DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Measurement and Mapping of Riverine Environments by Optical Remote Sensing DURIP: Remote Sensing and *In Situ* Instrumentation for Research on the Optical Characteristics, Morphology, and Dynamics of Riverine Environments

Carl J. Legleiter
Department of Geography
University of Wyoming
1000 E. University Ave.
Laramie, WY 82071
phone: (307) 766-2706 fax: (307) 766-3294 email: Carl.Legleiter@uwyo.edu

Award Numbers: N00014-10-1-0873, N00014-12-1-0737
http://www.fluvialremotesensing.org

LONG-TERM GOALS

The overarching objective of this investigation is to develop an advanced, operational capacity for characterizing river systems via remote sensing. We are particularly interested in methods for obtaining continuous, high resolution measurements of channel morphology and hydraulics from optical image data. The ability to efficiently and non-invasively map river corridors would afford significant advantages to both defense and research communities and could foster insight regarding fluvial processes. This project seeks to realize this potential by pursuing the following overall goals:

1. Improve our understanding of radiative transfer processes governing the interaction of electromagnetic energy with the atmosphere, air-water interface, water column, and substrate, and the measurement of this energy by a remote detector. Because these processes both enable and limit retrieval of river information from remotely sensed data, this effort could lead to novel techniques for measuring depth, velocity, bottom type, and water optical properties.
2. Systematically evaluate the ability of various remote sensing instruments to map a broad range of riverine environments. This assessment will help to define the extent to which different types of sensors deployed above a diverse range of channels can provide the accuracy, precision, and dynamic range necessary for specific kinds of applications.
3. Develop efficient procedures for extracting river information from remotely sensed data. Establishing integrated workflows for processing and analyzing such data will allow various forms of remote sensing to become viable, operational tools for quantitatively mapping rivers.

OBJECTIVES

Motivated by these research needs, we identified three principal objectives, each with a corresponding set of specific aims, that provide the organizing framework for our investigation:

1. Evaluate the potential of various sensing technologies for remote mapping of rivers by performing field-based, empirical testing of sensor/algorithm performance in a range of sites.

2. Develop improved methods for characterizing riverine environments via remote sensing, with an emphasis on inferring depth, velocity, and bottom type from passive optical image data.
3. Facilitate efficient extraction of river information from remotely sensed data by developing algorithms for identifying channels and producing continuous maps of various river attributes.

APPROACH

Our objective to measure, map, and better understand river systems via optical remote sensing motivates a number of different research activities: intensive field campaigns and image acquisition from a range of fluvial systems, data analysis, and algorithm development. This report discusses five **Specific Aims** upon which we have focused since our last annual report: **1) sensor comparison; 2) retrieving depth information without using field measurements for calibration; 3) mapping streambed composition; 4) assessing the impact of turbidity on depth retrieval;** and **5) isolating reflectance from the water surface and linking this component of the total at-sensor signal to the flow hydraulics**. In general, our approach involves collecting field observations of fundamental river charateristics, such as depth, velocity, substrate composition, and bed topography, as well as optical properties. These data are used to parameterize theoretical models of sensor performance and to calibrate image-derived estimates of key channel attributes, primarily depth. In addition, these dense, spatially distributed field data enable rigorous testing of algorithm performance. Moreover, acquiring various types of remotely sensed data from several distinct field sites allows us to examine the capabilities and limitations of different kinds of sensors in diverse riverine environments. Similarly, our efforts to process, analyze, and interpret these images will lead to more general, integrated workflows for efficiently extracting river information from remotely sensed data.

Key personnel involved in this study include the Principal Investigator, an Associate Professor at the University of Wyoming (UW), and Ph.D. student Brandon Overstreet. UW graduate students Chip Rawlins, Toby Stegman, Devin Lea, and Ryan Richardson also contributed to our work on the Snake River. In addition, we continue to work closely with colleagues from the National Center for Airborne Laser Mapping (NCALM), primraily Craig Glennie and Ph.D. student Zhigang Pan.

WORK COMPLETED

Since our last annual report, we have conducted a number of different studies but focus herein on the five specific aims identified above. The first of these aims, sensor comparison, already has progressed to publication, with one lead-authored, peer-reviewed paper and three co-authorships with colleagues from NCALM. Similarly, for Aim #2 (depth retrieval without field measurements for calibration), our FREEBIRD algorithm appeared in a recent issue of *Water Resources Research*. We have collected field measurements and image data to support Specific Aims 3-5 and currently are performing analysis and developing related computational tools. For the purposes of this report, we highlight key findings related to Aims 1 and 2 in the Results section. Here, we describe progress to date for the latter three aims, emphasizing field work along the Snake River. Figures appear at the end of the report.

We selected the Snake River as our primary field site for several reasons: 1) working within Grand Teton National Park guaranteed continuous access to long river segments; 2) a time series of remotely sensed data is available, with annual coverage from 2009-2015; 3) the river is clear-flowing in late summer, which is conducive to depth retrieval and substrate mapping, but more turbid during spring runoff due to tributary inputs, which allows us to assess the effects of redued water clarity; 4) the

system is highly dynamic, with significant changes occurring each year, and thus an appropriate venue for examining the form and behaviour of gravel-bed rivers; and 5) because the Snake is a valuable recreational resource, our studies will inform Park service river management strategies. The primary objectives of field campaigns conducted each year since 2010 were to: 1) collect an extensive, high resolution, long term data set on the morphologic, hydraulic, and optical characteristics of a dynamic gravel-bed river; 2) obtain *in situ* measurements for calibrating and validating image-derived estimates of various river attributes; and 3) support our general research interest in river channel change. The following sub-sections describe data collection and analyses associated with Aims 3 – 5.

