The Johnsons Landing Landslide of 2012 – Five years of monitoring post-failure activity

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ABSTRACT
The Johnsons Landing landslide of 2012 was a large debris avalanche that destroyed several homes and caused four fatalities in the Kootenay Lake area of British Columbia. The investigation that followed examined several aspects of the event including possible triggers and hazard analysis. Based on the recommendations of this investigation, monitoring of a potentially unstable area above the main landslide scarp was undertaken to determine the potential for a subsequent failure. The five years of monitoring results show ongoing minor downslope movement of an unstable mass above the main landside scarp. These observations may reflect the settling of the unstable mass, which would be expected to diminish with time. A challenging question is how to integrate these five years of monitoring data with the initial hazard estimates and effectively communicate the results to the public.

RÉSUMÉ
En 2012, une avalanche de débris de grande taille a détruit plusieurs maisons et causa le décès de quatre personnes à Johnsons Landing dans la région de Kootenay Lake en Colombie-Britannique. L'étude qui a suivit la catastrophe a examiné les possibles mécanismes déclencheurs du glissement de terrain et a mené une analyse des probabilités d'occurrence d'un événement de cette magnitude. En se basant sur les recommandations de l'étude, un programme d'échantillonnage des zones potentiellement instables au dessus de la fissure principale a été mené afin d'évaluer la possibilité d'une future avalanche de débris. Les cinq années d'échantillonnage ont montré le mouvement continu vers le bas de la pente d'une masse de sol localisée au dessus de la zone de décrochement principale. Ces observations peuvent être le reflet de la lente stabilisation de la masse de sol, un processus qui devrait s'estomper au cours du temps. La présente étude se pose la complexe question de comment réussir à intégrer les cinq années de données dans l'estimation des risques à l'origine de l'avalanche de débris ainsi que comment efficacement informer le publique de ces résultats.

1 INTRODUCTION

In July 2012 a large landslide occurred on the mountainside above Johnsons Landing, a small community in the West Kootenay region of British Columbia (Figure 1). Four houses were destroyed and two others damaged, and four people were killed in their homes. In terms of loss of life, this was the most devastating landslide incident to occur in western Canada since the 1980s.

A detailed investigation was commissioned by local government (funded by the provincial government through Emergency Management BC), and was completed by a team of engineers and geoscientists that included consultants and provincial government employees. The objectives of the study were to investigate the causes of the landslide, analyse the hazard and risk of further landslides and produce a map showing hazard zones. Following the completion of the investigation, a report was published, which is available to the public through the Regional District of Central Kootenay (Nicol et al. 2013).

The causes and behaviour of the landslide were described in a paper at the Geohazards 6 conference in 2014 (Jordan 2014). One of the recommendations from the initial investigation was to establish a simple landslide monitoring program to provide further information on the hazard. This paper will focus on the results of this monitoring program five years on, and report on further investigations into the causes and mechanism of the failure.

2 LANDSLIDE INVESTIGATION

The landslide occurred suddenly in the morning of July 12, 2012, and involved a total volume estimated at 320,000 m^3. It originated as a sudden failure in a deep deposit of glacial till and colluvium at 1050 to 1250 m elevation, and is classified as a rapid debris avalanche (Hungr et al. 2001). It descended the channel of Gar Creek, a steep narrow valley which occasionally carries small debris flows and snow avalanches (Figures 2 and 3). About half of the debris travelled up and over a low ridge at a bend in the creek 1.5 km from the initiation area, and spread out over a terrace at 690 to 740 m elevation which was occupied by forest, cultivated land, and houses. Less than 5% of the debris continued flowing down the narrow creek channel as a debris flow, inundating a portion of the alluvial fan of Gar Creek at 535 m elevation. Approximately 24 hours after the first landslide and debris flow, a second larger debris flow occurred, which originated from an area near the landslide source area and entrained loose landslide debris in the channel. It descended the full length of the Gar Creek channel, destroying an already damaged house on the fan.

The area most seriously affected, and where the fatalities occurred, was on a bench well above nearby stream channels in an area believed by both residents and expert terrain mappers to be not at risk from landslides, flooding, or other natural hazards.

In the investigation that followed, questions that were addressed included:

- Why and how did such a large landslide occur at a site with no history of previous landslide activity?
- What were the causes and triggering factors of the initial failure?
- Why and how did the landslide rise over the ridge (location b on Figure 2)?
- What is the likelihood of future large failures on this slope?
- If further landslides were to occur, what areas downslope might be at risk?

