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Assessing the ability of airborne LiDAR to map river bathymetry†

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Abstract

Airborne bathymetric LiDAR was collected for 220 river kilometres in the Yakima and Trinity River Basins in the USA. Concomitant with the aerial data collection, ground surveys of the river bed were performed in both basins. We assess the quality of the bathymetric LiDAR survey from the perspective of its application toward creating accurate, precise and complete streambed topography for numerical modelling and geomorphological assessment. Measurement error is evaluated with respect to ground surveys for magnitude and spatial variation. Analysis of variance statistics indicate that residuals from two independent ground surveys in similar locations do not come from the same population and that mean errors at different study locations also come from different populations. Systematic error indicates a consistent bias in the data and random error falls within values of expected precision. Published in 2007 by John Wiley & Sons, Ltd.

Keywords: bathymetric LiDAR; river survey; channel geometry

Introduction

There is a growing need to efficiently and accurately represent river channel geometry with high resolution to study fluvial environments for flow hydraulics, flood routing, sediment transport, aquatic habitat and monitoring of geomorphological change (Lane *et al.*, 1994; Marks and Bates, 2000; Westaway *et al.*, 2000). This is especially true for long study reaches at watershed scales where field survey methods can be time consuming and costly (Marcus, 2002). Although much progress has been made in the ability to represent complex hydraulic flow patterns with multidimensional numerical models, one of the problems that still exists is inadequate terrain representation, particularly river channel bathymetry (Marks and Bates, 2000; Westaway *et al.*, 2000; Lane *et al.*, 2003). Studies using multi- and hyperspectral imagery (e.g. Lyon *et al.*, 1992; Winterbottom and Gilvear, 1997; Roberts and Anderson, 1999; Marcus, 2002; Whited *et al.*, 2002; Marcus *et al.*, 2003) and standard photogrammetry (e.g. Lane *et al.*, 1994, 2003; Westaway *et al.*, 2000, 2001, 2003; Carbonneau *et al.*, 2006) have shown an ability to map bathymetry through shallow water. A distinct advantage of using imagery to map river channel bottoms is the relatively low cost. However, these studies have shown some limitations. First, there is a weakness inherent in photogrammetric methods in shallow water due to the use of the red colour band. It has been shown that the red colour band has a greater sensitivity to depth than blue or green (Winterbottom and Gilvear, 1997; Legleiter *et al.*, 2004; Carbonneau *et al.*, 2006) but does not penetrate the water column as deeply. Secondly, these studies use relationships of depth and water colour that are site specific and require ground surveys to calibrate this process (Westaway *et al.*, 2003; Carbonneau *et al.*, 2006). Third, changes in substrate material, overhanging vegetation, surface disturbance by waves, and shadows on the water surface can introduce error for image-based measurements using colour to determine depth (Roberts and Anderson, 1999; Carbonneau *et al.*, 2006).

Over the past two decades significant advances have been made in airborne LiDAR bathymetry (ALB) technology, which may provide an additional method for obtaining dense river channel bathymetry. Airborne LiDAR bathymetry overcomes some of the weaknesses of image based methods such as increased penetration for greater depth measurement and eliminates error induced by shadows or surface disturbance. Additionally, ALB is not affected by sun angle and glint on the water surface, and thus not limited to data collection during favourable light conditions. Ground surveys are not required to post-process ALB data although it is recommended for independent quantification of remote measurement error. The Bureau of Reclamation has recently used ALB to survey inland river channels in Washington and California, USA. To date, these data have been used to create two-dimensional hydraulic models to evaluate aquatic habitat (Hilldale, 2007), although many other uses are possible. As new surveying technologies are developed and made available it is important to assess the quality of the data being produced. In the past it has been noted that aerial mapping methods, particularly LiDAR, do not always meet the manufacturer's or contractor's published accuracies under all conditions (Bowen and Waltermire, 2002; Charlton *et al.*, 2003). Measurement error can come from a variety of sources, including weather conditions, vegetation, water clarity, GPS positioning error, inertial measurement of the aircraft attitude and data processing (Brinkman and O'Neill, 2000; Charlton *et al.*, 2003). Here we assess the ability of ALB to provide a quality representation of river channel bathymetry.

