Envisioning Hydrometric Data to Enhance Management of River Systems

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Abstract

Professor Dr. Edward R. Tufte of Yale University, a leading expert on visualizing scientific information states that, 'We envision information in order to reason about, communicate, document, and preserve knowledge...' and also, 'Modern data graphics can do much more than simply substitute for small statistical tables. At their best, graphics are instruments for reasoning about quantitative information.' Advances in hydrometric instrumentation have made possible unprecedented resolution in the data that describe processes occurring in streams and the surrounding riparian corridor. Although the instrumentation used in hydrometric studies has evolved rapidly, the analyses and interpretation of the resulting data has largely focused on the improved precision the resulting data provide for the same analyses that were done with earlier instruments. From a management perspective, the driving force behind the transition to the newer instrument technology is the improved measurement efficiency coupled with providing improved precision. However, by primarily focusing on the improvements to precision and efficiency of what was done with less sophisticated instruments, we may miss opportunity to provide much greater understanding of the phenomena occurring in riverine systems.

This paper examines the hypothesis that the efficiency and precision improvements that led to adoption of the new technology represent a small fraction of the potential benefit of modern measurement technology. The new instruments provide the opportunity to develop new measurement protocols that employ multiple sensors to obtain data describing in-situ phenomena that were impractical or impossible to measure only a few years ago. Analysis tools that couple the high-resolution data streams from multiple instruments and then present the merged data in graphics that illustrate the interactions among multiple processes allow for unprecedented understanding and reasoning about what is occurring in the river system. This paper will present case studies illustrating the coupling of multiple sensors, now measurement protocols, and data visualization to provide insight into processes occurring in streams and show how this insight facilitates management decisions for the streams..

1. INTRODUCTION

One of the grand challenges facing hydrologists is to understand the spatial variability and complexity of in-stream processes. Historically most hydrologic measurements have been spatially sparse, with data providing detailed description of a small number of points or cross sections of a stream. The history of hydrometry clearly shows that measurement of streamflow is the driving force leading to much of the current practice of hydrometry (Caesperlein, 1974). The value of a time-series record of streamflow for a variety of scientific and engineering questions has been widely recognized (Herschy, 2009, 3-5) However, determining a time-series of discharges is not a trivial task because of the time required to make an accurate measurement of the volumetric flow rate or discharge. What has been done for over a century is to make concurrent measurements of the discharge and water-surface elevation (stage) at a fixed location and use the measurements to develop a graphical or mathematical relation between the stage and discharge, This relation is called the rating curve. Because a variety of in-stream processes can alter the stage-discharge relation (Schmidt and Yen, 2008), measurements need to continue to be made routinely to evaluate the uncertainty in the rating and to update the rating as indicated by the data. Furthermore, decades of experience and research have shown that the selection of the measurement cross section plays a crucial role in the uncertainty of the discharge record (Herschy, 2009, p. 47). A measurement section perpendicular to the flow in a straight, uniform reach is desired to reduce errors in the measurement. Furthermore, a measurement section that is narrow (resulting in higher velocities) and uniform (minimizing secondary currents) reduces the uncertainties in the measurements.

Over the years, interest in other in-stream processes resulted in measurement of additional parameters. The streamflow is the primary factor affecting transport and dispersion of constituents carried by the flow and interactions between the flow and the stream bank. Therefore, it was logical to co-locate the measurements of other constituents and processes at streamflow monitoring stations. Hence many hydrometric measurements are conducted along cross sections (Sanders, et al, 1983, p. 98), even when advances in instrumentation may allow alternative measurement and analysis approaches.

The end result of these factors is that hydrometric data tends to provide detailed information obtained from many repeated measurements at a small number of locations. However, in order to understand the fluxes, transformation, and stores of flow and constituents carried by the flow, data are needed over the entire reach being studied. Because such data are rarely available, hydrologists often rely on numerical models to 'fill in the gaps' and provide physics-based estimates of the behavior between sampling locations (e.g., Brown and Pasternack, 2009; Wagner, 2003). Along with improvements in numerical methods and computational power, a wide variety of tools have been developed to manage, visualize, and analyze the output from numerical models. One factor that has facilitated development of these tools is that the models generally have a well-defined, often uniform computational mesh that makes comparisons among scenarios relatively straight-forward.