The landslide investigation included the acquisition of LiDAR imagery, which proved extremely useful for interpreting terrain features in this heavily forested area, and for preparing detailed maps for field work. Field work was conducted in September, when the site was deemed safe to work on. Field work and subsequent analysis included describing and sampling the landslide materials, estimating source area and deposit depth and volumes, and estimating landslide velocity. The investigation also included runout modeling by UBC landslide specialists.

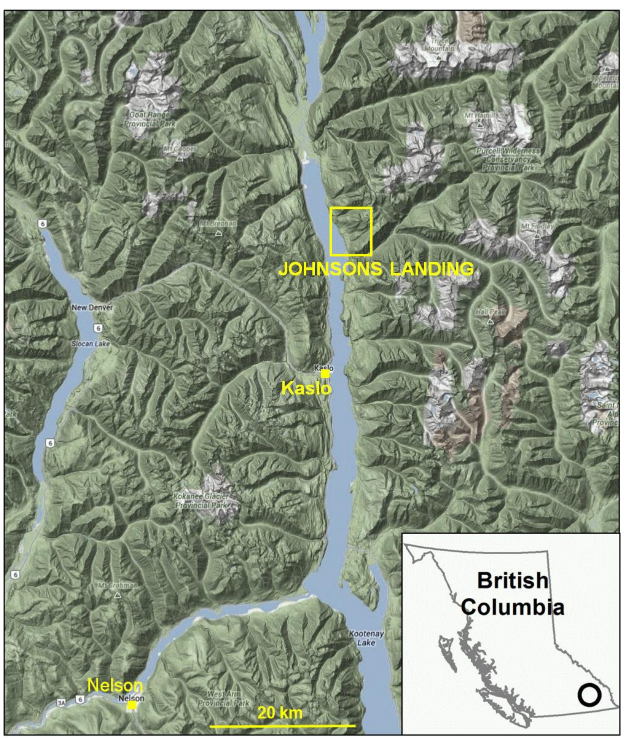

Figure 1. Map showing the location of Johnsons Landing at the north end of Kootenay Lake.

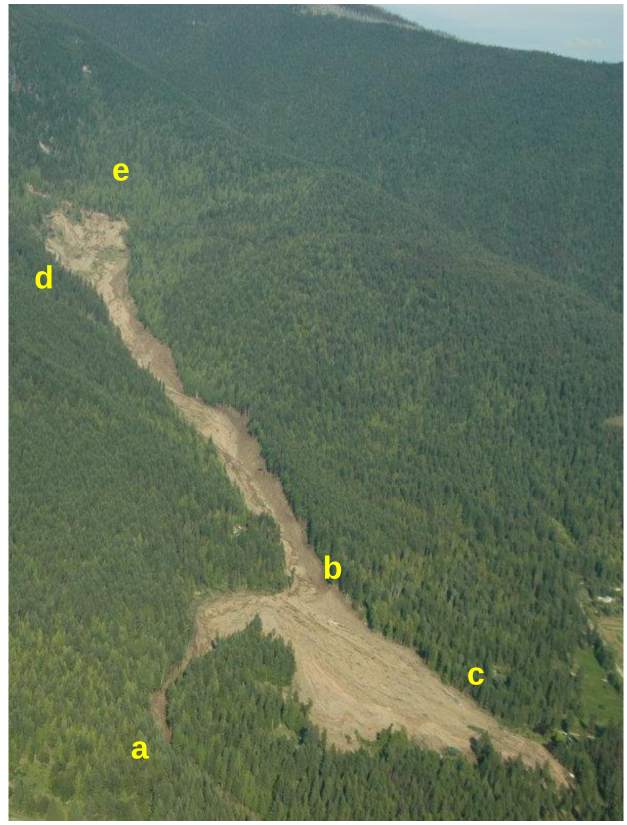

Figure 2. Photo of the landslide from the air, taken about 6 hours after it occurred. a – canyon with secondary debris flow; b – bend in channel and low ridge; c – bench where houses were destroyed; d – landslide headscarp; e – potentially unstable area with monitoring installations.

2.1 Landslide Characteristics and Physical Environment

The source area of the landslide was found to consist entirely of unconsolidated sediment of morainal, glaciofluvial, and colluvial origin. These deep glacial deposits form an irregular, gently-sloping (20-40%) terrace in the middle part of the Gar Creek valley. The glacial deposits at the main scarp largely consist of till and glaciofluvial sediments of predominantly silty sand loam texture, with roughly 50% gravel (SM and GM). The loose to compact deposits show some weak stratification and do not appear to be over-consolidated, and they are non-cohesive and non-plastic. The sediments in the main scarp area are typical of kame deposits, which are mixed glacial till, glaciofluvial sand and gravel, and colluvial material, which typically form along valley sides and in tributary valleys alongside retreating glacial ice. The silty sand texture of the glacial sediments reflects the sedimentary rocks of the area (phyllite, schist, quartzite, and limestone), and is typical of soils of glacial origin in this region.

