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A methodological intercomparison of topographic survey techniques for characterizing wadeable streams and rivers

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ABSTRACT

Fine-scale (submeter) resolution digital elevation models (DEMs) created from high precision (subcentimeter) instruments (e.g., total station, rtkGPS, and laser scanning) have become ubiquitous in the field of fluvial geomorphology. They permit a diverse range of spatially explicit analyses including hydraulic modeling, habitat modeling, and geomorphic change detection. While previous studies have assessed the quality of specific topographic survey methods at individual sites or across a limited number of sites, an intercomparison of survey technologies across a diverse range of wadeable streams could help clarify which techniques are feasible, as well as which work best under what circumstances and for what purposes. Although a wealth of existing studies and protocols explain *how* to undertake each individual technique, in this study we seek to provide guidance on *what* techniques to use in which circumstances. We quantified the relative quality and the amount of effort spent collecting data to derive bare earth topography from an array of ground-based and airborne survey techniques. We used topographic survey data collected over the summer of 2010 from six sample reaches of varying complexity in the Lemhi River basin, Idaho, USA. We attempted to conduct complete, replicate surveys at each site using total station (TS), real-time kinematic (rtk) GPS, discrete return terrestrial laser scanner (TLS), and airborne LiDaR surveys (ALS). We evaluated the precision and accuracy of derived bare earth DEMs relative to the higher precision total station point data. Discrepancies between pairwise techniques were calculated using propagated DEM errors thresholded at a 95% confidence interval. Mean discrepancies between total station and rtkGPS DEMs were relatively low ($\leq$0.05 m), yet TS data collection time was up to 2.4 times longer than rtkGPS. The ALS DEMs had lower accuracy than TS or rtkGPS DEMs, but the aerial coverage and floodplain context of the ALS data set was superior to all other techniques. The TLS bare earth DEM accuracy and precision were lower than any other technique because of vegetation returns misinterpreted as ground returns. Our results are helpful for understanding the strengths and weaknesses of different approaches.

1. Introduction

During the past two decades, the field of fluvial geomorphology has seen increased application of high resolution surveying technologies to characterize instream bathymetry and floodplain topography (Heritage et al., 2009; Milan et al., 2011; Marcus, 2012). These include topographic and bathymetric surveys from airborne (e.g., airborne laser scanning (ALS) and photogrammetry), boat-based (e.g., single-beam and multibeam SONAR), and ground-based platforms (e.g. total station (TS), real-time kinematic global positioning system (rtkGPS), terrestrial laser scanning (TLS), structure from motion; Lane, 1998; Keim et al., 1999; Lane et al., 2003; Heritage et al., 2009; Allouis et al., 2010; Schwendel et al., 2010). Traditionally, geomorphologists characterized topography using a series of discrete cross sections (sometimes monumented for repeat measurement) and longitudinal profiles. However, analyses using coarsely spaced cross sections can suffer from uncertainty introduced by interpolating over large distances and, as a consequence, can fail to capture the downstream effects of geomorphic changes (Brasington et al., 2000). The application of newer and established high precision surveying techniques has resulted in a transition from cross sections to collecting topographically stratified or grid-based *XYZ* data sets that can be interpolated into continuous topographic models, such as digital elevation models (DEMs; Brasington et al., 2003). An advantage of high spatial resolution DEMs is their demonstrated utility in spatially explicit analyses to develop hydraulic models (Higgitt and Warburton, 1999; Dauwalter et al., 2006), to construct morphological sediment budgets (Taylor, 1997; Fuller et al., 2003), and to track trends in physical habitat through time (Wheaton et al., 2010a). However, the results and scope of

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inferences of DEM-based analyses are inherently affected by the precision and spatial resolution of both the raw data and the derived DEM.

Sampling method is an important consideration that also influences the precision and accuracy of DEMs. A fundamental distinction exists between high precision techniques that may incorporate surveyor judgment into the sampling process (e.g., rtkGPS) and those that are remotely sensed and do not incorporate judgment into the sampling process (e.g., ALS). For example, when sampling with ground-based techniques such as TS and rtkGPS, the surveyor may implement a grid-based, cross section based, or topographically stratified method (e.g. Vallé and Pasternack, 2006). Of the three, topographically stratified sampling is arguably the most subjective as it requires the surveyor to select the XYZ points and breaklines that best represent topographic forms (e.g., delineating significant breaks in slope). While subjective, this sampling method can result in a more accurate representation of surface topography and increase survey efficiency by reducing the overall number of points necessary to represent site topography (Lane et al., 1994; Brasington et al., 2003). When implementing any technique that incorporates surveyor judgment, the training, experience, and skill of the surveyor may have much more of an impact on data and derived DEM precision and accuracy relative to techniques that rely less on surveyor judgment.

