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USE OF ACOUSTIC DOPPLER CURRENT PROFILERS TO DESCRIBE VELOCITY DISTRIBUTIONS AT THE REACH SCALE[1]

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ABSTRACT: Research has demonstrated the utility of metrics based on spatial velocity gradients to characterize and describe stream habitat, with higher mean spatial gradients indicative of higher levels of physical heterogeneity and thus habitat quality. However, detailed description of the velocity field that is needed to compute these metrics is difficult to obtain. Acoustic Doppler current profilers (ADCPs) may be used to rapidly collect detailed representations of river depth and velocity fields in rivers deeper than 1 m. Such data were collected in March 2000 from cross sections of the Little Tallahatchie River, Mississippi, representing three distinct habitat types (naturally sinuous, channelized, and abandoned channel). These datasets were used to compute component velocities, vorticity, and area weighted mean vorticity (circulation). Velocities and circulation were highest in the meander, lowest in the abandoned channel, and intermediate in the channelized reach. Secondary flow, expressed as the average magnitude of the lateral (transverse) velocity divided by the total velocity, was significantly higher in the meander. The sinuous natural channel and abandoned channel displayed distinctive spatial patterns, with regions of depressed velocity consistently occurring near banks. ADCPs hold great potential as tools for the study of riverine ecosystems, but data reduction is difficult using existing software.

(KEY TERMS: aquatic ecosystems; hydraulics; acoustic Doppler current profiler; velocity; vorticity; circulation; physical aquatic habitat quantification; fish; rivers.)

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INTRODUCTION

Current, or water velocity, is a key characteristic of riverine ecosystems (Hynes, 1970; Pennak, 1971) and perhaps is more important than substrate in explaining the distribution of lotic macroinvertebrates (Statzner *et al.,* 1988). Current has been used as a key variable to differentiate among and provide ecologically meaningful classifications of reach scale regions ("habitats") of large (Baker *et al.,* 1991; Grift *et al.,* 2001; Rutherford *et al.,* 2001) and medium sized (Whited *et al.,* 2002) river systems, but actual measurements of current within these studies tend to be relatively sparse.

Physical factors are frequently altered by human activity, and relationships between biota and physical factors are often investigated. For example, scientists have sought to define the "preferences" of various life stages of aquatic organisms for the magnitude of velocity and related variables in order to compare the quality of habitats created by various water discharge rates (Milhous *et al.,* 1989; Holm *et al.,* 2001). Depth and velocity data collected at points of a rectangular grid have been used to define key aspects of stream habitat degradation (Shields *et al.,* 1994) and to quantify habitat rehabilitation efforts (Habersack and Nachtnebel, 1995; Shields *et al.,* 1998).

Since current acts as a stressor and as an essential transport mechanism for many organisms, preferred habitats are frequently sheltered zones of moderate velocity adjacent to regions of swifter flow (Statzner *et al.,* 1988; Facey and Grossman, 1992; Hayes and Jowett, 1994). Simplification of channel boundaries (channelization) often results in significant negative impacts on resident biota, at least partially because of the loss of these zones (Brookes, 1988). Spatially detailed descriptions of the velocity field are needed for quantification of the availability of preferred zones across a range of scales. Detailed sets of velocity data may be used to compute metrics that depend on

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spatial gradients: kinetic energy gradients, vorticity, and circulation (Crowder and Diplas, 2000a, 2002). Kinetic energy gradients and vorticity may be qualitatively assessed graphically, allowing comparison of the same reach across flows or the impact of adding or removing various physical features for a given flow (Crowder and Diplas, 2000a, 2002).

In a river, velocity varies in all three spatial dimensions and continuously with time. Therefore it is necessary to quickly collect large numbers of measurements to fully describe the velocity regime of a habitat (e.g., Rinne, 1985). If such large data collections are not feasible, scientists attempt to characterize current using representative sampling based on assumptions about the spatial distribution of temporal mean velocity (e.g., assuming that the point velocity at 0.6 times the water depth below the surface is equal to the vertical mean). Point measurements are collected using thermistors, mechanical, or electromagnetic devices (Way *et al.,* 1993, 1995; Herschy, 1999). Indirect measurements, for example with head tubes (Ciborowski, 1991), standard ("FST") hemispheres (Statzner and Muller, 1989), particle image velocimetry (Stamhuis and Videler, 1995), or tracer dye injection (Shields and Smith, 1992), may be used to obtain velocity magnitudes or means for a given spatial or temporal domain. These methods face serious limitations in terms of their ability to resolve small scale phenomena and practical problems with deployment, logistics, etc. Furthermore, some mechanical current meters require a fixed length of time to obtain a point measurement, thereby obscuring short, turbulent fluctuations. Most of the aforementioned measurement methods simply measure velocity magnitude in one direction, combining or neglecting secondary components.

Velocity measurement problems are sometimes addressed by using numerical models to synthesize the velocity patterns of a given spatial domain (e.g., Milhous *et al.,* 1989; Leclerc *et al.,* 1995; Peters *et al.,* 1995; Crowder and Diplas, 2000b). Such models require channel geometry and assumed or measured data for flow resistance. Model calibration, appropriate levels of abstraction, and collection of the required bathymetric data are problematic. In some cases velocity patterns are based on one-dimensional computations, and assumed frequency distributions calibrated to limited field measurements are used to obtain multidimensional representations (e.g., Singh and Broeren, 1989; Lamouroux *et al.,* 1999; Azzellino and Vismara, 2001). Biologically important physical habitat features and the velocity and energy gradients that occur around them tend to be small in scale relative to standard types of hydraulic models and to require numerous very small grid cells for meaningful outputs (Crowder and Diplas, 2000b). Accordingly, the underlying bathymetric and calibration data must be quite detailed, and such models lose their validity at scales relevant to some macroinvertebrates and smaller fishes.