This study evaluates data quality in a similar fashion to that outlined in Lane *et al.* (1994) and Westaway *et al.* (2001, 2003), who based their analysis on Cooper (1998) and Cooper and Cross (1988). Quality of a surveyed surface is a function of accuracy, precision and internal reliability. Accuracy is a function of systematic error and is quantified using the mean error (ME) between ground survey data and remotely sensed data. Precision is a function of random error and is quantified with either an R^2 value or, as used here, standard deviation (SD). Internal reliability refers to gross error typically associated with an extreme error measurement caused by blunders or mechanical malfunction. These errors can be detected if there is some redundancy (Lane *et al.*, 1994) and may appear as outliers (Westaway *et al.*, 2003). This type of error is assumed to have been corrected prior to delivery of the final data by the contractor. Therefore data quality in this manuscript is evaluated with ME and SD.

Expected precision

The overall quality of bed elevation measurements with ALB should consider only those error sources related to the ALB. Methods used to evaluate the quality of the ALB have their own inherent sources of uncertainty that, if random, cannot be removed from error estimates. The overall quality of the ALB measurements presented here is therefore a function of all the sources of measurement uncertainty. We present this as the expected precision of the error measurements. The expected precision can be used to identify significant measurement error or outliers (e.g. Westaway *et al.*, 2003) or for evaluation of applicability purposes. As per Lane *et al.* (2003) the expected precision (e) comparing two sets of data for 95% confidence should fall below

$$|e| \le t_{\alpha/2}\sqrt{\sum_{i=1}^{N}\sigma_i^2}$$

where N is the number of sources of random error and i represents each random error such that σ_i^2 is the variance of the random error associated with process i and $t_{\alpha/2}$ is 1·96 for a 95% confidence level. The sources of random measurement uncertainties are: the precision of the ALB (±0·25 m obtained from the manufacturer); sites with ground survey performed with a survey rod using Real Time Kinematic Global Positioning Satellite (RTK GPS) equipment (±0·02 m obtained from the manufacturer); error related to acoustic Doppler current profiler (ADCP) surveys for those sites using boat mounted acoustics (±0·088 m, obtained from Wilson *et al.*, 1997); precision related to the placement of the survey rod on the river bed, here the uncertainty is a function of the rod base diameter relative to grain size (DeVries and Goold, 1999) and is assumed to be 0·5 d_{50} for d_{50} > the diameter of the foot of the survey rod (0·03 m) and 0 otherwise.

Current Channel Surveying Methods

Current bathymetric survey methods include ground survey while wading or boat mounted acoustics, using an ADCP (e.g. Vermeyen, 1996; Dinehart and Burau, 2005) or either single or multibeam SONAR (Sound Navigation And Ranging) (e.g. Poppe, 2006; Ferrari, 2005). Based on published values of precision, ground surveys using a total station or Kinematic GPS survey equipment probably provide the best quality for measuring bathymetry in shallow and slow water conditions but has obvious safety and logistical limitations with increasing water depth and velocity, and is impractical for long reaches. Multibeam SONAR can provide a dense coverage of bathymetry, depending on water depth and sampling frequency (Ferrari and Collins, 2006), however, this equipment is better suited for large rivers or reservoirs due to the size and vulnerability of the costly transducer and minimum depth requirements. The most common method for acquiring river bathymetry has been a single beam SONAR or an ADCP used in conjunction with RTK GPS. The surveying equipment obtains horizontal position and water surface elevations while the acoustic signal obtains depth. The bathymetry is obtained through post processing, which can be time consuming and subject to interpolation over long distances between known locations of water surface if GPS coverage is poor. Riparian vegetation and terrain features can interfere with satellite and radio reception for the GPS survey equipment which may add to sampling difficulty and measurement error. Due to the nature of these acoustic devices, the collection of depth data takes place directly under the transducer (nadir measurement) and is limited to the path taken by the vessel. Some investigators have had success obtaining bathymetric measurements by separating individual beam data from an ADCP (e.g. Dinehart and Burau, 2005). Obtaining a high density, complete coverage in this manner is difficult. A typical collection method is to cross back and forth across the river in conjunction with collecting data parallel to the shore line. If the river is surveyed with a non-motorized craft, multiple runs down the river are often necessary to survey near channel margins and the channel centre.

Published vertical precisions of RTK surveys using GPS surveying equipment are ±0·02 m under ideal conditions (Trimble, 2006). Precision of depth measurements from a TRD Instruments (Teledyne RD Instruments, 2006) ADCP are ±0·088 m (Wilson *et al.*, 1997). This does not account for rocking boat movement that could cause deviation from the nadir measurement assumption, potentially increasing the overall error unless an inertial measurement system is used. The errors associated with current bathymetric survey methods are provided for context and the calculation of expected precision.

