MEASURING THE MORPHOLOGY AND DYNAMICS OF THE SNAKE RIVER BY REMOTE SENSING

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✦ ABSTRACT

The Snake River is a central component of Grand Teton National Park, and this dynamic fluvial system plays a key role in shaping the landscape and maintaining a diversity of habitat conditions. The river’s inherent variability and propensity for change complicate effective characterization of this important resource, however; conventional, ground-based methods are not adequate for this purpose. Remote sensing provides an appealing alternative that could facilitate resource management while providing novel insight on factors influencing channel form and behavior. This study evaluates the potential for using optical data to measure the morphology and dynamics of a large, complex river such as the Snake. More specifically, we assessed the feasibility of estimating flow depth from multispectral satellite images acquired in September 2011. Our initial results indicate that reliable maps of river bathymetry can be produced from such data. We are also examining channel changes associated with a prolonged period of high flow during the 2011 snowmelt runoff season by comparing these satellite images with digital aerial photography from August 2010. An extensive field data set on flow velocities provides some hydraulic context for the observed morphodynamics. More sophisticated hyperspectral and LiDAR data sets are scheduled for collection in 2012, along with additional field measurements.

✦ INTRODUCTION

A defining feature of the Teton landscape, the Snake River plays an important role in the geomorphology and ecology of Jackson Hole and provides visitors to Grand Teton National Park with abundant recreational opportunities. This dynamic fluvial system collects water and sediment from a large, mountainous drainage basin and conveys these materials across the valley floor via various mechanisms of flow and sediment transport. These processes interact to produce coherent patterns of sediment transfer and storage that are manifested as distinctive landforms - channels, bars, floodplains, and terraces. These geomorphic surfaces are colonized by vegetation but eventually reclaimed as the river shifts laterally, incises new channels, or reoccupies former flow paths. This perpetual reworking of the riparian zone creates a patchy mosaic of habitat conditions that supports a diversity of terrestrial and aquatic organisms, including such iconic species as bald eagles, beaver, native trout, and moose. The potential to view such wildlife, along

Figure 1. Cataraft and kayak used for field data collection along the Snake River. Photo by Chip Rawlins.

with the unique scenery in part created by the Snake, makes this fluvial environment a source of considerable enjoyment by the public, for whom the river and surrounding National Park have been protected and preserved.

Managing these natural resources is the responsibility of the National Park Service, but this important task is complicated by the same variability and dynamism that make the Snake River such a vibrant element of the landscape. Basic information on the river's form and behavior are needed for resource assessment and monitoring purposes, but the logistical constraints associated with conventional field methods make even sparse data difficult to obtain. Measuring channel and floodplain topography, flow conditions, and streambed characteristics over long reaches is simply not practical in such a heterogeneous riverine environment. Moreover, the channel changes that occur during each spring's snowmelt imply that maintaining an accurate, current database would require annual surveys. Information of this kind would facilitate various ongoing ecological and geomorphic investigations while enabling the Park Service to more readily achieve certain management objectives. For example, studies of native cutthroat trout would benefit from a more detailed knowledge of the physical habitat conditions (e.g., depth, velocity, and bed material grain size) preferred by these species during different life stages. Similarly, research on the effects of flow regulation on floodplain inundation, bed mobility, and general channel stability, along with related efforts to develop reach-scale sediment budgets, would benefit from more extensive, higher resolution topographic data. For resource management, current information on channel depths, the distribution of bars, and the location of obstructions (e.g., accumulations of large woody debris) would allow navigability by rafts to be assessed more easily and could help recreational boaters to avoid potentially hazardous situations. For many reasons, then, an enhanced capacity to characterize the morphology and dynamics of the Snake River would be of great value.

Remote sensing techniques could provide such a capacity by enabling more efficient measurement of several key river attributes. A quantitative, remote sensing-based approach would have several distinct advantages in this context: 1) a synoptic perspective that allows long segments of broad riparian zones to be mapped in a matter of hours rather than weeks, 2) continuous, high-resolution data that capture the spatial variability of the riverine environment far more effectively than traditional methods based on isolated cross-sections, and 3) more frequent coverage that could not only facilitate monitoring but also lead to an improved understanding of the fluvial processes that drive channel change and thus create, modify, and maintain diverse terrestrial and aquatic habitats.

Research on the application of remote sensing to rivers has progressed rapidly over the past decade (Marcus and Fonstad 2010). For example, our earlier work demonstrated the feasibility of mapping flow depth from optical data (Legleiter et al. 2004, 2009). Field measurements and digital aerial photography collected along the Snake River in August 2010 also indicated that reasonably accurate depth estimates could be derived from relatively basic images of this kind (Legleiter, forthcoming 2012a). Our results thus suggest that integrated, spatially explicit analysis of remotely sensed data could enable scientists and managers to more efficiently characterize complex river systems like the Snake.

Research hypothesis and specific aims

The primary goal of our research in Grand Teton National Park is to apply remote sensing methods to an important problem that is not only of scientific interest but also of direct relevance to current management needs: characterizing the morphology and dynamics of the Snake River. This effort will yield insight on factors influencing channel form and behavior and facilitate the Park Service's efforts to protect this resource. We have a more general research interest in the remote sensing of rivers, but the Snake River is one of our primary field sites for developing and testing new methods. This dynamic fluvial system provides an opportunity to critically evaluate the feasibility of mapping a large, braided river from various types of image data. This project is also consistent with our overarching research objective: to understand the mechanisms by which flow, sediment transport, and channel form interact to direct a river's morphologic evolution. Motivated by these goals, our efforts over the past year have focused on the following specific aims:

1) Obtain field measurements of reflectance and water column optical properties to more rigorously assess the feasibility of spectrally-based depth retrieval in this environment.
2) Acquire a new multispectral satellite image of the Snake River and evaluate the utility of these remotely sensed data for bathymetric mapping.
3) Quantify the channel changes that occurred during the 2011 runoff season by comparing aerial photographs from 2010 to the 2011 image data.

4) Collect field data on flow depths and velocities to provide some hydraulic and geomorphic context for the observed dynamics.
5) Identify future research needs and develop a plan for collecting additional remotely sensed data and field measurements that will advance our understanding of the Snake River.

✦ STUDY AREA

This effort to characterize channel form and behavior via remote sensing focuses on the Snake River in Grand Teton National Park. This dynamic fluvial system is well-suited for such an investigation because the river encompasses a range of channel morphologies, valley floor environments, and disturbance regimes that not only pose a challenging test of remote sensing methods but also will allow us to examine various factors controlling river morphology. For example, the Snake includes both meandering and braided segments that are influenced by variations in slope and sediment supply, differences in streambank composition and riparian vegetation, a post-glacial legacy, and a strong tectonic signal. Field measurements and image data from the Snake thus allow us to draw comparisons among a variety of stream reaches in terms of both their amenability to remote mapping and their geomorphic controls. In addition, the Snake is an attractive site for study because the river features, 1) clear water conditions conducive to remote sensing of flow depths, 2) a pair of stream gages that provide a continuous record of river discharge, 3) relatively little direct human impact, apart from flow regulation by Jackson Lake Dam, and 4) a well-documented history of channel change based on archival aerial photography (Schmidt and Nelson, 2007). In any given year, a sizable portion of the Snake River could experience significant morphologic adjustment as a result of high snowmelt runoff; both existing and planned remotely sensed data sets provide an effective means of characterizing these dynamics.

