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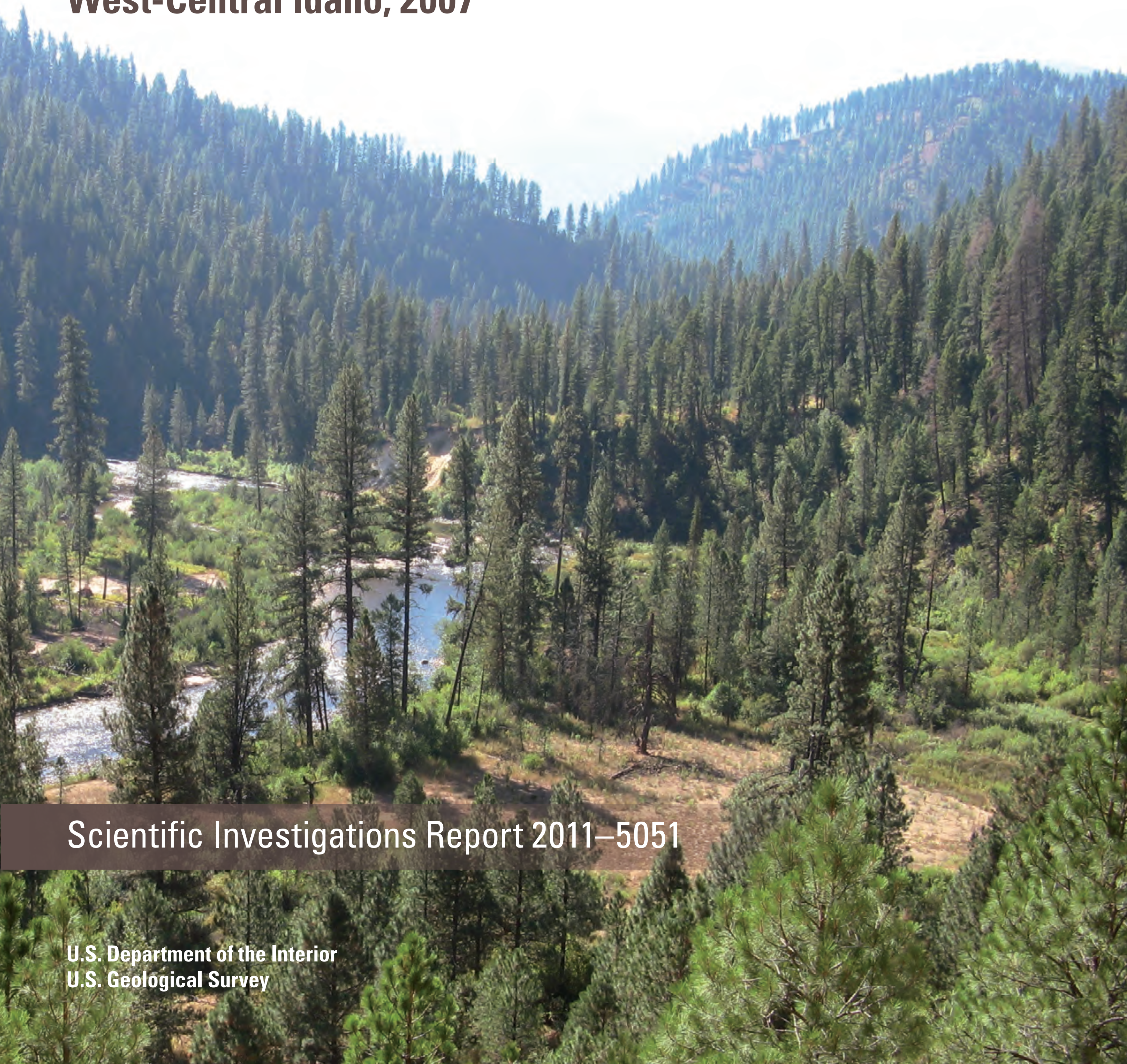

Scientific Investigations Report 2011–5051

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of the Deadwood River approximately 8 river kilometers from the confluence with the South Fork Payette River. (Photograh taken by Kenneth Skinner, U.S. Geological Survey, Idaho, 2007.)

Evaluation of LiDAR-Acquired Bathymetric and Topograhic Data Accuracy in Various Hydrogeomorphic Settings in the Deadwood and South Fork Boise Rivers, West-Central Idaho, 2007

By Kenneth D. Skinner

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KEN SALAZAR, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Acronyms and Abbreviations

ALPS	Airborne LiDAR Processing System
CORS	Continuously Operating Reference Station
DEM	digital elevation model
EAARL	Experimental Advanced Airborne Research LiDAR
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
ME	mean signed error
n.d.	not defined
OPUS-S	Static Online Positioning User Service
RKM	river kilometer
RMSE	root mean square error
RTK-GPS	real-time kinematic global positioning system
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

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Evaluation of LiDAR-Acquired Bathymetric and Topographic Data Accuracy in Various Hydrogeomorphic Settings in the Deadwood and South Fork Boise Rivers, West-Central Idaho, 2007

By Kenneth D. Skinner

Abstract

High-quality elevation data in riverine environments are important for fisheries management applications and the accuracy of such data needs to be determined for its proper application. The Experimental Advanced Airborne Research LiDAR (Light Detection and Ranging)—or EAARL—system was used to obtain topographic and bathymetric data along the Deadwood and South Fork Boise Rivers in west-central Idaho. The EAARL data were post-processed into bare earth and bathymetric raster and point datasets.

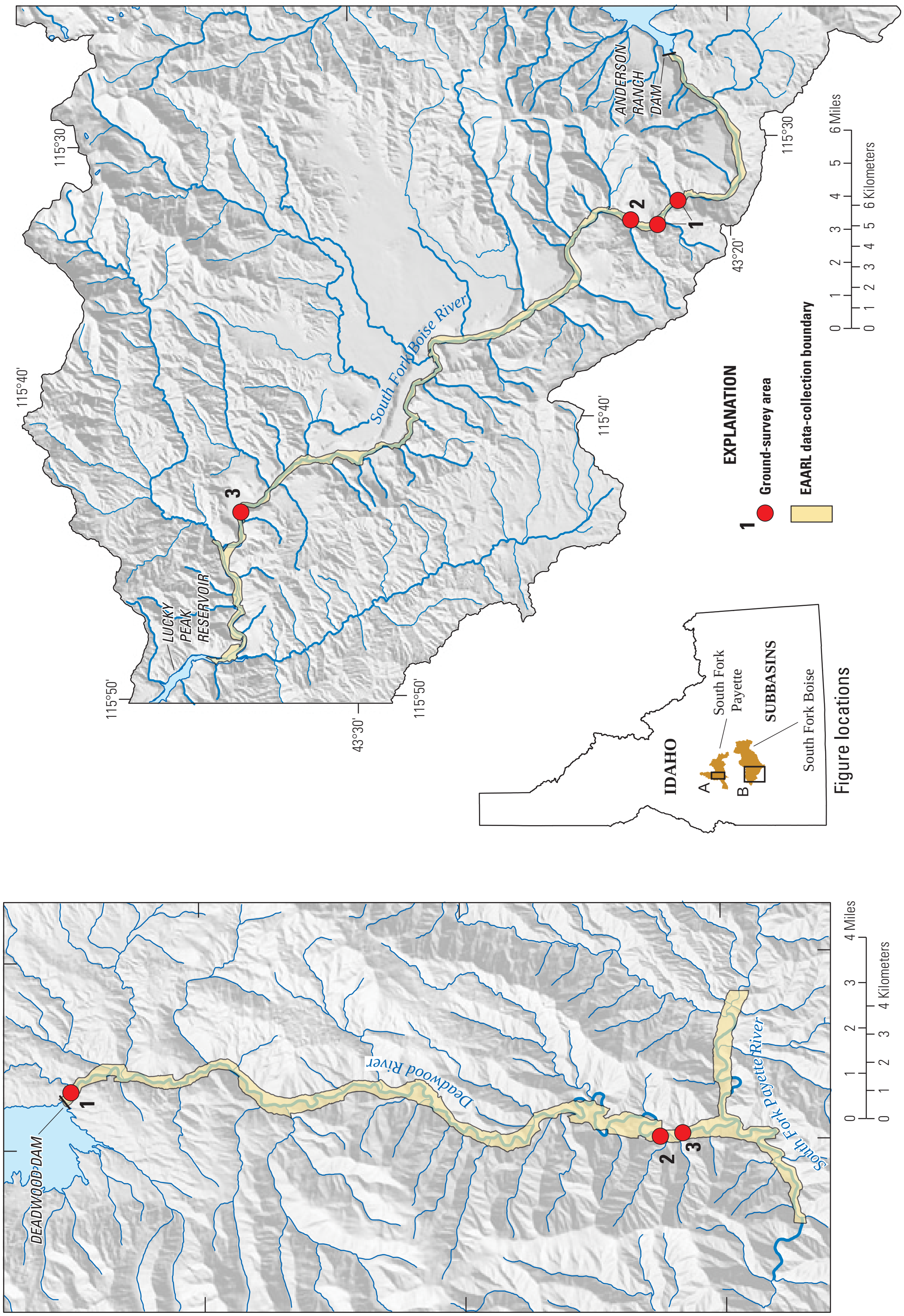
Concurrently with the EAARL surveys, real-time kinematic global positioning system surveys were made in three areas along each of the rivers to assess the accuracy of the EAARL elevation data in different hydrogeomorphic settings. The accuracies of the EAARL-derived raster elevation values, determined in open, flat terrain, to provide an optimal vertical comparison surface, had root mean square errors ranging from 0.134 to 0.347 m. Accuracies in the elevation values for the stream hydrogeomorphic settings had root mean square errors ranging from 0.251 to 0.782 m. The greater root mean square errors for the latter data are the result of complex hydrogeomorphic environments within the streams, such as submerged aquatic macrophytes and air bubble entrainment; and those along the banks, such as boulders, woody debris, and steep slopes. These complex environments reduce the accuracy of EAARL bathymetric and topographic measurements. Steep banks emphasize the horizontal location discrepancies between the EAARL and ground-survey data and may not be good representations of vertical accuracy.