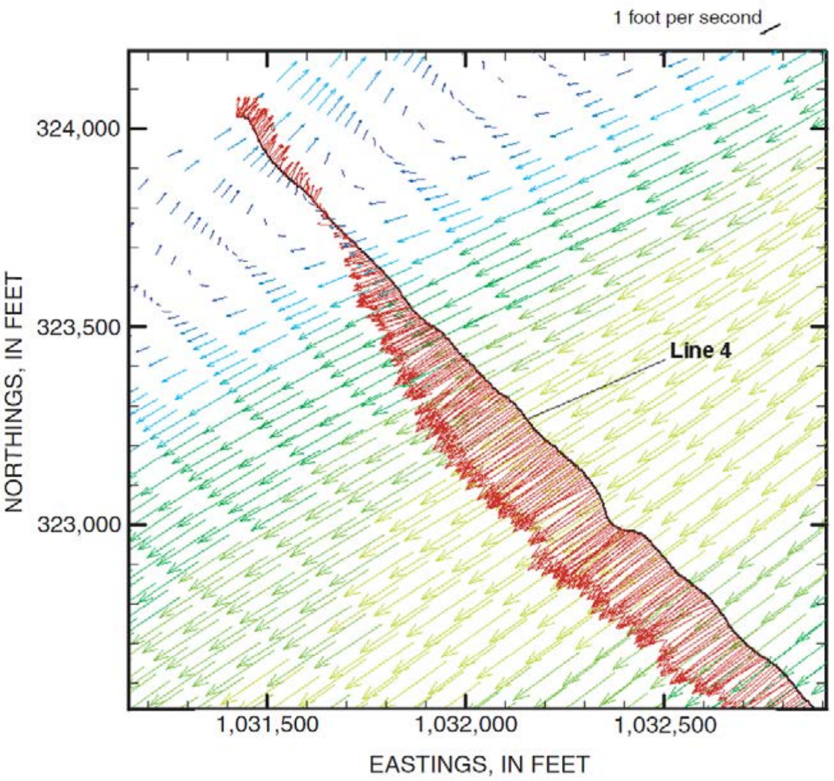

Figure 1--Measured and simulated 2-D velocity vectors (red arrows are measured by ADCP, multi-colored arrows are simulated my 2-D model). Image from Wagner (2003).

In contrast, even when reach-wise surveys are conducted (e.g., bathymetric surveys) the data are often replicate measurements at irregular locations with highly anisotropic measurement spacing. These factors lead to challenges in processing, managing, and analyzing the data. For example,

Figure 1 shows horizontal water velocity vectors from one of 15 transects surveyed by the U.S. Geological Survey to obtain data used to calibrate a numerical model of a 19.2 km reach of the Ohio River near its confluence with the Mississippi River. The longitudinal spacing of measurement transects ranged from 0.6 to 1.5 km. Water discharge and velocity were measured with an acoustic Doppler current profiler (ADCP) so the lateral spacing varies with boat speed, but will generally be of the order of one meter. This figure clearly illustrates the differences in lateral and longitudinal data densities and between the model grid and the location of observations.

As a result of the differences between model grids and measurement points, calibration of multi-dimensional models often is based on visual comparisons such as that illustrated in Figure 1, rather than numerical metrics of model performance. According to Osting and Hodges (2007, p.5), 'The minimum level of calibration evident in all modeling studies is matching of water surface elevation at the upstream boundary. Additional calibration is sometimes performed to match measured points of the water surface profile within the modeled reach. In very few cases are hydraulic model validation metrics presented in the literature.'

This paper will illustrate analysis of entire river reaches that are made possible by modern measurement technology and processing tools. These will be illustrated with example applications of data collected for entire reaches of rivers and analyzed with software that allows integration, visualization, computation, and comparison of data collected from a variety of sensors over an entire reach of a stream.

