A Proposed Methodology to Characterise the Hazard Posed by Boulders: A Case Study from Glen Croe

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Contents

Abstract

This report presents the development and trial of a methodology for determining the hazards posed by boulders to the A83 at Glen Croe on the westbound approach to the Rest and be Thankful in Scotland. This section of road has a history of hillside instability, in particular on the SW-facing slopes of Beinn Luibhean. Closure of this section of road following landslides and boulder fall incidents results in traffic delays and has wider socio-economic costs.

While methodologies to assess rock fall and landslide hazards are widely available, there have been few studies relating to individual boulders resting on the hillside that could pose hazards to infrastructure. A section of hillside measuring approximately 71,000m^2 was selected as the Detailed Study Area with the aim of developing a boulder hazard assessment methodology that could be used, or adapted for other sites.

Following a desk study exercise and fieldwork, an inventory of over 450 boulders located within a smaller Detailed Study Area was compiled. Data from the inventory was used to undertake a sensitivity analysis and fall path modelling to determine the boulder and hillside characteristics that are most likely to affect the run-out distances of boulders that have been released from the slope. The results of the sensitivity analysis indicate that boulder shape is the key parameter that controls run-out distance.

Rock run-out modelling software, RAMMS:Rockfall, was used to simulate boulder trajectories on a selected number of boulders within the Detailed Study Area. The results of the modelling were used to determine the probability of boulders of various shapes and sizes reaching the A83.

The results from this exercise were used to develop a hazard matrix so that individual boulders within the Detailed Study Area could be allocated a low, medium or high hazard-rating.

Using the methodology outlined in this report, it was found that the majority of boulders (83.3%), pose a low risk to the A83. Many of the boulders with a low hazard rating are tabular in shape that are associated with shorter modelled run-out distances in comparison to other boulder shapes.

Of the remaining boulders within the Detailed Study Area, 14.5% were allocated a medium hazard rating, and 2.2% a high hazard rating. It was outside the scope of this study to carry out fieldwork across the entire Study Area. However, due to the broad similarities in slope angle and likely boulder distribution across the wider Study Area, the approximate number of boulders within each hazard rating category has been estimated.

It is considered that the broad hazard assessment framework presented within this report can be used or adapted as necessary for other sites to assess the hazard posed by boulders. With respect to the Rest and Be Thankful Study Area, further recommended study includes compilation of a boulder inventory across the full Study Area, and also to assess the capacity of the debris barriers to determine whether these would be effective in preventing boulders reaching the A83.

1. Introduction

1.1 Background

This report, commissioned by the Scottish Road Research Board (SRRB) and sponsored by Transport Scotland, presents the development and trial of a methodology for determining the hazards posed by boulders to a section of the A83 on the uplink approach to the Rest and Be Thankful viewpoint in Glen Croe, Scotland.

The A83 trunk road connects rural communities in Argyle & Bute with the central belt of Scotland. The section of road between Ardgartan and the Rest and be Thankful viewpoint has a history of hillside instability, in particular on the SW-facing slopes of Beinn Luibhean in Glen Croe. This section of the A83 is currently maintained by BEAR Scotland Ltd on behalf of Transport Scotland. Closure of the road following landslides and boulder fall incidents results in traffic delays and has wider socio-economic costs (Jacobs 2013). When considering costs, there are direct costs, i.e. physical damage to the A83 infrastructure, as well as indirect costs such as emergency response, engineering evaluations, and the loss of the use of the infrastructure to name but a few (Winter et al 2018). To provide some context, it is estimated that economic losses caused by closure of the A83 in Glen Croe following a landslide in 2007 amounted to £1.2 million over the 15-day closure period (Postance et al, 2017). With respect to boulder fall, these events are likely to have less impact on the A83, but potentially more chance of causing a fatality.

Previous studies have been commissioned by Transport Scotland to characterise landslide hazards and risks posed by natural terrain slopes above Scotland's Trunk Road Network (Winter et al 2005, Winter et al 2009). This has led to the development of robust management measures to mitigate those risks (Jacobs 2013, Winter 2016, McMillan and Holt 2018). However, these studies have predominantly concentrated on rainfall-induced debris flow landslides or rock fall and have not specifically focussed on the presence of isolated boulders. It is considered that boulder fall requires separate consideration due to the differing triggers and mechanics involved in comparison with debris flows and rockfall.

The stability of the boulders deposited across the landscape and the hazard that they pose is currently not well understood. In some cases, boulders are mobilised during a landslide event and incorporated into debris flow material. However, it has been noted that on some occasions boulders have become destabilised during relatively small failure events and slope movements, and thus need to be considered separately from the effects of the associated debris flow.

To better understand the significance of the boulders in relation to hazards posed to the trunk road network, this study examines boulder hazards on the SW-facing slope of Beinn Luibhean above the A83 on the north-westward approach to the Rest and be Thankful in Glen Croe.