The EAARL point to ground-survey comparisons produced results with slightly higher but similar root mean square errors than those for the EAARL raster to ground-survey comparisons, emphasizing the minimized horizontal offset by using interpolated values from the raster dataset at the exact location of the ground-survey point as opposed to an actual EAARL point within a 1-meter distance. The average error for the wetted stream channel surface areas was -0.5 percent, while the average error for the wetted stream channel volume was -8.3 percent. The volume of the wetted river channel was underestimated by an average of 31 percent in half of the survey areas, and overestimated by an average of 14 percent in the remainder of the survey areas.

The EAARL system is an efficient way to obtain topographic and bathymetric data in large areas of remote terrain. The elevation accuracy of the EAARL system varies throughout the area depending upon the hydrogeomorphic setting, preventing the use of a single accuracy value to describe the EAARL system. The elevation accuracy variations should be kept in mind when using the data, such as for hydraulic modeling or aquatic habitat assessments.

Introduction

The Deadwood and South Fork Boise Rivers support important fisheries that are influenced by surface-water projects of the Bureau of Reclamation (Reclamation). In order to manage their projects effectively and to ensure compliance with environmental and Endangered Species Act regulations, Reclamation must have high-quality survey and environmental data with which to conduct hydraulic modeling and aquatic habitat assessments. Reclamation had coordinated efforts to acquire high-resolution bathymetric and topographic data along the Deadwood River and its floodplain from Deadwood Dam to the confluence with the South Fork Payette River and approximately 7 river kilometers on either side of the South Fork Payette River confluence. Data also were collected along approximately 64 kilometers of the South Fork Boise River and its floodplain from Anderson Ranch Dam downstream to the backwaters of Lucky Peak Reservoir (fig. 1). The data are essential to Reclamation's hydraulic and physical habitat modeling, and were collected from a National Aeronautics and Space Administration contracted aircraft using the Experimental Advanced Airborne Research LiDAR System (EAARL). Light detection and ranging (LiDAR) remote-sensing technology uses laser pulses to measure the distance from the EAARL system to topographic and bathymetric surfaces. The EAARL system uses a green laser to penetrate water bodies, and thus can be used to map riverbeds as well as the adjacent banks and floodplains.



A. Deadwood River data collection areas.

B. South Fork Boise River data collection areas.

Figure 1. Maps showing EAARL and ground-survey data collection areas along the Deadwood and South Fork Boise Rivers, west-central Idaho.

LiDAR data are collected as high-density point clouds that commonly are interpolated into a continuous elevation grid or digital elevation model (DEM). The DEM provides evenly spaced elevation data over an entire study area. This is different from traditional survey methods that provide discontinuous data only at the locations where measurements or observations are made. The preferred method of elevation-data collection is based on the needs of the study: either high-density data collected (using airborne LiDAR) throughout the study area, which possibly may miss specific features of interest, or low-density elevation-data collected (using traditional ground-survey methods) only at specific areas. Moreover, land access to desired data-collection areas can be limited by private property restrictions or simply by area remoteness, and the size of traditional survey datasets is limited by time and cost restrictions. With the EAARL system, an entire survey area can be flown and imaged in as little as 1 day.

Certain environmental conditions affect the accuracy of LiDAR-acquired topographic and bathymetric data, such as the density of the tree canopy, ground slope, and water depth and turbidity. As a result, the LiDAR-acquired data must be evaluated under varying hydrogeomorphic settings to determine the accuracy of the data in each setting, thereby ensuring that the data meet the basic standards required for the intended applications of that data.

Ground-level (or ground "truth") survey data provides the necessary means to assess the accuracy of LiDAR-acquired data. The ground-truth data must be collected at a higher degree of accuracy than that expected of the LiDAR dataset, and also must represent the same hydrogeomorphic settings that exist within the LiDAR data collection areas (American Society of Photogrammetry and Remote Sensing, 2004).

The U.S. Geological Survey (USGS), in cooperation with Reclamation, collected ground-truth data in three separate areas on two different rivers—the Deadwood and the South Fork Boise Rivers—coincident with the EAARL surveys. Statistical comparisons were made between the two datasets within similar hydrogeomorphic categories to evaluate the accuracy of the EAARL data.

Purpose and Scope

This report provides an evaluation of the accuracy of bathymetric and topographic elevation data acquired using the EAARL in different hydrogeomorphic settings along the Deadwood and South Fork Boise Rivers. This evaluation compares the EAARL data with ground-survey data collected using a survey grade, real-time kinematic global positioning system (RTK-GPS). The ground-survey data were collected in three areas along both the Deadwood and South Fork Boise Rivers; each "area" comprised about a 1-meter spacing grid of measurements across the rivers, including the banks and an average of 80 meters in downstream length. Ground-survey data were collected along the stream channel, banks, and floodplains where possible, and an additional grid of points were surveyed in a flat-open surface in each area. The three ground-survey areas represent differing stream conditions such as water velocity, water depth, and substrates. The areas were selected to assess the accuracy of EAARL-derived elevations in various hydrogeomorphic settings.

Description of Study Area

The EAARL data were collected along two rivers in west-central Idaho—the Deadwood and the South Fork Boise—which are about 50 kilometers apart and in different basins (fig. 1). The data were collected directly downstream of Reclamation's Deadwood and Anderson Ranch Dams. The narrow valleys and canyons of the two rivers limited the EAARL system data collection to about a 500-m wide swath along each river (fig. 1).

Ground-survey data were collected in a grid pattern at three ground-survey areas along each river in reaches that could be safely waded. The survey grids were located to encompass various channel and bank or floodplain settings. In addition, at each of the three areas, a grid of 100 survey points at about a 2-m spacing was surveyed on the floodplain if an appropriate surface was available. These surveyed grids were located on flat, open terrain to provide an optimal vertical comparison surface for the EAARL and ground-survey data.

Both the EAARL and ground-survey data were collected during late September and early October, 2007 during a period of stable, dam-controlled flows. The data were collected during this period because it occurs between reduced-flow releases from the upstream dams, which permits the rivers to become wadable, and before significant snowfall, which commonly prevents access to the rivers. An early season snow storm prevented the collection of ground-survey data at the Deadwood ground-survey area 1 in 2007, and the survey had to be postponed until the snow melted and flows were reduced again in September, 2008. Streamflow in September 2008 was 1.5 cms (cubic meter per second) higher than the previous year's ground-survey measurement flow, which correlates to a 2 cm (centimeter) increase in stage.

