Project Title: Evaluating Water Quantity and Water Quality Issues in Illinois Streams using Large-Scale Particle Image Velocimetry (LSPIV)

Research Category: Hydrologic Processes

Key Words: stream gauging, river velocity measurements, mixing processes, particle image velocimetry, unmanned aircraft systems in hydrology

Principle Investigators:

Quinn W. Lewis (Ph.D student, student researcher),
Department of Geography and Geographic Information Science,
University of Illinois at Urbana-Champaign,
qlewis2@illinois.edu, (217) 333-1880

Dr. Bruce L. Rhoads (fluvial geomorphologist, student's advisor)
Professor, Department of Geography and Geographic Information Science,
University of Illinois at Urbana-Champaign,
brhoads@illinois.edu, (217) 333-1322

Dr. Frank L. Engel (applied fluvial geomorphologist)
Geographer, United States Geological Survey,
Illinois Water Science Center,
fengel@usgs.gov, (217) 328-9774

Congressional Districts: #13, #15

Critical State and Regional Water Problem Statement

Water quantity and quality are vital environmental and economic resources provided by rivers. Discharge, the product of flow area and the mean velocity of the flow, is the fundamental metric by which water quantity in streams and rivers is measured. Capabilities for measuring discharge have improved greatly with the development of hydroacoustic instruments (Yorke and Oberg, 2002), yet challenges remain, especially in the context of flows that are difficult to measure, such as floods (Le Coz *et al.*, 2010). Moreover, manual measurements of river discharge require a considerable investment in instrumentation and labor. The development of inexpensive methods to rapidly measure discharge under challenging conditions, such as flash floods, shallow flows on floodplains, and dangerous high-velocity flows, is needed to accurately characterize water quantity over the full spectrum of hydrological conditions.

Poor water quality is one of the most publicized problems in river systems worldwide. Poor water quality can create toxic conditions in reservoirs (Keefer *et al.*, 2010), lead to algal blooms and dead zones in lakes and rivers (David *et al.*, 2010), degrade ecosystems, and negatively impact local economies by limiting recreational opportunities in unsafe waters. A key aspect of measuring and monitoring water quality in river systems is to link the dispersal of contaminants to the hydrodynamic processes that enhance or inhibit mixing in these systems. In particular, assessing mixing processes in the context of unpredictable chemical spills and point-source pollution hotspots is often difficult to accomplish using conventional hydroacoustic instruments, which must be deployed rapidly, can interfere with assessment and containment efforts, and might be fouled or rendered inoperable by some types of spills (e.g. oil slicks). Moreover, dispersal and mixing processes are difficult to assess under extreme conditions, such as floods, or in complex flow environments, such as forested floodplains (Rutherford, 1994). Thus, a critical need exists for low-cost methods of rapidly assessing the mixing processes that control pollutant dispersal in rivers under extreme conditions or where flow patterns are complex.

One potential way to address these problems is with large-scale particle image velocimetry (LSPIV). This low-cost method tracks the movement of discrete “particles” on the water surface between subsequent images (e.g. still images or video frames) and derives surface velocity from the distance particles move per unit time between images. This method has been used previously as an inexpensive way to measure discharge (Muste *et al.*, 2008; Le Coz *et al.*, 2010; Dramais *et al.*, 2011; Patalano *et al.*, 2015), but rigorous evaluations of the accuracy and consistency of the method are lacking. LSPIV has recently been used to investigate surface flow structure and patterns of surface mixing (Lewis and Rhoads, *in press*), yet no detailed studies that link surface mixing to three-dimensional velocity and mixing within the water column have been completed. Although the potential of using LSPIV to measure discharge and mixing processes is evident, rigorous testing and continued refinement are required before the method can be adopted on a large scale by the scientific community.

