USING RADAR TO MEASURE REAL-TIME STREAMFLOW

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Abstract Surface-water velocities were measured using hand-held radar at two existing U.S. Geological Survey streamflow-gaging stations in Pennsylvania. Streamflow was then computed in real-time using the velocity recorded from a single point that coincides with the maximum instream velocity. The results were corroborated using conventional methods such as hydroacoustics (acoustic Doppler velocimeters and acoustic Doppler current profilers), current meters, and rating curves. Percent differences between conventional and radar-derived discharges at Chartiers Creek at Carnegie, Pa. ranged from 0 to 11 percent with a standard deviation of 10 cfs and at the Susquehanna River at Bloomsburg, Pa from 0 to 8 percent with a standard deviation of 311 cfs.

Although environmental factors appear to influence the quality of the surface-water velocity recorded by the radar unit, the preliminary field tests suggest the radar-derived data is accurate and defensible relative to conventional methods. New generation equipment is under development and being tested to advance the use of radar- and microwave-measured surface-water velocity and streamflow.

INTRODUCTION

The project was designed to pilot the use of equipment and analytical solutions that support real-time, non-contact streamflow measurement (Fulton and Ostrowski, in review). This was accomplished by collecting a single surface-water velocity at a prescribed location within the channel cross-section using hand-held radar. The velocity data was used to compute an instantaneous streamflow using probability-based solutions developed by Chiu and Tung (2002).

Study Area Two existing USGS streamflow-gaging stations (stations) (Susquehanna River at Bloomsburg, Pa. – 01538700 and Chartiers Creek at Carnegie, Pa. – 03085500) were selected in part, 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 instream 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. The station is west of Bloomsburg, Columbia County, Pa., and drains an area of 10,500 square miles (mi^2). From 1995 through 1997, streamflows ranging from 2,390 cubic feet per second (cfs) to 223,000 cfs and corresponding gage heights varying from 0.8 foot (ft) to 25.5 ft, 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. The station is south of Pittsburgh, Allegheny County, Pa., and drains an area of 257 mi^2. Based on 74 years of record, minimum and maximum instantaneous flows are 16 and 13,500 cfs, respectively. Site location maps are illustrated in figure 1.

Susquehanna River at Bloomsburg, PA	Chartiers Creek at Carnegie, PA
	

Figure 1 Site location maps.

<u>Demonstration Project</u> Conventional and alternative methods for measuring water velocity and computing streamflow were compared. Because conventional methods listed are widely accepted as industry standards, they were used as a benchmark to evaluate the validity of the alternative methods for measuring streamflow.

Conventional Methods Water velocity was measured and streamflow was computed using an Acoustic Doppler current profiler (ADCP), acoustic Doppler velocimeter (ADV), current meter, and rating curves. A description of each is presented below.

<u>ADCP</u> Where conditions permitted, a boat-towed RD Instruments[1] 600 kHz Workhorse Rio Grande ADCP was used. The unit is mounted to either the port or starboard side of the boat and towed from one channel bank to the other; it operates in water depths greater than 3 ft and water velocities greater than 0.5 foot per second (fps). ADCPs transmit sound bursts into the water and measure the reflected signal from particles suspended 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. 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).

<u>Current Meter and ADV</u> For bridge measurements at Bloomsburg, conventional current meters (Price type AA) were used with bridge cranes. For wading measurements at Carnegie, top-setting rods were equipped with an ADV (SonTek[1] FlowTracker, a single-point, Doppler current meter). The ADV was also used to collect multiple point velocities along the single-vertical containing the maximum, instream-channel velocity (the y-axis). The ADV unit uses two

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

acoustic receivers and one transmitter to generate a pulse of sound at a known frequency. As the pulse passes through the sampling volume, the acoustic energy is reflected by suspended matter and returned to the receivers. The Doppler shift is proportional to the water velocity. It is capable of measuring flow velocities ranging from 0.003 to 16 fps and can be used in water depths as shallow as 1 inch (in). Streamflow was computed using the midsection method described by Rantz (1982).

Rating Curve The gage height was recorded using a wire weight or transducer at the time of measurement. The recorded gage height was used in conjunction with the established stage-discharge ratings at each station to determine the streamflow.