Ground photographs (provided in Appendix A) were taken with a 12.2-megapixel digital camera at each ground-survey area to document conditions during the surveys. The file name of each photograph indicates the location and direction in which the picture was taken or the focus of the photograph, which is explained in further detail within the README file in Appendix A.

Deadwood River

EAARL data were collected along the Deadwood River extending 37 kilometers downstream from the Deadwood Dam to the confluence with the South Fork Payette River and approximately 7 kilometers on either side of the South Fork Payette confluence. This portion of the Deadwood River flows southward in the 2,123 km^2 South Fork Payette Subbasin. The basin has a warm summer continental climate (Köppen, Dsb), and receives an average of 91 cm precipitation a year (Peel and others, 2007; PRISM, 2010).

Three ground-survey areas along the Deadwood River within the larger area covered by the EAARL data were selected to represent different hydrogeomorphic settings. Ground-survey area 1 is the farthest upstream in the basin, just below Deadwood Dam, at approximately river kilometer (RKM) 38. Ground-survey area 2 is at RKM 3.6 and ground-survey area 3 is at RKM 2.4. The large distance between ground-survey areas 1 and 2 is due to lack of access to the river.

Dense conifer trees line both banks of the Deadwood River in all three ground survey areas. Ground-survey areas 1 and 3 are riffle reaches of the river with a cobble substrate and some boulders. The reaches in these two areas have high-velocity streamflow and some air bubble entrainment, with maximum measured water depths of 1.7 m and 0.8 m, respectively. Ground-survey area 2 is a glide reach of the river with a sand and gravel substrate and some cobbles and a maximum measured water depth of 1.4 m.

Flat-surface grids were measured only at ground-survey area 1 at the Deadwood River due to the unavailability of a flat-surface in the other two survey areas. The flat-surface grids were measured on a smooth dirt-packed road.

South Fork Boise River

EAARL data were collected along the South Fork Boise River and its floodplain from Anderson Ranch Dam approximately 64 kilometers downstream to the backwaters of Lucky Peak Reservoir. The South Fork Boise River is within the 3,382 km^2 South Fork Boise Subbasin. The basin has a warm summer continental climate (Köppen, Dsb), and receives an average of 74 cm precipitation a year (Peel and others, 2007; PRISM, 2010).

Three ground-survey areas within the larger area covered by the EAARL survey were selected to represent different hydrogeomorphic settings. Ground-survey area 1 is the farthest upstream in the basin and 11 RKM below Anderson Ranch Dam at RKM 51. Ground-survey area 2 is at RKM 48 and ground-survey area 3 is at RKM 17. The large distance between ground-survey areas 2 and 3 is due to lack of access to that section of the river.

Ground-survey area 1 is a run reach with a gravel and cobble substrate, some areas of macrophyte growth on the water surface, and bushes and small trees along the banks. Ground-survey area 2 is a riffle-pool sequence with gravel and cobble substrate and small trees along the banks. The maximum measured water depth for ground-survey areas 1 and 2 are 1.3 m and 1.2 m, respectively. Ground-survey area 3 is a rapids reach with a cobble and boulder substrate, a maximum measured water depth of 1.2 m, and very little vegetation along the banks.

Flat-surface grids were measured on smooth dirt-packed roads at ground-survey areas 1 and 3. The flat-surface grid for ground-survey area 2 was measured in a short-grass field adjacent to the South Fork Boise River.

Data Collection Methods

To evaluate the accuracy of the EAARL data, bathymetric and topographic elevation data were collected using ground-surveying methods with known standards of accuracy. The ground-survey data were collected at three locations along the Deadwood and South Fork Boise Rivers (fig. 1): one in the upstream reach of the Deadwood River EAARL data area and two in the downstream-reach, and two in the upstream reach of the South Fork Boise River EAARL data area and one in the downstream reach. Long reaches of both rivers are virtually inaccessible. The characteristics of the ground-survey areas along the two rivers provided a basis for assessing the accuracy of the EAARL data under various environmental settings.

EAARL Bathymetric and Topographic Data

The EAARL system uses a green-wavelength (532 nm) LiDAR designed to measure or “map”, simultaneously the surface configuration of the bottom of water bodies (bathymetry), the bare land surface (topography), and vegetation. Under nominal conditions (speed of 97 knots, or 50 m/sec, and altitude of 300 m above ground level), the system emits laser pulses at 2×2-m spacing along the center of a 240-m swath and extending to 2×4-m spacing on the edges of the swath. Given the travel time of the laser pulse to a point on the surface of the ground and its return to the sensor, the distance to, or elevation of, the point on the ground can be calculated. The EAARL laser has a spot diameter of 20 cm when flown at the nominal surveying elevation. In addition to the LiDAR sensor, the EAARL system includes two down-looking cameras, an RGB (red, green, blue) digital camera and a multi-spectral infrared camera, two dual-frequency GPS (Global Positioning System) receivers, and an integrated digital inertial measurement unit. A complete description of the EAARL system and related publications is available at U.S. Geological Survey (2007) and Nayegandhi (2009).

The Airborne LiDAR Processing System (ALPS), developed in collaboration between the National Aeronautics and Space Administration and the USGS (Bonisteel and others, 2009), was used to process the EAARL data. The ALPS-generated point locations were provided to the USGS for analysis as two separate point datasets: bathymetric and bare earth. The bathymetric data, which represents the river bottom, was clipped to the submerged areas; the bare earth points were removed from these areas and exist only in the terrestrial areas. The EAARL data was collected at an average point density of 0.18 points/m^2 or 1 data point every 5.7 m^2 for the entire Deadwood River data collection area with local densities as high as 1 point/m^2. The South Fork Boise River EAARL data had an overall average point density of 0.36 points/m^2 or 1 point every 2.8 m^2 and local densities as high as 3.3 points/m^2. The bare earth data represent the ground surface, excluding vegetation or manmade structures. The EAARL raster elevation dataset is a combined bare-earth/bathymetry dataset with a 0.5-m resolution created from the corresponding ALPS-generated point elevation locations. All datasets are spatially referenced to Universal Transverse Mercator Zone 11 North referenced by the North American Datum of 1983 and the North American Vertical Datum of 1988.

Ground-Survey Bathymetric and Topographic Data

A survey grade real-time kinematic global positioning system (RTK GPS) was used to collected ground-survey data. The RTK GPS system provides an accuracy of 1 cm horizontally and 2 cm vertically (Trimble, 2003), and has built-in constraints to exclude any data collected outside of the desired accuracy limits.

Bathymetric and topographic data were collected in a grid pattern across the Deadwood and South Fork Boise Rivers at each of the three ground-survey areas along each river. An extra grid pattern of 100 data points spaced at about 2-m intervals was surveyed at each of the three areas in a flat, open area on the floodplain next to the river. Not every ground-survey area had a suitable open area available. Within each of the areas, survey points across the river were spaced at about 1-m intervals, with additional points in certain areas if considered necessary to accurately define changes in slope of the streambed profile, the thalweg of the river, and the water surface along each bank and bar edge if the latter feature was present.

Each ground-survey point was coded according to the hydrogeomorphic setting in which it resided. The three hydrogeomorphic settings in which surveys were made were: (1) stream channel, in which survey points were measured in the submerged stream channel; (2) streambank, which extended from the water's edge up to the level of the floodplain; and (3) instream bars, which were dry at the time of data collection. Additional coding was added to the field points to denote the presence of woody debris, submerged aquatic macrophytes, or an aerated portion of the stream (whitewater), all of which may affect the quality of the EAARL data.

The RTK GPS data were collected using the 2003 Geoid model (Roman and others, 2004) and post-processed in Trimble Geomatics Office software (Trimble Navigation Limited, 2005). The ground-survey data were referenced to the National Geodetic Survey's Continuously Operating Reference Station (CORS) network (Snay and Soler, 2008) by establishing accurate base-station locations using the Static Online Positioning User Service (OPUS-S) (Weston and others, 2007). This method allowed all ground-survey areas to be referenced to the same control network. The ground-survey data have the same spatial reference as the EAARL data: Universal Transverse Mercator Zone 11 North referenced by the North American Datum of 1983 and the North American Vertical Datum of 1988.

