Developing a Methodology to Characterize Aquatic Habitat at the Reach Scale Through Use of Acoustic Doppler Technology

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And, of course, thanks to my family for always reminding me just before I left the country that I must someday finish a degree.

Abstract

Mathematically derived indices for characterizing aquatic physical habitat are potentially a powerful method of quantifying habitat quality. The use of these metrics is ideal in computer modeling experiments, but field evaluation can be quite difficult. Acoustic Doppler Current Profilers offer an efficient method of collecting a large set of velocities in a river over a short period of time. For application in rivers, the ADCP was designed primarily to measure discharge and has only recently been applied to the realm of habitat measurement. Thus, the methodology of this application is in its early stages and deserves attention for development. Herein is discussed one application of ADCP technology to the characterization of aquatic habitat, specifically through calculation of vorticity and circulation metrics. Software was developed to reduce the vast amount of data collected by the instrument and to establish a standard method of data reduction for data collected across a river cross section. Experiments were run concerning the instrument's water mode and bin size configurations to determine configuration bias. The calculation of circulation and vorticity was found to depend highly on the configuration of the instrument. Only indices based on carefully matched configurations should be compared due to dependence of precision on configuration. With careful attention to proper use, the ADCP offers a powerful method of collecting physical habitat data.

I. Introduction

In surveying the natural world as it stands today, we are faced with a host of disturbed ecosystems where the balance of natural processes has been sacrificed in the wake of human settlement practices. While in a perfect world we might be driven to research and understand our environment for no other purpose than to understand and appreciate its complexity, the desire to develop environmental strategies that are less destructive has fostered a growing interest in environmental research. In rivers and streams, nearby human settlement and agriculture have reduced natural erosion control mechanisms, increased sediment loads, increased flow velocities, upset water chemistry, and incited channel bed erosion which lowers local water tables and triggers bank erosion (Simon and Darby 1999). The effects of human activities on stream water quality and local biodiversity has been so dramatic as to bring a large body of research to bear on understanding the mechanisms and interdependencies inherent in aquatic ecology.

Not only is it important to arrest detrimental management practices, but work is increasingly being done to counteract degradation and restore local ecosystems to a more natural state. Ecological restoration measures have been developed for many river systems around the world (Shields et al Submitted, Kern et al 2002, Shiemer et al 2001). The challenge before environmental managers in recent research has been developing appropriate procedures based on an understanding of ecological processes to counteract effects in disturbed ecosystems (Shiemer et al 2001).

Introduction of agricultural chemicals to watersheds has been a well-reported and broadly harmful consequence of human settlement. Predictably, a large body of research exists concerning water quality and chemical contamination. Improvements of water quality alone will, however, not suffice to restore riverine ecosystems (Kern et al 2002). In addition to the chemistry of aquatic habitat there must be considerations of physical dimensions including temperature, depth, structure and flow patterns. Several schemes have been suggested for physical aquatic habitat characterization including the PHABSIM computer model in conjunction with In-Stream Flow Incremental Methodology (IFIM). Research continues, however, in trying to establish methods of meaningful characterization (Poff and Ward 1990, Azzellino and Vismara 2001, Kern et al 2002).

In the efforts to characterize aquatic physical habitat (APH) a common theme arising in research is the interplay between geomorphic and hydrologic parameters (Shiemer et al 2001, Kern et al 2002, Buffington et al 2002). Floodplains provide an important aspect of habitat complexity by reducing flow velocities, providing refuge from in-bank currents during flooding, and the availability of structure around vegetation, which all positively correlate with fish biomass (Shiemer et al 2001). Also, depositional features (particularly coarse-grained bars) provide habitat for fish spawning and further diversity of flow conditions (Schiemer et al 2001).

Generally, greater spatial heterogeneity in the APH correlates to greater biotic diversity (Gorman and Karr 1978, Poff and Ward 1990, Way et al 1995, Azzelino and Vismara 2001). Spatial habitat diversity helps sustain genetic polymorphism in populations, which in turn helps to mediate disturbances of a sufficiently weak or infrequent nature (Poff and Ward 1990). Homogeneous habitats which are devoid of submerged structure and have relatively straight, simple channels typically decrease population tolerance to disturbance and are characterized by larger disturbance eventseither by formation (cutting a straight channel) or from effects that follow (loss of pool-riffle sequences, flashy hydrology) (Poff and Ward 1990, Simon and Darby 1999).

The straight channel described above rarely occurs in nature and is usually designed as a drainage canal to remove water from an area swiftly. Running water is generally a rather hostile environment causing large expenditures of energy by organisms (Shiemer et al 2001). For this reason hydraulic diversity, in which water flow regimes are characterized by spatial velocity gradients where regions of high velocity and corresponding refugia are provided, is considered a prime ecological indicator (Azzelino and Vismara 2001). With a concept such as hydraulic diversity, scale is an important research parameter (Poff and Ward 1990, Schiemer et al 2001, Kern et al 2002). Mediation of current velocities occurs on both the microscopic scale due to bed roughness or debris and on the reach scale due to meanders, pool-riffle sequences, and large debris formations. Much research has been conducted on the importance of micro-scale velocity refugia for invertebrate populations (Way et al 1995, Lancaster and Hildrew 1993, Benbow et al 1997, Way et al 1993). Research has been conducted with larger scale APH data to determine scales and indicators for fish (Gorman and Karr 1978, Habersack and Nachtnebel 1995, Kern et al 2002, Crowder and Diplas 2002). The methods for collecting such data have in the past been tedious and time consuming, culminating in a relatively small set of data.

