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Accuracy assessment of LiDAR-derived DEMs of bedrock river channels: Holtwood Gorge, Susquehanna River

Lucas Reusser[1] and Paul Bierman[1]

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[1] We evaluate the accuracy of 1 m, LiDAR-derived DEMs of an exposed bedrock channel, and use these high-resolution terrain models to calculate erosional fluxes between four levels of strath terraces dated previously with ^{10}Be. Recent investigations into the timing, rates, and processes by which rivers incise their bedrock channels have greatly enhanced our understanding of landscape evolution. However, measuring channel geometries in 3 dimensions is difficult; thus, volumes of bedrock eroded during incision events are rarely considered. Although our analysis successfully demonstrates the proportionality between incision rates and erosional fluxes for terraces high above the channel floor in this gorge, unusually high river flows on the date of acquisition inundated lower bedrock surfaces, preventing accurate volume estimates. To ensure optimal low-flow LiDAR coverage for fluvial environments, we discuss methods to improve the scheduling of data acquisition by using archived discharge records and predictive models based on real-time data. **Citation:** Reusser, L., and P. Bierman (2007), Accuracy assessment of LiDAR-derived DEMs of bedrock river channels: Holtwood Gorge, Susquehanna River, *Geophys. Res. Lett.*, *34*, L23S06, doi:10.1029/2007GL031329.

1. Introduction

[2] Responding to changing climatic and tectonic boundary conditions, bedrock river channels provide an important control on rates of landscape evolution [e.g., *Howard et al.*, 1994; *Pazzaglia et al.*, 1998]. Although our understanding of the nature and timing of bedrock incision has improved remarkably through numerous field and modeling efforts [e.g., *Crosby and Whipple*, 2006; *Leland et al.*, 1998; *Reusser et al.*, 2006; *Whipple et al.*, 2000], estimating the volume of bedrock eroded during episodes of incision is rarely attempted due to the difficulty of measuring accurately complex channel geometries in three dimensions. Vertical incision rates have been estimated using detailed resurveying of river cross-sections [*Hartshorn et al.*, 2002] and cosmogenic exposure age modeling [e.g., *Leland et al.*, 1998; *Reusser et al.*, 2004]; however, these rates alone can be misleading metrics of erosion within bedrock channels. For example, if the cross-sectional area of a river channel decreases through the formation of inner-gorges during incision, the rate of downcutting by itself does not reflect the volume of bedrock eroded or the corresponding change in channel geometry.

[3] Light detection and ranging (LiDAR) has been used for more than a decade to generate highly accurate 3D digital representations of Earth's surface [*Flood and Gutelius*, 1997]. Here, we evaluate the accuracy of 1 m LiDAR-derived Digital Elevation Models (DEMs) representing four levels of strath terraces in a bedrock channel environment, calculate erosional fluxes during episodes of late Pleistocene incision previously dated with ^{10}Be [*Reusser et al.*, 2006], and suggest ways in which LiDAR acquisition and data processing can improve results in bare-rock landscapes.

2. Field Site and LiDAR Acquisition

[4] Holtwood Gorge, located along the lower reaches of the Susquehanna River and approximately 50 km upstream from Chesapeake Bay, lies at the bottom of a wide bedrock valley carved nearly 150 m into the Appalachian Piedmont [*Pazzaglia and Gardner*, 1994]. Several distinct levels of bedrock strath terraces are preserved along the sides of the ~5 km long gorge, and as isolated bedrock islands (dissected straths) standing between <1 and ~20 m above the channel floor (Figure 1). In 2002 and 2003, we collected 77 bedrock samples from these terraces for cosmogenic ^{10}Be exposure age modeling in order to investigate the nature and timing of incision through rock in Holtwood Gorge. In addition, we conducted a high-precision differential GPS survey of each sample location [*Reusser et al.*, 2006].

[5] Our analysis indicates that the Susquehanna River underwent an episode of rapid incision during the last glacial cycle. Beginning ~36 ka, rates of vertical incision increased dramatically (from <0.2 m/ky to ~0.5 m/ky), and remained elevated until ~14 ka, after which rates dropped to <0.07 m/ky [*Reusser et al.*, 2006; *Reusser et al.*, 2004]. While these data clearly demonstrate the episodic nature of river incision into rock, taken alone they tell little about the volume of material removed during periods of incision.