Evaluation of Eaarl Data Accuracy

The ground-survey data were compared to both the EAARL bare-earth/bathymetry raster and point datasets. The EAARL raster dataset comparisons were made in a geographic information system (GIS) by extracting the EAARL raster elevation value to the ground-survey point that coincided at that location. The EAARL point datasets were compared with the ground-survey data in a GIS by locating the nearest EAARL point within 1-m distance to each of the ground-survey points. The 1-m distance limitation minimizes the ground-slope change between the two comparison points. Comparisons with the raster dataset allow for a zero offset distance between the comparison datasets by using an interpolated EAARL value at the ground-survey point location. Not every ground-survey point had an EAARL point within the 1-m radius, tables 1 and 2. The EAARL point's value was then related back to the ground-survey point within a 1-m distance. The combined ground-survey point and raster elevation datasets were then exported to another software package for statistical analysis.

Table 1. Comparison of EAARL bare earth/bathymetry raster datasets to ground-survey data, Deadwood and South Fork Boise Rivers, west-central Idaho.

[Numbers 1, 2, and 3 are ground-survey areas along each river. **Abbreviations:** EAARL, Experimental Advanced Airborne Research LiDAR; m, meter; –, hydrogeomorphic type not present in the survey area]

Ground-survey area type	Deadwood River			South Fork Boise River		
	Root mean square error (m) block adjusted			Root mean square error (m)		
	1	2	3	1	2	3
Bank	0.407	0.413	0.726	0.507	0.524	0.667
Channel (not aerated)	0.482	0.271	0.417	0.387	0.396	0.422
Aerated channel	–	–	–	–	–	0.563
Instream bar/island	–	0.351	0.251	0.353	–	–
Macrophytes	–	–	–	0.507	–	–
Woody debris	–	0.415	0.782	0.361	–	–
Flat-surface grid 1	0.214	–	–	0.234	0.134	0.347
Flat-surface grid 2	0.276	–	–	–	–	–
	Mean signed error (m) block adjusted			Mean signed error (m)		
	1	2	3	1	2	3
Bank	0.243	0.114	0.058	0.417	0.128	0.301
Channel (not aerated)	0.296	0.102	0.253	0.306	0.231	0.313
Aerated channel	–	–	–	–	–	0.537
Instream bar/island	–	-0.186	-0.090	0.309	–	–
Macrophytes	–	–	–	0.417	–	–
Woody debris	–	0.140	-0.354	0.235	–	–
Flat-surface grid 1	0.027	–	–	-0.205	0.007	0.345
Flat-surface grid 2	0.113	–	–	–	–	–
	Number of comparisons (n)			Number of comparisons (n)		
	1	2	3	1	2	3
Bank	82	192	226	57	212	96
Channel (not aerated)	318	391	286	263	527	265
Aerated Channel	–	–	–	–	–	18
Instream bar/island	–	64	27	52	–	–
Macrophytes	–	–	–	52	–	–
Woody debris	–	57	32	13	–	–
Flat-surface grid 1	73	–	–	105	109	100
Flat-surface grid 2	110	–	–	–	–	–

Table 2. Comparison of EAARL point datasets to ground-survey data within a 1-meter radius, Deadwood and South Fork Boise Rivers, west-central Idaho.

[Numbers 1, 2, and 3 are ground-survey areas along each river. **Abbreviations:** EAARL, Experimental Advanced Airborne Research LiDAR; m, meter; –, hydrogeomorphic type not present in the survey area]

Ground-survey area type	Deadwood River			South Fork Boise River		
	Root mean square error (m) block adjusted			Root mean square error (m)		
	1	2	3	1	2	3
Bank	0.437	0.521	0.485	0.702	0.646	1.120
Channel (not aerated)	0.510	0.387	0.434	0.404	0.463	0.925
Aerated channel	–	–	–	–	–	0.595
Instream bar/island	–	0.374	0.249	0.446	–	–
Macrophytes	–	–	–	0.518	–	–
Woody debris	–	0.477	0.698	0.375	–	–
Flat-surface grid 1	0.343	–	–	0.269	0.186	0.419
Flat-surface grid 2	0.371	–	–	–	–	–
	Mean signed error (m) block adjusted			Mean signed error (m)		
	1	2	3	1	2	3
Bank	0.129	0.108	-0.047	0.494	0.190	0.263
Channel (not aerated)	0.274	0.124	0.232	0.279	0.241	0.370
Aerated channel	–	–	–	–	–	0.555
Instream bar/island	–	-0.147	-0.041	0.362	–	–
Macrophytes	–	–	–	0.394	–	–
Woody debris	–	0.043	-0.580	0.207	–	–
Flat-surface grid 1	0.025	–	–	-0.184	0.026	0.350
Flat-surface grid 2	0.043	–	–	–	–	–
	Number of comparisons (n)			Number of comparisons (n)		
	1	2	3	1	2	3
Bank	54	119	142	49	114	35
Channel (not aerated)	257	170	178	156	280	139
Aerated channel	–	–	–	–	–	12
Instream bar/island	–	26	10	43	–	–
Macrophytes	–	–	–	38	–	–
Woody debris	–	30	19	13	–	–
Flat-surface grid 1	70	–	–	87	38	51
Flat-surface grid 2	106	–	–	–	–	–

Although the EAARL point datasets provide a direct point-to-point comparison with the ground-survey data, the EAARL raster datasets do not provide such a comparison because an actual EAARL data point does not exist for every raster cell. Therefore, the EAARL raster to ground-survey comparison results include any effects of the interpolator used to infer elevations at cell locations from the EAARL point datasets .

To evaluate the differences between the EAARL elevation datasets and the ground-survey data, the root mean square error (RMSE) and the mean signed error (ME) statistics were calculated for each hydrogeomorphic setting to evaluate performance under those conditions. The RMSE and ME are defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{iLiDAR} - Z_{iground}\right)^2}{n}}, \quad (1)$$

and

$$ME = \frac{\sum_{i=1}^{n}\left(Z_{iLiDAR} - Z_{iground}\right)}{n}, \quad (2)$$

where

Z is elevation, and

n is the number of hydrogeomorphic comparisons.

The lower the RMSE and ME values, the better the agreement between the EAARL data and the ground-survey data. The ME helps identify bias while the RMSE defines the statistical error.

The guidelines of the American Society of Photogrammetry and Remote Sensing (2004) indicate that the dataset to be tested against (in this case, the ground-survey data) be at least three times more accurate than the dataset being tested (the EAARL data). For the study described here, the ground-survey data has a vertical accuracy of 2 cm, providing an acceptable comparison dataset for EAARL data, which can have vertical accuracies as low as 8 cm. Potential sources of error that can affect accuracy are inherent in both LiDAR data collection and ground-surveying techniques. Errors in the LiDAR-derived elevation data can result from various factors, including the presence and type of vegetation cover, water clarity, GPS positioning error, errors in inertial measurement of the aircraft attitude, and the roughness and reflectivity of the measurement surface. These errors can be intrinsic to the data-collection process (for example, GPS positioning error) or be an artifact of that process (for example, roughness of the measurement surface). Errors in the LiDAR data can also be a function of the post-processing of the data, the specific algorithms that are used, and the assumptions that are built into their development and application (Bonisteel and others, 2009).

The values for the surface area and volume of the river channels and banks derived from the EAARL system and the ground surveys were also compared. The surface area and volume were calculated using the water-surface elevation measured from the ground-survey data. EAARL first-surface data were not provided to use as a potential water-surface elevation, and as noted in Skinner (2009), the first-surface data of the EAARL dataset were too variable to use as a water-surface elevation.

Bare-earth and water-surface triangulated irregular networks (TINs) were created for the ground-survey areas using the point ground-survey and the EAARL datasets. The extent of the TINs were limited to the extent or TIN hull of the ground-survey areas so the comparisons between the EAARL and ground-survey TINs had equivalent spatial extents. To make the water-surface TINs, each data point from both datasets was assigned a water-surface elevation from the nearest ground-survey measured water elevation. The volumetric difference between the water-surface and bare-earth TINs was calculated providing the surface area and volume for where the water surface is greater than the bare-earth surface (the river channel), where the water surface is equal to the bare-earth surface, and where the water surface is less than the bare-earth surface (banks, bars, and islands). A percent error was calculated to compare the EAARL to the ground-survey data derived surface areas and the river channel volumes. The volume uncertainty pertains only to the water-surface measurement error and was calculated using the 2 cm elevation error inherent to the GPS equipment used to measure the water-surface elevations and an additional centimeter to account for typical water-surface movement during a water-surface measurement.