Our 2011 field campaign involved extensive data collection along the Snake River and encompassed a broad range of channel configurations. We covered the segment from Pacific Creek downstream to Moose, with much of our effort focused on a pair of meander bends: 1) Swallow Bend, located at 537500 m E, 4851200 m N and 2) Rusty Bend, located at 535160 m E, 4849650 m N (UTM Zone 12N). In addition to these two detailed study sites, we performed a longitudinal survey using a specially designed cataraft outfitted with equipment for measuring flow depths, velocities, and various optical properties.

✦ METHODS

For 2011, the general strategy of our investigation was to: 1) Make field measurements of flow conditions and optical properties along the Snake River, 2) Obtain multispectral satellite images of the riparian corridor, 3) Develop and evaluate image processing methods for retrieving water depth from remotely sensed data, 4) Combine the new satellite imagery with previously acquired aerial photography to examine the channel changes associated with high flows during the 2011 spring runoff and, 5) Interpret the observed dynamics in terms of flow and sediment transport processes and landscape-level controls on channel form and behavior. The data acquired in 2011 also provide a basis for planning future remote sensing missions, with additional flights scheduled for August 2012. This project thus involved a combination of geospatial data analysis and field work; these two components are described in the following sections.

Remotely sensed data and image processing

In 2010, the first year of this ongoing study, we focused on compiling existing remotely sensed data sets and acquiring digital aerial photography along the Snake River corridor; these data sets are described in detail in our previous report. Our attention has now turned to satellite images acquired by the WorldView2 sensor on 13 September 2011. This new instrument features a unique combination of spatial and spectral resolution well-suited for river applications. The WorldView2 data set consists of 2 m-pixel size multispectral images with eight bands spanning the visible and near-infrared wavelengths, and panchromatic images that are acquired simultaneously and have the same area of coverage but a smaller pixel size of 0.5 m. Other satellites can provide similar spatial resolution, but not with the same level of spectral detail as WorldView2. We obtained two cloud-free images that cover the Snake River from Jackson Lake dam downstream past the Park boundary at Moose. These data were delivered in a geo-referenced format, and alignment between the images and our field-based surveys was highly accurate. The data provider, Digital Globe, also performed a radiometric calibration and atmospheric correction that served to convert the original, raw digital numbers for each pixel to apparent surface reflectance values. To facilitate data processing and reduce computational requirements, we subdivided the original images into a series of 22 individual tiles extending from Jackson Lake to Moose (Figure 2).

Figure 2. WorldView2 satellite image of the Snake River acquired 13 September 2011. Star symbols indicate locations of detailed study sites at a pair of meander bends.

Our analysis of the satellite images has focused on evaluating whether these data might be useful for mapping river bathymetry. Previous studies have shown that, under appropriate conditions (i.e., relatively shallow, clear water), water depth can be estimated from passive optical images. More specifically, because the rate at which light is attenuated by the water column varies as a function of wavelength, as depth increases the amount of reflected solar energy recorded in a spectral band experiencing stronger attenuation decreases more rapidly than does the amount of energy measured in a band for which attenuation is weaker. Calculating the logarithm of the ratio of the pixel values for two spectral bands thus yields an image-derived quantity that is linearly related to water depth. Whereas the attenuation coefficient of pure water increases by an order of magnitude from the visible into the near-infrared, the bottom reflectance of different substrate types varies by only a few percent over this range of wavelengths, so the band ratio is highly sensitive to depth and robust to variations in bottom type. Calibration is achieved by regressing values of this image-derived quantity against depths measured in the field (Legleiter et al. 2009). This relatively simple method of retrieving depth information was appropriate for the WorldView2 images because these data were acquired in late summer, when concentrations of suspended sediment were minimal, water clarity was high, and field data were collected within a few days of image acquisition. This technique was also applied to a mosaic of digital aerial photographs from 2010, which were also collected under low-flow, clear-water conditions. The ratio-based depth retrieval algorithm allowed us to develop bathymetric maps that depict pools, riffles, and shallow submerged bars for both time periods.

To complement these data sets and extend our image time series, we have already made plans to acquire more sophisticated hyperspectral and light detection and ranging (LiDAR) data that will further enhance our capacity to measure the morphology and dynamics of the Snake River. Ultimately, the principal channel attributes we intend to map via remote sensing are flow depth, bed topography, and water surface slope. Several data sets potentially useful for these purposes have been compiled in a GIS, as described in our previous report. Although LiDAR provides highly accurate topographic information from exposed bars and floodplains, LiDAR is of little value within the wetted channel proper due to strong absorption of near-infrared laser pulses by water. To produce a complete topographic representation of the riverine environment, LiDAR topography and spectrally-based bathymetry can be combined into a single digital terrain model. The LiDAR provides elevations for exposed areas, and bed elevations within the channel can be determined by subtracting image-derived depth estimates from water surface elevations recorded for LiDAR points along the edge of the water (Legleiter, forthcoming 2012b). Some adjustment might be necessary to account for differences in flow level if the LiDAR and optical data were not acquired simultaneously, but this offset can be determined from gage heights recorded at Jackson Lake and Moose on each date. This analysis will be completed after we obtain LiDAR coverage in August 2012.

Field data collection

In addition to the geospatial data analysis described above, our study also involved extensive field work intended to validate remotely sensed river information and to support our geomorphic research agenda. As part of our overall effort to advance the remote sensing of rivers, the development of which has been hindered by a lack of *in situ* observations, we made direct field measurements of several optical characteristics of the Snake River. Reflectance spectra were recorded above the water surface using an Analytical Spectral Devices (ASD) FieldSpec3 spectroradiometer. A 100% reflectant Spectralon calibration panel was used to establish a white reference prior to each round of measurements. The spectroradiometer was mounted on a specially designed cataraft and configured to record spectra once each second as we traversed the river on a series of channel-spanning transects (Figure 3a). Flow depths were recorded simultaneously using the survey instrumentation described below. This protocol thus provided paired observations of depth and reflectance needed to develop and refine bathymetric mapping algorithms. Moreover, these data extended the range of river conditions under which spectra have been measured from shallow, wadable streams (Legleiter et al., 2009) 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 3b).

In addition to bathymetry, the composition of the streambed also might 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 bottom types. As for the above-water measurements, 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 included the following features: submerged aquatic vegetation (Figure 4a); fine-grained sediment; clean gravel; and periphyton (algae attached to the bed; Figure 4b).

An important constraint on remote mapping of bathymetry and/or bottom type is the optical properties of the water column, and we collected field data on several characteristics of the Snake River water itself. For example, connecting the spectroradiometer to a waterproof, upward-facing detector allowed us to measure the amount of downwelling radiant energy propagating to various depths within the water column (Figure 5a). These data were used to calculate a diffuse attenuation coefficient at each wavelength following the procedure outlined by Mishra et al. (2005). In addition, we used a WetLabs ac-9 to directly measure two key inherent optical properties of the water column, the absorption and attenuation coefficients, *a* and *c* (Figure 5b). These optical data were collected on several dates at sites along the Snake River. Ancillary data in support of these measurements included water samples analyzed for suspended sediment concentration and *in situ* turbidity readings with a Eureka Environmental Manta 2 multi-probe.