Bathymetric LiDAR

Currently there are a few operational bathymetric LiDAR systems in use; including the Scanning Hydrographic Operational Airborne LiDAR System (SHOALS, Optech, Toronto, Ontario, Canada, U.S. Navy and Army Corps of Engineers), the Hawk Eye, a SHOALS derivative (Saab Instruments/Optech, Swedish Royal Navy), the Laser Airborne Depth Sounder (LADS; Tenix LADS Corporation, Mawson Lakes, South Australia, Australia) and the Experimental Advanced Airborne Research LiDAR (EAARL). The Hawk Eye, LADS and SHOALS are of similar design (Finkl *et al.*, 2005), and the EAARL is operated by NASA and designed for surveying shallow coral reefs using a less powerful laser. The EAARL has been used recently to survey the Platte River in Nebraska, USA (Kinzel *et al.*, 2006). China, France and Russia have also undertaken efforts to develop bathymetric LiDAR technology (LaRocque and West, 1990).

The SHOALS-1000T

The ALB data for this study was collected with a SHOALS-1000T. The system consists of a sensor, operator console, chiller rack and the laser rack. An inertial measurement unit is incorporated to track aircraft attitude while its position is tracked using kinematic GPS. The SHOALS-1000T is capable of recording x–y–z data at a rate of 1000 Hz with a sounding density of 2×2 to 5×5 m. The point data for the bathymetry meets Order 1 accuracy standards of the International Hydrographic Organization (IHO) (USACE, 2002). The manufacturer states a depth penetration of 50 m under ideal conditions with a horizontal precision of ±2·5 m and a vertical precision of ±0·25 m (Optech, 2006). The U.S. Army Corps of Engineers claims slightly different specifications, ±3 m horizontal precision, ±0·15 m vertical precision, and a depth penetration of 40 m (Lillycrop *et al.*, 1996). For more information on hydrographic surveying accuracies, development of the SHOALS system, and the IHO, see the U.S. Army Corps of Engineers Hydrographic Survey manual (USACE, 2002).

The SHOALS-1000T in bathymetric mode uses a pulsed Nd:YAG flashlamp laser transmitter with both green (520 nm wavelength) and infra-red (1064 nm wavelength) output beams. The average energy per pulse is 5 mJ with a 5 ns pulse width (Lillycrop *et al.*, 1996). The green pulse is used for bottom detection because its wavelength allows it to penetrate water with the least amount of attenuation. The infra-red pulse is used to detect the water surface, as its wavelength allows very little water penetration. When these pulses are reflected and returned to the receiver, distances to the water surface and sea/river bed are calculated, based on the speed of light in air and water. The laser pulses are transmitted at an angle of 15°–20° from nadir toward the front of the aircraft using a scanning mirror (Guenther *et al.*, 2000). Both the green and infra-red beams are expanded to a diameter of at least 2 m at the water surface to achieve eye-safe operation. The green beam continues to spread as it penetrates the water column. The beam diameter is a critical factor that determines precision in the horizontal measurement and large beam diameters may limit the proper representation of high relief features in the bed.

The ability of the SHOALS-1000T to successfully detect the river bed can be affected by overhanging riparian or heavy aquatic vegetation, which will produce spurious data. In some cases successful bottom detection is possible during leaf-off conditions. Significant air entrainment in the water column, as is seen in severe rapids or just downstream of a dam or spillway, can interfere with the laser pulses and prevent accurate bathymetric measurement. These limitations are typically very local and result in 'holes' in the data. Bottom reflectivity plays a small role in reflecting laser pulses however; a more important condition is water clarity (Guenther *et al.*, 2000). A common measurement of water clarity is the Secchi depth, the depth at which a disc, usually painted black and white, can no longer be seen by the naked eye. A successful ALB survey can typically be made to depths of about two to three times the Secchi depth. The variability in the depth measurement capability results from the fact that the Secchi depth does not measure the true parameter affecting green laser penetration, which is reflection and scatter. A factor of two applied to the Secchi depth is more appropriate for water that has a significant amount of absorption, whereas a factor of three is appropriate for water dominated by scattering (Guenther *et al.*, 2000).

Study Locations

Yakima Basin

The Yakima River Basin in Washington has a drainage area of 16 000 km^2, produces a mean annual unregulated runoff of 158 m^3 s^{-1}, and a mean annual regulated runoff of 102 m^3 s^{-1} (Mastin and Vacarro, 2002). The Yakima Basin headwaters are on the eastern slope of the Cascade Range and the Yakima River terminates at its confluence with the Columbia River (Figure 1). Basin elevations range from 122 to 2440 m (Mastin and Vaccaro, 2002). Much of the Yakima River has a slope in the range of 0·25% from the headwaters to the city of Yakima (Figure 1), downstream of which the slope slowly begins to decrease to less than 0·1% near the mouth. Seven separate reaches were surveyed using ALB, covering approximately 153 km of the Yakima and Naches Rivers. The water depth of the Yakima Basin along these reaches did not exceed 6 m at the time of measurement.

