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Applicability of acoustic Doppler devices for flow velocity measurements and discharge estimation in flows with sediment transport

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S U M M A R Y

Acoustic Doppler devices (Unidata Starflow) have been deployed for velocity measurements and discharge estimates in five contrasted open-channel flow environments, with particular attention given to the influence of sediment transport on instrument performance. The analysis is based on both field observations and flume experiments. These confirm the ability of the Starflow to provide reliable discharge time-series, but point out its limitations when sediment is being transported. (i) After calibration of the instrument by the Index Velocity Method, the deviation from reference discharge measurements was < 20% at the 95% confidence level. (ii) In ungauged conditions at high flows, the Starflow was particularly useful in providing velocity data for approximating measurements of discharge. (iii) However, channel and flume experiments revealed the effects of mobilised sediment on velocity estimates: coarse particles ($\geqslant$ 150 μm) transported by way of saltation or as bedload caused a significant underestimation of velocity by as much as 50%; a slight underestimation (10–15%) was also observed when significant quantities of fine particles ($\leqslant$150 μm) were transported in suspension; this underestimation was shown to reach 20–30% when suspended sediment concentrations were very high (c. 50–100 g L^{-1}).

1. Introduction

In a world where population is growing rapidly, wastewater policies are becoming increasingly stringent and require a thorough knowledge of flow characteristics (Abda et al., 2009). An understanding of water flow-paths at different scales in catchments is also critical for water resource and flood risk management and requires spatially distributed data (Ali and Roy, 2009; Horsburgh et al., 2010). Agricultural engineers, water resources engineers, ecologists, geochemists, geomorphologists, urban and forest hydrologists all require means by which they can continuously monitor water discharge in different environments (irrigation canals, urban canals, sewers and natural streams). In these contexts, the availability of reliable, low-cost methods of establishing accurate, continuous, operational monitoring of water discharge in pipes, canals and natural channels is essential.

Acoustic Doppler Flow Monitoring (ADFM) is often considered an attractive option for measuring flow velocity in sewer networks, irrigation canals, and small first- and second-order streams because it is relatively cheap, causes no head loss, and is easy to install and maintain (McIntyre and Marshall, 2008). In theory, ADFM can be used in any section of channel or open conduit, with or without a stable cross section. The instrumentation typically comprises an acoustic Doppler velocimeter (ADV) and a depth-measuring pressure probe, both sealed in a streamlined 'mouse' which is attached to a pipe invert or the channel bed (Blake and Packman, 2008). Two types of ADV are currently employed in ADFM. The simpler type emits a continuous ultrasonic signal of constant frequency, the reflected signal having a distribution of shifted frequencies representing the spectrum of particle velocities in the sampled volume of water (McIntyre and Marshall, 2008). From this spectrum, either a mean, a median or a maximum value of velocity is derived (Larrarte et al., 2008). More complex types of ADV (profilers or range-gated meters) emit sequences of ultrasonic pulses. The pulses are encoded so that the origins of the returned signals can

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be resolved, thereby allowing the spatial velocity distribution to be determined (Lozano and Mateos, 2009). The ADFM device examined in this paper is of the simpler, continuous-signal type.

Before using ADFM devices to obtain continuous velocity measurements and subsequent estimates of discharge, their performance should be assessed by rating their output against that of conventional methods, though few such comparisons have been published hitherto. One such rating in a 2.6 m wide rectangular flume, under a range of velocities, showed that the Unidata Starflow ADFM overestimated average velocity and discharge by 24% when compared with baseline values derived by flumes and other Doppler instruments (Vermeyen, 2004). McIntyre and Marshall (2008) rated the Unidata Starflow velocity data against that of impeller current meters in various conduits, including circular-section concrete culverts, a small diameter plastic pipe, and natural, gravel-bed and silty-clay river channels. For sites with concrete-lined sections, they showed that accuracy was reasonable without calibration and good after calibration (to within 20% of current meter measurements). For natural channels, accuracy was generally poor even after calibration. King et al. (2002) emphasized that a 0.1–0.2 m minimum water depth is required to achieve velocity measurements. Under such low-flow conditions, the Starflow produced very good results in the laboratory, but neither it nor the ISCO Area Velocity Flow Logger performed well in the field (Soupir et al., 2009).

Various technical and environmental factors can explain the discrepancy between measurements derived using ADFM and those using conventional techniques:

(i) A first concern, previously highlighted by Larrarte et al. (2008), is linked to the volume sampled by the velocity sensor and local hydrodynamic conditions. The velocity measured by an ADFM device pertains to a single vertical and this is not easily related to the average velocity of the cross-sectional area of the flow. This difficulty is particularly critical in natural streams, where the distribution of velocity within a cross-section can be complex (Birgand et al., 2005; McIntyre and Marshall, 2008; Blake and Packman in McIntyre and Marshall, 2010).

