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Local boundary shear stress estimates from velocity profiles measured with an ADCP

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ABSTRACT: The acoustic Doppler current profiler (ADCP) has become an important tool in the study of river processes. When measurements are obtained at a fixed location within the river channel, time-averaged velocity profiles can be calculated. These profiles have the potential to quantify flow properties such as secondary currents and boundary shear stress. Velocity profiles from ADCP measurements obtained on the lower Roanoke River in the USA are used to estimate local mean boundary shear stress. The procedure combines the well known log-law with visually establishing the region within the flow depth where this law is valid. Additionally, methods are presented to (*i*) determine if movement of the ADCP adversely affects the measured velocity profile, (*ii*) test whether the recorded data is stationary, and (*iii*) calculate the depth-averaged velocity.

Keywords: Acoustic techniques, Boundary shear, Field tests, Stationary processes, Velocity profile

1 INTRODUCTION

Field measurements of river velocity can provide a valuable contribution to understanding morphological processes, contaminant transport, and stream ecology. The acoustic Doppler current profiler (ADCP) is used increasingly in river-related studies to measure velocity and determine flow rate (Simpson 2001), turbulence characteristics (e.g. Stacey et al. 1999, Nystrom et al. 2007), boundary shear stress (Sime et al. 2007), and sediment transport (Rennie & Millar 2004). Additionally, the high spatial resolution data from ADCPs may provide a useful tool for calibrating and validating computational fluid dynamics models. This study presents ADCP measurements from the lower Roanoke River, a regulated river in eastern North Carolina, USA and describes a procedure for determining local boundary shear stress. Fixed-vessel measurements (Muste et al. 2004) were obtained at a location within a meander bend for two flow rates, one close to the mean annual flow (flow rate, Q = 220 m^3 s^{-1}) and the other at near bankfull conditions (Q = 565 m^3 s^{-1}). Maintaining a fixed location within the river for the entire measurement duration presented a challenge. The effect of the ADCP motion on the measured velocity profiles is assessed.

Velocity profiles are often used as an indirect method to determine mean boundary shear stress in natural rivers (Wilcock 1996). While several methods are available to determine the time-averaged local boundary shear stress (e.g. Biron et al. 2004, Dietrich & Whiting 1989), this study employs the theoretical log-law, given as:

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_o}\right) \tag{1}$$

where u = velocity, u_* = shear velocity ($u_* = (\tau_o/\rho)^{0.5}$, where τ_o = boundary shear stress and ρ = fluid density), κ = von Karman's constant (κ = 0.40), z = position perpendicular to the channel bed, and z_o = roughness height. Following the approach of Raupach et al. (1991), the perpendicular position above the bed is defined as $z = Z + d$, where Z = position above the origin as defined by the top of the roughness elements and d = zero displacement plane. When a measured velocity profile is available, a least squares error approach can be used to fit a linear equation to the profile of u vs. ln(z). This approach has two primary advantages: (*i*) no knowledge of the roughness height is required to determine the shear velocity and (*ii*) a measure of the goodness of fit for the data is available through the coefficient of determination, also known as the R^2-value. The least square error approach has been used both in the laboratory (e.g. Dancey & Diplas 2008) and the field (e.g. Papanicolaou & Hilldale 2002, Stone & Hotchkiss 2007).

2 STUDY SITE

The lower Roanoke River is a regulated river located on the coastal plain of eastern North Carolina, USA. The study site, shown in Figure 1, is approximately 77 river kilometers downstream of the Roanoke Rapids Dam. Due to a lack of major tributaries, the flow rate is largely controlled by dam releases. The ADCP measurements were obtained near the channel centerline at the bend apex (Fig. 1b) on May 28 and June 14, 2009. The dam releases were constant for at least a week prior to each measurement date as necessitated by different operational modes. The field work in May occurred during spawning operations, which require steady flow releases for a duration of at least one week. This operational mode resulted in a flow rate close to the mean annual flow (Q = 220 m^3 s^{-1}) for several weeks. The June field work followed a period of heavy rainfall in the watershed surrounding the reservoir resulting in flood control operations which produced a sustained release of Q = 565 m^3 s^{-1}. The flood control releases generated bankfull conditions at the measurement site. These flow rates resulted in flow depths at the measurement location of 5.84 m (Q = 220 m^3 s^{-1}) and 9.21 m (Q = 565 m^3 s^{-1}) as determined by the ADCP.

