Design of deflection berms for small post-wildfire debris flows

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ABSTRACT
Debris flow hazards are widely acknowledged to increase after a wildfire occurs in a watershed. This paper examines three small post-wildfire debris flows from June 2019 to illustrate how low-cost deflection berms can be designed using aerial imagery collected by a Remotely Piloted Aircraft System (RPAS). Structure-for-Motion photogrammetric software is used to generate a detailed topographic map of a fan along the Bonaparte River in BC. The detailed topography and orthomosaic created from the RPAS imagery are used to determine the optimum locations for deflection berms on the fan.

RÉSUMÉ
Il est reconnu à grande échelle que les risques de coulée de débris augmentent après un incendie de forêt dans un bassin versant. Cet article examine deux petits torrent de débris à partir de juin 2019 après un incendie de forêt pour illustrer comment des bermes de déviation de flux de débris à faible coût peuvent être conçues en utilisant des images aériennes collectées par un système d'aéronef piloté à distance (RPAS). Un logiciel photogrammétrique structure de motion est utilisé pour générer une carte topographique détaillée d'un éventail le long de la rivière Bonaparte en Colombie-Britannique. La topographie détaillée et l'orthomosaic créées à partir de l'imagerie RPAS sont utilisées pour déterminer les emplacements optimaux pour les bermes de déviation sur le cône alluvial.

1 INTRODUCTION

Wildfires impact the hydrologic responses of watersheds through alterations to soil surface infiltration and erodibility. High soil burn severity has been determined to decrease infiltration rates and increase erodibility (Debano et al. 1998). Changes to the soil surface contribute to the development of post-wildfire debris flows and debris floods through two primary processes (Canon and Gartner 2005). The most common initiation mechanism is runoff dominated erosion by surface overland flow, which is supported by the progressive downstream bulking of sediment and water. The second and less common post-wildfire debris flow initiation is triggered by infiltration and landslide mobilization. The largest events typically occur soon after the fire, but post-wildfire debris flows and debris floods may occur for several years until the soil surface returns to pre-fire conditions (Hope et al. 2015). Debris flows have also been generated in burned basins from response to increased runoff by water cascading over a bedrock cliff and incorporating material from readily erodible colluvium or channel bed (Parise and Canon 2012).

Many debris flows and floods occurred in 2018 and 2019 in the general area affected by the 190,000-hectare 2017 Elephant Hill wildfire in central BC (Fig. 1). Several important transportation corridors were disrupted by debris flows caused by the Elephant Hill wildfire. Debris and mud repetitively blocked sections of Highways 97 and 99, as well as other major roads in the burn area. Unfortunately, one person was killed, and many properties were damaged (Global News 2018, CBC News 2018, 100 Mile Free Press 2018).

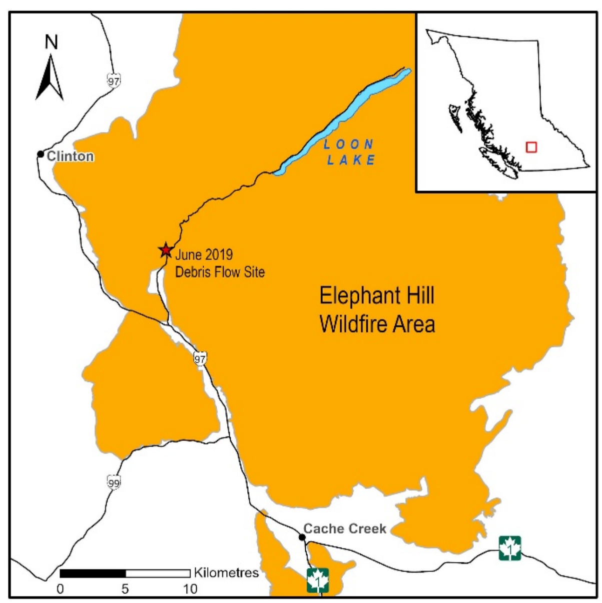

Figure 1. Area affected by the 2017 Elephant Hill wildfire and location of the study site along Loon Lake Road

This paper presents a case analysis of three small post-wildfire debris floods or debris flows that occurred on June 22, 2019. These originated in an area burned by the Elephant Hill wildfire. The surge of water and mobilized debris flowed across Loon Lake Road, blocked traffic and caused minor property damage.

