Measurement and Mapping of Riverine Environments by Optical Remote Sensing

Carl J. Legleiter
Department of Geography, Dept. 3371
University of Wyoming
1000 E. University Ave.
Laramie, WY 82071
phone: (307) 766-2706 fax: (307) 766-3294 email: cleglei1@uwyo.edu

Award Number: N00014-10-1-0873
http://uwadmnweb.uwyo.edu/geog/displayfaculty.asp?facultyid=6324

LONG-TERM GOALS

The primary long-term goal of this study is to develop an improved capacity for mapping river corridors and obtaining high-resolution measurements of channel morphology and hydraulics by means of optical remote sensing. The ability to efficiently and non-invasively characterize riverine environments could benefit both the national defense and scientific research communities in a number of important ways. In order to fully realize this potential, however, several key issues must be addressed. The overall goals of this new project, initiated in July 2010, are to:

1. Refine our understanding of the radiative transfer processes that govern the interaction of electromagnetic energy with the atmosphere, air-water interface, water column, and substrate, and the measurement of that energy by a remote detector. Because these processes both enable and limit the inference of river attributes from optical data, this effort could lead to novel techniques for measuring depth, bottom composition, and flow velocity, along with an awareness of the inherent uncertainties associated with these methods.

2. Systematically evaluate the ability of various remote sensing technologies to map a range of riverine environments. This assessment will help to define the extent to which different types of instruments deployed above a diversity of channel types can provide the accuracy, precision, and dynamic range required by specific applications.

3. Develop more efficient ways of 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:

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

- Evaluate the potential of various sensing technologies for remote mapping of rivers through a combination of modeling and field-based empirical validation at different sites.

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

APPROACH

As we pursue our overarching goal to measure, map, and better understand river systems via optical remote sensing, we are engaging in a variety of research activities – this project involves field measurements, numerical modeling, and image acquisition in a range of fluvial environments. Our field campaigns are intended to provide the basic data on river channel optical characteristics needed to parameterize radiative transfer models that can then be used to simulate spectra for known combinations of depth, bottom type, water surface state, and concentrations of various materials within the water column (Legleiter et al., 2004, Legleiter and Roberts, 2005, Legleiter et al., 2009). Incorporating the resulting spectral library into the forward image modeling framework described by Legleiter and Roberts (2009) will enable us to develop and systematically evaluate algorithms for inferring channel attributes from image data. To empirically validate these techniques and assess their performance across a range of conditions, a series of remote sensing missions will be conducted and image-derived estimates compared to ground-based measurements coordinated 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, the experience we gain while working with these images will allow us to develop integrated workflows for efficiently extracting 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 Paul Kinzel, a hydrologist with the U.S. Geological Survey. In addition, UW students Brandon Overstreet and Chip Rawlins have contributed to the field effort. A graduate student assistant will be recruited to begin work on this project in the fall semester of 2011.

WORK COMPLETED

The early stages of this investigation have focused on acquiring field measurements and remotely sensed data from a number of different rivers. In the first couple of months of this project we have made significant progress toward our first two objectives by (1) characterizing the optical properties of stream channels; and (2) evaluating the performance of various kinds of sensors in a range of fluvial environments. Work completed so far includes the following field sites and data collection activities:

1. Soda Butte Creek and the Lamar River, Yellowstone National Park. Both hyperspectral image data (HyMap) and high-resolution digital aerial photography (UltraCam) were acquired along these dynamic gravel-bed channels on August 2. In anticipation of this flight, field measurements of bed topography, flow depth, and river discharge were collected for two study reaches on July 20-22, with additional surveying performed during a second trip August 7-13. In addition, a newly obtained spectroradiometer was used to measure reflectance spectra from above the water

surface and, importantly, within the water column directly above the streambed. The survey data have been processed to derive digital terrain models for each reach and will be used to assess the accuracy of image-derived depth estimates. Initial inspection of the field spectra indicates that the data are of reasonably good quality, but some refinements to our field protocols will be necessary, particularly for measuring bottom reflectance. We have just received the UltraCam digital photography and these images appear promising; an example is shown in Figure 1. The hyperspectral data should be forthcoming, and we intend to assess their utility for bathymetric mapping as well.