- **3) Mapping streambed composition.** Each year since 2012 we have collected field data from a specially-designed research cataraft used to deploy various measurement devices. For example, in pursuit of this aim we have recorded: 1) depth with an echo sounder coupled to an RTK GPS; 2) spectral reflectance with an Analytical Spectral Devices (ASD) FieldSpec3 spectroradiometer; 3) water column optical properties with a number of instruments described below in the context of Specific Aim 4; and 4) streambed composition with a waterproof GoPro camera looking downward from beneath the cataraft. Data from these sensors were linked using GPS time stamps and provide spatially distributed information on depth, reflectance, water column attenuation, and bottom type. To facilitate analysis of these data, we developed a MATLAB-based interface (Figure 1) for mapping depth measurements onto a remotely sensed background image, examining substrate photos, plotting the corresponding field spectra, and assigning each sample to a substrate category (sand, gravel, cobble, or boulder) and an ordinal ranking (1 – 5) of the density of algae on the streambed. We are using these field data to assess the feasibility of inferring bottom reflectance and hence streambed type from hyperspectral image data. Building upon the work of Dierssen et al. (2003) for mapping seagrass in shallow marine settings, we parameterized the Hydrolight radiative transfer model using field observations of the inherent optical properties of the water column and performed a series of simulations to summarize the attenuation of bottom-reflected light. This modeling exercise provided the information needed to account for the influence of the water column and thus calculate bottom reflectance from spectra recorded above the water surface. At this point, our inspection of these data through the interface depicted in Figure 1 qualitatively indicates that different substrate types, most notably portions of the streambed with dense filamentous algae, can be identified from field spectra. The final stages of this analysis are underway and we expect to submit a manuscript in the near future.

  As an example of how this approach might be applied, we are exploring the potential to map salmon spawning locations, called redds, from hyperspectral image data, a possibility suggested by our previous research at the Outdoor Stream Lab (Legleiter and Overstreet, 2014). As an initial test, we constructed a series of artificial redds along the Snake River prior to the acquiring hyperspectral images with our CASI-1500 sensor in 2013 and 2014. A related project on the Merced River in California in November 2014 involved mapping real salmon redds in the field during the fall Chinook run and assessing whether spawning locations could be detected in hyperspectral images acquired at the same time. Initial results from both of these studies suggest that artificial and natural redds of various ages (0 – 9 days) can be mapped from image data.

- **4) Assessing the impact of turbidity on depth retrieval.** In previous years, our field data collection occurred in August or September, after snowmelt had receded and the Snake River was flowing low and clear. In 2014 and 2015, however, we conducted a second field campaign earlier in the season, during the height of spring runoff, to exploit a unique opportunity to assess the

impacts of turbidity on remote sensing of river morphology. Our study area begins at Jackson Lake Dam, which releases clear, essentially sediment-free water into the Snake River. A short disance downstream, however, two significant tributaries, Pacific Creek and the Buffalo Fork, introduce large amounts of suspended sediment that increase the turbidity of the main stem, first along the left bank from which these streams enter the Snake and then gradually mixing across the channel before beginning to clear again further downstream. This configuration allowed us to collect data spanning a range of water clarity and we obtained *in situ* observations of: 1) depth with an echo sounder and RTK GPS; 2) spectral reflectance with the ASD spectroradometer; 3) inherent optical properties of the water column (beam absorption and attenuation coefficients) with a WetLabs ac-s; 3) diffuse attenuation coefficients, an important apparent optical property, by deploying the ASD with an upward-facing cosine receptor positioned at various depths within the water column, following the approach of Mishra et al. (2005); 4) turbidity, scattering, and concentrations of chlorophyll and colored dissolved organic matter with a WetLabs EcoTriplet; and 5) suspended sediment concentration and particle size distribution with a Sequoia LISST-100X. Except for the diffuse attenuation coefficient, all of these data were collected from the moving cataraft, with a "zig-zag" sampling strategy intended to capture the pronounced variations in water clarity from left to right across the channel in the Pacific and Buffalo confluence zones (Figure 2). This component of our investigation remains in a preliminary stage due to instrument failures and problems in synchronzing data from the various sensors, which is critical for establishing the position of each measurement. We have made some progress on the time sync issue and now are working to: 1) assess the feasibility of inferring water depth under varying levels of turbidity; 2) identify wavelengths that are relatively robust to turbid conditions; and 3) develop techniques for estimating suspended sediment concentration from reflectance data.

- **5) Isolating reflectance from the water surface and linking this component of the total at-sensor signal to the flow hydraulics.** In our experience working with a large number of remotely sensed data sets from a range of river environments, we have learned that sun glint (strong, specular reflections from the water surface) can render unusable images acquired for certain combinations of illumination and viewing geometry (Figure 3). To mitigate this problem, we have developed a specialized algorithm for identifying and removing sun glint based on anomalously high radiance in the near-infrared (NIR) for deep water pixels. Because surface reflectance is spectrally uniform (Legleiter et al., 2009), this contribution to the total, at-sensor radiance can be subtracted from all wavelengths. Our new Depth-Assisted Glint Removal (DAGR) technique performs this correction while accounting for non-negligible amounts of bottom-reflected, water-leaving NIR radiance in very shallow water along the channel margins. Initial results based on 2014 CASI data from the Snake River indicate that this approach to identifying and removing sun glint could be highly effective and that glint-corrected images enable more accurate depth retrieval.