The purpose of this paper is to illustrate the use of a Remotely Piloted Aircraft Systems (RPAS) for documenting the area affected by debris flows as well as aiding in the design of low-cost deflection berms to protect property and structures from small debris flows. The key input needed to design berms is the detailed topography of the depositional fans on which most structures are located. In many rural areas, the existing topographic maps do not have sufficient resolution, and lidar mapping is not available. The images acquired with the RPAS are used to create a detailed topographic map, digital surface model, and georeferenced orthomosaic.

2 JUNE 2019 LOON LAKE ROAD DEBRIS FLOWS

The owners of the house affected by the debris flows noted a period of intense rainfall immediately preceding the event. An examination of the Doppler weather radar history shows that the area first received a period of steady rain on June 20. Then on June 22, a series of localized intense convective rainstorms passed over the area between 12:00 and 16:30 PDT (Canadian Historical Weather Radar 2019). The convective rainstorms triggered three small debris flows or floods that travelled down adjacent gullies and across a sequence of depositional fans located along the Bonaparte River. The events had characteristics of both a debris flood and debris flow. For simplicity, they will be classified as debris flows in the remainder of this paper.

The finer fraction of the saturated material flowed down a driveway and across the property and around and beneath the main house. The road was cleared soon after the event occurred, and the debris was piled at a nearby location. The debris flows scoured new channels and deposited material on the fan. Immediately after the event, a sandbag barrier was placed along the driveway to protect buildings in response to fears of a repeat occurrence of a debris flow.

Figure 2 shows a contour map with the burn severity boundaries for the 2017 Elephant Hill wildfire. The burn severity map was obtained from the BC historical burn severity database (DataBC 2020). This figure also shows the inferred watershed boundaries for the three watercourses that were involved in the debris flows. The watershed boundaries and the watercourse locations were estimated using the topographic contours from the open-source 1:250,000 BC Digital Elevation Model (DEM) and Google Earth imagery. The flow of the Bonaparte River at the SE corner of the map is to the southwest. Interestingly, the watercourses to the NE and SW of those that experienced debris flows appear to have remained stable on June 22, even though they experienced similar wildfire damage in 2017 and had similar elevation changes and slope gradients. Their difference in geomorphic response to the precipitation may indicate that the convective rainstorm was highly concentrated over the small watersheds that experienced debris flows.

The wildfire in 2017 burned most of the valley side down to Loon Lake Road. Figure 3 shows a view of the watershed above the depositional fan near the bottom of the Bonaparte River valley. The burn severity was high to moderate in the upper watershed, where the forest was denser. The burn severity was low immediately above and on the depositional fan, where the terrain was covered by open forest and grasslands. It is likely that the overland flow initiated in the upper watershed where the burn severity was highest, while sediment bulking occurred lower in the watercourse. In particular, the addition of sediment to the flow may have occurred at lower elevations as runoff concentrated into rills and channels where colluvial material was readily available.

The lower flanks the Bonaparte valley side walls are covered with easily erodible glacial till and post-glacial colluvial materials (Plouffe 2009). The dark coloured fine-grained material on the edge of a poorly defined valley wall terrace seen in Figure 3 is believed to be a veneer of glacial till and the source for much of the materials that were mobilized in the debris flows. Outcrops of bedrock (Cache Creek Complex marine sedimentary and volcanic rock: undivided phyllite, siliceous phyllite, ribbon and massive chert, argillite, tuff, mafic volcanic rocks, serpentinite, limestone, sandstone, conglomerate) are present along and between the watercourses (Schiarizza et al. 1994).