Alternative Methods Surface-water velocities were measured using a Decatur[2] SVR™ gun. 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 beams 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 SVR™ gun includes a tilt sensor that compensates for the cosine errors when the unit is pointed towards the water surface (pitch) and when it is pointed at the water surface from the waters edge (yaw). For this effort, all measurements were made using a pitch (or tilt) of 45 degrees and yaw of 0 degrees. The configuration of the SVR™ gun relative the channel width is illustrated in figure 2.

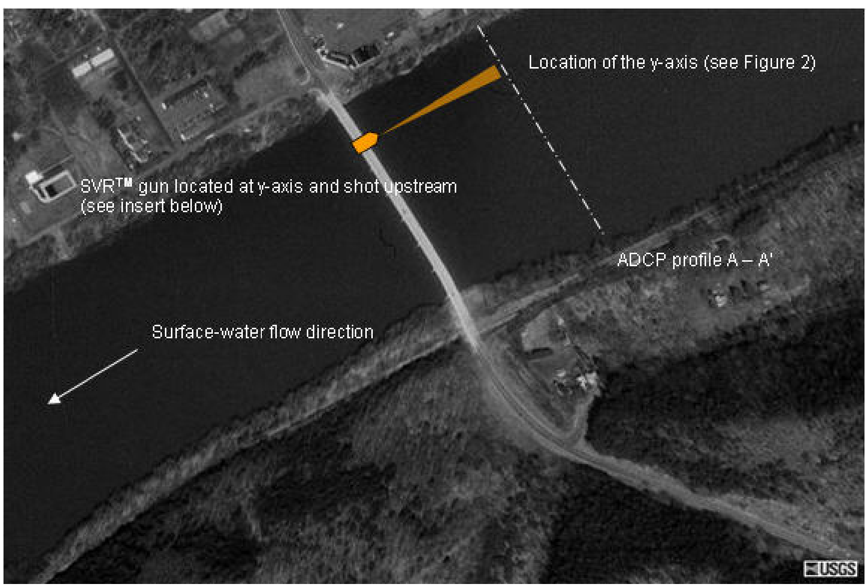

Figure 2 SVR™ gun configuration.

Streamflow Computation Streamflow was computed using conventional and probability-based solutions. 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

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single vertical are needed to compute 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.

Probability-based solutions are 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 a device such as radar and relying on probability-based solutions to compute the mean-channel velocity, unsteady streamflow can be estimated (Chiu 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 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, and (6) determine M using Equation 1 or 2 and (7) compute streamflow using Equation 3.

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

$$u_{\max} = (u_D M) \div \ln\left[1+(e^{M}-1)\frac{1}{1-\frac{h}{D}}\exp\left(1-\frac{1}{1-\frac{h}{D}}\right)\right] \quad \text{(Eq. 2)}$$

$$Q = u_{avg}\cdot A = \phi \cdot u_{\max}\cdot A \quad \text{(Eq. 3)}$$

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

RESULTS

The measured water velocities and computed streamflow for the Bloomsburg and Carnegie stations are presented in Fulton and Ostrowski (in review).

Velocity Measurements Multiple SVR™ velocity measurements recorded at Carnegie ranged from 2.5 to 2.6 fps; the near-surface, ADV-derived velocity was 2.6 fps. The SVR™ gun was used in two modes to measure surface-water velocity at the y-axis (1) in-channel, standing approximately 10 ft downstream of the waded cross-section and (2) from the bridge deck approximately 100 ft 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 intercepted by the SVR™ receiver.

Multiple SVR™ velocity measurements recorded at Bloomsburg ranged from 2.0 to 2.3 fps; the near-surface, ADV-derived velocity was 2.35 fps. The SVR™ gun was used from the bridge deck; the point measured on the water surface coincided with the y-axis and was approximately 100 ft upstream of the bridge.

SVR™ Gun Use and Limitations Environmental factors may influence the quality of the surface-water velocity recorded by the SVR™. In addition, there was concern regarding the maximum distance over which the return energy could be measured by the gun's antenna. For example, wind moving across the water surface may create wave forms, which result in motion different from the main direction of surface-water flow. During high flows, this turbulence 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 (1 to 2 fps), the vertical velocity component produced by precipitation can be substantial, resulting in errors (Decatur Electronics, 2001).

