Chapter 2.—Stream and Riparian Habitat Analysis and Monitoring with a High-Resolution Terrestrial-Aquatic LiDAR

Jim McKean[1], Dan Isaak[1], and Wayne Wright[2]

Abstract

Management of aquatic habitat in streams requires description of conditions and processes both inside the channels and in the adjacent riparian zones. Biological and physical processes in these environments operate over a range of spatial scales from microhabitat to whole river networks. Limitations of previous survey technologies have focused management and research activities on either ends of this spectrum. Environmental monitoring also is very challenging as habitat conditions and specie use can vary over a wide range of temporal scales. We used a narrow-beam airborne green LiDAR, the Experimental Advanced Airborne Research LiDAR (EAARL), to study channel and floodplain conditions and processes at length scales from several meters to tens of kilometers with a spatial resolution of about 1 meter. We also monitored channel change over a period of 3 years using repeated EAARL surveys. The EAARL mapped beds of channels correctly, but tended to smooth the edges of steep banks. In 10 kilometers of unconfined channel, there is a hierarchy of spatial scales of salmon spawning habitat controlled by a combination of post-glacial valley evolution and modern channel hydraulics. Wavelets are a powerful technique to analyze the continuous EAARL data and describe habitat distribution in the frequency domain. This terrestrial-aquatic LiDAR could catalyze rapid advances in understanding, managing, and monitoring aquatic ecosystems.

Introduction

Integrated management of stream and riparian habitat is hampered by a limited ability to define, analyze, and monitor the basic topographic template on which physical and biological processes operate, particularly inside active channels. Detailed stream studies have been of restricted spatial extent because of costs and logistics; consequently, it has been difficult to analyze process interactions and habitat among larger channel domains or to extrapolate to the scale of whole stream networks. Earlier remote sensing techniques have shown some capacity to map channel bathymetry over larger stream segments, but not with high resolution or without some local calibration (see review in Mertes, 2002).

We successfully used the Experimental Advanced Airborne Research LiDAR (EAARL) to map and monitor channels and floodplain topography in streams that provide spawning and rearing habitat of a federally listed (threatened) population of Chinook salmon (*Oncorhynchus tschawytscha*) in central Idaho. EAARL data allowed us to investigate and analyze spatial scales of habitat distribution ranging from meters to tens of kilometers, considering both bed topography in the mainstem channels and the location and extent of features in the adjacent floodplain such as “off-channel” aquatic habitat. We also observed local changes in stream physical habitat between LiDAR surveys done 3 years apart.

Field Area and Methods

Channel characteristics in our study area ranged from low-gradient, sand- and gravel-bed streams with meandering pool-riffle morphology, to steeper confined channels carrying gravel- and cobble-sized sediment. The median grain size in the bed ranged from about 50 mm in the low gradient streams to about 120 mm in the steeper confined channels. Channel size ranged from 10 to 30 m wide, 0.1 to about 4 m deep, and longitudinal gradients were 0.17–1.5%, calculated over 200 m reach lengths. Our analyses to date have concentrated on upper Bear Valley Creek and Elk Creek (fig. 1). Figure 2 shows the typical low gradient gravel-bed meandering channel with pool-riffle form in upper Bear Valley Creek.

[1]USDA, Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Lab, 322 E. Front St., Suite 401, Boise ID, 83702

[2]U.S. Geological Survey, Center for Coastal and Watershed Studies, USGS FISC - St. Petersburg, 600 Fourth Street South, St. Petersburg, FL 33701

The technical specifications of the EAARL system are described in Wright and Brock (2002), Brock et al. (2004), Nayegandhi et al. (2006), and Nayegandhi et al. (this volume). EAARL data were acquired over about 150 km of streams during 5 hours of flight-time in October 2004 and about 75 km during 3 hours of flight-time in October 2007 (fig. 1). All flights were done in low-flow conditions with very good water clarity. The bathymetric data were gridded with a 3-m spacing to construct a digital representation of the channel topography. The digital topography was processed into basic visual displays for interpretation of channel and floodplain topographic characteristics. Typical products included shaded relief models, contour maps, and 3D wire mesh models. When the data are viewed at greater than reach scales, the valley topographic gradient can be distracting in standard shaded relief models. We used a lowess local regression procedure (R Project, 2008) to "detrend" the data and remove the valley gradient while still preserving the local morphology of the floodplain and channel.

EAARL data always include high resolution digital color-infrared photos and medium resolution color videography (Wright and Brock, 2002; Brock et al., 2004; Nayegandhi et al., 2006; Nayegandhi et al., this volume). Although not used extensively in this study, these data complement the LiDAR information and should be extremely valuable, for example, for defining riparian vegetation characteristics. An example of the photography is provided later.

