Proceedings of the Institution of Civil Engineers
Water Management 161
August 2008 Issue WM4
Pages 199–206
doi: 10.1680/wama.2008.161.4.199
Paper 700026
Received 28/06/2007
Accepted 06/02/2008
Keywords:
field testing & monitoring/hydrology & water resource

Neil McIntyre
Senior lecturer, Imperial College London, UK

Miles Marshall
Post-doctoral research associate, Imperial College London, UK

ice
Institution of Civil Engineers

Field verification of bed-mounted ADV meters

N. McIntyre MSc, PhD, MICE, CEng and M. Marshall MSc, PhD

The accuracy of continuous-signal acoustic Doppler velocity (ADV) meters for gauging stream flows is examined, using a case study of nine bed-mounted 'Starflow' meters currently installed at a range of sites in the Pontbren catchment, Wales. The accuracy of the ADV meters was tested, under a range of velocities and depths, by comparing flow estimates with those based on a standard method of measurement with an impeller meter. The accuracy of the ADV meters was found to be poor for very low flows. For higher flows, in five concrete-lined sections, accuracy was reasonable without calibration of the ADV meter (estimates were within 20% of the current-metered flow for 68% of samples) and accuracy was good after calibration (estimates were within 20% of the current-metered flow for 93% of samples). In one natural channel, the performance after calibration was similarly good, while performance was fair to poor for two other natural channels. The predictability of the calibration results, and the reasons for the poor performance, are discussed.

1. INTRODUCTION

Instruments based on acoustic Doppler velocity (ADV) technology have become established for continuous-time flow gauging and look set to replace more traditional methods (e.g. weirs, flumes, ultrasound time-of-flight) due to ease of installation and maintenance, versatility and low intrusiveness. Their low cost (of purchase, installation, operation, decommissioning and reuse) and low environmental impact can make some ADV products especially attractive for non-permanent flow gauging stations, particularly for research projects that require significant spatial coverage of a stream network. For example, recent national hydrology research programmes in the UK[1,2] have applied low-cost bed-mounted ADV meters. The literature indicates that the performance of these meters is variable and sensitive to field circumstances.[3] Very few analyses of accuracy have, however, been published.

This paper reports an investigation into the accuracy of Unidata's bed-mounted 'Starflow' ADV meters at nine sites in the Pontbren experimental catchment in Wales[4] from December 2005 to June 2007. The data encompass a range of channel types, flow rates and depths, allowing discussion of the hydraulic features that control the accuracy of this type of meter. The results allow assessment of the applicability of this type of meter, with and without calibration, to Pontbren and similar sites. The paper first outlines the general principles of the Starflow meter and previous relevant research into the performance of bed-mounted ADV products.

2. PRINCIPLES OF FIXED ADV METERS

The Doppler shift, f_D (measured in Hz), between an emitted and reflected signal in any medium is related to the velocity of the reflecting body in the direction of the signal v_s (m/s), the frequency of the emitted signal f_s (Hz) and the wave velocity in the medium c (m/s). Assuming v_s to be much smaller than c, the relationship is

$$f_d = \frac{2vf_s}{c} \quad (1)$$

In the context of stream flow measurement, the medium is water, the signal is an ultrasonic wave and the reflectors are suspended particles in the water (or, in some cases, air bubbles) assumed to be travelling at the same velocity as the water. In practice, the ADV meter will be at an angle θ to the flow direction, as illustrated in Fig. 1, in which case v_s is resolved to give the velocity in the direction of flow v

$$v = \lambda f_D \quad (2)$$

where λ is defined by

$$\lambda = \frac{c}{2f_s \cos\theta} \quad (3)$$

Using a typical signal frequency, $f_s = 1{\cdot}56 \times 10^6$ Hz, in fresh water of temperature $T = 20°$C (for which $c = 1482$ m/s) and using a typical inclination angle $\theta = 30°$, then $\lambda = 0{\cdot}55 \times 10^{-3}$ m. Typically, the ADV meter will include a temperature sensor so that the value of λ can be automatically increased by approximately 0·2% for every 1°C increase in water temperature.

The simpler types of ADV meter use a continuous ultrasound signal with a constant frequency, and the reflected signal has a distribution of frequencies representing the spectrum of velocities of particles in the sampled volume of water. By integrating this distribution, the mean water velocity in the sampling volume v_m (m/s) may be estimated. If a large number of signals are reflected from random locations over the

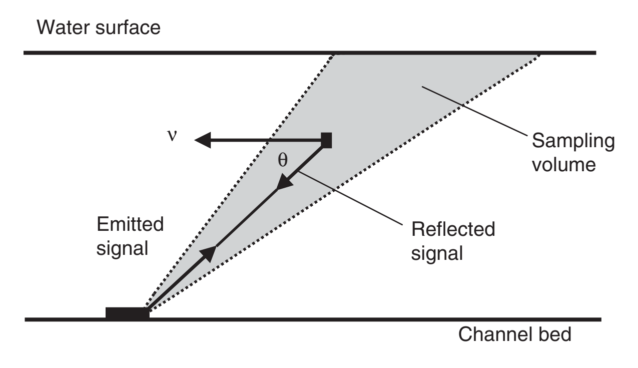

Fig. 1. Sampling volume of a typical bed-mounted ADV meter (side view)

sampling volume, v_m will represent the average velocity within that volume, irrespective of the velocity distribution over the volume. More complex types of ADV (profilers or range-gated meters) emit sequences of ultrasound pulses. The pulses are encoded so that the origins of the returned signals can be resolved, thereby allowing the spatial velocity distribution to be measured, as well as the sampling volume average.[3] The ADV meters examined later in this paper are of the simpler, continuous-signal type.