[6] To estimate the rate at which rock was removed over time from within the complex bedrock channel of Holtwood Gorge, the National Center for Airborne Laser Mapping (NCALM) acquired LiDAR coverage on January 9th, 2005, and generated 1 m DEMs from both the unfiltered and filtered (last-return) LiDAR point clouds using Kriging. Filtering of the LiDAR data was accomplished with the Interpolate-Compare (IC) filter developed by NCALM at the University of Florida, which produces a gridded surface from ground-points selected through multiple iterations of a decreasing-sized search window, and user defined height-difference tolerances between adjacent points. Flow in the Susquehanna reached ~4100 m^3/s on the day of LiDAR

[1]Rubenstein School of Environment and Natural Resources and Department of Geology, University of Vermont, Burlington, Vermont, USA.

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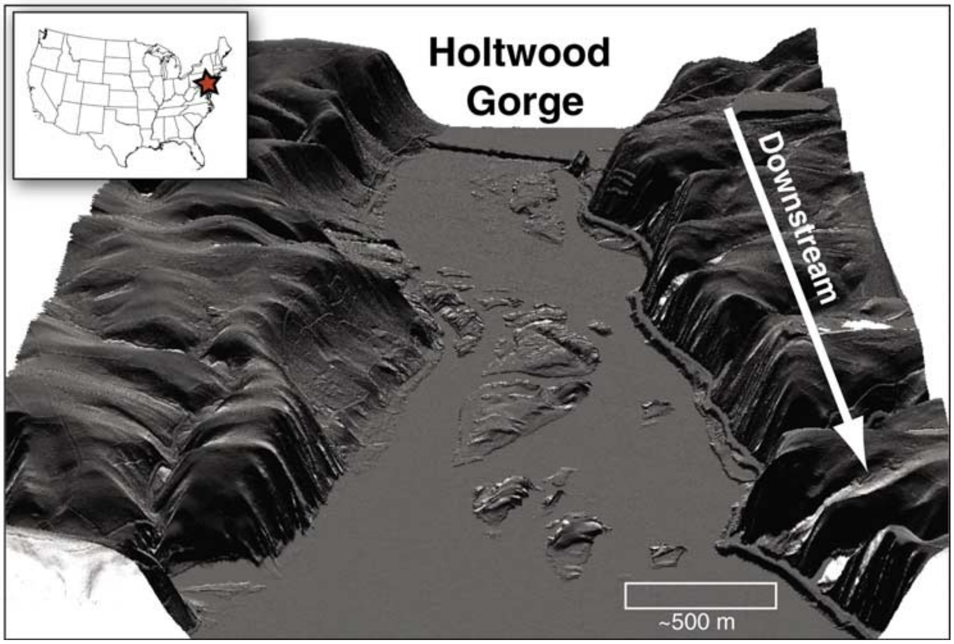

Figure 1. 3D representation of Holtwood Gorge along Susquehanna River, PA (with 3 X vertical exaggeration), produced from NCALM LiDAR DEM. When coverage was acquired (January 9th, 2005) discharge was $\sim$4100 m^3/s, inundating the channel with >3 m of water. Dark cross-stream line at upstream end of gorge is Holtwood Dam.

acquisition (>5 times the historic median flow for this day) (http://waterdata.usgs.gov/nwis/uv?01576000, Marietta, PA), inundating the channel with >3 m of water, and covering all of the lowest terrace, and portions of the next higher terrace. As a result, accurate volumetric calculations for incision are limited to higher terraces.

3. Calibration of LiDAR-Derived DEMs

[7] We vertically calibrated the delivered DEMs produced from the LiDAR coverage with two GPS control points along the western bank of the gorge (originally, the lowest point on each DEM was assigned zero instead of its elevation above sea-level). Differences between our GPS elevations and the elevations of the LiDAR grid cells underlying each control point were 33.39 m and 33.42 m. As such, we raised each of the LiDAR DEMs by the average difference (33.40 m) in order to facilitate accurate comparison between elevations of our ground-truth GPS data and the corresponding LiDAR elevations elsewhere in the gorge.