Performance of the instrument was evaluated by comparison with intensive field surveys of channel morphology in six stream reaches, each about 150 m long. Each control site survey was done over about a 2-day period by a two-person crew using a combination of total station

Figure 2. Typical meandering pool-riffle, gravel-bed channel mapped with the EAARL instrument in Bear Valley Creek, Middle Fork Salmon River, Idaho. Channel is 15 m wide and gradient is about 0.2%. Median grain size in bed is 50 mm. View is downstream.

and survey-grade GPS methods to measure point elevations of channel bed and bank topography. These site surveys were designed to have greater precision, accuracy, and overall data density than did the LiDAR data. Both the LiDAR and field survey data were then gridded and contoured in exactly the same manner. Assessment of accuracy of remote measurements of channel morphology is complex and appropriate metrics depend strongly on the intended use of the data. Accuracy can be measured at points, along lines of data, across areas or volumes, or using higher order derivatives such as slope or topographic curvature. Our principal concern has been mapping basic fish habitat units and here we report tests of EAARL accuracy for that purpose using surface areas and volumes of "pools," which are perhaps the primary morphologic feature of streams. Pools were defined as portions of the streambed lying below an arbitrary contour elevation and having a concave-upward form.

We quantitatively analyzed the spatial structure of channel physical habitat using 1D continuous wavelet transforms (McKean et al., 2008). The channel bed topography was described by the thalweg profile, hand digitized in the digital topography produced from the 2004 data. The wavelet technique analyzes spatial or temporal patterns in the frequency domain by comparing pieces of a continuous signal (the channel thalweg elevation profile) to a reference waveform and calculating transform coefficients that describe the similarity of any portion of the original signal to the reference wavelet (Mallat, 1989; Daubechies, 1992; Hubbard, 1998;Torrence and Compo, 1998). We used an 8th order Gaussian reference wavelet that has a smoothly varying form similar to channel bed profiles. When centered

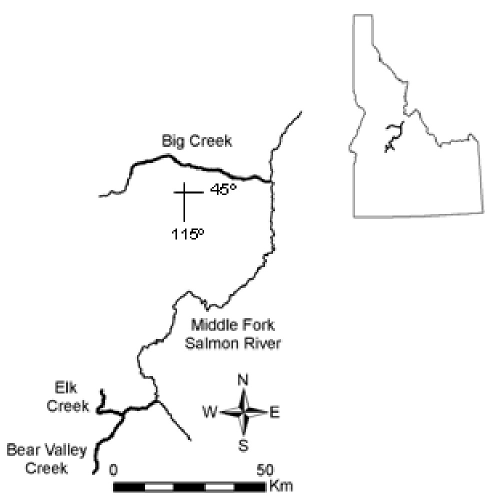

Figure 1. Locations of 2004 and 2007 EAARL data. Big Creek was only mapped in 2004. Elk and Bear Valley Creeks were mapped both years.

on a channel profile convexity, the wavelet coefficients are positive; when the wavelet is out-of-phase and centered on a pool or concavity, the coefficients are negative. The magnitude of coefficients is proportional to the vertical amplitude of the bed elevation changes. Spatial scaling can be explored by recalculating the wavelet similarity coefficients while changing the length, or spatial scale, of the reference wavelet. The wavelet coefficients at any spatial scale can be squared to predict the distribution of spectral power at that spatial scale.

Monitoring of channel change between 2004 and 2007 has been done to date by simply constructing digital channel topography from each year, using identical gridding methods, and subtracting the 2007 topography from that of 2004.

Results

Figure 3 shows a typical result of a performance test of the EAARL sensor in a 150 m long reach of pool-riffle topography in upper Bear Valley Creek. The 3D surface area of pools was essentially identical in the data pair. However, the EAARL bathymetry predicted 17% greater pool volume than did the field survey. Later field checking revealed the field survey had missed a small (in surface area) deep pocket in the pool at coordinates 626890E, 4913265N, and thus in this case, the LiDAR data appear to be more accurate than the control field data.

Figure 3 also illustrates a bias in the bathymetric data. The instrumentation and geometry of airborne terrestrial and aquatic LiDARs dictates they measure elevations more accurately than horizontal position. Fewer LiDAR measurements also are taken from bank surfaces and the edges of banks than on the gentler channel bed and floodplain. As a result, EAARL mapping errors are larger along channel banks, particularly when the bank slope approaches vertical. The result is that steep banks in the LiDAR-mapped topography are gentler and the top and bottom edges of banks are more rounded than is correct. In figure 3, this bias is revealed by the wider-spaced LiDAR contours on the outside of meander bends where the flow has eroded near-vertical banks.

