Evaluating Survey Instruments and Methods in a Steep Channel

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Abstract

Methods for surveying and analyzing channel bed topography commonly lack a rigorous characterization of their appropriateness for project objectives. We compare four survey methods: a hand level, two different methods of surveying with a laser rangefinder, and a real-time kinematic GNSS (RTK-GNSS) to explore their accuracy in determining channel bed slope and roughness for a study reach in a small, dry, steep channel. Additionally, we evaluate the variability among four operators for each survey technique. Two methods of calculating reach slope were computed: a regression on the channel profile and a calculation using only survey endpoints. Using data from the RTK-GNSS as our accuracy reference, the hand level and two-person laser rangefinder surveying systems performed with high accuracy ($<5\%$ error in estimating slope, $<10\%$ error in estimating roughness), while the one-person laser rangefinder survey system performed with considerably lower accuracy (up to 54% error in roughness and slope). Variability between operators was found to be very low (coefficients of variation ranged from 0.001 to 0.046) for all survey systems except the one-person laser rangefinder system, suggesting that survey data collected by different operators can be validly compared. Due to reach-scale concavity, calculating slope using a regression produced significantly different values than those obtained by using only survey endpoints, suggesting that caution must be taken in choosing the most appropriate method of calculating slope for a given project objective. We present recommendations for choosing appropriate survey and analysis methods to accomplish various surveying objectives.

Keywords: roughness; slope; interoperator variability; laser rangefinder

1. Introduction

Topographic surveying is commonly used in geomorphic studies to measure channel slope, channel bed roughness, and other spatial characteristics of geomorphic features; however, multiple survey techniques exist. Investigators often use the most convenient survey technique available and report their methods in insufficient detail, resulting in an inability to assess the appropriateness of the survey procedure for achieving the project objectives. We are unaware of any rigorous comparison of different methods of surveying and calculating channel slope, despite numerous high-profile studies reporting channel bed slopes that provide important evidence for their conclusions without explicitly detailing how slope was calculated (e.g. Adams et al., 2000; Howard and Kerby, 1983; Montgomery et al., 1996; Seidl and Dietrich, 1992; Snyder et al., 2000; Wood-Smith and Buffington, 1996).

Surveying remote, difficult-to-access, or inaccessible locations requires either techniques that are able to measure the surfaces remotely (e.g., airborne laser scanning, terrestrial laser scanning, or structure-from-motion photogrammetry) or equipment that is transportable to the survey site (e.g., Mikoš et al., 2005; Santangelo et al., 2010; Smith et al., 2015; Vianello et al., 2009). We present a rigorous comparison of four topographic survey systems: hand level (HL), handheld laser rangefinder requiring one (LR1) or two (LR2) operators, and a real-time kinematic GNSS (RTK-GNSS). Although there are other field survey systems available (e.g. total station, which is bulky, difficult to operate in steep terrain, and difficult to carry great distances), all of these systems can function well in difficult-to-access locations, are generally portable, and can operate in high-relief terrain. We focus on survey scenarios in difficult-to-access locations because the choice of survey system in easy-to-access locations is typically not

59 dependent on the versatility of the survey system, but instead depends on the resolution needed
60 and cost of the equipment.

61 The laser rangefinder is a relatively recent development in surveying that permits fast
62 measurement of distance, azimuth, and inclination using a laser projected from the rangefinder to
63 a reflective or non-reflective target. Laser rangefinder systems have been used to measure
64 landslide scars (Santangelo et al., 2010), rock outcrops (Alfarhan et al., 2008), three-dimensional
65 topography (Hayakawa and Tsumura, 2009; Hayakawa et al., 2007), rock fall (Mikoš et al.,
66 2005), sampling distances (Ransom and Pinchak, 2003), and snow depth in inaccessible terrain
67 (Hood and Hayashi, 2010). Laser rangefinders display accuracy similar to traditional survey
68 methods such as GNSS or levels when collecting individual distance measurements or surveying
69 terrain that is measured using an approach that combines independent distance measurements
70 (Hayakawa and Tsumura, 2009; Hayakawa et al., 2007; Hood and Hayashi, 2010; Ransom and
71 Pinchak, 2003). This suggests that laser rangefinders could be a viable method for the rapid and
72 versatile surveying of fluvial features with decimeter-scale accuracy. The relatively cheap cost
73 and the ease, versatility, and speed of operation for a laser rangefinder indicate that it may be a
74 viable surveying choice and an alternative to the more traditional hand level, which is
75 comparable in portability and ease of use. This potential motivates our examination of its
76 appropriateness compared to other methods for channel bed surveys.