  In addition to removing sun glint from images, a related goal is to explore relationships among reflectance from the water surface, the texture or roughness of that surface, and the hydraulics of the underlying flow field. Data collected to support this inquiry include field measurements of flow depth and velocity profile with a Sontek S5 acoustic Doppler current profiler (ADCP) and water surface roughness (WSR) with an ultrasonic distance meter. Both instruments were deployed from an inflatable kayak for a series of streamwise profiles along the Snake River. The example in Figure 4 illstrates a reach with strong contrasts in WSR, quantified as the standard deviation of water surface elevation time series, between a deep, slow-flowing pool at the start of the profile and a shallower, faster riffle beginning ~150 m downstream (Figure 4c). These

hydraulic variations are spatially correlated with an index of surface reflectance (Figure 4a) and WSR (Figure 4b): minimal glint and a smooth water surface in the upstream pool and more pronounced glint and a rougher surface texture through the riffle. These observations imply a connection among surface reflectnce, WSR, and flow hydraulics that could be exploited to infer velocity from optical image data. Establishing this relationship is a priority for our ongoing work.

RESULTS

This section summarizes published results related to Aims 1 and 2. Also note that we have established a website for disseminating the latest results from our group: www.fluvialremotesensing.org.

- **1) Sensor comparison.** Although the Optimal Band Ratio Analysis (OBRA) method highlighted in our previous reports has been applied successfully to data sets ranging from publicly available air photos (Legleiter, 2013) to satellite images (Legleiter and Overstreet, 2012) and in a diversity of river environments including supraglacial streams on the Greenland ice sheet (Legleiter et al., 2014), we recognize that other forms of remote sensing also have much to offer. For example, we evaluated the capabilities of the CASI-1500 hyperspectral imaging system and Aquarius bathymetric LiDAR for measuring riverbed topography (Legleiter et al., in press). In addition to the Snake River, we also collected field and image data from the confluence of the Blue and Colorado Rivers, a much more complex optical environment due to the mixing of not only these two rivers but also the aptly named Muddy Creek. This site thus enabled us to systematically evaluate the performance of each type of sensor across a range of water clarity. We linked field measurements of optical properties to radiative transfer theory to characterize depth retrieval precision and dynamic range for both the optical and LiDAR systems. Detailed field surveys of bed elevation enabled rigorous accuracy assessment and we found that although both systems provided reliable bathymetric information in the clear-flowing Snake River, accuracies were reduced in the more complex confluence setting. More specifically, CASI-derived depths were biased shallow due to turbid conditions whereas the Aquarius elevations plotted below our field data (Figure 5).

- **2) Retrieving depth information without using field measurements for calibration.** Although OBRA has proven effective, empririical methods of this kind suffer from a fundamental limitation that undermines the potential utility of remote sensing: field measurements are needed to calibrate image-derived depth estimates. To circumvent this issue, we introduced an alternative strategy that links image data to channel hydraulics by incorporating principles of open-channel flow (Legleiter, 2015). This Flow REsistance Equation-Based Imaging of River Depths (FREEBIRD) approach enables depth retrieval in the common situation where field data are not available for calibration. One FREEBIRD algorithm requires as input only channel slope, an estimate of the channel aspect (width/depth) ratio, and cross-sections extracted from an image with pixel values linearly related to depth. A second technique applicable to gaged rivers employs numerical optimization to match a known discharge. We applied these two methods to a public domain multispectral image and a panchromatic satellite image of the Snake River and obtained bathymetric maps that were just as accurate as those produced when field measurements were used to calibrate image-derived depth estimates (Figure 6). This novel approach still requires a strong, linear relation between an image-derived quantity X and flow depth but could facilitate river research and management by enabling regular, remote sensing-based monitoring as well as retrospective analyses of image archives.

IMPACT/APPLICATIONS

The results of this investigation will substantially improve our capacity to measure riverine environments via remote sensing. Because rivers are important elements of the landscape, both strategically and scientifically, an efficient means of characterizing river form and behavior could not only facilitate various defense missions but also advance scientific understanding of fluvial systems.

TRANSITIONS

I will be leaving the Unviersity of Wyoming at the end of the fall semester to begin a new position with the United States Geological Survey's National Research Program, based at the Geomorphology and Sediment Transport Laboratory in Golden, CO. This transition will allow me to devote more time and energy toward research on remote sensing of rivers, without the teaching and other responsibilites associated with my current academic role. In addition, I believe joining the Survey will facilitate broader dissemination and implementation of the techniques we have developed and should enable me to begin translating these tools from research into application. I also intend to develop training materials for delivery in workshop, short course, or online formats, witht the goal of educating a larger workforce skilled in remote sensing of rivers. Although I am still negotiating with the University regarding the fate of my research equipment, I am optimistic that the instrumentation I obtained through our ONR Defense University Research Instrumentation Program (DURIP) award "Remote sensing and *in situ* instrumentation for reserach on the optical characteristics, morphology, and dynamics of riverine environments" will accompany me to the USGS and thus continue to be put to beneficial use. The most noteworthy item is the CASI-1500 hyperspectral imaging system, which I hope to be able to deploy more frequently from USGS aircraft. Overall, moving to the USGS will enable me to advance remote sensing of rivers more efficiently, more directly, and with greater impact.

RELATED PROJECTS

In addition to the research highlighted in this report, I am actively engaged in a number of related projects led by the graduate students I advise at the University of Wyoming. For example, one student built upon our work on the Snake River by examining an intensively managed reach just downstream from Grand Teton National Park to assess the impacts of levees on braided river dynamics. Another student demonstrated the utility of Structure-from-Motion (SFM) photogrammetry for measuring topgraphy and sediment grain size to support river restoration project monitoring. A third student is using hyperspectral image data to map spawning gravels and quantify potential salmon habitat on the Merced and Tuolumne Rivers in California. These projects illustate the breadth of applied studies in which remote sensing of river can play a prominent role.

