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Characterizing debris transfer patterns in the White Canyon, British Columbia with terrestrial laser scanning

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Abstract

In the Thompson-Fraser Rail Corridor in Interior British Columbia, the Canadian National (CN) rail line traverses several alluvial fans, which are subject to occasional debris flows. Debris flows pose a significant geohazard due to the combination of high flow velocities, large impact forces, long runout distances and poor temporal predictability. When a debris flow occurs, the cost of repairs, maintenance, and construction along these single-track railway lines is compounded by the fact that these activities also impede the flow of rail traffic, which has financial repercussions for the operators. As a result, it is vital to be able to identify and prioritize the slopes that pose the greatest hazard to the rail lines. A thorough understanding of the geohazards present on site is an essential component of risk assessment. The Canadian Railway Ground Hazard Research Program (RGHRP) was established in 2003 with the aim of better understanding the natural hazards impacting railway operations across Canada. The present study is part of this initiative and focuses on an active site called the White Canyon, which is located 275 kilometers northeast of Vancouver, BC. In this study, we use terrestrial laser scanning (TLS) and panoramic imagery datasets to analyze the debris recharge patterns that develop between debris flows in a select channel in the White Canyon. TLS scans taken before and after the events provide insight into the volumes of material mobilized and how we can leverage this series of TLS data to give insight into the amount of debris accumulating in the channels prior to failure. The temporal data acquisition rate was found to have a significant influence on the amount of movement that can be interpreted from the TLS change detection analysis and panoramic images. Therefore, the temporal data acquisition rate is key consideration when using TLS to support the determination of accurate return periods on debris flows.

Keywords: Terrestrial Laser Scanning; Channel Recharge

1. Introduction

Over the past decade, the use of remote sensing technologies for the monitoring of landslides and rock slope instabilities has increased dramatically (Jaboyedoff et al. 2012; Abellán et al. 2014; Telling et al. 2017). Airborne Laser Scanning (ALS) and Terrestrial Laser Scanning (TLS) have increased the spatial coverage and density of available datasets through non-selective sampling of millions or even billions of survey points to produce 3D point clouds. Advances in new algorithms for point cloud comparison and acquisition have improved the level of detection to mm-scale using advanced temporal filtering techniques and continuous TLS data acquisition (Kromer et al. 2015, 2017; Williams et al. 2018).

Remote sensing techniques have been used to characterize and monitor the transport of debris in steep channels and processes occurring on alluvial fans. In Switzerland, both ALS (Bennett et al., 2013) and TLS (Oppikofer, 2009; Schürch et al., 2011) have been applied to document movements occurring in the Illgraben debris-flow channel. ALS or TLS have been used to monitor volumes of sediment moving in channels in the Manival Torrent, in France (Theule et al., 2012), the Glyssibach and Glattbach channels in Switzerland (Scheidl et al., 2008), and the Chalk Cliffs in the USA (McCoy et al., 2010; Staley et al., 2011; Scheinert, 2012). Wasklewicz and Hattanji (2009) use cross-sections derived from TLS scans to investigate changes in channel shape and dimensions following a debris flow in the Ashio

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Mountains in Japan. In almost all studies, the methodology of performing change detection has been primarily restricted to Digital Elevation Model (DEMs) of Difference (DoD). A DoD is used to quantify the volumetric change between two DEMs. The process involves subtracting the two digital elevation models from one another and then with subsequent error analysis, real topographic changes can be distinguished (Williams, 2012). DoDs are restricted to quantifying change in a single vector direction (vertical), as opposed to methods like Multiscale Model to Model Cloud Comparison (M3C2) (Lague et al., 2013). Schürch et al. (2011) address issues arising from DEM generation on complex surface geometry with abrupt changes in slope, aspect, local surface roughness and high local relief. In their study, they present a method to quantify volumetric uncertainty in change detection specific to data from terrestrial laser scanning in a 300 m reach of the Illgraben.