77 Variability between operators (interoperator variability) during repeated measurements of
78 clast size on river beds can be significant and hamper comparisons of clast size measurements
79 taken by different investigators (Wohl et al., 1996). Like clast counting methods, surveying
80 involves the subjective choice of where measurements will be taken along the channel bed. This
81 leads us to hypothesize that it may be similarly problematic to compare channel bed surveys

done by different operators. To address this, we compare surveys of the same channel done by different operators to determine whether there is significant variability between operators.

We evaluate the efficacy of the laser rangefinder as a survey tool for determining longitudinal channel profiles, with the specific objectives of determining channel bed slope and roughness. We also address the appropriateness of various methods of calculating channel bed slope from channel bed elevation data. Measuring bed slope and roughness allows for a good evaluation of a survey method's local accuracy (i.e., the ability to determine small changes in elevation for accurately characterizing roughness) and reach-scale accuracy (i.e., the ability to characterize broad-scale topographic trends needed to understand channel slope).

Based on previous evaluations of the laser rangefinder as a surveying system, we hypothesize that a laser rangefinder will perform similarly to a hand level and possibly an RTK-GNSS in terms of the accuracy of slope and roughness estimations, thus making it a viable and potentially more versatile tool for rapidly surveying difficult-to-access channels. We use the results of a test of four survey methods, four separate surveyors, and two methods of calculating channel bed slope to: 1) evaluate the appropriateness of two methods of calculating channel bed slope, 2) test the efficacy of various survey systems, 3) evaluate the degree to which surveys performed by different operators differ from one another, 4) evaluate the effects of temporal and spatial point density on survey accuracy, and 5) provide best-practice recommendations for survey methodologies for a broad set of survey goals.

2. Field Site

The unnamed, 0.71 km² watershed used in this study lies on the eastern slope of the Colorado Front Range and drains into the Cache la Poudre River (Figure 1). We surveyed a 61 m

study reach that is characterized by a mix of step-pool and cascade morphology and a boulder-dominated bed at the bottom of the watershed just above an alluvial fan (Figure 2). We completed field surveys on 3 October 2015. The primary mechanism for runoff in the channel is summer convective thunderstorms (Jarrett and Costa, 1988), and the current morphology of the channel is largely the result of post-wildfire generated peak flows and a single long duration flood in September 2013 (Gochis et al., 2015). The study watershed is predominantly comprised of ponderosa pine (*Pinus ponderosa*) woodland supporting scattered trees over a graminoid-dominated understory. In its lower portions, the forest grades into shrubland, supporting mountain mahogany (*Cercocarpus montanus*) and skunkbush sumac (*Rhus trilobata*). In-channel vegetation was sparse and created almost no obstruction to surveying.

3. Methods

3.1 Summary of Survey Systems and Data Collection Methods

We compared survey methods by developing multiple topographic models of a single channel thalweg as measured by four operators and four survey methods. The HL and LR1 systems are limited in that they can only survey one-dimensional paths along a surface unless special measures are taken to adapt them to a two-dimensional path. The LR2 and RTK-GNSS systems can survey two-dimensional paths along a surface without any modification. All survey systems measure the location and elevation of a point or series of points in space. With the exception of the RTK-GNSS, the location and elevation of survey points are not referenced to a specific coordinate system, but instead are referenced to the starting point of the survey.

3.1.1 Hand Level (HL)

The hand level is a simple magnified sighting instrument that allows one to sight a level plane from their eye using a stadia crosshair and a bubble level. Prior to our hand level surveys, we laid a graduated tape with centimeter resolution along the channel thalweg. During each survey, the operator placed the stadia rod on survey locations they selected as being necessary to accurately model the channel bed. The recorder sighted the hand level on the stadia rod, reading the elevation measured by the stadia rod at the given point. This measurement was recorded along with the location of the survey point along the tape. When the recorder could no longer accurately sight the stadia rod due to the operator having moved too far downstream, the recorder moved to a new location and a backsight was made on the last point, allowing for an unbroken survey.

3.1.2 Laser Rangefinder

A laser rangefinder is a handheld device that projects a beam of light and measures the time of reflection to calculate the distance to the object off which the beam reflects. We used a TruPulse 360 with 7x optical magnification that also records the inclination (tilt) and the azimuth (the heading of the shot referenced to magnetic north measured by an electronic compass) of the device at the time of the shot. According to the manufacturer, the typical accuracy is ± 30 cm in measuring distance, $\pm 0.25^\circ$ in measuring inclination, and $\pm 1^\circ$ in measuring azimuth. This allows for the measurement of the three-dimensional location of a target in reference to the device. The laser automatically reports the resolution of the target after taking a shot, allowing the user to verify that the laser reflected off a high quality target, maximizing distance accuracy.

