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River Habitat Quality from River Velocities Measured Using Acoustic Doppler Current Profiler

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ABSTRACT / Prior research has demonstrated the utility of metrics based on spatial velocity gradients to characterize and describe stream habitat, with higher gradients generally indicative of higher levels of physical heterogeneity and thus habitat quality. However, detailed velocity data needed to compute these metrics are difficult to obtain. Acoustic Doppler current profilers (ADCP) may be used to rapidly collect detailed representations of river velocity fields. Herein we demonstrate use of ADCP to obtain ecologically relevant data and compute associated metrics. Data were collected from four reaches of the Little Tallahatchie River in northern Mississippi. Sampled reaches were selected to observe velocity regimes associated with three distinctly different conditions: downstream from a major flow obstruction (a low weir), downstream from the apices of each of two bends, and within an extremely long, straight reach created by channelization. Three-dimensional velocity data sets from each site were used to compute metrics of habitat quality proposed by others. A habitat metric based on the presence of rotational flow in the vertical plane proved to be the best discriminator among conditions within the sampled reaches. Two of four habitat quality metrics computed from these measured velocities were greatest for the sharpest meander bend. ADCP hold great potential for study of riverine physical aquatic habitats, particularly at the reach scale. Additional work is needed to develop generally applicable field protocols and data reduction tools. Specifically, guidelines for ADCP settings and configuration appropriate for a range of riverine site conditions must be developed. Advances in instrumentation are needed to allow collection of information in closer proximity to the free surface and solid boundaries.

Current, or water velocity, is a key characteristic of riverine ecosystems (Hynes 1970, Gorman and Karr 1978, Pennak 1971, Lamouroux and others 1999), but ''because of difficulties in characterizing flow in biologically meaningful ways and the complexity of interacting factors, it is apparent that we are still very far from a complete understanding of the effects of current on organisms and processes in river ecosystems'' (Allan 1995). This article describes a relatively new technology for measuring river velocity and tests approaches developed by others for extracting biologically meaningful information from the data.

In rivers, topographic features, woody debris, irregularly shaped cross sections, meanders, rocks and boulders create wakes, velocity shelters and other flow patterns across a range of scales that are important habitats for flora and fauna (Lancaster and Hildrew 1993, Freeman and Grossman 1993, Way and others 1995, Benbow and others 1997, Biggs and others 1997, Harding and others 1998, Kern and others 2002, Daniels and Rhoads 2003). Simplification of channel boundaries (channelization) often results in significant negative impacts on resident biota, at least partially because of the loss of these zones of complex flow gradients (Brookes 1988, Rhoads and others 2003). Crowder and Diplas (2000a) noted that despite their widespread use, simple focal point velocities derived from one-dimensional computer models (e.g., PHABSIM, Bovee 1982) are inadequate descriptors of physical habitat because they do not contain information on spatial velocity gradients that are associated with biologically important characteristics (Statzner and others 1988, Facey and Grossman 1992, Hayes and Jowett 1994). Current thinking emphasizes the importance of flow patterns—the availability of a diverse set of habitat conditions across a range of scales in some sort of useful structure—for stream organisms to rest, feed, reproduce, and take refuge (e.g., Booker and others 2004).

KEY WORDS: Rivers; Habitat; Acoustic Doppler current profiler; Current; Velocity gradients; Metrics

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Therefore, study of riverine habitats requires spatially detailed descriptions of river velocity fields derived from either numerical simulation or measurement. Numerical simulation models (e.g., Leclerc and others 1995, Crowder and Diplas 2000b) require channel geometry and assumed or measured data for flow resistance. Biologically important physical habitat features and the velocity gradients that occur around them tend to be small scale relative to standard types of hydraulic models and require numerous very small grid cells, particularly in areas near obstructions, for meaningful outputs (Crowder and Diplas 2000b). Accordingly, the underlying bathymetric and calibration data must be quite detailed. Collection of the required bathymetric data, model calibration, and achieving appropriate levels of abstraction are problematic. On the other hand, if measurements are to be used instead of model outputs, it is necessary to quickly collect large numbers of measurements to fully describe the velocity regime of a river reach. Most existing methods for such measurements are slow and laborious (Herschy 1999, Rhoads and others 2003), but acoustic Doppler current profilers (ADCP) offer promise for rapidly mapping velocity and depth at scales appropriate for habitat simulation or assessment from a moving boat. Herein, we test the use of the voluminous data output by ADCP to compute metrics of habitat quality based on velocity gradients. We use these data to compute metrics that depend on spatial gradients: kinetic energy gradients, vorticity, and circulation (Crowder and Diplas 2000a, 2002). In addition, we show how qualitative assessment of habitat conditions may be obtained by comparing graphical depictions of velocity fields for a given reach at different flows or at a given flow with and without various physical features (Crowder and Diplas 2000a, 2002). Reduction of ADCP data to produce habitat information requires an understanding of the fundamental principles of operation.