4. Validation of Unfiltered and Filtered DEMs

[8] To assess the accuracy of the LiDAR-derived DEMs in and around the bedrock channel, we compared the elevation of our GPS survey data to that of the underlying LiDAR grid cells at each of the 77 locations where samples were collected in 2002 and 2003. This analysis demonstrates that on bare bedrock surfaces, the unfiltered last-return point cloud yielded a more accurate DEM than the IC filtering algorithm that was used to generate the filtered DEM (Figure 2 and Table S1 of the auxiliary material).[1]

[9] Considering all data, the average Δ_z value (Δ_z = GPS − LiDAR) for the unfiltered LiDAR (n = 77) was 0.85 m with a Root Mean Square Error (RMSE) of 1.4 m. In contrast, the filtered LiDAR data yielded a considerably higher average Δ_z and RSME, 2.20 m and 3.26 m, respectively (Table S1). These differences become more pronounced when the position of each sample site is considered in relation to the level of water flowing through Holtwood Gorge on January 9th, 2005. Not surprisingly, when the analysis is limited to the 38 underwater sample sites, the differences between Δ_z and RSME for the unfiltered and filtered LiDAR are quite small (1.00 m and 1.12 m, 1.45 m and 1.68 m respectively); the IC algorithm has little effect at the water's surface. In contrast, for bedrock sample sites above the water's surface at the time of LiDAR acquisition (n = 39), differences between Δ_z and RSME values for the unfiltered and filtered DEMs increase considerably relative to the underwater samples (0.71 m and 1.34 m, 3.26 m and 4.27 m respectively) (Table S1). In Holtwood Gorge, the filtered DEM underestimated the actual elevation of bedrock outcrops by as much as 10 m. In general, the degree to which outcrop height is underestimated increases with height above the channel floor (Figure 2).

[10] We can speculate on why the filtered LiDAR has a tendency to underestimate the height of bedrock outcrops. Most previous work comparing ground-truth GPS or survey data with LiDAR-derived DEMs either evaluated the effects of different land cover conditions in forested environments [e.g., *Hodgson*, 2005; *Webster et al.*, 2006], or considered alluvial channels where river terraces generally exist as wide, flat surfaces [*Charlton et al.*, 2003]. Ground conditions in bedrock channels such as Holtwood Gorge are markedly different. Terrace remnants preserved along channel walls and as mid-channel islands are composed of

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2007gl031329.