Expected Results and Benefits Statement

The proposed research will result in two main outcomes: 1) an improved capability to determine discharge from LSPIV and an assessment of the advantages and limitations of LSPIV compared to hydroacoustic instruments, and 2) a better understanding of how complex surface flow structure is related to mixing processes which impact water quality at local and network scales. Results supporting the first outcome will include the development of protocols for measuring discharge with LSPIV, a detailed assessment of LSPIV discharge measurement error sources, strategies for minimizing measurement error, comparisons of discharge measurements from LSPIV to discharge measurements from hydroacoustic measurements at U.S. Geological Survey (USGS) stream gauge sites, and one of the first comprehensive tests evaluating the potential use of unmanned aircraft systems (UAS) to obtain rapid LSPIV discharge measurements (Detert and Weitbrecht, 2015). The second outcome will be completed by implementing LSPIV at a river confluence, where rapid flow mixing takes place. Mixing patterns and rates will be derived from measurements of two-dimensional surface velocities using LSPIV, three-dimensional velocities at cross sections using hydroacoustic instruments, and measurements of conservative flow properties (e.g. temperature, turbidity/suspended sediment concentration, and electrical conductance) both at the water surface and within the fluid volume.

The benefit of this proposed study is that it will provide the first detailed comparisons between LSPIV and hydroacoustic discharge measurements at multiple field sites under variable flow conditions using both UAS and rigid camera platforms. The study will also evaluate the capabilities of LSPIV to characterize flow structure and mixing and promote further innovative LSPIV use for studying water quality issues. These outcomes are important for future adoption and continued use of this promising method to provide new insights into water quantity and quality issues in Illinois and elsewhere. The results of this research will be disseminated through local and regional meetings at professional conferences and among interdisciplinary river scientists and practitioners within the USGS and the U of I. The USGS and U of I will host LSPIV workshops and demonstrations in the field. Finally, the results of the proposed research will be published in high-profile scientific journals.

Project Nature, Scope, and Objectives

The nature and scope of this project is *to foster collaboration between the USGS and the University of Illinois (U of I) by exploring the utility of state-of-the-art image-based measurement techniques to address problems related to water quantity and quality in Illinois*. The objective of the proposed research is to meet the critical needs for rapid, low-cost assessments of discharge and the processes controlling mixing in river systems by exploring the capabilities of LSPIV to produce accurate information on mean velocities and evolving patterns of instantaneous surface velocities in these systems. The proposed research involves a partnership between the USGS and U of I. Mr. Quinn Lewis, a third year PhD student in Geography and Geographical Information Science at the U of I, will lead the project. An international dimension will be included through collaboration with Dr. Carlos Marcelo Garcia and his PhD students at the Universidad National de Córdoba, who already are working with USGS personnel on the problem of LSPIV measurements in rivers. Dr. Garcia received his PhD from the University of Illinois and is interested in collaborating through sharing of data and methods. He also plans to visit the United States in the summer 2016 to collaborate on the project in person. This collaboration will help to expand the scope of the project to a wide range of river systems.

Methods, Procedures and Facilities

<u>Methods:</u> LSPIV can use seeded flows in which particles such as chipped wood, confetti, or biodegradable packing peanuts are spread on to the water surface, or it can use naturally occurring particles such as bubbles or leaves. Particle quality is perhaps the most important obstacle to successful LSPIV studies (Kim, 2006) because the highly optimized particles typically used in small laboratory flumes are often too expensive to seed the entire camera field of view (FOV) and may not be recoverable in the field (Tauro, 2015). However, previous LSPIV work in agriculture channels successfully used recycled landscape mulch (Lewis and Rhoads, *in press*). Continued work on the seeding issue by the PIs on this proposal shows that inexpensive, ecologically inert pine chips (commonly used for horse bedding) is an ideal seeding particle.

Small inexpensive action cameras are well-suited for LSPIV because they are mobile, waterproof, have high resolutions, and can be operated remotely. LSPIV requires a stable camera platform to prevent motion of the FOV that can introduce error into calculations of surface velocities. To evaluate the effects of camera instability on results a GoPro Hero4 action camera will be deployed both on rigid mounting systems (i.e. a bridge rail for discharge measurements and a mast or anchored to the channel banks for mixing studies at stream confluences) and on an UAS. For the UAS deployment ground control points (GCPs) will be surveyed and used to stabilize UAS imagery. Results from the rigid mount and UAS deployments will be compared to assess the precision of the two methods. LSPIV image processing will be accomplished with both free (Thielicke and Stamhuis, 2014) and commercial (Insight3D) software to evaluate the quality of results in relation to cost.

