## ✦ INTRODUCTION

The Snake River in Grand Teton National Park (GTNP) is a highly dynamic gravel-bed river that represents an important Park asset as well as an iconic component of the Jackson Hole landscape. In addition, frequent channel changes along the river create a rich diversity of habitat for aquatic and terrestrial species. The Snake River's scenery, fishery, and wildlife draw thousands of river users each year, making the river a key element of the local tourist economy.

Regionally, the river is a prime source of irrigation water for agriculture on Idaho's Snake River Plain. Flows on the Snake have been regulated since 1907 by Jackson Lake Dam (JLD), which was constructed at the outlet of the preexisting, Pleistocene aged Jackson Lake (Love, 2003). The Snake River in GTNP is distinct from most other dam-regulated gravel-bedded rivers in that abundant coarse sediment supplied from tributaries downstream of the dam allows the river to maintain a braided morphology that is typically associated with a sediment surplus.

While the sediment supply to the Snake River has been unaffected by JLD, flow regulation at the dam has reduced the magnitude and altered the timing of peak streamflows in an effort to prolong late summer flows to meet downstream water demands (Erwin et al. 2011, Marston et al. 2005). Within GTNP, a balanced approach to flow management is critical to the health of the riparian ecosystem. A complete understanding of the river's sediment budget also is crucial to effective flow management. Climate change and associated shifts in the timing of water demands might necessitate corresponding adjustments in flow regulation by JLD. A refined understanding of the geomorphic effects of such flow regulation will inform managers seeking to maintain the physical and ecological integrity of the Snake River within GTNP while also meeting downstream water demands.

In this study we are coupling remote sensing data with extensive field surveys to closely monitor the geomorphic changes occurring on the Snake River. This study seeks to track how annual runoff events and flow management strategies influence patterns of sediment transfer and storage throughout the river system, with a particular focus on tributary junctions. More specifically, we are using an image time series to identify areas of erosion and deposition and hence to infer bed material transport from the observed changes in channel morphology.

In addition, the consistent, clear late-summer releases from JLD make the Snake River an ideal location for testing remote sensing technology and developing new techniques for deriving various kinds of river information attributes from image data. In addition to tracking geomorphic change on the Snake River, we are also developing new techniques for extracting channel attributes from the water surface, water column, and bed from hyperspectral image data.

## ✦ STUDY AREA

The remotely sensed data available to support this investigation provide complete coverage of the Snake River from JLD to Moose (Figure 2a). To be consistent with previous sediment budget studies (Erwin et al. 2011), we are initially focusing on the area between Pacific Creek and Deadman's Bar. In this reach, the river alternates between a relatively stable, single-channel configuration and a highly dynamic multi-channel pattern. In addition to quantifying the overall dynamics of this river segment, we are working to characterize in greater detail the channel changes occurring at confluence zones associated with Pacific Creek, Buffalo Fork, and Spread Creek, as well as two meander bends, referred to as Rusty Bend (Figure 2b) and Swallow Bend (Figure 2c), where we are focusing on understanding the relationships among point bar growth, the flow field within the channel, and bank erosion.

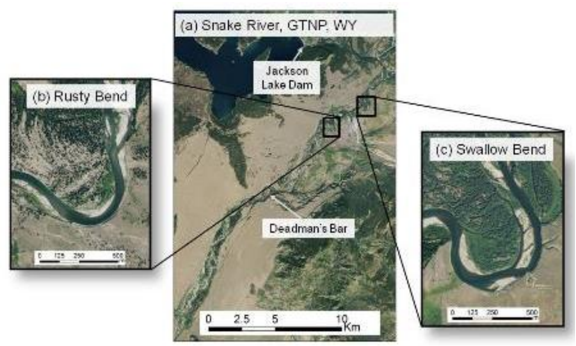


**Figure 2.** (a) Location of two primary study sites along the Snake River in Grand Teton National Park: (b) Rusty Bend and (c) Swallow Bend.