The Easton and lower Kittitas reaches were surveyed in 2004. A second set of ALB data in the Yakima Basin was collected in 2005 on the upper Kittitas, Naches, Sunnyside, Prosser and Chandler reaches. Table I shows individual reach properties. The ALB data collected in the Yakima Basin was flown with the SHOALS-1000T mounted in a fixed wing aircraft flying at an altitude of 300 m collecting data at a 2×2 m spot density.

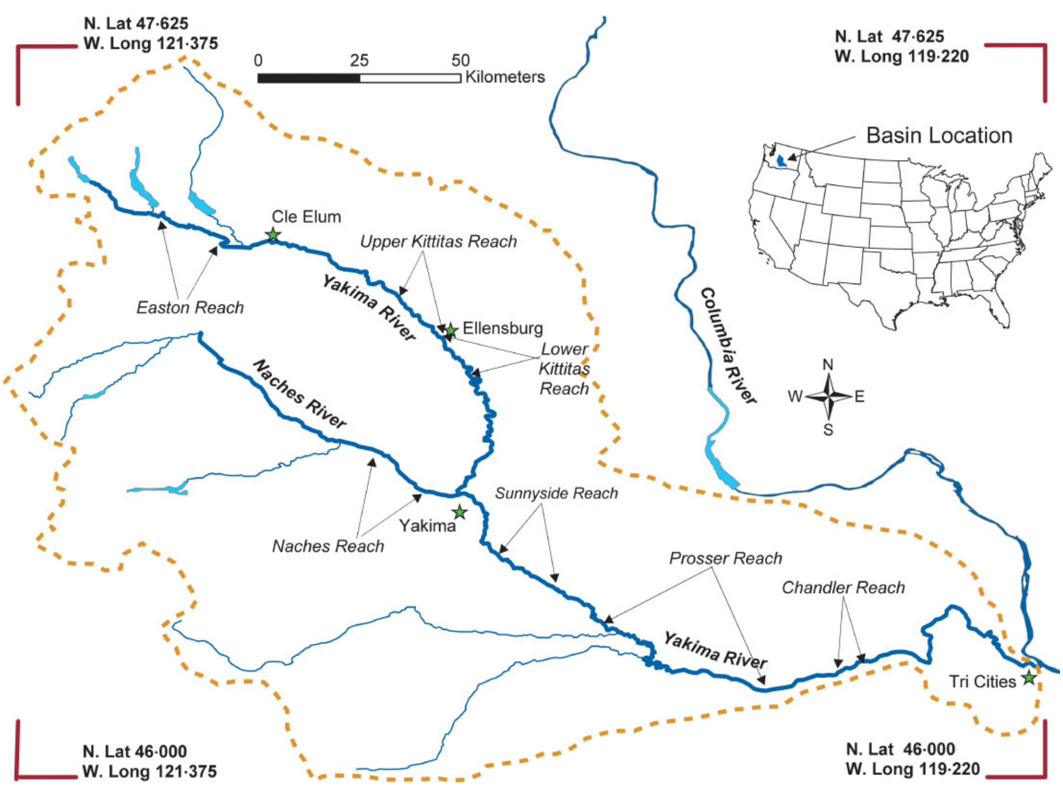

Figure 1. Site map of the Yakima River Basin, Washington and the study reach locations. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table I. Reach properties for the Yakima Basin. A range of values is shown for some reaches because there is significant variation throughout the reach.

Reach name	Average slope (%)	Typical discharge ($m^3 s^{-1}$)	Length (km)	Average d_{50} (mm)
Easton	0·25	6–11	19·3	55
Upper Kittitas	0·25	23–88	16·6	74
Lower Kittitas	0·25	23–88	6·4	74
Naches	0·50	25–42	16	105
Sunnyside	0·20	9–56	24·4	65
Prosser	0·004–0·09	16–68	58	0·4–50
Chandler	0·08–0·20	16–68	9	42–100

Trinity River

The Trinity River Basin has its headwaters in the Trinity Alps Wilderness Area of the southern Cascade Range in California and drains 7640 km^2. The basin terminates at the confluence with the Klamath River. Altitudes range from 152 to 2740 m (Figure 2) (McBain and Trush, 1997). Following the initial ALB data collection on the Yakima River, 67·6 contiguous river kilometres were flown with ALB on the Trinity River. The data collection began at Lewiston Dam and extends downstream to the confluence with the North Fork, Trinity River (Figure 2). The deepest water depths on the river did not exceed 6 m at the time of data collection. The average bed slope throughout this reach is approximately 0·25%. Bed material d_{50} falls within the range of 35–55 mm (McBain and Trush, 1997). Discharge on the Trinity River is controlled by releases from Lewiston Dam and is most commonly 10–12 $m^3 s^{-1}$.