Acoustic (sonar) techniques have been used to rapidly collect water depth data from rivers (Habersack and Nachtnebel, 1995; Flug *et al.,* 1998), and refinement of Doppler technology suggests simultaneous collection of depth and velocity data may be feasible for description and evaluation of riverine habitats at the reach scale. This paper shows how ADCPs may be used to rapidly collect velocity and depth data to describe aquatic habitats in rivers with average depths greater than 1 m. Methods for analyzing data obtained from a commercially available ADCP to provide ecologically meaningful information (hydraulic metrics) across a range of riverine habitat types are also proposed. These methods are then used to compare the hydraulic properties found at selected cross sections typical of a meandering river, a channelized river, and a river channel abandoned due to cutoff channelization. The ecological relevance of the ADCP data is examined using available data representing samples of fish and benthic macroinvertebrates collected from the reaches sampled with ADCPs.

ACOUSTIC DOPPLER CURRENT PROFILERS

Acoustic Doppler current profilers have been commercially available for almost 20 years and have been used for oceanographic investigations, measurement of river discharge (Herschy, 1999; Callede *et al.,* 2000), studies of turbulence in open channels (Stacey, 1999a, 1999b), and measurement of suspended sediment (Shen and Lemmin, 1999) and bedload (Rennie *et al.,* 2002). An ADCP measures water velocity by propagating a fixed frequency sound wave through the water column and computing the Doppler frequency shift on echoes from suspended particles and bubbles. The method assumes that these particles ("scatterers") are moving at the same speed as the water. Internal software allows interpretation of the returning signals (echoes) to segregate velocities for vertical ranges called "bins." Thus a vertical profile of velocity is obtained. Use of ADCPs that propagate multiple sound beams at angles to one another and that contain internal compasses and gyroscopes allows measurement of the x- y- and z-component velocities relative to an earth based coordinate system. Inclinometers and gyroscopes are also used to correct for vessel pitch and roll. Velocity is measured relative to the reference frame of the instrument. If the instrument is mounted on a moving boat, the corrections may be made for boat velocity using either simultaneous differentially corrected output from a global positioning system (DGPS) or by "bottom tracking." Bottom tracking refers to measuring the Doppler shift in the frequency of echoes returning from the bed. Bottom tracking is typically more accurate than DGPS, but bed movement (e.g., when active bedload transport is occurring) introduces error.

ADCPs are capable of rapid data acquisition, so a complete description of the velocity field in a reach or cross section may be obtained from a moving boat in a few minutes. About two weeks of training is required to use most of these instruments, and all the instruments have limitations with respect to resolution and range. For example, the ADCP cannot measure velocity in the top 10 to 50 cm or in the bottom 6 percent of the water column due to limitations of the acoustic technique. Velocities from the region near the top of the water column cannot be obtained because a short pause is required between transmission of the sound pulse and echo reception. This pause is needed to allow for dissipation of "ringing," or energy remaining from the transmitted pulse. Data cannot be obtained very close to the bottom because the stronger bottom echoes obscure the echoes from the water column scatterers in this region. Thus, unless additional refinements are made, ADCPs are not useful for regions with depths shallower than about 0.5 m and are not useful for microhabitat studies that require measurements within a few centimeters or millimeters of a solid boundary (e.g., Lancaster and Hildrew, 1993; Way *et al.,* 1993, 1995; Stamhuis and Videler, 1995; Benbow, 1997) or within or underneath a permeable submerged object (woody debris). However, these devices are extremely useful for reach scale habitat characterization (e.g., Hortle and Lake, 1983; Meador *et al.,* 1993; Simons *et al.,* 2001). ADCPs have not been widely used for aquatic habitat data collection, and commercially available software for obtaining and processing ADCP data is not designed to produce data useful for description or evaluation of habitats. The primary challenge encountered when applying ADCPs for ecological studies is reducing the large volume of numerical data into meaningful information. A large number of parameters may be specified by the user when operating the ADCP, and a judicious selection of parameter values produces optimum precision for the range of depths and velocities encountered. It is important that identical configurations (suites of parameter values) be used when collecting velocity data for comparison.

Recent developments feature smaller instruments that may be deployed on small rafts or model boats and measure velocities in depths as shallow as 15 cm. Commercially available systems suitable for riverine habitat measurements currently sell for $13,000 to $33,000. Data from boat mounted or float mounted ADCPs are typically stored on a laptop or notebook computer and include records for each "ensemble." Ensembles of data are collected for very brief periods at intervals on the order of 1 sec and include the water depth, temperature, boat displacement, heading, velocity magnitude, direction, echo intensity, and several parameters related to data quality.

As noted above, relatively small scale velocity gradients are often more ecologically meaningful than average conditions. Vorticity is one measure of the magnitude of local velocity gradients. Vorticity, a measure of the rate of rotation of a fluid element about its axis, is mathematically defined (Liggett, 1994) as

$$\xi = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\hat{k} \tag{1}$$

where u, v, and w are velocity components in the x (streamwise), y (lateral), and z (vertical) directions, respectively, while $\hat{i}$, $\hat{j}$, and $\hat{k}$ are unit vectors in the x, y, and z directions. Practically speaking, vorticity may be approximated by replacing the partial differences in the above expression by finite differences for an array of measured velocities, and the computed vorticity may be assumed to represent conditions within the cell defined by the finite distances between measuring points. Due to the wide range of turbulence scales present in riverine flows and due to the highly unsteady nature of turbulent eddies, velocity data must be collected at constant spatial intervals and nearly instantaneously for reproducible results – criteria met by ADCPs but not more orthodox techniques.