During our surveys, we used only measurements taken from high quality targets, ensuring that accuracy remained within manufacturer specifications.

3.1.2.1 Two-Person Laser Rangefinder (LR2)

Similar to the hand level system, the two-person laser rangefinder system uses a stadia rod mounted with a reflector and the laser rangefinder as a sighting instrument. We used a reflector approximately 5 cm in diameter affixed to the top of an adjustable stadia rod. The operator placed the rod at individually and subjectively chosen points while the recorder shot the rod with the laser rangefinder and recorded the slope distance, azimuth, inclination, vertical distance, and horizontal distance to the target. Only the slope distance, azimuth, and inclination are directly measured; the laser rangefinder calculates the horizontal and vertical distances internally. The long range of the laser rangefinder and the adjustable height of the stadia rod allow the recorder to remain stationary over relatively long survey distances. This system takes measurements that are independent of one another.

3.1.2.2 One-Person Laser Rangefinder (LR1)

Unlike the hand level or two-person laser rangefinder systems, the one-person laser rangefinder system requires only one operator who can take measurements and record data. However, we paired the operator with a recorder to expedite the survey. The operator shot consecutive points along the channel bed using the missing line routine of the laser rangefinder, which measures two points and provides data describing a line connecting those two points. Each point had to be measured twice, once to describe its position relative to the previously shot point and once to reference the next point to it. By effectively connecting missing lines down a

channel, a surveyor can create a profile of the channel bed. For each pair of points, the recorder noted the azimuth, horizontal distance, and vertical distance between the two points. These line segments were used to construct a topographic profile. Thus, unlike the LR2 system, survey points measured by the LR1 system are dependent on one another.

3.1.3 Real Time Kinematic Global Navigation Satellite System (RTK-GNSS)

The RTK-GNSS system uses two high-resolution GNSS units, one of which is mounted to an adjustable rod (the rover), while the other is mounted on a tripod (the base station). The base station collects repeat measurements of its location during the survey (also known as static data), which can then be used to correct the location of the points collected by the rover. We used a Topcon GR-5 system, which has a horizontal accuracy of 10 mm and a vertical accuracy of 15 mm. Because accuracy of the survey improves the longer the base station collects static data, we set up the base station as soon as we reached the field site in a location adjacent to the study area with high visibility of the southern sky. We collected ~10 hours of static data. This system requires only one operator and records data digitally on a data logger (in this study, a Topcon Tesla). During each survey, the operator placed the rover rod on a subjectively chosen survey point, recorded the position as the average of three GNSS measurements and moved to the next survey point, continuing until the survey was complete.

3.2 Field Methods

To test the efficacy of various survey methods in a real-world setting, we first marked the start and end points of the chosen survey reach using flagging and stakes. Prior to surveying, a tape was laid in the thalweg of the channel to facilitate HL surveys. This tape was not used for

any of the other survey methods. Four experienced survey operators (OP1 - OP4) operated survey instruments to measure the elevation of the channel bed along the reach, while three recorders wrote down measurement data and operated the sighting instruments (hand level or laser rangefinder). The RTK-GNSS method, which records data automatically without the need for note taking, only required the survey operator. Each operator surveyed the channel twice using each survey method, for a total of eight surveys per operator and 32 surveys total. We performed all 32 surveys on the same day with consistent weather conditions. We timed each survey beginning from when the operator took the first point and ending when the operator took the last point. This survey duration did not include any time taken to set up equipment.

Prior to surveying, all operators and data recorders were instructed in the proper use of each survey instrument. This ensured that all operators used the survey equipment in the same manner. To accurately represent the actual surveying habits of four different operators, no instruction was provided in terms of where to select survey points. The only instruction given was that the objective of the survey was to accurately characterize the reach-average channel bed slope and roughness.

After preliminary analyses were completed, OP3 returned two weeks later (after no recorded major rain events in the area) and performed one more survey using the LR1 method in which only step-crests were surveyed. These data allow a limited analysis of the effect of drastically reducing point density on the accuracy of the LR1 method.