Figure 4 is an EAARL-derived DEM of 10 km of upper Bear Valley Creek with elevations classified by color. A distinctive change in valley and channel morphology occurs at a channel distance of 4 km. There is about a 3 m-tall step in the valley profile at this location, interpreted by McKean et al. (2008) as the headward extent of post-glacial valley erosion that has regraded the lower valley to the level of a base level control at the valley outlet at a channel distance of about 10 km. A similar, but smaller, step occurs at a channel distance of about 3 km. Downstream of 4 km, the channel is unconfined, meanders widely, and has very good pool-riffle morphology preferred by species like salmon. Upstream of that point, the channel is against a Pinedale-age glacial terrace (about 22,000 years old; Schmidt and Mackin, 1970) and has a straight, plane-bed morphology that is seldom used by spawning fish.

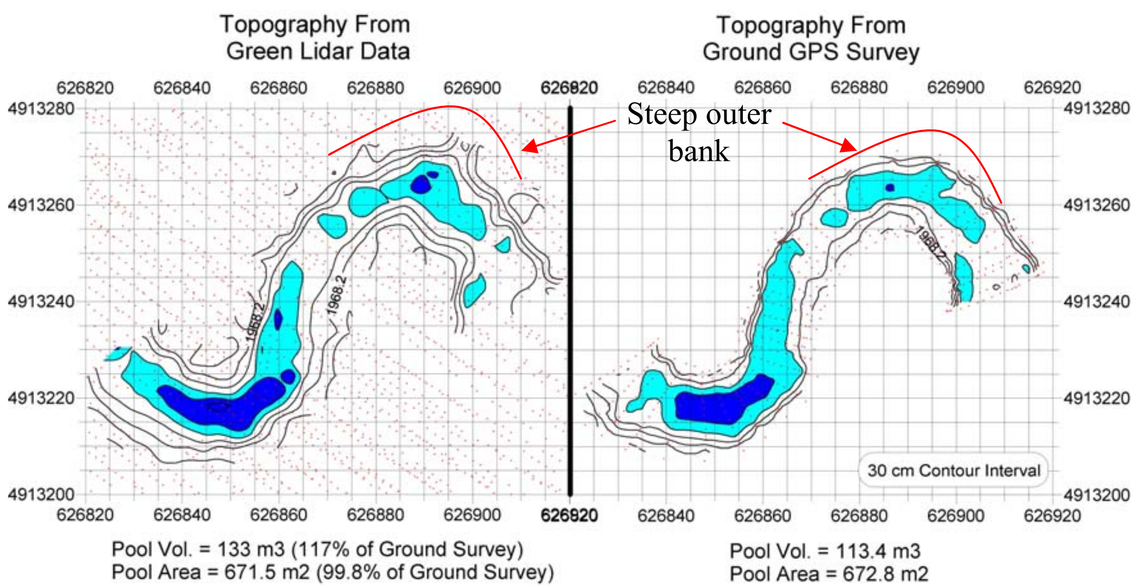

Figure 3. Comparison of topography mapped in the same pool-riffle channel reach with EAARL data (left panel) and survey-grade GPS (right panel). Red dots are points were elevation data were collected by each method. Notice the continuous EAARL data acquisition inside the channel and in the surrounding floodplain.