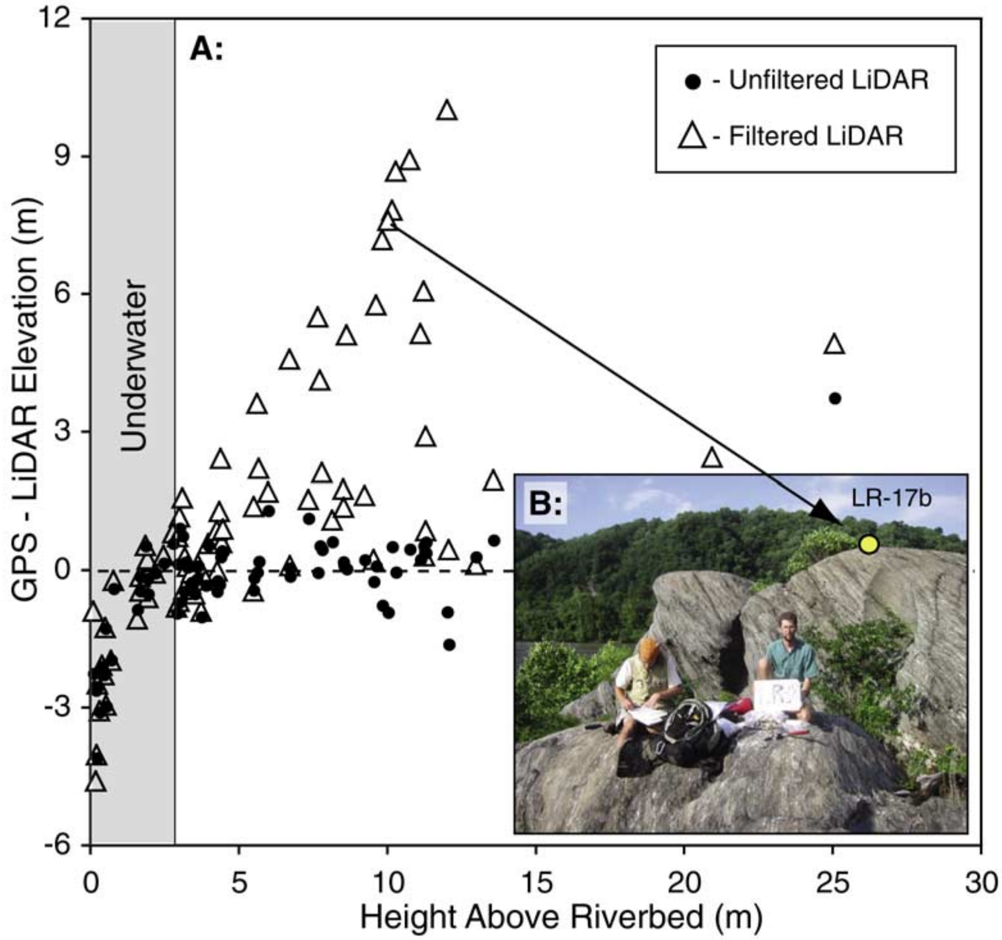

Figure 2. (a) Point-by-point difference between elevations of RTK GPS survey data and corresponding grid cells for both unfiltered and filtered LiDAR DEMs as a function of height above the riverbed for each of the 77 sample sites. Grey region denotes underwater samples. Circles and triangles are unfiltered and filtered DEMs, respectively. Points plotting above the zero line indicate LiDAR underestimates the actual elevation. (b) Example of terrace remnant truncated by >7 m in the filtered DEM (photo does not obscure data).

exposed, meter-scale rock outcrops that are highly variable in elevation (Figure 2b). In addition, some larger islands are partially vegetated. Effective bare-earth filtering algorithms must thus be capable of both rejecting vegetation points while at the same time accepting the natural variability between elevations of small adjacent bedrock outcrops. Unfortunately, our analysis is limited to the 39 above-water sample sites, all of which are located on exposed bedrock surfaces. Thus, we have no way to assess the accuracy of bare-earth elevations under vegetated terrace remnants; a necessary comparison for other applications of LiDAR DEMs, such as the construction of river cross-sections for flow modeling [*Charlton et al.*, 2003; *Reusser et al.*, 2006].

5. Calculating Erosional Fluxes Between Strath Terrace Levels

[11] We used the xyz coordinates collected at each sample site to calculate volumes of rock removed and the corresponding erosional fluxes during incision between the four levels of terraces preserved within Holtwood Gorge (Level 4 being the highest in elevation and oldest, and Level 1 being the lowest and youngest). These calculations demonstrate that increases in rates of vertical incision beginning approximately 36 ka are closely mirrored by increases in fluxes of bedrock eroded during incision.

[12] We assumed the average age and height of each of the four terraces represent paleo-channel floors just prior to abandonment at the onset of incision events. Using the coordinates of each sample site along a given terrace, we generated 3D paleo-riverbed surfaces (Figure 3). Regression models of distance downstream vs. elevation for each sample site yield nearly identical paleo river gradients for the level 3, 2 and 1 terraces (~1.5 m/km) and R^2 values of 0.87, 0.91 and 0.87, respectively [*Reusser et al.*, 2006], indicating that our sample site locations accurately trace ancient riverbeds both across and downstream for these three terraces. Only two samples were collected from the highest level 4 terrace, and the resulting paleo-riverbed surface is correspondingly crude. Exposure ages for these two samples are given as lower limits due to poor surface preservation of the sampled bedrock [*Reusser et al.*, 2006], making volumetric calculations and fluxes between this level and lower level 3 terrace upper limits only. Using cut and fill 3D operations in an ESRI ArcGIS environment, we calculated volumes of rock eroded between pairs of