The landslide source area is heavily forested. Other than some selective horse logging 50 to 100 years ago, there has been no industrial development in the area. An old road built for fire fighting access is nearby, but had no

Figure 3. Orthophoto showing Johnsons Landing and the July 12, 2012, landslide. See Figure 4 for enlargement of the headscarp area. (Regional District of Central Kootenay orthophoto.)

apparent effect on the landslide.

The landslide appears to have originated in the southern part of the source area, where the main scarp is about 10 to 15 m high. The landslide gained speed rapidly, and climbed about 30 m up the opposite valley wall. It then continued at high speed down the valley, climbing up the alternate valley walls three more times, with superelevations of 15 to 25 m. In the lower part of the valley, it straightened out, although still travelling at high speed with a depth of about 13 m.

At location b (Figure 2), there is a sharp right bend (about 70°) and widening in the valley, below which the creek enters a narrow canyon incised into the deep glaciofluvial and morainal deposits of the Johnsons Landing bench. At this location, most of the landslide debris climbed 10 to 25 m onto a ridge, with enough speed to overtop it, and then spread out onto the bench to the southwest, where the homes were located. Debris filled the bend area to a probable thickness of 5 to 10 m. From photos taken soon after the event, and from later ground observations, a possible temporary blockage of trees formed at the head of the canyon, and this may have helped to divert most of the subsequent debris over the ridge and onto the bench. The blockage then broke, sending a debris flow which contained a large proportion of trees down the canyon to the Gar Creek fan.

Most of the landslide volume originated from the immediate source area. Erosion and entrainment of debris along the Gar Creek valley appears to be limited to the loose soil at the rooting depth of the forest, which is typically under 1 m. It is estimated that about 10,000 m^3 of trees were included in the landslide. Many of these trees were deposited in the lower channel and on the fan by the first debris flow, and were carried into Kootenay Lake by the second debris flow.

From eyewitness descriptions and the superelevation magnitudes, the landslide velocity down the channel is estimated at 90 to 120 km/h (25 to 33 m/s) with a reduced speed as it flowed onto the Johnsons Landing bench. Although the landslide was described by eyewitnesses as a single event which lasted less than a minute, there is some evidence from the deposits that it may have been a more complex event with several surges of debris, maybe only seconds apart. A substantial amount of debris was deposited in a wide part of the upper channel.

Above the main scarp, a prominent feature is a large block of more-or-less intact glacial deposits (Figure 4) which dropped down about 20 m and then stopped. It may have been arrested by a bedrock outcrop visible below the main scarp. During the search operations, there was concern that this block could fail; however, no further movement occurred. The failure plane of the landslide could not be directly observed, as it was covered by trees and loose debris which had dropped down from the scarp. Significant water was observed at the landslide scarps a week after the event; in particular, seeping from the upper scarp located above the dropped block, and from several springs within the scarp area.

2.2 Landslide Triggering Factors

The investigation suggested that the main triggering factor for the Johnsons Landing landslide was elevated groundwater levels caused by the exceptionally high rainfall in June 2012, as well as by above-average snowpack and late snowmelt. In 2012 the June rainfall set many records in the West Kootenays, including a new