Comparison of Datasets

The ME and RMSE for the EAARL raster and point-elevation data comparisons with the ground-survey data are shown in tables 1 and 2, respectively. The tables list the RMSE and ME for each hydrogeomorphic type and the flat-surface grid measurements for each ground-survey area. The paucity of data for some hydrogeomorphic types, such as that for aerated channel in the lower South Fork Boise River ground-survey area, resulted in a low statistical confidence for these comparisons and may not fully represent the true population.

EAARL Raster and Ground-Survey Datasets

The RMSE values for the comparison of the EAARL raster data to the ground-survey data (table 1) range from 0.134 m for the flat-surface grid 1 in ground-survey area 2 of the South Fork Boise River area to 0.782 m for a woody debris area in ground-survey area 3 of the Deadwood River. Along with the instream bar and the channel hydrogeomorphic types in ground-survey area 2 at the Deadwood River, the EAARL system has the least amount of external error in the flat-surface grid measurements. These areas have the least amount of elevation change and tree density. The Deadwood ground-survey area 2 differed from areas 1 and 3 in that the channel and bars were composed of smaller sediments and the overall channel structure is smooth with minimal abrupt elevation changes. Except for the flat-surface grid 1 at survey area 2 of the South Fork Boise River, the RMSEs for both areas are higher than other reported accuracies for EAARL-derived elevations (Kinzel and others, 2007; Barlow and others, 2008; Nayegandhi and others, 2009; Skinner, 2009).

The greatest uncertainty in elevations derived from EAARL data were for those areas with abrupt elevation change, such as stream banks, or for surfaces with the potential to scatter or absorb the EAARL signal, such as woody debris, submerged aquatic macrophytes, or aerated water. The largest elevation differences within a hydrogeomorphic type were for steep banks, for which RMSEs ranged from 0.407 m to 0.726 m. The elevations determined for woody debris and aerated channel hydrogeomorphic types were both problematic in that such surfaces likely scatter the EAARL signal, resulting in RMSEs ranging from 0.361 m to 0.782 m. In ground-survey area 1 on the South Fork Boise River, an RMSE of 0.507 was calculated for elevations in an area of submerged aquatic vegetation. And although this was the only area at both rivers where macrophytes were present, the relatively high RMSE is indicative of the effect such plants can have on the EAARL sensors and the resulting elevation data.

The EAARL data also are affected by noise from random errors in the dataset and by the introduction of errors from specific sources, such as absorption or scatter from vegetation, woody debris, or surfaces with abrupt elevation change. Two TIN surfaces created from the ground survey and EAARL point datasets are compared in Figure 2. Figure 2*A* shows a smooth surface derived from the ground-surface data for an area with fairly well-defined banks. Figure 2*B* shows the same area, but this image was created by using a TIN surface defined from the EAARL data. The EAARL-data-derived surface in figure 2*B* closely matches the ground-survey data in figure 2*A*, but with a rougher surface because of the noise in the EAARL data. The EAARL data in Figures 2*B* and 3 also indicate the smoothing or offset of the near vertical banks as noted in previous studies (McKean, 2009; Skinner, 2009). The bank smoothing or widening is most noticeable along the eastern bank of the river by having a sloping transition between the channel and bank or an offset from the surveyed edge of water. The noise in the EAARL data also corresponds to the presence of artificial "holes" identified in stream channels in Skinner (2009). These "holes" or "divots" are deep areas where the EAARL is measuring the elevation deeper than the true elevation at a small number of points, creating what appears to be a hole in the surface. The opposite also occurs where some EAARL points measured the elevation higher than the true elevation and appear as elevated islands in the surface.

EAARL Point and Ground-Survey Datasets

Comparisons between the EAARL point dataset and the ground-survey dataset are presented in table 2. Fewer comparisons (n) are typical between the EAARL point and ground-survey datasets than between the EAARL raster and ground-survey datasets because not all ground-survey points had a corresponding EAARL point within the required 1-m radius for the comparison (tables 1 and 2). The 1-m radius was selected to encompass enough EAARL points near the ground-survey points for a reasonable comparison while trying to minimize any natural elevation change between points. This assumption is most likely to be "violated" in the bank setting, which may explain the high RMSEs for some ground-survey areas, most notably those of near vertical banks within ground-survey area 2 of the South Fork Boise River.

The comparison of EAARL point to ground-survey data produced results similar to those for the EAARL raster to ground-survey comparisons, even though few data points were available for some of the hydrogeomorphic types. The RMSE values range from 0.186 m for the flat-surface grid 1 in ground-survey area 2 to 1.120 m for the bank hydrogeomorphic type in ground-survey area 3, both on the South Fork Boise River. The relatively high RMSEs for elevations of bank areas of the South Fork Boise are due to a combination of factors, including the presence of bank vegetation, primarily in ground-survey area 1 and in part of ground-survey area 2; steep banks, primarily in ground-survey area 2 and in part of ground-survey area 1; and boulders in ground-survey area 3. These results for the EAARL raster to ground-survey data indicate that the interpolation from the EAARL points to the EAARL raster datasets did not introduce additional error, but resulted in lower RMSEs than their point comparison equivalents. Comparison between an interpolated EAARL raster value at the same location as a ground-survey point (zero horizontal offset) provides lower RMSEs than comparisons between the actual measured EAARL point with a horizontal offset of up to 1 meter and a ground-survey point. One exception to this is the RMSE for the bank hydrogemorphic setting in survey area 3 of the Deadwood River area. The RMSE for raster data for the bank type is much higher than for the point data bank type, which indicates the influence of woody debris in the rasterization of the EAARL point dataset.

A. Ground-survey elevation

B. EAARL elevation

Figure 2. Topographic and bathymetric elevations for the ground-survey (*A*) and EAARL (*B*) derived elevations, ground-survey area 2, South Fork Boise River, west-central Idaho.