Recent use of Doppler technology to make discharge measurements on rivers has opened a new set of possibilities for APH data collection. Where traditional flow measurements were made discretely with considerable effort, the acoustic Doppler current profilers (ADCP) are capable of taking hundreds of velocity measurements per second. The USGS routinely uses the ADCP for discharge measurements and has tested some commercial versions against traditional measurement methods, showing the ADCP's measurements to be within 5% of traditional measurements under most flow regimes (Mueller 2002). The potential for such fast and accurate ADCP technology, however, far exceeds discharge measurements.

This paper follows the work of Crowder and Diplas (2002) in using theoretical metrics (discussed later) of hydraulic diversity to characterize riverine habitat, and the work of Shields et al (Submitted) on applying the ADCP to this model. Using ADCP technology a very large set of velocity data can be collected from river cross-sections for the purpose of applying these diversity metrics to collected hydraulic data. As in other attempts to quantify aquatic habitat it is necessary first to establish a conceptual framework for the indicator, in this case the mathematical framework of Crowder and Diplas, before determining experimentally its relevance in the real world of ecology (Azzelino and Vismara 2001). In addition, the instrument used for data collection must be characterized and a methodology presented for its use to ensure proper comparisons of results and reproducibility. Herein is an attempt to characterize use of the RD Instruments 1200 kHz "ZedHed" ADCP as a tool in quantifying aquatic physical habitat.

II. Acoustic Doppler Current Profilers

Acoustic Doppler current profilers (ADCPs) are commercially available instruments that use fixed-frequency acoustic pulses to measure the velocities in a column of water with adjustable resolution. The ADCP measures the Doppler shift of acoustic signals that are reflected by suspended matter in the water and assumes that the particles have approximately the same velocity as the water. From the distribution of reflected pulses the instrument then computes a weighted mean velocity. The RDI 1200kHz "ZedHed" ADCP has four transducers at 90 degree intervals in the horizontal plane, each sending its own beam of pulses down through the water column 20 degrees from the vertical[1]. Each beam measures the Doppler shift parallel to its own axis.

Each transducer face sends a broadband acoustic pulse through the water. After a short "black out" period the transducer begins recording reflected pulses. This "black out" period may be adjusted by the user, but is recommended to remain above a specified minimum value to avoid acoustic ringing, which may interfere with accurate velocity determination. The entire water column below the transducer face is range-gated into a series of depth cells, or bins, with a height specified by the user. Each beam ensonifies a column of water approximating a cylinder with a diameter of 7cm (with 1.5 degree beam spreading). As pulses return to the transducer face, the instrument uses the speed of sound in water, temperature, pressure, and (in marine cases) salinity to calculate the depth at which the signal was reflected. A complex algorithm for averaging these returned

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[1] All descriptions of ADCP physical principles and operation are taken from the RDI Primer on Acoustic Doppler Technology and may not apply to other commercial equipment.

pulses is then employed by the instrument to produce a weighted mean velocity for the region corresponding to the depth cell in which the signals were reflected.

The instrument employs the axes of beams 1-3 as a vector basis for the measurements of velocity. From the three beams, all three spatial components of velocity can be extracted. The ADCP uses both beam 3 and beam 4 in determining the vertical velocity and then computes the difference in vertical velocities to produce an "error velocity" which may reflect either the complexity of fluid motion or problems with the instrument. Typical error velocities are on the order of a few cm/s. The output velocity, then, represents an average for the entire cone of water underneath the instrument in the region bounded by the four beams. Near the surface, this region has a diameter of about 0.3 m and increases as the beams spread toward the bottom.

In addition to the velocity components, the ADCP keeps track of its heading, pitch, roll, and boat velocity. Each of these is taken into account in the process of determining velocities and is highly accurate for moderate boat velocities, pitch, and roll (RDI). Boat velocity is determined by bottom tracking, using differences in Doppler shifts off of the riverbed from the four beams. The pulses used for bottom tracking are longer than those used for profiling so that the full width of the pulse ensonifies the bottom. Since the beam has a finite width with some spreading, the angle of incidence for the two edges of the beam will be different, producing different Doppler shifts. In this way accurate boat velocity can be measured if, in a river, there is a negligible degree of active bed transport. Uncertainties in bed media, obstructions, and moving bed in high flow situations can cause bottom track errors. Differentially corrected GPS may also be used when available.