Methods

Acoustic Doppler Current Profiler

Principles of ADCP operation are described by instrument vendors (Gordon 1996) and several others (e.g., Yorke and Oberg 2002). Briefly, the ADCP measures the Doppler shift of acoustic signals that are reflected by suspended matter in the water. From the distribution of reflected pulses, the instrument then computes a weighted mean velocity, and it is assumed that the echo-producing targets have the same velocity as the water. The ADCP used in this study had four transducers at 90° intervals in the horizontal plane, each sending its own beam of pulses down through the water column 20° from the vertical (Figure 1). The region of water encompassed by these beams has a cross-sectional diameter of about 0.3 m in the horizontal plane near the instrument that increases as the beams spread toward the bottom. After transmission of a sound pulse and a short ''blackout'' period, each of the four transducers begins recording reflected pulses. The water column below the transducer face is divided into a series of depth cells, or bins, with a constant vertical dimension specified by the user. As pulses return to the transducer face, the instrument uses the speed of sound in water to group signals reflected from a given depth cell. Data are collected for very brief periods at intervals on the order of 1 s, and include the water depth, temperature, boat displacement, heading, echo intensity, and several parameters related to data quality as well as water velocity. A complex algorithm is used by the ADCP to produce a weighted mean velocity for each depth cell. Boat motion, including pitch and roll, but not acceleration are taken into account when computing water velocities. Boat velocity is determined by echoes of sound pulses from the bottom when bed sediments are not in motion. Use of ADCP in situations where beds are active requires interfacing the ADCP with a differentially corrected global positioning system. Recent developments feature smaller instruments that may be deployed on small rafts or model boats and measure velocities in depths as shallow as 0.15 m.

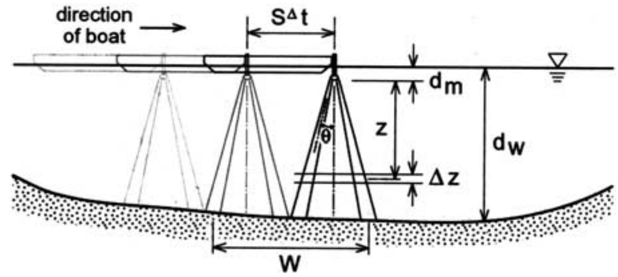

Figure 1. Geometry of acoustic Doppler sound beams. The instrument used in this study actually produces four beams at 90° angles to each other; only two are shown above for simplicity.

The advantage of an ADCP over other current measuring devices is the speed with which data can be collected. On the other hand, ADCP face important limitations with respect to resolution and range. For example, the ADCP used in this study cannot measure velocity in the top 0.2 to 0.5 m or in the bottom 6% of the water column due to limitations of the acoustic technique. ADCP are not useful for studies that require measurements within a few centimeters or millimeters of a solid boundary or within or underneath a perme-

Table 1. Physical conditions at study sites.

		Downstream from weir		Downstream from meander bend apex	
	Channelized	June	October	Gentle bend	Sharp bend
Discharge, m^3/s	10	89	127	96	125
Mean ± SD velocity magnitude, m/s	0.20 ± 0.10	0.52 ± 0.19	0.61 ± 0.20	0.70 ± 0.16	0.68 ± 0.21
Bend radius/channel width	Straight	2.6	2.6	3.4	1.3
Mean water width, m	24	60	68	59	60
Max water depth, m	3.3	5.1	5.4	4.1	6.4

able submerged object (woody debris). Finally, ADCP cannot resolve velocity fields into instantaneous point values (Nystrom and others 2002) because velocities produced by ADCP are temporal and spatial averages over finite domains. For example, a velocity measurement output by the ADCP is actually the mean velocity within four cylindrical volumes over some period of time (Figure 1). Computation of ecologically important velocity gradients presumes the use of instantaneous point values. Thus, small-scale spatial and temporal variations cannot be described using the ADCP. ADCP data are inherently noisy because of turbulence, instrument noise, and variations in environmental factors such as water and scatterer properties. Muste and others (2004a) proposed a method for estimating uncertainty involved in measuring river discharge and mean velocity with ADCP. River velocity profiles measured by ADCP from a moving boat varied about long-term averages from fixed instruments by ±20% (Muste and others 2004b).