The ALB data for the Trinity River were acquired using the SHOALS-1000T mounted in a Bell 206L helicopter flying at an altitude of 200 m collecting data at a 2×1 m spot density. The shorter dimension is in the direction of flight; as the helicopter flies slower compared with the fixed wing aircraft.

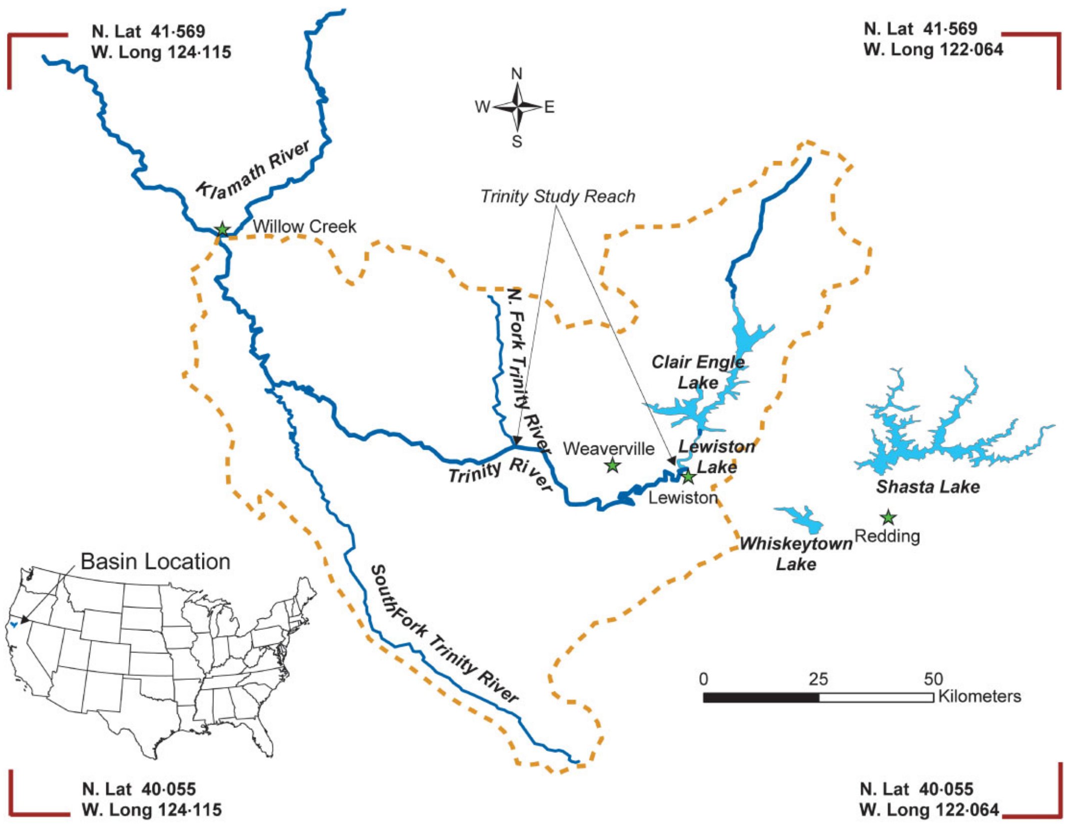

Figure 2. Site map of the Trinity River Basin, California and the study reach location. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Aerial and Ground Surveys

Concomitant with the aerial data collection, ground surveys of the river channel were performed. All ground surveys used the same control points, or were tied to the control used for the ALB survey.

Yakima basin survey

The ALB surveys of the Easton and lower Kittitas reaches were flown in September 2004 and the upper Kittitas, Naches, Sunnyside, Prosser and Chandler reaches were flown in April and May 2005 (Figure 1). In all but the lower Kittitas reach, bed elevations were surveyed by wading. For the lower Kittitas reach only, bed elevations were determined by placing the survey rod on the channel bed from a motorized boat. It appears this method may have produced greater uncertainty than bed elevations obtained while wading due to the difficulty of placing the foot of the survey rod in a stable location while maintaining a perpendicular rod. The amount of error generated when obtaining bed elevations in this fashion could not be quantified. It is expected that this uncertainty is small, although perhaps not negligible.