The surface-water roughness at Bloomsburg was less, and the wind velocity was more dominant than that observed at Carnegie. These factors may have attributed to the variability in the measured surface-water velocity recorded by the SVR™ at Bloomsburg. The low end of the surface-water velocities recorded at Bloomsburg (2 fps), which were used to generate the probability-based streamflow, imparts a bias. For example at 2 fps, the streamflow would be approximately 8,650 cfs. At these velocities, pool-like conditions and wind may have compromised the reproducibility of the computed streamflow. This spurious data may be related to the magnitude of the return energy received by the antenna. Based on the site conditions observed at Carnegie (no wind, precipitation), the gun provided reliable results at a distance of at least 140 ft along the hypotenuse from the target.

Method Comparison Conventional streamflow computations were compared to those derived using the SVR™ gun and probability-based solutions. As previously indicated, probability-based solutions require (1) a single surface-water velocity or a velocity profile 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 channel area. Historical USGS Discharge Measurement Notes (Form 9-275) were reviewed to confirm the location of the y-axis by selecting the vertical that exhibits the greatest 0.2D point velocity. Additionally, the location and magnitude of the maximum surface-water velocity was determined for each channel section using the SVR™.

The ratio of u_{avg} / u_{max} at Carnegie was approximately 0.58 based on multiple point velocities recorded along the y-axis (at a distance of 66 ft 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 2.59 fps and occurred at a depth of 0.2 ft below the water surface. The water depth at the y-axis was approximately 1.7 ft. Probability-based streamflow (equations 1 and 3) ranged from 193 to 209 cfs; current-meter was 210 cfs; and rating curve was 189 cfs. Percent differences between actual and computed streamflow ranged from 0 to 11 percent; the average percent difference was 5 percent and the standard deviation was 10 cfs.

The ratio of u_{avg} / u_{max} at Bloomsburg was approximately 0.78, which and 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 990 to 1,207 ft for various streamflows with the y-axis occurring at bridge station 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. Historically, the standard deviation of the y-axis location is ±74 ft. This finding is consistent with Chiu and Chen (1999) and Fulton (1999), who reported similar observations in other stations where historical records were available. The maximum velocity measured was 2.43 fps at a depth of 0.5 ft below the water surface. The water depth at the y-axis was approximately 6.0 ft. Probability-based streamflow ranged from 9,947 to 10,328 cfs; ADCP was 10,130 cfs; current meter was 10,800 cfs; and rating curve was 10,550 cfs. Percent differences between actual and computed discharge ranged from 0 to 8 percent; the average percent difference was 4 percent and the standard deviation was 311 cfs.

The streamflows computed using conventional and probability-based solutions are summarized in table 1. The velocity distribution at the y-axis was recorded at Carnegie (figure 3) and Bloomsburg (figure 3) 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 instream velocity.

			Percent difference		
			Alternative methods		
Station location	Conventional methods		Multiple point velocities	Near- surface water velocity ADV	Surface water velocity SVR™
			193 cfs	209 cfs	205 cfs
Chartiers Creek at Carnegie PA	Current meter	210 cfs	8%	0%	2%
	Rating Curve	189 cfs	2%	11%	8%

			Percent difference		
			Alternative methods		
Station location	Conventional methods		Multiple point velocities	Near- surface water velocity ADV	Surface water velocity SVR™
			10,328 cfs	10,163 cfs	9,947 cfs
Susquehanna River at Bloomsburg, PA	ADCP	10,130 cfs	2%	0%	2%
	Current meter	10,800 cfs	4%	6%	8%
	Rating Curve	10,550 cfs	2%	4%	6%

Table 1 Streamflow computed using conventional and alternative methods.