The sampled volume of water (e.g. Fig. 1) does not generally cover the full cross-sectional area of flow Q (m^3/s). To estimate Q, the sampling volume average velocity v_m therefore needs to be adjusted to the average velocity over the cross-sectional area A by a factor α. Furthermore, because the meter may only become submerged once a flow threshold is reached, a constant β may be required.

$$Q = \alpha v_m A + \beta \tag{4}$$

The factor α is a function of the velocity distribution over the cross-section. Unidata[5] indicates that the value of α for a Starflow meter may be expected to lie between 0·9 and 1·1 when the flow can be considered laminar. Its value may be expected to be close to 1·0 where there is little variation in velocity over the cross-section, for example in wide, smooth, straight, prismatic channels, although may be much more variable for natural streams.[6] Potentially, α can also compensate for a range of errors in the measurement of v.

3. SOURCES OF ERROR USING ADV METERS

The factor α is expected to change between ADV sites and between flow rates, and may be unstable, for example due to the dynamics of local channel geomorphology and vegetation. The cross-sectional area A is calculated as a function of the measured depth and hence the accuracy of depth measurements and the depth–area relationship also affect the accuracy of Q.

Noise in the raw ADV signal will arise from natural transience in velocity fields as well as transience in depth and suspended sediment distributions. Typically, therefore, the ADV is programmed to sample the velocity at a frequency considerably higher than the required time resolution of processed flow data, so that noise may be smoothed.

Low flows and high flows may be special challenges for ADV meters, and may dictate suitable sites. High velocities increase debris load, potentially exposing the ADV to damage. For bed-mounted meters, the meter will lose accuracy at low flows as the signal–noise ratio in both depth and velocity measurements increases; no measurements are possible when the flow falls below transducer levels (i.e. flow threshold β in equation (4)). This may encourage installation in slower, deeper waters. Low velocity may, however, lead to siltation over the transducers and the lower velocity limit of operation is typically 0·020 m/s.

Another potential source of inaccuracy common to continuous-signal ADV meters is range bias. If more signals are consistently received from some parts of the sampled volume of water (for example due to higher concentrations of suspended sediment near the bed, or due to weaker reflections from near the sampling limit), these will bias the average velocity calculation.

In summary, sources of error for a bed-mounted, continuous-signal ADV meter for measuring flow in freshwater streams can include

(*a*) inaccurate estimation of velocity factor
(*b*) inaccurate measurement of depth–area
(*c*) unstable channel morphology
(*d*) range bias due to uneven distributions of suspended particles and air bubbles
(*e*) sampling errors due to noise in the flow signal
(*f*) error in the estimated angle between flow direction and signal
(*g*) errors associated with the variability of c with temperature and salinity
(*h*) malfunctions due to damage or obstruction from debris
(*i*) low-flow errors due to inadequate coverage of the transducers
(*j*) tolerances in the meter's depth and velocity measurements.

Other practical issues include accessibility and security of the ADV and data logger.

4. PREVIOUS EVALUATIONS OF BED-MOUNTED ADV METERS

Vermeyen[7] tested bed-mounted ADV meters in a laboratory, in a 2·6 m wide rectangular channel under a flow of 0·85 m^3/s and a range of velocities; further tests were conducted in a 0·3 m wide channel with a flow of 0·028 m^3/s and water depth of 0·3 m. The uncalibrated meter (i.e. using $\alpha = 1$, $\beta = 0$) quite consistently overestimated average velocity and discharge by 24% compared to baseline values measured by flumes and other Doppler instruments. The overestimation was expected because the meter was sampling the faster-flowing water near the centre of the channel cross-section. This implies that calibration is important and can potentially lead to good quality results over a range of flows for a stable rectangular channel.

Chalk[8] reported an experiment in which an ADV meter, designed to be bed-mounted, was moved along a rectangular channel at a constant known velocity, repeatedly for a large number of velocities between 0·035 and 1·75 m/s. The measured ratios of water velocity to Doppler shift were compared to the theoretically calculated value of $0·547 \times 10^{-3}$ m. The results were good, with the measured ratio averaging $0·55 \times 10^{-3}$ m over the range of velocities, with a standard deviation of 1·5%. The good performance without calibration may be associated with the movement of the meter through static water, which implies a near-uniform velocity field. The variability was, however, much larger at velocities less than 0·5 m/s and there was a significantly different average value below 0·25 m/s.

In a report commissioned by the Environment Agency of England and Wales, King *et al.*[6] tested the performance of a continuous-signal bed-mounted meter (Unidata's Starflow) in conditions where there was insufficient head loss for effective operation of a weir or flume. They compared current-metered velocities and flows with ADV meter data, always assuming $\alpha = 1$. The first site was a 2·15 m wide concrete-lined rectangular channel of depth ranging from 0·8–1·0 m and cross-section average velocities ranging from 0·08–0·17 m/s over five samples. They concluded that the ADV meter, in general, measured depth and local velocity accurately, although the sampling volume velocity did not represent the cross-section average velocity well; hence, ADV estimates of flow were on average 53% different from current-metered values. The second site was a natural channel, approximately 2 m wide, where a series of flow measurements were taken on each of two days. On the first day, cross-section average velocities ranged from 0·42–0·51 m/s over four samples and the depth was relatively constant at about 0·24 m. Compared to the current-metered values, the ADV consistently overestimated the local velocity and the cross-section average velocity; flows were overestimated by between 36 and 52% over the four samples. On the second day, two samples were taken under similar velocity and depth conditions, and the ADV overestimated the flows by 34 and 40%. The authors noted problems with the meter at this site becoming buried by silt bed-load. Bed-mounted ADV meters were tested by King *et al.* at five further sites (widths 3–4·5 m), including sites with evident oblique flow problems. The accuracy compared to current-meter flow estimates was found to be generally poor, with error magnitudes consistently worse than 20% and in most cases worse than 40%.