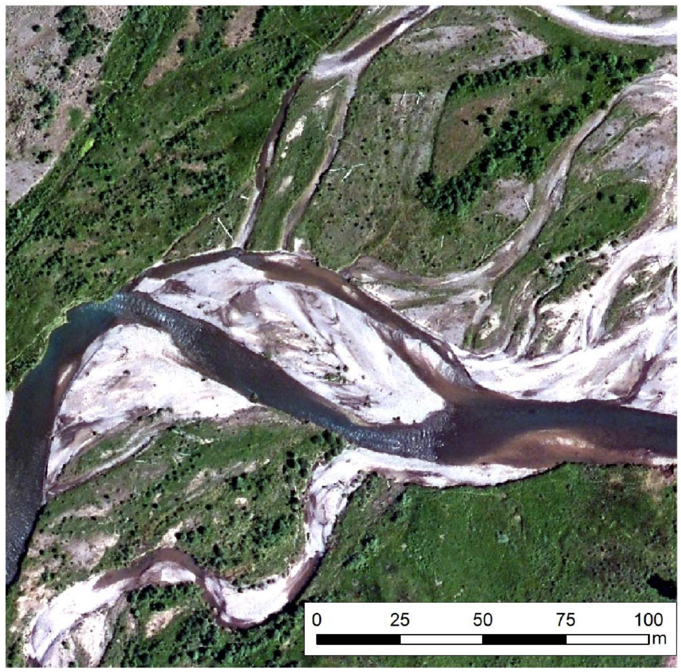

Figure 1. High resolution digital aerial photography from the Round Prairie Reach of Soda Butte Creek, Yellowstone National Park, August 2, 2010.

2. Snake River, Grand Teton National Park. Our initial plans for this new site called for a relatively simple reconnaissance in anticipation of a more intensive field campaign in 2011. A fortuitous combination of qualified personnel and equipment loans instead allowed us to complete bathymetric surveys and record flow velocities along 22 km of this complex, braided river system. During our August 2-6 campaign we learned to use new equipment including an RTK GPS, echo sounder, and acoustic Doppler current profiler and gained valuable experience with the logistics of boat-based measurements on larger rivers. The small cataraft shown in Figure 2 was outfitted to serve as a measurement platform, and flow depths and vertical velocity profiles were recorded along cross sections (Figure 3) and a series of longitudinal passes down the channel; additional depth measurements were obtained via wading the shallow margins of the river. In addition to these field data, multispectral images were acquired through the Upper Midwest Aerospace Consortium's AEROCam program on August 11 (Figure 4). This latter data set will allow us to assess the feasibility of mapping river bathymetry from relatively basic, readily available image data. More importantly, we gained familiarity with the Snake River and these new measurement techniques that will allow us to effectively plan field activities and image acquisition for 2011.

Figure 2. Cataraft, echo sounder, and acoustic Doppler current profiler used on the Snake River.

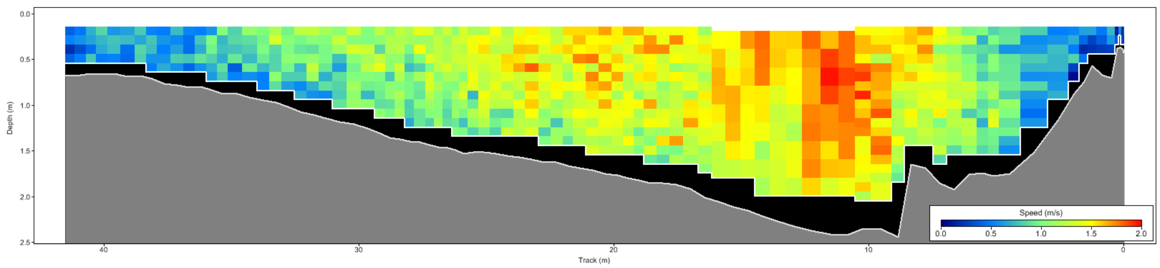

Figure 3. Flow field measured with an acoustic Doppler current profiler on the Snake River.