The advantage of an ADCP over other current measuring devices is the speed with which data can be collected. A typical configuration for the ADCP may easily take a measurement of the velocities in the water column once per second from a moving boat. The disadvantage to this speed is the volume of data that must be reduced after collection. Since the ADCP samples at regular time intervals rather than distance intervals, much of the velocity data may be from overlapping water columns, depending on the velocity of the boat. Currently, the only commercial software available for the ADCP is concerned with discharge measurements in which this overlapping data is averaged, and thus this software provides little help with other uses of the instrument.

One particular disadvantage of the ADCP in applications to aquatic habitat is that the acoustics make regions near hard boundaries impossible to measure. At the top of the water column, approximately 30-50cm of blanking distance is needed below the transducer face to avoid acoustic ringing as energy is dissipated through the water. At the bottom of the water column, echoes from the lower 6% of the column are obscured by the stronger echoes off of the bottom. Near any hard boundaries or obstructions in the water similar difficulties may be expected. This introduces gaps in the cross-sectional data when submerged debris is present and in shallower waters which are particularly interesting for the presence of eddies and other complex flow phenomena important in habitat characterization.

III. Methods

Field Collection

Data was collected using the 1200kHz ADCP mounted on the bow of a 15 ft jon boat. At each collection site buoys were anchored to mark the approximate endpoints of the cross-section. The boat was then driven between the buoys with the ADCP collecting velocity information. Each trip across the river, with starting and ending points at the buoys, was saved as a separate transect file to be analyzed. Generally, multiple transect files were collected at each site to allow for averaging.

All data was collected on a meandering reach of the Little Tallahatchie River approximately 1 mile south of Sardis Dam in Lafayette County, Mississippi. Average discharge during collection was approximately 4,000 cfs. The channel width was approximately 70 meters with a maximum depth of 5 meters, and a mean flow velocity of 45 cm/s. Prior to collecting cross-sectional data, the boat was anchored and data was collected from the stationary boat to determine whether active bed movement would interfere with collection. No bed movement was detected immediately prior to data collection.

Software and Data Reduction

All data reduction for this paper was accomplished with our own VBA software in Microsoft Excel. A data reduction worksheet was developed to reduce large volumes of Acoustic Doppler Current Profiler data in ASCII format (formatted by RDI WinRiver software) output by an RD Instruments 1200 kHz "ZedHed" ADCP. The Vorticity Data Reduction Worksheet (VDRW) is designed specifically to compute a value termed "vorticity" from the velocity data collected by the instrument. VDRW's macros reduce the data from a river cross-section and estimate the vorticity by selecting data from the ASCII output file with an appropriate spatial sampling rate and then using measured differences between samples to perform finite-difference calculations of velocity gradients. VDRW outputs the vorticity and circulation metrics as well as the x, y, and z component velocities and the velocity magnitude along with relevant statistics for each cross-section.

Spatial Sampling:

When the ADCP is deployed from a moving boat, the acoustic sampling rate may be so rapid that the same region is sampled more than once. To avoid redundant velocity data, it is necessary to consider the geometry of the measured region as a function of depth. If the instrument has beam angle β from the vertical (the "ZedHed" has a standard beam angle of 20 degrees), the width (w) of the measured region bounded by the four beams at a depth (d) is given by:

$$w = 2d\ Tan(\beta)$$

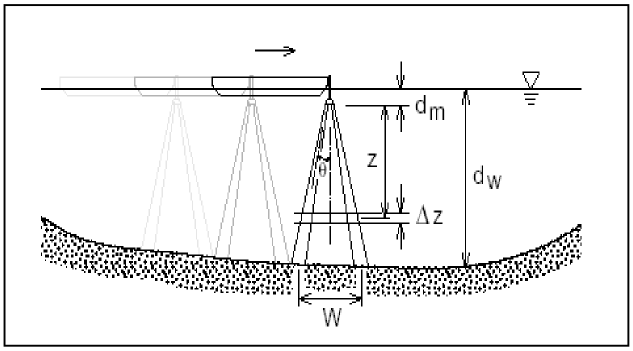

Figure 1. Diagram of ADCP operation from a moving boat where d_m = mounting depth (depth of the transducer faces on the instrument), d_w = water depth, z = vertical spatial coordinate, and w = width of the region bounded by the beams (Shields et al).

The width of the region at the maximum depth is then the minimum desirable spacing between samples to ensure independent data and may be input on the "Data Retrieval" sheet for VDRW to delete redundant data (data taken at smaller intervals). Since boats rarely travel in a straight path, there is some work to be done in adapting this straight-line spacing to a cross-section taken in a real-world situation. First, it is necessary to discuss definitions and use of coordinate systems.

Coordinate Frames:

The ADCP records velocity components, magnitude, and heading in the North-East-Vertical coordinate frame. When working with flow in rivers, the conventional reference frame is one in which the positive x-axis is in the streamwise direction and the y-axis is perpendicular to x and in a plane parallel with the water surface. The definition of the "streamwise" direction can be somewhat problematic in natural channels where the channel is almost never straight. For our purposes, the "streamwise" or x-axis will be defined as the direction of the average heading (direction in the North-East plane) of the velocities measured over a river cross-section. Averaging is, of course, sensitive to repetitious data, so redundant data must be removed from the data set before averaging the velocity headings. VDRW uses a two-step coordinate transformation from the North-East frame to the Streamwise-Cross-section frame to solve this problem.