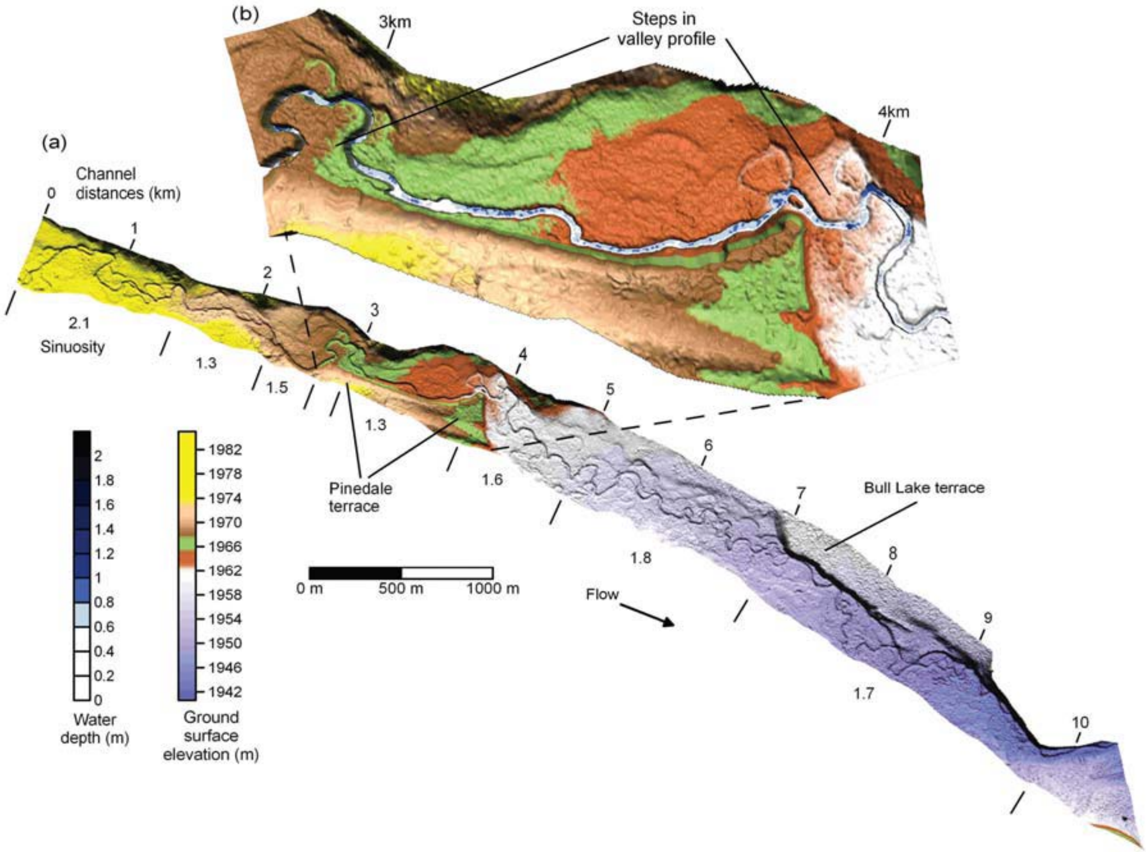

Figure 4. (a) Digital elevation model of upper Bear Valley Creek. Digital topography produced from EAARL data gridded to a 3 m interval. Reference distances are measured along the channel and sinuosity is calculated as channel length/straight-line valley distance over the indicated valley segments. (b) Inset showing degraded step in the valley profile at distance about 3,800 m and shorter valley step at about 2,800 m.

In figure 5, the EAARL data have been "detrended" to remove the valley gradient. Now the numerous inset erosion surfaces and abandoned channel positions are readily visible in the floodplain. Figures 5b and 5c show the bathymetric detail that can be mapped simultaneously with the floodplain topography. Much of the off-channel habitat used by small fish is in semi-abandoned channels that are still connected to the mainstem at higher flow stages. Several of these are noted in figure 5c.

Figure 6 illustrates the spatial distribution of spectral power in upper Bear Valley Creek at a scale of 100 m, i.e. the reference Gaussian wavelet was made 100 m long. Power is not evenly distributed along the channel but rather is concentrated at 0–2 and 8–10 km of channel distance with more isolated power spikes from 2 to 8 km. Over this 10 km stream segment, changes in power as a function of the spatial scale of the reference wavelet depend on a combination of geomorphic history and contemporary channel hydraulics (McKean et al., 2008). They also found that concentrations of fish spawning sites closely follow the bed topography spectral power over a wide range of spatial scales.

Repeated high-resolution EAARL surveys allow monitoring of changes in physical habitat conditions over large portions of channel networks. Figure 7 shows topographic change in a 400 m reach of Elk Creek between 2004 and 2007 mapped by the LiDAR. In this sand-gravel reach, the channel 3D geometry often changes significantly during the annual snowmelt peak runoff. Scour can be seen at several meander bends and a large pool near the downstream end of the reach also filled significantly over this period.

Figure 8 shows a combination of the CIR camera imagery of the floodplain and EAARL bathymetry within the channel in a portion of Elk Creek. Patterns of riparian vegetation and many abandoned channels are easily seen in the image.