As a component of the Canadian Railway Ground Hazard Research Program (RGHRP), TLS and other remote sensing techniques have been applied to monitor active rock slopes in the Thompson-Fraser Rail Corridor in Interior British Columbia (BC), Canada. The White Canyon located just outside the community of Lytton, BC, has been a central focus of this research effort. Over the 5+ years of TLS monitoring at the White Canyon, several debris flows have occurred on this active slope. In a few cases, these events have overwhelmed mitigation and have directly impacted the track. These events disrupt the safe operation of rail traffic through this major transportation corridor. As noted by Jakob et al. (2016), the most significant contributor to debris flow occurrence is a supply of readily erodible material, often created by rockfalls and other types of landslides. Additionally, May (2002) notes that as the channel length increases, the relative contribution of the initial failure volume decreases. In other words, the total debris-flow volume approaches more closely the volume of entrained sediment and depends strongly on the length of channel travelled by the debris flow. Therefore, understanding the processes and time-frame that recharge debris to the channel is crucial for evaluating debris-flow hazard.

The aim of this study is to present a methodology to monitor the spatial and temporal accumulation of debris on a slope with terrestrial laser scanning. This methodology will help evaluate the recharge threshold for debris flow initiation as suggested by the supply-limited threshold proposed by Jakob (1996). The supply-limited threshold indicates that a debris flow will occur when a precipitation threshold is exceeded provided sufficient debris is present in the channel. In addition, the work also supports considerations for evaluating return periods on debris flows with remote sensing approaches.

2. Study Site

The steep slopes of the White Canyon (50.266261°, -121.538943°), located 5 km northeast from the community of Lytton, BC, near the confluence of the Thompson and Fraser Rivers, present geohazards to the safe operation of the Canadian National (CN) mainline (Fig 1a). Rockfalls and rockslides contribute to the production of debris which accumulates in channels (Bonneau and Hutchinson, 2017; van Veen et al., 2017). Dry granular flows and debris flows facilitate the transport of debris downslope, which can result in consequences that range from minimal maintenance and repair of warning systems, to complete closure and rebuilding of the impacted rail lines and most unfortunately, the loss of life. The consequence of repairs, maintenance, and construction along single-track railway lines is compounded by the fact that during any such activity the flow of traffic is impeded or stopped.

Differential erosion of the White Canyon has formed a morphology that is highly complex and consists of vertical spires and deeply incised channels (Fig 1b). The Canyon spans approximately 2.2 km between Mile 093.1 and 094.6 of the CN Ashcroft subdivision. The active portion of the Canyon reaches up to 500 m in height above the railway track. Two short portals (tunnels) mark the entrances to the Canyon. A third portal is located in the middle of the Canyon which separates the eastern and western portions of the Canyon.

The dominant geological unit in the White Canyon is the Lytton Gneiss. The Lytton Gneiss is composed of a quartzofeldspathic gneiss with amphibolite bands, containing massive quartzite, gabbroic and amphibolite intrusions. Two sets of dykes have intruded the Lytton Gneiss. The first dyke set consists of tonalitic intrusions that are believed to be related to the emplacement of the Mt. Lytton Batholith (Brown, 1981). The second dyke set is a series of dioritic intrusions that cross cut the Lytton Gneiss and tonaltic dykes. These dioritic intrusions are believed to be part of the Kingsvalle Andesites (Brown, 1981). All of these units contribute to the production of material to the debris channels, and the dykes provide geometric controls on flow of material toward the rail line.

For this study, the focus will be on a specific channel in the eastern section of the Canyon. The selected channel is highlighted in red in Fig 1. The channel is approximately 450 m in length and has an average slope angle of 35 degrees (Fig 1c). Draped mesh and a ditch protect the rail line at the base of the channel. Due to the vantage of the TLS system in the survey design, a portion of the ditch is occluded in the TLS scans.