Vorticity throughout a region of flow may be examined graphically or by computing summary statistics. If velocity gradients that produce rotation about the y and z axes are neglected, the above expression simplifies to

$$\xi = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i} \tag{2}$$

which is twice the rate of rotation of a small fluid element about its horizontal axis that is parallel to the streamwise direction. A similar simplification may be used to obtain an expression for vorticity based on rotations in the horizontal plane (about a vertical axis). Crowder and Diplas (2002) used two-dimensional model output and field data from a relatively shallow gravel bed river to compute vorticity in the horizontal plane, ignoring rotation in the vertical plane. However, the primary feature influencing flow in their study was a cluster of boulders. The primary features generating rotational flow in our study were meander bends, which produce vortices in the vertical plane stronger than those found in straight reaches (Bathurst, 1997). Clearly, riverine habitats are characterized by fully three-dimensional flow phenomena, and subsequent investigations should consider ADCP data collected from both lateral and streamwise transects to quantify horizontal plane vorticity. Nevertheless, patterns of secondary flows typical of relatively deep sand bed rivers are captured in detail using the approach shown here.

For practical computation, partial derivatives in Equation (2) may be replaced by ratios of finite differences. Using this approach, vorticity may be computed for each interior cell of an array of velocities representing conditions in a river cross section such as the one shown in Figure 1. However, cells adjacent to the boundary of the array may not be used to compute vorticity because velocities adjacent to them are unknown. This is a major shortcoming.

Vorticity may be used to compute the circulation, Γ, which is mathematically defined as the line integral of vorticity for the closed path, L, bounding the region in two-dimensional space (Crowder and Diplas, 2002)

$$\Gamma = \oint_L \vec{V} \cdot d\vec{L} = \iint_S \xi \cdot d\vec{A} \qquad (3)$$

where Γ is the circulation, $\vec{V}$ is the velocity vector, and $d\vec{L}$ is the unit vector along the length of a closed path L. The closed curve, L, surrounds a surface area S, and dA represents the area of an infinitesimal element of the surface S. If the curve L is drawn around a vortex such as those that occur just downstream of solid objects, the circulation will reflect the strength of the vortex or eddy. However, the value of circulation is highly dependent upon the location of L. For example, if circulation is computed for a region containing areas of positive (counterclockwise rotation) and negative (clockwise rotation) vorticity, the areas of opposing sign will cancel each other out. The resulting value will not reflect the availability of vortices and other complex flow features that may be of ecological importance. To address this problem, physical complexity throughout a region of flow may be expressed as the area-weighted mean vorticity (Crowder and Diplas, 2002)

$$\frac{\Gamma_{ABS}}{A_{TOT}} = \frac{\iint_S |\xi| \Delta A}{A_{TOT}} \qquad (4)$$

where Γ_{ABS} is the "modified" circulation. The numerator of the right hand term represents the sum of the absolute value of each grid cell's vorticity times its area. This quantity is zero for perfectly uniform flow with no vorticity and increases as the strength of velocity gradients and attendant flow heterogeneities increase. By dividing by A_{TOT}, circulation values for different sized areas may be compared if the grid cells are the same size and the overall flow regimes are similar.

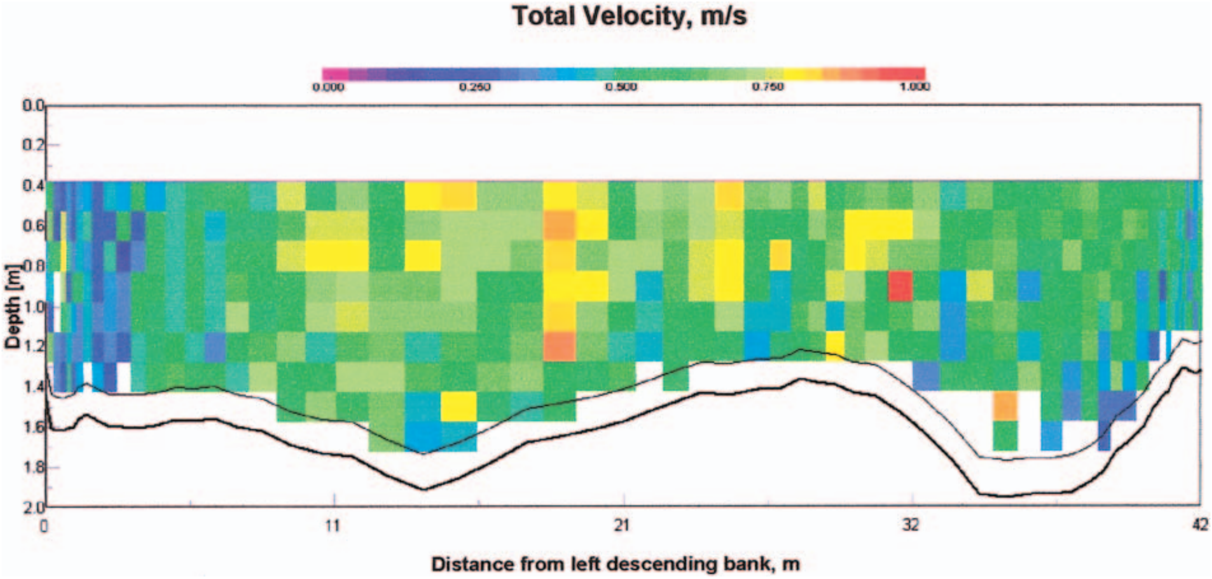

Figure 1. Graphical Representation of Rectangular Array of Velocity Magnitudes Collected From a River Cross Section Using a Boat Mounted ADCP.