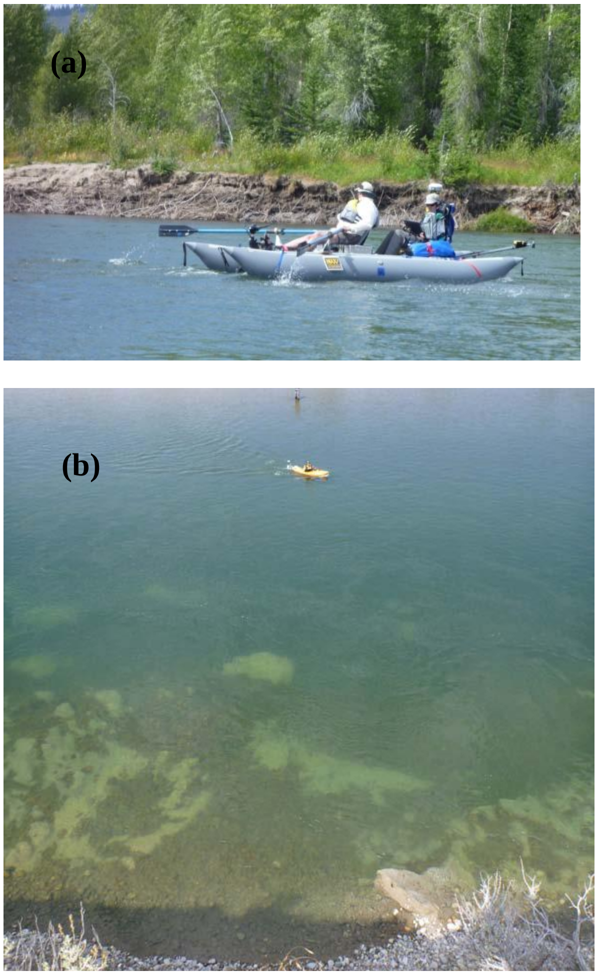

Figure 3. (a) Field measurements of flow depth and spectral reflectance were obtained from a cataraft; the spectroradiometer extends out over the water from the rear of the raft (right in this photo). (b) Blocks of light-colored material present along Rusty Bend.

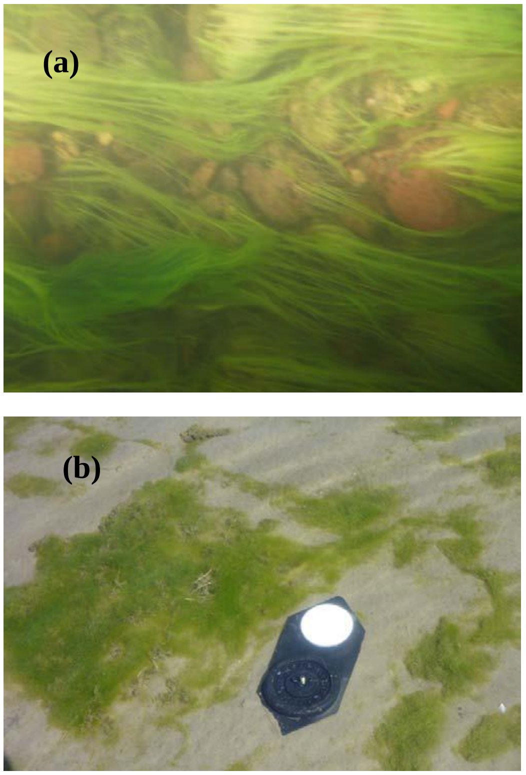

Figure 4. (a) Underwater photograph from Swallow Bend showing the submerged aquatic vegetation present on the riverbed. (b) Clean, fine-grained sediment and green algae along a side channel of the Snake River. The calibration panel used to establish a white reference is shown as well.

A second key component of our field effort was a survey of channel bed topography. These data were collected using a high-precision (sub-centimeter) real-time kinematic GPS receiver that was attached to a survey rod for measuring terrestrial surface elevations. Survey points were arranged along cross-sections traversing exposed bars and shallow areas of the active channel and selected so as to emphasize important breaks in slope, such as the top and base of stream banks. For areas that were too deep to wade safely, the GPS receiver was mounted on the cataraft and configured to record water surface elevations while communicating with an echo sounder that measures flow depths; subtracting the depth from the water surface elevation yielded measurements of the bed elevation. Over 22 km of the Snake River was surveyed in this manner. Measurements were obtained along a series of transects in our detailed study sites 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 Rusty Bend is shown in Figure 6. These field measurements allowed us to relate depths to WorldView2 image-derived quantities.

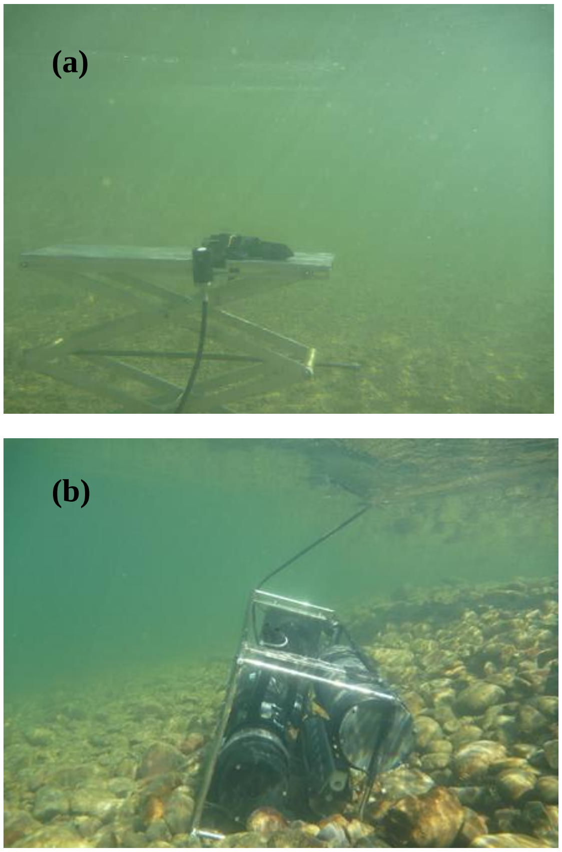

Figure 5. (a) Underwater photograph of the scissor lift apparatus used to measure downwelling radiant energy at different depths within the water column. (b) The ac-9 inherent optical property measurement system; this instrument provided data on the absorption and attenuation coefficients of the very clear water along this stream.

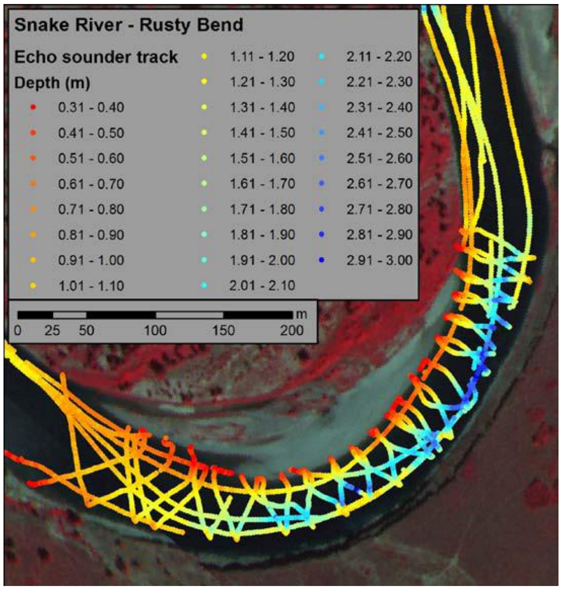

Figure 6. Channel bathymetry measured with an echo sounder along our Rusty Bend study site.