An ongoing collaboration with UW Geology colleagues Brandon McElroy and Jason Alexander focuses on the sand-bed Niobrara River in Nebraska. We have obtained CASI-1500 hyperspectral image data and Aquarius bathymetric LiDAR, as well as detailed field surveys, from this braided channel and now intend to perform a sensor comparison similar to that we conducted for the Snake and Blue/Colorado Rivers. An additional research objective at this site is to use repeat hyperspectral imaging to track the movement of bedforms and hence infer sediment transport rates. Another collaboration with Lee Harrison of the National Oceanographic and Atmospheric Administration will involve acquiring hyperspectral image data and a new form of multi-wavelength LiDAR to map salmon spawning habitat on the upper Sacramento River in California. We also enjoy a productive working relationship with ITRES, the Canadian manufacturer of the CASI-1500, and are currently

exploring the utility of thermal image data for mapping river systems. Moreover, I am confident that my transition to the USGS will open up a number of exciting collaborative research opportunities to further advance remote sensing of rivers and put these techniques into practice.

REFERENCES

Dierssen, H.M., Zimmerman, R.C., Leathers, R.A., Downes, T.V. and Davis, C.O., 2003. Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high-resolution airborne imagery. *Limnology and Oceanography*, 48(1): 444-455.

Legleiter, C.J., 2013. Mapping river depth from publicly available aerial images. *River Research and Applications*, 29(6): 760-780.

Legleiter, C.J., 2015. Calibrating remotely sensed river bathymetry in the absence of field measurements: Flow REsistance Equation-Based Imaging of River Depths (FREEBIRD). *Water Resources Research*, 51(4): 2865-2884.

Legleiter, C.J. and Overstreet, B.T., 2012. Mapping gravel bed river bathymetry from space. *Journal of Geophysical Research - Earth Surface*, 117(F04024): doi: 10.1029/2012jf002539.

Legleiter, C.J. and Overstreet, B.T., 2014. Retrieving river attributes from remotely sensed data: An experimental evaluation based on field spectroscopy at the Outdoor Stream Lab. *River Research and Applications*, 30(6): 671-684.

Legleiter, C.J., Roberts, D.A., and Lawrence, R.L. 2009. Spectrally based remote sensing of river bathymetry. *Earth Surface Processes and Landforms*, 34(8): 1039-1059.

Legleiter, C.J., Tedesco, M., Smith, L.C., Behar, A.E. and Overstreet, B.T., 2014. Mapping the bathymetry of supraglacial lakes and streams on the Greenland ice sheet using field measurements and high-resolution satellite images. *The Cryosphere*, 8(1): 215-228.

Legleiter, C.J., Overstreet, B.T., Glennie, C.L., Pan, Z., Fernandez-Diaz, J.C., and Singhania, A., In press. Evaluating the capabilities of the CASI hyperspectral imaging system and Aquarius bathymetric LiDAR for measuring channel morphology in two distinct river environments. *Earth Surface Processes and Landforms*: doi: 10.1002/esp.3794.

Mishra, D.R., Narumalani, S., Rundquist, D. and Lawson, M., 2005. Characterizing the vertical diffuse attenuation coefficient for downwelling irradiance in coastal waters: Implications for water penetration by high resolution satellite data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 60(1): 48-64.

PUBLICATIONS

NOTE: This list includes relevant publications published since our previous annual report. All publications listed as submitted in the earlier report now have been published as well.

Legleiter, C.J., Overstreet, B.T., Glennie, C., Zhigang, P., Fernandez-Diaz, J., Singhania, A. In press. Evaluating the capabilities of the CASI hyperspectral imaging system and Aquarius bathymetric LiDAR for measuring channel morphology in two distinct river environments. *Earth Surface Processes and Landforms*, doi: 10.1002/esp.3794. [In press, refereed]

Pan, Z., Glennie, C. L., Legleiter, C. J., and Overstreet, B. T. In press. Estimation of water depths and turbidity from hyperspectral imagery using support vector regression. *IEEE Geoscience and Remote Sensing Letters*, doi: 10.1109/LGRS.2015.2453636. [In press, refereed]

Lea, D.M., and Legleiter, C.J. In press. Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone. Geomorphology, doi: 10.1016/j.geomorph.2015.05.033. [In press, refereed]

Legleiter, C.J. In press. Downstream effects of recent reservoir development on the morphodynamics of a meandering channel: Savery Creek, Wyoming, USA. *River Research and Applications*, doi: 10.1002/rra.2824. [In press, refereed]

Legleiter, C.J. 2015. Calibrating remotely sensed river bathymetry in the absence of field measurements: Flow Resistance Equation-Based Imaging of River Depths (FREEBIRD). *Water Resources Research*, 51(4): 2865-2884, doi: 10.1002/2014WR016624. [Published, refereed]

Pan, Z., Glennie, C. L., Hartzell, P. J., Fernandez-Diaz, J. C., Legleiter, C. J., and Overstreet, B. T. 2015. Performance Assessment of High Resolution Airborne Full Waveform LiDAR for Shallow River Bathymetry. *Remote Sensing*, 7(5): 5133-5159. [Published, refereed]

Smith, L.C., Chu, V.W., Yang, K., Gleason, C.J., Pitcher, L.H., Rennermalm, A.K., Legleiter, C.J., Behar, A.E., Overstreet, B.T., Moustafa, S.E., Tedesco, M., Forster, R.R., LeWinter, A.L., Finnegan, D.C., Sheng, W., and Balog, J. 2015. Efficient meltwater drainage through supraglacial streams and rivers on the southwest Greenland Ice Sheet. *Proceedings of the National Academy of Sciences*, 112(4): 1001-1006. [Published, refereed]