Data Collection

Water velocity and depth data were collected from three reaches of the Little Tallahatchie River in Lafayette County, Mississippi on June 13, 2003. Similar data were collected from one of these reaches and an additional reach during a higher discharge on October 22, 2003. Reaches were selected in order to test the ability of the ADCP to characterize three distinctly different river habitats: a reach ~160 m downstream from a major flow obstruction (a low weir), downstream from the apices of two sharp bends, and within an extremely long, straight reach created by channelization several decades ago (Table 1). In order to examine repeatability, data were also collected by traversing the same transect adjacent to one of the sample reaches 10 times in less than one-half hour. Data were collected using a Workhorse 1200 kHz ''ZedHed'' ADCP (RD Instruments, San Diego, CA) mounted on the front of a 3.6-m long aluminum jon boat. Within each of the sampled reaches, flow depths and velocity profiles were collected as the boat was driven along 9 or 10 transects at right angles to the flow. Deviations of the boat course from a perfect right angle to flow direction were addressed in our data reduction protocol described below. Transect endpoints were marked with wire flags placed on one bank (inside bank for bends) at 5-m intervals. Transect spacing was chosen to satisfy horizontal spacing criteria developed below. Each transect was traversed one time, which required 1 to 2 minutes. Measurements of apparent boat velocity obtained while anchored at mid-channel were used to indicate the magnitude of error introduced by assuming a stationary bed (RD Instruments 1999).

ADCP manufacturers have developed a range of instrument settings and configurations in order to optimize discharge measurements in various hydraulic environments. However, when obtaining velocity data for computing habitat metrics based on spatial velocity gradients, one must ensure that instrument settings are held constant because the variance of velocity measurements (and thus the average velocity gradient) is strongly related to these settings (Rigby 2003). All data presented below were collected using water mode 12, which the ADCP manufacturer recommends for high-resolution profiling in rivers, streams, and shallow estuaries. Bin size (vertical dimension of water column elements sampled for velocity) was held constant at 0.25 m, and the instrument was configured to average the results of 25 ''subpings'' transmitted at 0.04-s intervals. The manufacturer's software predicts a standard deviation of 0.036 m s^{-1} for velocity measurements obtained with this configuration. In addition, because the conical volume sampled by the ADCP (Figure 1) is a function of depth, in all cases described herein we analyzed only the data from the top eight bins (~2.5 m).

Data Reduction and Analysis

We used the ADCP data sets to compute metrics of riverine aquatic habitat quality proposed by Crowder and Diplas (2000a, 2002). All four of the metrics are based on spatial velocity gradients (Table 2), and are designed to differentiate among points or areas with similar current magnitudes but different spatial gradients. Crowder and Diplas used velocities output from

Table 2. Spatial metrics of flow complexity in riverine habitats proposed by Crowder and Diplas (2000a and 2002)

Metric	Meaning	Approximate range of observed magnitudes[a]	Remarks	Mathematical definition [b]	Vector or scalar	Applies to	Finite-difference form[c]
M_1	Spatial gradient of kinetic energy per unit mass and per unit distance	0–0.2 J $kg^{-1}m^{-1}$	Proportional to drag force on an organism, and a measure of the amount of power expended in moving from one location to another	$\frac{\partial V^2}{\partial s}$	Scalar	Single point	$\bar{V}\left\lvert\frac{V_2 - V_1}{\Delta s}\right\rvert$
M_2	First metric scaled by flow kinetic energy at point of lower velocity	0.9–1.3 m^{-1}	A measure of how much more energy an organism must expend if it moves from the lower velocity to the higher velocity location.	$\left(\frac{\partial V^2}{\partial s}\right)\Big/\frac{V^2}{2}$	Scalar	Single point	$2\bar{V}\left(\frac{\left\lvert\frac{V_2-V_1}{\Delta s}\right\rvert}{V_{min}^2}\right)$
M_3	Weighted average of flow rotation in the vertical plane transverse to channel. Also known as ''modified circulation.''	0.2–1 s^{-1}	A measure of the strength and frequency of eddies and other complex flow phenomena	$\frac{\int\int_s \lvert\xi\rvert \Delta A}{A_{TOT}}$, where $\xi = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i}$ *for* M_3, *and* $\xi = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\hat{k}$ *for* M_4	Scalar	Area	$\frac{\sum\left\lvert\left(\frac{\Delta w}{\Delta y} - \frac{\Delta v}{\Delta z}\right)\right\rvert * \Delta y * \Delta z}{\sum \Delta_Y * \Delta_z}$
M_4	Weighted average of flow rotation in the horizontal plane. Also known as ''modified circulation.''	0.001–0.2 s^{-1}	A measure of the strength and frequency of eddies and other complex flow phenomena		Scalar	Area	$\frac{\sum\left\lvert\left(\frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y}\right)\right\rvert * \Delta x * \Delta y}{\sum \Delta x * \Delta y}$

[a] Range for M_1 is for single-point values reported by Crowder and Diplas (2000a) based on fine-mesh two-dimensional depth-averaged flow simulations. M_2 range is for reach averages based on the same simulations (Crowder and Diplas 2002). Range for M_3 is based on ADCP measurements (Shields and others 2003). Ranges for M_4 are from numerical simulations and limited field data reported by Crowder and Diplas (2002).