## ✦ METHODS

Our research group has obtained an extensive dataset to monitor geomorphic changes occurring on the Snake River that includes: 1) an annual time series of aerial images from 2009-2014; 2) LiDAR-derived digital elevation models from 2007, 2012, and 2014; and 3) field measurements of bathymetry and hydraulics collected annually from 2010-2014. This combination of optical image data, LiDAR, and field data allows us to precisely measure annual channel changes and associate these changes with specific run-off events. The six consecutive years of imagery encompass a range of flow regulation strategies, as well as natural runoff events on Snake River tributaries, that include both high magnitude flow events and the second lowest peak discharges observed on the Snake River in 111 years of record.

In 2013 and 2014, we continued to build upon these extensive remote sensing and field data sets. In the past two years we have greatly expanded the types of field measurements we can obtain from large rivers such as the Snake by acquiring new instrumentation for measuring various river attributes and by building new platforms for deploying these sensors. These new measurement capabilities, coupled with new image processing techniques, help to expand the utility of remotely sensed data for river management.

**Remotely sensed data collection**

In August of both 2013 and 2014 we acquired hyperspectral imagery deploying our CASI 1500H hyperspectral imaging system from a Cessna Caravan fixed-wing aircraft operated by contractor Quantum Spatial. This specialized instrument has allowed us to adjust the sensor's configuration to meet the unique requirements for imaging river environments. For example, in 2013 and 2014, we collected imagery with a higher spatial resolution than has been previously collected on the Snake River. The 2013 and 2014 hyperspectral images are important additions to the database of hyperspectral, multiband satellite, and publically available imagery that we have compiled for the Snake River.

LiDAR data collection was planned for both 2013 and 2014. LiDAR uses laser pulses to precisely map surface topography. Traditional LiDAR systems emit near-infrared (NIR) laser pulses to measure surface topography. While NIR LiDAR create accurate maps of terrestrial surfaces, the NIR wavelength pulses are rapidly attenuated in water; hence it cannot be used to map river bathymetry.

The classified LiDAR point cloud in Figure 3 produced from 2012 NIR LiDAR at Rusty Bend illustrates the 3-dimensional view of the riverscape that LiDAR provides. While vegetation (green points) and terrestrial features (brown points) are accurately mapped, the only in-channel points (black) returned to the sensor are from laser pulses reflected from the water surface. In 2014 NIR LiDAR was collected during hyperspectral image acquisition using a Leica ALS50 system mounted on the Cessna Caravan.

Bathymetric LiDAR systems have recently been developed which are capable of mapping both terrestrial and aquatic topography. Bathymetric LiDAR systems use green wavelength lasers which are less susceptible to attenuation in water. Bathymetric LiDAR was collected along the Snake River in August 2012 by the National Center for Airborne Laser Mapping (NCALM) and by Quantum Spatial in August 2013. Topography and bathymetry derived from bathymetric LiDAR point clouds (Figure 4) are being compared to NIR LiDAR and image derived bathymetric maps to test the validity of this new technology. A sensor malfunction occurred during the 2013 bathymetric LiDAR acquisition. Despite extensive efforts to resolve the error during data post-processing, the data could not be reconciled.