Constantine, J.A., Dunne, T., Ahmed, J., Legleiter, C.J., and Lazarus, E.D. 2014. Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin. *Nature Geoscience*, 7(12): 899-903. [Published, refereed]

Legleiter, C.J., and Overstreet, B.T. 2014. Retrieving river attributes from remotely sensed data: An experimental evaluation based on field spectroscopy at the Outdoor Stream Lab. *River Research and Applications*, 30(6): 671-684. [Published, refereed]

Legleiter, C.J., Tedesco, M., Smith, L.C., Behar, A., and Overstreet, B.T. 2014. Mapping the bathymetry of supraglacial lakes and streams on the Greenland Ice Sheet using field measurements and high resolution satellite images. *The Cryoshpere*, 8: 215-228. [Published, refereed]

Fernandez-Diaz, J.C., Glennie, C.L., Carter, W.E., Shrestha, R.L, Sartori, M.P., Singhania, A., Legleiter, C.J., and Overstreet, B.T. 2014. Early Results from a Simultaneous Airborne Terrain and Shallow Water Bathymetry Mapping LiDAR Sensor. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS)*, 7(2): 623-635. [Published, refereed]

Legleiter, C.J., and Overstreet, B.T. 2012. Mapping gravel-bed river bathymetry from space. Journal of Geophysical Research - Earth Surface, 117(F04024): doi: 10.1029/2012jf002539. [Published, refereed]

HONORS/AWARDS/PRIZES

Brandon Overstreet, Ph.D. Student, Unversity of Wyoming, Wyoming NASA Space Grant 2015-2016 Graduate Research Fellowship, Wyoming NASA Space Grant Consortium.

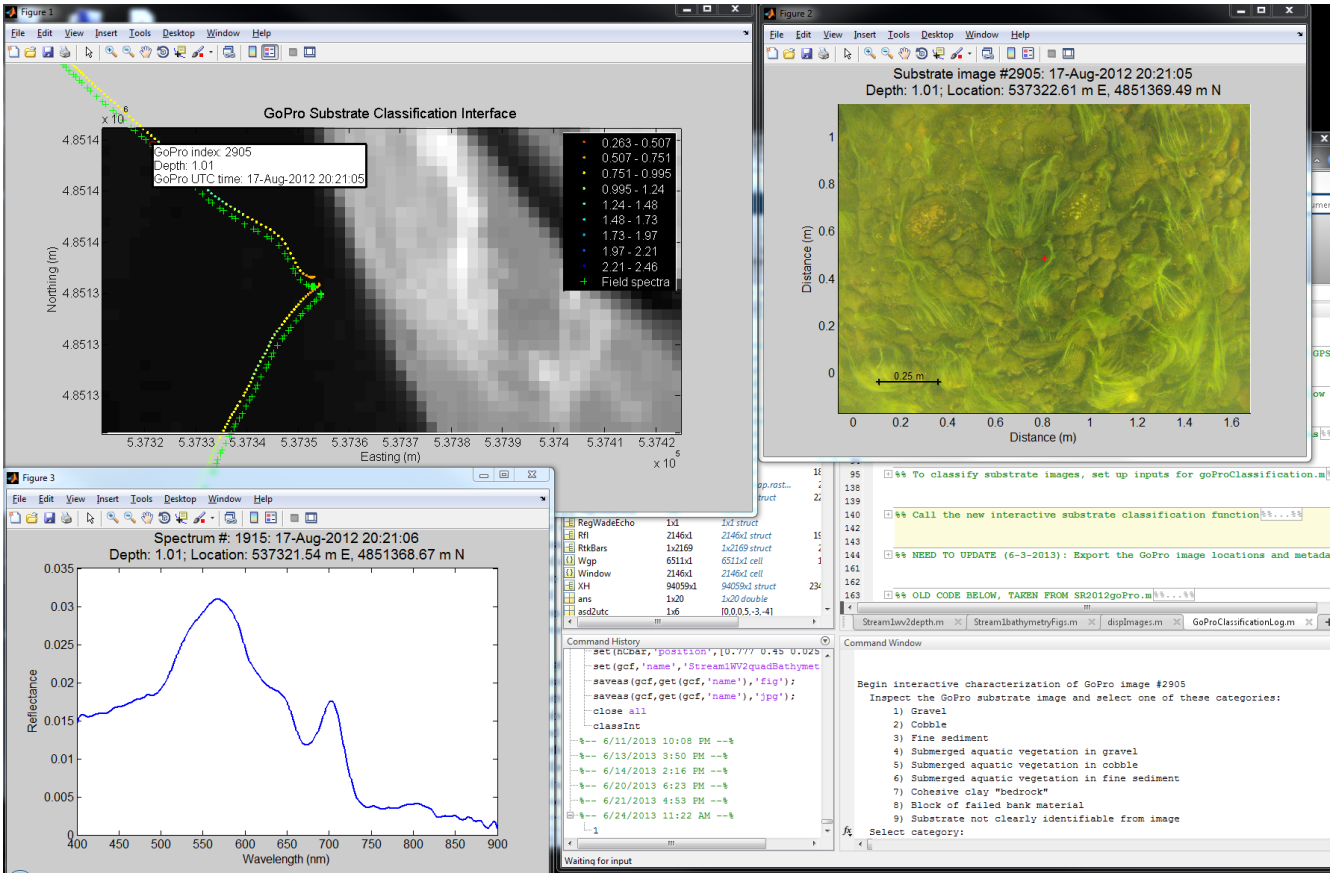

Figure 1. MATLAB interface for examining: 1) field measurements of depth in the context of a background remotely sensed image (upper left); 2) reflectance spectra recorded above the water surface (lower left); and 3) substrate photographs (upper right). This tool facilitated assigning each sample to a substrate category and a ranking of algae density. Data compiled in this manner now is being used to develop algorithms for inferring bottom reflectance and substrate composition.