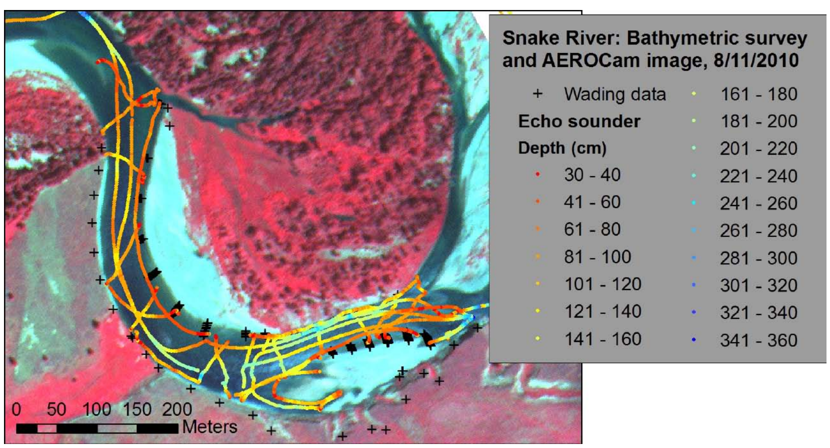

Figure 4. Bathymetric survey and AEROCam multispectral image of the Snake River.

3. Platte River, Nebraska. Ground-based surveys, field spectra, and hyperspectral image data were acquired from three reaches of the Platte River in central Nebraska on August 14-18. Topographic data consisted of a series of regularly spaced cross-sections, established by the U.S. Geological Survey as part of a long-term monitoring study, spanning the wide, braided channel. Flow depths were derived from these data by subtracting bed elevations from surveyed water surface elevations. In addition to reflectance spectra recorded above the water surface, attenuation within this turbid river was characterized by measuring the downwelling spectral irradiance at different depths within the water column. Water samples collected at the same time are being processed to determine suspended sediment concentration. Hyperspectral images acquired by an

Airborne Imaging Spectrometer for Applications (AISA) sensor operated by the University of Nebraska were used in combination with the field measurements to produce continuous bathymetric maps. Our analysis of this Platte River data set is underway and our initial results are described below.

4. Laramie River, Little Laramie River, and Savery Creek, Wyoming. Detailed surveys of bed topography and direct measurements of river discharge were completed along these three streams in September 2010. AEROCam multispectral images were acquired from each site as well. Similar image data were obtained for the Laramie River in August 2009 and will be used to examine the effects of record flooding that occurred in June 2010. Savery Creek is the focus of an ongoing study of bank erosion and channel migration processes in relation to the modified flow regime dictated by a new reservoir. For the purposes of this investigation, field data from these sites will be used to parameterize forward image models and assess the feasibility of mapping the bathymetry of smaller streams via remote sensing. The AEROCam image data will enable empirical evaluation of this potential and should also facilitate the development of novel algorithms for calibrating image-derived depth estimates.

RESULTS

We have amassed a large amount of data from several different sites during the first couple of months of this project, but our analysis to date has focused primarily on the Platte River. This section reports some initial results from this location, and we are scheduled to present our findings at the AGU conference in December. Our primary objective was to derive continuous bathymetric maps from the hyperspectral image data. Reflectance spectra R_λ measured in the field for flow depths from 5- 67 cm and a range of substrate types were subjected to the Optimal Band Ratio Analysis (OBRA) procedure described by Legleiter et al. (2009). Briefly, this algorithm involves regressing log-transformed band ratio values against measured depths for all possible band combinations, with that pair of bands yielding the highest regression R^2 considered optimal. OBRA thus serves to identify an appropriate combination of bands for depth retrieval and to calibrate a relation between an image-derived quantity X and flow depth d. On the Platte, OBRA of field spectra yielded a strong, linear relationship (R^2 = 0.95) between $X = \ln(R_{593}/R_{647})$ and d. Figure 5 also indicates that many other band combinations would also yield high X vs. d R^2 values, implying that bathymetric information can be obtained from a fairly broad portion of the optical spectrum, even under fairly turbid water conditions.