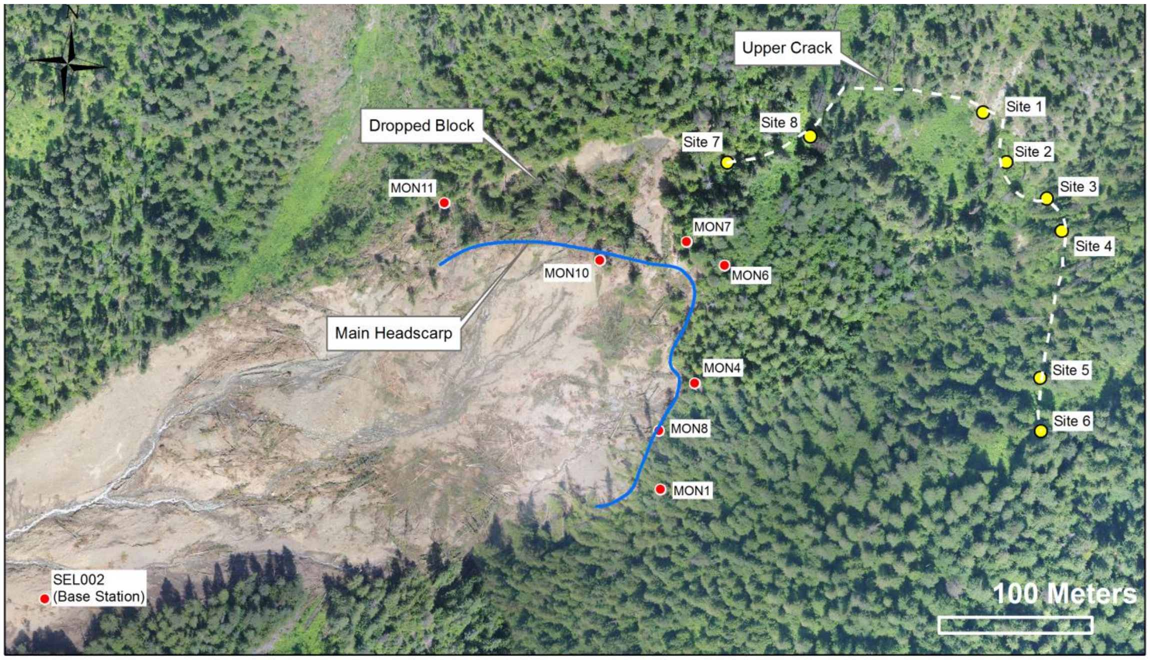

Figure 4. Orthophoto of the landslide source area showing the main scarp, dropped block and upper crack. Stake measurement sites (Site 1 through Site 8) and the survey reflector sites (MON1 through MON11) are labelled. The site from which the survey reflector measurements were made is SEL002.

record for precipitation for any month in the nearby Village of Kaslo which has 105 years of record.

Gar Creek is groundwater-fed, and is known to respond slowly to snowmelt and rainfall compared with other streams in the area. Karst aquifers in the mountains to the east and north may also contribute to the streamflow. When the slide occurred in early July, there was no snow remaining in the Gar Creek watershed and the weather was clear and hot. The springs that were observed flowing out of the landslide source area immediately after the slide suggest that high groundwater levels were likely the main triggering factor. The high groundwater levels in early July may have been a delayed response to the June snowmelt and rain or possibly snowmelt runoff contributions through the karst aquifers from nearby higher-elevation watersheds.

The geotechnical factors that contributed to the instability of the landslide source area are not well understood. A complex of inactive or slow-moving bedrock failures was identified east of the landslide through the LiDAR imagery and field traverses. The age of these features is unknown, although there is no evidence of recent movement over the past 1000 years or so. The investigation report hypothesized that the movement of the bedrock failure may have placed stress on and deformed the thick glacial deposits in which the failure occurred.

2.3 Hazard Analysis

A continuous crack, approximately 400 m long with visible displacements of up to 4 m, was identified 200 m above the main scarp (Figure 4). The surface area bounded by the crack and the main scarp below is about 6.4 hectares. The depth to bedrock is unknown and the average depth of a potential failure surface is uncertain. However, lower and upper bounds of the volume of this unstable area can be estimated by assuming its depth varies from 1 to 5 m at the crack, to 8 to 12 m at the main scarp.

Topographic cross-sections and limit equilibrium analysis were used to estimate the pore water pressures that could result in failure of various parts of the potentially unstable volume. Corresponding return periods were assigned by judgment and consensus amongst the four authors of the report (Table 1). These return periods (or annual likelihoods of occurrence) are subjective probabilities and are very approximate.

To estimate the potential run-out distances and deposit thickness for these potential events, landslide runout modeling was done by the Department of Earth and Ocean Sciences at the University of British Columbia. Two landslide run-out models were utilized, DAN-W and DAN-3D (Hungr 1995; McDougall and Hungr 2004; Hungr & McDougall 2009). The inputs to the model include basal shear resistance parameters that can only be determined through empirical means. To determine these parameters, a back analysis of the landslide event was undertaken. This back analysis provided the calibrated parameters used for the forward analysis. Both DAN-W and DAN-3D were used in order to exploit the strengths and weaknesses of both models.

It was noted that DAN-3D had difficulties in reproducing the overtopping of the channel at the bend of Gar Creek. This is likely due to a combination of two factors. It is hypothesized that a channel obstruction composed of timber at the flow front developed during the debris avalanche, which caused most of the debris to be diverted onto the bench. Also, DAN-3D explicitly neglects

Table 1. Estimates of future landslide magnitude and probability.