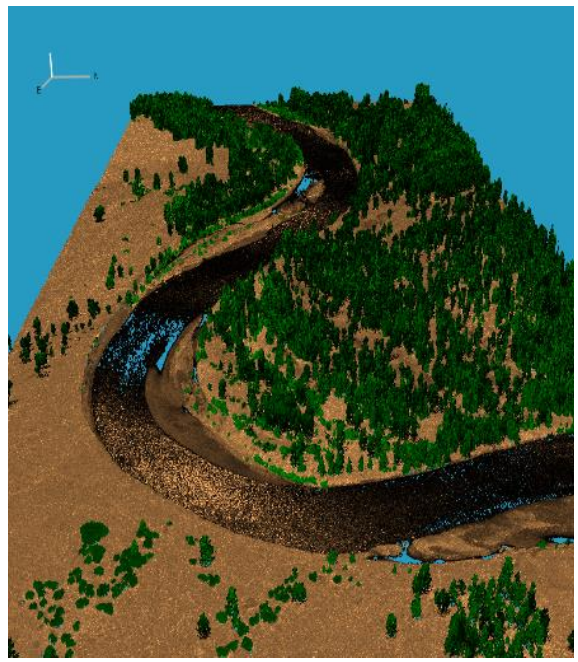

**Figure 3.** Classified NIR LiDAR point cloud from Rusty Bend on the Snake River. Green points are trees and other vegetation, brown points are the land surface and black points are water surface points. No river bathymetry is available from NIR LiDAR.

**Field data collection**

Our study also involved extensive field work to calibrate and validate remote sensing algorithms and to support our geomorphic research. Our previous field campaigns have been coordinated with image acquisitions occurring in August when late summer flows are low and water clarity is high. In 2013 and 2014 we conducted additional field work in June to take advantage of higher water levels and a greater range in turbidity between the clear water released from JLD and highly turbid snowmelt runoff from tributaries (Figure 5). The strong contrast in turbidity between the Snake River and tributaries provide a unique opportunity to study the effects of suspended sediment on the optical characteristics of the river. Additionally, the higher flows measured during the June data collection were more representative of geomorphically significant flow events.

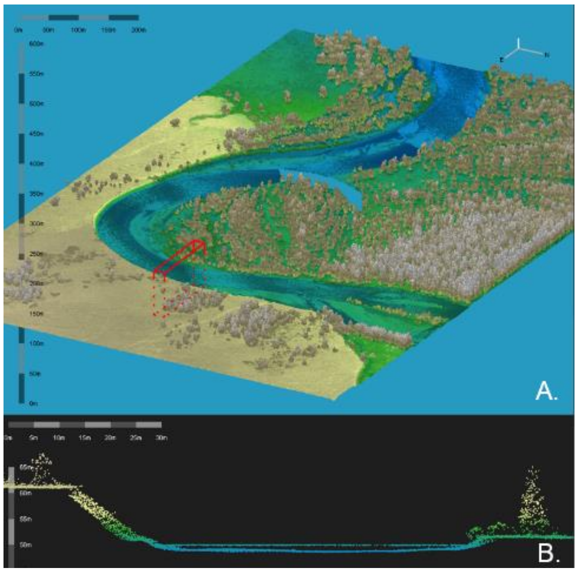


**Figure 4.** Bathymetric LiDAR point cloud color coded by elevation from Rusty Bend on the Snake River (A). A cross-section through the data (red box in A. shown in B.) shows the topographic, bathymetric and water surface points collected by the sensor.

**Figure 5.** Sediment laden water from the Buffalo Fork (left side of photo) slowly mixes with clear, sediment-free water of the Snake River (right side of photo).

During June field data collection a suite of instruments were deployed from a cataraft along downstream profiles to measure the optical properties of the water column and the bathymetry of the channel. The concentration and size distribution of suspended sediment were measured in real-time using a Sequoia Scientific LISST-100X. Spectral absorption and attenuation coefficients, inherent optical properties that control the distance light can travel through water, were measured by continuously pumping river water through a WetLabs ac-s Spectrophotometer. A second WetLabs instrument, the EcoTriplet, provided observations of the scattering coefficient, turbidity, and concentrations of chlorophyll and colored dissolved organic matter (CDOM). A Eureka Environmental Manta 2 multi-probe was used to measure blue-green algae concentrations as well. 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 regularly during the downstream profile. A Trimble RTK GPS receiver was coupled with a SonarMite echo-sounder to map depth and water surface elevations. Time stamps from all of the instruments were used to define the GPS locations of all measurements.