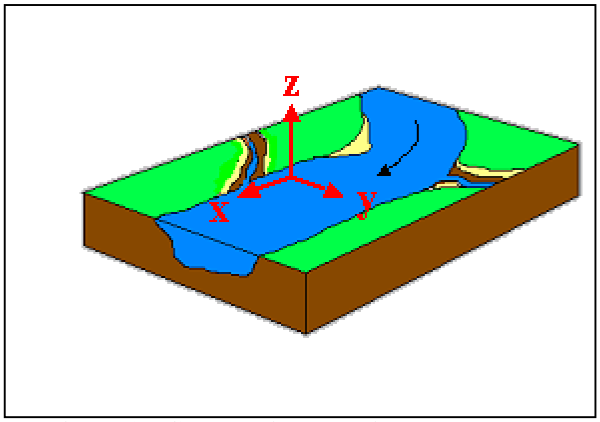

Figure 2. Streamwise coordinate system.

The first step is to define a reference frame that is sufficiently close to the x-y frame that the data may be reduced according to the spatial sampling criterion above. This allows us to remove most of the repetitious sample points and the corresponding bias in the averaging process. To achieve this end, we assume that the buoys used as endpoints for data collection are deployed approximately perpendicular to the flow and that driver of the boat begins at the buoy or marker anchored at one bank of the river and ends up at the second marker across the channel. Note that, for the purpose of defining the coordinate system, it does not matter how much the driver zig-zags or crosses his/her own path as long as the ADCP ends up basically across the river from where it started (though straighter, of course, is better). With this in mind, we define the y-axis as the straight line connecting the boat's (ADCP's) starting and ending points.

At the start of each cross-section or data collection cycle, the ADCP defines the point of its first "ping" as the origin of its N-E coordinate frame. All coordinates given by the instrument are determined by bottom tracking (or GPS interface) and an internal gyrocompass relative to that first point. In defining the y-axis as the line adjoining the starting and ending points of the data collection run, and accepting a common origin with the ADCP, the new x-y frame is simply a rotation about the origin[2]. The degree of rotation φ is given in terms of the North and East coordinates of the endpoint (N and E respectively) by:

$$\varphi = Tan \quad (\tfrac{N}{E})$$

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[2] VDRW also takes into account the starting bank and always displays output from left bank to right.

The reference frame is then rotated through the angle φ by using the familiar rotation matrix:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} Cos\varphi & -Sin\varphi \\ Sin\varphi & Cos\varphi \end{pmatrix} \begin{pmatrix} N \\ E \end{pmatrix}$$

which differs slightly from the common notation because of our naming conventions. The corresponding velocity component data received from the ADCP is rotated in a like manner.

Once the data has been rotated into the new coordinate frame, VDRW applies the spacing criterion to the new y-values of the ADCP sample coordinates by deleting overlapping ensembles[3]. Ideally, once the transformation into x-y coordinates has been made, the x position coordinates should be near zero for all of the data samples (since the cross section runs along the y-axis). It is evident that the variance in x should be kept as low as possible to ensure that measured regions are very nearly adjacent along the y-axis.

The workbook is then ready to calculate the mean velocity heading. Note that in the rotation, the workbook did not transform the explicit velocity heading data output by the ADCP. When the mean heading is computed by summing the individual bins, the answer is given in N-E coordinates as a heading[4]. This heading is then taken as the "true" streamwise direction relative to N-E coordinates. The difference between this heading and our x-axis is calculated and the x-y frame is corrected by rotating it through the difference (γ) producing the finalized x'-y' coordinate frame where x' is in the streamwise

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[3] The program also deletes all data with a "Percent Good" parameter of less than 100%.

[4] Headings are generally a bad choice for computing average direction since, for example, with an average heading of 4 degrees, an additional datum of 355 degrees would tend to make the average higher rather than lower. An algorithm for correcting this problem was incorporated in which VDRW keeps an updated average as it cycles through the headings. When a heading is reached that is greater than 180 degrees different from the average, 360 degrees is added or subtracted from the heading, depending on whether the180 degree difference is positive or negative, before it is included in averaging.

direction according to our definition above. This primed coordinate frame will from here on be referred to as simply the x-y frame.

Calculating Vorticity:

With the data properly spaced in the new coordinate frame, VDRW calculates the vorticity metric from the component velocity data. Mathematically, the vorticity (ξ) is the curl of the velocity vector:

$$\overline{\xi} = \overline{\nabla} \times \overline{V}$$

Collecting data by cross-sections provides information regarding velocity gradients in only two of the three spatial dimensions- y and z in our case. With this information we can compute only one component of the vorticity vector. The x component of the vorticity is given by:

where *v* and *w* are the y and z components of the velocity, respectively. It is then necessary to insert finite differences from collected data to find a value for the x-component vorticity for a specific (y,z) location of a river cross section (Shields et al, Submitted).