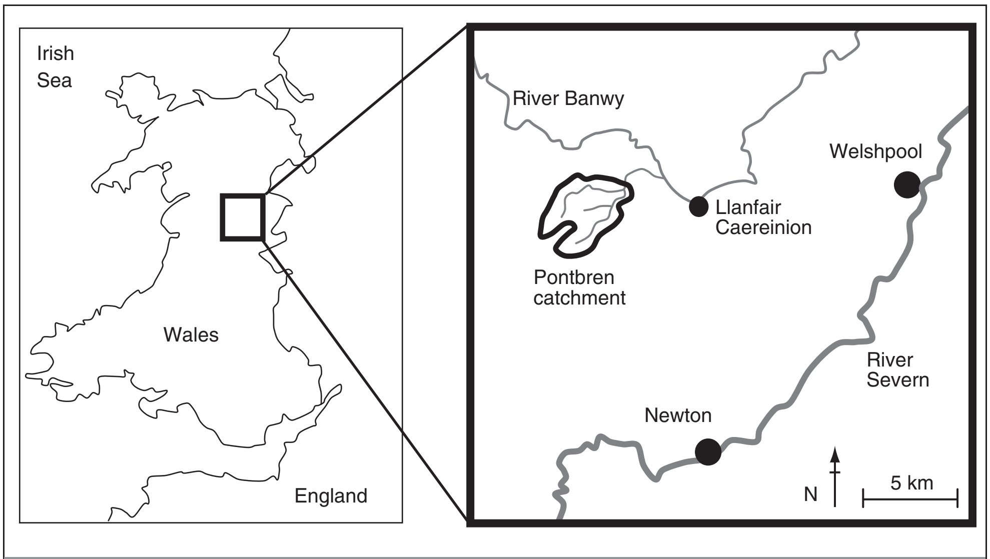

Fig. 2. Location of the Pontbren catchment

The recommendations of King *et al.*[6] included

(*a*) weeds around the ADV meter site should be carefully cleared
(*b*) more than one bed-mounted meter should be used for channels more than 2 m wide and also for smaller channels with significant variations of velocity across the channel width (otherwise a side-mounted meter should be considered)
(*c*) 0·1–0·2 m minimum depth of water is required in order to achieve accurate velocity measurements.

They also tested range-gated bed-mounted meters at the same sites. They had more reliability problems, however, and no clear benefit in terms of flow accuracy over the simpler, continuous-signal type of meter.

Zaidman *et al.*[3] reviewed recent and new technology for stream flow measurement. They also noted the potential inaccuracy of fixed continuous-wave ADV meters, citing various published[8,9] and unpublished reports, including one that noted 50% overestimation of flows. They note that the manufacturers' specifications of accuracy (typically ±2%) for velocity neglect the complicating factors of field circumstances.

A review of the literature for this work indicated that bed-mounted ADV meters can deliver good performance in stable rectangular channels, especially if α is calibrated. Published data on accuracy in more complex channel types and field conditions are very limited; however, they indicate very variable performance and that calibration is essential.

5. CASE STUDY

5.1. Site and instrument description

The Pontbren catchment is situated in Powys, Wales (Fig. 2). The catchment has been instrumented with the aim of evaluating the effects of land use on flood risk[4] within a national programme of flood risk research conducted by the Flood Risk Management Research Consortium.[2]

The bed-mounted ADV meters used at Pontbren are Unidata Starflow 6526b; specifications are summarised in Table 1. Depth, velocity and temperature measurements are recorded by the Starflow once per minute and 15-minute average values logged. Velocity measurements are obtained by integrating over the sampling volume in the following manner (pers. comm.). Each returned frequency shift is converted into velocity using equation (2). These velocity samples are accumulated over a 2 s

Beam inclination: degrees	30
Beam spread: degrees	10
Signal frequency: Hz	$1{\cdot}56 \times 10^6$
Temperature correction ($d\lambda/dT$): m/°C	$1{\cdot}38 \times 10^{-6}$
Depth accuracy: %	0·25
Velocity accuracy: %	2·5
Depth range: m	0–2
Velocity range: m/s	0·021–4·5