In an effort to better characterize and understand the fluvial processes driving the channel changes observed in our image time series, we measured flow conditions within the Snake River using an acoustic Doppler current profiler (ADCP). This instrument was deployed from a kayak outfitted with a specialized mounting system (Figure 7a) and recorded flow velocities in a series of cells distributed vertically throughout the water column. The ADCP measured streamwise, cross-stream, and vertical velocity components at a frequency of once per second and thus provided a very detailed characterization of the flow field. We also used the ADCP to measure river discharge by integrating the product of depth and velocity as we moved across the channel. In addition to cross-sections located in our two primary study sites (Figure 7b), we also recorded flow velocities along profiles oriented down the river. The ADCP also recorded flow depths and thus provided an additional source of field data for evaluating remotely sensed bathymetry. In addition, data acquired with the ADCP will support future work on the interactions between flow processes, bed material transport, and the evolution of channel form.

✦ RESULTS

In 2011, the second year of this ongoing study, we conducted a successful field campaign from 29 August to 16 September. Our field work was delayed until this 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 season, which occurred in early August. In any case, we enjoyed favorable weather conditions and took full advantage of our new research cataraft, kayak, and measurement devices. To date, our analysis has focused on characterizing the river's optical properties, evaluating the feasibility of mapping river bathymetry from satellite image data, summarizing the hydraulic information collected with the ADCP, and documenting channel changes between 2010 and 2011. The following sections report some of our initial findings and discuss our plans for further work along the Snake.

Optical properties of the Snake River

An impediment to progress in the remote sensing of rivers has been a paucity of direct, *in situ* measurements of spectral reflectance and water column optical properties; our field data from the Snake River address this void. Although measuring spectra aboard a moving cataraft was a new challenge for our research team, the data we obtained have already yielded some encouraging results. Reflectance spectra measured from above the water surface on transects across Rusty Bend are shown in

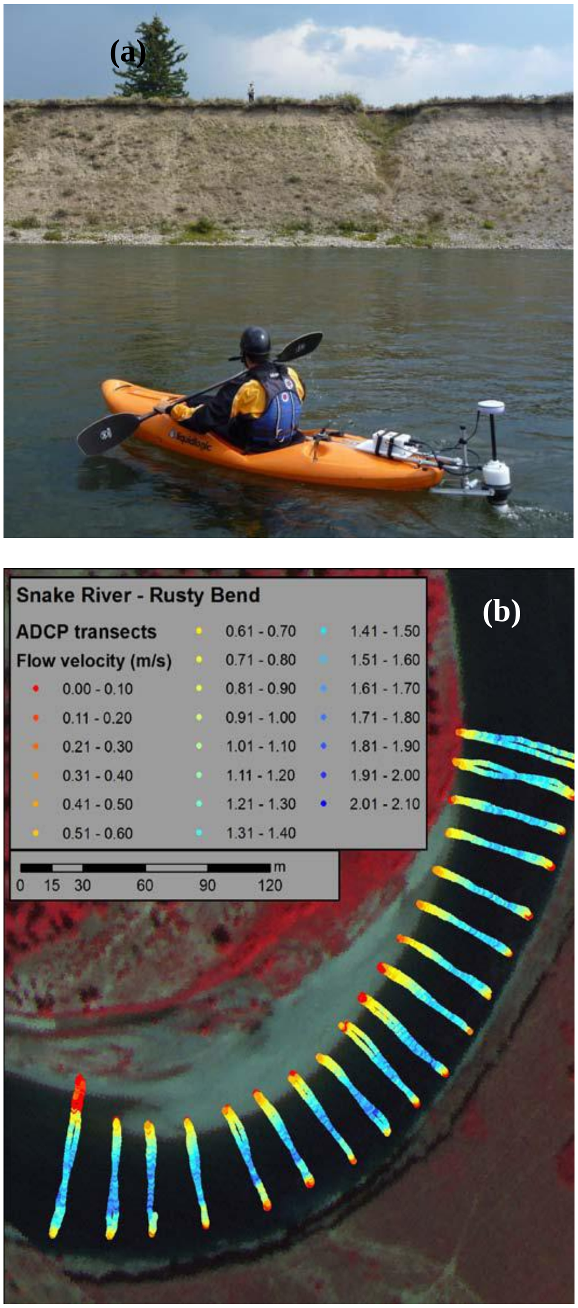

Figure 7. (a) Flow velocities were measured with an acoustic Doppler current profiler (ADCP) deployed from a kayak. (b) Velocity data from our Rusty Bend study site along the Snake River; the variable depicted in this map is the depth-averaged three-dimensional velocity magnitude.

Figure 8a to illustrate variability in brightness and spectral shape; note that only 10% (95, selected at random) of the measured spectra are included in this plot. Figure 8b is an example spectral/bathymetric cross-section where as depth increased toward the left (outer) bank, the reflectance at a wavelength of 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 3b). To evaluate 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). Briefly, this technique: 1) takes as input paired observations of depth and reflectance, 2) computes an image-derived quantity X, defined the logarithm of the ratio of two spectral bands, for all possible pairs of wavelengths, 3) performs a regression of depth vs. X for each band combination; and 4) identifies the optimal band ratio as that which yields the highest regression R^2 value. OBRA results can be represented as a matrix that highlights spectral variations in the strength of the relationship between depth and X. For the Rusty Bend data set, defining X using reflectances measured in green and red wavelengths yielded a strong linear relationship with depth ($R^2 = 0.884$). Applying the OBRA equation to the field spectra produced a spectrally-based depth estimates (dashed blue line in Figure 8b) that agreed closely with the surveyed cross-section (solid blue line). Moreover, the extensive warm tones in the matrix of R^2 values shown in Figure 8c indicates that many other band combinations would yield reliable depth information as well.

We also obtained data on the optical properties of the water itself. Vertical profiles of downwelling irradiance were recorded on four different dates along the Snake River. Diffuse attenuation coefficient K_d values calculated from these data are shown in Figure 9a, along with similar data from Soda Butte Creek, a smaller gravel-bed river in nearby Yellowstone National Park (Legleiter et al., 2009).