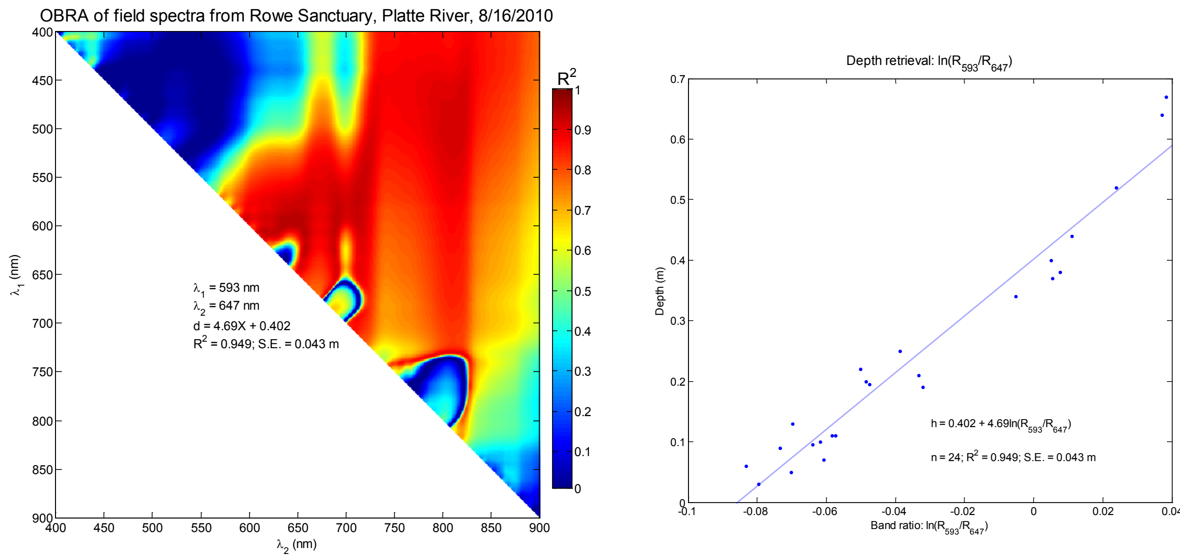

Figure 5. Optimal band ratio analysis (OBRA) of field spectra from the Platte River. The left panel depicts R^2 values resulting from regressions of log-transformed band ratio values for all possible combinations of bands; λ_1 and λ_2 denote the numerator and denominator, respectively. A scatter plot and regression relation for the optimal band ratio (highest R^2) are shown in the right panel.

Similar band ratio analyses were performed using reflectance spectra extracted from the hyperspectral image data at survey points. Image-based OBRA produced variable results for the three study sites along the Platte. For a narrower, deeper reach lacking mobile mid-channel bars, an $X = \ln(R_{490}/R_{638})$ vs. d relation had an R^2 of 0.83; applying this expression to the image generated a bathymetric map that agreed closely with our survey data (Figure 6). The other two sites featured fully braided morphologies, shallower depths, and numerous lobate bar forms, and image-based OBRA resulted in lower maximum R^2 values of 0.47 and 0.53. Closer inspection of image-derived and surveyed cross-sections indicated that this poor agreement was partially explained by: 1) inaccurate geo-registration between the image and field data; 2) translation of the bar forms during the four days between the image acquisition and the completion of the field surveys; and 3) the presence of a range of depths within individual 0.75 m image pixels due to the abrupt variations in bathymetry associated with the bar-chute morphology. Examination of depth maps for the latter two reaches suggested that image-derived depths were actually more reliable than conventional accuracy metrics, such as regression R^2 values, might seem to indicate. Moreover, applying the band ratio relation derived from field spectra directly to the image data yielded depth estimates that closely matched our field data. This latter finding implies that calibration based on field spectra is a viable alternative to pairing image pixels with ground-based depth measurements, which can be highly problematic for the reasons cited above.