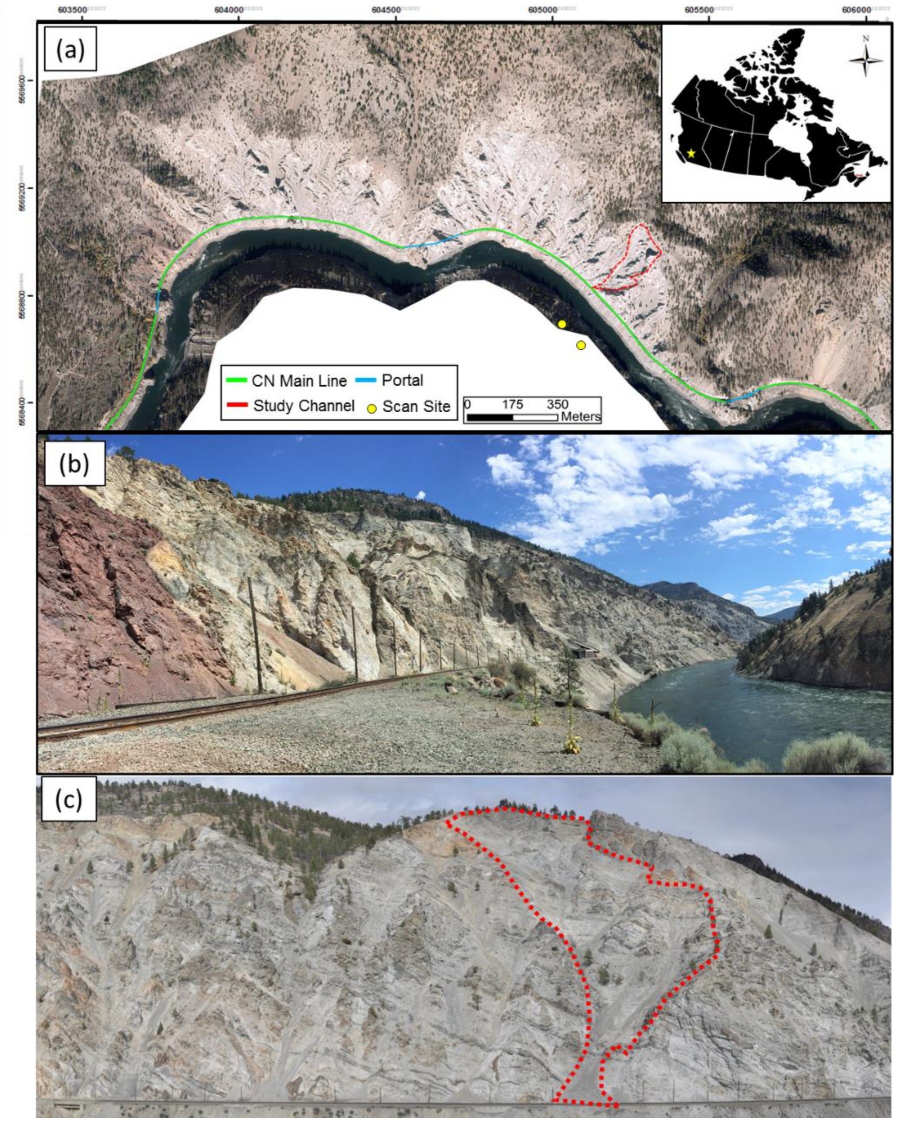

Fig. 1. (a) Map view of an October 2015 orthophoto of the White Canyon and location map; (b) August 2016 panoramic photograph taken from track level at the western end of the canyon displaying the complex morphology of the White Canyon; (c) April 27, 2017 photograph looking North across the Thompson River at the channel being analyzed in this study. The channel is highlighted in the red dashed line.

3. Methods

3.1. Remote sensing datasets

Terrestrial laser scans (TLS) were taken with an Optech Illris 3D-ER scanner. The Optech Illris is a time-of-flight terrestrial laser scanning system that utilizes a 1,535 nm (infrared) wavelength. The reported instrumental accuracy of the Optech Illris 3D-ER is 0.008 m in horizontal and vertical directions with a 0.007 m accuracy in range at a distance of 100 m (Optech, 2014).

For this study, seven TLS scans were taken approximately every two to three months from two scan positions across the Thompson River (Fig. 1A). These two scan positions were used for all TLS scan acquisitions. The baseline scan being taken in November 2014 and the last scan used in this study was taken in May 2016. All TLS scans, with an average point spacing of 10 cm, were first parsed using the Optech Parsing software. Once parsed, vegetation, slide-detector fences and mesh were all manually removed from the point clouds. After the scans were cleaned, they were aligned to the baseline scan using the Polyworks ImAlign module. The alignment process was completed in two steps; 1) a coarse point picking of common geometric features in each scan, and 2) an iterative closest point algorithm for fine alignment (Besl and McKay, 1992). The standard deviation for alignments varied from 0.018 to 0.025 in the summer months, and 0.035 to 0.05 m in the winter months. The higher standard deviations corresponded to the winter scans where there is a higher amount of humidity in the air and possibly water on the slope surface which have all been noted to influence the alignment process (Abellán et al., 2014). To compute the changes between sequential TLS scans, the limit of detectable change must be specified. The limit of detection (LOD) can be defined based on the registration error (Abellán et al., 2014). In this study, we take two times the standard deviation (95% confidence interval) of the registration error to define the LOD. This limit equates to approximately 5 cm in the summer months and 7 to 10 cm in the winter months. The higher limit of detection in the winter months correspond to a higher standard deviation in the registration error (alignment).