[b] V is the magnitude of the depth-averaged velocity, s is the distance between points 1 and 2, V_2 and V_1 are depth-averaged velocity magnitudes at points 1 and 2, $\overline{V}$ is the mean of V_1 and V_2, and V_{min} is the lower of the two. Crowder and Diplas (2000a) chose to measure s in the direction perpendicular to the channel. In the equation for vorticity, u, v and w are velocity components in the x (streamwise), y (lateral) and z (vertical) directions, respectively, while $\hat{i}$ and $\hat{k}$ are unit vectors in the x- and z-directions.

[c] Absolute values ensure that the gradient term is independent of the direction of calculation. In addition, the absolute values in the equations for M_3 and M_4 ensure that clockwise and counterclockwise eddies do not cancel one another out in the summation for an area.

two-dimensional numerical simulations of a river reach to compute the metrics, and therefore the gradients they computed were essentially differences between temporal mean values of velocities that were computed as single values for rectangular grid cells. On the other hand, we used ADCP data that are short (<1 s)-term temporal means of the average value for four cylindrical sections (Figure 1).

In all cases, higher values of the metrics are indicative of larger gradients and thus higher levels of flow heterogeneity. The first two metrics, M_1 and M_2, are based on local gradients in velocity magnitude without considering velocity direction. These metrics are measures of fish energy expenditure required for moving between two points. Alternatively, they may be thought of as a measure of the proximity of sheltered zones to swifter regions with potentially high drift rates. For calculation of M_1 and M_2 from ADCP data sets, we always determined velocity differences in a horizontal direction, *s*, which was perpendicular to the primary current (Table 2). Clearly, different directions for *s* might be used depending on the species and life stage of interest (Crowder and Diplas 2000a).

The latter two metrics, M_3 and M_4, are area-weighted averages of the vorticity, which is twice the rate of rotation of a fluid element about its axis. For simplicity, M_3 is based only on rotation in the vertical plane *transverse* to flow (Figure 2). Although M_3 could be computed in the vertical plane *parallel* to flow, rotational flow in this plane in the sand-bed stream we sampled would be dominated by upwelling associated with flow over dunes and would be less important as habitat because of its transient nature (Yalin 1972, Simons and Senturk 1976). Conversely, rotational flow in the plane transverse to flow reflects secondary currents driven by less transient channel morphology (e.g., bends). Shields and others (2003) found that the average M_3 computed using ADCP data from a naturally meandering river reach were 45% larger than those from a channelized reach. M_4 is based only on rotation in the horizontal plane (Figure 2), which is typically produced by flow obstructions, bends, and other boundary irregularities.

We developed Visual Basic software to facilitate ADCP data reduction and analysis. The ADCP was set up to record an ensemble of data (depth and velocity profile with attendant parameters) every 1.16 s regardless of the distance traveled by the boat. This ensemble was actually the average of 25 measurements. The data analysis software screened ensembles for quality based on indices computed by the ADCP software, and deleted poor quality data. The ADCP records horizontal velocity components and boat displacements relative to compass directions (north and east) for each cell. The streamwise direction relative to north was computed for each transect by computing the mean of the recorded horizontal directions. Then the horizontal velocity data were resolved into streamwise and transverse components using this direction.

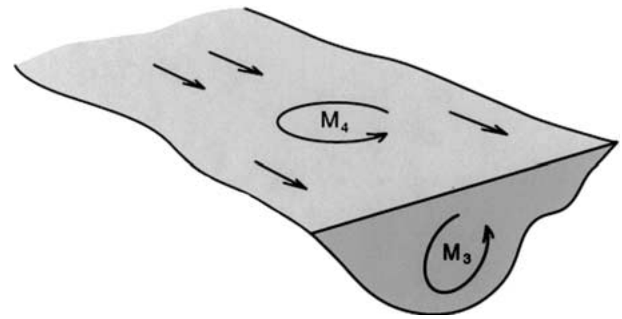

Figure 2. Metric M_3 reflects rotational motion in the vertical plane transverse to flow, whereas M_4 reflects rotational motion in the horizontal plane.

Formulas from Table 2 were used to compute the four metrics. Metrics M_1 and M_2 were computed for each cell using velocity magnitude, $V = \sqrt{u^2 + v^2 + w^2}$, and resulting distributions were compared among reaches. Metric M_3 was computed for each transect by applying the finite-difference form of the area integral (Table 2) across all bins in the cross-section, and metric M_4 was computed in a similar fashion but only for data from the 0.7-m depth, because preliminary computations showed little variation of M_4 with depth. M_4 values were not computed for two of our data sets because of a lack of reliable horizontal position data. Because velocity gradients cannot be computed for cells on the boundary of an array, M_3 cannot be computed for cells adjacent to the bed or one of the two banks, and M_4 cannot be computed for the first or last transects in a reach. We set up our analysis routine to always include data from the same bank (usually the one with greater depth) when computing M_3 values for several transects in a given reach.