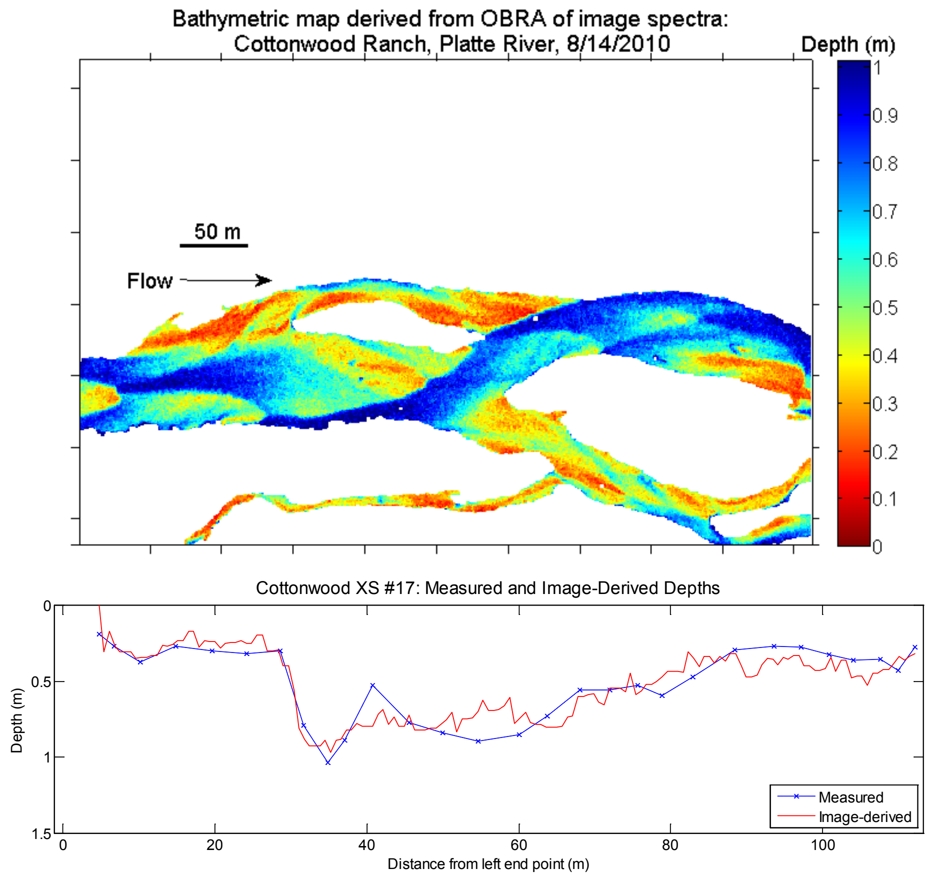

Figure 6. Top: A bathymetric map derived from a hyperspectral image of the Cottonwood Ranch section of the Platte River via OBRA of spectra extracted from the image. Bottom: Comparison of field measurements and image-derived depth estimates along a surveyed cross-section.

These results are encouraging because the Platte River represents a more turbid optical environment than the relatively clear-flowing streams we had examined previously. In order to characterize attenuation within the water column, we used a specialized waterproof 180° foreoptic with a cosine response to measure the downwelling spectral irradiance at different depths within the water column. Following Mishra et al. (2005), we used these data to estimate the diffuse attenuation coefficient K_d, an apparent optical property that influences the precision of image-derived depth estimates and largely determines the maximum detectable depth. Initial results from this ongoing analysis are summarized in Figure 7, which is consistent with the expected pattern of strong attenuation in the blue and green wavelengths < 600 nm due to scattering by suspended sediment and in the near-infrared (>700 nm) due to rapid absorption by pure water. Future work will focus on incorporating these data into radiative transfer models and calculating metrics of bathymetric precision and depth retrieval dynamic range.