Mathematically vorticity is vector field defined at every point in the river. While the ADCP presents a very fast, accurate method of taking velocity data in a river, its resolution is limited. This resolution is dependent upon several factors, including depth, obstructions, and beam angle, which will affect the size of our difference elements. These effects will be discussed shortly. First, there are some conventions that VDRW assumes in making these calculations that should be discussed. The data for a cross section represents a 2D grid of velocities in the y-z plane, a cross-sectional slice of the river. The convention established for the finite difference equation for these cross sections has the following form.

$$\vec{\xi}_x = \left(\frac{w_{n+1,m} - w_{n,m}}{y_{n+1,m} - y_{n,m}} \right) - \left(\frac{v_{n,m} - v_{n,m+1}}{z_{n,m} - z_{n,m+1}} \right)$$

For this equation, *n* increases from the left bank to the right and *m* with increasing depth. Thus, VDRW uses the finite differences from three “bins” arranged in an inverted "L" shaped region of the cross-section to compute the vorticity.

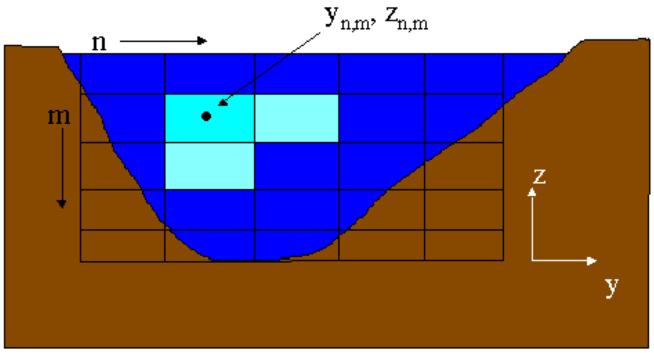

Figure 3. The inverted "L" convention used to calculate Vorticity.

Again, vorticity is a vector at a point, which makes it a poor choice for characterizing regions of habitat. For this reason, we follow the theoretical framework proposed by Crowder and Diplas (2002) in using an area averaged absolute vorticity termed the “Modified Circulation Metric”. Take first the definition of circulation given by Crowder and Diplas:

o

To calculate Circulation, which characterizes a region rather than a point, we may use the expression on the right that essentially sums the product of differential areas and their corresponding vorticities. The important characterization of a habitat in this study is that of flow complexity. Since two counter-rotating vortices would cancel each other in the Circulation calculation, we follow Crowder and Diplas in using the magnitude of the vorticity values when computing the product of the vorticities and their areas. Also, it must be possible to compare values between reaches of a river or between different rivers. To compensate for differing channel dimensions, we divide by the total area of the Circulation measurement, so that our expression is then:

$$\vec{\ } \qquad \frac{1}{\ } \; \left|\vec{\ }\right| \qquad \vec{\ }$$

Adapting this to a finite sum, we have, for the circulation over a cross-section:

$$\vec{\Gamma}_x{}' = \frac{1}{A}\sum_i \left|\vec{\xi}\right|_i a_i$$

$$\textit{where}$$

$$A = \sum_i a_i$$

In this equation A is the total area and a_i is the i^{th} partial area used in the summation. Notice that presently we assume that $d\vec{A}$ is parallel to the x-axis so that the dot product becomes simple multiplication. This is equivalent to having a perfectly straight collection path across the river. If the starting and ending points of the collection path lie on the XS line, as it does by definition, and if the dA elements are relatively uniform, which they are, we may treat this error as very small.

When VDRW encounters a bin of missing data, it simply skips that bin and continues the summation. The missing vorticity also results in a missing area component so that the final circulation value is based on the area with good data and not necessarily the full cross-sectional area. In the event that the data for some (y,z) in the equation is missing, an "*" value is written to the output array.

Experiments

Two basic experiments were performed to characterize the use of the ADCP in measuring aquatic habitat. The ADCP has several configuration options that may be used to optimize discharge measurements. These include water mode, bin size, sampling rate, and pings per ensemble. The water mode option allows the user to select among several methods of taking the data, each with advantages and disadvantages in varying flow conditions. For example, WM 1, the most robust mode, uses extensive averaging and may be used over a wide range of depths and velocities. On the other hand, the standard deviation of the measurements is too large for use in slower currents. WM 12 compensates by allowing for sub-pings, which reduces the standard deviation but increases the navigational error since navigational instruments are queried less often.

The following experiments concerning bin size and water mode (WM) are aimed at characterizing the instrument and the influence of its configuration on the proposed habitat metrics.

Water Mode

The RDI ADCP comes with several configuration modes geared toward specific collection conditions. Our instrument allows for use with WM 1, 5, 8, 11, and 12. As mentioned above, WM 1 is advertised as the most robust collection mode while 5 and 8 are for shallower, slower conditions. WM 11 is suggested for situations where the maximum velocity is less than 1m/s and the depth is less than 3m. WM 12 returns to the more robust side of measurement allowing for large depths and faster flows but with a navigational trade-off.