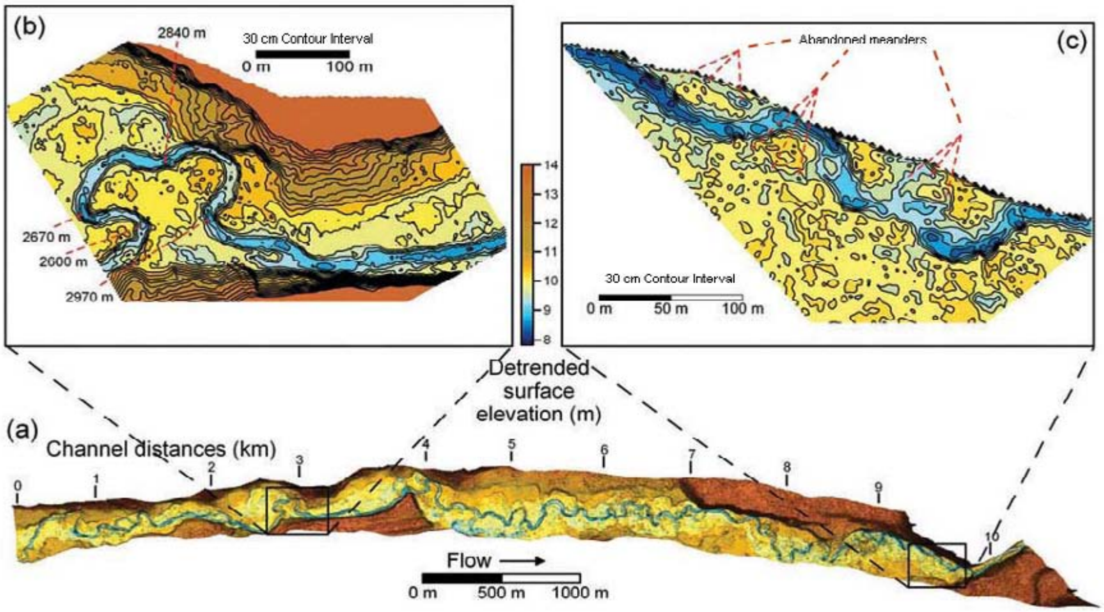

Figure 5. (a) Channel, floodplain, and terrace topography after the valley gradient has been removed. (b and c) Contour maps of selected channel reaches, showing the ability of EAARL to simultaneously resolve floodplain, terrace, and channel topography. All digital topography produced from EAARL data gridded to a 3-m interval.

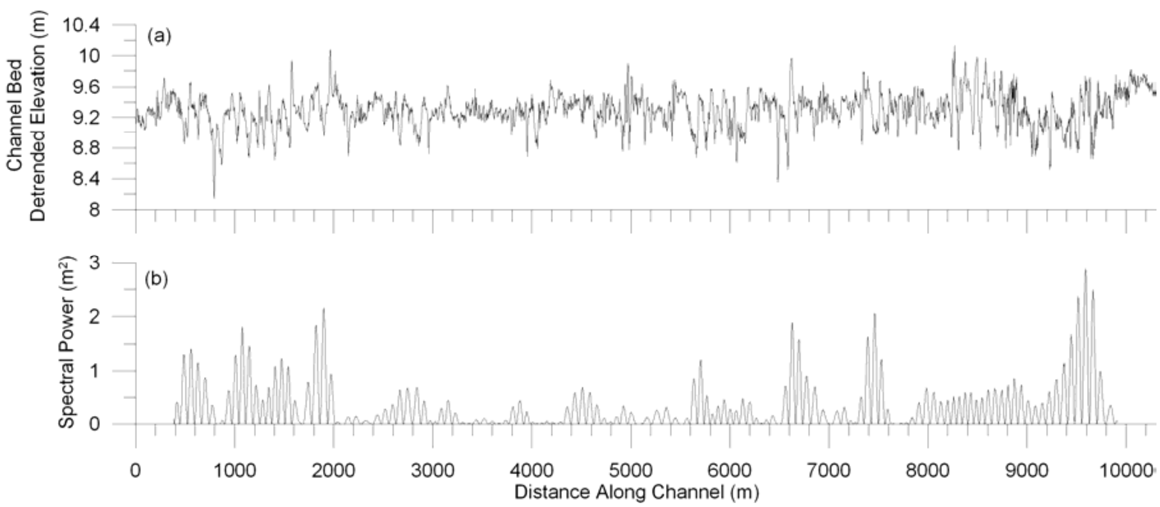

Figure 6. (a) Detrended thalweg profile of upper Bear Valley Creek mapped by EAARL in 2004. (b) Spatial variation in thalweg profile elevations described by 1D continuous wavelet analysis. The reference wavelet was a Gaussian 8th order wavelet with a length of 100 m. Larger spectral power peaks correspond to segments of the channel with higher amplitude bedforms having a wavelength of about 100 m. Wavelet analysis was done on undetrended thalweg profile; detrended profile shown for clarity of local bed elevations.