Transect mean values for M_1, M_2, and M_3 were compared across reaches using one-way ANOVA. A nonparametric test (Kruksal-Wallis analysis of variance [ANOVA] on ranks) was used when samples were not normally distributed or when sample variances were significantly different. Pairwise comparisons (Tukey Test for standard ANOVA and Dunn's method for nonparametric ANOVA) were used to test for significant differences between reaches.

Table 3. Habitat metrics computed using velocity data collected from ten repeated traverses of a single transect of the Little Tallahatchie River, Mississippi, October 22, 2003

	Maximum	Mean	Median	Standard Deviation	Minimum
Discharge, m^3/s	125	121	122	4.8	109
Mean velocity magnitude, m/s	0.65	0.62	0.63	0.02	0.58
M_1, J $kg^{-1}m^{-1}$	0.039	0.032	0.026	0.004	0.022
M_2, m^{-1}	17.1	3.63	0.762	5.98	0.326
M_3, s^{-1}	0.299	0.252	0.251	0.025	0.211

Table 4. Habitat metrics (mean ± std dev) computed using velocity data collected from three reaches of the Little Tallahatchie River, Mississippi. Means followed by different superscripts indicate significant differences ($p \leq 0.05$).

		Downstream from weir		Downstream from meander bend apex	
	Channelized	June	October	Gentle bend	Sharp bend
Number of points (transects)*	562 (11)	(1191) 11	1691 (11)	554 (10)	704 (10)
M_1, J $kg^{-1}m^{-1}$	0.013 ± 0.012^a	0.023 ± 0.005^a	0.030 ± 0.006^a	0.024 ± 0.007^a	0.034 ± 0.009^b
M_2, m^{-1}	4.5 ± 26.1^a	0.90 ± 10.0^b	0.59 ± 6.2^{bc}	0.26 ± 1.14^d	0.34 ± 0.76^c
M_3, s^{-1}	0.20 ± 0.020^a	0.22 ± 0.014^a	0.22 ± 0.030^a	0.26 ± 0.034^b	0.30 ± 0.038^b
M_4, s^{-1}	—	—	0.065	0.024	0.034

Results

Mean current velocities were 0.50 to 0.70 m s^{-1} except for the straight channelized reach, where mean velocity was only 0.20 m s^{-1}. Coefficients of variation ranged from 23% to 50%, highest in the low-velocity channelized reach (Table 1). Stationary boat measurements indicated that the error in velocity due to bed movement was only 1–5% of mean velocity. Repeated runs across a single transect in a straight reach produced normally distributed (Kolmogorov-Smirnov $p > 0.2$) values for metrics M_1 and M_3 with coefficients of variation less than 13% (Table 3). Isolated high values of metric M_2 occurred when very low velocities were detected, producing a non-normal distribution with relatively large variance (Table 3). M_2 is elevated when one of the two velocities is very small because of the presence of *Vmin* in the denominator (Table 2) (Crowder and Diplas 2000a, Crowder 2002).

Habitat metrics varied little with discharge but were influenced by channel geometry. Two sets of measurements within the same reach (downstream from weir) at discharges varying by 43% had statistically similar mean values of M_1, M_2, and M_3 (Table 4). Transect mean values of M_1 (sharp bend) and M_3 (both bends) decreased with distance downstream from the meander apex, but similar spatial patterns were not observed in the less natural reaches (Figure 4). When data from all reaches were compared (Table 4 and Figure 4), metrics M_1 and M_3 were highest in the sharp meander bend and lowest in the straight channelized reach. Mean values of metrics for the two bends were not significantly different. M_2 was much higher in the channelized reach because it is heavily influenced by the presence of isolated zones of low velocity. Metric M_3 proved to be the best discriminator between modified sites and those with natural planform (Table 4). M_4 values appeared consistent with patterns of rotational flow in the horizontal plane observed on two-dimensional vector plots (Figure 3).