The differences between the modes lie primarily in the method of collection. WM 1 uses a single short pulse as its “ping” and uses the distributions from that pulse to create a velocity profile (note that multiple pings may be averaged together into an “ensemble” but the single ping is still the unit measurement). WM 5 and 8 follow WM1 but with differing energies in the pulses. WM 11 uses a pulse-to-pulse coherent method in which pulse pairs are released separated by a precise lag time allowing drastically reduced variance in velocity information. WM 12 sends a user selected multiple of “sub-pings” through the water column, again with precise lag times, to reduce the variance. Mode 12 allows for more sub-pings (essentially an extension of WM 11 methodology) by only querying the navigational systems after each set of sub-pings.

Given these broad differences in the methods of measurement and the extensive use of averaging to produce results, we would expect to see some difference in the output of the instrument, and perhaps some effect on our habitat metrics. As WM 1 and 12 are the most versatile modes, applications of the instrument to reach scale habitat characterization will be centered on those modes, thereby making them the most important for examination of comparison criteria.

To see what effect there might be on habitat measurement, WM 1 and 12 are compared and contrasted. WM 12 uses a series of 25 subpings to assess its single "ping" whereas WM 1 uses a true single ping to establish its ensemble of velocities. Both WM were configured to "ping" at a frequency of once per second (1 Hz)[5]. The bin size was set to 25cm for each. The only differences in configuration were the WM and the subping aspect of WM12. Five cross-sections were collected for each WM. All 10 cross-sections took a combined time of 18 minutes to collect including pauses for configuration change and failed collection attempts (which were few).

Bin Size

Velocity data were obtained from twenty-two cross-sectional runs with 11 bin sizes ranging from 5cm to 150cm. Duration of the collection was only 32 minutes including configuration changes and failed collection attempts (3). WM12 was used throughout with 25 sub-pings. The number of bins was adjusted as needed to ensure maximum depth coverage.

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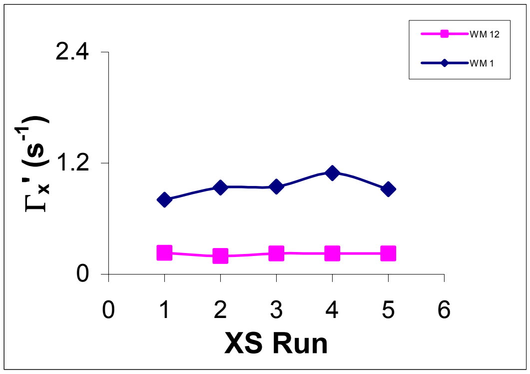
[5] The WM 12 collection included 25 subpings at 40ms intervals within this 1 second collection time.

IV. Results

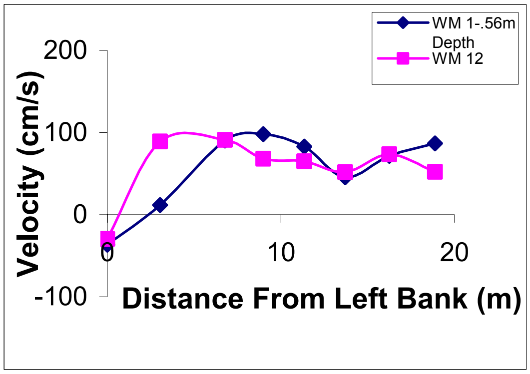
Water Mode

Graph 1 illustrates the differences observed for five transect measurements with the two modes. The modified circulation metric calculated by the VDRW differs consistently between modes by about a factor of 4.



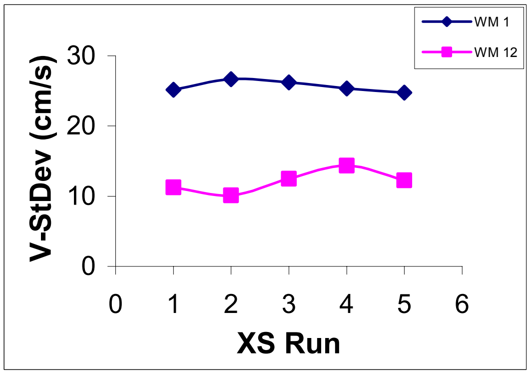
Graph 1: Modified Circulation metric for five (5) cross section runs in WM 1 and WM 12.

The graph shows, as do repeated observations, a consistent difference between our metric as produced by WM 12 data compared with that produced by WM 1. One might expect the raw velocity data from the instrument taken by the two water modes to show similar discrepancies. Graphing the velocity profile across the river (Graph 2) shows no such trend.



Graph 2: X-velocity component (u) at 0.56 m depth for the five cross-sections in WM 1 and 12.