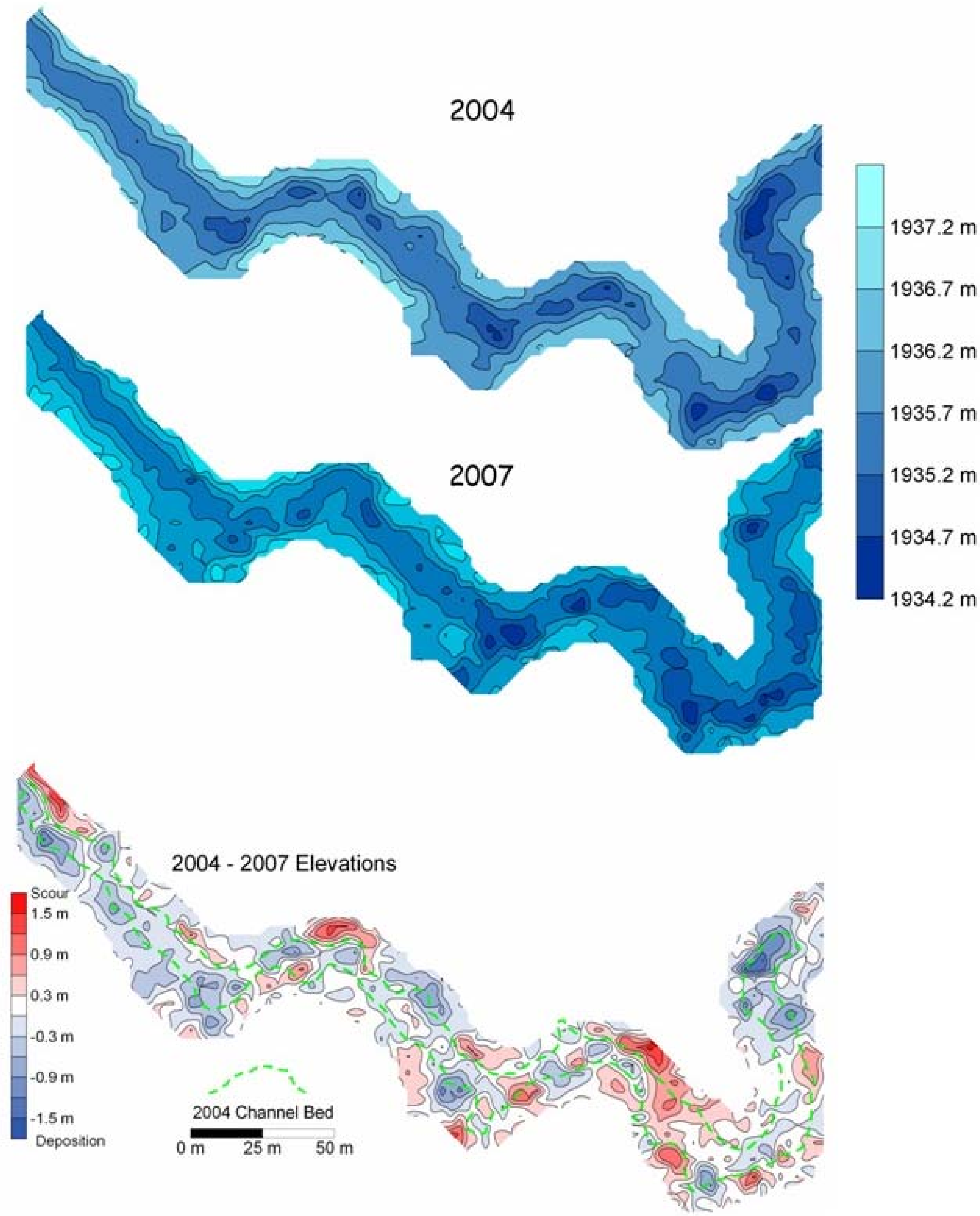

Figure 7. Change in Elk Creek between EAARL surveys in 2004 and 2007. Flow is left to right. The dashed green line shows the limits of the channel bed in 2004 for reference.

Figure 8. EAARL bathymetry of a portion of Elk Creek (bathymetry confined to area of channel within white box) overlaid on a mosaic of digital color-infrared imagery. The color-infrared imagery has not been rigorously ortho-rectified and co-registered to the bathymetry. The imagery and bathymetry were acquired simultaneously by the EAARL system. Bathymetric contours are at 50 cm intervals.

