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Measurement and Mapping of Riverine Environments by Optical Remote Sensing

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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 in this manner would afford a number of significant advantages to both the defense and research communities and could foster novel insight regarding fluvial processes. Before this potential can be realized, however, several important issues must be considered. More specifically, the overall goals of this project are to:

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 the retrieval of river information from optical data, this effort could lead to novel techniques for measuring depth, velocity, bottom composition, 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 diverse types of channels can provide the accuracy, precision, and dynamic range necessary for specific kinds of applications.

3. Develop more efficient procedures for extracting river information from optical data. Establishing integrated workflows for processing and analyzing such data will allow optical remote sensing to become a viable, operational tool for quantitative mapping of river systems.

OBJECTIVES

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

1. Develop improved methods of characterizing riverine environments via remote sensing, with an initial emphasis on estimating water depth from passive optical image data.

2. Evaluate the potential of various sensing technologies for remote mapping of rivers via forward image modeling and field-based empirical testing in a number of different sites.

3. Facilitate the efficient extraction of river information from optical data by developing algorithms for identifying channel features and producing continuous bathymetric maps.

APPROACH

Our objective to measure, map, and better understand river systems via optical remote sensing motivates a number of different research activities: this project involves detailed field measurements, numerical modeling, and image acquisition from a range of fluvial systems. Field campaigns provide the basic data on river channel optical characteristics needed to parameterize radiative transfer models that can in turn be used to simulate spectra for known combinations of depth, bottom type, water surface state, and water column constitunet concentrations (Legleiter et al., 2004; Legleiter et al., 2009). Incorporating the resulting spectral library into a forward image model (Legleiter and Roberts, 2009) will enable us to develop and systematically evaluate algorithms for inferring channel attributes from image data. To assess the performance of these techniques across a range of conditions, image-derived estimates obtained from a series of remote sensing missions will be compared to ground-based measurements collected in coordination with each flight. By acquiring data with a number of different sensors from several field sites, we will be able to examine the capabilities and limitations of various kinds of instruments in diverse riverine environments. Moreover, our efforts to process, analyze, and interpret these images will lead to more general, integrated workflows for efficient extraction of river information from remotely sensed data.

Key personnel involved in this study include the Principal Investigator, an Assistant Professor at the University of Wyoming, and Brandon Overstreet, a new Ph.D. student beginning this fall. UW graduate student Chip Rawlins and undergraduate Stephanie Bartlett also contributed to our work on the Snake River. In addition, we continue to work closely with U.S.G.S. hydrologist Paul Kinzel.

WORK COMPLETED

Over the past year, our efforts have focused on: 1) radiative transfer modeling of a turbid, sand-bed river; 2) refining algorithms for integrating LiDAR topography with passive optical bathymetry to obtain a more complete, composite representation of riverine terrain; 3) formalizing a geostatistical framework for characterizing river morphology; 4) evaluating the utility of publicly available multispectral image data for depth retrieval; and 5) an intensive field campaign intended to provide a more thorough data set on the optical characteristics of gravel-bed rivers and to test methods of inferring channel attributes from remotely sensed data. The first four of these research activities have already proceeded to the publication stage, including a two-part paper describing our work on spectrally-based bathymetric mapping of the Platte River in Nebraska that has just been published in *Water Resources Research*. Manuscripts based on items (2) through (4) have been submitted to *Earth Surface Processes and Landforms*, *Geomorphology*, and *River Research and Applications*, resepctively, and are listed in the Publications section of this document; copies of these papers are available from the Principal Investigator upon request. For the purposes of this annual report, we emphasize our recently completed field work on the Snake River and in Yellowstone National Park.

The primary objectives of this field campaign were to: (1) collect a more extensive data set on the morphologic, hydraulic, and optical characteristics of a pair of highly dynamic gravel-bed rivers; (2) obtain ground-based measurements for calibration and validation of image-derived estimates; and (3) support our ongoing, more general research interest in river channel change. These goals motivated our activities throughout the August 29 - September 16 excursion, which was delayed until the late summer/early fall time period due to a large snowpack last winter that translated into unusually high flow conditions throughout the spring and summer. Only in late August did the discharge along the Snake River recede to a level at which we could work safely, and even then flows were ~75% higher than during our 2010 field campaign, which occurred in early August. In any case, we enjoyed favorable weather conditions and took full advantage of a new, specially-designed research cataraft and Brandon Overstreet's kayaking skills (Figure 1) to successfully collect the following data sets:

Figure 1. (a) Research cataraft instrumented with an echo sounder, RTK GPS, turbidity sensor, and spectroradiometer deployed along the Snake River. Here, we are measuring reflectance via the fore-optic mounted on the boom extending from the rear of the vessel. (b) Kayak with acoustic Doppler current profiler used to measure vertical profiles of flow velocity along the Snake River.