High-resolution digital images were taken with Nikon D800 and D7200 DSLR cameras. The DLSR cameras were mounted on a Gigapan robotic head and equipped with a Nikkor 135mm 2/f prime lens. For each TLS scan location, a swath of overlapping photographs were additionally captured using the described setup. After the photos were captured they were then stitched together using Gigapan Stitch software to generate high-resolution panoramic images. These panoramic images were used for verification of all changes seen in the change maps and visual inspection of the slope.

3.2. Debris monitoring methodology

Figure 2 displays a visual representation of the methodology developed. At Time 1 (T1), a preliminary TLS scan of the channel is completed. The volume of debris in the channel is at this point unknown. However, preliminary estimates of the volume of channel material can be made utilizing approaches developed by Jakob et al., (2005). Locations in the channel where debris is accumulating can also be documented from visual inspection of the panoramic imagery. Subsequently at T2, a debris flow has occurred and scoured the channel to bedrock at select locations along the channel length. With an additional TLS scan and panoramic imagery, the channel bed and geometry can be captured. Locations of exposed bedrock along the channel length are first confirmed with the panoramic imagery and theses locations within the TLS scans are stored to generate a bedrock baseline model of the channel. The orientations and spacing of discontinuities in the rockmass can be assessed using the TLS scan and panoramic imagery. The lithology of the channel bedrock can also be mapped from photographs. The areas of exposed bedrock within the channel serve as the baseline for subsequent monitoring. As time progresses (T3), the channel bed begins to recharge with debris from rockfall and rockslides. Debris from accumulations on benches moves into the main channel. When a scan taken at T3 is compared to the bedrock baseline model (T2), volume estimates demonstrate the spatial and temporal location of debris accumulating in the channel. These estimates are all confirmed with visual inspection of the panoramic imagery. Finally, a debris flow occurs at T4. Comparing a TLS scan captured after the debris flow to the bedrock baseline (T2) permits the calculation of the degree of entrainment and bedrock incision.

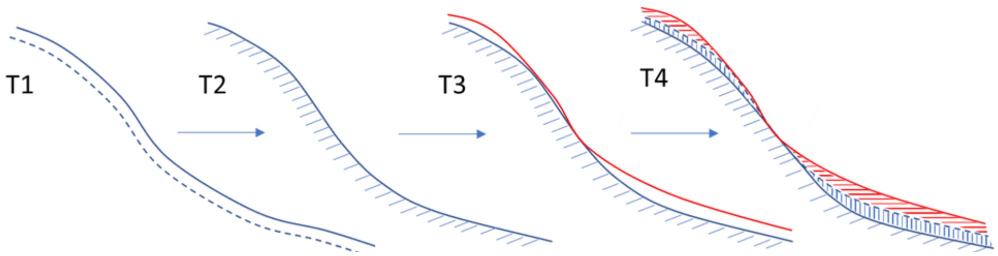

Fig. 2. Overview of the proposed recharge monitoring methodology. T1 – baseline scan of channel. T2 – debris flow has occurred and scoured channel to bedrock. T3 – channel begins to recharge from rockfall and rockslides. T4 – debris flow occurs. Using the T2 baseline, the degree of debris and bedrock incision can be calculated for T4.

3.3. Change detection methodology and volumetric analysis

Multiscale Model to Model Cloud Comparison (M3C2) (Lague et al., 2013), a vector-based change detection algorithm, was used for all change detection computations used in this study. M3C2 does not require mesh generation and operates directly on point clouds. For further details on M3C2, readers are referred to Lague et al. (2013).

All volume calculations were completed in CloudCompare. To compute the volume, CloudCompare first generates rasters in a user defined projection direction. After this process is completed, the contributions of each cell are summed together. The contribution is the volume corresponding to the cell footprint multiplied by the difference in heights between sequential 3D models. To calculate the volumes, areas of change, based on the limit of detection and confirmation of changes within the panoramic imagery, were first segmented out using the segmentation tool in CloudCompare. The area of change was translated to align with one of the principal axes of the scene orientation. This ensured that the projection direction would correspond to the change direction, to minimize the potential for over or underestimation of the volume.