Ground surveys for the Yakima Basin were performed at two or more sites within each reach. These surveys were projected in State Plane Coordinates, Washington South. Horizontal and vertical datums were NAD 83 and NAVD 88, respectively.

Two separate and independent ground surveys were performed for some of the Yakima Basin reaches. Ground survey data set 1 is used to make comparisons with and draw conclusions about the quality of the ALB data. Ground survey data set 2 is used for comparison with ground survey data set 1 in order to draw conclusions regarding the quality of the ground survey.

Trinity River survey

The Trinity River ALB survey took place in December 2005 over one continuous 67·6 km reach of the river (Figure 2). The Trinity River ground surveys were performed at four sites using RTK GPS survey equipment while wading, and from a boat using single beam sonar in conjunction with RTK GPS survey equipment. The sonar survey was performed in locations where flow depth prevented wading, otherwise closely spaced cross sections were surveyed. Surveys for the Trinity river were projected in State Plane Coordinates, California I. Horizontal and vertical datums were NAD 83 and NAVD 88, respectively.

Assessment of Quality

The ability of the ALB to accurately and precisely represent river channel geometry was assessed through a comparison between ground surveys and ALB surveys. This was performed using two separate methods. The first method used the point-distance function within Arc GIS, which captures any and all LiDAR points within a given radius from each ground survey point. The radius chosen for this study was 1 m. In some cases, there were multiple LiDAR points within the given radius that were compared with a single ground survey point. A radius of 1 m was chosen based on the spot size of the LiDAR, which has a 1 m radius at the water surface. When the data were exported, ground survey elevations were subtracted from ALB elevations to obtain the error statistics.

The second method used to compare ALB data to ground truth data accounts for the lack of spatial coincidence between the ground survey points and the ALB points. Arc GIS was used to construct a 0·5 m grid using universal kriging with a linear semivariogram to build a surface from the ALB point data. Kriging provides a geostatistical interpolation, whereby a spatial-dependence model is created from the existing data used to predict values where none exist (ESRI, 2006). It has been shown that kriging is a reliable spatial estimator, expected to produce more reliable estimates of elevation data than conventional interpolations (Chappell *et al.*, 2003). Grids were constructed from the ALB point data in the vicinity of each ground survey. The ground survey elevations were then subtracted from the ALB elevations provided by the grid to obtain the error statistics.

Assumptions regarding both analysis methods must be made. With the point comparison method, it is assumed that the elevation at the location of the ground survey point is the same as the elevation of the ALB point, which can be up to 1 m away. When the grid comparison method was used, it was assumed that the bed topography was properly modelled in the absence of ALB point data. It is felt that both methods merit investigation, and in most applications of ALB, some type of surface will be generated, be it grid interpolation or triangulation.

Table II. Absolute difference of error between data set 1 and data set 2.

	Absolute median residual difference (m)	
Reach	**Grid comparison**	**Point comparison**
Upper Kittitas	0·09	0·8
Naches	0·10	0·11
Sunnyside	0·02	0·0
Prosser	0·12	0·13
Chandler	0·10	0·13

The error for data set 1 was tested for normality using the Lilliefors test (Lilliefors, 1967). In all cases, except the Naches and lower Kittitas reaches, the assumption of normality can be rejected in favour of a non-normal alternative hypothesis. Non-parametric tests were then used to determine if two independently collected sets of ground truth data (data set number 1 and data set 2) in the Yakima Basin had differing population medians with respect to the LiDAR measurements. This analysis is limited to five reaches (Chandler, Prosser, Naches, Sunnyside and upper Kittitas) in which the two independent ground surveys were performed. The non-parametric Kruskal–Wallis (Gibbons, 1985; Hollander and Wolfe, 1973) test was used to compare the medians of the samples and test the null hypothesis that all samples are drawn from the same population. The first test was used with data set 1 and the *p*-value was sufficiently low to reject the null hypothesis at the alpha = 0·01 level. The second test was used with data set 2 and the *p*-value was also sufficiently low to reject the null hypothesis at the alpha = 0·01 level. The residuals at each reach do not all come from the same distribution, and thus to compare the ground surveys from data set 1 with data set 2, a N-way ANOVA would not be appropriate. For each location an ANOVA was performed to compare the populations of data sets 1 and 2. The *p*-values associated with all but the Sunnyside reach were << 0·01 and the Sunnyside reach had a *p*-value of 0·0062. Not only do the residuals differ spatially but also differ based on who collected the ground truth data (Table II).