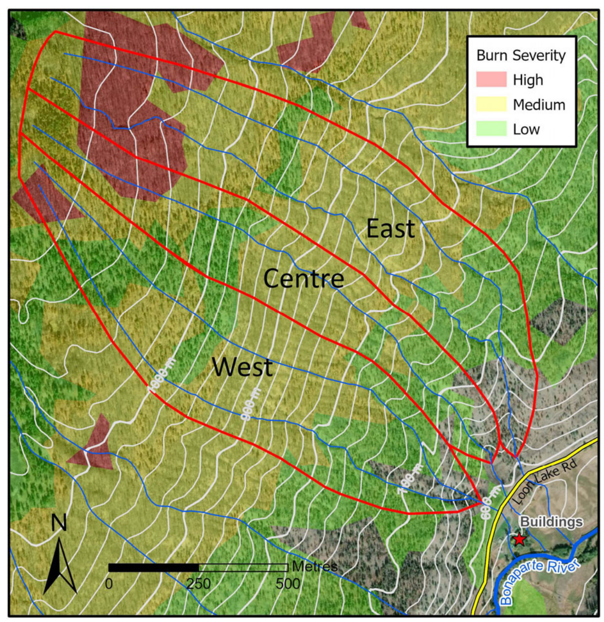

Figure 2. Burn severity map at the debris flow site and the three small watersheds

Figure 3. View of the burnt upper watershed looking up the west debris flow channel taken 2 years after the fire

A profile of the centre watercourse involved in the event is shown in Figure 4. The profiles for the other watercourses were similar. The gradient of the middle reaches is approximately 20°. Immediately above the valley bottom depositional fan, the channel gradients are highest where each channel has cut through a terrace flanking the lower sides of the Bonaparte River valley. The characteristics of the three watersheds are listed in Table 1. Based on watershed morphometric research by Wilford et al. (2004) and Holm et al. (2016), each small watershed was a likely candidate for a debris flow because the Melton ratio was higher than 0.5 to 0.6.

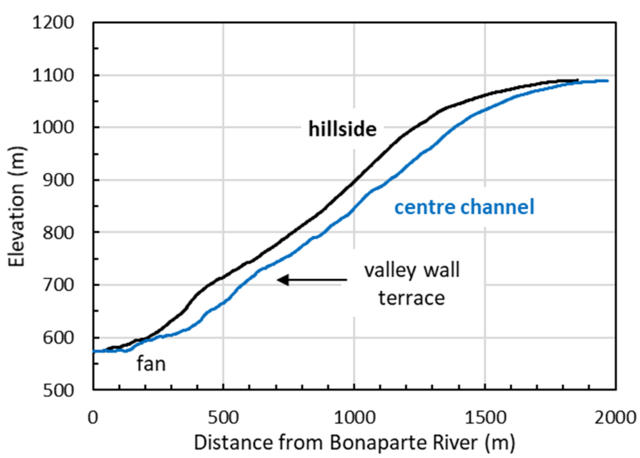

Figure 4. Profiles of the centre watercourse channel and the adjacent hillside (2X vertical exaggeration)

Figures 5 and 6 show the west and centre flow paths viewed looking upstream from Loon Lake Road toward the fan apex. The transported debris was dominated by soils with particle sizes less than 1 cm, although occasional cobbles and small boulders were also present in the debris. These channels only experience flow during high precipitation events or snow-melt. The flows on June 22 were significantly larger than what had been recently experienced. While there was no evidence of prior post-wildfire debris flows, smaller events could have been hidden by new vegetation and the reworking of sediment caused by the June 22, 2019 flows.

Table 1. Watershed characteristics

	West	Centre	East
Watershed length, L (km)	1.64	1.65	1.90
Watershed area, A (km^2)	0.443	0.291	0.478
Watershed relief, R (km)	0.491	0.493	0.495
Melton ratio	0.738	0.915	0.716
Relief ratio	0.299	0.299	0.260

Melton ratio = R/√A (Melton 1957, Patton and Baker 1976, Jackson et al. 1987)
Relief ratio = R/L (Strahler 1958, Costa 1988)

Figure 5. West channel looking upstream toward the fan apex from Loon Lake Road

Figure 6. Centre channel looking upstream above Loon Lake Road toward the fan apex

3 FIELDWORK

In sparsely vegetated areas such as rock slopes and debris fans, a Remotely Piloted Aircraft System (RPAS) is an excellent tool to capture topographic features on the ground (Tannant 2015, Barnhardt et al. 2019). The property owners were interviewed on June 25. With their permission, the area was flown with an RPAS the following day (four days after the event) to collect aerial images of the alluvial fan and debris flow paths. A DJI Phantom 4 Pro RTK was used along with a DJI D-RTK 2 GNSS mobile base station to enable post-processing of the RPAS camera coordinates for each image. A morning flight time was selected to take advantage of the eastward facing slopes, the sun angle, and the increased likelihood of low wind speeds. Two grid patterns were flown, and a series of oblique images were collected with a separate free flight. No ground control points were used on the depositional fan.