METHODS

Velocity data were collected along selected cross sectional transects on March 22, 2000, from the Little Tallahatchie River about 25 km upstream from Sardis Reservoir in Lafayette County, Mississippi. Three 500 m reaches were sampled: a naturally sinuous reach; a straight, channelized reach immediately upstream; and a moderately sinuous reach of abandoned river channel created by channelization in about 1960. Based on substrate, planform, cross sectional shape and woody debris density, each reach was expected to produce unique patterns of vorticity and circulation representative of differing habitat quality (Table 1). Physical conditions in the sampled reaches were typical for the season. However, flow from the upstream 1,500 km^2 watershed and operation of the downstream reservoir produce a range of depth and velocity regimes, particularly in the naturally sinuous reach. Greatest depths and lowest velocities typically occur during May, June, and July. During periods of low flow, there is no current in the abandoned channel, and water temperature is elevated and dissolved oxygen is depressed relative to the other reaches.

Velocity and water depth data were collected using a Workhorse 1,200 kHz ADCP (RD Instruments of San Diego, California) mounted on the front of an aluminum jon boat 3.6 m long with a specially fabricated aluminum mounting bracket. This ADCP must be set up using one of three “water modes” based on the anticipated range of depths and velocities to be encountered. All data presented below were collected using water mode 8, which the manufacturer recommends for “shallow (< 3.5 m deep) streams with velocities less than 1 m/s and moderate shear or turbulence.” Bin size (vertical dimension of water column elements sampled for velocity) was set at 15 cm. The manufacturer’s software predicts a standard deviation of 2 cm/s for velocity measurements with this configuration. Precision of measured velocities varies with water mode and bin size, so quantities such as vorticity and circulation that depend upon velocity differences will vary with instrument configuration.

Within each of the three reaches, flow depths and velocity profiles were collected as the boat was driven across one or two transects subjectively selected to be representative of physical conditions within the surrounding reach. Transects were at right angles to the flow, and endpoints were marked with stationary buoys. Each transect was traversed nine or ten times. A single traverse is referred to below as a “run.” Outputs from typical runs in each reach are depicted in Figure 2. Measurements of apparent boat velocity obtained while anchored at midchannel were used to indicate the magnitude of error introduced by assuming a stationary bed (RD Instruments, 1999).

Data Reduction and Analysis

Initial qualitative evaluations of depth and velocity patterns were performed by examining plots similar to Figure 1, vertical velocity profiles, and tabular outputs from software provided by the ADCP manufacturer. Visual Basic software was developed to facilitate data reduction and analysis. The ADCP was set up to record an ensemble of data (depth and velocity profile with attendant parameters) every second, regardless of the distance traveled by the boat. Data analysis software screened ensembles for quality based on indices computed by the ADCP software and deleted poor quality data. Then additional ensembles were deleted to achieve a minimum spacing, W,

TABLE 1. Physical Characteristics of Reaches of the Little Tallahatchie River, Mississippi, Sampled Using ADCPs on March 22, 2000.

Sampled Reach	Habitat Type	Cross Section	Sinuosity	Bed Material	Water Width (m)	Mean/ Maximum Water Depth (m)	Mean Velocity (cm/s)	Discharge (m^3/s)
Natural River	Sinuous with plentiful submerged woody debris	Asymmetrical v-shape	1.1	Medium sand, organic detritus	43	1.9/3.2	70	51
Channelized River	Straight with no woody debris	Trapezoid with steep sides	1.0	Medium sand	38	1.6/1.4	61	38
Abandoned Channel	Sinuous with intermediate density of woody debris and emergent woody vegetation	Parabolic	1.2	Recently deposited silts and clays (“muck”)	25	1.7/2.1	33	12