Likelihood of Landslide Occurrence per year	Landslide Magnitude (m^3)	Description
0.01 (1:100)	100,000	Failure of dropped block and adjacent oversteepened upper scarp
0.001 (1:1000)	300,000	This is the estimated volume represented by failure of the dropped block and retrogression of the upper scarp, with a groundwater level slightly higher than in 2012. This volume is similar to the 2012 event.
0.0001 (1:10,000)	500,000	Representative of failure of most of the potentially unstable volume, which would require substantially higher pore water pressures than the 1:1000 case.
0.00001 (1:100,000)	900,000	This represents the failure of the maximum feasible estimate of the potentially unstable volume under extremely unlikely pore water pressure conditions.

lateral shear strength, and it is likely that significant lateral shear stresses developed when the flow reached the sharp bend. With the inclusion of a channel obstruction it was possible to achieve reasonable results using DAN-3D; however both the volume and geometry of this obstruction are assumed parameters.

The DAN-W back analysis determined that there are two sets of parameters that are able to reproduce the bulk characteristics of the July 12th landslide. One set of parameters uses only one rheology to model the channel and debris field, an approach consistent with past analyses undertaken with DAN-W. The other set of parameters uses two flow rheologies, one to simulate the channel and another to simulate the debris field where basal resistance was expected to be higher due to the fact that it is mostly forested. Both sets of parameters were able to reproduce the run-out, duration, velocities and debris field volume observed during the event.

The back analysis conducted using DAN-3D determined that only a two-rheology set of parameters could reasonably reproduce the bulk landslide characteristics of the event. This back analysis did not predict that any material would deposit in the upper channel; however, using an assumed channel blockage, the back analyzed volume deposited on the Johnsons Landing bench was relatively close to the measured volume. The duration, velocities and 3-D debris deposit shape of the event were well predicted.

Several forward analyses were conducted, corresponding to the range of possible initiation volumes of a future event. These were used to prepare a hazard map, showing areas that could potentially be inundated by future landslide events with various annual probabilities. Table 1 shows the estimated source area volumes and likelihoods, as determined by the 2012 analyses. The results of the monitoring program described below may help evaluate whether these estimates are realistic and enable a revised hazard map to be prepared in the future.

3 MONITORING PROGRAM

The slope features adjacent and upslope of the 2012 landslide source area are shown on Figure 4. A potentially unstable area above the main scarp was identified during the initial investigation. The upper crack and main scarp have been the focus of the monitoring activities over the past five years.

The landslide monitoring program that was implemented involves site observations of new signs of instability (e.g. tension cracks, shear zones, scarps), repeated photographs of the main scarp, the manual measurement of displacement at the upper crack, and surveying reflectors located on the main headscarp.

Eight measurement sites are located along the upper crack that bounds the top edge of the potentially unstable area (Sites 1 through 8 in Figure 4). One of these sites (Site 1) is a line of 6 metal pins, with the top pin drilled into bedrock above the crack. The other sites consist of two or three wooden stakes driven into soil above and below the crack. The distance between the stakes is measured manually with a tape measure three times a year in spring, summer, and fall. One limitation to this method is that the displacement value measured between the two stakes is the total 3-dimensional movement, and is not broken down into x, y and z components. Another limitation is that the wooden stakes are susceptible to damage from freezing, snow load, and soil movement.

Survey reflectors were installed on the rim of the main headscarp in 2014 to provide an additional method of measuring movement of the potentially unstable area. The reflectors have been measured once a year in the fall from 2014 through 2017. A Topcon IS-303 total station was used to measure from a base station to the reflectors, which is an average distance of about 400 m. The instrument error at 400 m includes both a 6 mm angular resolution as well as a distance accuracy of approximately 3 mm. One possible source of error is that the reflectors were installed on trees instead of an anchored stationary structure. Another error is the pointing repeatability as some targets are barely visible from the measurement station. The survey company (Sproulers' Enterprises Limited) estimates that the accuracy of the measurements is likely several centimetres. Unfortunately a closer base station is not feasible given the layout of the site.

4 MONITORING RESULTS

Other than minor sloughing at the main headscarp, no additional visual indicators of instability such as new tension cracks or scarps have been observed over the past five years. Seepage from the landslide source area has been occasionally observed in the springtime; however, there has been no evidence of substantial flow from this area that would compare in magnitude to the flow rate from the springs observed immediately after the slide in 2012.