3.3 Data Processing

Data entered by hand (for methods HL, LR1, LR2 above) were first electronically scanned and then entered into spreadsheets manually. All data were double-checked for

transcription errors by the person who originally recorded the data entry. We copied the RTK-GNSS data from the data logger directly to a spreadsheet.

We processed the raw data to obtain horizontal survey distance and elevation for each survey. Because we recorded extra data for the two-person laser rangefinder method, we analyzed the data using the vertical distance, horizontal distance, and azimuth (LR2VHA) and again using the slope distance (actual distance between the device and the reflector), the azimuth, and the inclination (LR2SAI). This was done to evaluate which measures produced the most accurate survey results and to determine whether values calculated internally by the laser rangefinder (vertical and horizontal distance to target) contained more error than values directly measured by the laser rangefinder (slope distance, azimuth, and inclination).

For each survey, we calculated reach-average channel bed slope using two methods. First, we fit a linear regression to the horizontal distance and elevation data and took the slope of that regression as the reach-average channel bed slope (henceforth referred to as the regression slope). Second, we used only the first and last survey point to calculate the total elevation difference divided by the total horizontal length of the survey reach, which we used to define the two-point reach-average channel bed slope (two-point slope). We also calculated channel bed roughness for each survey by taking the standard deviation of the orthogonal residuals between the linear regression line and each survey point, following the methodology of Cavalli et al. (2008). Using the duration, total number of survey points, and horizontal length of each survey, we calculated temporal point density and spatial point density, measuring the number of points per unit of time and per unit horizontal survey length, respectively.

3.4 Analytical and Statistical Methods

Data were analyzed using MATLAB and the R statistical package (R Core Team, 2015). To quantify the error inherent in any variable derived from survey data, we needed to establish a reference survey method that we assumed to provide accurate data. Previous comparisons of survey methods indicate that the RTK-GNSS is a high accuracy, millimeter-scale surveying tool (Chekole, 2014; Lee and Ge, 2006; Pirti et al., 2010). We chose the RTK-GNSS as a reference against which we compared the accuracy of other methods because the RTK-GNSS has a resolution higher than the variations in bed topography. That is, the substrate size in this channel is larger than the resolution of the RTK-GNSS measurements, so that the limiting factor in accurately describing the channel bed topography is not the RTK-GNSS resolution, but instead the roughness of the channel bed surface at the scale on which we are surveying. We chose to use the RTK-GNSS as our accuracy reference instead of a more conventional total station due to the difficulty of transporting and operating a total station in difficult-to-access terrain and the comparable accuracy in high surface roughness conditions. To quantify error in the slope and roughness measurements derived from the HL, LR2, and LR1 methods, we calculated the percent error between those measurements and measurements derived from RTK-GNSS data. To maintain consistency between operators, a given survey was compared to the average measurement derived from that operator's two RTK-GNSS surveys.

To quantify the variability between operators within a given survey method in terms of the slope or roughness calculated from each operator's survey data, we used the coefficient of variation. The coefficient of variation provides an estimate of population variance normalized by the mean such that it can be compared between populations. We compared the coefficient of variation (i.e., interoperator variability) between the various survey methods used. The

population used for each measure of the coefficient of variation was derived by averaging the two slope or roughness measurements calculated from each of the four operator's two surveys from a given survey method. Thus, each coefficient of variation describes the variance among four operators.

To test for a relationship between error in slope or roughness and the spatial or temporal point density for each survey, we used a Spearman Rank Correlation Coefficient (ρ), which describes a monotonic relationship between two variables. We used a 95% confidence interval to determine statistical significance. For the purpose of this analysis, we tested surveys independent of operator and method in order to identify a correlation between survey detail (spatial point density) or speed (temporal point density) and survey error. When testing for a relationship between point density and slope, we used only the regression slope and not the two-point slope, as the regression slope is more strongly determined by point density compared to the two-point slope. Sample sizes were too low to test for such relationships for individual survey methods or operators, so we performed these tests across all operators and all survey methods. This examination only regards the question of whether slope or roughness error correlates with temporal or spatial point density. It does not provide insights into how these relationships might differ for various survey systems.

4. Results

4.1 Variation between Two Methods of Calculating Slope

The calculated slope of the study reach differed based on the calculation method (i.e., regression slope vs. two-point slope), with the regression method resulting in a steeper slope

(10.35%) compared to the two-point slope (10.02%) averaged over all survey methods and survey operators (Figure 3). A Kruskal-Wallis rank sum test (Kruskal and Wallis, 1952) indicates that the two populations of slope are significantly non-identical ($p = 0.02$). The channel surveyed has a slight concave profile, as seen in the average slope from all of the RTK-GNSS points (Figure 3), resulting in the two-point slope underestimating the average slope for the entire profile compared to the regression slope.