- **Detailed surveys of flow depth, water surface elevation, and channel bed topography.** Along the larger Snake River, these data were collected onboard the cataraft with an echo sounder interfaced with an RTK GPS to obtain precise positions and elevations; over 22 km of this complex, braided channel was surveyed in this manner. Measurements were obtained along a series of cross-sections in a pair of meander bends selected for detailed study as well as longitudinal profiles recorded as we progressed downstream each day. In total, 73,686 point measurements were obtained in this manner, and an example from one of our primary study sites is shown in Figure 2a. These data were also supplemented by wading measurements along the shallow margins of the channel, collected by mounting the RTK rover on a survey rod. In Yellowstone, we performed detailed topographic surveys of the highly dynamic Soda Butte Creek. This data set included 25 cross-sections distributed over the lower 10 km of Soda Butte that were measured initially in 2007 and revisited during this year's field campaign. In addition, we also

conduted a high-resolution, intensive survey of a meander bend that we have monitired each year since 2005 and is now in the midst of a chute cutoff. Water surface elevations were recorded along the channel margins and will be used to obtain flow depths for validating image-derived estimates. Together, the field measurements and image time series we have acquired from Yellowstone will provide a valuable data set for evaluating the feasibility of quantifying river channel change from various types of remotely sensed data. We are particularly interested in the influence of riparian vegetation and bank material composition on river morphodynamics and documented these properties during our surveys (Figure 2b).

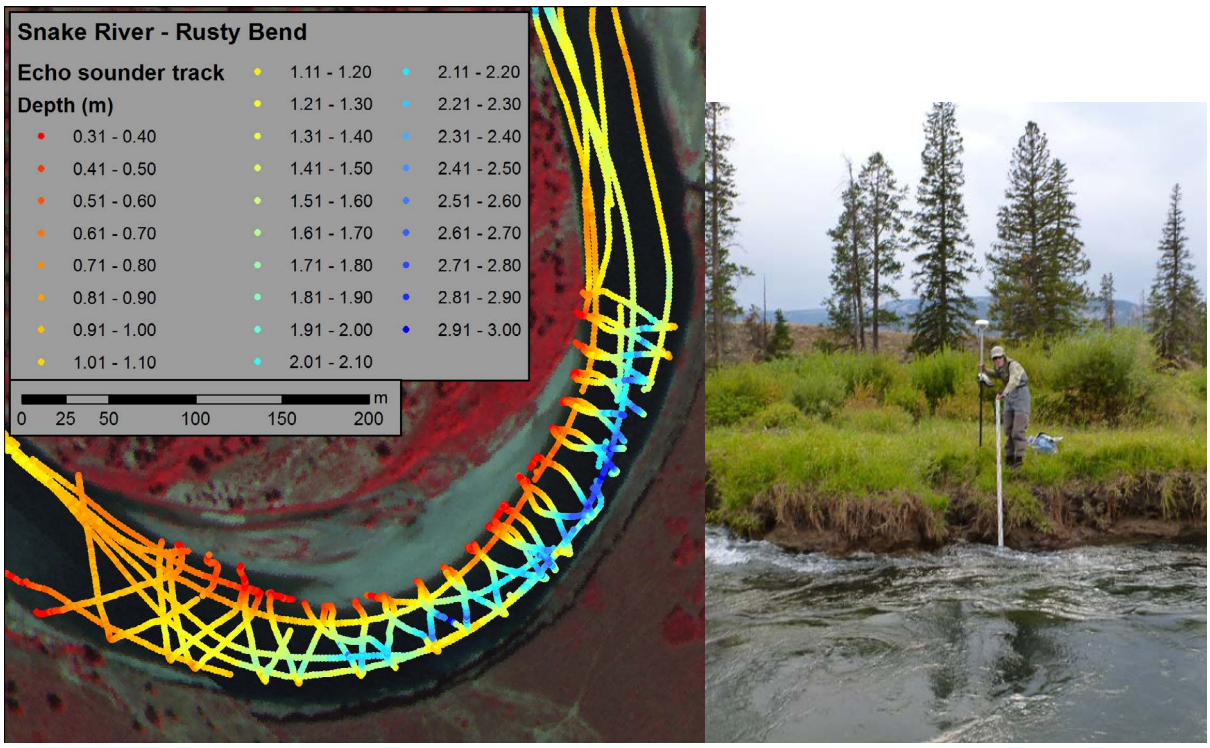

Figure 2. (a) Channel bathymetry measured with an echo sounder along one of our primary study sites on the Snake River. The background is an Aerocam multispectral image acquired in 2010. (b) Field surveys of topography, vegetation, and bank material along lower Soda Butte Creek, YNP.