2. OVERVIEW OF DATA COLLECTION APPROACH

Advances in hydrometric instruments—particularly hydroacoustic instruments, satellite positioning systems, and optical instruments—have revolutionized how hydrologic data are collected. These instruments allow unprecedented density of data with a precision that equals, and often exceeds that available from the instruments that they replace. Light detection and ranging (LiDAR) systems provide topographic measurements with a density of many points per square meter, replacing surveys of a small number of control points to calibrate optical determination of contour lines. Satellite positioning systems are now capable of providing horizontal positioning with a precision of less than 10 cm and updates of the order of several Hz. This is particularly useful for river surveys where movement of the boat made optical surveys of instrument position difficult. Acoustic Doppler current profilers (ADCPs), that measure water velocities through much of the water column, along with movement of the boat relative to the streambed, provide much greater detail of the three-dimensional (3-D) water velocity throughout a cross section than traditional current meters, where the downstream component of velocity was typically measured at one or two points in each of about 25 to 30 verticals in a cross section.

The adoption of ADCPs by hydrometric agencies worldwide was driven more by their ability to simultaneously measure both boat and water velocities than by their ability to measure the 3-D velocity field. Because boat and water velocities were measured simultaneously, the discharge for any individual measurement of velocity (often called an ensemble) is the vector cross product of the boat and water velocities. As a result, measurements no longer needed be done by measuring water velocity while holding stationary at a number of points along a cross section, as well as measuring the depth and lateral location of each vertical. Rather than needing a cable across a stream to aid in positioning the boat and holding it stationary, ADCPs allowed moving-boat measurements in which the boat transected the stream while measuring boat and water velocities, and at the end of the transect the total discharge through the transect was reported. This greatly reduced the time and personnel required to measure discharge, particularly for large rivers.

Despite the ability of these instruments to measure discharge through any arbitrary path, analyses of the uncertainty in the measurements indicated that the measurement precision was improved by making multiple replicate measurements along a transect that is roughly perpendicular to the flow. Because the motivation for adapting these instruments discharge measurement, the measurement protocols gravitated to measurement along fixed transects (Herschy, 2009, Ch. 6). Even when measurements were done to characterize velocity fields in a reach, the measurements were typically done for a series of transects, perpendicular to the flow, spaced at intervals along the reach (e.g., Fig. 1).

Combining satellite positioning with ADCPs provides the opportunity to collect data, for conditions that are approximately steady, independent of any fixed transects. Each vertical (ensemble) measured by the ADCP contains the coordinates of that measurement, along with the 3-D boat and water velocities referenced to world coordinates. This means that the velocity field can be measured for any path or set of paths spanning a reach. For this study the recently released CubeIt software (WaterCube, 2015) was used to combine the data to describe the bathymetry and the entire velocity field in the reach. Figure 2 shows the boat paths for a survey of a 1.6 km reach downstream from a hydropower plant. This survey used multiple ADCPs, with most of the boat paths moving longitudinally, but additional paths crossing the stream in a region where greater detail was desired.

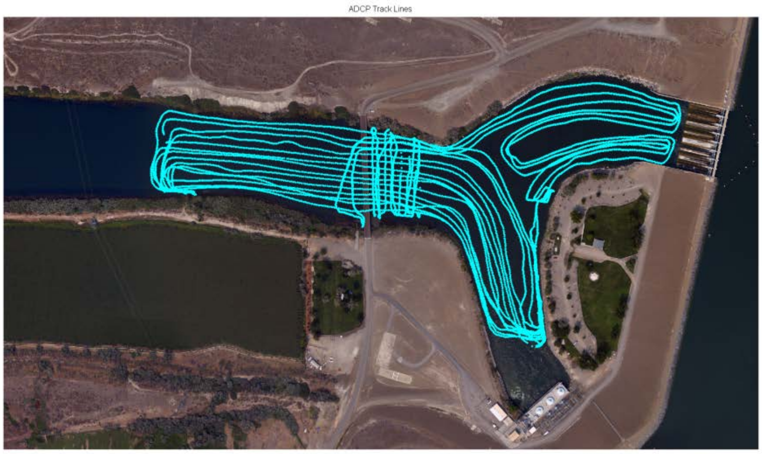

Figure 2--Aerial orthophoto of study reach showing location of ADCP tracks.