4.2 Accuracy of Each Survey Method in Determining Reach-Scale Slope and Channel Bed Roughness

The percent error between a survey method and the survey operator's average RTK-GNSS slope is the highest for the LR1 survey method, ranging from 2% to 54%, and is relatively low for the HL, LR2SAI, and LR2VHA methods, ranging from 0% to 4% (Figures 4 and 5). The LR2 and LR1 methods show no distinct measurement bias, whereas the HL method has a distinct negative bias across all surveys. The LR1 method is also the least accurate method for determining channel roughness, with errors ranging from 4% to 49% (Figure 6). The HL and LR2 methods show a positive bias in estimating roughness, whereas the LR1 method shows no distinct bias. However, the LR2 and HL methods have relatively low absolute percent error across all surveyors, ranging from 0% to 11%. Interestingly, the range in measured elevation of the LR2SAI data across all operators is less than that of the LR2VHA data across the entire study reach (Figure 7). Although the two LR2 methods are comparable in determining slope and roughness, they differ in terms of the total variability in the measurement of individual points across all operators.

A single survey of this study reach completed two weeks after the initial study date using the LR1 method only shooting step crests obtained a percent error in regression slope of 10.2%. The objective of that particular survey was only to obtain slope and, without surveying pool bottoms, any measure of channel bed roughness would be meaningless.

4.3 Variability between Operators of Various Survey Systems

The coefficient of variation describing interoperator variability in regression slope, two-point slope, and roughness is less than 0.05 for all methods except for the LR1 method, which displayed coefficients of variation ranging from approximately 0.12 to 0.18 (Figure 8). Across all surveys performed, different operators did not produce large variation in the survey's accuracy.

4.4 Effects of Spatial and Temporal Point Density on Survey Accuracy

Spearman correlation coefficient significance tests performed on a dataset comprised of all surveys by all operators with the HL, LR2, and LR1 methods indicate that the percent error in calculating roughness decreases as the spatial point density of the survey increases ($\rho = -0.62$, $p < 0.001$) (i.e., a more dense series of points yields higher accuracy in calculating roughness). In addition, slope error decreases as temporal point density decreases ($\rho = 0.54$, $p < 0.01$), indicating that taking points more slowly yields higher accuracy in calculating slope. Roughness error decreases as temporal point density increases ($\rho = -0.41$, $p = 0.02$), indicating that taking points more quickly yields higher accuracy in calculating roughness. Spatial point density and temporal point density are positively related ($\rho = 0.54$, $p < 0.01$); a higher spatial point density corresponded to the operator taking points at a faster rate.

5. Discussion

5.1 Variation between Two Methods of Calculating Slope

The bias observed between the different methods used to calculate slope on this reach indicates that reach-scale curvature can influence the measured reach-scale slope. For example, the two-point slope method in our results underestimated the regression slope due to a slight concavity of the profile near the downstream end of the survey. This underestimate is due to the two-point slope method essentially neglecting the data between the top and bottom of the study reach. Based on this interpretation, we suggest careful consideration of potential longitudinal curvature in a study reach when determining which method of calculating slope is more appropriate, similarly to how previous research has suggested that scale be taken into account before choosing a method of determining slope from a digital terrain model (Vianello et al., 2009). Although regression slope can accommodate curvature, a delineation of reach lengths that avoids curvature within reaches could make a two-point slope appropriate. However, the difference between the two methods of calculating slope highlights the need to detail the methodology used to determine slope, as different methods may produce different results and a lack of detailed reporting may lead to irreproducible survey results.

5.2 Accuracy of Each Survey Method in Determining Reach-Scale Slope and Channel Bed Roughness

For both slope and roughness, the LR1 method has a large range of variability, with errors ranging from less than 5% to over 40% across all individual surveys. We suspect that the high errors observed in this method are mainly due to the dependency of subsequent points. The

accuracy of each observed point in this method depends entirely on the operator's ability to locate and shoot the previously taken point with no physical marker of that point. Because of the dependence of each point on previous points, error compounds throughout a survey.

The aforementioned error source in the LR1 method is corrected for in the LR2 method, in which every point is shot as an independent observation whose position in space does not depend on any other measured points, so errors do not compound throughout the survey. The LR2 method correspondingly performed much better in terms of determining slope and roughness. We conclude that the laser rangefinder is a highly accurate survey tool only when measurements taken by it are made independently of each other, thus reducing error sources to only those inherent in the device (its resolution) and the operator (normal variability in posture, shooting accuracy, note-taking accuracy, etc.). However, the LR1 method utilizing dependent measurements may be suitable for very approximate and rapid estimations of channel bed characteristics.