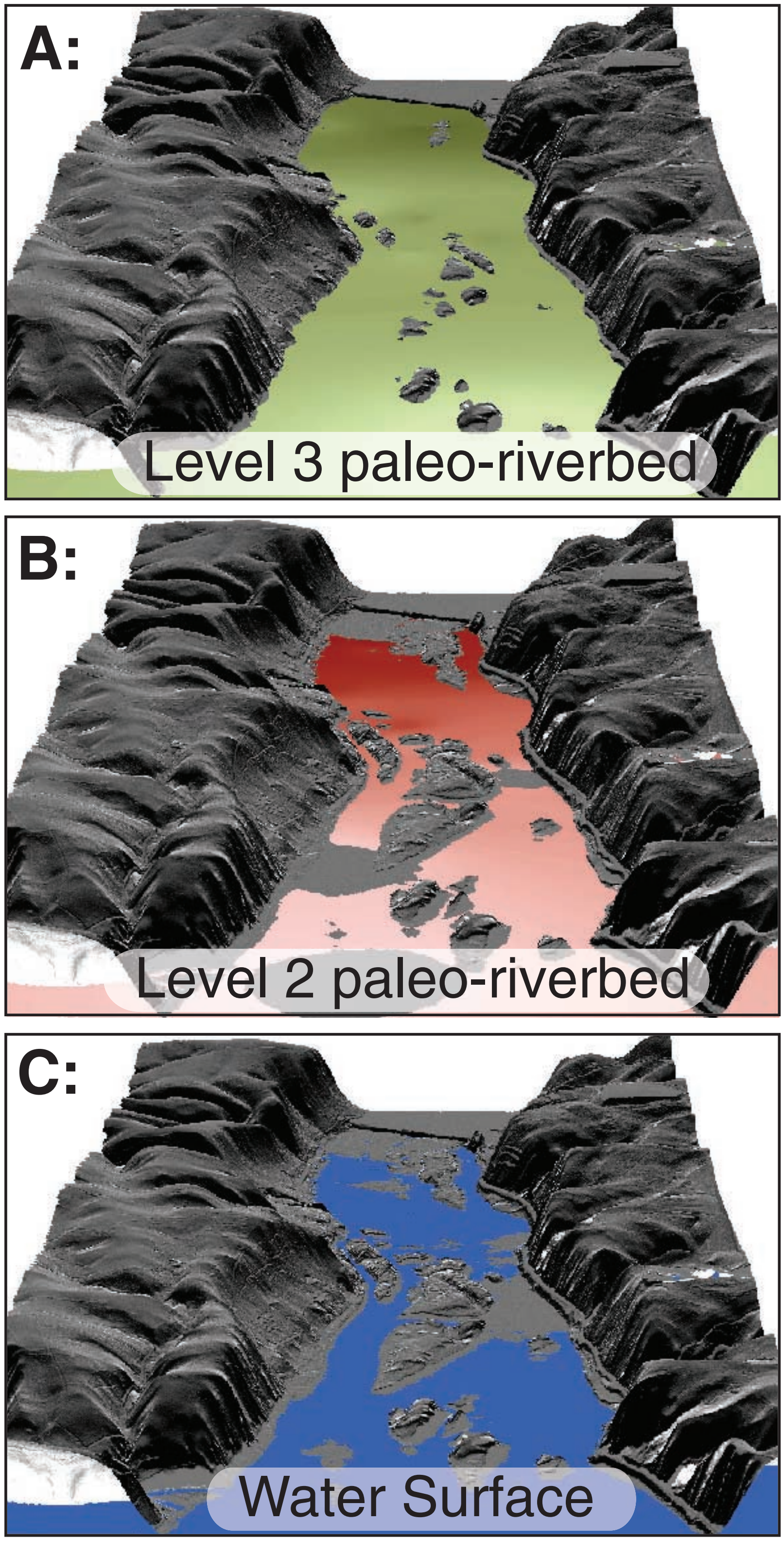

Figure 3. Gridded paleo-riverbed surfaces for the (a) level 3 and (b) 2 strath terraces generated using xyz GPS data for all sample sites from each terrace. (c) Water surface at time of LiDAR acquisition constructed using DEM elevations for underwater samples.