Discussion

Crowder and Diplas (2000a and 2002) argued that two-dimensional numerical models of riverine habitats were superior to one-dimensional models (e.g., PHABSIM) because the latter rely on the assumption that habitat suitability at a given point is independent of surrounding conditions, and therefore ignore ecologically important physical gradients. Abundant literature supports the notion that higher levels of spatial habitat heterogeneity associated with spatial gradients produced by features such as eddies, wakes, and transverse flows support higher levels of biodiversity (e.g., Gorman and Karr 1978, Harper and Everard 1998). Many techniques have been used for quantifying physical habitat heterogeneity, and these measures

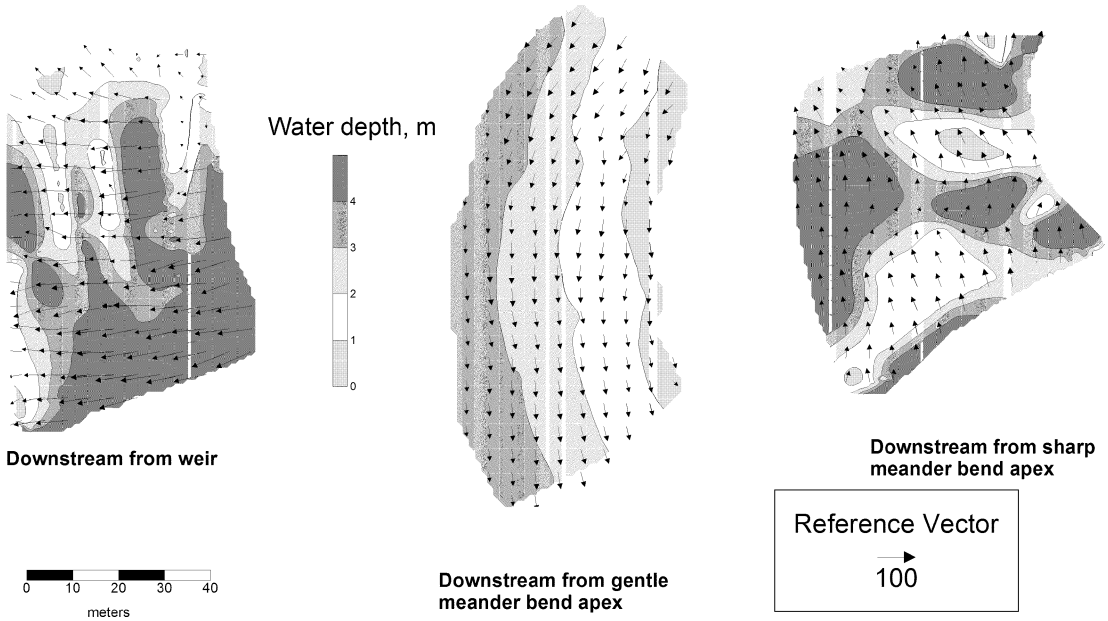

Figure 3. Flow depth and horizontal velocity vectors measured at 0.7 m below surface at three sites along the Little Tallahatchie River, Mississippi, June 13 and October 22, 2003. Units for reference vector are cm s^{-1}.

have been correlated with one or more biological variables (Gorman and Karr 1978, Foltz 1982, Shields and others 1994, Hugueny 1990, Jungwirth and others 1995, Kern and others 2002, Hortle and Lake 1983). However, these techniques require laborious field data collection and are particularly difficult to implement in rivers too deep to wade. Acoustic profilers may be used to rapidly measure fully three-dimensional flow patterns in rivers deeper than about 1 m (Laenen and Bencala 2001, Carling and others 2002, Gard and Ballard 2003, Shields and others 2003). The volume of data produced by these instruments necessitates use of indices or metrics such as those described above. The usefulness of such metrics requires definition of their relationship to more traditional measures of stream habitat quality.

Computation of the metrics of Table 2 using ADCP outputs and finite-difference forms of the equations produces metrics that are based on gradients of temporal and spatially averaged velocities. On the other hand, metrics derived from two-dimensional numerical simulations (Crowder and Diplas 2000a and 2002) are based on gradients of vertically averaged temporal mean velocities, and the temporal averaging is over longer intervals than for the ADCP data. Current meter measurements are also temporal averages (usually for 1 to 30 s) of conditions over some spatial domain that depends on the size and type of the instrument. Because aquatic organisms experience instantaneous and not average conditions, it stands to reason that the ADCP data are better indicators of habitat conditions, particularly velocity gradients, than averaged velocities.

Values of metrics computed from velocity fields that were generated by numerical model or ADCP data sets were of consistent magnitude with metrics computed from more orthodox field measurements. Crowder and Diplas (2000a) compared metric values they computed using a two-dimensional numerical simulation to values computed from six field data sets from similar streams reported by others (Hayes and Jowett 1994, Fausch and White 1981). The field data sets consisted of focal point velocities and velocity gradients for drift-feeding salmonids obtained using current meters. Computational results simulated flow conditions in a 61-m-long reach of a 15-m wide by 1.5-m deep cobble bed river without boulders, with addition of a single boulder, and with addition of eight boulders. Metrics based on simulations were highest within a meter of flow obstructions (boulders) or channel banks and smaller and less variable elsewhere. For example, point values of M_1 and M_2 ranged from near zero to 0.16 and 100, respectively, with pronounced spikes in wake regions often associated with trout feeding locations. Extreme values of metrics M_1 and M_2 reported by Crowder and Diplas (2000a) are plotted in Figure 5 as a function of the distance between velocity measurements (grid spacing), Δs. Also shown are all of the values of these metrics obtained for this study. The upper limits of M_1 and M_2 values based on simulated velocities, which presumably represented