It should be noted that discharge measurement protocols specify averaging multiple replicate measurements along a transect and examining the variance of these measurements to quantify the precision. This is because ACDP measurements of a vertical are fast compared to the time scale of large-scale turbulence in streams. The result of the fast measurements is significant noise in the velocities at any vertical because of turbulent fluctuations. Averaging multiple transects diminishes the noise, giving a more precise estimate of the flow. In the same manner, averaging multiple verticals provides better resolution of the depths and velocity field in the reach. The software used in this paper averagies multiple velocities measured in the vicinity of each grid point where data will be extracted to reduce the noise from turbulent fluctuations. The software also determines the bathymetry of the reach using the depth measured by each beam of the ADCP for every vertical. If LiDAR data are available for the reach, the LiDAR data are combined with the bathymetry data from the ADCPs to provide a complete map of the ground surface and river bathymetry for the reach. Other two-dimensional (e.g., bed material size) or 3-D (e.g., profiles of water-quality constituents) data for the reach can also be combined into the data base, allowing visualization and analysis of multiple parameters.

3. HYDRAULIC APPLICATION OF 3-D REACH DATA

The data collection procedure described above along with the visualization and analysis afforded by the software facilitates a variety of hydrometric analyses that heretofore were commonly done by fitting a model to a limited data set and using the model to estimate the spatial distribution of the parameters. This section presents some example analyses illustrating the understanding afforded by visualization of 3-D data for a reach.

3.1. Discharge Measurement Site Selection

Many streams are affected by backwater conditions, highly unsteady flows, flow regulation, and other factors that introduce significant error in discharges estimated from a conventional stage-discharge rating An approach that is gaining wide-spread acceptance is installation of an upward- or side-looking ADCP to continuously measure the velocity at a fixed location in the cross section. An empirical relation (‘index-velocity rating’) between the velocities measured by this instrument (‘index velocities) and the mean velocity in the cross section (as determined from discharge measurements) is used to estimate the mean velocity in the cross section. This mean velocity is used with the area of the flow to calculate the discharge.

The fundamental assumption underlying this approach is that the index-velocity rating is a unique and stable relation between the index velocity and the mean velocity. Furthermore, the uncertainty in the mean velocities determined from this relation are minimized if the index velocity is located near the location of the maximum velocity in the cross section. While many index-velocity stations have successfully demonstrated application of this approach, some stations exhibit unstable index-velocity ratings or significant noise in the estimated mean velocities. Often this is the result of conditions in the flow that are not evident from observations typically available during site selection. Figure 3 shows data from a survey of the 1.6 km reach from Fig. 2. The WaterCube software was used to output the data in a series of transects aligned perpendicular to the flow for purposes of this visualization. The velocity contours illustrate the velocity profile at any potential measurement point. Figure 4 shows a slice from two potential measurement locations for four different flow conditions. The upper row of figure 4 shows that the velocity profile and location of the maximum velocity is stable for this location, while the lower row shows a location where the size and shape of a low-velocity region near one bank of the stream changes significantly among flow conditions. This will affect the mean velocity in relation to the maximum velocity, indicating that this site would have an unstable index-velocity rating. Analysis of slices along the reach identified sites where the velocity profile is stable over a range of flow conditions, indicating good locations for installation of an index velocity instrument