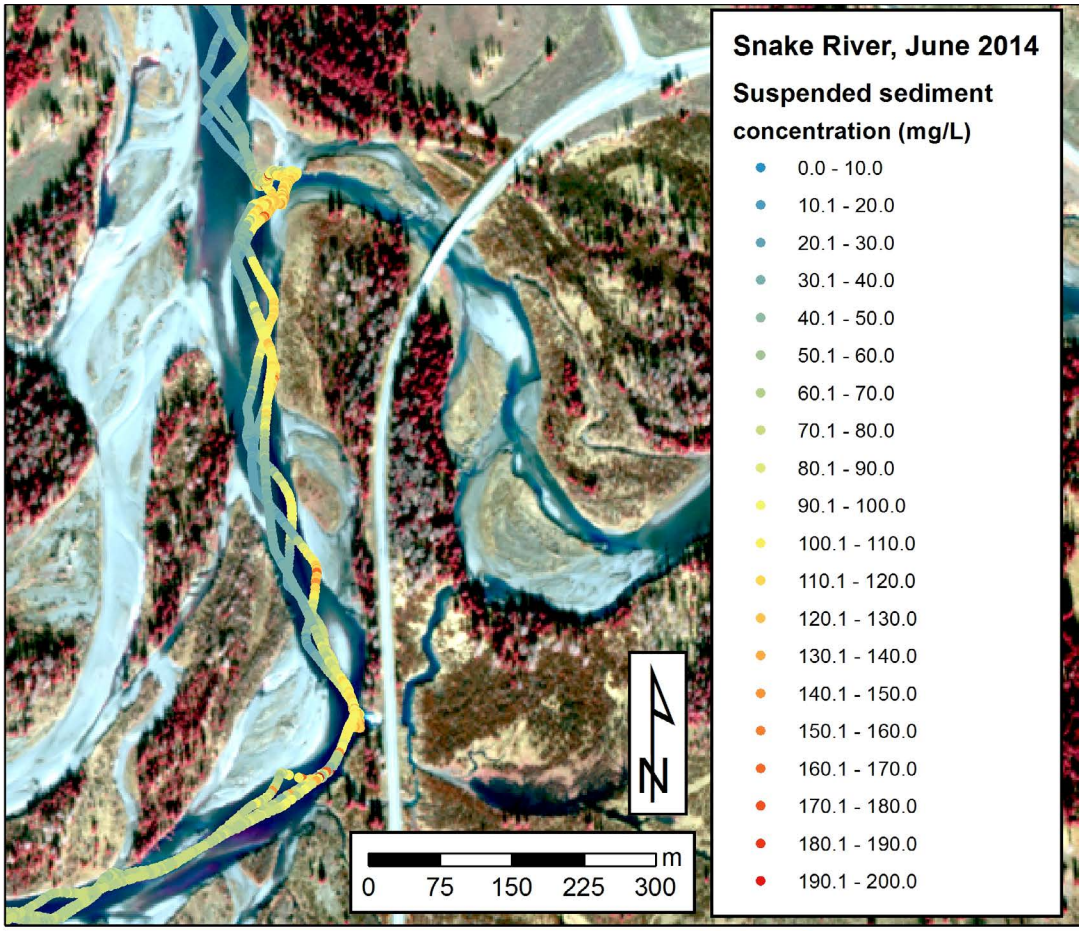

Figure 2. Spatial patterns of suspended sediment concentration recorded with a LISST 100-X in June 2014 where the clear waters of the Snake River (flowing from north to south) mix with far more turbid water from the Buffalo Fork tributary entering from the east. The photograph below is directed upstream and shows a distinct line between the clear Snake River water on the left and the sediment-laden water from the Buffalo Fork on the right.

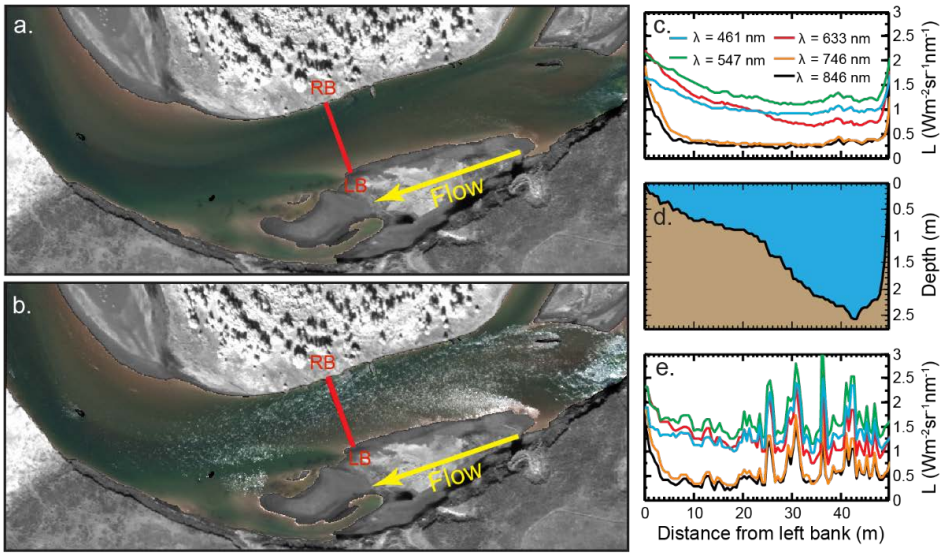

Figure 3. Overlapping region of two flight strips of CASI-1500 hyperspectral image data from the Snake River, acquired along (a) south → north and (b) north → south trajectories; the latter image is noticeably more affected by sun glint from the water surface. The panels on the right side of the figure feature spectral cross-sections from (c) the image with minimal glint and (e) the image with pronounced glint, as well as (d) field measurements of depth along the red line in both images.