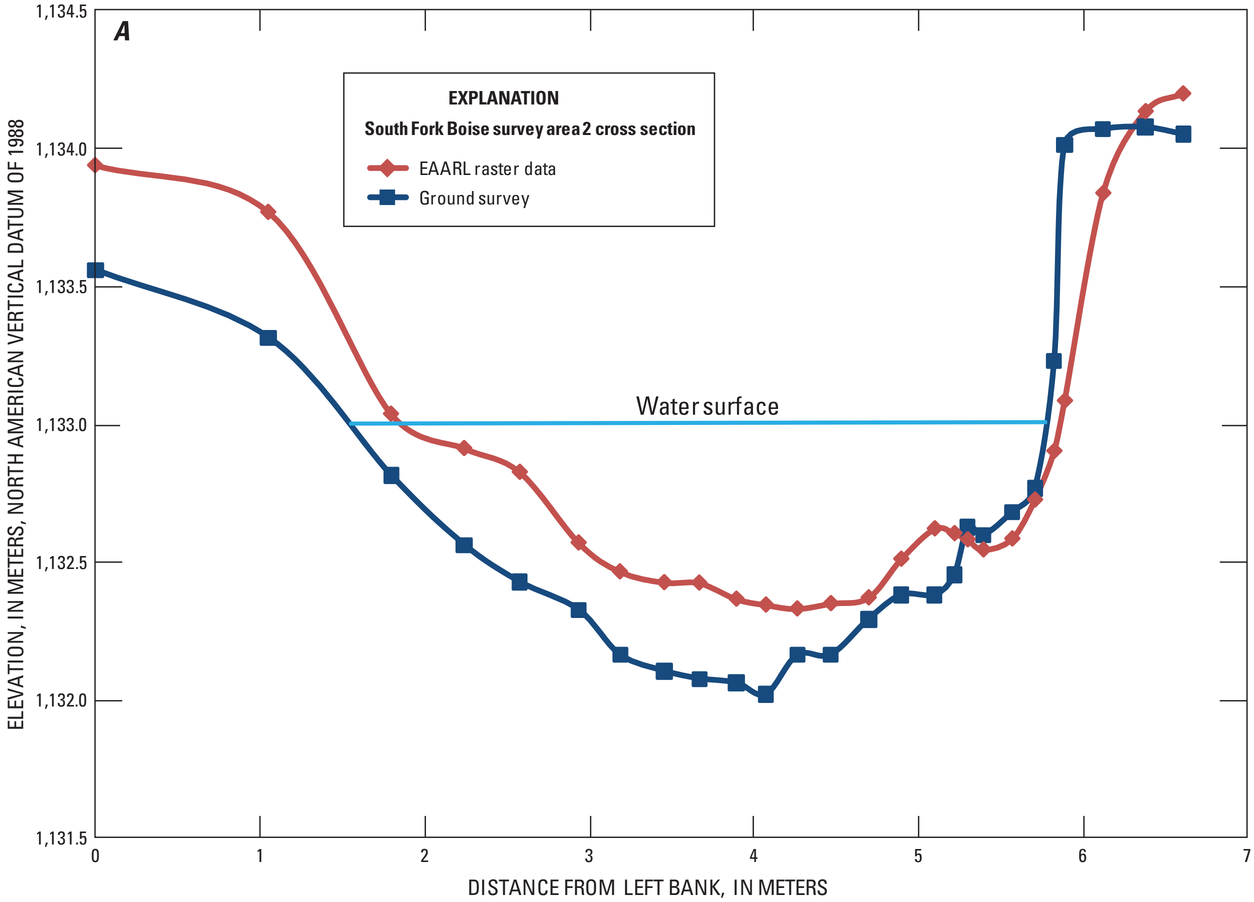


Figure 3. EAARL raster and ground-survey elevations at cross sections at the (*A*) South Fork Boise River survey area 2 and (*B*) Deadwood survey area 3, west-central Idaho.

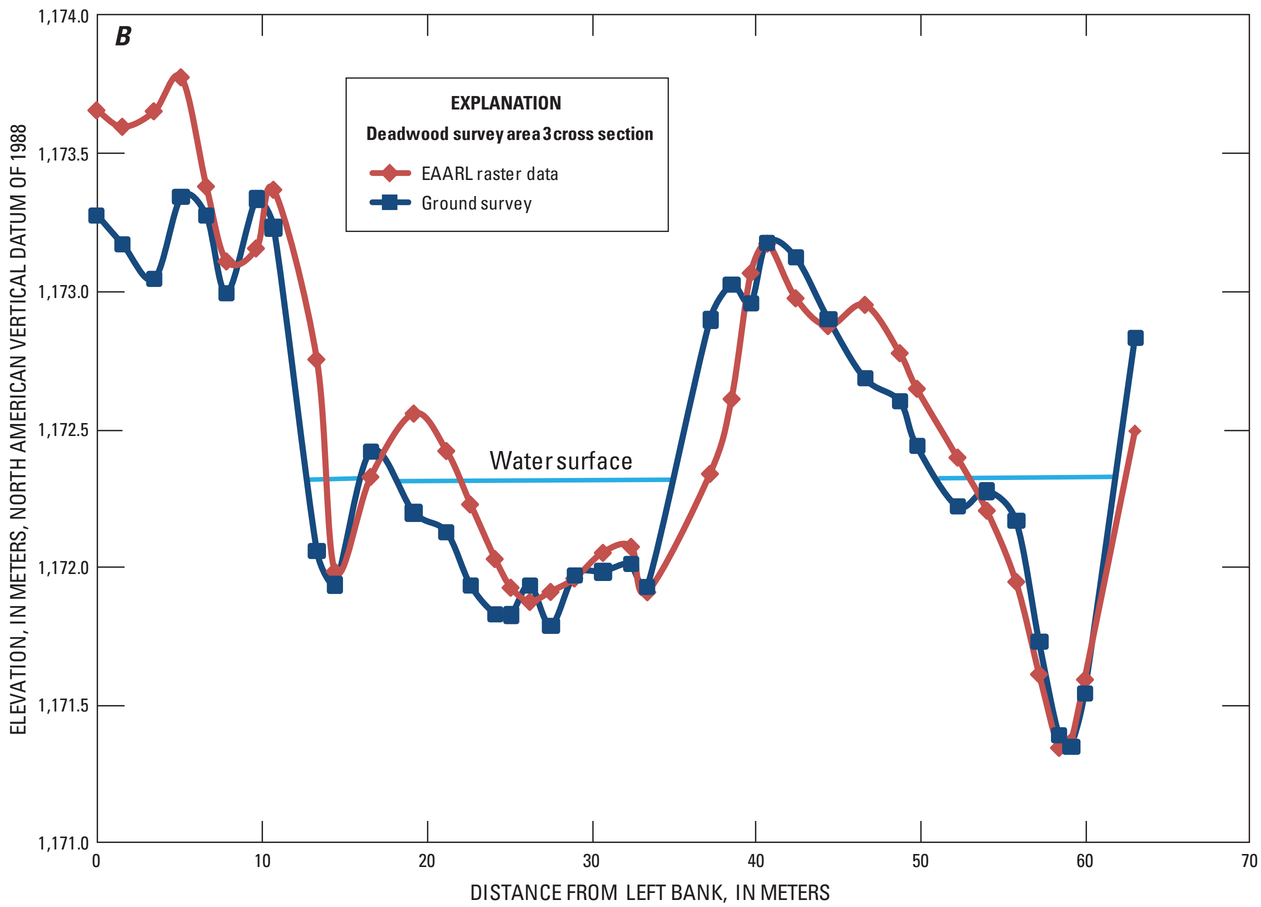


Figure 3.—Continued

Analysis for Bias

The mean signed error (ME) comparison results indicated a consistent bias in the Deadwood survey area—the EAARL elevations were less than the ground-survey elevations. On the basis of the mean error of the best reflective surfaces, a positive block shift of 0.351 m was applied to the Deadwood EAARL elevations. The data on tables 1 and 2 reflect the resulting shifted ME for the Deadwood survey area.

The data for the South Fork Boise survey area did not indicate a consistent ME, so that neither a block shift nor other bias corrections were applied to this dataset (tables 1 and 2). Overall, the data for the South Fork Boise River hydrogeomorphic types have a positive mean error; however, the mean errors in the data for the flat-surface grid, whose purpose is to provide an ideal location for identifying bias, are neither solely positive nor negative, so a bias correction was not applied to the dataset.

Stream Surface Area and Volumetric Percent Error

The river surface-area calculations that were derived from the volumetric difference between the water-surface and bare-earth TINs indicate that the EAARL-derived data generally defined river channel extent very well (fig. 4). The error for elevations of the wetted river channel surface area averaged -0.5 percent and ranged from -12 to 13 percent (table 3). On average the EAARL correctly delineated the wetted river channel area.

The “elevation coincident with water-surface elevation” category (table 3) indicates high percentage errors but are misleading due to the small areas represented. This category represents areas for which the surveyed elevation matches the surveyed water elevation, and if such an area is present tends to occur along the river banks or bar margins in flat areas.