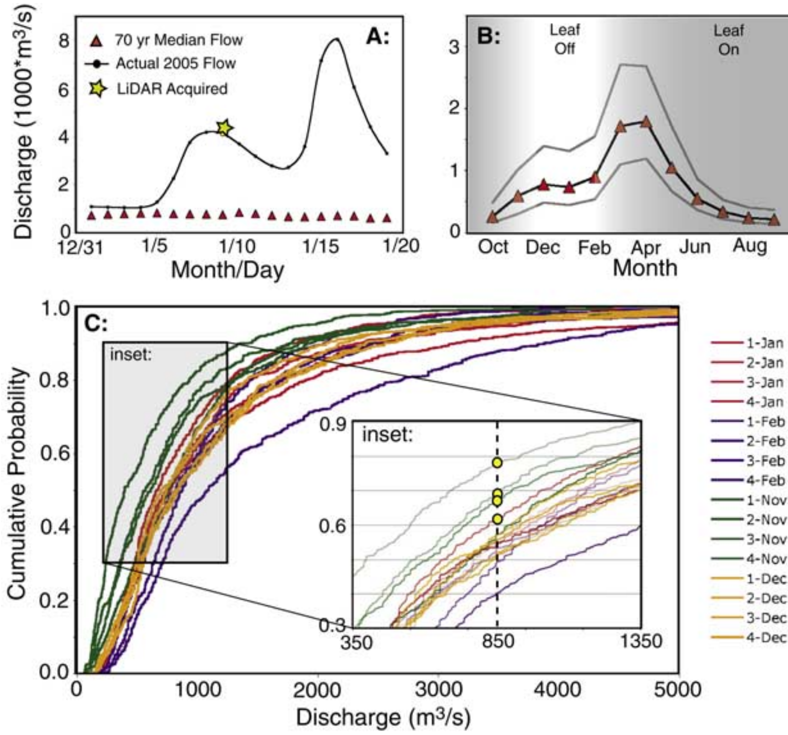

Figure 4. (a) Discharges surrounding the date of LiDAR acquisition (January 9th, 2005) relative to median daily flows based on the 70-year flow record at Marietta, PA. (b) Monthly median flows with 25% and 75% confidence bands. (c) Probability Density Functions for each week during the leaf off period (Nov. through Feb.). Notation to right denotes week number and month. Yellow circles in inset denote the four leaf-off weeks with the highest probability of yielding low flows.

successive terrace level surfaces (level 4 to 3, 3 to 2, 2 to 1) constrained by the 3D geometry of Holtwood Gorge provided by the unfiltered LiDAR DEM (Figure 3 and Table S2). Due to the differences in data types used in our analysis (exposure age modeling, GPS data, and 3D terrain models), as well as the inability to calculate realistic confidence bands around paleo-riverbed elevations, we do not assign errors to these erosional fluxes.

[13] Our analysis indicates that from ~90 to ~36 ka, the Susquehanna was incising at a maximum rate of 0.23 m/ky yielding a maximum normalized erosional flux of $<2.5 \times 10^5$ m^3/ky per river km (Table S2). From ~36 ka to ~20 ka, both incision rates and erosional fluxes nearly doubled to 0.44 m/ky and 4.1×10^5 (m^3/ky)/km respectively. Incision rates increased again to 0.53 m/ky between ~20 ka ~14 ka. Because all level 1 samples were underwater at the time that the LiDAR was flown, accurate volumetric calculations between the level 2 and 1 terraces are not possible. We provide an upper limiting estimate of $<4.9 \times 10^5$ (m^3/ky)/km by assuming an identical channel geometry to that between the level 3 and 2 terraces and scaling the erosional flux by the change in average height above the channel floor between each pair of terraces (7.23 m for levels 3 to 2, and 2.85 m for levels 2 to 1; see Table S2).