The grid flights acquired 224 images with an approximate 80% forward and 70% side overlap of the flight lines. The RPAS was set to fly at a speed of 3.5 m/s to minimize blur in the images. The first grid pattern was flown parallel to the contours on the fan and Loon Lake Road, starting near the bottom of the fan near the Bonaparte River and extending up to Loon Lake Road. The second grid pattern was flown at a higher altitude to capture the upper part of the fan. The camera was approximately 50 m above the ground for both grid patterns. Oblique images taken during a subsequent free flight captured the lower gullies and watercourses entering the fan apex.

The total length of time to conduct the RPAS survey and ground investigations of the fan, including set-up and takedown, was approximately two hours.

4 IMAGE PROCESSING

The GNSS observation file (rinex data) stored onboard the RPAS was processed using the Natural Resources Canada Precise Point Positioning (PPP) tool (NRC 2020). In-house software and a custom-designed workflow were used to handle systematic formatting errors in the rinex file, and to create a list of corrected UTM coordinates for the precise camera location for every image collected in the grid patterns. The Canadian Spatial Reference System (NAD83) with a CGVD2013 vertical reference system was used for the coordinate system. Obtaining the precise camera locations eliminated the need for ground control targets, although, for redundancy and precision checking, ground control should still be used.

The images and the list of their corrected UTM coordinates were loading into the Structure-from-Motion (SfM) software Pix4D. The camera coordinates recorded in the EXIF header for each image were not used when processing the images. The SfM software was used to generate a dense 3D point cloud and a georeferenced orthomosaic of the fan area (Fig. 7). To create a bare-earth terrain model, it is necessary to disable points representing high vegetation and other objects within the point cloud. This was done by manually selecting these points and disabling them as there were few trees and buildings captured in the point cloud. As an alternative, automatic point cloud classification methods could be used, but it takes significant effort to calibrate the optimal parameters (Asghar and Tannant 2018). The bare earth model (digital surface model) was then used to create a detailed contour map of the fan with a 0.5 m contour interval (Fig. 8).

Figure 7. Orthomosaic of the debris flow site

5 FAN TOPOGRAPHY AND DEBRIS FLOW PATHS

The orthomosaic (3D geotiff format) and the contour map created from the SfM processing of the aerial images were used to map the paths of the debris flows. Loon Lake Road and smaller roads accessing the buildings and nearby agricultural land have influenced the natural topography and flow patterns across the fan.

Figure 8 shows the results of the mapping overlaid on a contour map with the orthomosaic removed for clarity. The depositional fans coalesce near the bottom of the three watercourses. The house and other structures were built on a fluvial terrace along the Bonaparte River. The depositional fan above Loon Lake Road has a slope of approximately 10°.

There is a significant gradation change at the boundary between the Bonaparte River valley wall and the fan. The steepest sections occur immediately upslope of the fan apexes, which suggests that debris flow velocity was highest shortly before encountering the fan. Out-of-channel deposition on the fan began once each debris flow exited a steep, confined gully, and the flow's kinetic energy was lost.