- **High-resolution measurements of the flow field.** Along the Snake River, we used a SonTek RiverSurveyor S5 acoustic Doppler current profiler (ADCP) deployed from a kayak outfitted with a specialized mounting system to record vertical profiles of three-dimensional flow velocity. These data were collected along streamwise traverses spanning several km of the river, and on a series of cross-sections in two separate meander bends (Figure 3). The ADCP also recorded flow depths and thus provided an additional source of field data for evaluating remotely sensed bathymetry.

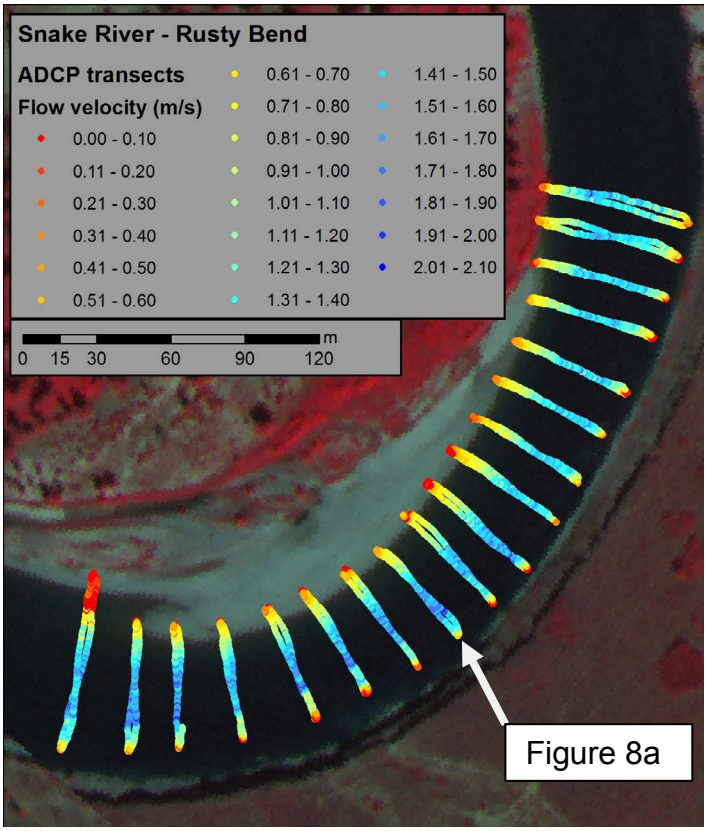

Figure 3. Flow velocity measurement transects from our Rusty Bend study site along the Snake River. These data were collected with an acoustic Doppler current profiler (ADCP), and the variable depicted in this map is the depth-averaged three-dimensional velocity magnitude.

- **Reflectance spectra measured above the water surface.** To pursue our objective of mapping bathymetry and bottom type from optical image data, we used an Analytical Spectral Devices (ASD) spectroradiometer deployed aboard the cataraft to record reflectance spectra along the Snake River. Importantly, this effort extended the range of river conditions under which spectra have been measured from shallow, wadable streams to a deeper, larger channel with more diverse bottom types. For example, our Swallow and Rusty Bend study sites were up to 3 m deep and featured submerged aquatic vegetation and bright-colored clay bedrock substrates, respectively.

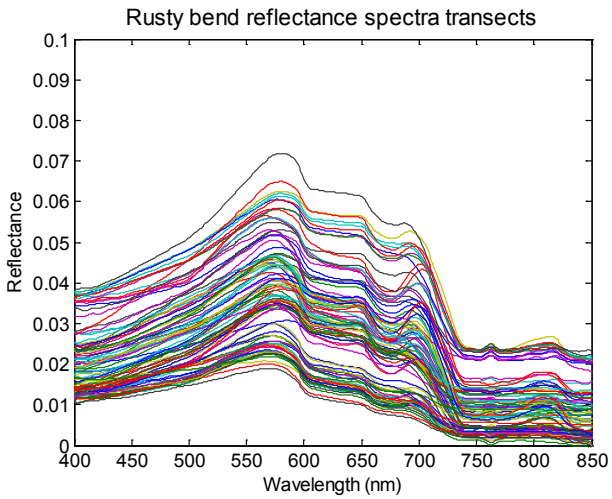

Figure 4. (a) Reflectance spectra measured from the cataraft along transects across our Rusty Bend study site on the Snake River. Only 10% (95, selected at random) of the spectra we recorded are shown here to illustrate variability in brightness and spectral shape. (b) Photo from the high terrace along the outer bank of Rusty Bend, showing the light-colored blocks of clay bedrock that produce high reflectance even in deeper water due to the presence of a bright substrate.