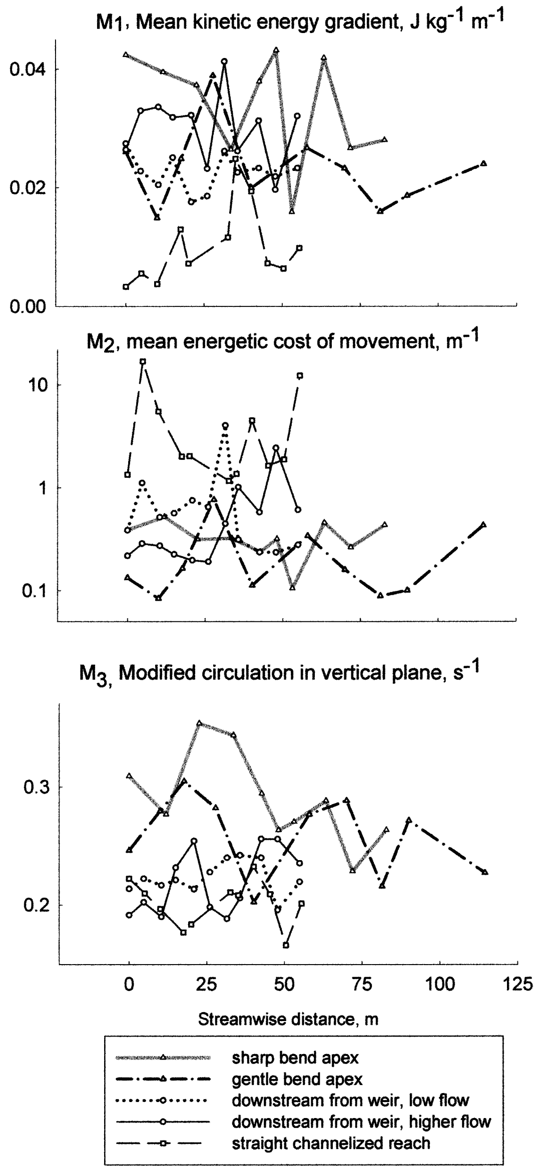

Figure 4. Physical habitat metrics computed using data obtained using acoustic Doppler current profiler, Little Tallahatchie River, Mississippi, June 13 and October 22, 2003.

points that would be selected by fish, were of similar magnitude to focal point field data. Metrics based on ADCP data from a large, sand-bed river overlapped the lower part of the range for the smaller, cobble-bed streams, but the ADCP metric values represent all measurement points, not simply fish focal points.

Figure 5 also shows that metrics M_1 and M_2 based on ADCP data were not significantly correlated with the grid spacing. Clearly, flow heterogeneities of ecological importance occur from the scale of channel width down to 1 mm or less (Way and others 1995, Benbow and others 1997, Harding and others 1998), and the metrics may be computed over any scale within this domain. Ecologically meaningful scales might correspond to the size of key organisms (Crowder and Diplas 2000a). This scale would be 0.15–0.30 m for the salmonid species represented in Figure 5, but 0.5–1.2 m for the largest fish species common to our study sites on the Little Tallahatchie River. Obtaining ADCP data at such close spacing from a moving boat is complicated by the difficulty of maintaining control when boat velocity is less than current velocity. Figure 5 does not suggest that Little Tallahatchie River metric values would have been different if more closely spaced data were used, but this question remains open for additional investigation.

The metrics varied systematically with channel planform. Longitudinal variations in metrics M_1 and M_3 (Figure 4) appeared to be consistent with detailed observations of three-dimensional flow structure by Frothingham and Rhoads (2003). The higher values for these metrics in meander bends are also consistent with expectations for flow heterogeneity based on planform and associated bed topography (Rhoads and others 2003). Therefore, the ADCP produced velocity field descriptions that were qualitatively within reasonable expectation, and metrics M_1 and M_3, but not M_2, reflected these descriptions. M_2 was highest for the most uniform channel boundary, and lowest for the bends. The only previously published values of M_3 are from earlier work on the Little Tallahatchie River using a different ADCP configuration (Shields and others 2003). The earlier work showed that M_3 values were higher for meander bend reaches than for straight channels, consistent with results presented here. However, the earlier M_3 values were generally larger than those computed in this study because of different instrument settings that produced greater variation in velocities (Rigby 2003).