Discussion and Conclusions

The EAARL bathymetric LiDAR offers many advantages to aquatic ecologists and river managers. The ecological scope of the instrument (defined as the length of channel that can be surveyed divided by the finest scale resolvable in the data) is about 105–106. Thus, the data can be used to study channel and floodplain physical characteristics that range from meters to many kilometers in scale. The larger end of this spectrum has always been relatively inaccessible to high resolution analyses. For example, detailed field surveys are normally limited to less than perhaps a few hundred meters of channel length. The airborne bathymetric survey also resolves channel and floodplain access issues. Data describing the bare earth floodplain topography, channel bathymetry and the vegetation canopy can be collected in one integrated mission. The integrated bathymetry, terrestrial bare earth topography, vegetation DEM, and broad-band spectral data from the CIR camera are a particularly powerful combination of data to map and investigate riparian and channel habitat and process interactions.

The EAARL instrument is currently based in Virginia and operated by the USGS LiDAR survey costs are very site-specific and affected by mobilization, terrain flying conditions, length of channel surveyed, and the mapping width of channel plus floodplain. Estimates of data acquisition costs in 2008 projects in the western U.S. have ranged from $1,400 to $5,300 per kilometer. These costs do not include data processing, which can be contracted from the USGS or done by individual users with training and access to the processing software ALPS (Nayegandhi et al., this volume). Plans are underway to improve the system in 2009 with the goal of increasing the density of data (number of point elevation measurements per area) by about six-fold and increasing the power of the laser for better water penetration. The synoptic spatially continuous EAARL data lends itself to analysis in the frequency domain. Techniques such as wavelets offer the possibility to depict and monitor aquatic and riparian habitat in powerful new ways. Wavelets rapidly describe habitat over a large range of spatial scales and identify nested scalar hierarchies of topography and habitat. Wavelet analyses are objective, quantitative and completely repeatable. It also is possible to quantify stream restoration measures by their wavelet characteristics.

The simplest applications of EAARL data include basic habitat mapping (subaqueous and subaerial topography as well as vegetation) and monitoring habitat change over time. Current channel monitoring protocols are based on labor-intensive field samples of small stream reaches. The limited size of each sample reach mandates great care in placement and number of sample sites. Federal land management agencies budget several millions of dollars per year for this work. The EAARL sensor can efficiently inventory and monitor much of the topography of large portions of channel networks and allow local field-based monitoring to focus on biological attributes and those geomorphic attributes that are inaccessible to the LiDAR (e.g., undercut banks and bank stability). Table 1 defines the physical habitat attributes mappable with the EAARL system.

The high resolution of EAARL data provides an opportunity for automated mapping of many aspects of channel geometry. We are constructing a web-based GIS tool that will interrogate EAARL data and extract commonly used at-a-station channel characteristics (see fig. 9 for a screen capture of the partially completed tool). Users will be able to define where they want channel and floodplain cross sections and the tool will compute metrics such as channel width/depth, point of maximum depth, longitudinal channel gradient, and amount of off-channel habitat connected to any channel reach at a given water stage. An option is included to incorporate field photos with any cross-section and data from groups of cross-sections can be copied for use, for example, in a 1D flow model. When completed, this tool will be made freely available on a website.

The data also describe the channel and floodplain boundary condition topography necessary to operate computational fluid dynamics models of channel flow and sediment transport and flood routing models. The topographic data could also be used to support individual-based and population-level biological models.

Although the EAARL system is clearly a major advancement in stream mapping technology, there are, of course, limits to its performance. In particular, shallow water (less than about 10–15 cm depth) and turbid conditions can be problematic. The instrument distinguishes water depth by the difference between the detected water surface and channel bed in each laser pulse. In very shallow flow conditions,