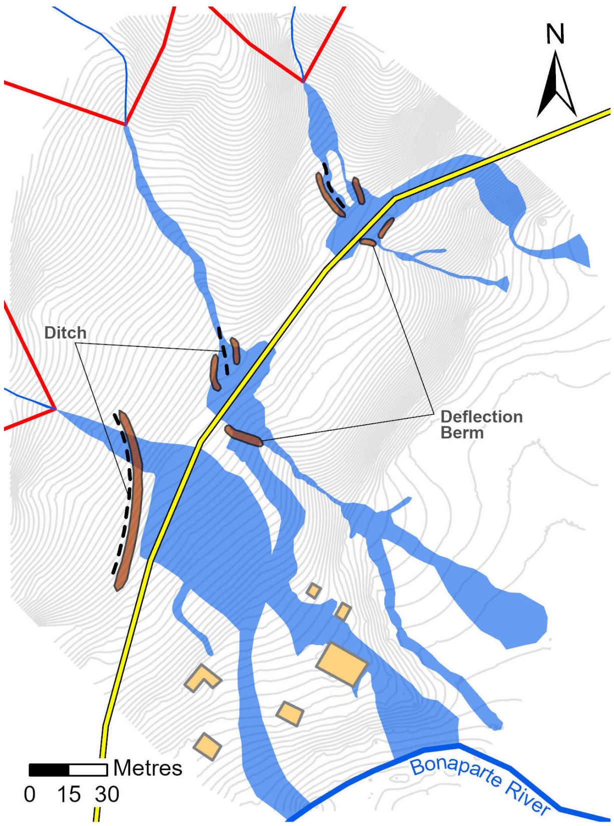

Figure 8. 2019 debris flow paths (blue shaded areas), contours (0.5 m intervals) and proposed locations of deflection berms and small ditches

6 DEBRIS FLOW DEFLECTION BERMS

The orthomosaic and the 0.5-metre contour map were used to determine effective locations for potential deflection berms to protect the buildings below Loon Lake Road from future debris flows in the same watersheds. A deflection berm is designed to direct hazardous flows away from important structures on the fan and direct the flow to an area that does not contain elements at risk. Unlike a catchment basin, a deflection berm is not designed to stop or retain the debris flow.

The challenge with debris flows at this site is the presence of Loon Lake Road. There are no culverts beneath the road in the fan area, and culverts will likely never be installed. The cleanup of the 2019 debris resulted in the creation of a small shallow ditch along the northwest side of the road. The road slopes downwards in opposite directions from where the debris flows have crossed the road. The suggested strategy is to use small deflection berms and ditches to direct future debris that travels as far as Loon Lake Road into existing natural gullies and away from the property. Except at the western fan, the debris flows would once again cross Loon Lake Road. However, berms and ditches would guide the flow into narrower paths that would prevent the lateral spreading of the debris before encountering the road. Material is intercepted by small berms on the southeast side of the road and directed into natural gullies. Compared to the 2019 event, the narrower flow path would result in a smaller volume of debris deposited on Loon Lake Road and no debris deposited on the main driveway or around the buildings.

Figure 8 shows the suggested locations for small deflection berms and ditches. These structures would be roughly 0.5 to 1 m high with a 1 m top width and 1.5H:1V side slopes. They could be built from locally available material on the fan, including the soil excavated to build ditches. Ideally, the side of the deflection berm facing a potential debris flow would be steeper and armoured with boulders. But in this case, the berms would be placed far enough from the fan apex such that a future debris flow would have low velocity and erosive capability once it reached the berms. Thus, the berms can be protected by a vegetated cover of grasses and shrubs. A shallow (0.5 m deep) ditch should also be used in combination with the deflection berms upslope of the road.

The deflection berms and ditches at the east and centre channel are designed to guide and funnel the debris flows across the road and directly into small gullies minimizing the spread of debris across the road and preventing travel along paths that might impact structures. The deflection berm on the west channel would be the longest, as it is placed to guide potential debris flows diagonally across the fan towards a ditch that runs southwards along the west side of the road, thereby avoiding the driveway and buildings on the fan.

If small deflection berms had been present on the fan before the 2019 debris flows, they could have guided the flows to more defined crossing locations on Loon Lake Road such that the debris would have continued down small gullies and avoided wrecking the lawn and driveways on the property. The suggested sites for the deflection berms would significantly decrease the debris flow risk for infrastructure developed on the fan, while minimally disturbing the access roads to the existing buildings and fields. This paper does not cover the details for the structural design of deflection berms. A berm design is largely based on estimates of event magnitude, run-up height and debris velocity (Prochaska et al. 2008). Deflection berms are typically over-engineered to ensure high factors of safety with excess freeboard, in the case a debris event occurs larger than anticipated.

7 CONCLUSION

Properties on valley-bottom alluvial fans can deploy RPAS to map and measure the fan geometry and topography in great detail. These data can then be used to proactively mitigate against debris flow hazards via predicting debris flow paths and designing protective structures. As wildfires and climate change become more common, people living on fans will need low cost and robust methods to protect their property. In some cases, little more is needed than small berms and ditches on the fan to direct debris flows away from important structures.

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