**Figure 6.** In 2014 a larger cataraft was built to accommodate the additional instruments used to map the physical and optical properties of the Snake River.

SonTek acoustic Doppler current profilers (ADCP) were used to collect hydraulic and bathymetric data during both June and August field data collection. These instruments were deployed from kayaks outfitted with a specialized mounting system 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 sampling frequency of 1 Hz 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 at Swallow and Rusty Bends, we recorded 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.

To advance our goal of extracting other kinds of hydraulic information from remotely sensed data, we developed a new system for mapping water surface roughness. During the August 2014 field campaign we used a downward-facing ultrasonic distance sensor deployed from a spar mounted on the front of a kayak. This small sensor sampled the distance to the water surface at a frequency of 5 Hz. Data was collected along streamwise oriented transects. Water surface roughness data collected with the ultrasonic sensor was paired with simultaneous ADCP measurements using GPS timestamps on both instruments

## ✦ PRELIMINARY RESULTS

**Implications of flow management for hydrology and geomorphology of the Snake River in GTNP**

The Bureau of Reclamation (BoR) manages flow releases from JLD and is faced with the challenge of balancing a wide range of environmental, agricultural, and recreational water demands. The BoR's highest priority is to ensure that Snake River flows are sufficient to meet irrigation needs downstream in Idaho. Irrigation water is conveyed to agricultural lands on the Snake River Plain through a number of reservoirs and canals comprising the Minedoka project. JLD is the highest dam on the Snake River and allows the BoR to store late spring snowmelt high in the basin and deliver water to Pallisades Reservoir, 160 km downstream, as needed later in the summer. Therefore, flow releases at JLD are dictated by irrigation demands in Idaho and water levels in Palisades Reservoir. Variables such as local and regional snowpack, timing and duration of runoff, temperatures in Idaho, as well as water deficits carried over from previous years all factor into the timing, magnitude, and duration of flow releases from JLD.

In spring 2012, snowpack in the Snake River basin was 53% of average. While snowpack in upper basin tributaries such as Pacific Creek and the Buffalo Fork were closer to average, lower basin tributaries such as the Salt, Greys, and Hoback Rivers had below-average snowpack (NRCS, 2012). Low snowpack, especially in tributaries feeding directly into Palisades, lead to significant drawdown of Palisades and increased demand for water stored in Jackson Lake. After the 2012 irrigation season, storage in Palisades was only 56% of average for that time of year.

The drought-like conditions continued in 2013. In June of that year the snow water equivalent in the Snake River Basin was 46% of normal (NRCS, 2013). Two consecutive years of low snowpack placed significant stress on the water storage in the Snake River system. In June 2013, Palisades Reservoir was 75% of average. Later in the summer, low water levels in Palisades, along with persistent irrigation demands, led to a management decision to release higher than normal flows from JLD throughout the summer, causing significant depletion of storage in Jackson Lake itself. Despite increased releases from JLD, storage in Palisades Reservoir and Jackson Lake were drawn down to 50% and 43% of average, respectively, for that time of year (USDA NRCS, 2014). As of January 2014, Jackson Lake was only 20% of total capacity (Figure 7).

**Figure 7.** Water level in Jackson Lake was less than 20% capacity in January 2014 due to two consecutive years of below average snowpack in the Snake River Basin.

The dry conditions of 2012 and 2013 thus depleted both Palisades Reservoir and Jackson Lake and left managers with a storage deficit that had to be remedied in order to continue to provide water for downstream users. Above average snowfall during the winter of 2013 – 2014 provided a much needed respite from the drought. Snowpack in the Snake River basin was 140% of average in June 2014. Snowpack in the Salt and Greys Rivers, which directly feed Palisades Reservoir, were 257% and 342%, respectively (NRCS, 2014). The deep snowpack in the lower basin implied that less water needed to be released from JLD. In an attempt to refill Jackson Lake, releases from JLD were kept very low during runoff in May and June.