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

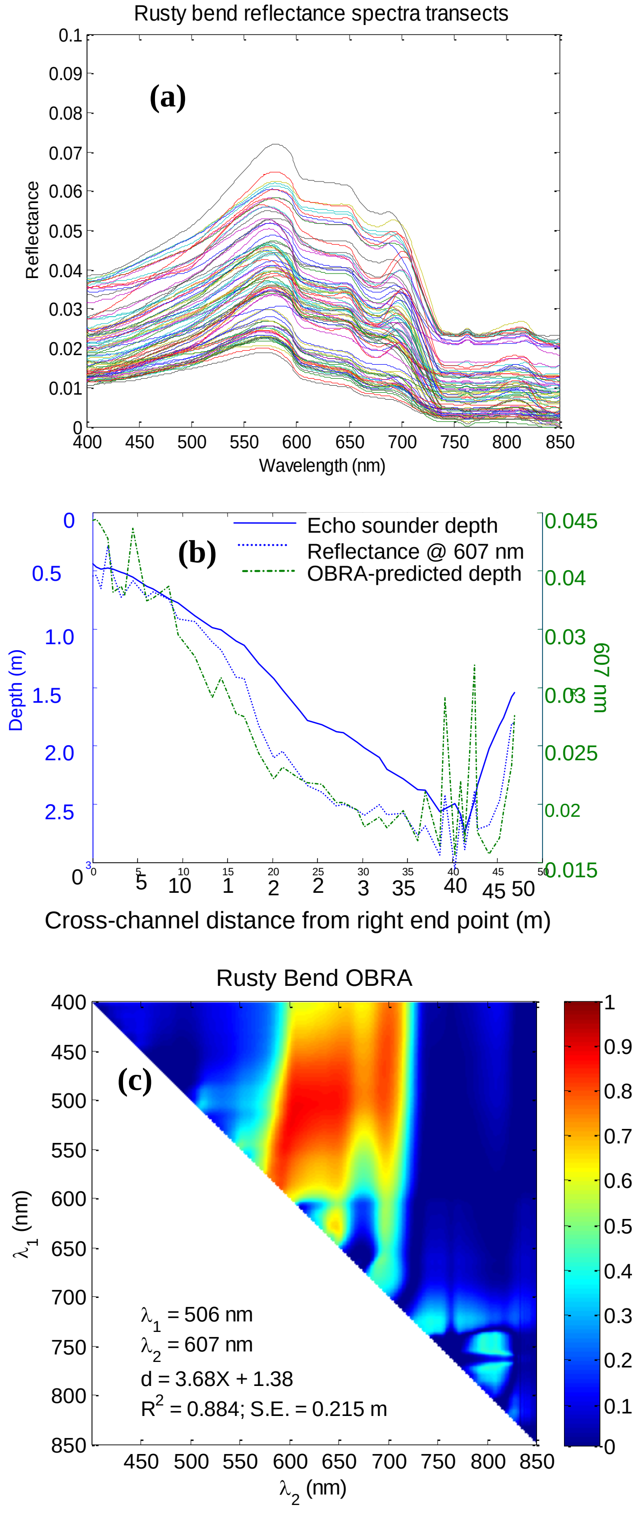

Figure 8. (a) Reflectance spectra from Rusty Bend. (b) A single transect of depth and reflectance observations showing the effect of bright failed bank blocks. (c) Optimal band ratio analysis used to establish a relationship between reflectance and water depth; see text for details.

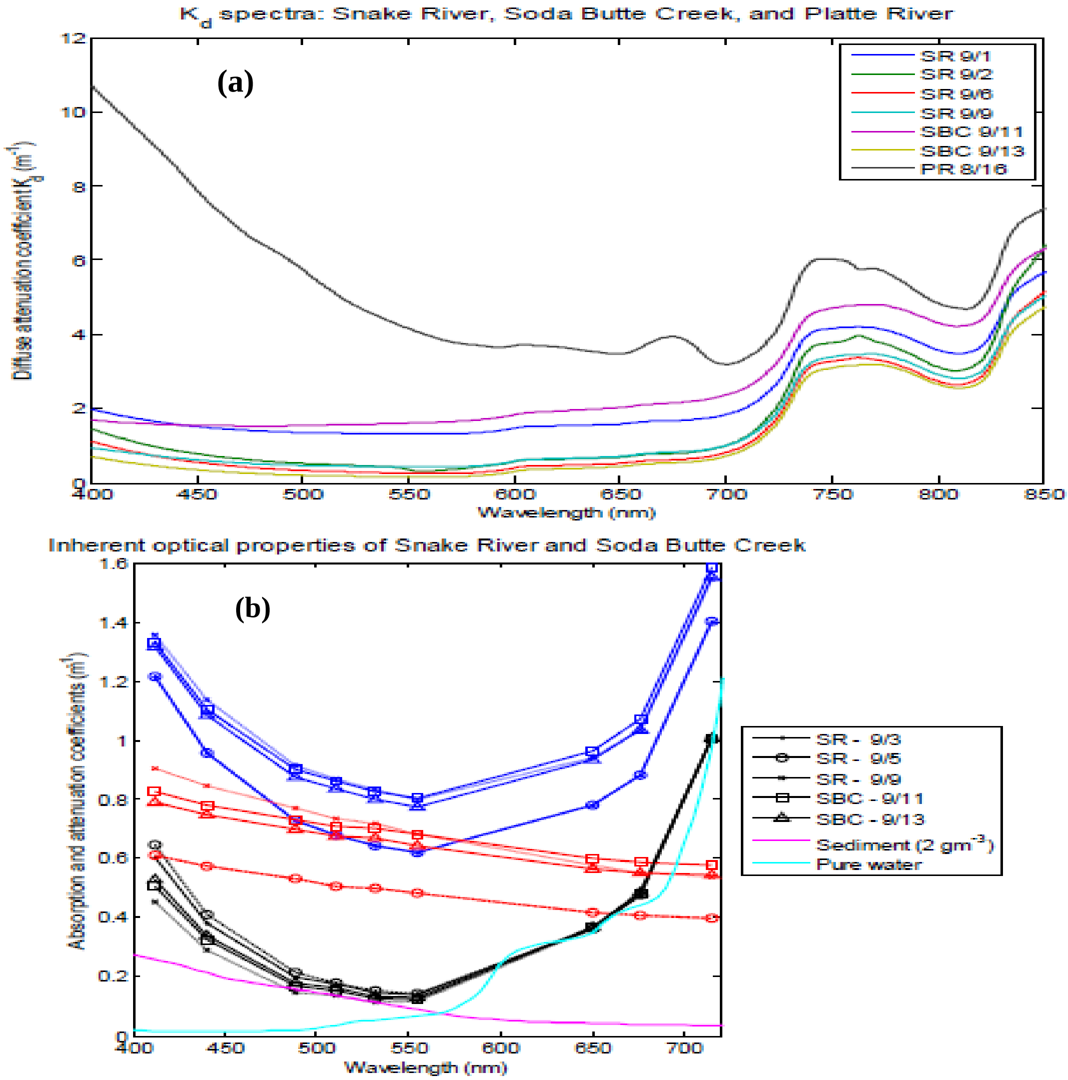

Figure 9. (a) Diffuse attenuation coefficient K_d spectra measured along the Snake River and Soda Butte Creek; the more turbid Platte River is also shown for comparison. (b) Inherent optical properties measured with an ac-9, along with absorption coefficients for pure water and suspended sediment. Absorption, scattering, and attenuation coefficients are represented by black, red, and blue lines, respectively, with unique symbols for each site/date.

from Platte River, a much more turbid stream where we have examined previously (Legleiter et al., 2011), 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 9b, 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 optical model might be sufficient to describe these streams, although colored dissolved organic matter should be considered as well to account for the increase at wavelengths shorter than 500 nm. The turbidity values recorded during our field campaign were consistent and low: 2 - 3 NTU. Suspended sediment concentrations were also minimal: 2 mg/L for each of three water samples. These data quantify the exceptional clarity of the Snake River and imply that this stream is amenable to remote sensing techniques.

Also during our 2011 field campaign, we made significant progress toward our goal of establishing 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 10a 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 10b indicate that various substrate types are spectrally distinct from one another, however, implying that this type of 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 possibility via radiative transfer modeling and hyperspectral image data to be acquired in 2012.