Over the past five years residents have reported several times that Gar Creek was running dirty and were concerned about possible instability at the headscarp. After investigating the reports, it was determined that on all occasions the sediment was not from the landslide source area or headscarp, but instead originated from either from a bank failure that temporarily blocked the creek or the diversion of the creek channel through exposed sediment. Ongoing turbidity events are probable in years to come because the landslide path continues to be mostly unvegetated.

The measurement of the displacement of the upper crack over the past five years shows systematic, progressive movement at several locations at the apex of the tension crack, but limited or no movement towards the outer edges. The first year after the slide, displacement along the apex of the upper crack was 40 to 60 cm, although over the subsequent four years the annual displacement has been less. Sites 5 and 6 located near the southern end of the upper crack have shown virtually no displacement. Sites 7 and 8 on the north end of the crack have shown some minor annual displacement ranging from 0 to 20 cm depending on the year. While the stakes at Sites 2 and 3 have been destroyed by falling rocks or snowload, Sites 1 and 4 near the apex of the upper crack exhibit ongoing annual displacements in the range of 3 to 30 cm over the past four years (Figure 5).

The displacement measured at the upper crack has generally diminished each year until 2017. While 2017 was not a particularly wet spring, increased displacement was measured at both Sites 1 and 4. Over the last five years, the snowpack and spring precipitation in the West Kootenays has been much closer to normal than in 2012. Figure 6 shows a record of monthly spring (April to June) precipitation in Kaslo combined with the snow water equivalent (SWE) on April 1 at the Upper Gray Creek manual snow measurement site. Although the data only span five years, the pattern of wet and dry years does not seem to correspond to increased or decreased displacement at the upper crack. For example, 2016 was wetter than 2017, yet the crack displacement in 2017 was higher.

The spatial and temporal pattern of movement of the surveyed reflectors along the headscarp rim indicates that there has been some minor westerly movement of the headscarp over the past four years. The survey data show that since 2014 the reflectors along the main scarp (MON 1, 4, 6, 7, 8) have moved 7 to 14 cm in two dimensions (Figure 7). The majority of the movement has been in the negative x-direction (i.e. downslope and perpendicular to the headscarp). The movement in the z direction is negligible within the measurement error and shows no overall pattern. Figure 8 is a spatial representation of the magnitude and direction of movement at all sites. The total two-dimensional movement along the main scarp corresponds to an annual displacement of approximately 2.5 to 4.5 cm per year. Less two-dimensional movement was observed at the reflector at MON10 which is located on the dropped block, and no movement (within measurement error) was observed at MON11, which is located on stable ground outside the landslide source area.

It is difficult to have confidence in the precise annual displacement values because of various sources of error inherent in the surveying methods. However, the consistency in the pattern of movement over the past four years does provide some assurance that the measured displacements reflect real movement. In all years and at all reflectors along the main headscarp, the movement in the x-direction was negative (i.e. downslope). Furthermore, where no movement was expected (for example at site MON11 and in the z-direction), no displacement was measured outside the estimated uncertainty. As such, given that the survey measurements

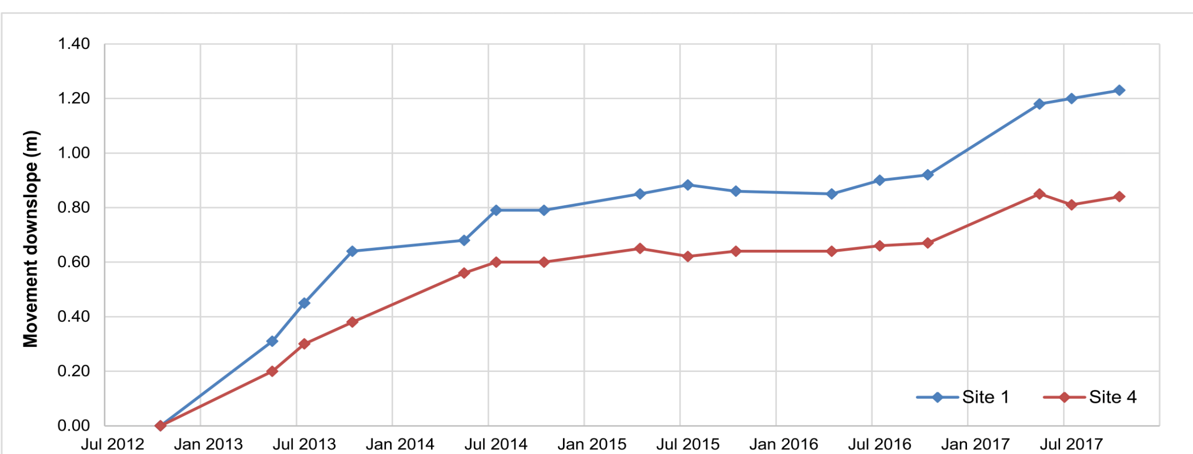

Figure 5. Cumulative downslope movement along the upper crack at Sites 1 and 4 (see Figure 4 for site locations). Downslope movement was measured as the distance between stakes spanning the crack.

are thought to be accurate within several centimetres, the total observed displacements of 7 to 14 cm along the headscarp are interpreted to represent real movement.