The hydrographs in Figure 8 illustrate the differences between the regulated Snake River and the unregulated, snowmelt-driven Pacific Creek, which joins the Snake River 8.8 km downstream from JLD. This confluence marks the first significant sediment input to the Snake River below the dam and thus represents an ideal location to investigate the impact of flow regulation on the morphology of tributary junctions. On a year-to-year basis, the dynamics of confluence zones depend on the relative magnitudes of stream flows along the mainstem channel and the tributary, summarized in Figure 8 for 2012-2014.

One strategy managers use to satisfy downstream water demands while conserving reservoir storage is to minimize reservoir releases while tributary flows are high. This strategy is evident in the hydrographs from the 2013 season (Figure 8). As snowmelt runoff increased on Pacific Creek in May and June, releases from JLD were drastically reduced to conserve water in the reservoir. This management strategy resulted in overall flows in the river that remained consistent while Pacific Creek delivered a higher proportion of the flow in the river.

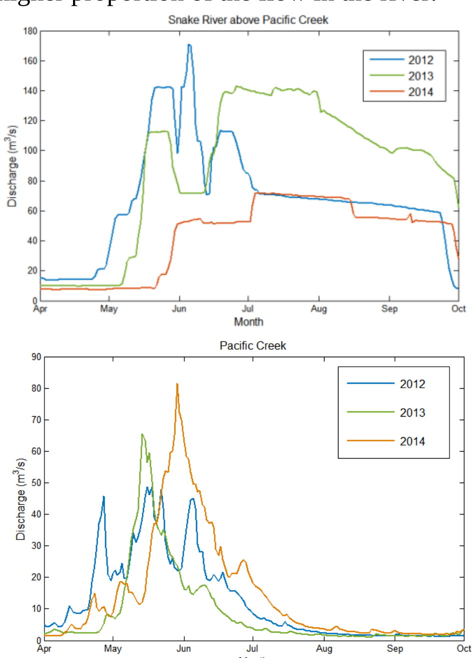


**Figure 8.** Hydrographs for the Snake River and Pacific Creek. Flows in the Snake River above Pacific Creek reflect dam operations at Jackson Lake Dam, whereas the tributary is unregulated.

Later in the summer of 2013, the low water levels in Palisades Reservoir described above necessitated releasing higher than normal flows from JLD throughout the summer, causing significant depletion of storage in Jackson Lake itself.

In an attempt to replenish storage in Jackson Lake, peak flows released from the dam in 2014 were the second lowest in 111 years of record, even though a substantial snowpack contributed to high flows on Pacific Creek. For two consecutive years, this tributary delivered sediment to the Snake River while flows on the main channel were low, possibly less than what would be required to transport the sediment supplied from Pacific Creek. If this were the case, we would expect sediment to accumulate at the Pacific Creek confluence. This hypothesis was evaluated by inspecting channel changes that occurred between 2012 and 2014 (Figure 9). Differences between the digitized 2012 wetted channel (blue line, Figure 9) and the 2014 channel (background image) shows a narrowing of the main channel from 35 meters in 2012 to 24 meters in 2014 even though discharge at the time the two images were acquired was similar. In addition, a large mid-channel bar has been created downstream of the confluence, further evidence that sediment is accumulating and being stored at this confluence.

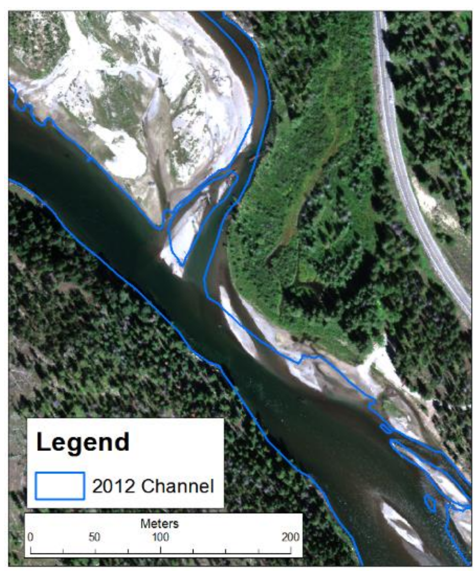


**Figure 9.** Channel changes observed at the confluence of Pacific Creek with the Snake River are highlighted by overlaying the 2012 channel boundary on an image acquired in August 2014.