Table 1. Summary of Starflow specifications

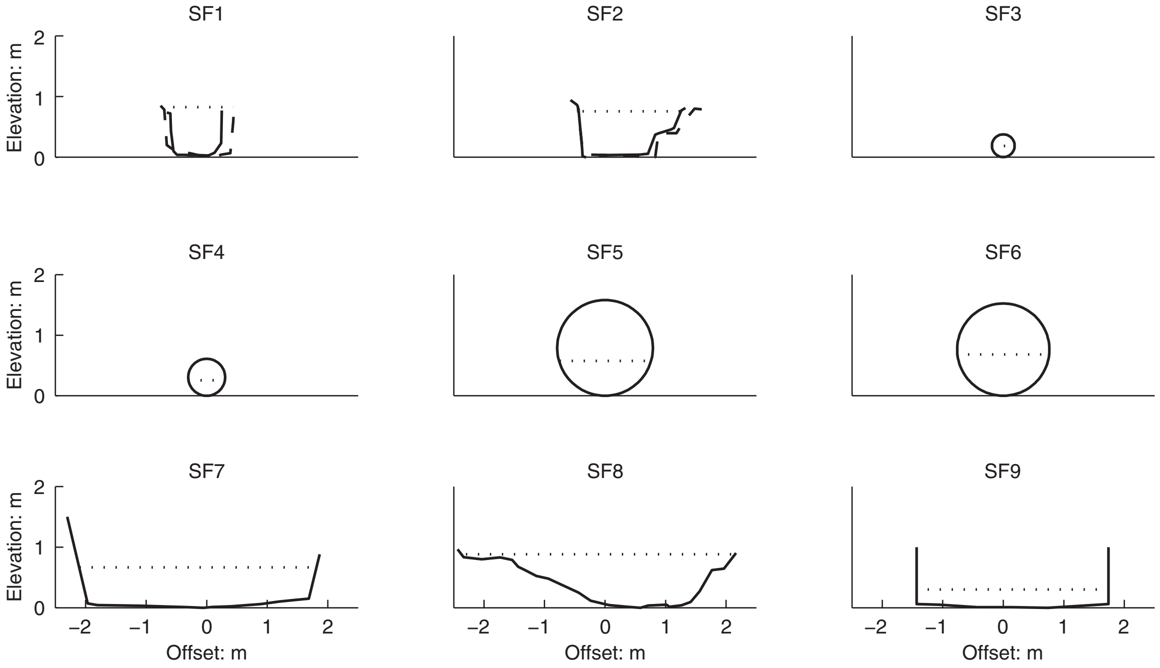

Fig. 3. The cross-sections at the nine sites (SF1–SF9). The Starflow in each case is located at offset = 0. The solid lines for SF1 and SF2 show the section shape as measured in October 2005, and the dashed lines as measured in March 2007. The dotted lines show the maximum water level over the period of Starflow operation

time period, up to a maximum of 500 samples. The integrated velocity measurement is the median of all these samples (the median gives a more accurate representation of channel velocity as the mean can be unreasonably biased by outlying velocity values). Upon downloading the logged data, the Starflow software computes the cross-sectional area using a user-specified depth–area curve and the flow using equation (4) assuming $\alpha = 1$, $\beta = 0$.

Ten Starflow meters have been installed in the Pontbren catchment. One of the sites is not considered here because it was out of operation for much of the experimental period. Cross-sectional profiles and photographs of the other nine sites are shown in Figs 3 and 4. The sites include circular-section concrete culverts, rectangular-section concrete culverts, a relatively small diameter plastic pipe, natural gravel bed sections and a slower-flowing silty clay bed stream. Hydraulics range from slow moving, deep flow (logged velocities from 0–0·3 m/s) to much faster flow (logged velocities ranging from 0–3·9 m/s). The basic characteristics of the sites are listed in Table 2. Scatter in the depth–velocity relationships (Fig. 5) illustrates that none of the sections are effective hydraulic controls; water depth is therefore not expected to be a sufficient index of flow, with the possible exception of SF8. Usual practice is to point the Starflow beam upstream. Initial damage to the transducers from

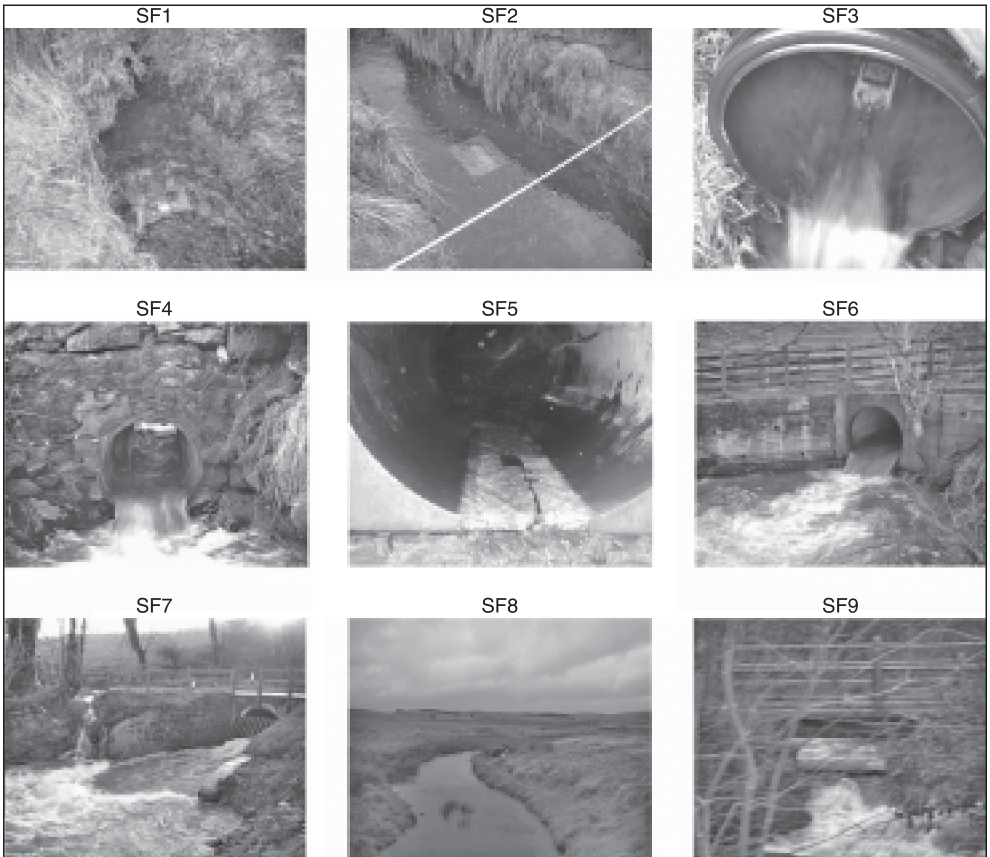

Fig. 4. Starflow sites

Starflow meter	Site description	Diameter or width: m	Depth range: m	Velocity range: m/s	Emitted signal direction
SF1	Natural gravel-bed channel	1·2 (max.)	0–0·80	0–1·7	downstream
SF2	Natural gravel-bed channel	2·25 (max.)	0–0·76	0–1·6	downstream
SF3	Circular plastic pipe	0·375	0–0·18	0–2·8	upstream
SF4	Circular concrete culvert	0·61	0–0·26	0–2·9	downstream
SF5	Circular concrete culvert	1·58	0–0·58	0–2·8	downstream
SF6	Circular concrete culvert	1·524	0–0·71	0–3·0	downstream
SF7	Rectangular concrete culvert	4·17	0–0·67	0–3·9	downstream
SF8	Natural silty clay bed channel	4·4 (max.)	0–0·88	0–0·3	upstream
SF9	Rectangular concrete culvert	3·17	0·04–0·30	0–2·5	upstream