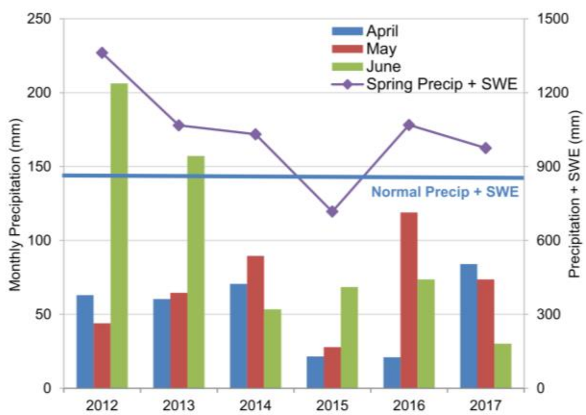

Figure 6. Record of monthly spring precipitation at the Kaslo Environment Canada station 20 km SSW of Johnsons Landing and the spring (April to June) precipitation from the Kaslo station plus the snow water equivalent (SWE) on April 1 at the Upper Gray Creek snow survey site 55 km south of Johnsons Landing.

5 DISCUSSION AND CONCLUSIONS

The greater displacement at the upper crack relative to the headscarp may indicate that the unstable area is settling and will eventually reach a new static equilibrium. In this case the movement would be expected to diminish with time. Significant displacement was observed in the first year after the slide, with decreasing movement over the following four years. However, an increase in displacement was observed at the upper crack in 2017 despite that spring not being particularly wet. Ongoing monitoring will help to determine if the movement in 2017 is an episodic settlement event or represents the beginning of wider-scale ongoing instability. If equivalent displacement at the upper crack and the headscarp is observed in the coming years, this pattern could be evidence of translational movement of the unstable area, and thus a higher likelihood of failure in the coming years.

Given that one of the main triggering factors of the landslide was elevated groundwater levels after a particularly wet spring, the spring precipitation and snowpack are assumed to also be a factor in any ongoing instability. Since 2012 the spring precipitation and snowpack have been remarkably consistent, with the exception of 2015 which was drier. However, there does not seem to be an obvious association between the annual displacement at the upper crack and the precipitation and snowpack records. The movement that has been observed at the upper crack and headscarp could simply by progressive settling of the disturbed area rather than year-to-year variation in groundwater or pore water pressure levels. Alternatively, the interannual variations in precipitation may not have been sufficient to have a detectable impact on the movement. The spring snowpack and precipitation was almost 150% of normal in 2012, whereas in the years since the snowpack and precipitation has been within 15% of normal.

In view of the increased displacement at the upper crack in 2017 and the progressive movement at the headscarp, ongoing monitoring of the site is planned for at least the next few years. Ideally monitoring will continue until a particularly wet spring occurs with no consequent increased displacement or until movement at the headscarp and upper crack slows to zero.

The current monitoring program does not provide any early warning of landslide movement. A near real-time monitoring system involving high-precision GPS or geotechnical instrumentation would require remote transmission of the signal, full-time surveillance of the data by qualified personnel and an efficient method of notifying and evacuating residents. Furthermore, advanced monitoring methods such as geotechnical instrumentation or high-precision GPS units were not considered practical at the site considering the lack of road access and the large cost of such systems relative to the downslope values. GPS reception at the site is also limited by the steep terrain. Therefore, this type of complex warning system was not recommended in the initial post-slide report. The decision to implement the simpler stake measurement and survey-based methods seem appropriate based on the monitoring results over the past five years.