(ii) Another source of error in velocity measurement by ADFM devices may be attributed to sediment transported in suspension, saltation or bedload (Wagner and Mueller, 2011). Doppler instruments require the presence of particles (or air bubbles) in the water column, but their optimal concentration is comparatively low and they must travel at the same velocity as the water. To date, the successful use of acoustics to measure flow velocity has been confined mostly to low to moderate ranges of suspended sediment concentration (SSC), i.e. less than a few grams per litre (Thorne and Hanes, 2002; Sontek Application Notes, 1997). For higher SSC, multiple scattering and attenuation can become significant and this results in too low signal-to-noise ratio (Riebel and Löffler, 1989; Gratiot et al., 2000; Sottolichio et al., 2011; Su et al., 2008). Coarse particles transported near the channel bed can also affect seriously the ADFM response. These particles move slower than the water, which leads to an underestimation of the flow velocity (Nord et al., 2009; Blake and Packman in McIntyre and Marshall, 2010). To date, manufacturers have not provided any clear guidance and recommendations about the use of ADFM in situations where transported sediment is likely to affect instrument performance and scientific references to the problem are scarce.

In this study, the Unidata Starflow (Unidata Pty Ltd., O'Connor W.A., Australia) is used to measure flow velocity and determine water discharge in different open-channel flows (three natural channels, a canal, and a flume). The specific objectives are twofold: (i) to evaluate the performance of the device in the determination of water velocity and discharge and (ii) to define to what extent transported sediment can affect instrument performance. The findings should broadly be applicable to all ADFM devices.

2. Experimental sites and instrumentation

This study was based on field observations and flume experiments in five contrasted environments: (i) a small, spring-fed, incised natural channel with silty-clay banks and bed in the Ein Fesh'ha Nature Reserve on the north-western shore of the Dead Sea, Israel; (ii) the natural channel of the Cal Rodó catchment at its gauging station in Spain; (iii) the Sant Jordi irrigation canal in Spain; (iv) a flume in the laboratory of the Department of Geography, Loughborough University, UK; and (v) the natural 6 m-wide gravel-bed Nahal (Wadi) Eshtemoa in the northern Negev of Israel. Table 1 presents the main characteristics and experimental conditions of these sites.

All sites were equipped with a Unidata Starflow. The outputs of this instrument are flow depth, given by a vented pressure transducer, and the median velocity of the water column above a bed-mounted ADV. The system emits a continuous ultrasonic signal at 1.563 MHz. The beam angle (between the sound cone axis and the mounting plate of the sensor) is 30°. The operating ranges are 0 to 2 m or 0 to 5 m for flow depth (Table 2) and 0.02 to 4.5 m s^{-1} for velocity. According to the manufacturer, the accuracy is ±0.25% in the calibrated range for flow depth and ±2% of the measured value for velocity. More specifications about the Unidata Starflow 6526B are given by the Starflow manual (Unidata, 2000) and summarized by McIntyre and Marshall (2008). The Starflow model and the specific configuration for each site are presented in Table 2. All Starflow devices were located approximately at the centre-line of the channel/flume cross section, with the velocity sensor pointing upstream, as recommended by Unidata (2000) and Blake and Packman (in McIntyre and Marshall, 2010), except in the extreme high-energy bottom environment of Nahal Eshtemoa, where, because of the intensity of bedload impact, the sensor pointed downstream.

2.1. Ein-Fesh'ha springs

The Starflow was tested in the Ein-Fesh'ha Nature Reserve located in the northern margins of the Dead Sea (Israel), a baseflow environment where flow is fairly constant. Water discharge was found to be almost steady (0.32 m^3 s^{-1}) during 26 months of survey, except for a four-week period, during which, a minor surge occurred (Vachtman, 2009). The Starflow was located in a, straight channel-reach with cohesive banks and bed. Multipoint velocity was established independently throughout the flow cross-section using an electromagnetic current meter (ECM) – Flo-Mate, Marsh-McBirney model 2000. Manual sampling (5 times during the 26-month period) revealed that SSC was nearly constant (1.5 g L^{-1} ± 25%), apart from the small surge event, during which, SSC rose to 16.3 g L^{-1}.

2.2. Cal Rodó

A Starflow was deployed at the outlet of the Cal Rodó catchment (4.2 km^2) in the eastern Pyrenees (Spain) at 42°12N, 1°49E. Climate is Mediterranean sub-humid. Runoff is distributed very unevenly in time and flash floods are common from April to September. Suspended sediment transport may be important due to the presence of badlands in the catchments (2.8% of the area) and represents the