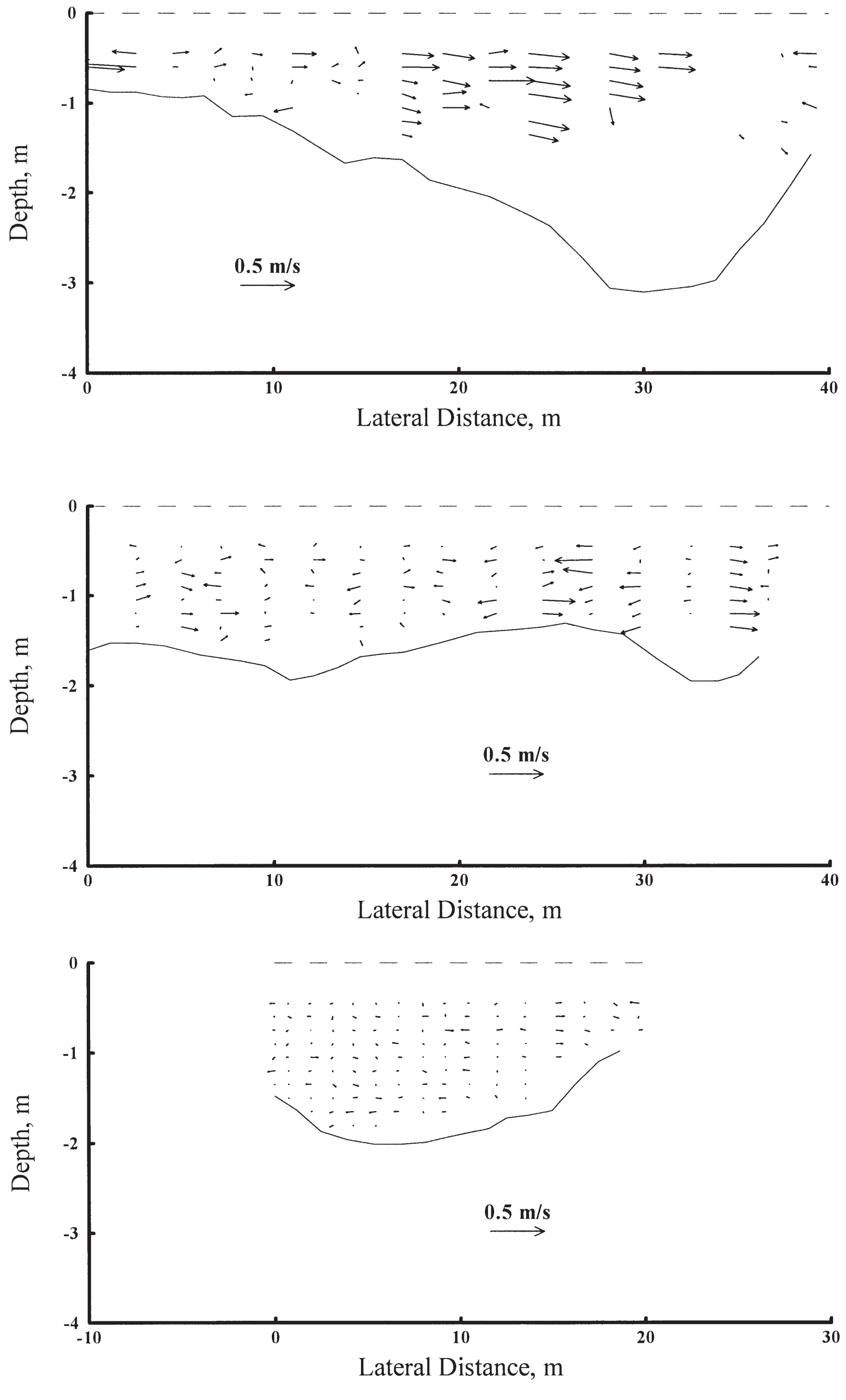

Figure 2. Vector Plots for Resultants of Lateral (*v*) and Vertical (*w*) Velocity Components Measured Using ADCP in Selected Cross Sections in Reaches Representing Three Types of Habitat (natural reach, channelized reach, and abandoned channel – top to bottom), Little Tallahatchie River, Mississippi. Solid line indicates riverbed, while dashed line indicates position of water surface.

between adjacent ensembles in order to eliminate redundant (overlapping) data (Figure 3). Minimum horizontal spacing, W is given by

$$W = 2(d_w - d_m)\tan\theta \tag{5}$$

where d_w is the maximum water depth in the run, d_m is the distance between the water surface and the face of the ADCP, and θ is the beam angle, which was 20 degrees for our instrument. For data reduction, horizontal spacing was measured along a straight line between transect endpoints, and a constant W value was used regardless of local water depth since the spatial velocity differences used to compute vorticity are influenced by spatial sample frequency.

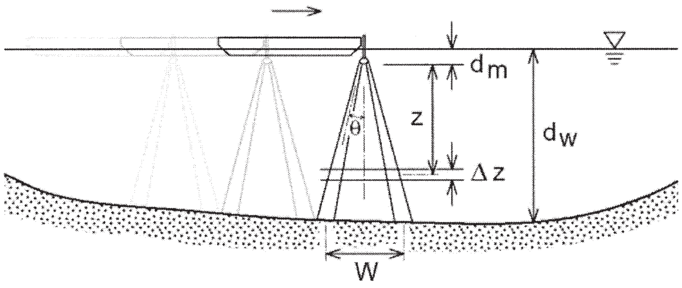

Figure 3. Derivation of Minimum Lateral Spacing, W, for ADCP Ensembles as a Function of Water Depth Below the ADCP, d_w, and Bin Size Δz. ADCP velocity profiles (ensembles) must be at least W apart to prevent redundant velocity readings.

The ADCP records horizontal velocity components relative to compass directions (north and east) for each cell. The streamwise direction relative to north was computed for each run by computing the mean of the recorded horizontal directions. For each cell, the total horizontal velocity was resolved into streamwise (u) and transverse (v) components using this direction. To compare the vorticity regimes in the three reaches we sampled, we computed vorticities and modified circulation for each run using finite difference forms of Equations (2) and (4). Application of a finite difference form of Equation (2) normally requires uniform values of Δy and Δz. Use of the ADCP data to compute vorticity violated this constraint, because the portion of the water column intersected by the four beams projected downward from the ADCP becomes larger with depth (Figure 3). The spread between the four beams, W, is given by Equation (5) above, and the volume of water, V, ensonified by the four beams at a given depth is

$$V = \Delta z A \tag{6}$$

where Δz is the ADCP bin size and A is the area described by the intersection of the beam and a horizontal plane. A is an elliptical area

$$A_1 = \pi a b \tag{7}$$

where

$$a = d$$

$$b = \left[\frac{d}{\sin\theta}\right]$$

where d is the beam diameter and θ is the beam angle (7 cm and 20 degrees, respectively, for our instrument). The difference between the region of the water column sampled for velocity and the elemental volume assumed by Equation (2) may be determined using Equations (5), (6), and (7) above. For example, velocities recorded by the ADCP for the bin (or cell) centered 75 cm below the transducer represent information from four cylindrical sections, each containing approximately 2.4 liters of water and centered on a point about 49 cm from the corresponding section in the opposite beam. The bin or cell adjacent to and immediately below this one represents information from a similar arrangement cells spaced approximately 60 cm apart and centered 90 cm below the ADCP.