Discharge Measurements: LSPIV will be deployed at local USGS stream gauging sites (e.g. Sangamon River at Monticello, Sangamon River at Fisher, Copper Slough at Champaign) in conjunction with simultaneous hydroacoustic measurements of discharge at these sites. Both the U of I and USGS maintain an array of hydroacoustic instruments for deployment in shallow (<1 m) and deep (>1 m) flows (Oberg and Mueller, 2007; Boldt and Oberg, 2015). Seeding particles will be cast onto the surface of the flow on the upstream side of a bridge and imaged with a camera mounted on the downstream side of the bridge. In addition, a UAS will record video of the water surface and GCPs along the banks of the river just downstream of the bridge (Detert and Weitbrecht, 2015). LSPIV surface velocities will be converted to depth-averaged velocities based on a relation established between the LSPIV and hydroacoustic measurements (Creutin *et al.*, 2003; Costa *et al.*, 2006; Muste *et al.*, 2008; Tauro, 2015). Discharges (Q) will be computed as Q = WDV where V = mean velocity, W= flow width, and D = mean flow depth. Comparisons among discharge estimates obtained from rigid-mounted LSPIV, UAS LSPIV, and hydroacoustic instruments at study sites with well-developed rating curves and a long history of discharge measurements will provide the basis for achieving research outcome 1. Every effort will be made to obtain measurements for a variety of different flows, including flood events, to determine the reliability of the LSPIV method for estimating discharge over a range of hydrological conditions. Moreover, estimates of discharge will also be attempted at the sites using images of naturally occurring surface particles and debris to evaluate whether accurate estimates of discharge can be obtained without the need for artificial seeding of particles on the water surface.

Mixing Measurements:

The proposed study will achieve research outcome 2 by using LSPIV to measure surface velocity and assess surface flow structure at several local river confluences (Rhoads and Sukhodolov, 2001; Lewis and Rhoads, *in press*). LSPIV is ideally suited to help describe and quantify mixing patterns at confluences, where flows with different properties join one another. Surface velocity data will be supplemented with more detailed three-dimensional hydroacoustic velocity measurements along predetermined cross sections. Through ongoing research, the PIs have developed and refined methods for measuring mixing at confluences using based on measurements of temperature, conductivity, and turbidity at these locations. The change in these conservative flow properties within and downstream of the confluence will be used to determine mixing rates and patterns. This method of measuring mixing is often used (Biron *et al.*, 2004, Lewis and Rhoads, 2015) because an upstream, unmixed value can be determined by the ratio of values for the two incoming flows, therefore normalizing the mixing metric regardless of differences in each tributary. Overall, these data will be used to assess mixing patterns and rates under variable flow conditions and shed light on the relation between large scale flow structure, surface velocity, and three-dimensional mixing. Results will improve knowledge of water quality by leading to an improved understanding of the relation between the hydrodynamics of complex flows and mixing processes as well as the dynamics of mixing at confluences, locations within fluvial systems that play a critical role in mixing not only locally, but at the scale of river networks.

Student Training Statement

The proposed research will contribute to the training of an advanced Ph.D. student (Mr. Quinn Lewis), who will lead the project in coordination with supervision from a faculty member at the U of I (Dr. Bruce Rhoads) and a professional scientist (Dr. Frank Engel) at the USGS. The project will constitute a major component of Mr. Lewis' doctoral dissertation research. The project will also expose an advanced undergraduate, who will assist in the collection and analysis of field data, to the process of scientific research in the field of water resources.

References

Biron, P., A.S. Ramamurthy, and S. Han (2004), Three-dimensional numerical modeling of mixing at river confluences, Journal of Hydraulic Engineering, 130, 243-253.

Boldt, J. and K. Oberg (2015), Validation of streamflow measurements made with M9 and RiverRay acoustic doppler current profilers, Journal of Hydraulic Engineering, doi:10.1061/(ASCE)HY.1943-7900.0001087.