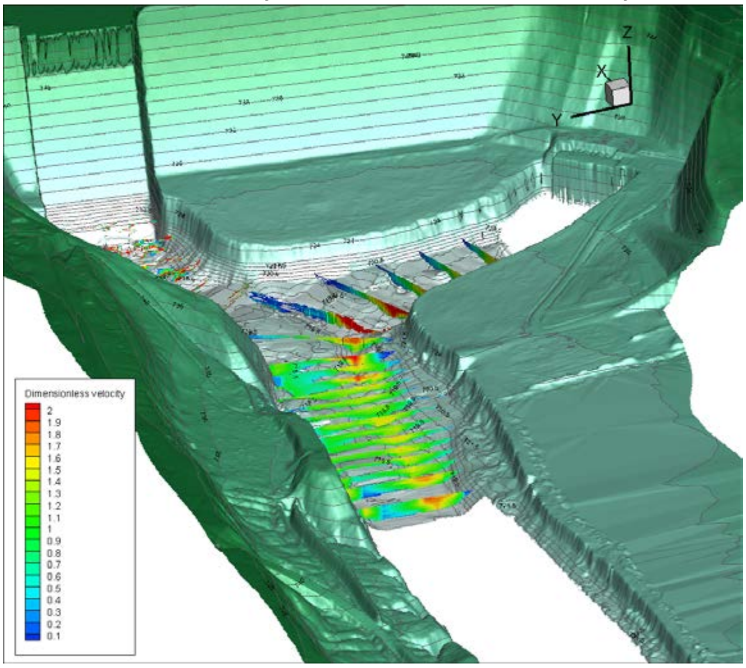

Figure 3--Downstream velocity measured throughout reach.

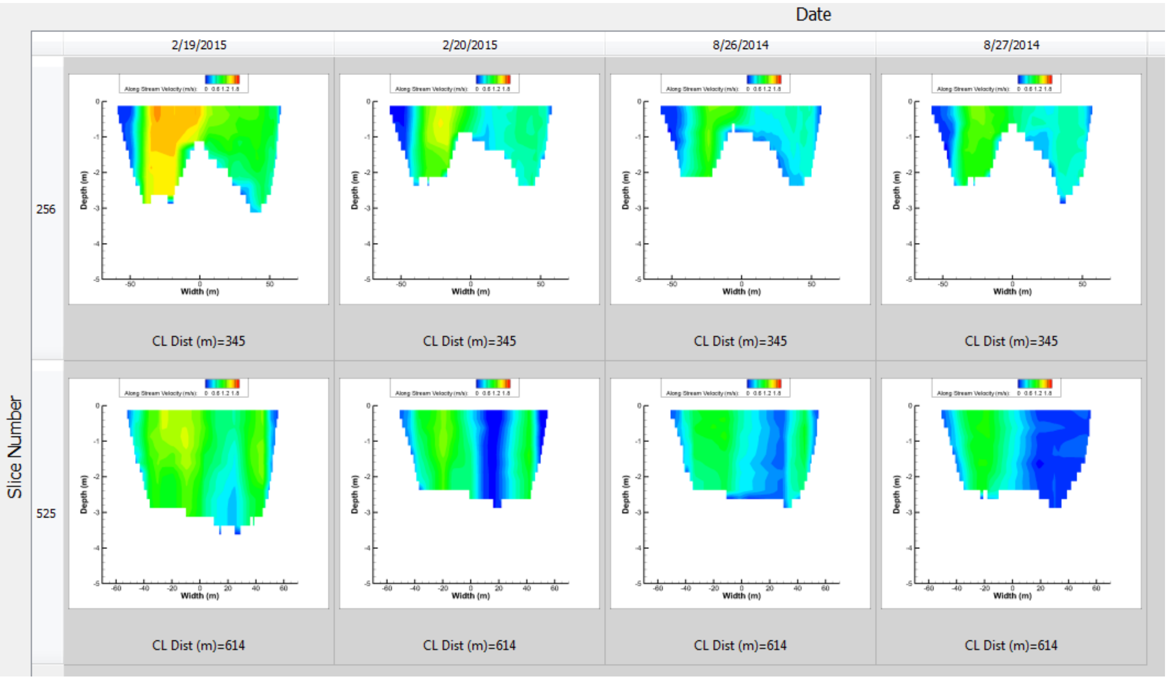

Figure 4--Graph showing downstream velocity from two potential measurement sections for four flow conditions

In addition, the reachwise data coupled with the ability to slice velocity field along any arbitrary plane allowed simple examination of the stability of the velocity-index rating for different potential instrument configurations

3.2. Bed Shear and Stability Assessment

Shear stress (t) is a measure of the tractive force from the friction from moving water along the bed of the channel. The basis for stable channel design is that flow-induced tractive force should not exceed the permissible or critical shear stress of the bed material. Calculation of the shear stress at the channel bed is necessary for many engineering, geomorphological, and habitat studies. The shear at the bed is directly proportional to the velocity gradient normal to the bed:

$$\tau_o = \mu \left.\frac{du}{d\eta}\right|_{\eta=0}, \tag{1}$$

where *u* is the velocity η is the direction normal to the wall, and μ is the dynamic viscosity of the fluid.