3 BACKGROUND

A brief review of relevant ADCP operational principles is provided here, while more complete coverage can be found in Simpson (2001). Velocity is measured in each of four beams emitted from the ADCP and the results are averaged at discrete intervals throughout the flow depth known as either bins or depth cells. For the current measurements, a bin size of 0.25 m was used. Near-bed and near-surface measurements are not possible with an ADCP. A variety of settings are available for the ADCP depending on flow characteristics such as depth and velocity. For the measurements reported here, water mode 12, a high ping rate mode, was used with 20 sub-pings sent 50 milliseconds apart, then averaged together to create a single measurement. Further details on the water modes available for RDI ADCPs can be found in Simpson (2001). The resulting sampling frequency was approximately 10 Hz. Measured velocities include contributions from both the flowing river water and the motion of the boat. To isolate the river velocity, the ADCP software can subtract the boat velocity from the total measured velocity using a velocity reference which defines the boat motion. This velocity reference can be found using GPS data or bottom-tracking. Bottom-tracking is a feature available with many ADCP models that determines the boat velocity relative to the channel bottom. Additionally, the velocity reference may be set to none, which retains the original measured velocities.

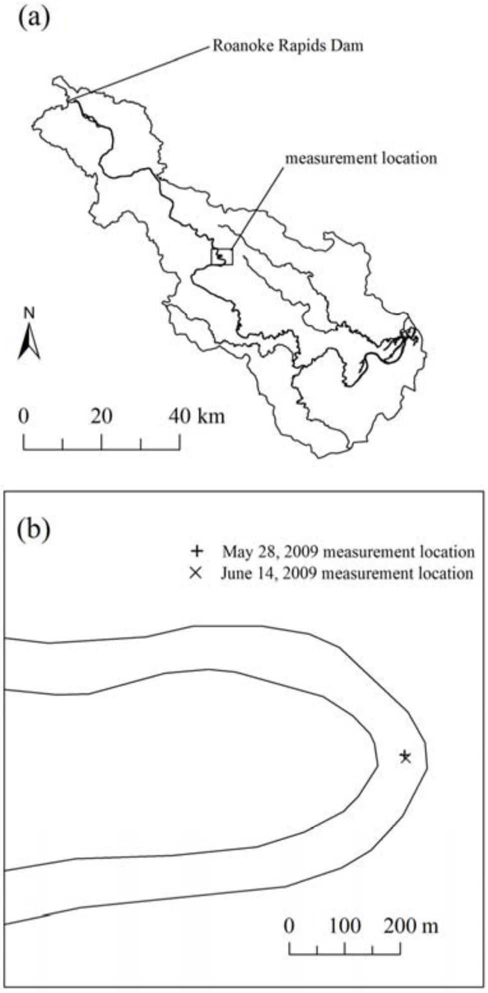

Figure 1. (a) The Roanoke River watershed below the Roanoke Rapids Dam. (b) The measurement locations on the lower Roanoke River.

The ADCP velocity output is defined in an earth coordinate system with components in the north, east, and vertical directions. These components can be transformed using the average flow direction determined by an internal compass to a curvilinear river coordinate system with components in the streamwise (tangential), spanwise (normal), and vertical directions, shown in Figure 2. The streamwise component represents the primary flow direction, while the spanwise component represents the flow across the channel, such as secondary circulation.

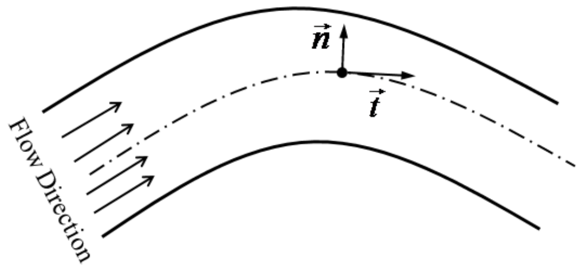

Figure 2. Curvilinear river coordinate system showing streamwise (tangential) and spanwise (normal) directions. The vertical axis is directed outward from the page.

4 MEASUREMENT PROCEDURE

A 1200 kHz Workhorse Rio Grande ADCP manufactured by Teledyne RD Instruments (Poway, CA) and a Trimble DSM 232 GPS (Sunnyvale, CA) were mounted to a Riverboat tethered boat (Oceanscience, Oceanside, CA). The tethered boat was attached using rope to a motor boat (length = 6 m) for all measurements. The ADCP and GPS data were recorded with WinRiver II software (Teledyne RD Instruments). The GPS data is used to determine the boat position only and has no bearing on the velocity measured by the ADCP. The horizontal accuracy of the GPS is approximately 1.0 m. The measurement locations were recorded using HYPACK LITE (HYPACK, Inc, Middletown, CT) so that the locations from May could be revisited in June.

