conditions, forecast reliability can be increased.

Environmental factors appear to influence the quality of the surface-water velocity recorded by the hand-held radar unit. The influence of wind in low-velocity waters may create wave forms that result in a motion different from the principal surface-water flow direction and magnitude. Surface-water roughness may also impact the measurements recorded by the unit. At low velocities (0.61 m/s), pool-like conditions and wind may compromise the reproducibility of the computed streamflow. However based on these preliminary field tests, the hand-held radar unit is capable of providing accurate measures of surface-water velocity and streamflow when compared to conventional methods.

The probability concept developed by Chiu (1989) can be used to quantify instantaneous streamflow during unsteady flow events (Chiu and Chen, 1999) such as looped ratings and flood flows; however, additional data are required to fully evaluate the robustness of the solution. In addition research is needed to develop a more reliable radar unit capable of filtering the effects associated with wind and precipitation on the velocity spectrum.

Newer equipment is being explored and includes fixed-mount, CW microwaves equipped with homodyne or heterodyne transceivers and upward-looking ADCP units. This instrumentation is being evaluated for near-real time transmission of velocity and streamflow data for open water and for partial and full-ice cover. It is anticipated that the data will be transmitted using radio modems or acoustic modems linked to a data-collection platform and satellite telemetry.

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