Similarly to the LR2 method, the HL method performs with high accuracy in determining slope and roughness. It is not subject to the compounding error of the LR1 system and has a high potential resolution. The error in this method likely stems from the fact that the hand level is usually not held at consistent heights throughout the survey, although this could be corrected for by mounting the hand level on a tripod or monopod.

Although data from the separate LR1 survey that occurred two weeks after the other surveys should be interpreted cautiously, the relatively low error of this survey suggests that the LR1 method could be improved by taking fewer or independent points. Fewer points would reduce the degree to which error can compound. Another option includes measuring easily identifiable points on the channel bed, such as step crests (reducing the potential for the operator

to miss consecutive points). The LR1 method could also be improved by shooting independent points whose location can be calculated without depending on the location of previously calculated points. This would, however, necessitate that the operator remain in the same location as consecutive survey points are measured, similar to the HL and LR2 methods.

5.3 Comparing Two Methods of Recording Data for the LR2 Method

Although the LR2VHA and LR2SAI methods showed no noticeable difference in terms of interoperator variability or their ability to estimate slope or roughness, there was a noticeable difference between the methods in terms of the range of elevation for each point along the survey across all operators. The VHA method produced a greater range of variability in elevation for the entire survey reach than did the SAI method (Figure 7), indicating that the SAI method is a slightly more reliable method of modeling a channel bed. Vertical and horizontal distances are calculated by the laser rangefinder itself, so that the user cannot check for rounding errors or the accuracy of internal calculations. It may be more reliable to use only measurements directly made by the laser rangefinder, (i.e., slope distance, azimuth, and inclination).

5.4 Variability between Operators of Various Survey Systems

Many projects depend on the idea that two independent surveyors can survey the same land surface and obtain a comparable result. This assumes that both operators produce surveys in similar ways and with similar variabilities. Our analyses of coefficient of variation within survey methods largely substantiate this common assumption. Low interoperator variability indicates that investigators may reasonably make the assumption that surveys performed by different operators are comparable. The large interoperator variability in the LR1 method is likely due to

the large, compounding error amplifying what might otherwise be small differences between operators. With the exception of the LR1 method, surveys performed by different operators are comparable. This result contrasts the results of Wohl et al., (1996), who showed that interoperator variability can introduce significant and unaccounted for variability in clast counts, and indicates that the assumption of negligible interoperator variability is only valid for certain methods.

It is worth noting that interoperator variability for this study could be low due to the simple channel morphology and clear study methods. A reach of poorly defined length, with multiple channels or with an indistinct thalweg, may be more difficult to survey consistently and thus give rise to greater interoperator variability. We suggest that comparisons of two or more surveys done by more than one operator define the longitudinal extent of the channel as clearly as possible and be aware that different operators may identify and survey different thalwegs. The tape laid along the thalweg prior to the surveys in this study (necessary only for the HL surveys) likely reduced uncertainty in identifying the thalweg.

5.5 Relationships between Spatial or Temporal Point Density and Slope or Roughness Error

Our analyses point to a general trend whereby slower and more spatially detailed surveys produce less error in terms of estimating slope or roughness of the channel bed. This makes sense intuitively: taking one's time leads to a more accurate representation of slope, and taking more points more accurately describes the variability in the channel bed surface, leading to a more accurate estimation of roughness. We unexpectedly found that taking more points per unit time significantly increased the accuracy in estimating roughness. This is likely due to the

positive correlation between temporal point density and spatial point density, whereby taking more points was achieved by taking points at a faster rate. This suggests that one could obtain more accurate results for roughness calculations by taking more spatially dense points, independent of how quickly the points are taken.

5.6 Comparative Evaluation of Survey Methods

We compiled basic comparison metrics from our results for each survey technique and gathered information about each method such as cost, weight, and personnel requirements of the survey system (Table 1). We use these data to assess the overall appropriateness of each survey method and provide recommendations for different scenarios.