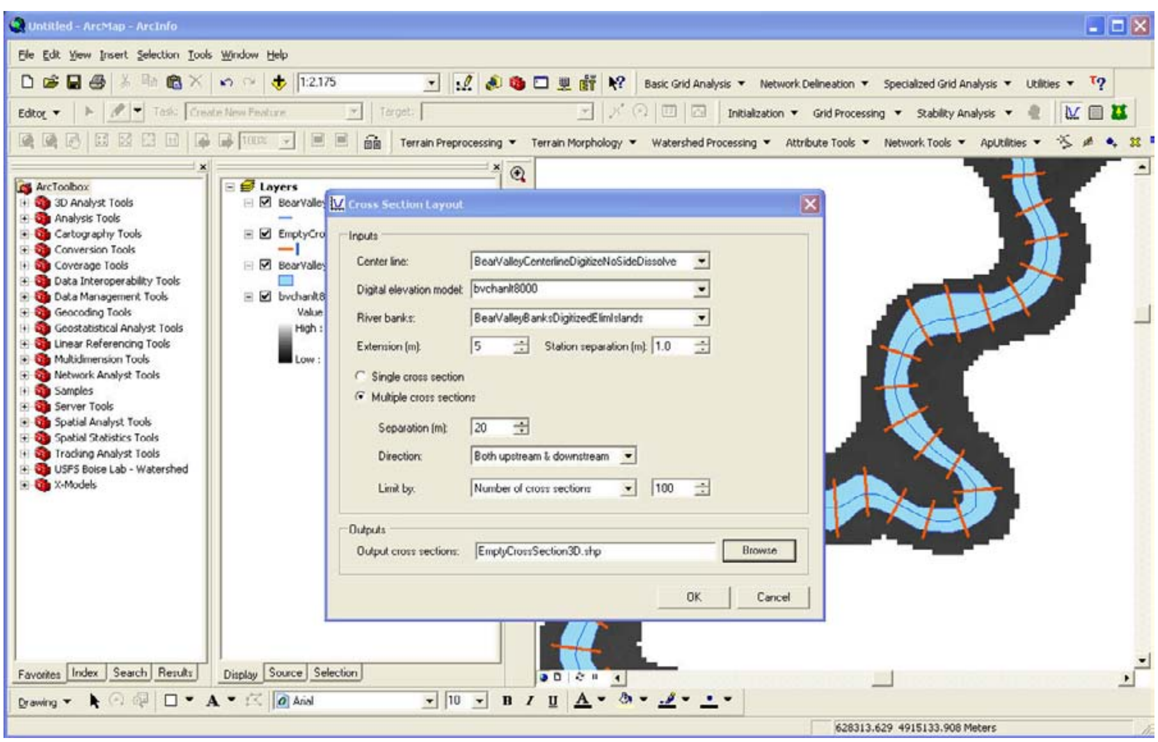

Figure 9. Screen capture of a web-based GIS tool being developed to automatically extract common channel and stream habitat metrics from EAARL data.

Table 1. Channel and floodplain topographic attributes (arranged by spatial scale) that can be mapped with the EAARL sensor.

Spatial extent	Stream feature	Comments
Microhabitat scale (10^0 m)	Water depth	
	Bed slope	Over user-defined channel length.
Channel unit scale (10^1–10^2 m)	Pools, riffles, runs, backwaters	Areal extent, volume, residual pool depth, bedform amplitude, etc.
	Channel cross-section	Bankfull width, depth, cross-sectional area, maximum depth, wetted perimeter, hydraulic radius, bank height and angle, channel entrenchment, symmetry, etc.
	Off-channel habitat	Length, area, volume, connection to mainstem, stage dependence.
Reach-to-network scale (10^2–10^4 m)	Planform geometry	Sinuosity, axial wavelength, arc wavelength, bend amplitude, arc height, radius of curvature, etc.
	Diversity/complexity	Spatial metrics characterizing composition, configuration, complementation, and connectivity of habitats.
	Off-channel habitat	Length, area, volume, connection to mainstem, stage dependence.

the signals from the surface and bed can sometimes become convolved. Suspended sediment and/or entrained air bubbles are point laser reflectors and if too dense, they can prevent the laser energy from reaching the bed. Research is currently ongoing to improve separation of the water surface and bed reflections in shallow water and to quantify the limitations posed by poor water quality and the range of field conditions within which acceptable bathymetric data can be expected.

The instrument resolves surface elevations better than horizontal positions, due to the geometry of the data acquisition and the GPS solutions of the aircraft position during flights. Consequently, points of sharp topographic curvature, such as the top and bottom edges of channel banks, are mapped less accurately than are the elevations of gentler surfaces such as floodplains, terraces, and the channel bed. This bias against correctly mapping high topographic curvature will be lessened, but not eliminated, by increasing the data density as a result of the 2009 system improvement mentioned above. A more inclusive accuracy assessment of the 2004 and 2007 Bear Valley and Elk Creek data is underway. A full assessment of the accuracy of EAARL measurement of point elevations inside a shallow sand-bed channel was reported by Kinzel et al. (2007).

The EAARL appears to be a new generation of technology that could revolutionize how we map, monitor, and investigate integrated aquatic and terrestrial habitat and physical and biological processes. In particular, it will allow high-resolution studies of habitat and processes over a much wider range of spatial scales than previously possible.

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