Mapping flow depth from remotely sensed data

In addition to their more traditional role as a means of recording changes in channel planform, remotely sensed data can be used to quantify spatial variations in flow depth, thus adding a third dimension to the analysis of river dynamics. In this study, we applied the band ratio-based algorithm described above to retrieve depth information from the WorldView2 images acquired in September 2011. Whereas the reflectance spectra measured in the field were essentially continuous, with a 1 nm sampling interval, the multispectral satellite measures reflectance in a set of only eight discrete bands. To assess whether this reduction in spectral resolution might affect depth retrieval performance, we resampled the original field spectra to the band passes of the WorldView2 sensor and repeated the OBRA calculations for the degraded, eight-band spectra. This analysis is summarized in Figure 11a, which is remarkably similar to Figure 8c, with only a slight reduction in the depth vs. X regression R^2 for the optimal band ratio: 0.839 for green/yellow. These results imply that mapping the bathymetry of a gravel-bed river from space was not only possible but potentially highly accurate.

More direct evidence to support this contention was obtained by extracting spectra from WorldView2 image pixels at the locations of field-based depth measurements. These data were then used to perform an OBRA of the WorldView2 spectra, and the results depicted in Figure 11b once again imply a strong, linear relationship between the image-derived quantity and flow depth, with an R^2 value of 0.819 for the ratio of blue and yellow bands.

Applying the corresponding equation to the image produced the continuous bathymetric map in Figure 12. The greatest depths occur along the outer bank, with much shallower flow over the point bar on the right (north) side of the channel through the apex of Rusty Bend. A riffle extends across the channel at the exit to the bend before entering a pool along the right bank where the channel curves to the left. This spatial pattern is hydraulically reasonable and consistent with our field observations.

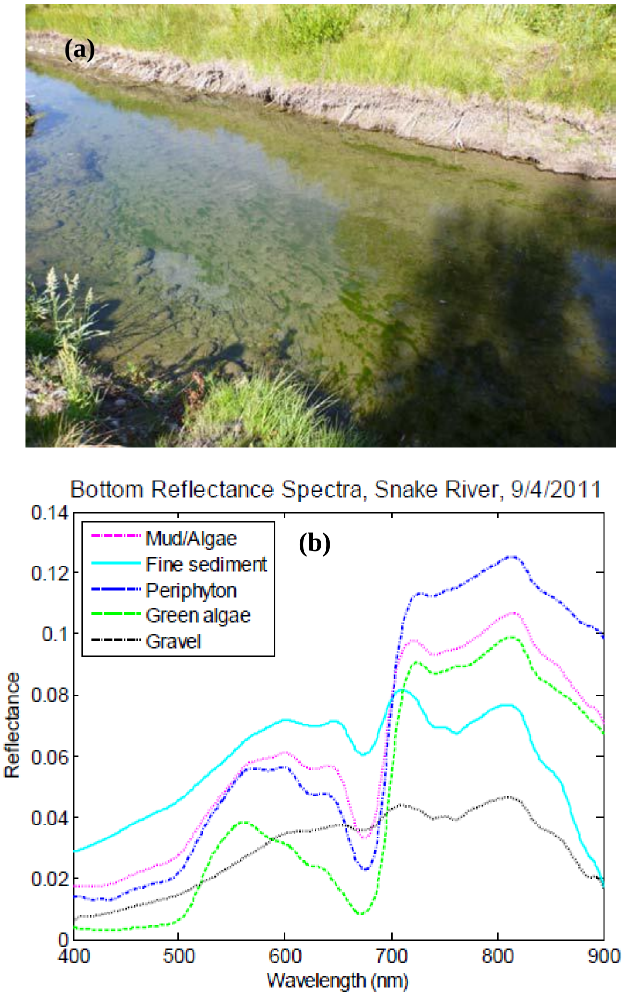

Figure 10. (a) Photo showing the complex spatial distribution of different substrates along a side channel of the Snake River, including fine sediment, gravel, and green algae. (b) Bottom reflectance measurements from this site, illustrating that various bottom types are spectrally distinct.

To assess the accuracy of the image-derived bathymetry, we compared the spectrally-based depth estimates to field measurements obtained via wadingin shallow areas or with the echo sounder mounted on the cataraft. Of thses field data, half were selected at random for use in calibrating the OBRA realtion and the other half set aside for validation. A plot of observed vs. predicted depths is shown in Figure 13a, which indicates a strong agreement with an R^2 value of 0.83. Moreover, the slope and intercept of the regression line are nearly equal to 1 and 0, respectively, indicating that depth estimates are unbiased on average. A closer inspection, however, reveals that the scatter plot includes some curvature, which is manifested as under-estimation of both the smallest and largest depths. To visualize the spatial distribution of these depth retrieval errors, we produced a continuous

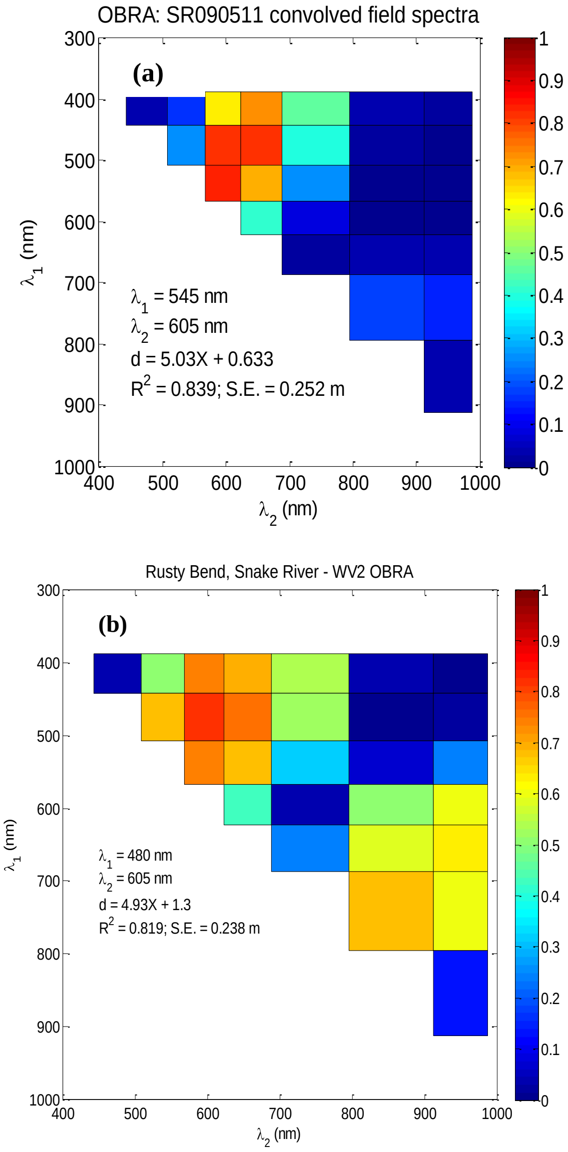

Figure 11. (a) Optimal band ratio analysis (OBRA) of field spectra convolved (resampled) to the spectral bands of the WorldView2 satellite. (b) OBRA of WorldView2 image spectra from pixels with field-based depth measurements.

depth map from our field data via ordinary block kriging (OBK), a geostatistical interpolation technique, and subtracted the image-derived bathymetry from this map. The resulting map of residuals, or depth retrieval errors, is shown in Figure 13b. In this representation, positive values occur where depths were under-predicted from the image and negative values where spectrally-based depth estimates were greater than those interpolated from the field data (i.e., over-predicted from the image).