While the planform changes observed between 2012 and 2014 are consistent with our hypothesis that sediment is being stored at tributary junctions, a more thorough analysis of annual changes occurring throughout our image time series is necessary to more fully understand how flow regulation impacts confluence zone dynamics. Additional image acquisitions scheduled for 2015 may also yield insight as to how the two years of sediment stored at the Pacific Creek tributary junction is routed downstream, provided that this year's JLD releases are capable of transporting the sediment.

In addition, channel bathymetry derived from optical image data will be fused with LiDAR topography to produce continuous maps of tributary junctions. These maps will allow us to relate annual geomorphic changes to volumes of storage and evacuation of sediment (Figure 10).

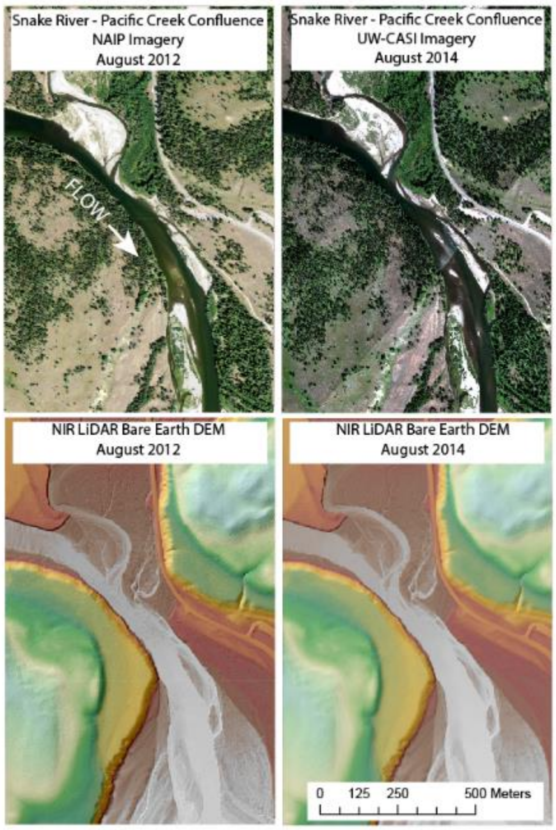


**Figure 10.** Image data (upper panels) will be used to derive bathymetric maps of tributary junctions. When image-derived bathymetry is coupled with LiDAR topography (lower panels) we will be able to map volumetric changes at tributary junctions.

**Isolating sun glint and mapping water surface roughness**

Sun glint, which occurs when light reflects from the water surface directly to the remote sensor without entering the water column, results in anomalously bright pixels that can severely degrade the quality of an image. In addition to clarifying the signal associated with the water column and bed of the river, isolating sun glint could unlock important hydraulic information related to water surface topography. Radiant energy reflected from the water surface does not interact with the water column; therefore, surface reflected light resembles the solar spectrum. Conversely, light that enters the water column is subject to strong absorption of near-infrared (NIR) wavelengths; therefore, light that has interacted with the water column has little NIR signal. The reflectance in a NIR wavelength thus serves as an indication of the amount of sun glint for each pixel.

Building upon glint removal procedures created for shallow marine environments (Hedley et al. 2005), we have created a river-specific method to isolate and remove sun glint (Figure 11). In panel A, strong sun glint overwhelms much of the in-channel information in the image. The glint removal procedure isolates the sun glint component of the image (Panel B). Panel C is the final de-glinted image produced by subtracting the glint image from the original image. In the new de-glinted image, water depth is the primary control on image brightness. As a result, removal of sun glint increased the agreement between field-measured depths and image-derived depths from an $R^2$ of 0.65 to an $R^2$ of 0.8.