- **Water column optical properties.** We have also become more interested in retrieving information on the water itself and obtained various field measurements to support this goal. We used the ASD with a waterproof fiber-optic cable and am upwaard-facing, cosine response detector to measure downwelling spectral irradiance at different depths beneat the water surface (Figure 5a). These data were used to calculate a diffuse attenuation coefficient at each wvelength following the procedure outlined by Mishra et al. (2005). In addition, we used a WetLabs ac-9 loaned from the Naval Research Laboratory to directly measure two key inherent optical properties of the water column, the absorption and attenuation coefficients, *a* and *c*. These optical data were collected on several dates at sites along the Snake River and Soda Butte Creek (Figure 5b). Ancillary data in support of these measurements included water samples to be analyzed for suspended sediment concentration and *in situ* readings of turbidty with a Eureka Environmental Manta 2 multiprobe.

Figure 5. (a) Underwater photograph of the scissor lift apparatus used to measure downwelling spectral irradiance at different depths beneath the water surface; these data were used to compute a diffuse attenuation coefficient. (b) Deployment of the ac-9 inherent optical property measurement system at the Footbridge Reach of Soda Butte Creek. This instrument provided data on the absorption and attenuation coefficients of the very clear water along this stream.

- **Bottom reflectance.** In addition to bathymetry and water column optical properties, the composition of the streambed also could be mapped via remote sensing. To explore this possibility and begin the process of building a spectral library of different substrate types, we attached the ASD to a submersible cable and waterproof fore-optic to make direct measurements of the bottom reflectance of various substrate types. Raw spectra were converted to reflectance using digital counts from a white reference panel adjacent to the target. Data were collected from side channels of the Snake River and along Soda Butte Creek and included the following features: aquatic vegetation prominent along the Snake (Figure 6a); fine-grained sediment; clean gravel; periphyton; filamentous green algae (Figure 6b); and blocks of failed bank material with submerged grass.

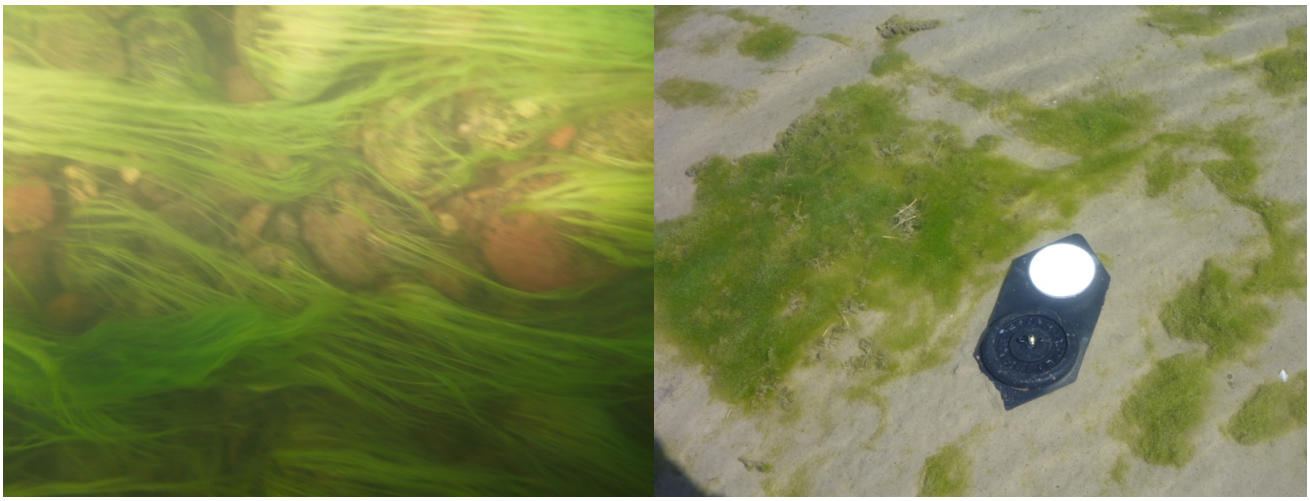

Figure 6. (a) Underwater photograph taken from the cataraft while in transit through Swallow Bend on the Snake River, showing the filamentous submerged acquatic vegetation present on the riverbed. (b) Clean, fine-grained sediment and green algae along a side channel of the Snake River. We measured the bottom reflectance of these features and other substrate types using a spectroradiometer calibrated using the Spectralon calibration panel shown in the photo.

- **Remotely sensed data.** Initially, we had planned to collect hyperspectral image data, bathymetric (green) LiDAR, and high-resolution digital aerial photography of the Snake River in collaboration with the National Center for Airborne Laser Mapping (NCALM), but high flow conditions and problems with some of NCALM's new sensors ultimately resulted in this mission being postponed until next year. In the meantime, we worked with colleagues from the Naval Research Lab and DigitalGlobe to request the acquisition of a satellite image from the new WorldView-2 multispectal sensor. This instrument features a high spatial resolution (0.5 m pancrhomatic, 2.0 m spectral bands) and a larger number (8) of wavelengths than other satellites. Images of the Snake River and Soda Butte Creek were obtained on 9-13-2011 but only previews are available at this time. Once we receive the actual data, we will use these images to evaluate the feasibility of retrieving, from space, information on the bathymetry, bottom type, and optical properties of gravel-bed rivers.