4. Results and Discussion

Using the debris monitoring methodology and panoramic imagery described above, the spatial and temporal accumulation of debris was able to be monitored within the study period. Over the course of the study, two debris flows occurred which scoured the channel to bedrock in several locations along the channel length. These scour locations were confirmed with visual inspection of the panoramic photographs. The first debris-flow occurred between November 2014 and February 2015 (Fig. 3A) while the second event occurred between February 2016 and May 2016. The first debris flow had an estimated volume of approximately 135 m^3. The second debris flow had an estimated volume of approximately 120 m^3. Although these volumes are relatively small, they represent an operational challenge for CN with substantial financial repercussions for each hour the rail line is out of service. Both events deposited levees in some locations along the channel length. In addition, in-channel deposits were observed in the panoramic imagery in both events. Inspecting the levees of the debris-flow deposit in the panoramic imagery, the outer extents of the levees displayed a concentration of coarse clasts, where the orientation of apparent long-axis of some of the clasts, was parallel to flow direction. Both debris-flow events overwhelmed draped mesh, installed immediately upslope of the rail line, and filled the ditch adjacent to the rail line.

Between February 2015 (after the first debris flow) and February 2016, the channel was replenished with debris from rockfalls and granular flows which moved debris from directly below the cliffs into the channel. Several rockfalls were detected from the analysis of sequential scans leading up to the second debris-flow event. We estimated the calculated in-channel stored debris for each of the scan dates used in this analysis as shown in Fig 4. The maximum estimated volume accumulated prior to each debris flow event was approximately 150 m^3.

The channel can be classified as a weathering-limited system (supply-limited) following Jakob's (1996) definition. The definition indicates that a debris flow will occur when a precipitation threshold is exceeded provided sufficient debris is present in the channel. It should be noted that the intrinsic precipitation threshold is constant throughout time in Jakob’s model. Brayshaw and Hassan (2009) presented an updated model of sediment recharge, whereby the threshold value for debris-flow initiation is dependent on the volume of sediment in the gully channel, hence on sediment recharge rate and time since last debris flow. A debris flow occurrence resets the volume threshold value to a lower level. Volumetric analysis before and after each debris flow event can provide insight into the amount of material mobilized. However, the TLS scans were taken approximately every 3 months. As a result, we cannot assess whether any additional debris was deposited into the channel prior to the debris flow occurring. In addition, the volumes of material mobilized and deposited do not always match up, due to fact that CN removes debris that is deposited on the track to allow operation of the trains. Furthermore, the TLS scanning survey setup from across the river results in the occlusion of part of the ditch. Moving forward, a 4D monitoring system, which provides near real-time data, such as proposed by Cucchiaro et al. (2018) (SfM) or Kromer et al. (2017) (TLS), would provide great insight into the rate of debris accumulation. This would provide engineers with information about the volume of in-channel stored debris to permit forward modelling under a variety of different precipitation scenarios.

The temporal sampling interval has a significant influence on the amount of change detected (Fig. 3a & 3c.). If only the first and last scans are analyzed, the intermittent change that occurred between these dates is not detected and is overprinted by apparent larger scale movements within the debris (Fig. 3c). Change detection between the first and last scans, misses the second debris-flow event entirely. This has significant implications for assessing the return period and trying to establish a frequency-magnitude relationship for the channel (Jakob et al., 2016). Therefore, decreasing the time between scans should help refine the movements and recharge occurring in the channel.