A data set's admissible level of precision and spatial resolution should be framed by the research questions and the analyses it is intended to support and not by the ability to collect high resolution data sets alone (Bowen and Waltermire, 2002). Arguably, the recent explosion of new data acquisition techniques has fostered a fixation with brute force collection of data at the highest possible resolution, without adequate consideration of what is necessary to address the question at hand. Each technique has limitations that result in tradeoffs between cost, accuracy, resolution, spatial coverage, and frequency of sampling (Brasington et al., 2003; Allouis et al., 2010). The level of point precision and spatial resolution (i.e., point spacing) afforded by each technique should be considered in the context of how much effort may be required to collect the data and what may be gained or lost in spatial coverage relative to other available techniques. For instance, high instrument or point precision does not necessarily translate into high precision or accuracy of derived bare earth surfaces, particularly if data is not collected at an adequate spatial resolution. As a result, even if a researcher has control over the data collection process and is surveying with high precision equipment capable of producing high resolution data, this does not ensure sufficient data quality for the intended analyses (Lane and Chandler, 2003).

When analyzing data collected using high precision surveying techniques, *it is* necessary to consider not only the accuracy of the raw point data but also the uncertainty of the topographic surfaces (e.g., DEMs) interpolated from the data. Digital elevation model uncertainty varies spatially and is a function of individual point accuracy, survey strategy, point density, raster resolution, and interpolation method (Lane, 1998; Fisher and Tate, 2006; Heritage et al., 2009). In the context of rivers and streams, elevation uncertainty tends to be higher in areas with greater topographic complexity and steeper slopes (such as along bank and bar edges) and lower on flatter surfaces (such as bar tops) (Charlton et al., 2003; Heritage et al., 2009). Several studies have characterized DEM uncertainty by applying uniform error estimates across the entire DEM surface (Brasington et al., 2000) or spatially segregating estimates by wet and dry areas (Lane et al., 2003; Milan et al., 2007). However, a limitation of this approach is a tendency to overestimate uncertainty on low gradient features (e.g., bar tops) and underestimate uncertainty on high gradient features (e.g., banks). More recent studies (e.g. Heritage et al., 2009; Wheaton et al., 2010b; Milan et al., 2011) have developed methods for spatially (i.e., cell-by-cell) variable estimates of elevation uncertainty.

The purpose of this paper is to quantify the relative accuracy and precision of different ground-based (TS, rtkGPS, TLS) and airborne (ALS) topographic survey techniques at characterizing instream and floodplain topography across several sites representing a diversity of channel planform, width, gradient, and riparian vegetation types. This understanding is fundamental to characterizing uncertainty when inter-comparing data sets collected using different sampling techniques at variable spatiotemporal scales. We identify where specific techniques performed well, where they performed poorly, and how well they performed relative to the other techniques analyzed in this paper. We present topographic accuracy and precision of each survey type using DEMs rather than individual data points as the majority of high resolution data set analyses and models use some form of an interpolated surface (e.g., DEM, digital terrain model (DTM), mesh) and not raw data. Additionally, we provide explicit cost estimates associated with each sampling method including summarizing the relationship between quality (i.e., accuracy and precision), efficiency (i.e., data collected per unit time), and effort (i.e., hours in the field). This paper does not cover basic surveying principals nor propose new systematic surveying protocols for each technique, as these exist elsewhere in literature (e.g. Keim et al., 1999; Leick, 2004; Heritage and Hetherington, 2007; Van Sickle, 2008; Heritage and Large, 2009).

2. Methods

2.1. Study site

The Lemhi River is located in eastern Idaho, flows in a northwesterly direction, and is a major tributary to the Salmon River (Fig. 1). The mainstem is characterized as low gradient, spring-fed, and flowing through a broad alluvial valley (IDEQ, 1999; Good et al., 2005). The watershed lies at the northern extent of the Basin and Range province and is bordered by the Lemhi Mountains to the west and the Beaverhead Mountains to the north and east (IDEQ, 1999). The basin encompasses 3267 km^2 with elevations ranging from 1190 to 3450 m. Average precipitation varies from 180 mm in lower portions of the valley to 580 mm at higher elevations. Peak flows generally occur in June, with lowest flows typically in August.

Six sample sites of varying habitat complexity (Table 1; Fig. 2) were selected from preexisting NOAA Integrated Status and Effectiveness Monitoring Program (ISEMP) study sites (Fig. 1). These sites have variable planform, gradient, and vegetation and were selected as a reasonable proxy for the range of sampling challenges present in many of the wadeable streams throughout the Columbia River basin. Sample sites were chosen in full anticipation that not all survey techniques would perform well at all sites and that some sites would challenge techniques to the point of failure. As such, the diversity of site conditions highlights contrasts between techniques and shows where specific survey techniques performed best.

2.2. Field methods

Topographic surveys were conducted from July through September of 2010 during low flow conditions. We sampled during low flow conditions because (i) surveying instream topography is more efficient when water velocity is lower, and (ii) discrepancies in measured topography could be attributed to discrepancies among techniques and not owing to geomorphic changes associated with high flows.

2.2.1. Common ground control

Prior to field sampling, an extensive control network of three to six survey benchmarks was established by a professional surveyor at each site. Using established benchmarks ensured that disparities between techniques were a result of differences between survey methods and not caused by factors related to the control network (e.g., disparate control, inconsistent projections, and transformations). The benchmarks were subsequently used to set additional common control points to achieve the line of sight necessary for both total station and TLS surveys. These additional control points were established by the field crew using a