Results

The results of the analysis for the Yakima Basin survey are shown in Table III. The data shown are statistics of the residuals, obtained by subtracting the ground survey elevations from ALB derived elevations. Results from both the point and grid comparisons are shown as well as values of expected precision. A significant result is that the residuals all indicate a higher bed elevation measured with ALB than with the ground survey. This result indicates a systematic error, creating a bias in the data.

The results of the Trinity River data comparison are shown in Table IV for both methods of comparison. The ME values are somewhat smaller than the Yakima Basin data whereas the SD values are larger. Similar to the Yakima Basin, the data show a bias, where the ALB data indicate a higher bed elevation than the ground survey data.

Table III. Error statistics for residuals in the Yakima Basin data comparison using data set 1 with both the grid and point comparison: ME, mean error; SD, standard deviation; *n* number of samples; *e*, expected precision.

	Grid comparison			Point comparison			
Reach name	**ME (m)**	**SD (m)**	***n***	**ME (m)**	**SD (m)**	***n***	**e (m)**
Easton	0·15	0·22	159	0·10	0·22	106	0·49
Upper Kittitas	0·19	0·12	342	0·20	0·14	377	0·50
Lower Kittitas	0·29	0·31	49	0·25	0·36	98	0·50
Naches	0·25	0·12	340	0·27	0·17	279	0·50
Sunnyside	0·17	0·15	331	0·15	0·20	387	0·50
Prosser	0·17	0·15	352	0·14	0·16	364	0·49
Chandler	0·19	0·18	367	0·19	0·19	323	0·50
Mean	0·19	0·18		0·19	0·21		

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Table IV. Error statistics for residuals in the Trinity River data using both the grid and point comparison methods: ME, mean error; SD, standard deviation; *n* number of samples; e, expected precision.

	Grid comparison			Point comparison			
Site name	**ME (m)**	**SD (m)**	***n***	**ME (m)**	**SD (m)**	***n***	**e (m)**
Indian Creek	0·12	0·44	3620	0·14	0·53	3211	0·52
Chapman Ranch	0·11	0·27	158	0·18	0·39	177	0·49
Rush Creek	0·08	0·37	4927	0·12	0·47	4608	0·52
Lewiston	0·11	0·22	169	0·16	0·29	155	0·49
Mean	0·10	0·32		0·15	0·42		

Residual values consistently indicate a bias when compared with ground surveys. Although the two independent surveys in the Yakima Basin (data sets 1 and 2) indicate a varying magnitude of error, they are consistently biased. Similarly, bias is seen in the Trinity River data, where ground surveys were collected independently from both Yakima ground surveys.

Associating mean error with depth and local topographic variance

The results of the ANOVA indicate that there may be significance associated with where the ground survey data are collected. Two potential causes for this were explored. First is the proximity of the ground survey point to high relief features in the bed. Because the spot size of the laser is 2 m at the water surface and only the first return is processed, the elevation provided by the ALB survey will necessarily be that of the highest feature within the spot. For this reason, ME was further evaluated based on local elevation variance. This was performed by producing a slope grid from the ALB data. A slope grid will identify the rate of change of elevation in each grid cell as a percentage change, which provides a spatial context for reviewing ME. Three bins of localized slope were created arbitrarily, with slopes less than 10% representing relatively flat portions of the bed or gradually varying topography. The second category included slopes between 10 and 20%, representing a moderate variation of topography. The third classification contained slopes greater than 20%, representing rapidly varying topography. Using this grid, ME was categorized by the slope on which it exists. In all but the Indian Creek and Rush Creek sites of the Trinity River, differences in ME among the three categories were not statistically significant based on the 95% confidence interval. Ground surveys for the Indian Creek and Rush Creek sites on the Trinity River used boat mounted acoustics for the ground truth surveys, which provided a more comprehensive ground survey than wading, which in turn provided a greater amount of data on steeper slopes as well as many more points within the data set. Error statistics for the Rush Creek and Indian Creek sites based on the slope on which they exist are shown in Table V. The second potential cause for spatial significance is varying error with flow depth. Correlations between ME and depth were investigated and showed no consistent trend among the data. The depth values used were based on remotely sensed water surface elevations acquired at the time of the ALB. The flow depth was determined by obtaining a difference grid between the modelled bed surface and modelled water surface. During the ground surveys, flow depth was not recorded and only a few water surface elevation points were collected. Orthorectified photography was not obtained during the acquisition of the ALB data and therefore could not be used to obtain an independent water surface elevation.