As noted above, the proprietary software within the ADCP interprets the returning signal in such a way that a velocity is obtained for each "bin" or cell within the vertical. However, the reported velocity for a given cell is actually the average of velocities measured for scatterers within a region that overlaps immediate neighboring cells above and below. The means are computed using weight functions that emphasize signals returning from scatterers located in the middle of the vertical range. Correlation of velocity between vertically adjacent cells is less than about 15 percent (Gordon, 1996). We made no effort to remove effects of vertical overlap from our data.

Distributions of modified circulation and cross sectional (run) mean values for component velocities, total velocity, and water depth for each reach were compared using one-way ANOVA. A nonparametric test (Kruksal-Wallis ANOVA on ranks) was used when 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. Absolute values of secondary velocities ($|v|$ and $|w|$) were used to compute run means since instantaneous mean values of v and w for a given cross section are zero.

Since natural reaches tended to display regions of reduced velocity near banks, nonlinear regression was used to fit quadratic equations to datasets consisting of velocity at a given depth (x) versus lateral distance across the channel (y), and coefficients of determination (r^2) were computed and compared. The y coordinate was assigned a value of 0 at the point where measurement began, even though this point was usually 1 to 5 m from the water's edge.

RESULTS

After faulty and redundant data were eliminated as described above, about 50 to 100 velocities were recorded for each run and about 500 velocity measurements for each reach. Runs took an average of 103 seconds to complete, and runs across a given transect were consistent, with mean velocities differing by 15 percent or less, but temporal variation (variation from run to run) was greatest for the natural reach (Figure 4). Mean current velocities were highest