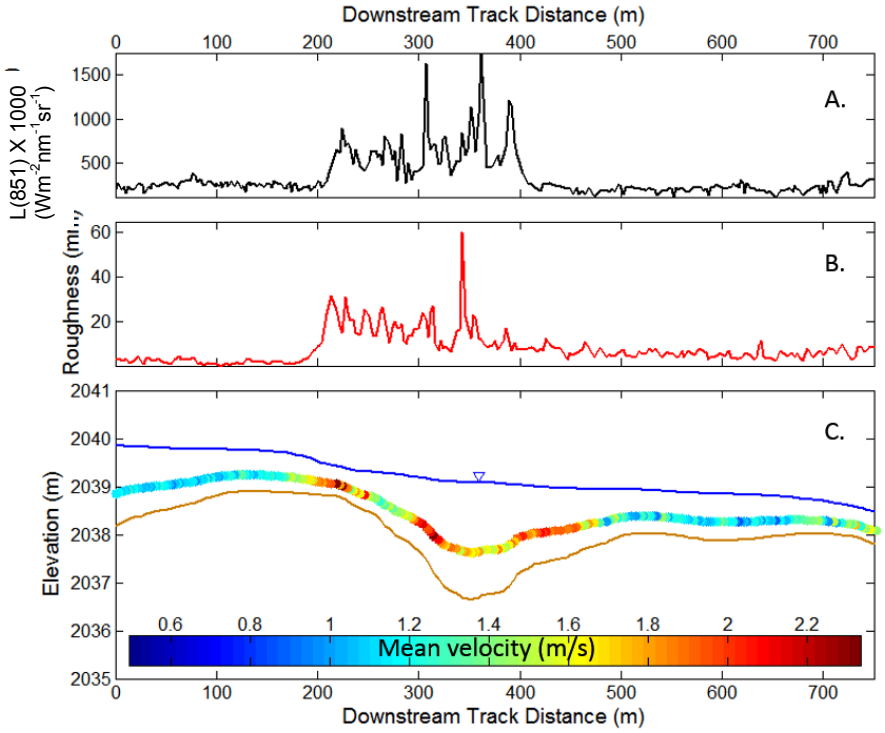

Figure 4. Downstream profiles from a pool-riffle sequence on the Snake River. (a) Near-infrared radiance, a metric of sun glint intensity. (b) Field measurements of water surface roughness. (c) Water surface elevation (blue line), bed elevation (brown line), and depth-averaged velocity.