Costa, J.E., R.T. Cheng, F.P. Haeni, N. Melcher, K.R. Spicer, E. Hayes, W. Plant, K. Hayes, C. Teague, and D. Barrick (2006), Use of radars to monitor stream discharge by noncontact methods, Water Resources Research, 42.7, W07422, doi:10.1029/2005WR004430.

Creutin, J.D., M. Muste, A.A. Bradley, S.C. Kim, A. Kruger (2003), River gauging using PIV techniques: a proof of concept experiment on the Iowa River, Journal of Hydrology, 277.3-4, 182-194, doi: 10.1016/S0022-1694(03)00081-7.

David, M.A., L.E. Drinkwater, and G.F. McIsaac (2010), Sources of nitrate yield in the Mississippi River Basin, Journal of Environmental Quality, 39.5, 1657-1667.

Detert, M. and V. Weitbrecht (2015), A low-cost airborne velocimetry system: proof of concept, Journal of Hydraulic Research, doi:10.1080/00221686.2015.1054322.

Dramais, G., J. Le Coz, B. Camenen, and A. Hauet (2011), Advantages of a mobile LSPIV method for measuring flood discharges and improving stage-discharge curves, Journal of Hydro-Environment Research, 5, 301-312. doi:10.1016/j.jher.2010.12.005.

Keefer, L., E. Bauer, and M. Markus (2010) Hydrologic and nutrient monitoring of the Lake Decatur watershed: Final report 1993-2008. Contract Report 2010-07. Prepared for the City of Decatur, Illinois State Water Survey, University of Illinois, Champaign, IL.

Kim, Y. (2006), Uncertainty Analysis for Non-Intrusive Measurement of River Discharge Using Image Velocimetry, Department of Civil and Environmental Engineering, University of Iowa, Iowa City, IA, USA.

Le Coz, J., A. Hauet, G. Pierrefeu, G. Dramais, and B. Camenen (2010), Performance of image-based velocimetry (LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers, Journal of Hydrology, 394.1-2, 42–52. doi:10.1016/j.jhydrol.2010.05.049.

Lewis Q.W. and B. L. Rhoads (2015), Spatial and temporal patterns of thermal mixing at a small stream confluence, Hydrological Processes, 29.20, 4442-4456, doi: 10.1002/hyp.10496.

Lewis, Q.W. and B.L. Rhoads (*in press*), Resolving two-dimensional flow structure in rivers using large-scale particle image velocimetry: an example from a stream confluence, Water Resources Research, doi: 10.1002/2015WR017783.

Muste, M., I. Fujita, and A. Hauet (2008), Large-scale particle image velocimetry for measurements in riverine environments, Water Resources Research, 44, W00D19, doi:10.1029/2008WR006950.

Oberg, K. and D. S. Mueller (2007), Validation of streamflow measurements made with acoustic Doppler current profilers. Journal of Hydraulic Engineering, 133.12, 1421-1432, doi: 10.1061/(ASCE)0733-9429(2007)133:12(1421).

Patalano, A., C. M. García, W. Brevis, T. Bleninger, N. Guillen, L. Moreno, and A. Rodriguez (2015), Recent advances in Eulerian and Lagrangian large-scale particle image velocimetry, E-proceedings of the 36th IAHR World Congress, 28 Jun – 3 July, The Hague, Netherlands.

Rhoads, B.L., and A.N. Sukhodolov (2001), Field investigation of three-dimensional flow structure at stream confluences: 1, Thermal mixing and time-averaged velocities, Water Resources Research, 37.9, 2393-2410, doi: 10.1029/2001WR000316.

Rutherford, J.C. (1994), River Mixing, J. Wiley & Sons, New York.

Tauro, F. (2015), Particle tracer and image analysis for surface flow observations, Wiley Interdisciplinary Reviews: Water, doi:10.1002/wat2.1116.

Thielicke, W., and E.J. Stamhuis (2014), PIVlab – Towards user-friendly, affordable and accurate digital particle image velocimetry in MATLAB, Journal of Open Research Software, 2. doi:10.5334/jors.bl.

Yorke, T. and K. Oberg (2002), Measuring river velocity and discharge with acoustic Doppler profilers, Flow Measurement and Instrumentation, 13.5, 191-195, doi: 10.1016/S0955-5986(02)00051-1.