Table 2. Summary of Starflow sites

storm debris, however, led to some of the meters being pointed downstream. In theory this does not affect performance.[7]

Verification of the Starflow measurements relied on current metering using a Valeport flow meter BFM002 (a hand-held water-lubricated meter) with 1178 series impeller.[9] Data were manually recorded via a digital 0021B control display unit. Velocity precision is specified by the manufacturer to be ±2·2% (at the 95% confidence level) for velocities 0·50–5·0 m/s and ±0·010 m/s for velocities between 0·060 and 0·50 m/s. The impeller may not rotate at velocities less than 0·060 m/s and the depth of water needed for full submergence of the impeller is 0·075 m.

5.2. Method description

Flows were estimated using the current meter at each of the nine sites (or within a few meters of the actual Starflow site) on a number of different dates in order to capture as wide a range of flows as practicable. The number and spacing of point velocity samples and the depth of velocity samples taken using the impeller meter were designed to limit sampling uncertainty to ±5% (at the 95% confidence level) according to published guidelines.[10] A period of 60 s was used to sample each velocity. Typically, the measurement of velocity over each cross-section took 20 min. For comparison, the Starflow readings within this 20-min. period were averaged.

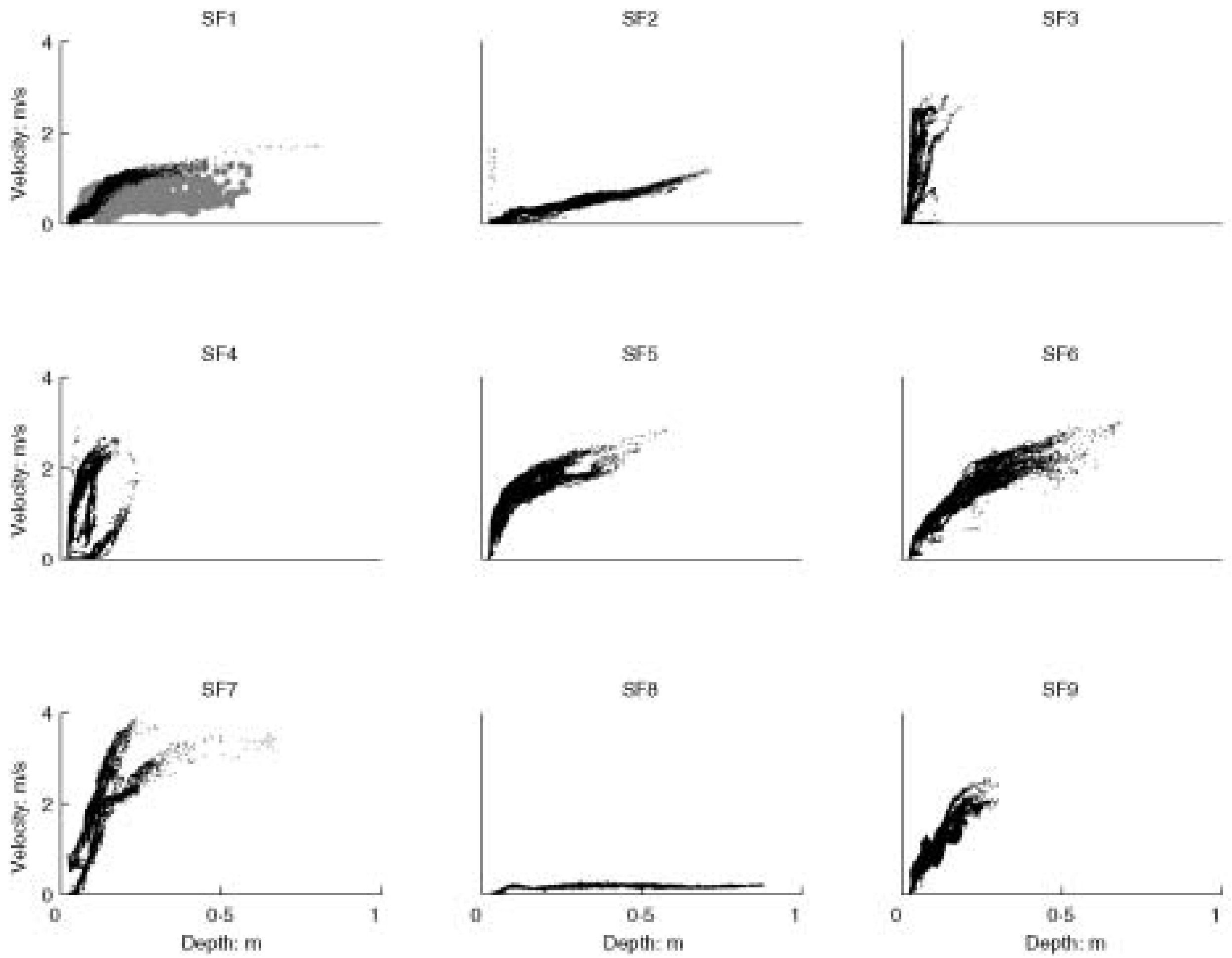

Fig. 5. Depth–velocity data for the nine sites. For SF1, the lighter shade represents data collected after July 2006

The flow Q_c calculated from current-meter data is given by the mean-section formula[10]

$$Q_c = \sum_N \left(\frac{s_1 + s_2}{2} \cdot \frac{y_1 + y_2}{2} \cdot b_c \right) \quad (5)$$

where s_1 and s_2 are the measured velocities at each pair of verticals, y_1 and y_2 are the measured depths at the verticals, b_c is the spacing between the verticals and N is the number of segments.