Crowder and Diplas (2002) demonstrated the relevance of M_4 by comparing values for regions of complex flow created by boulders with those for nearby regions of similar depth and velocity, but without boulders. The computations were done using current meter measurements from the Smith River, Virginia and velocities derived from the two-dimensional simulation described above. M_4 values based on field data were two orders of magnitude greater for a 20-m^2 area between two large boulders than for a similar region nearby that was distant from flow obstructions. The zone between boulders contained brown trout redds, whereas the region free of boulders did not. Reach-scale M_4 values based on simulated flow fields were 20% greater when eight boulders were added to the 61-m-long reach, and

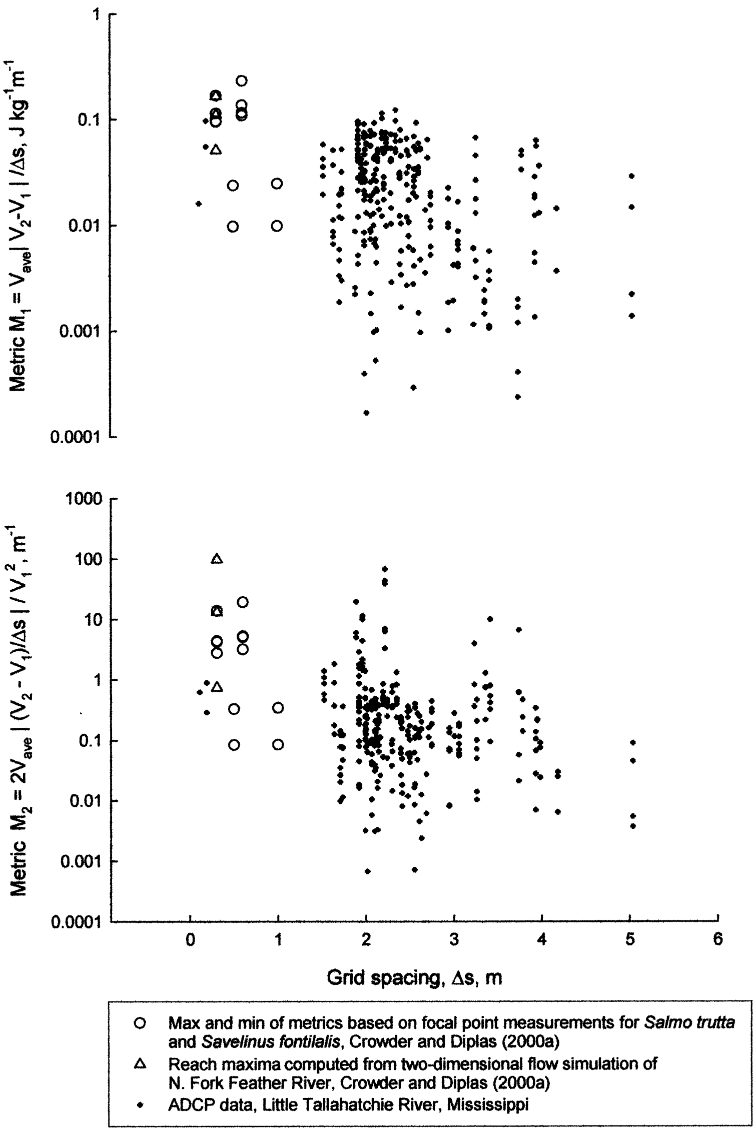

Figure 5. Values of metrics M_1 and M_2 based on velocity measurements using current meters, simulated velocities from two-dimensional numerical model, and ADCP data.

were 3.4 times greater for a ~30 m^2 area when boulders were included within the area. Field measurements were collected at 0.15-m intervals, whereas numerically simulated velocities were spaced at 0.3 m. M_4 values based on ADCP data ranged from 0.024 to 0.065 s^{-1}, which were of comparable magnitude to values obtained from reach simulations by Crowder and Diplas (2002) (0.054 and 0.045 s^{-1} for the reach with and without boulders, respectively).

Conclusions

ADCP hold great potential for detailed study of riverine physical aquatic habitat, particularly at the reach scale. In some cases, ADCP-derived data might be used in place of model simulations in instream flow assessments. However, additional work is needed to develop generally applicable field protocols and data reduction tools. More research is also needed to allow collection of information in close proximity to the free surface and solid boundaries. Perhaps most important, detailed biological studies are needed to investigate links between ecological processes and the types of flow heterogeneity measurable using ADCP. Questions remain about selection of the most appropriate values for spatial and temporal data frequency for a given study.

Metrics proposed by Crowder and Diplas may be used to reduce the large data sets produced by the Doppler devices into values that allow comparisons of flow regimes, design scenarios, or management options. Only metrics computed from velocity data sets collected using the same instruments, protocols, and configurations are directly comparable. The M_3 metric, which is based on the presence of rotational flow in the vertical plane, proved to be the best discriminator between modified reaches and those with natural planform sampled in this study.

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