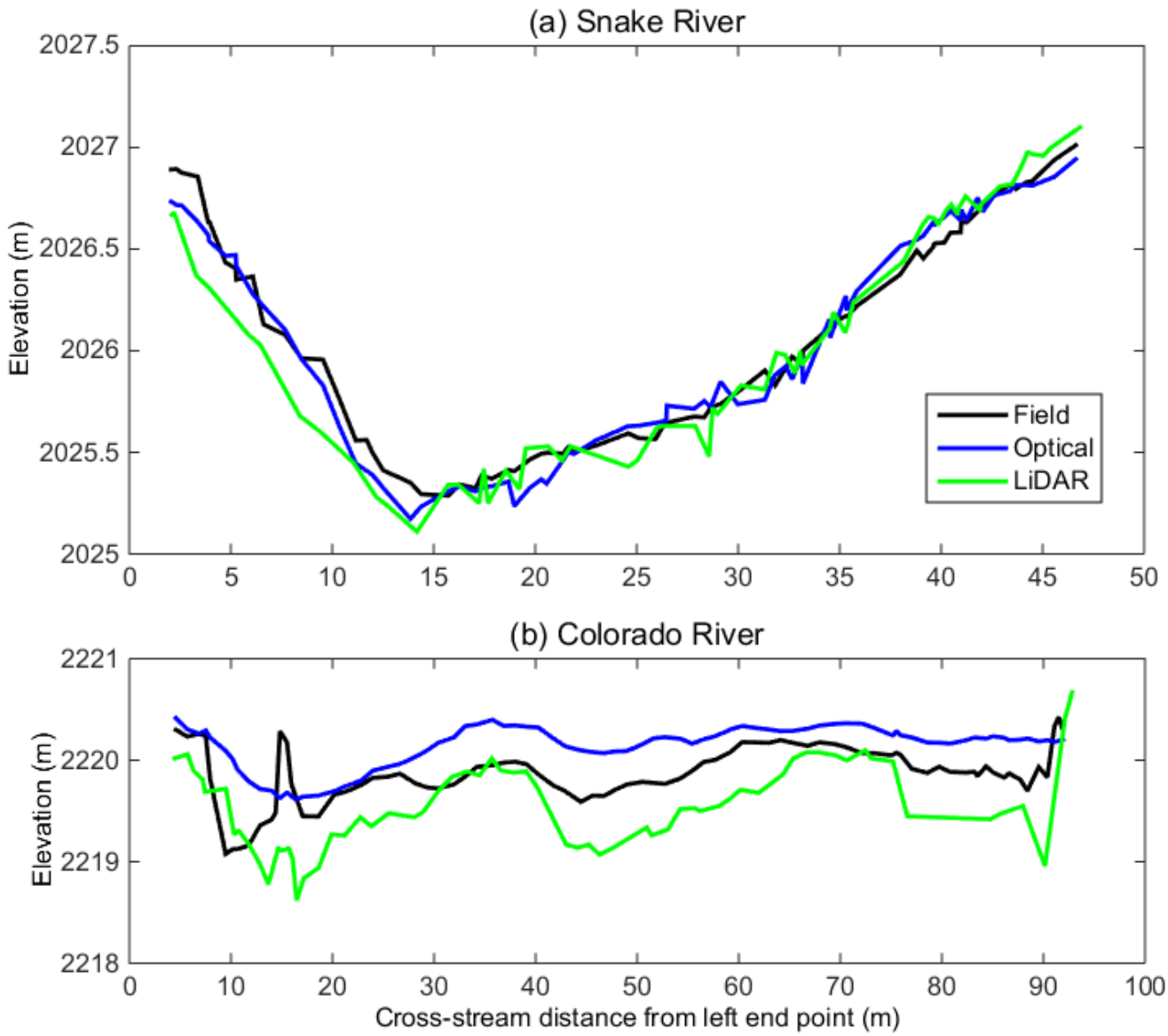

Figure 5. Comparison of remotely sensed bed elevations from the CASI-1500 hyperspectral imaging system (optical) and Aquarius bathymetric LiDAR and direct field surveys for cross-sections extracted from (a) the clear-flowing Snake River and (b) the more optically complex Colorado River, joined from the right by Muddy Creek just upstream of this transect (Legleiter et al., In press).

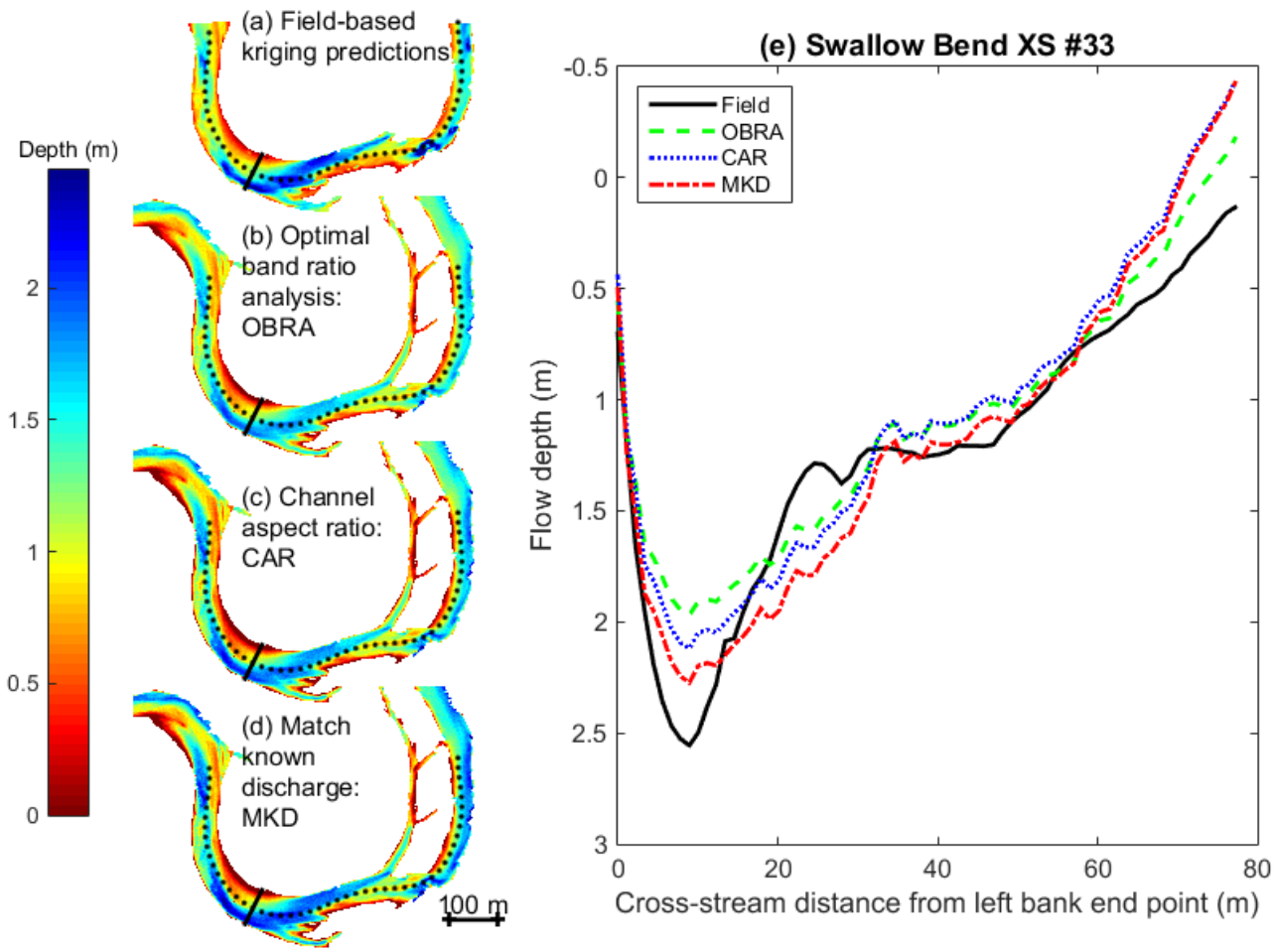

Figure 6. Comparison of field-based and image-derived depth maps obtained via Optimal Band Ratio Analysis (OBRA), which requires field measurements for calibration, and two FREEBIRD (Flow Resistance Equation-Based Imaging of River Depths) algorithms, which do not require field measurements for calibration (Legleiter, 2015).