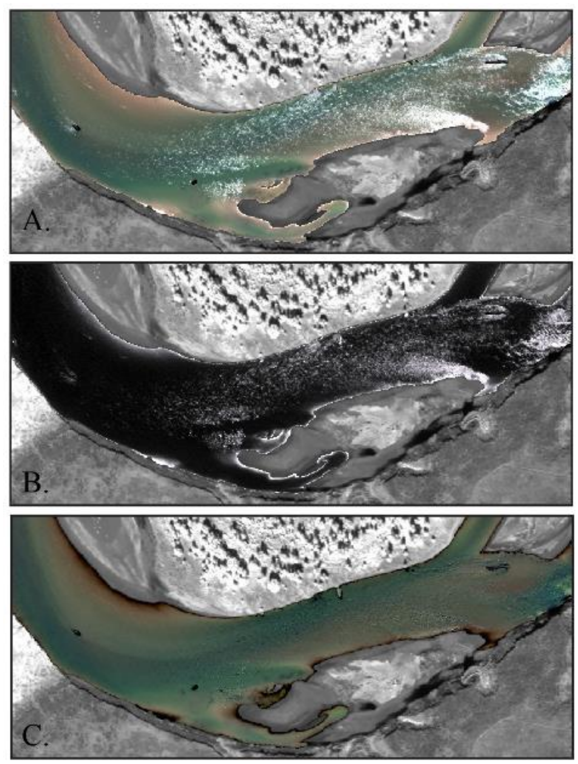


**Figure 11.** 2014 hyperspectral image from Swallow Bend was contaminated by sun glint (A). We used a glint removal procedure to isolate sun glint (B) so it could be removed from the original image which produced a new glint-free image (C).

As water surface roughness (WSR) increases, a greater number of surface facets are oriented so as to reflect the direct solar beam, implying that the texture of the water surface exerts a primary control on the amount of sun glint in an image. WSR in rivers is affected by flow depth and velocity, but this relationship has not been quantified due to the lack of an established method for mapping WSR in the field.

To identify the relationship between surface roughness, sun glint, and channel hydraulics we identified a reach of the Snake River upstream of Rusty Bend that had strong contrasts in WSR (Figure 12). In this reach, the river transitions from a deep, slow moving pool with a smooth surface to a shallow, high gradient, high velocity riffle with high surface roughness. At the end of the riffle the river transitions back into a deeper, slower flowing pool (Figure 12 A). We used a NIR wavelength (851 nm) in the radiance image ($L_{851}$) as metric for glint intensity (Figure 12 B). The patterns of sun glint closely match patterns of surface roughness with low surface roughness pools corresponding to areas with minimal glint (blue colors, Figure 12 B) and high surface roughness riffles corresponding to areas with strong sun glint (red colors, Figure 12 B). These results indicate that sun glint is strongly related to WSR.

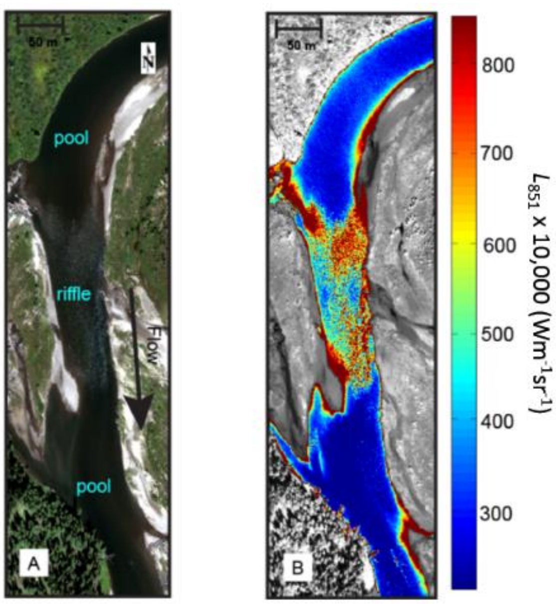


**Figure 12.** 2014 hyperspectral image of a pool-riffle sequence on the Snake River upstream of Rusty Bend (A). The sun glint intensity is well represented by plotting the intensity of the 851 nm band (B). Low roughness pool corresponds to regions with minimal sun glint and high roughness riffles correspond to regions with high sun glint.