Notwithstanding the current authors' attempts to limit error in the estimates of Q_c to within 5% by following standard practice, it was important for our purposes to more rigorously estimate the accuracy of the current-meter flow data. This was done by judging the accuracy of the individual components in the mean-section flow calculation (velocity, depth and segment width) and assigning a standard deviation to each. The standard deviation of the segment width was judged to be 0·005 m and that of the depth to range from 0·01–0·03 m, depending on the roughness of the channel bed and turbulence of the water surface at the site. Error in the velocity measurement may arise from three sources: the standard deviation associated with noise over the sampling period of 60 s (this standard deviation was recorded during the metering); error due to the precision of the instrument (specified by the manufacturer, see earlier); and error in the approximation of the true velocity distribution within each segment (which is unknown, but thought to be small given the procedures followed, and judged as 3% of the average velocity for each segment). These three components of variance in the velocity measurement were added. All errors were assumed to be normally and independently distributed. The probability distribution and 95% confidence limits of flow were then estimated by implementing equation (5) within a Monte Carlo analysis. The values of α and β were calculated using linear regression of current-meter flow data against Starflow data for each site.

6. RESULTS AND DISCUSSION

The performance of the Starflow meters is reported, for each site, as the number of flow measurements that fell within an acceptable deviation from the current-metered flow. The performance is reported before and after calibration of α and β. The acceptable deviation was chosen, arbitrarily, as 20% of the current-meter flow. The results are shown in Table 3. Additionally, the two sets of flow estimates (Starflow data and current-meter data) are plotted for each site in Fig. 6. This figure gives an idea of the relationship between them and allows a review of the following attributes.

(*a*) The precision of the relationship: ideally there would be little or no scatter of data around the fitted relationship.
(*b*) The stability of the relationship: ideally there would be no evidence that the relationship at a site changes over the sampled range of flows.
(*c*) The predictability of the relationship: ideally the values of α and β would be predictable, either as the default values ($\alpha = 1$, $\beta = 0$) or by considering the hydraulic nature of the site. Here, no prior knowledge is assumed of how α and β relate to the hydraulic nature of the site and therefore predictability at this stage is taken to mean the applicability of the default values.

SF6, a circular culvert of diameter 1·524 m, has all three of the above attributes and uncalibrated performance is good (Table 3). SF5, a very similar section, has a value of α significantly greater than 1·0 and performance is good only after calibration. SF4, a circular culvert of diameter 0·61 m, seems to have a stable relationship and good general performance after calibration, although there are large errors at low flows ($<0{\cdot}02\ m^3/s$), presumably due to noise in the depth and velocity readings. SF3, a plastic pipe of diameter 0·375 m, has serious accuracy problems due to its low range of flows and depths, and moving this site is recommended. SF7 and SF9 are both near-rectangular concrete-lined culverts. For SF9, the relationship in Fig. 6 appears stable, precise and predictable, and uncalibrated performance is good. SF7 appears to have a good relationship in Fig. 6. Only two out of four samples fell within the 20% criteria after calibration, however, and further data collection is recommended for this site.

SF1, SF2 and SF8 are sited in natural channels. Analyses of SF1 and SF2 were complicated because the channel banks at these sites were eroded at uncertain times during the measurement period. The total erosion over the period February 2006 to March 2007 is shown in Fig. 3. The cross-section shapes measured during current metering indicate that the bulk of the erosion at SF1 occurred before the first current-meter application, and erosion at SF2 occurred between the third and fourth applications (current-meter data were collected slightly upstream or downstream of the Starflow site, therefore the true depth–area relationship for each

Starflow meter	α*	β*: m^3/s	Number of samples†	Performance (uncalibrated)‡: %	Performance (calibrated)‡: %
SF1	0·62 (0·43)	0·02 (0·05)	6	0	17
SF2	0·57 (0·04)	−0·01 (0·01)	7	0	86
SF3	0·88 (0·33)	0·02 (0·01)	2	50	50
SF4	0·87 (0·09)	0·02 (0·003)	5	25	100
SF5	1·20 (0·03)	0·01 (0·01)	7	71	100
SF6	1·07 (0·05)	−0·03 (0·02)	6	83	100
SF7	0·77 (0·21)	0·03 (0·23)	4	40	60
SF8	0·65 (0·21)	0·00 (0·04)	5	0	40
SF9	0·85 (0·05)	0·04 (0·04)	6	100	100

*Standard deviations of α and β, estimated from the regression, are in parentheses
†Low flows ($<0{\cdot}02\ m^3/s$) are omitted from this number and from the performance analysis (1 for SF2, 5 for SF3, 3 for SF4 and zero for the others)
‡Percentage of Starflow data within 20% of current-metered flow data