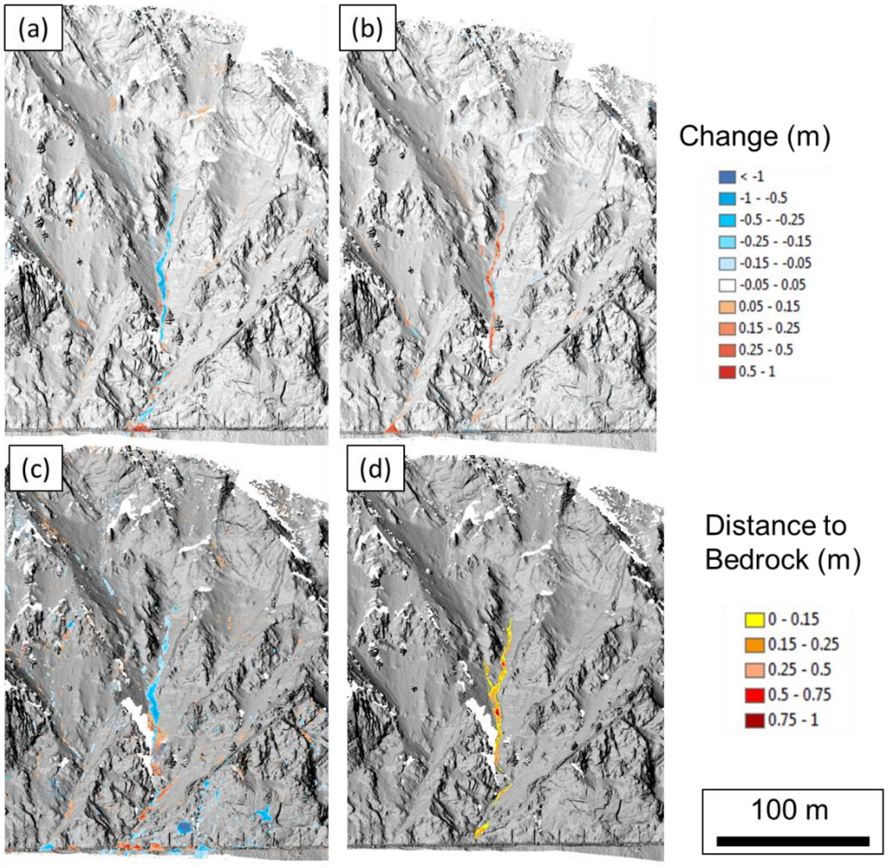

Fig. 3. (a) Change map between scans taken on November 4th, 2014 and February 18th, 2015; (b) Change map between scans taken on February 18th, 2015 and June 9th, 2015. Note that the levees have collapsed and the channel has begun to recharge; (c) Change map between scans taken on November 4th, 2014 (first scan) and May 6th, 2016; (d) Estimated spatial in-channel stored debris accumulation for the scan taken on June 9th, 2015.

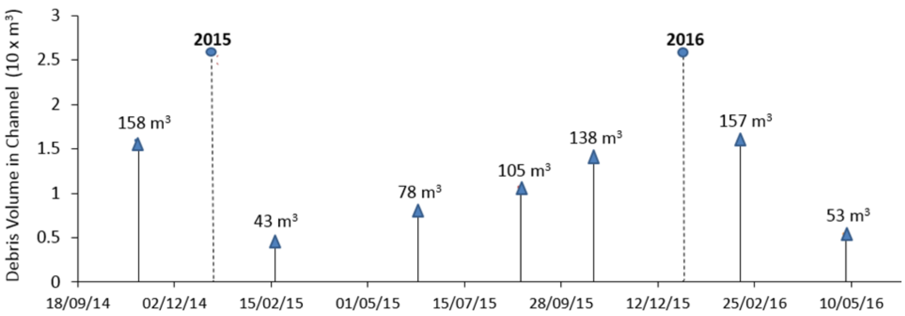

Fig. 4. Estimated in-channel stored debris volumes for each scan date. Volumes are measured using the proposed methodology.

5. Conclusions and Future Work

The use of remote sensing techniques, such as sequential TLS scanning and panoramic photography, offers the ability to document changes occurring on the slope over time, including the volume and size of material moving or accumulating and the time-period over which the activity is occurring. This study has demonstrated that terrestrial laser scanning can be implemented to successfully monitor the spatial and temporal accumulation of debris on a geometrically complex slope.

From an operational standpoint, the results of the current study can be integrated into engineering risk decision making for maintenance planning. The current study demonstrates the ability to document when, where and how much debris is stored in locations along the channel length. Integrating this knowledge into maintenance planning would allow operators to clear ditches or debris build-up behind draped mesh to ensure there is sufficient capacity for future debris-flows.

This study has demonstrated that the temporal data acquisition rate has a significant influence on the amount of movement that can be interpreted from the TLS change detection analysis and panoramic images. During larger scanning intervals, larger debris movements was shown to overprint smaller magnitude debris movements that are occurring in this active channel in the White Canyon. Therefore, the temporal acquisition interval is a component that must be considered when considering survey design for a monitoring program. More frequent scanning or moving towards a near real-time monitoring system is proposed to capture the timing of channel recharge to better establish if the selected channel follows Jakob's (1996) or Brayshaw and Hassan's (2009) debris recharge model. Furthermore, more frequent scanning would capture the small magnitude events which will help to refine the cumulative frequency magnitude curves that can be generated and, in turn, improve the design of mitigation measures.

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