The RTK-GNSS is by far the most accurate survey technique tested here. It can survey points quickly (Table 1), although setup takes much longer for a given field site than other methods. It is also hampered by overhead obstructions (Lee and Ge, 2006), whereas other survey methods are not. If the GNSS signal is weak or lost, the speed of this method can greatly decrease, and the equipment can be rendered useless if the GNSS signal is lost completely. The RTK-GNSS system may be prohibitively expensive, costing one to two orders of magnitude more than other systems tested. It also weighs much more than other systems tested, making it much more difficult to transport to certain field sites. Given its extremely high accuracy and the potential for it to perform very efficiently under ideal conditions, we recommend it for surveying conditions in which access is easy, overhead obstructions are minimal, and high accuracy is necessary. However, for conditions in which access is difficult, overhead obstructions are unavoidable, or the cost of an RTK-GNSS is prohibitive, we recommend the HL or LR2 systems because of their relatively high accuracy compared to the RTK-GNSS.

The LR2 method provides some distinct advantages over the HL method that may justify its higher cost in specific scenarios. The LR2 method is better able to deal with obstacles between the surveyor and the stadia rod, as it can easily accommodate a change in reflector height using an adjustable stadia rod, as long as such adjustments are noted while recording data. It can also greatly reduce the number of backsights necessary when surveying extremely steep channels. Whereas the HL method is limited to covering a net elevation change between points equal to the maximum height of the stadia rod, the LR2 method can accommodate an elevation change between consecutive points limited only by the sight distance of the laser, which, in extreme cases, could be on the scale of tens of meters. Whereas the HL method requires a tape to determine horizontal distance, the LR2 method does not require any objects to be left in the channel during the survey. This can provide distinct advantages when the channel bed is either under water or when the survey must cover a non-linear feature that would be difficult to measure with a linear tape. Both the HL and LR2 methods are comparably lightweight.

From this evaluation, we recommend the use of the LR2 method when the cost is not prohibitive and the surveying conditions may involve high flow depth, steep surfaces, abundant obstacles between the laser and the stadia rod, or when the survey must cover a three-dimensional surface. However, we recommend the HL method due to its low cost if the surveying conditions involve low flow depth, lower gradient surfaces, few obstacles between the operator and stadia rod, and when the survey will cover a path along which a tape can easily be laid.

Individual project objectives and the error inherent in other data used to achieve those objectives can determine the acceptability of the high error shown by the LR1 method. Costa and Jarrett (2008) judged errors in flood discharge estimations as “good” if error was less than 10%,

“fair” if error was less than 15%, “poor” if error was between 25% and 50%, and “estimate” if error was greater than 50%. A rating system based on theirs would evaluate all methods except for the LR1 method as “good.” The LR1 method as described here is certainly inappropriate for determining channel bed roughness and slope if a highly accurate characterization is needed. However, the LR1 method may be acceptable if only an estimation or general characterization of slope is necessary, if a very rapid, lightweight surveying system is needed, or if the survey site is entirely inaccessible (e.g., Hood and Hayashi, 2010). Based on limited data and our observations of this method compared to the LR2 method, we suggest that the LR1 method could be refined to either use fewer or independent observations to more accurately and reliably survey channel bed slope. This suggestion is supported by other investigations of the laser rangefinder when used as a single-person surveying system, which generally find that independently collected observations are highly accurate (e.g., Hayakawa and Tsumura, 2009; Hayakawa et al., 2007; Ransom and Pinchak, 2003).

6. Conclusions

Surveying is an essential component of modern Earth surface research and land management. We present an evaluation of surveying methods and their applicability in difficult-to-access locations. This evaluation shows that the laser rangefinder is a viable survey method when used in a way that takes independent measurements. As a two-person surveying method, it is as accurate as a hand level, but provides distinct advantages in difficult surveying conditions, despite its higher cost. As a lightweight, one-person surveying method, the laser rangefinder performs poorly in terms of accurately characterizing channel bed topography. However, it may

be improved by utilizing fewer observations or only measuring independent points, reducing compounding error.

Slope is one of the most commonly reported variables used to describe channels for purposes such as hydraulic modeling, hazard evaluation, and site characterization. We show that calculating slope using only the top and bottom points of a reach yields significantly different results compared to calculating slope using a regression on many points taken along a reach, and we suggest that the broad-scale curvature of the reach contributes to this bias. Because such broad-scale curvature is not usually identifiable in the field, we strongly suggest that surveyors exercise caution when using only a two-point slope for analysis. Additionally, our analyses highlight the need for better reporting of slope calculation methods to evaluate the efficacy of the chosen method and ensure reproducibility. In general, however, a regression slope will provide a more reliably unbiased estimate of reach-scale slope that takes into account broad-scale curvature in the profile.