Table 3. Summary of Starflow performance

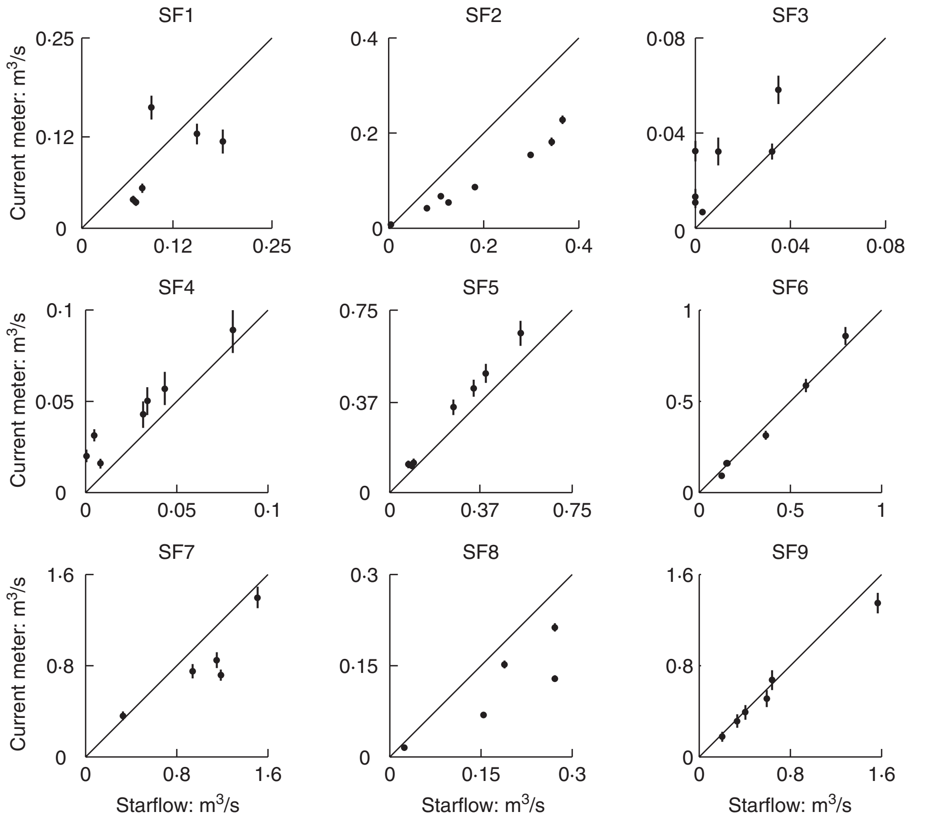

Fig. 6. Comparison of Starflow estimates of flow with current-meter estimates. The diagonal line represents the hypothetical condition (zero error, $\alpha = 1$, $\beta = 0$). The vertical error bars are 95% confidence limits on current-meter measurements

sample of flow at SF1 and SF2 is unknown). The Starflow calculations for SF1 and SF2 were adjusted on the assumption that either the initial or the final depth–area relationship applies to each depth and velocity sample.

The variability in the SF1 data is unexplained, but an analysis of the depth–velocity relationships (Fig. 5) provides some insight into the problem. Although this relationship is not used directly in the flow calculation, a marked change in the depth–velocity relationship over time would indicate that the velocity distribution across the channel cross-section may also have changed in nature, and hence instability of parameters α and β is expected. Fig. 5 illustrates that this may be the case for SF1, indicating that the relationship shifted and became more scattered after July 2006. Further data collection is recommended under the new cross-section shape; re-location of the meter is recommended if channel instability persists. For SF2, there is less erosion (Fig. 3), less variability in the depth–velocity data (Fig. 5) and a well-defined relationship with current-metered flow (Fig. 6) and good performance after calibration (Table 3). For SF8, no instability in the channel was observed; however, performance is unsatisfactory. This may be related to the natural bend in the channel (Fig. 4). For this site, however, a strong power-law relationship is found between the Starflow depth data and the current-meter flow data. This stage–flow relationship allows 80% of the current-metered data to be predicted to within 20%, as opposed to a success rate of only 40% when using the flow–flow relationship shown in Fig. 6.

The variety of sites used in this study allows some analysis of the causes of variability of α in Table 3. It is expected that α is equal to the ratio between the average flow velocity and that sampled by the Starflow, and that this is related to the distribution of the velocity across the channel cross-section relative to the location of the Starflow meters. From Tables 2 and 3, it is notable that the three sites in natural channels (SF1, SF2 and SF8) have the lowest values of α, all significantly less than 1·0, and the values most significantly different from 1·0. These sites also had the lowest average velocities at the times of current metering (recorded by the Starflows as 0·76, 0·43 and 0·28 m/s for SF1, SF2 and SF8 respectively, compared with average velocities of at least 1·05 m/s for the other sites). This supports the view that the cross-sectional variance in flow velocity (which, in general, is expected to increase with more natural channel conditions and with lower flow velocity) is a primary control in variation in α. The fact that α was considerably less than 1·0 for all these three sites is consistent with the Starflow meters being positioned in the faster-moving, deeper areas of the streams.

The magnitude of α is related to the cross-section average flow velocity, with a correlation coefficient of 0·56. This significant correlation is due to the difference between the average value of α for the low-velocity group of sites (SF1, SF2 and SF8) and the value for the other sites; there are no significant trends within either group. Using alternative hydraulic properties of the flow (estimates of bed shear stress and Froude number) did not improve predictability of α. One site, SF5, had a value of α significantly higher than 1·0 ($\alpha = 1{\cdot}20$). This implies that this meter was sampling a velocity or depth less than the cross-section average. Although there was no clear evidence of this by inspecting the SF5 site, variations in depth and velocity across the section due to the two-dimensional nature of the flow were noted.

Because of the depth of the Starflow meter itself, and the depth of any board it is mounted on (e.g. SF1, SF2 and SF8), β is expected to be positive. Consistent with this, the data (Table 3) show that no values are significantly less than zero (90% significance level). Only two values (SF3 and SF4) are significantly greater than zero, although this is because the uncertainty in β is generally high due to lack of low-flow data. For SF3, the value of β is high relative to the range of measured flows (Fig. 6), somewhat restricting the utility of this meter.