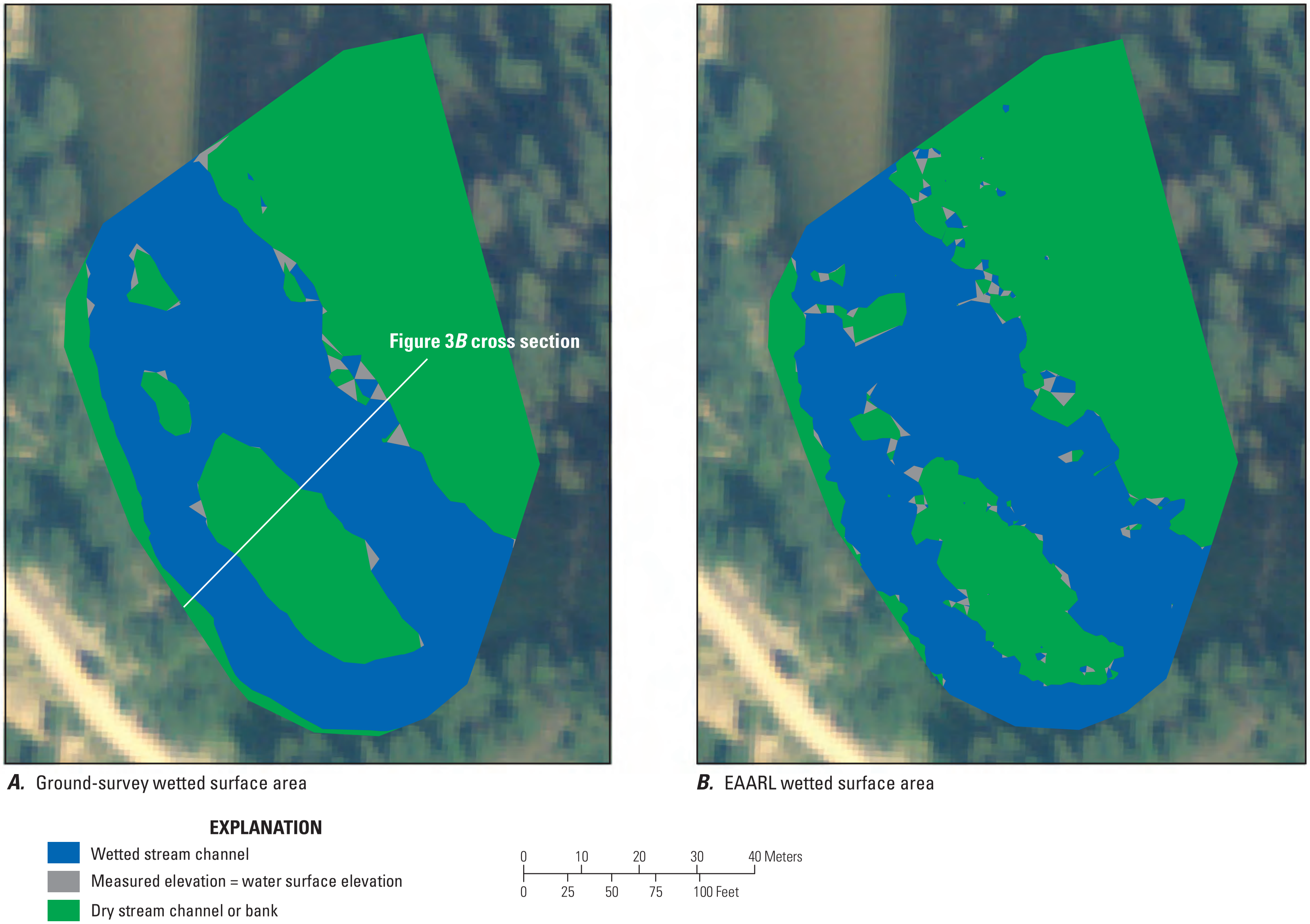


Figure 4. MWetted surface area comparison between ground-survey (*A*) and EAARL (*B*) derived elevations in ground-survey area 2, Deadwood River, west-central Idaho.

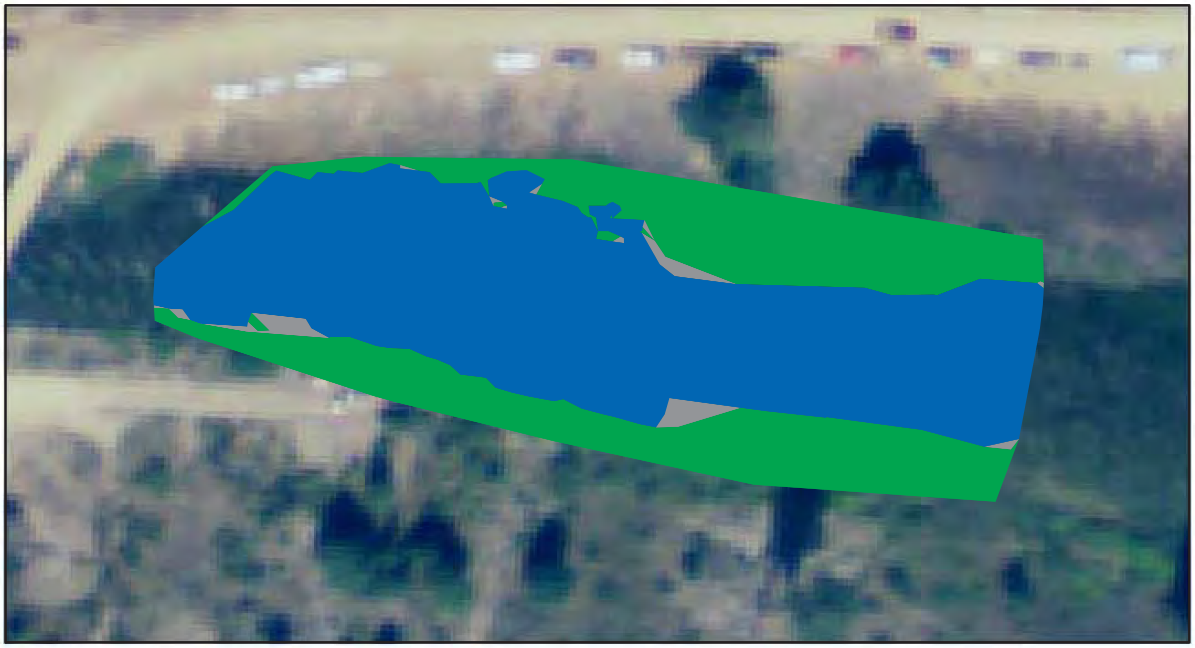
Table 3. Comparison of surface areas delineated by ground surveys and EAARL system derived data for the Deadwood and South Fork Boise Rivers, west-central Idaho.

[**Abbreviations:** EAARL, Experimental Advanced Airborne Research LiDAR; m^2, square meter]

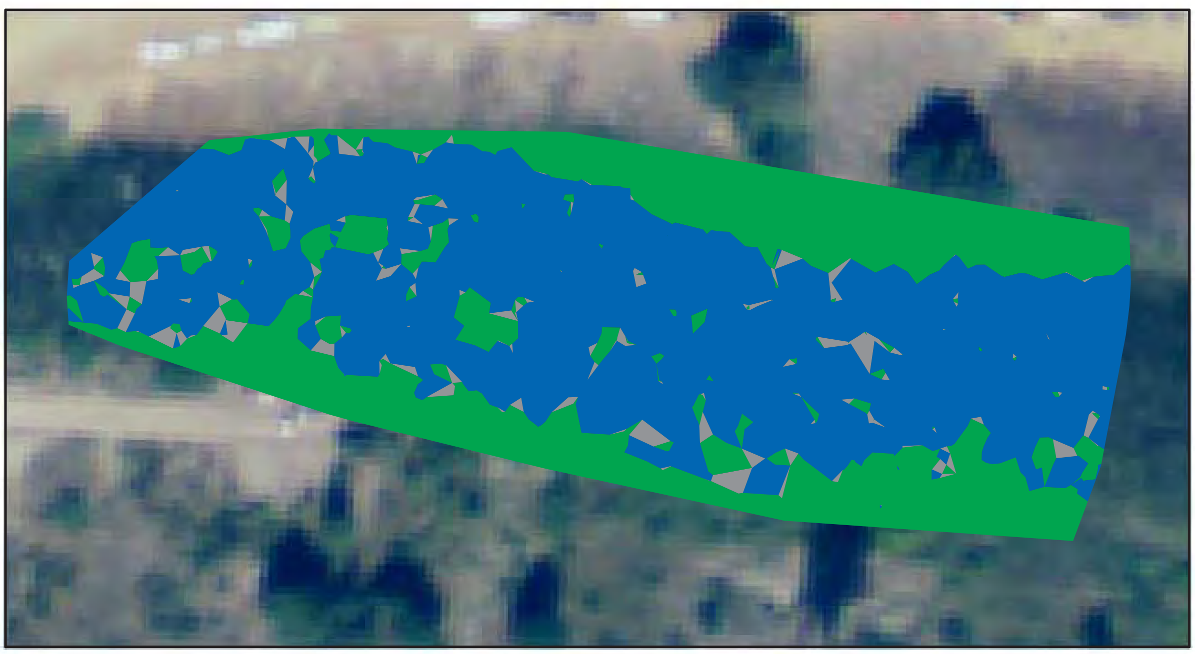
Ground-survey area type	Surface area (m^2)		Percent error
	Ground survey	EAARL	
Deadwood River			
Ground-survey area 1			
Wetted stream channel	425	479	13
Elevation coincident with water-surface elevation	5	14	192
Dry stream channel or bank	218	154	29
Ground-survey area 2			
Wetted stream channel	3,119	3,065	-2
Elevation coincident with water-surface elevation	67	97	46
Dry stream channel or bank	3,428	3,449	1
Ground-survey area 3			
Wetted stream channel	1,051	926	-12
Elevation coincident with water-surface elevation	21	55	168
Dry stream channel or bank	1,509	1,598	6
South Fork Boise River			
Ground-survey area 1			
Wetted stream channel	3,582	3,524	-2
Elevation coincident with water-surface elevation	66	35	-47
Dry stream channel or bank	1,748	1,835	5
Ground-survey area 2			
Wetted stream channel	2,888	2,900	0
Elevation coincident with water-surface elevation	10	28	171
Dry stream channel or bank	2,295	2,263	-1
Ground-survey area 3			
Wetted stream channel	2,790	2,767	-1
Elevation coincident with water-surface elevation	79	145	84
Dry stream channel or bank	1,686	1,645	-2

While this category was delineated correctly for some areas like the South Fork Boise ground-survey area 3 (fig. 5*A*), it also incorporates incorrectly measured elevations or transition zones like that for the EAARL data in the center of the river in the same area (fig. 5*B*).