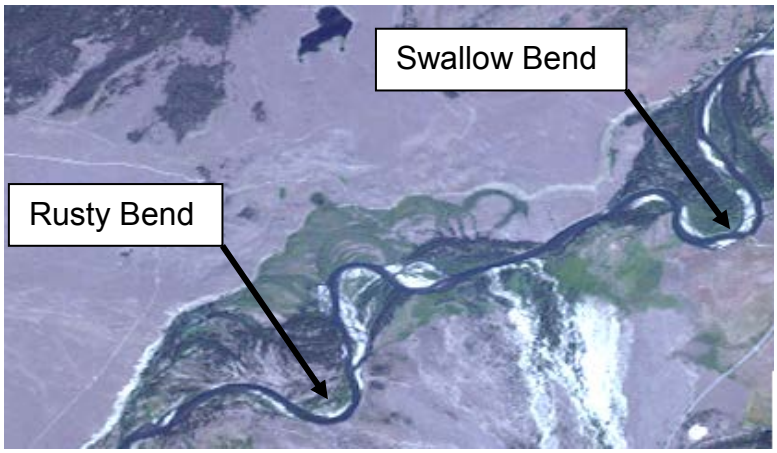

Figure 7. WorldView-2 satellite image showing a portion of our Snake River study area, with detailed measurement sites labeled. Note that this is only a preview image provided immediately after acquisition; the full-resolution, geo-referenced data are forthcoming.

RESULTS

In this section, we present some initial results from our recently completed field campaign on the Snake River and in Yellowstone, organized by data type. Please note that these data were collected within the past couple of weeks and that our analysis of these measurements is in a very early stage.

- **High-resolution measurements of the flow field.** Our ADCP data collection along the Snake River focused on a pair of meander bends that have a similar curvature and overall geometry but a very different morphology (Figure 7). The first site, Swallow Bend, is unusual in that an obstruction where a terrace protrudes into the channel near the bend entrance has modified the flow field such that a large gravel bar has accumulated along the outside of the bend, in addition to a point bar along the inner bank. The second study reach, Rusty Bend, has a more typical configuration, with a single point bar located along the inside of the curve (Figure 3). Comparing the flow field through these two bends will thus allow us to isolate the influence of a constriction on patterns of velocity, shear stress, bed material transport, and channel morphology. The ADCP data provide detailed information on three-dimensional flow structure for examining these issues. For example, the transect shown in Figure 8a illustrates the helical flow pattern typical of meander bends, with outward-directed flow (toward the left bank) along the shallow margins of the point bar on the right (inside) of the channel and near the water surface, and inward flow near the bed in the pool and onto the lower slope of the point bar. Similarly, streamwise profiles like that shown in Figure 8b highlight along-channel undulations of the bed topography and their influence on the flow field and will be used to examine the relationship between bar amplitude and form-related flow resistance. The ADCP was also configured to measure river discharge, with typical values of 85-90 m^3/s recorded on the Snake during our field campaign. These discharge readings will be used to develop algorithms for retrieving flow depth information from remotely sensed data when direct field measurements of depth are not available for calibration, using hydraulic relationships (i.e., flow resistance equations) as a constraint in a numerical optimization procedure.