Finally, we provide data that justify the common assumption that variability between operators surveying the same reach is negligible enough to allow for robust comparison of surveys by different operators. We caution, however, that this result is based on an idealized scenario and does not include potential variability introduced by a poorly delineated study reach or multiple channels.

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Figure 1: The study site is located within the northern Colorado Front Range (inset) on a small 0.71 km² tributary to the Cache la Poudre River.

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Figure 2: The authors surveying in the study reach. Note the large clasts and incised channel.

Figure 3: Average profile from all RTK-GNSS surveys (blue) shown with lines indicating the regression on the survey points (regression slope) as well as a line connecting the top and bottom of the profile (two-point slope). The residuals between each line and the survey points are shown in the bottom plot.

Figure 4: Percent error (deviation from RTK-GNSS) in estimating regression slope for each method. Bars are colored by operator and survey number, with two surveys done per operator per method. Abbreviations indicate survey methods, including the hand level (HL), two person laser rangefinder using slope distance, azimuth and inclination data (LR2SAI), two person laser rangefinder using vertical distance, horizontal distance, and azimuth (LR2VHA), and one person laser rangefinder (LR1).

Figure 5: Percent error (deviation from RTK-GNSS) in estimating two-point slope for each method. Bars are colored by operator and survey number, with two surveys done per operator per method. Abbreviations indicate survey methods, including the hand level (HL), two person laser rangefinder using slope distance, azimuth and inclination data (LR2SAI), two person laser rangefinder using vertical distance, horizontal distance, and azimuth (LR2VHA), and one person laser rangefinder (LR1).

Figure 6: Percent error (deviation from RTK-GNSS) in estimating roughness for each method. Bars are colored by operator and survey number, with two surveys done per operator per method. Abbreviations indicate survey methods, including the hand level (HL), two person laser rangefinder using slope distance, azimuth and inclination data (LR2SAI), two person laser rangefinder using vertical distance, horizontal distance, and azimuth (LR2VHA), and one person laser rangefinder (LR1).

Figure 7: The range between the maximum and minimum elevation for each survey point taken from all surveys using the LR2 method. The VHA variant of the LR2 method uses only vertical distance, horizontal distance, and azimuth to determine the position of a point, while the SAI variant uses slope, azimuth, and inclination. The black curve shows the difference (VHA-SAI) between the VHA and SAI ranges. Note that SAI generally has a lower range than VHA.

Figure 8: Variability in two-point slope, regression slope, and roughness measurements between all operators shown for all survey methods. Abbreviations indicate survey methods, including the hand level (HL), two person laser range finder using slope distance, azimuth and inclination data (LR2SAI), two person laser range finder using vertical distance, horizontal distance, and azimuth (LR2VHA), one person laser range finder (LR1), and RTK-GNSS (RTK).

Tables and Captions

Table 1: Comparison of four tested survey systems in terms of their values. The green to red color scheme delineates the relative rank of each system compared to the others, where green delineates the highest ranked system and yellow, orange, and red delineate the 2nd, 3rd, and 4th ranked systems for the given value, respectively. Grey boxes are shown when a ranking is not applicable. Interoperator variability is reported as a coefficient of variation.

Method:	Hand Level	Two-Person Laser Rangefinder	One-Person Laser Rangefinder	RTK-GNSS
<i>Items needed</i>	Hand level, stadia rod, notebook	Laser rangefinder, stadia rod, reflector, notebook	Laser rangefinder, notebook	Two receivers, tripod, data logger, adjustable rod
<i>Weight (kg)</i>	3.0	3.1	0.38	24
<i>Cost (USD)</i>	\$160 - \$280	\$900 - \$1900	\$800 - \$1700	\$14,000 - \$60,000
<i>No. of operators</i>	2	2	1	1
<i>Average points/minute</i>	1.90	1.28	2.12	6.32
<i>Automated data recording</i>	no	optional	optional	yes
<i>Effect of overhead vegetation</i>	none	none	none	reduces accuracy (Lee and Ge, 2006), increases survey time
<i>Effect of surrounding vegetation</i>	increases survey time	minimal	negligible	negligible
<i>Average regression slope % error</i>	-2.74	-0.27 (for the SAI method)	14.95	N/A
<i>Average roughness % error</i>	2.64	5.17 (for the SAI method)	6.70	N/A
<i>Interoperator variability in two- point slope</i>	0.01	0.01	0.18	0.00
<i>Interoperator variability in regression slope</i>	0.01	0.02	0.16	0.00
<i>Interoperator variability in roughness</i>	0.03	0.04	0.12	0.01