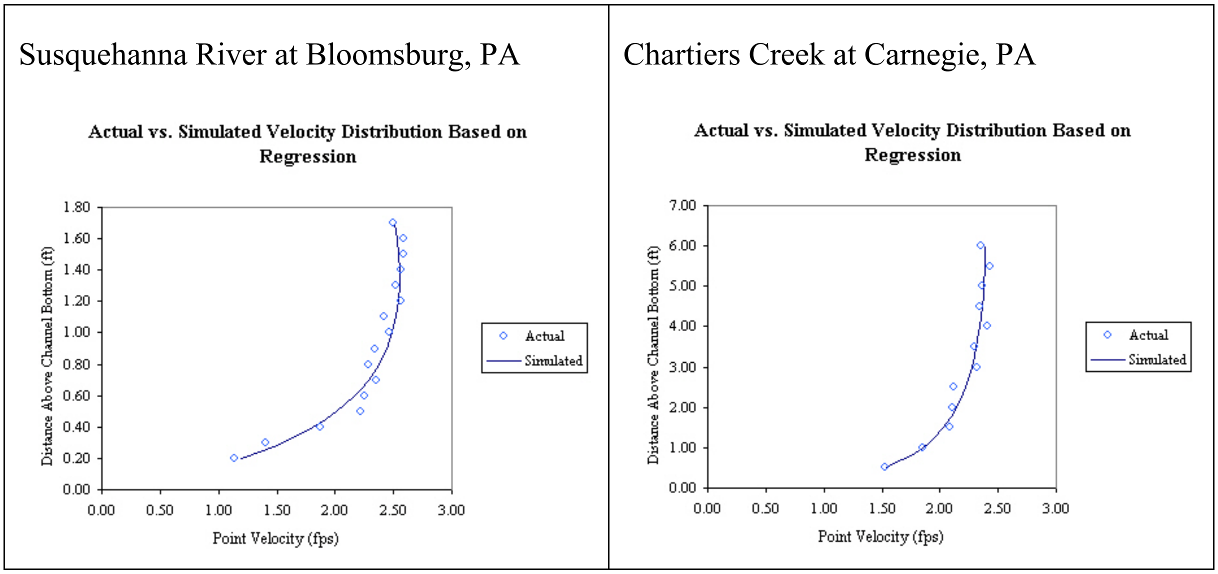

Figure 3 Velocity distribution along y-axis [ft, feet; fps, feet per second].

Quality Assurance Accuracy of the SVR™ gun measurements was evaluated by investigators at the HIF Testing Section and reported by Fulford (written commun., 2003). Test results provided by the HIF indicate that the SVR™ guns are accurate relative to

- velocity at 0 degrees, ± 0.1 fps
- vertical angle, $\pm$ 4 degrees

The estimated range of velocity error (in fps) was estimated using Equation 4

$$error_{estimated} = V_{reading}\left[\frac{\cos\alpha}{\cos\left(\alpha \pm 4^{\circ}\right)} - 1\right] \pm \frac{0.1}{\cos\left(\alpha \pm 4^{\circ}\right)} \quad \text{, where} \qquad \text{(Eq. 4)}$$

$V_{reading}$ is the average velocity measurement recorded by the SVR™ gun and α is the vertical angle at 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 2.5 fps and a tilt of 45°, the estimated range of error is +0.3 to –0.3 fps.

Additionally, 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 0.1 to 3 fps. The mean percent difference from actual for the range of tested velocities was approximately -2.5 percent. 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 data collected at two stream sites in Pennsylvania, a hand-held SVR™ gun coupled with probability-based solutions is capable of providing accurate and defensible measures of surface-water velocity and streamflow. When compared to conventional methods such as ADCP, current-meter measurements, and rating curves, probability-based solutions provide agreement. Additionally, the field time needed to measure and compute the streamflow is significantly reduced. The ratio u_{avg} / u_{max} or ϕ at Carnegie and Bloomsburg appears to be extremely stable and invariant to changes in streamflow and stage and is applicable over the entire range of streamflow reported at the stations.

Depending on site conditions, environmental factors such as wind and rain may influence the velocity spectrum produced by the radar unit. Additional 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 tested. In addition, under-ice applications are being considered including upward-looking ADCP units and instrumentation capable of transmitting velocity data streams using acoustic modems linked to a data-collection platform and satellite telemetry. By developing procedures that account for these variable flow conditions, forecast reliability can be increased.

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