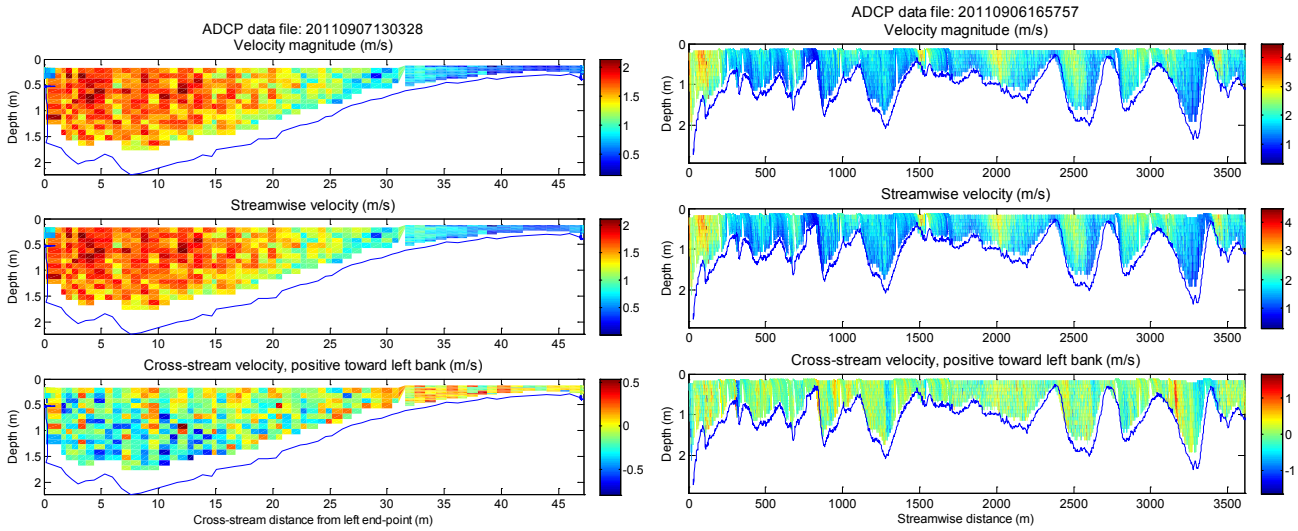

Figure 8. (a) ADCP measurements of the flow field through Rusty Bend, at the cross-section indicated in Figure 3. Data have been resolved into streamwise and cross-stream components. (b) ADCP data along a longitudinal profile extending over 3.6 km downstream from Rusty Bend, highlighting undulations in the bed topography and the associated variations in the velocity field.

- **Reflectance spectra measured above the water surface.** Although measuring spectra aboard a moving cataraft was a new challenge for our research team, the data have already yielded some encouraging results. An example is shown in Figure 9a, a cross-section in Rusty Bend where as depth increased toward the left (outer) bank, the reflectance at 607 nm decreased at a faster rate, due to exponential attenuation by the water column, only to spike near the outside of the bend where bright blocks of exposed bedrock were exposed on the bed (Figure 4b). To evalaute the feasibility of spectrally-based depth retrieval in this environment, the 953 reflectance spectra measured at Rusty Bend were subjected to the Optimal Band Ratio Analysis (OBRA) procedure described by Legleiter et al. (2009). A simple, log-transformed band ratio, $X = \ln(R_{506}/R_{607})$, was strongly linearly related to depth d ($R^2 = 0.884$), and the matrix of d vs. X regression R^2 values in Figure 9a indicates that many other band combinations also would yield reliable depth information.

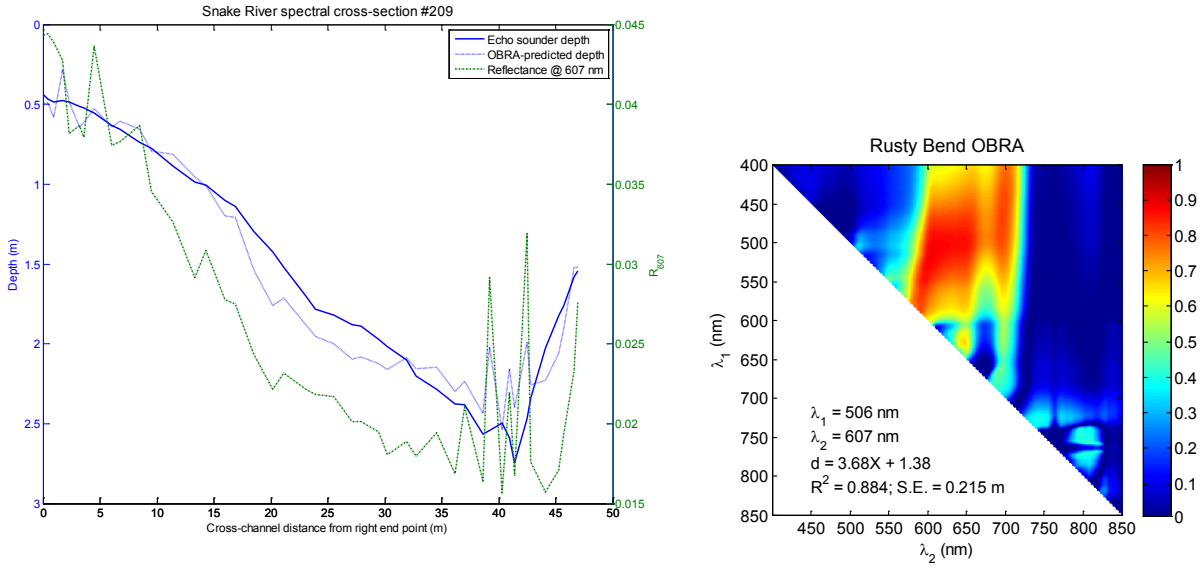

Figure 9. (a) A cross-section of measured depth and reflectance and OBRA-predicted bathymetry from the Rusty Bend site along the Snake River. (b) Results from an Optimal Band Ratio Analysis (OBRA) of spectra from Rusty Bend, indicating the band combination that yields the strongest linear relation with flow depth, and a matrix of R^2 values for all possible pairs of bands.