Considering the inexact nature of the hazard analysis, it is challenging to refine the estimates in Table 1 given that only five years of monitoring data have been collected and the return periods are orders of magnitude greater. The most likely scenario in this analysis is the failure of the dropped block and adjacent oversteepened upper scarp. However, the survey data indicate that the movement of the dropped block is less than the movement along the main scarp. The dropped block may have been arrested by underlying bedrock, as an outcropping is visible on the slope below. If monitoring data continue to show slowing displacement, then the

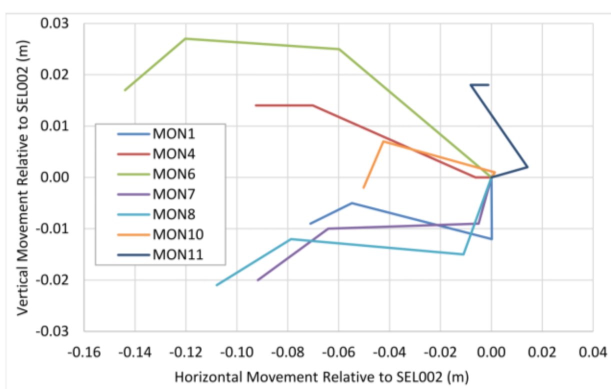

Figure 7. The horizontal and vertical movement of the survey reflectors along the headscarp. The movement is relative to the base station (SEL002). See Figure 4 for survey reflector locations. Negative horizontal values indicate movement towards the base station.

annual likelihood of landslide occurrences in Table 1 may be deemed to have been too conservative. Also, the lack of movement observed along the southern end of the crack may indicate that the unstable area is smaller than originally estimated; therefore, the landslide volume estimates in Table 1 may be overly conservative as well.

The residents of Johnsons Landing have been engaged with the slide investigation and monitoring process. Several have volunteered to assist with monitoring activities and some individuals have been active in reporting observations of the creek and slide area. Residents have been updated annually with the monitoring results. Since the landslide, residents not only of Johnsons Landing but also from around the region have been diligent in reporting unusually dirty water events in creeks around the West Kootenays. This increased public awareness provides one of the best early-warning systems for landslides, as many properties around the Kootenays are subject to a landslide hazard and it is impractical to install instrumentation on all potentially hazardous slopes.

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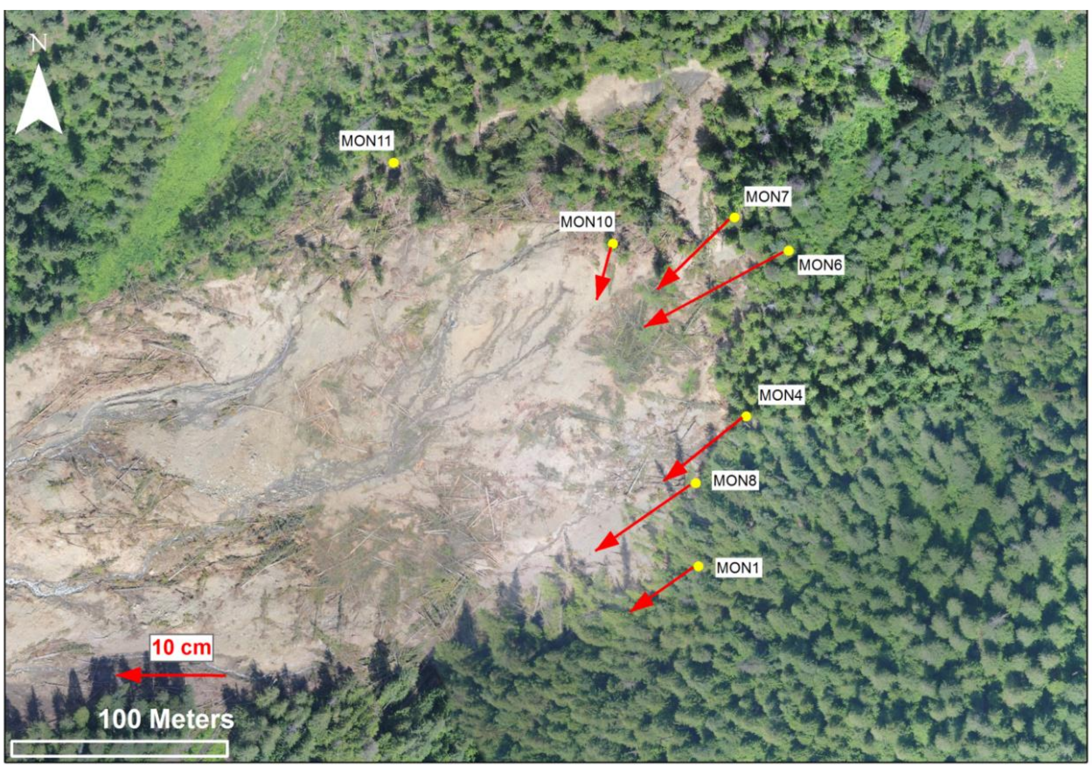

Figure 8. Horizontal movement at each of the reflector locations represented by the red arrow distance (to scale) and direction. See Figure 4 for survey reflector locations.