For the Pontbren field study, flow measurements using the current meter and subsequent calibrations indicated good performance of the Starflow meters at six of the nine sites (all but SF1, SF3 and

SF8). This will allow the continuous sequence of 15-min. resolution Starflow data to be used with a good level of confidence for these six sites. Two meters (SF1 and SF8) may need to be relocated due to instability in the channel banks and velocity distributions, pending further data, and one meter (SF3) needs to be relocated due to inadequate depth of flow. In addition to the improvements in accuracy achieved by the analysis, the data in Table 3 and Fig. 6 provide a basis for formal uncertainty analysis, so that hydrometric uncertainty can be accounted for in a hydrological analysis. The major limitation of the work, as a contribution to the Pontbren project, is the lack of current-meter data collection during high flows (impractical mainly because of safety concerns). Even for the six sites where the Starflow meters seem to perform well, there is therefore significant scope for errors due to the need to extrapolate data to high flows.

7. CONCLUSIONS

The accuracy of nine bed-mounted continuous-signal ADV Unidata Starflow meters currently installed in the Pontbren experimental catchment in Wales was assessed, covering a range of hydraulic conditions in small streams. The Starflows generally showed poor accuracy for very low flows. For flows $>0{\cdot}02\,m^3/s$, the accuracy at five concrete-lined cross-sections without calibration was reasonable (to within 20% of current-metered flow for 68% of samples); with calibration, the accuracy was considered good (to within 20% of current-metered flow for 93% of samples). For a 0·375 m diameter plastic pipe with low flows, performance was poor due to inadequate depth of flow and a new site is recommended. For two sites in unlined, natural channels, significant erosion of the channel was observed over the period of work. At the first of these sites, accuracy was poor even after calibration (to within 20% of current-metered flow for only 17% of samples), while accuracy was good at the other (to within 20% of current-metered flow for 86% of samples). At a third site in a natural channel, where no erosion was noted, performance was poor; however, the calibrated stage–flow relationship (rather than the flow–flow relationship defined in Table 3) performed well (80% of the flow data were predicted to within 20%).

The hydraulic nature of the measurement sites was found to have an effect on the calibrated parameter α (see equation (4)). The data did not, however, allow the value of α to be usefully related to hydraulic parameters.

In summary, site selection should give preference to straight, stable lengths of channel with suitable depths of flow and site-by-site field calibration is strongly recommended. Further research into performance under different hydraulic conditions may potentially reduce the need for calibration.

ACKNOWLEDGEMENTS

This research is being undertaken as part the Flood Risk Management Research Consortium (www. floodrisk.org.uk). Thanks go to the Pontbren group and Llyn Hir land-owners for access and to Matt Clifford for assistance with current metering. Two reviewers provided very useful remarks.

REFERENCES

1. Wheater H. S. and Peach D. Developing interdisciplinary science for integrated catchment management: The UK LOwland CAtchment Research (LOCAR) Programme. *International Journal Of Water Resource Development*, 2004, **20**, No. 3, 369–385.
2. Pender G. Introducing the Flood Risk Management Research Consortium. *Water Management*, 2006, **159**, No. 1, 3–8.
3. Zaidman M. D., Lamb R., Mawdsley J., Lawless M. R., Archer D. R. and Melching C. S. *Non Invasive Techniques for River Flow Measurement*. Environment Agency of England and Wales, Bristol, 2005, Report SC030230/SR.
4. Marshall M., Frogbrook Z. L., Francis O. J., Reynolds B., McIntyre N. and Wheater H. S. The impact of upland land management on flooding: preliminary results from a multi-scale experimental programme. *Proceedings of the British Hydrological Society 9th National Hydrology Symposium, Durham*, 2006. See http://www3.imperial.ac.uk/portal/pls/portallive/docs/1/9005697.PDF for further details. Accessed 03/2008.
5. Unidata. *Starflow User's Manual (Model 6526B), Revision F*. Unidata, O'Connor, Australia, 2003, pp. 1–20.
6. King M. J., Clare-Dalgleish A. and Child S. C. *The Evaluation of Ultrasonic Doppler Techniques for Measuring Open Channel Flow in Low Head Loss Conditions. Stage 2: Detailed Investigation*. Environment Agency of England and Wales, Bristol, 2002, R&D Technical Report W6-008/TR1, pp. 8–41.
7. Vermeyen T. B. P. A laboratory evaluation of Unidata's Starflow Doppler flow meter and MGD Technologies' Acoustic Doppler Flow Meter. *Proceedings of Joint Conference on Water Resource Engineering and Water Resources Planning & Management*, 2000. See www.usbr.gov/pmts/hydraulics_lab/tvermeyen/starflow/index.html for further details. Accessed 06/2008.
8. Chalk A. *A Review of the Theoretical and Practical Calibration of the Unidata Starflow Ultrasonic Doppler Instrument*. Water Resources Directorate, Welshpool, Australia, 1995, Instrument Facility Report.
9. Valeport Ltd. *Braystoke BFM001 and BFM002 Current Flow Meters Operating Manual*. Valeport, Totnes, 1996, pp. 36–37.
10. Herschy R. W. *Streamflow Measurement*, 2nd edn. Spon, London, 1995.

What do you think?
To comment on this paper, please email up to 500 words to the editor at journals@ice.org.uk

Proceedings journals rely entirely on contributions sent in by civil engineers and related professionals, academics and students. Papers should be 2000–5000 words long, with adequate illustrations and references. Please visit www.thomastelford.com/journals for author guidelines and further details.