The error for the wetted river channel volume averaged -8 percent and ranged from -42 percent for survey area 3 of the Deadwood River and up to 16 percent for survey area 2 of the South Fork Boise River. All of the volume differences were greater than the volume uncertainty calculated from the ground-survey water-surface elevation measurement error. The volume of the wetted river channel was underestimated by an average of 31 percent in half of the survey areas, and overestimated by an average of 14 percent in the remainder of the survey areas (table 4). Figure 5*B* illustrates the underestimation of river channel volume by the EAARL system —the data indicated a too shallow water depth. The EAARL derived wetted river surface area for this survey area is very close to the ground-survey surface area; however, the EAARL river channel volume is much less than the ground-survey volume due to the shallow depths measured. This may be due to the presence of aerated water or bubbles (whitewater) and/or large substrate (boulders) in this survey area.



A. Ground-survey wetted surface area



B. EAARL wetted surface area

EXPLANATION

- Wetted stream channel
- Measured elevation equal to water-surface elevation
- Dry stream channel or bank

0 10 20 30 40 Meters
0 20 40 60 80 100 120 Feet

Figure 5. Wetted surface area comparison between ground-survey (*A*) and EAARL (*B*) derived elevations in ground-survey area 3, South Fork Boise River, west-central Idaho.

Table 4. Comparison of river channel volumes between ground-survey and EAARL data for the Deadwood and South Fork Boise Rivers, west-central Idaho.

[**Abbreviations:** EAARL, Experimental Advanced Airborne Research LiDAR; m^3, cubic meter]

Ground-survey area	Wetted stream channel volume (m^3)		Percent error	Ground-survey uncertainty
	Ground survey	EAARL		
Deadwood River				
Ground-survey area 1	163	186	14	13
Ground-survey area 2	938	1,084	16	94
Ground-survey area 3	303	191	-37	32
South Fork Boise River				
Ground-survey area 1	2,324	2,028	-13	107
Ground-survey area 2	1,206	1,352	12	87
Ground-survey area 3	1,119	645	-42	84

Summary

To assist in managing surface-water projects that influence important fisheries in the Deadwood and South Fork Boise Rivers, Idaho, high-resolution topographic and bathymetric data were needed to develop hydraulic models and make assessments of aquatic habitat. The Experimental Advanced Airborne Research LiDAR (EAARL) system was used in attempts to acquire such data.

To evaluate the accuracy of the elevation datasets acquired with the EAARL system, it was necessary to collect data on the ground in the various hydrogeomorphic settings within the Deadwood and South Fork Boise River basins. Ground-truth data were collected in three areas representing different hydrogeomorphic settings along each river concurrent with the collection of EAARL system data using a survey grade global positioning system, which provided elevation and positional accuracies ranging from 1 to 3 centimeters. Ground surveys included a grid of measurements in a flat, open area to provide an optimal vertical comparison surface for the EAARL and ground-survey data. Additional surveys were conducted across the rivers to determine the accuracy of the EAARL system acquired data for assessing hydrogeomorphic settings such as banks, the configuration of stream bottoms (bathymetry), woody debris, air bubble entrainment (whitewater), and wetted channel surface areas and volumes.

Both point and raster datasets from the EAARL system were compared with data from the ground-surveys. Root mean square errors (RMSEs) in elevations, calculated for the flat-surface grid surveys to assess the accuracy of the EAARL datasets with minimal introduction of error, ranged from 0.134 to 0.347 m. RMSEs for elevation data representing the various hydrogeographic settings ranged from 0.251 to 0.782 m. This high range of root mean square errors exemplifies the dynamic performance of a LiDAR in various hydrogeomorphic settings and the need to define how LiDAR data varies amongst these environments. Of the hydrogeomorphic settings assessed, elevations for the instream bars were the most accurate. This is likely due to their smooth surface without abrupt elevation changes. Errors in elevations for the surfaces of river channels were slightly greater than those for instream bars and were likely influenced by the presence of entrained air bubbles or submerged aquatic macrophytes. Elevations for streambanks had the highest RMSEs of all the categories due to their steep slopes, and the presence of vegetation and/or large substrate (boulders). These conditions were most prevalent along the South Fork Boise River. The presence of a steep slope exacerbates the vertical error in elevation data due to horizontal spatial differences (up to 1 m) between the EAARL and ground-survey datasets, thereby invalidating the assumption that ground-survey and EAARL points near each other represent the same location. Comparisons between the EAARL point datasets to ground-survey datasets produced results similar to the EAARL raster to ground-survey comparisons, with slightly improved RMSEs for the EAARL raster comparisons, indicating the possibility that interpolation of the EAARL points to rasters reduces the horizontal offset between the comparison datasets.

The average error in elevations for the wetted river channel surface area was -0.5 percent, and ranged from -12 to 13 percent. On average, the elevation values derived from the EAARL system data correctly delineated the wetted river channel surface area. The wetted river channel volume error averaged -8 percent and ranged from -42 percent up to 16 percent. The volume of the wetted river channel was underestimated by an average of 31 percent in half of the survey areas, and overestimated by an average of 14 percent in the remainder of the survey areas.

The EAARL system is an efficient way to obtain topographic and bathymetric data in large areas of remote terrain. The elevation accuracy of the EAARL system varies throughout the collection area depending upon the hydrogeomorphic setting. The elevation accuracy variations should be kept in mind when using the data, such as for hydraulic modeling or aquatic habitat assessments.

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Appendix A. Ground Photography

Deadwood River ground-survey area 1 looking downstream, early October 2008.

Deadwood River ground-survey area 2 looking downstream, late September to early October 2007.

Deadwood River ground-survey area 2 left bank, late September to early October 2007.

Deadwood River ground-survey area 2 looking upstream, late September to early October 2007.

Deadwood River ground-survey area 2 woody debris, late September to early October 2007.

Deadwood River ground-survey area 2 looking across the stream, late September to early October 2007.

Deadwood River ground-survey area 3 looking downstream (downstream section), late September to early October 2007.

Deadwood River ground-survey area 3 looking downstream (upstream section), late September to early October 2007.

Deadwood River ground-survey area 3 right bank (upstream section), late September to early October 2007.

Deadwood River ground-survey area 3 woody debris, late September to early October 2007.

Deadwood River ground-survey area 3 looking across the stream (downstream section), late September to early October 2007.

Deadwood River ground-survey area 3 looking across the stream (upstream section), late September to early October 2007.

South Fork Boise River ground-survey area 1 looking downstream, late September to early October 2007.

South Fork Boise River ground-survey area 1 left bank, late September to early October 2007.

South Fork Boise River ground-survey area 1 right bank, late September to early October 2007.

South Fork Boise River ground-survey area 1 looking upstream, late September to early October 2007.

South Fork Boise River ground-survey area 2 looking downstream, late September to early October 2007.

South Fork Boise River ground-survey area 2 flat-surface area, late September to early October 2007.

South Fork Boise River ground-survey area 2 right bank, late September to early October 2007.

South Fork Boise River ground-survey area 2 looking upstream, late September to early October 2007.

South Fork Boise River ground-survey area 3 looking downstream, late September to early October 2007.

South Fork Boise River ground-survey area 3 flat-surface area, late September to early October 2007.

South Fork Boise River ground-survey area 3 looking upstream, late September to early October 2007.

South Fork Boise River ground-survey area 3 looking across the stream, late September to early October 2007.

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