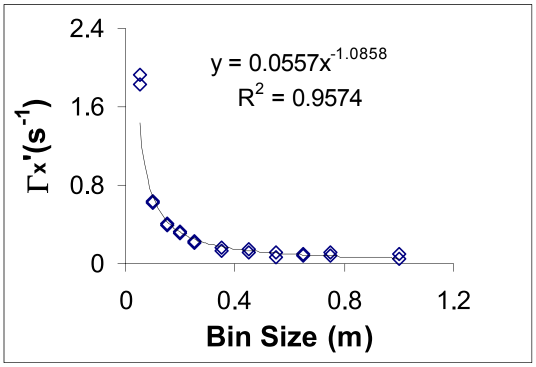
The distributions for the two transects are remarkably consistent and suggest that the velocity data is accurate in both water modes. The standard deviation of y component velocities (v) for the transects with differing water modes provides a measure of the precision of the velocity measurements and shows the same trend as the modified circulation metric (Graph 3).



Graph 3: Standard deviation of y-component velocity (v) for the five cross sections.

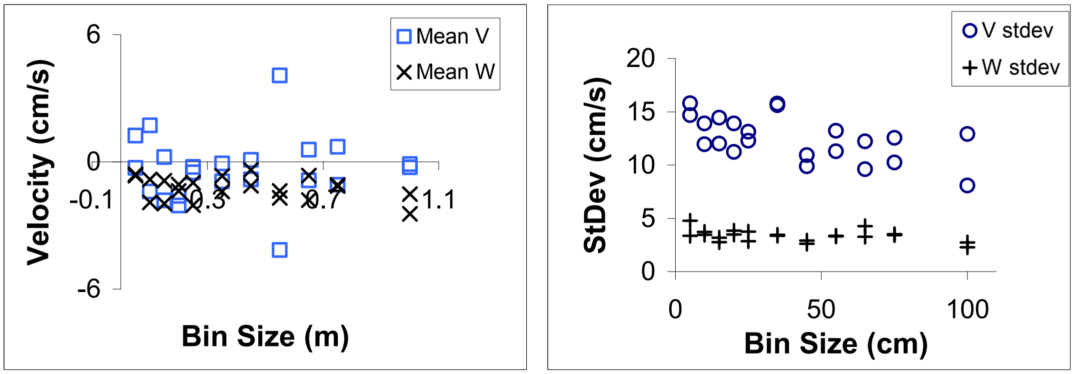
Bin Size

Graph 4 shows a pronounced relationship between the circulation metric and bin size in WM 12. Each bin size shows two data points representing the two transects taken with that configuration.



Graph 4: The 1/Δz relationship between Modified Circulation metric and bin size.

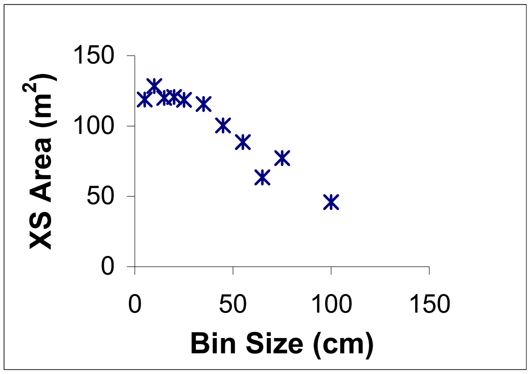
As with the water mode experiment a strong dependence is found between the modified circulation metric and the bin size configuration. The means and standard deviations for the velocity data are plotted below providing quantitative measures of



Graph 5: Velocity component means and Standard deviations show no trend with bin size.

the variance in the measurements under differing bin size configurations. No trend is apparent from the graphs.

Graph 6 shows the dependence of the effective area on bin size for data collected from the same river cross-section. The effective area over the cross-section decreases substantially as the bin sizes increase beyond 50cm.



Graph 6: Effective cross section area shows dependence on bin size, but slight for smaller bins.

V. Discussion

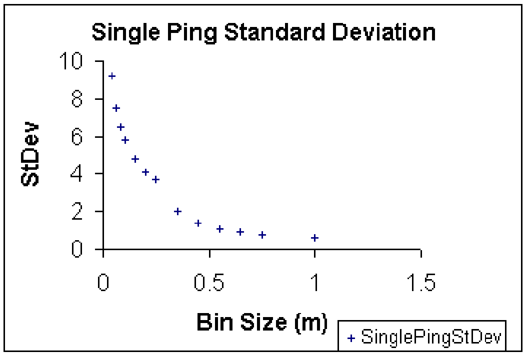
Water Mode

Results of the methodology experiments show that the calculated habitat metrics, vorticity and modified circulation, are very sensitive to the configuration of the measuring instrument. The water mode experiment results suggest that the metrics are particularly sensitive to the variance in velocity data, and thus to the precision of the instrument collection configuration. This may be understood intuitively by considering two populations with widely differing variances. A distribution with a relatively large variance will have a greater average difference between elements. Since the vorticity and circulation metrics depend on finite differences, an increase in the measurement variance over a cross-section will produce a corresponding increase in the metric values. This is exactly the phenomenon seen in the water mode experiments.

The variance in velocity measurements is a function of acoustic method and the flow regime of the river. It is important to be able to distinguish the two, since one is an instrumental bias and the other is the very object under investigation. The variance inherent in the acoustic method may be gauged in advance by the Single Ping Standard Deviation (SPSD) given by RD Instruments software.