- **Water column optical properties.** Vertical profiles of downwelling spectral irradiance were recorded on four different dates along the Snake River and twice on Soda Butte Creek; diffuse attenuation coefficient K_d values calculated from these data are shown in Figure 10a. K_d is an apparent optical property that influences the precision of image-derived depth estimates, as well as their dynamic range; higher K_d values imply less precise depth retrieval and shallower maximum detectable depths. The K_d spectra from each date/site are quite similar, but data acquired under more overcast conditions plot higher than those obtained under clear skies. A K_d spectrum from the turbid Platte River is also included to highlight the greater clarity of the water in the Snake River and Soda Butte Creek, where optical methods are a more viable means of mapping bathymetry. These results were corroborated by the ac-9 data shown in Figure 10b, in which the inherent optical properties are seen to be quite similar across all sites and dates. This plot also depicts the absorption coefficients of pure water and a small concentration of suspended sediment to show that a simple, two-component model might be sufficient to describe these streams, although colored dissolved organic matter should be considered as well. The turbidity values recorded during our field campaign were consitent and low: 2 - 3 NTU. Suspended sediment concentration analyses are yet to be performed, but values are expected to be quite low. Future work will focus on relating water column optical properties to suspended sediment concentrations.

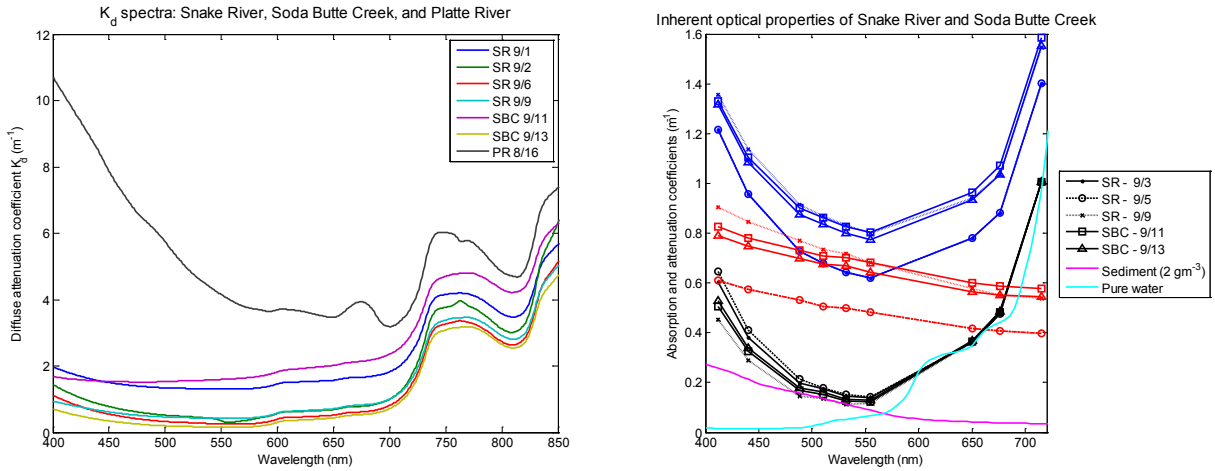

Figure 10. (a) Diffue attenuation coefficient K_d spectra computed from vertical profiles of downwelling spectral irradiance measured along the Snake River and Soda Butte Creek. A K_d spectrum from the much more turbid Platte River is also shown for comparison. (b) Inherent optical properties measured with an ac-9, along with absorption coefficient values for pure water and suspended sediment. The absorption, scattering, and attenuation coefficients a, b, and c are represented by the black, red, and blue lines, respectively, with different symbols for each site/date.

- **Bottom reflectance.** During our recent field campaign we made significant progress toward our goal to establish a spectral library of different riverbed bottom types, ranging from submerged vegetation and green algae to fine sediment, clean gravel, and blocks of failed bank material. The photo in Figure 11a shows how these features are arranged in complex patterns along a side channel of the Snake River, with considerable fine-scale spatial variability. The bottom reflectance data in Figure 11b indicate that various substrate types are spectrally distinct from one another, implying that this information might be used to map various substrates at a sub-pixel scale via spectral mixture analysis or similar techniques. Future work will explore this possiblity via radiative transfer simulations and hyperspectral image data scheduled for acquisition in 2012.