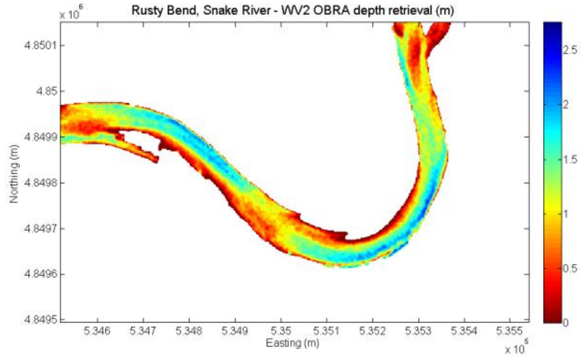

Figure 12. Bathymetric map derived from a WorldView2 satellite image using the OBRA relation from Figure 11b. Flow is to the west, from top right to middle left.

In Rusty Bend, positive residuals along the outer bank suggest that the full depth of the pool on the left side of the channel could not be resolved from the image data. Conversely, the red tones past the bend apex indicate an area where depths were over-predicted from the image. These results are consistent with radiative transfer theory (Legleiter et al., 2004) and imply that some systematic biases in depth retrieval performance might arise solely as a function of the river morphology itself, most notably a tendency to under estimate pool depths. Nevertheless, these errors were relatively small, and the overall depth retrieval performance of the WorldView2 satellite was quite good. In general, our results suggest that spectrally-based bathymetric mapping from space is not only feasible, but potentially sufficiently accurate for many practical applications. At a minimum, a remote sensing approach can provide an informative, qualitative impression of the gross morphology of a channel.

Obtaining precise measurements of bed elevation to serve as topographic input data for hydraulic modeling or for quantifying erosion and deposition might require more sophisticated hyperspectral image data with greater radiometric resolution. We intend to acquire such data in 2012 and will evaluate the extent to which reliable river information needed to support more demanding applications can be obtained via remote sensing. Although the potential for remote mapping of fluvial systems is clearly significant, the inherent limitations of this approach - shadows, reduced water clarity, greater depths, etc. - must be borne in mind as well.

Channel change during the 2011 spring runoff

An unusually large snowpack accumulated in the Snake River watershed during the winter of

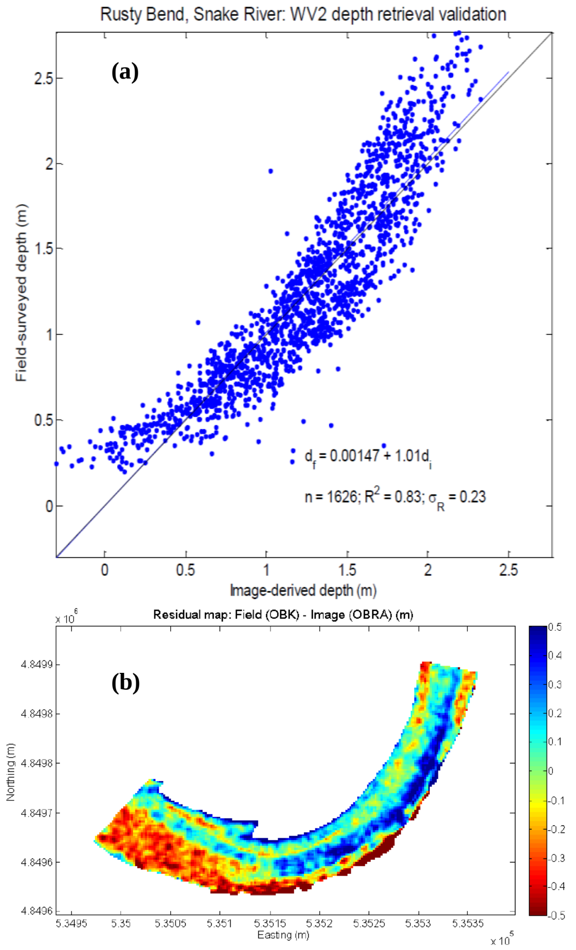

Figure 13. (a) Validation of image-derived depth estimates via observed vs. predicted regression analysis. (b) Residual map of depth retrieval errors produced by comparing a continuous depth map based on field measurements to image-derived estimates. Positive residuals indicate under-prediction of depth from the image and negative residuals correspond to over-predictions of depth from the image.

2010-2011 and persisted well into the spring. When the snow finally melted, a prolonged period of sustained high flow ensued and lasted throughout August. We hypothesized that this flood event would produce significant channel changes along the Snake River corridor and we used the 2010 digital aerial photography and 2011 satellite images to examine the magnitude, nature, and extent of morphologic adjustments. We have only recently initiated this analysis and the results reported herein are preliminary and might be revised to some extent as we refine our methodology. Also, for the purposes of this report, we focus on a segment of the river upstream from the Deadman's Bar boat access that we expected to be dynamic based on field observations, the braided morphology of the reach, and geomorphic context.

To identify areas of channel change, we produced land cover classifications from each image date using a decision tree algorithm. This technique assigns a heterogeneous population (i.e., image pixels) into pre-defined groups by creating a set of rules based on training data provided for each class. These rules take the form of simple binary choices based on thresholds for one of the variables (i.e., spectral bands) used to perform the classification. In this study, we sought to distinguish six classes present along the valley floor: water, gravel, riparian vegetation, forest, sage, and shadows. Representative training sites for each of these classes were digitized from both the 2010 air photos and the 2011 satellite image and a separate decision tree developed for each date. Applying the trees to the images produced the land cover maps shown in Figure 14.

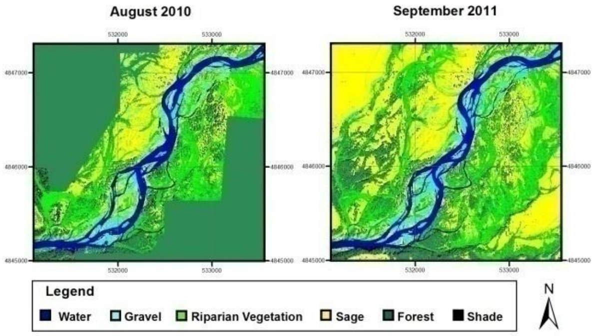

Figure 14. Land cover maps of a portion of the Snake River upstream from the Deadman's Bar boat access, produced from digital aerial photography from 2010 and a 2011 WorldView2 satellite image. This pair of maps thus captures changes that occurred during the 2011 runoff.

The macroscopic impression given by these maps is not of change, but rather stability. In contrast to the dynamic behavior we hypothesized, this segment of the Snake River appears to have experienced only relatively minor morphologic adjustments. To confirm this inference and more effectively highlight those changes that did occur, we compared the 2010 and 2011 classifications by identifying the active channel for each time period as those pixels classified as water or gravel and creating a binary channel mask. Subtracting the 2011 active channel mask from the 2010 mask thus served to isolate areas of erosion (active channel in 2011 but not in 2010), recovery (active channel in 2010 but not in 2011), and no change. The results of this simple, preliminary analysis are shown in Figure 15, which confirms that most of the reach remained stable. The red areas along either side of the channel might indicate actual erosion but are largely a consequence of the higher flows at the time the 2011 image was acquired, implying a greater inundated area and not necessarily erosion. Similarly, some areas mapped as recovery could be an artifact of classification errors, as the gravel and sage categories were easily confused with one another. Despite these caveats, we were underwhelmed by the amount of change that occurred during the 2011 flood within a reach that we had expected to exhibit much more dynamic behavior. These results might imply that the channel morphology is adjusted so as to remain relatively stable from a larger-scale, synoptic perspective, despite local reworking of mid-channel bars. Ongoing work will examine other reaches along the river and assess whether the river is, as these preliminary results suggest, dynamically stable.