The single ping standard deviation (SPSD) is the standard deviation of the distribution of echoes from one “ping” of the instrument. For one ping there will be thousands of small echoes from particulate matter in the water producing a distribution of measured Doppler shifts. The standard deviation of this distribution, the SPSD, is inversely related to the precision of velocity data.

The SPSD is not measured directly but may be estimated for a given configuration by software provided by RD Instruments (PlanADCP). According to RDI, the SPSD depends on the water mode and bin size in the configuration in a nonlinear manner. Graph 7 shows the dependence of SPSD on bin size as calculated by PlanADCP software.



Graph 7: Dependence of Single Ping standard deviation with bin size.

Currently, the PlanADCP software created by RDI that calculates SPSD is not equipped to calculate WM 12 configurations with multiple sub-pings. To get around this, WM 12 sub-pings may be treated as an ensemble of single pings for an approximation of the SPSD (personal correspondence with RDI). The curve in Graph 7 looks very similar to the one we saw in the bin size experiment. Standard deviations in WM 12 with 25 sub-pings, however, are so low that practically no dependence is seen in the bin size experiment.

When using the ADCP in dynamic situations where ensembles consist of only a single ping, the SPSD may play a large role in biasing calculated metrics. In the water mode experiment above, the standard deviations of the velocity components differed between water modes due, no doubt, to the difference in SPSD between WM 1 and WM 12. According to PlanADCP, the SPSD for WM 1 is 19.35 cm/s, while for WM 12 the SPSD is only 1.58 cm/s. No quantitative relationship between SPSD and modified circulation can be drawn since PlanADCP only gives an estimate of the variance. However, the estimates show a striking difference in the variance of the two measurement techniques and should be taken into account when using the instrument to calculate indices of habitat quality.

Bin Size

While the water mode experiment showed a significant change in modified circulation with respect to the variance in measured velocities, Graph 5 shows that there is no strong dependence between the bin size and the cross-sectional means or standard deviations of velocity components in WM 12. However, as shown in Graph 4, there is a strong dependence between the habitat metric and bin size. In this case the modified circulation metric follows an expected trend. Recall that the finite difference equation for the vorticity is $\Delta w/\Delta y-\Delta v/\Delta z$. Reasonably we may claim that the only variable that changes value appreciably between cross-section measurements is the change in bin size (Δz). Thus the curve should have the form $1/\Delta z$, which it does.

One further aspect of the modified circulation worth noting is the dependence of cross-sectional area on bin size, since the circulation is weighted by cross-sectional area. As was described in the methods, the software uses an "effective" area of the cross-section when calculating the modified circulation. This "effective" area is the sum of all the area elements in the cross-section for which vorticity data may be computed. Thus, as the bin size decreases, the effective area should increase as shallower regions are represented in the calculation. The results support this conclusion but with little effect on the metric for bin sizes below 40 cm (Graph 6).

VI. Conclusion

In conjunction with studies of water quality and submerged structure, hydraulic diversity may be a powerful ecological indicator. Research has shown that substrate roughness creates mm-scale velocity refuges valuable for the life cycles of many invertebrates (Way et al 1993). Hydraulic diversity studies on larger scales (meters) are based on the idea that current eddies and vortices create “refuges” for organisms which decrease energetic costs while stronger currents transport food and wastes nearby (Azzelino and Vismara 2001, Shiemer 2001). This diversity of flow regime may be created by submerged structures such as logs and boulders or it may be a product of the morphology of the stream channel itself.

The ADCP with its capability of making thousands of velocity measurements per minute has great potential as a tool for measuring hydraulic diversity in aquatic ecosystems. The speed, precision, and scope of measurements vastly out paces competing methods of velocity measurement. Applicability is limited to meso or macro-scale studies characterizing flow characteristics on the order of meters. While it allows for resolutions of 1cm in the vertical water column, the large radius of the velocity cone formed by the beams and the difficulties near obstructions make the ADCP impractical for micro-scale habitats.

The RD Instruments ADCP also allows for several configurations which make it a useful tool over a broad range of riverine environments, from high fast flows to near zero flow conditions. Care must be placed in choosing a configuration to optimize performance in a particular situation. Only data with carefully matched configurations should be considered comparable. Differences in water mode, bin size, and sub-pings all contribute to different SPSD and should be considered carefully when taking data for comparative studies of habitat. The RDI software may be used to estimate SPSD and develop approximate proportionality factors, but for confident comparisons it is best to use identical configurations where possible. If data is intended for comparison across several collection sites, configurations should be matched as closely as possible while ensuring proper operation. Any published results should include details of the configuration settings.

While the ADCP is highly useful as a tool for measuring velocities and discharge, the change in variance discussed here makes the vorticity and circulation metrics suspect. However, since hydraulic diversity depends directly on the variance of velocities at different scales, the variance bias is more a weakness of the instrument than the metrics. As the conceptual framework of the vorticity metric is tested against ecological data, the metric may prove too valuable of an indicator to ignore, in which case configuration matching will become of great importance.

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