Because of the challenges of measuring the bed shear, what is commonly done is to calculate the mean shear for the cross section as

$$\tau_o = \gamma R S_f, \tag{2}$$

where:γ is the specific weight of the fluid, *R* is the hydraulic radius of the flow (*R=A/P*); S_f is the friction slope of the flow, *A* is the cross sectional area of the flow, and *P* is the wetted perimeter of the flow. Furthermore, the bed slope is typically used to estimate the friction slope, assuming a steady, uniform flow condition. Because the shear is not uniformly distributed around the cross section, engineering design uses the maximum shear in the cross section:

$$\tau_{o_{max}} = \gamma \eta_{max} S_f, \tag{3}$$

where η_{max} is the maximum depth in the cross section.

While Eq. 1 is a theoretically correct definition of local bed shear, it is generally not useful for determining bed shear. Eq. 1 requires the velocity gradient immediately above the stream bed. However, the instruments available cannot measure immediately adjacent to the bed because of acoustic interference from the bed. Szupiany et al (2009) used a method developed by Kostaschuk et al (2004) that fits a linear regression between the velocity at different depths and the logarithm of the measurement height (η):

$$u(\eta) = C_1 \ln(\eta) + C_o, \tag{4}$$

This allows estimation of the bed shear as:

$$\tau_o = \rho (u_*)^2, \tag{5}$$

where ρ is the density of the fluid and u_* is the shear velocity, which is determined from the slope of the regression between velocity and logarithm of measurement height ($u_* = \kappa \times C_1$), and κ is the von Karmen constant ($\kappa \approx 0.4$).

This approach, coupled with the data collected as described above, allows computation of the bed shear at every vertical with enough velocity measurements to fit the regression to Eq. 4. The result is a map of the bed shear for the entire reach.

The bed shear is a measure of the friction force on bed-material particles that can result in particles being dislodged from the bed and entrained into the flow. However the bed shear alone does not predict scour of bed material because it does not include the gravity force on the sediment resisting motion. Engineering design often utilized tables of critical shear stress for different types of bed materials. For a reach with a uniform bed material, the critical shear stress can be compared with the calculated bed shear to identify locations where scour is likely for a given flow condition. In many natural streams, the bed material is not homogenous. The *Shields stress* (τ_{*_c}) is a dimensionless

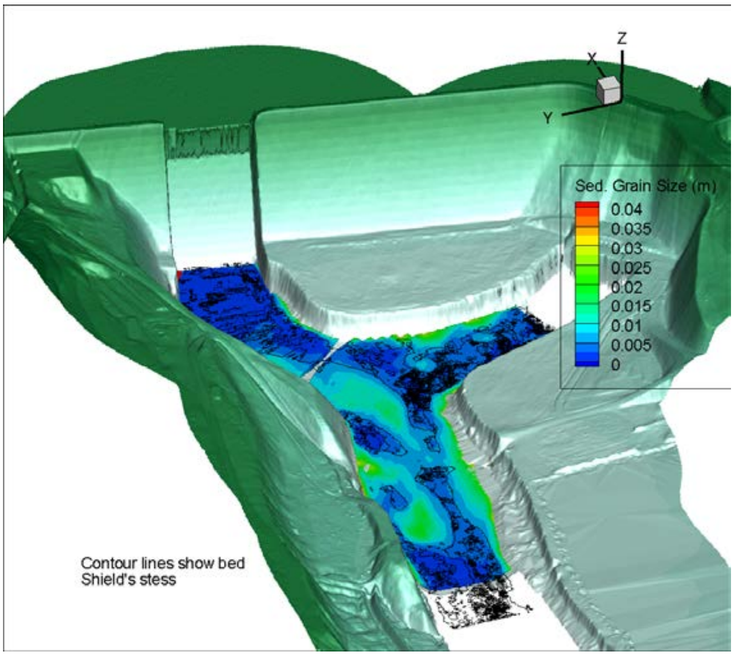

Figure 5--Shield's stress and bed-material size.

stress that includes the density and size of the sediment in making the stress dimensionless.

$$\tau_{*_c} = \frac{\tau_o}{(\rho_s - \rho) g D_s} = \frac{(u_*)^2}{r g D_s},$$

where ρ_s is the density of the sediment, D_s is the particle diameter, and $r = \frac{\rho_s - \rho}{\rho}$ is the submerged specific density of the sediment. Yalin and Karahan (1979) showed that the Shields stress at incipient motion is roughly constant $(\tau_{*_c} \approx 0.045)$for grain sizes greater than 3mm. The complete velocity profiles for points throughout the reach allow calculation of the Shield's stress for an entire study reach and from this maps can be produced showing locations where sediment mobilization is likely to occur (Fig. 5).