Based on the findings of this report, there is no compelling evidence that ME varies with depth over the range of depths evaluated with ground surveys (0–4 m). Findings in this study were not conclusive regarding increasing ME

Table V. Error statistics considering local elevation variance for the two sites where these data were statistically significant using the grid comparison.

	Slope < 10%			10% < slope < 20%			Slope > 20%		
Site name	**ME (m)**	**SD (m)**	***n***	**ME (m)**	**SD (m)**	***n***	**ME (m)**	**SD (m)**	***n***
Indian Creek	0·04	0·31	1913	0·08	0·42	1018	0·52	0·63	689
Rush Creek	0·04	0·31	2438	0·09	0·37	1573	0·18	0·46	916

with local elevation variance, although this may be a real issue. Further investigation will be required to conclusively determine if ME increases in the proximity of high relief features.

Data adjustment

It is desirable to make corrections for the systematic error in the ALB data when they are to be combined with topographic data collected separately. This bias correction will improve the quality of the complete surface when combined with above-water terrain data by correcting for the systematic error in the ALB survey. Because no meaningful trends were apparent with respect to local topographic variance or flow depth, a block correction was made to the data based on the ME. In rivers that cannot be waded to the greatest flow depth, future studies may be better served by collecting ground check data with boat mounted acoustics and RTK GPS so that a more complete representation of the wetted portion of the channel is obtained for comparison. Furthermore, surveys conducted in this manner necessarily provide water surface elevation and depth, although that information was not available to the authors when compiling these data for the Indian Creek and Rush Creek sites of the Trinity River.

Discussion and Conclusions

The data quality obtained with ALB are on the order of most terrestrial LiDAR data (e.g. French, 2003; Bowen and Waltermire, 2002; Marks and Bates, 2000) and river channel bathymetry obtained with photogrammetry (e.g. Lane *et al.*, 2003; Westaway *et al.*, 2003). Although the horizontal error was not evaluated in this study, introduction of vertical error due to a misrepresented horizontal position is probable. These two types of error are inextricably linked when ground elevations vary significantly with spatial position. When a bed elevation is to be derived from the green laser pulse, it is the shallowest depth that is recorded. That elevation can occur at any location within the laser spot, which is then assumed to occur at the geometric centre of the spot.

It has been noted that the ME in the Trinity River data is less than that of the Yakima River data although the SD for the Trinity River is larger. An explanation for the increase in SD of the Trinity River data may be related to the remotely sensed water surface elevations. There is significant vertical variation of water surface elevations (~0·6 m) within a very small change in horizontal distance (~0·6 m) for the Trinity River data while much less variation was present in the Yakima data. The Trinity River in the locations surveyed does not experience surface disturbance of this magnitude.

Given the abundance of data provided by ALB, there may be a distinct advantage to the ALB survey over traditional methods for large-scale projects. The quality of ALB data may be somewhat less than traditional ground survey methods, particularly with respect to the precision. The existence of a greater point density and coverage with an ALB survey may result in a net improvement in the overall surface model, as there is less interpolation for a modelled surface with a greater point density. The usefulness of ALB data will depend on its application and future improvements in measurement accuracy and precision.

It is not possible, at this time, to use ALB to map riverine environments on a microscale, either for numerical modelling or geomorphological analysis. The ME and SD of this method is on the order of a large cobble. Features in the size range of a large cobble or smaller are generally thought of as being microscale. Present horizontal resolution also precludes microscale modelling. Mesoscale features are more ambiguously defined. For example, mapping pool, riffle and glide features, typically thought of as mesoscale, are possible with current survey quality, depending on the size of the river. However, there are mesoscale features that are not able to be sufficiently defined by the resolution of the current ALB capabilities, such as large boulders, rootwads or other obstructions, as discussed by Crowder and Diplas (2000). For numerical modelling of localized hydraulics, these features are responsible for potentially critical flow patterns, depending on the application. It is important to consider those features to be analysed when deciding upon a survey method.

Future improvement in ALB technology will likely be driven by its application. To date, coastal applications have driven the technological advances of ALB, with greater concern for depth penetration and less concern for resolution. It stands to reason that if those interested in river channel bathymetry take an active role in the determination of hardware and software improvements, resolution and data quality will increase. For example, a reduction in output power of the laser will allow the spot size to be decreased while maintaining eye-safe standards. This would sacrifice depth penetration of the laser, however, for river applications depth penetration beyond approximately 10 m is not needed. If a river channel has a significant portion of its depth greater than 10 m it will likely suffer from clarity issues, preventing the use of ALB. The smaller spot size would allow for better definition of high relief bed topography. Improvements in the spot spacing will improve resolution, increasing the applicability of the survey.

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