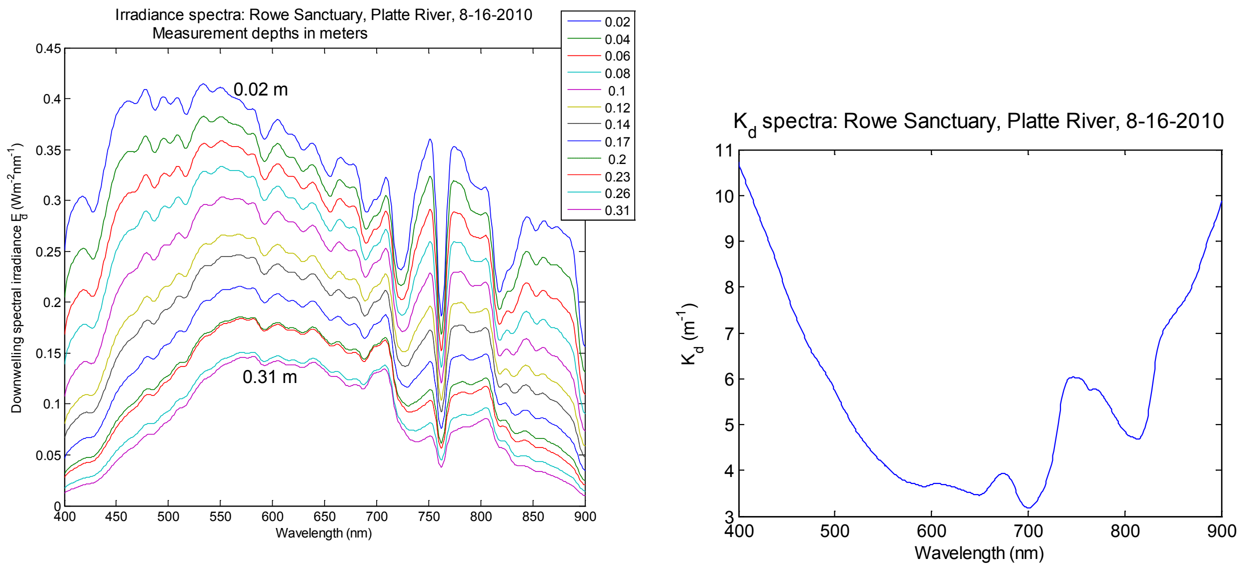

Figure 7. Left: field measurements of downwelling spectral irradiance obtained at different depths within the water column of the Platte River. Right: Values of the diffuse attenuation coefficient derived from these irradiance data following the approach of Mishra et al. (2005).

IMPACT/APPLICATIONS

This investigation will substantially improve our capacity to measure riverine environments via optical remote sensing. Because rivers are important elements of the landscape, strategically as well as scientifically, this efficient approach to obtaining basic data on river form and behavior could not only facilitate defense missions but also advance our scientific understanding of fluvial systems.

RELATED PROJECTS

This new project represents an outgrowth and extension of work initiated while the Principal Investigator was employed as a post-doctoral researcher with the U.S. Geological Survey's Geomorphology and Sediment Transport Laboratory as part of the related study "Computational Modeling of River Flow, Sediment Transport, and Bed Evolution Using Remotely Sensed Data" (Award # N0001409IP20057, Principal Investigator Jonathan M. Nelson).

REFERENCES

Legleiter, C.J., and Roberts, D.A. 2005. Effects of channel morphology and sensor spatial resolution on image-derived depth estimates. *Remote Sensing of Environment*, 95(2): 231-247.

Legleiter, C.J., and Roberts, D.A. 2009. A forward image model for passive optical remote sensing of river bathymetry. *Remote Sensing of Environment*, 113(5): 1025-1045.

Legleiter, C.J., Roberts, D.A., Marcus, W.A. and Fonstad, M.A. 2004. Passive optical remote sensing of river channel morphology and in-stream habitat: physical basis and feasibility. *Remote Sensing of Environment*, 93(4): 493-510.

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.

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

Legleiter, C.J., Kyriakidis, P.C., McDonald, R.R., and Nelson, J.M. In revision. Effects of uncertain topographic input data on two-dimensional flow modeling in a gravel- bed river. *Water Resources Research*. (Accepted subject to minor revisions)

Legleiter, C.J., Harrison, L.R., and Dunne, T. In revision. Effect of point bar development on the local force balance governing flow in a simple, meandering gravel-bed river. *Journal of Geophysical Research — Earth Surface*. (Accpeted subject to moderate revisions)

Harrison, L.R., Legleiter, C.J., Wydzga, A., and Dunne, T. In review. Channel dynamics and habitat development in a meandering, gravel-bed river. *Water Resources Research*. (Revised once, currently in second round of external review)

Marcus, W.A., Fonstad, M.A., and Legleiter, C.J. In revision. Management applications of optical remote sensing in the active river channel. In *Remote Sensing of Rivers: Management and Applications*, Carbonneau, P.C., and Piegay, H., eds. (One review, currently being revised).

Legleiter, C.J., and Fonstad, M.A. In press. An introduction to the physical basis for deriving river information from remotely sensed data. In *Remote Sensing of Rivers: Management and Applications*, Carbonneau, P.C., and Piegay, H., eds. (Accepted, book to be published in 2011)

Legleiter, C.J., and Roberts, D.A. 2009. A forward image model for passive optical remote sensing of river bathymetry. *Remote Sensing of Environment*, 113(5): 1025-1045.

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.