3.3. Habitat Suitability Assessment

Wilkes et al (2013) reported that flow forces are the dominant factors influencing the processes of dispersal, reproduction, habitat use, resource acquisition, competition and predation in river ecosystems.They reported velocity, bed shear, shear velocity, Reynolds number, Froude number, and boundary layer thickness as key parameters with demonstrated flow-biota links.

Brown and Pasternack (2009) used Shield's stress and habitat-suitability indices based on depth and velocity (DHSI and VHSI) to quantify the habitat impacts of different stream restoration alternatives. They merged the habitat-suitability indices into a generalized habitat-suitability index (GHSI). Computation of DHSI requires depth at each point, and VHSI requires depth-average velocity at each point Brown & Pastarneck (2009) used a numerical model to simulate these. However, reach-wise data collection and software analyses allows computation and display of all of these hydraulic parameters that quantify habitat. Figure 6 shows the GHSI and depth-average velocity magnitude based on field measurements for an entire reach of a stream.

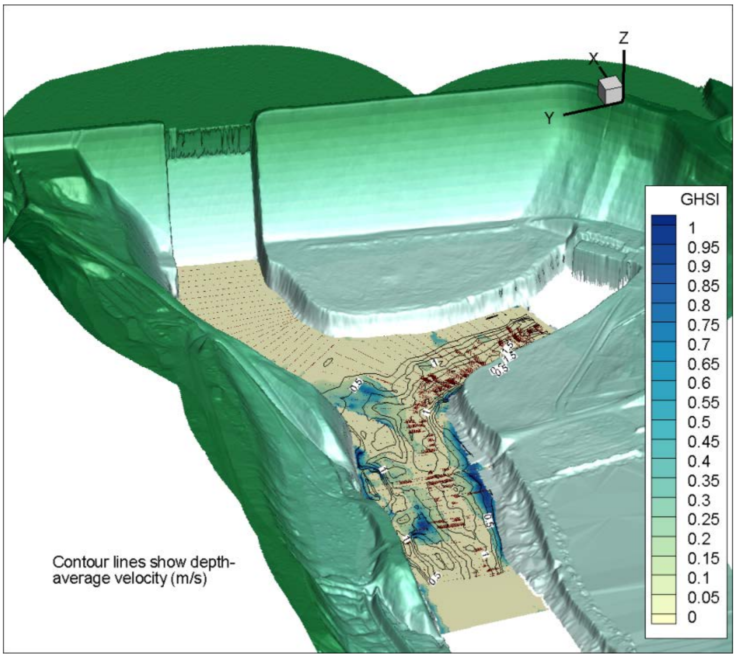

Figure 6--Generalized Habitat Suitability Index (GHSI) and depth-average water velocity.

4. SUMMARY

Advances in instruments for hydrometric measurement provide unprecedented opportunity to rapidly and economically gather large amounts of data describing hydraulic and other riverine-associated parameters for entire reaches of streams. Gathering such data, however, requires different measurement procedures that the transect-based measurements traditionally used in hydrometry. Furthermore, measurements of an entire reach result in very large data sets with measurements at non-uniform intervals. As a result, not only are different measurement procedures needed but also software to manage, analyze, and visualize the data. Recent advances in software for processing such data sets now allow unprecedented opportunity to comprehend the hydraulic behavior in rivers. Furthermore, the ability to compute other parameters based on the measured 3-D velocity fields, the bathymetry and depths, and other parameters such as sediment size provides opportunity to understand and visualize the spatial pattern of a variety of parameters, such as bed shear, location of incipient sediment motion, and habitat.

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