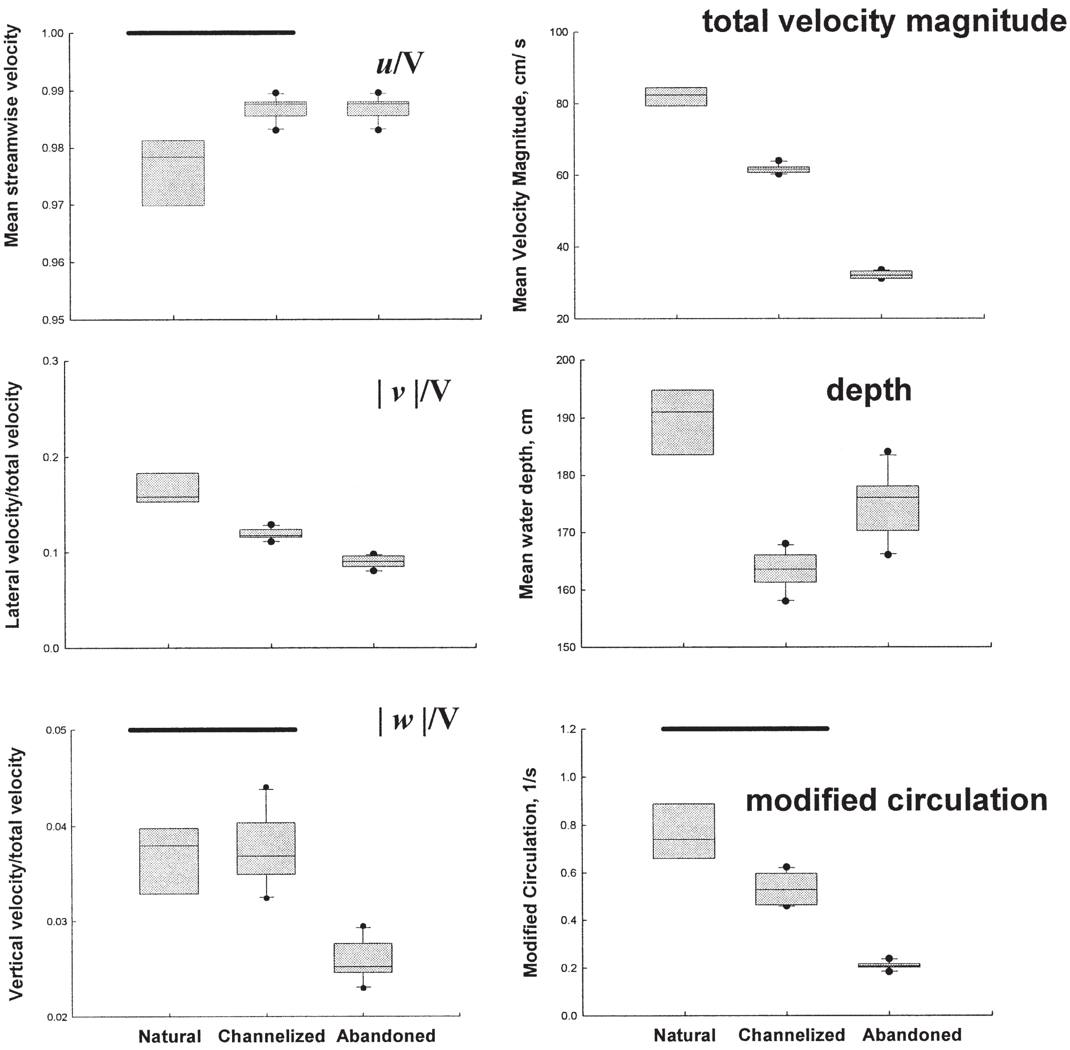

Figure 4. Distribution of Cross Section Mean Values of Streamwise Velocity Divided by Total Velocity (u/V), Absolute Lateral Velocity Divided by Total Velocity ($|v|/V$), Absolute Value of Vertical Velocity Divided by Total Velocity ($|w|/V$), Total Velocity Magnitude, Water Depth, and Modified Circulation Measured Using ADCPs in Three Reaches of the Little Tallahatchie River, Mississippi. N = 8, 10, and 10 for natural, channelized, and abandoned channel reaches, respectively. Box upper and lower boundaries represent the 75th and 25th percentiles of cross section means, line within box represents median, error bars represent 90th and 10th percentiles, and points are outliers. Boxes not under the same horizontal bar are significantly different ($p < 0.05$).

in the natural river reach, about 25 percent lower in the channelized reaches, and about 60 percent lower in the abandoned river channel, but mean water depths only varied about 15 percent among the three reaches. Stationary boat velocity measurements indicated that the error in velocity due to bed movement was less than 3 cm/s for the natural channel and less than 2 cm/s for the channelized reach. Missing data were more common for the natural river reach, perhaps due to submerged woody debris along the thalweg (Figure 2). GPS maps of debris formations collected concurrently with ADCP data show large emergent debris formations upstream and downstream from the ADCP transect.

Velocity distributions in the natural reach were skewed toward lower values, while those from the channelized reach were positively skewed and more sharply peaked, and those from the abandoned channel displayed bell shaped distributions. In a fashion typical of riverine habitats, primary or streamwise velocity, *u*, was equal to 97 to 99 percent of the total velocity (Figure 4). The horizontal velocity component at right angles to the primary current, *v*, comprised about 10 to 20 percent of the total velocity magnitude and vertical velocities, *w*, were 2 to 4 percent of the total velocity. Vorticity and modified circulation differed among reaches in a fashion similar to mean velocity: the average computed mean modified circulation was 0.77/s, 0.53/s, and 0.21/s for natural, channelized, and abandoned channel reaches, respectively. Although physical variables for the abandoned channel were all significantly different from those for other reaches, the natural and channelized reaches were more similar (Figure 4). Values for modified circulation, relative streamwise velocity, and relative absolute vertical velocity were similar for natural and channelized reaches. Relative absolute lateral velocity was significantly greater in the natural reach, evidently due to flow patterns typical of meanders (Bathurst, 1997).

To examine spatial patterns, equations of the form $V = ay^2 + by + c$ were fit to plots of total velocity magnitude (V) at 0.45 m depth versus lateral distance across the channel (y) for each run. Mean coefficients of determination (r^2) for the natural river, channelized reach, and abandoned channel were 0.57, 0.37, and 0.77, respectively. The inverted parabolic pattern was typical of the natural cross sections found in the natural reach and the abandoned channel, but velocity gradients near banks were weaker in the channelized reach (Figure 5).

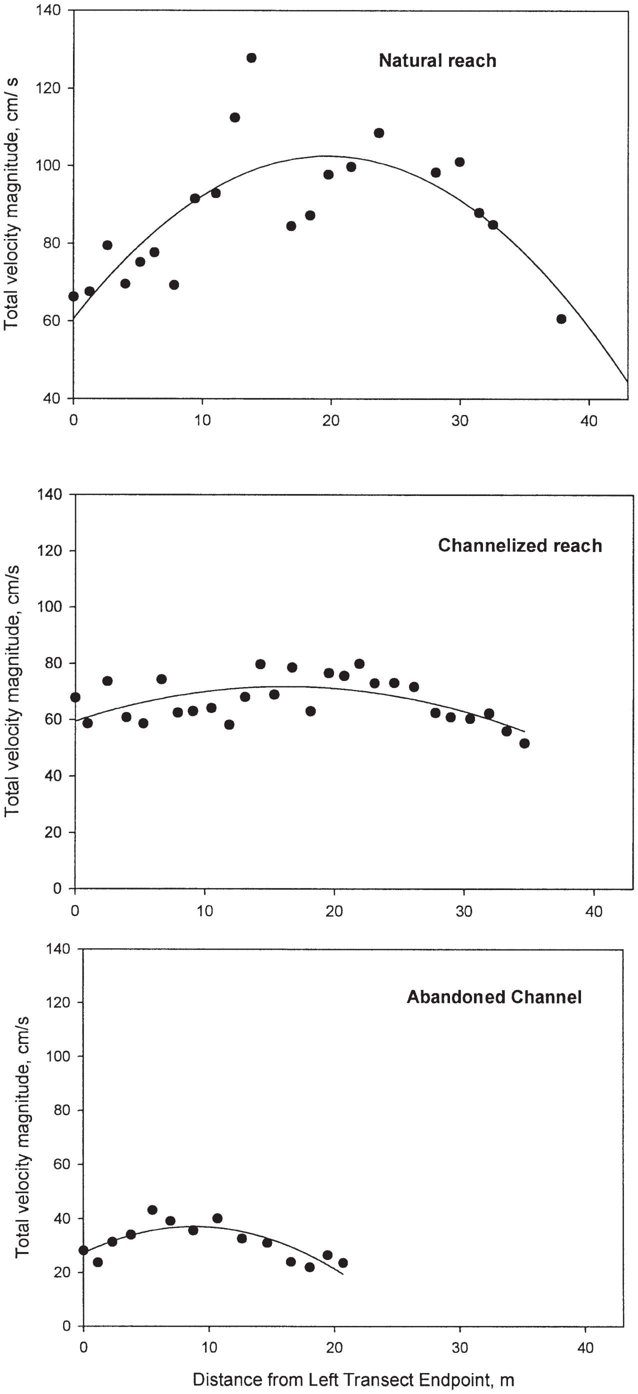

Figure 5. Typical Plots of Total Velocity Magnitude Measured at a Depth of 0.45 m Versus Lateral Distance for Each Reach.