The boat was secured within the river channel using anchors at the bow (front) and port-side stern (left-side rear) similar to the approach of Stacey et al. (1999). The typical procedure to secure the boat involved driving upstream some distance of the desired measurement point and releasing the bow anchor. The boat was then slowly steered to the measurement location where the stern anchor was released and both anchor lines were secured. The bow anchor required a rope with a length approximately three times the flow depth. The total set up time ranged from 10 minutes to one hour depending on flow conditions and the desired location within the channel. The tethered boat was placed near the middle of the motor boat which prevented the anchor lines from intersecting with the ADCP beams. Once the boat was stabilized in the measurement location, ADCP velocity measurements were recorded for approximately 20 minutes. During the measurement period, the boat motor was turned off and movement by the technicians was minimized. This approach to fixing the boat within the channel is preferred to mooring, due to the excessive wear on the motor that mooring may cause.

The sample record length of 20 minutes was selected to be conservative. Measurement durations as small as 6 minutes have been shown to be sufficient for determining mean quantities in larger rivers than the lower Roanoke River (Muste et al. 2004). To demonstrate that 20 minutes is a sufficient sample record length, Taylor's hypothesis may be used to convert between length and time scales (Soulsby 1980):

$$\mathrm{T} = \frac{H}{U} \tag{2}$$

where T = integral time scale, H = flow depth, and U = depth-averaged velocity. While this approximation is not strictly correct for all flows, it provides a useful tool prior to performing ADCP measurements. Applying Taylor's hypothesis results in integral time scales of 8.52 s (Q = 220 m^3 s^{-1}) and 9.30 s (Q = 565 m^3 s^{-1}) for the conditions encountered on the lower Roanoke River. The sample record length is then at least 130 times the integral time scale, which is judged to be sufficient.

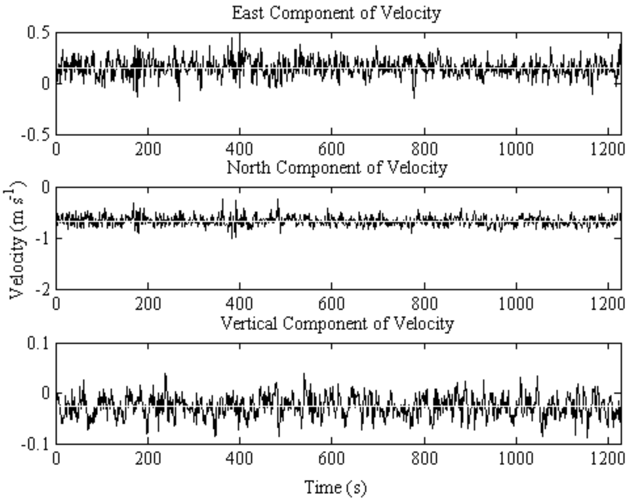

Figure 3. Times series of velocities in earth coordinates for bin 10 (z/H = 0.49) from May 28, 2009 (Q = 220 m^3 s^{-1}). The mean of each component is shown with a white line.

5 RESULTS

The data output from WinRiver II was analyzed using codes developed in MATLAB© at the Baker Environmental Hydraulics Laboratory. All velocity, location, and depth measurements marked as "bad" by WinRiver II were removed. No additional smoothing or filtering of the data was performed. The preliminary data analysis involves establishing that the boat motion during each measurement was not significant so that the results may be considered a fixed-vessel measurement and that the measured velocity time series are stationary.

5.1 *Establishing Stationarity*

A time series may be considered stationary when the mean value and autocorrelation function are constant (Bendat & Piersol 1986). As many analysis techniques for turbulent flow data are limited to stationary data (Tennekes & Lumley 1972), whether or not the data is stationary should be established at the outset. The approach used here follows the previous work presented in Soulsby (1980) which employs the run test, a nonparametric test of statistical independence (Bendat & Piersol 1986). In summary, the 20 minute sample record is divided into subsamples, each with a duration of 30 seconds, and the run test is performed on the mean and variance of the subsamples. This procedure is performed on each velocity time series, i.e. north, east, and vertical components, for all bins in the profile. The run tests failed to reject the hypothesis of stationarity for all velocity records in both profiles at the $\alpha = 0.05$ level of significance, indicating that the data is stationary. Visual confirmation of stationarity can be seen in the sample velocity record provided in Figure 3.