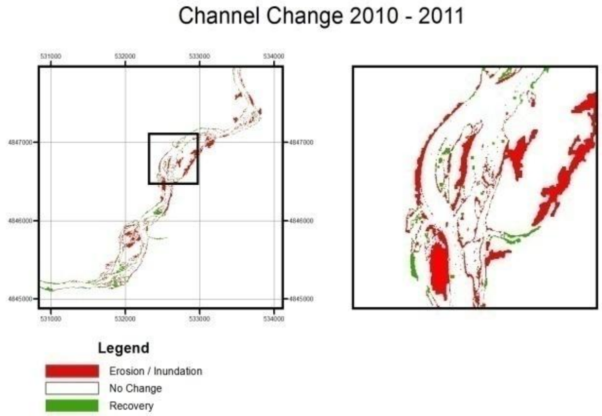

Figure 15. Summary of channel changes occurring in 2011 along a segment of the Snake River above Deadman's Bar.

Field measurements of river hydraulics

In addition to field surveys of channel and floodplain topography, we also used an acoustic Doppler current profiler (ADCP) deployed from a kayak to measure flow velocities on cross-sections and longitudinal profiles distributed throughout our study area along the Snake River. This instrument provided a wealth of hydraulic information, including observations of three-dimensional velocity components in a set of vertical cells distributed throughout the water column, recorded at a frequency of once per second as the kayak moved along and across the river. These data thus yield a detailed depiction of the flow patterns that determine the magnitude and orientation of fluid forces that in turn mobilize and transport sediment and thus dictate the trajectory of channel change. Though not directly relevant to remote sensing, the ADCP data will thus help us to understand the geomorphic processes responsible for the river dynamics observed in our image time series.

We have made significant progress analyzing the ADCP data collected in 2011, but only a couple of examples are presented here to illustrate the kind of information we have obtained. Our efforts to characterize the flow field were focused on a pair of meander bends that have a similar curvature and overall geometry but a very different morphology. The first site, Swallow Bend, is unusual in that a terrace protruding into the channel near the bend entrance has created an obstruction that 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 7b). Comparing the flow field through these two bends will thus allow us to isolate the influence of a constriction on patterns of velocity, sediment 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 16a 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 16b 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 during our field campaign. These discharge readings will be used to develop new algorithms for retrieving depth information from remotely sensed data when direct field measurements are not available for calibration, based on hydraulic relationships that serve to constrain a numerical optimization procedure. Future work also will involve collecting additional ADCP data to help advance our understanding of the manner in which river morphology and hydraulics influence sediment transport and ultimately channel change.

✦ MANAGEMENT IMPLICATIONS

This ongoing study directly contributes to the Park Service's current management priorities and could provide a powerful tool for assessment and

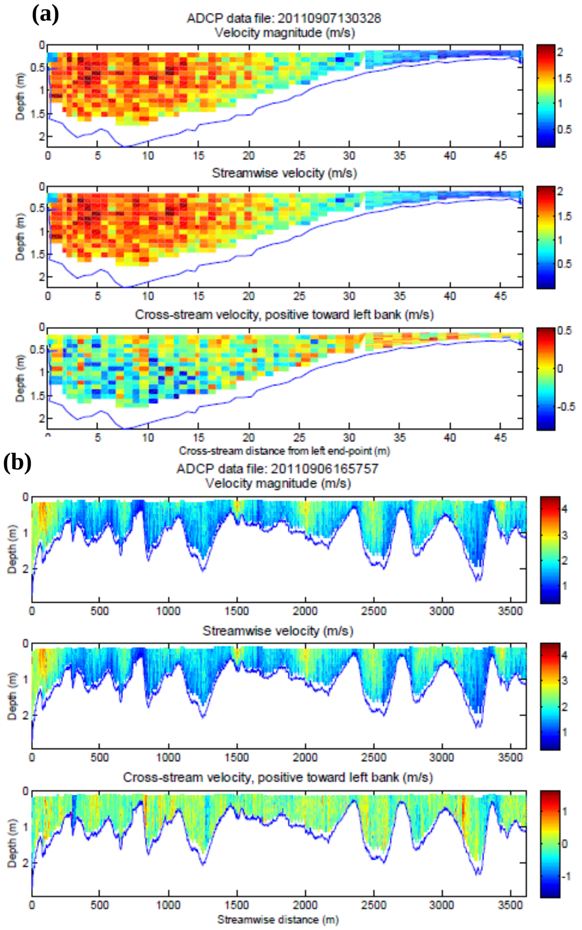

Figure 16. (a) ADCP measurements of the flow field through Rusty Bend. Data have been resolved into streamwise and cross-stream components. (b) ADCP data along a longitudinal profile extending over 3.6 km downstream from Rusty Bend, highlighting undulations in the bed topography and the associated variations in the velocity field.

monitoring of riverine resources throughout the region. The 2009 Craig Thomas Snake River Headwaters Act designated the river above Jackson Lake as a Wild River and the segment from Jackson Lake Dam to Moose, along with the Pacific Creek and Buffalo Fork tributaries, as Scenic Rivers in recognition of their ecological, aesthetic, and recreational value. This legislation provides these streams with protected status as part of the National Wild and Scenic Rivers System and ensures the free-flowing condition of these waterways. Along with this designation comes the task of determining how best to preserve this remarkable fluvial system. Accordingly, the Park Service has set out to develop a new river management plan, which will involve documenting these unique natural resources and identifying effective strategies for their protection. Park managers are thus obligated to characterize the form and behavior of the Snake River, along with the associated habitat conditions and recreational opportunities. Our primary objective is to derive such information from remotely sensed data; this continuing project will thus directly inform the Park's river management plan. Moreover, the techniques developed as part of this investigation could be applied to other streams throughout the Snake River headwaters, both those that have already been awarded Wild and Scenic status and others that might merit such consideration in the future. Although remote sensing clearly offers significant potential to facilitate a number of river-related applications, this potential has not been realized in practice, and the capabilities and limitations of a remote sensing-based approach must first be established. By demonstrating the utility of these methods, and also acknowledging their deficiencies, this study of the Snake River could lead to more widespread, effective use of remote sensing in river research and management.

Acknowledgements

In addition to logistical support from the UW-NPS Research Station, this project received funding from the Office of Naval Research. Field work along the Snake River would not have been possible without the able assistance of Clem Rawlins. Annie Toth also contributed to the field effort. Satellite image acquisition was coordinated by Gregory Miecznik, and Amanda Marchetti. Alan Wiedemann of the Naval Research Laboratory loaned the ac-9 instrument and Wesley Goode provided guidance for its use. We are grateful to Kathy Mellander, Susan O'Ney, Sue Consolo-Murphy, and Linda Franklin of the National Park Service for their support of our study.

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