To further investigate the relationship between sun glint, WSR, and hydraulic conditions, we collected field measurements of WSR, depth and velocity along a downstream profile (Figure 13). Image-derived sun glint (black line, Figure 13A) is strongly correlated to the field-measured WSR (red line, Figure 13B). The longitudinal profile shown in Figure 13C highlights the relationship between WSR and geomorphic and hydraulic conditions. The water surface elevation (blue line) was derived from NIR LiDAR surface returns. The bed elevation (brown line) is the difference between the LiDAR WSE and field-measured depth. The filled points in 13C are the field-measured mean velocity corresponding to the color bar at the bottom of Figure 13C.

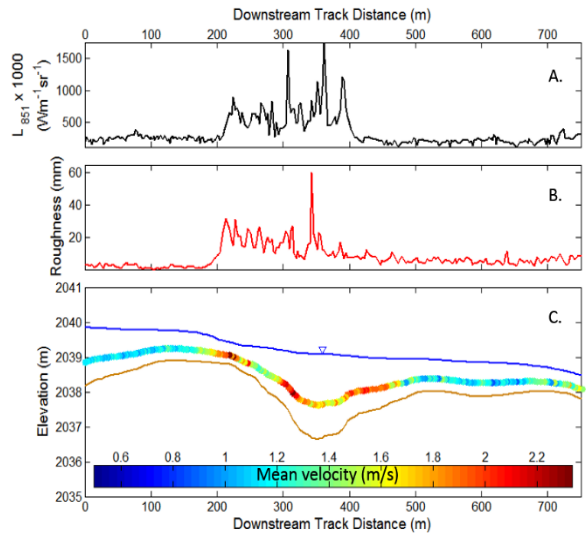


**Figure 13.** A) Image-derived sun glint (represented by radiance of the 851 nm wavelength) along a downstream profile of the pool-riffle sequence in figure 12. B) Field measured water surface roughness along the profile. C) Water surface elevation (blue line), bed elevation (brown line) and field-measured mean current velocity (filled points corresponding to color bar) along the downstream profile.

The spike in the image-derived sun glint and WSR both occur as water surface slope increase, depth decreases, and velocity increases. As the water surface slope decreases the roughness and glint also decrease. These initial results imply a relationship between sun glint, WSR, and flow velocity that might enable river hydraulics to be inferred from remotely sensed data. Image-derived sun glint also could be used to identify hydraulic biotopes distinguished on the basis of WSR.

## ✦ MANAGEMENT IMPLICATIONS

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

Regionally, the Snake River is a prime source of irrigation water for agriculture on Idaho’s Snake River Plain. Climate change and associated shifts in the timing of water demands might necessitate corresponding adjustments in flow regulation by JLD. A refined understanding of the geomorphic effects of such regulation will allow managers to devise a strategy for maintaining the physical and ecological integrity of the Snake River within GTNP while also meeting downstream water demands.

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 Chip Rawlins, Carlin Gerard, Steve Brandebura, Toby Stegman, Devin Lea, Lincoln Pitcher and Annie Toth. Remotely sensed data were acquired through collaboration with NCALM and Quantum Spatial.

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**Figure 14.** 2014 field crew at Deadman’s Bar on the Snake River. From left to right: Lincoln Pitcher (UCLA), Toby Stegman (UW), Brandon Overstreet (UW), Carl Legleiter (UW), Chip Rawlins (UW), Devin Lea (UW).