5.2 *Depth-averaged Velocity*

The depth-averaged velocity, U, is used to scale the velocity profile measurements in the following sections. If the velocity profile can be described as a function of the height above the channel bottom, then:

$$U = \frac{1}{H}\int_d^H u(z)dz \qquad (3)$$

where U = depth-averaged velocity, $u(z)$ = streamwise velocity profile as a function of height above the channel bed, and H = flow depth. The flow depth is determined by averaging the sample records for depth measured by the four ADCP beams. Stone & Hotchkiss (2007) applied this approach by fitting a logarithmic profile to velocity profiles measured with an ADCP. However, if the entire flow region cannot be described by a single function, determining U from ADCP profiles is not straightforward due to the lack of velocity measurements in the near-bed and near-surface regions of the flow depth.

To overcome this issue, the flow depth is divided into the three regions illustrated in Figure 4: (1) the near-bed region, (2) the middle region containing velocity measurements, and (3) the near-surface region. Equation (3) then becomes:

$$U = \frac{1}{H}\left[\int_{R1} u_1(z)dz + \int_{R2} u_2(z)dz + \int_{R3} u_3(z)dz\right] \qquad (4)$$

where $R1$ and $u_1(z)$ correspond to Region 1 and the streamwise velocity profile in Region 1, respectively.

The integral for Region 2 is calculated by numerically integrating the velocity measurements from the ADCP. Separate logarithmic profiles were then fit to Regions 1 and 3 using several velocities measured by the ADCP adjacent to each region. The logarithmic equations were then integrated over the appropriate region of the flow depth. For example, the near-surface logarithmic equation is integrated from the height of the top of the bin closest to the free surface to the free surface height above the channel bed.

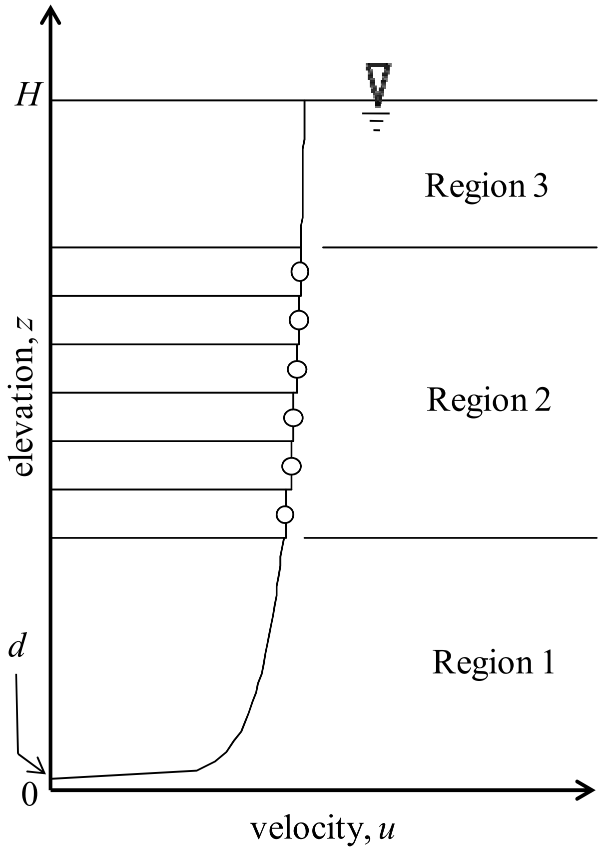

Figure 4. Demonstration sketch for depth-averaged velocity calculations with measured ADCP velocities shown with open circles (not to scale).

5.3 *Effect of ADCP Motion on Velocity Profiles*

During the duration of each measurement, some ADCP movement is unavoidable as demonstrated by the GPS measurements provided in Figure 5. As one would expect, the bankfull conditions (Fig. 5b) produce increased ADCP motion resulting in a range of 4.28 m in the east direction and 6.51 m in the north direction. The range for the mean annual flow rate (Fig. 5a) is 1.25 m in the east direction and 1.42 m in the north direction. As noted previously, the measurement location in May was recorded in HYPACK so that the same location could be revisited. In June, it was not