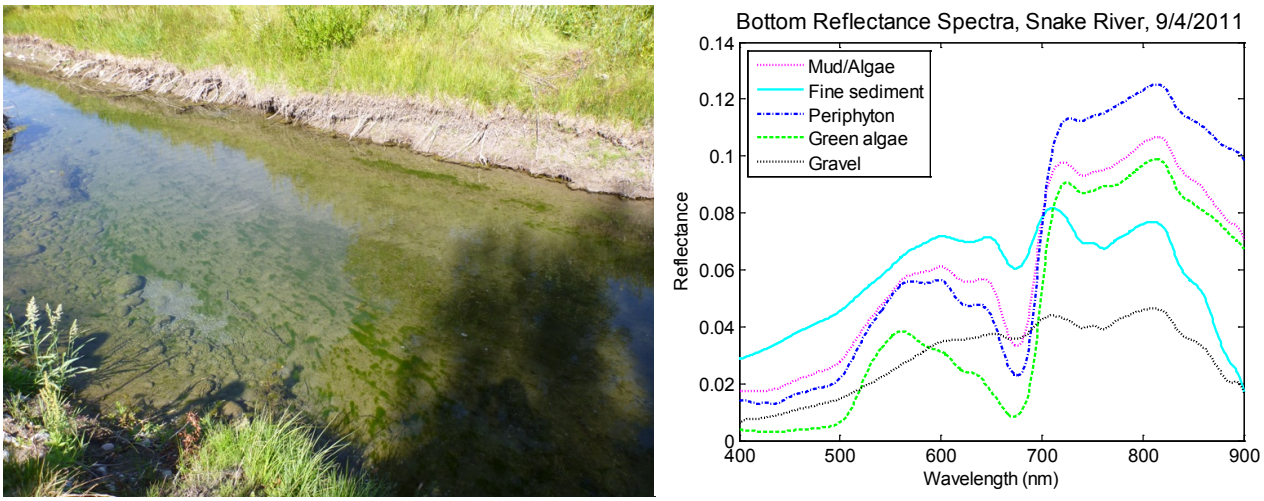

Figure 11 (above). (a) Photo showing the complex spatial distribution of different substrates along a side channel of the Snake River, including fine sediment, gravel, and green algae. (b) Bottom reflectance measurements from this site, illustrating that various bottom types are spectrally distinct.

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

To support our ongoing efforts to develop an advanced capacity for remote sensing of rivers, we have just submitted a proposal to the ONR's Defense University Research Instrumentation Program (DURIP) entitled "Remote sensing and *in situ* instrumentation for reserach on the optical characteristics, morphology, and dynamics of riverine environments." Our application requests funding to purchase a hyperspectral imaging system and a suite of *in situ* measurement devices that would signicantly enhance our ability to pursue the research objectives outlined at the beginning of this report. The DURIP is thus closely related to our current work and the proposal was motivated by a desire to streamline the logistics and reduce the cost of acquiring image data and field measurements from a broader range of river systems. Looking forward more generally, a DURIP award would allow us to establish the University of Wyoming as a center of excellence in the remote sensing of rivers and to transition into a number of different, future projects. In addition, we intend to make these facilities avaliable to other researchers in this rapidly evolving field, leading to many fruitful collaborations.

RELATED PROJECTS

We are collaborating with Arete Associates to develop techniques for mapping river surface currents from optical and thermal remote sensing as part of their Riverine Dynamics Experiment 4. Beginning tomorrow (9-30-2011), we will be working with Arete at the confluence of the Blue and Colorado Rivers to collect field measurements of flow velocity, channel bathymetry, and optical properties in coordination with a series of remote sensing flights. Arete will also be collecting image data from our study area along the Snake River in early October, and the field measurements we obtained earlier this month will be used to test velocity and depth retrievals at this site as well.

We have also initiated a new collaboration with Alan Weidemann and colleagues at the Naval Research Laboratory that focuses on inferring bathymetry, bottom type, and water column optical properties from optical image data. Dr. Weidemann loaned an ac-9 instrument for measuring absorption and attenuation coefficients and helped to coordinate the acquisition of WorldView-2 satellite images from our study sites along the Snake River and in Yellowstone National Park.

Next week (October 2-8, 2011), Ph.D. student Brandon Overstreet and I will travel to the University of Minnesota's St. Anthony Falls Laboratory (SAFL) to conduct field spectroscopy experiments in their Outdoor Stream Laboratory (OSL) through a grant from the National Center for Earth Surface Dynamics (NCED) SAFL Visitor's Program. This project, titled "Retrieving river attributes from remotely sensed data: an experimental evaluation based on field spectroscopy at the Outdoor Stream Lab," will allow us to make measurements under controlled conditions and thus more effectively isolate the influences of depth, bottom composition, suspended sediment concentration, and water surface state on reflectance characteristics. These experiments will thus yield a valuable initial assessment as to the feasibility of deriving this type of information from remotely sensed data and will also help us to refine our methods of collecting spectral measurements in the field.

In addition, we continue to work closely with Paul Kinzel and Jon Nelson of the U.S. Geological Survey's Geomorphology and Sediment Transport Laboratory to pursue the objectives set forth in the closely related, ONR-supported study "Computational Modeling of River Flow, Sediment Transport, and Bed Evolution Using Remotely Sensed Data" (Award # N0001409IP20057).

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Legleiter, C.J. A geostatistical framework for quantifying the reach-scale spatial structure of river morphology: 2. Application to restored and natural channels. *Geomorphology*. (Submitted 6-9).

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