[14] Rates of vertical incision can be misleading measures of the erosional efficiency of rivers carving through rock. In Holtwood Gorge, increasing erosional fluxes estimated using LiDAR DEMs are proportional to increasing rates of vertical incision measured with ^{10}Be during the late Pleistocene. This condition is a direct outcome of the rectangular geometry of the gorge, which changes little horizontally during periods of incision. Alternatively, if a river channel's width were to decrease through the formation of inner-gorges as incision accelerates (e.g., Mather Gorge [*Bierman et al.*, 2004]), erosional fluxes will no longer scale with incision rates. Comparing relationships between vertical incision and erosional fluxes in bedrock channels of varying geometries could yield valuable insights into the distribution of energy expenditure during incision, as well as provide further constraints for stream-power erosion laws and models of landscape evolution [e.g., *Howard et al.*, 1994; *Whipple et al.*, 2000]. When combined with field observations, such analysis could also elucidate the effects of varying erosional processes on the formation of different bedrock channel morphologies [*Whipple et al.*, 2000].

6. Improving Data Acquisition

[15] While LiDAR can facilitate otherwise difficult research in bedrock river channels, our analysis highlights the complexity of employing ALSM in fluvial environments. Unlike terrestrial landscapes, LiDAR in river channels and gorges must contend with flowing water, rendering the scheduling of LiDAR flights critically important. As an example, we use 70 years of daily discharge records from the Susquehanna River at Marietta (USGS 01576000), just upstream of Holtwood Gorge, to demonstrate several

methods capable of improving future data acquisition in fluvial environments.

[16] Because a hydroelectric dam spans the river channel at the upstream end of Holtwood Gorge, the majority of the channel floor and bedrock terraces below the dam remain above water at flows <850 m^3/s, making the optimal timing of LiDAR acquisition near or below this value and during leaf-off months. On January 9th, 2005, when LiDAR was collected, flow through the gorge was exceptionally high (~4100 m^3/s; daily exceedance probability of <5%). Five days previous, flow through the gorge was ~1000 m^3/s at which all but the very lowest bedrock outcrops were above water (Figure 4a).

[17] Using the example of Holtwood Gorge, records of past discharge can help to optimize flight scheduling in advance, while allowing for a degree of flexibility when the scheduled date approaches. Limiting the potential flight season to leaf-off and lower flow variability months, the first three weeks of November and the third week of January hold the most potential for yielding a day of low flow (<850 m^3/s) conditions (~80%, ~70%, ~66%, and ~62% chances respectively; Figures 4b and 4c). Several days prior to the scheduled week, the Advanced Hydrologic Prediction Service (http://www.weather.gov/ahps) can be used to predict flows over the upcoming week based on predictions driven by real-time weather and discharge data. Considering the cost of acquisition, and the investment of time required for data processing and analysis, serious consideration should be given to rescheduling LiDAR flights if suboptimal flow conditions are predicted.

7. Conclusions and Future Research

[18] With the aid of high-resolution 3D terrain models generated with LiDAR data, we demonstrate that within Holtwood Gorge, increasing rates of bedrock channel incision beginning ~36 ka are mirrored by increasing erosional fluxes. This condition is related to the rectangular geometry of the Gorge. Similar studies conducted within bedrock channels displaying more pronounced inner gorges could provide useful information regarding the expenditure of energy during incision events.

[19] Our point-by-point GPS – LiDAR comparison provides new information regarding the strengths and weaknesses of highly detailed DEMs in bedrock fluvial environments. In Holtwood Gorge, the unfiltered bare-earth LiDAR-derived DEM provides a more accurate representation of bedrock terrace elevations than data filtered by algorithms designed to achieve bare-earth DEMs primarily in forested environments.

[20] Our analysis is limited to fully exposed bedrock surfaces; we have no comparison points under tree cover. If point elevation data are needed under tree cover, interweaving several LiDAR datasets (unfiltered data for regions of bare-rock exposure, and filtered data under tree cover) could prove useful in partially vegetated bedrock channel environments.

[21] **Acknowledgments.** Project funded by NSF-EAR-0003447 supplement to Bierman. We thank NCALM for the acquisition and processing of the Holtwood LiDAR, the staff at the Holtwood Dam Hydropower station for access and support.

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P. Bierman and L. Reusser, Rubenstein School of Environment and Natural Resources and Department of Geology, University of Vermont, Delehanty Hall, 180 Colchester Avenue, Burlington, VT 05401, USA. (lreusser@uvm.edu)