DISCUSSION AND CONCLUSIONS

Human activities often perturb physical aspects of river systems in ways that degrade ecological resources, and efforts to address such impacts often focus on physical manipulations (e.g., Langler and

Smith, 2001). Abundant literature supports the notion that higher levels of spatial habitat heterogeneity measured at the reach scale support higher levels of biodiversity (e.g., Gorman and Karr, 1978; Harper and Everard, 1998). Various techniques have been used successfully for quantifying aspects of physical habitat heterogeneity that are correlated with one or more biological variables. Among these are Shannon indices based on habitat variables measured at regular spatial intervals (Gorman and Karr, 1978; Foltz, 1982; Shields *et al.,* 1994), current speed diversity (Hugueny, 1990), the variance of maximum depths measured at regular intervals along regularly spaced cross sections (Jungwirth *et al.,* 1995), the occurrence of bars (Kern *et al.,* 2002), and the area of slack water based on a limited number of current meter measurements (Hortle and Lake, 1983). These studies generally did not develop causal linkages between physical diversity and biological variables, but recent investigations at smaller physical scales have highlighted the importance of hydraulic gradients for riverine macroinvertebrates (Remple *et al.,* 1999a, 1999b) and fish (Hayes and Jowett, 1994; Harding *et al.,* 1998). All of the aforementioned efforts required laborious field data collection approaches that yield relatively few data and are particularly difficult to implement in rivers too deep to wade. Lamouroux *et al.* (1999) have developed statistical models for predicting the frequency distributions of hydraulic variables in reaches with natural morphology that represent a major saving in the effort that is required. However, these models still require significant field data as input: (1) the changes in reach average depth and width as function of discharge, (2) the spatial frequency distribution of depth for one given discharge, and (3) the average size of the bed material particles.

Above, we demonstrate how ADCPs may be used to rapidly collect discharge, depth, and velocity data in riverine habitats with average water depths greater than 1 m. Data sets produced by the ADCP are so large that they are unwieldy unless methods are available to extract information from the data. A modified circulation parameter may be used as an index of physical heterogeneity in the same fashion that others have used diversity indices based on more sparse data sets (Crowder and Diplas, 2002). We found that modified circulation in the vertical plane averaged across an entire river cross section was about 45 percent higher in a natural meander than a straight, trapezoidal channel upstream in the same river. Stronger differences were documented between these two reaches and a more quiescent abandoned channel nearby. Our collections of fish and invertebrates from the three habitats (unpublished data, National Sedimentation Laboratory) mirror the physical differences.

The differences we observed among the three sampled reaches are subtle relative to observations by Crowder and Diplas (2002), who computed modified circulation in the horizontal plane that was 95 times greater in a small (20 m^2) area of a gravel bed river containing brown trout redds than a similar region nearby that did not contain redds. Vorticity within the region containing redds was generated by two large boulders. Using two-dimensional numerical model simulations, they computed values of horizontal plane modified circulation of 0.054/s and 0.045/s for a 61 m reach of a river 15 m wide with and without boulders, respectively. Values of modified circulation in the vertical plane that we observed were an order of magnitude higher (0.53/s and 0.77/s for channelized and natural reaches, respectively), but the difference between the uniform and complex channels was similar. Crowder and Diplas (2002) admitted that their findings merely suggested and did not prove that flow complexity (as measured by modified circulation) at the spatial scale they studied was an important component of brown trout spawning habitat. However, they reasoned that processes such as aeration, local scour, and particle sorting are driven by vorticity and thus are associated with high values of modified circulation.

In contrast to the channelized reach, the natural reach and the abandoned channel exhibited consistent regions of lowered velocity adjacent to the bank. Habitats adjacent to banks of large rivers, particularly those governed by stage fluctuations, play a key role in large river ecosystems, providing sites for fine material retention, fish rearing, and refugia for invertebrates (Schiemer and Spindler 1989; Remple *et al.,* 1999a; Schiemer *et al.,* 2001). Geometrically complex boundaries that give rise to eddies, helical flow patterns, and smaller vortices are associated with higher levels of species diversity, both due to the wider range of physical niches available and because habitat complexity may support fish assemblage resilience in the face of natural disturbances like floods (Pearsons *et al.,* 1992).

ADCPs hold great potential for detailed study of riverine physical aquatic habitat, particularly at the reach scale. However, users must recognize key limitations. Deployment is limited to water depths greater than about 0.3 m, and thus key shallow habitats adjacent to margins and in riffles or thalweg crossings may be missed. In addition, permeable objects within the flow such as vegetation or woody debris interfere with echoes and thus limit data acquisition. Existing software is tuned for oceanographic applications and river discharge measurement. Therefore, until better alternatives are developed, application to riverine aquatic habitat studies requires custom development of software or spreadsheets. Metrics such as vorticity and circulation offer promise for extracting information from large datasets derived from ADCP deployments, but the values obtained are dependent on the horizontal and vertical spacing adopted for velocity data. Appropriate spatial densities for various combinations of ADCP hardware, software, and river conditions remain to be determined.

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