1.2 Project Aims and Methodology

The aim of this project is to develop appropriate methodologies for determining hazards posed by boulders on the hillside of Beinn Luibhean above the A83. It is anticipated that the methodology for this assessment will be later adopted, and adapted as necessary, for other slopes adjacent to the road network, to assess the hazards posed by boulders. The following methodology has been adopted for determining hazards posed by boulders at Beinn Luibhean:

1) Desk study - there is a significant amount of existing information on landslides and rockfall at the site, dating back to 1999. This data along with other pre-existing information that will

assist the study, has been compiled and summarised to ascertain the properties of the site that could affect boulder fall.

2) Digital elevation model (DEM) and preliminary boulder fall inventory - existing LiDAR and high-resolution imagery for the hillside above an approximate 1500m stretch of the road have been used to generate a GIS-based preliminary boulder inventory and a DEM of the site.

3) Field work – site visits have been undertaken on the slopes above the Phase 1 and Phase 7 debris barriers to assess the effectiveness using remotely sensed data, and to validate and enhance the preliminary boulder inventory. This provided information on boulder and landscape properties to establish parameters for fall-path modelling.

4) Initial fall-path modelling – this was undertaken to compute end-point terminations of simulated boulder falls from the starting points on the slope. The modelling was used to determine whether individual boulders pose a hazard to the road. An initial phase of fall-path modelling was undertaken for a discrete area where there have been known boulder-falls and where boulder fall pathways have been recorded. This confirmed whether the boulder fall behaviour can be replicated in the model and also allowed the model parameters to be refined.

5) Detailed fall-path modelling – once model parameters were refined, fall-path modelling was undertaken on selected boulders across the Detailed Study Area above the debris barriers known as Phase 1 and 7 (see Section 1.4). This allowed boulders in this area that pose a significant hazard to the A83 to be identified.

6) Hazard Assessment – modelling outputs were used to compile a comprehensive hazard assessment of boulders within the Detailed Study Area on Beinn Luibhean.

1.3 Project Limitations

The scope of this study examines hazards only associated with discrete boulder falls and does not consider the hazard caused by boulders that are mobilised during debris flow events and become entrained within the debris flow material. The hazard and risk associated with debris flows and suggested methodologies relating to the assessment of this are widely discussed in other literature (e.g Lee and Jones 2014, Winter et al, 2009, Winter & Wong 2020).

The scope of this commission is to provide details of hazard assessment only. Risk assessment in relation to the boulder hazards is not within the scope of this study.

Due to the significant number of boulders across the Beinn Luibhean Study Area, and the time it would take to carry out a detailed verification exercise across this area, a portion of the site above the Phase 1 and Phase 7 debris barriers (see Section 1.4) was selected as a Detailed Study Area for the following reasons:

1) Several large debris flows have occurred in this area in recent years, and as a result this area being extensively studied.

2) Due to the higher number of debris flows in this area, a large number of boulders have been freshly exposed in this area in comparison with other areas of the hillside, thus allowing easier identification of boulders from the remotely sensed data in comparison with other areas of the hillside where boulders are more likely to be obscured by overlying vegetation.

1.4 Study Area Description

The A83 Trunk road stretches for approximately 157km between Tarbet on the western shore of Loch Lomond, to Campbeltown, located at the southern end of the Kintyre peninsula. The road provides a strategic link between populations in Argyll & Bute and the rest of Scotland.

For the purpose of this report, the 'Study Area' is used to describe the 1.5km section of the A83 road within Glen Croe and the SW-facing hillside of Beinn Luibhean, and the area of hillside below the A83 and above the Old Military Road. The boundaries of the Study Area are the bridge over the Croe Water (NGR 224242 706032), and the bend in the road before the Rest and be Thankful viewpoint (NGR 223385 707342). In terms of height, the Study Area reaches a maximum elevation of approximately 600mAOD. The characteristics of the slope change above this level from a predominantly soil covered slope to a shallower slope with numerous crags and rock outcrops approaching the 858mAOD summit of Beinn Luibhean. The Study Area location is defined in Figure 1-1.

The A83, a two-lane carriageway, passes through Glen Croe in a north westerly direction, and is formed on side-long ground. The road rises steadily through the Study Area at a gradient of around 5% (1 in 20) before reaching a high point beside the Rest and Be Thankful viewpoint. A photograph showing the nature of the site in October 2018 is provided in Photograph A.1, Appendix A.

The hillside within the Study Area is typically very steep, in some places in excess of 35 degrees. Boulders of varying size and shape litter the hillside, and rock outcrops are also common.

The Study Area is incised by many channels, which typically flow to the south-east. The channels are typically culverted beneath the A83, continue to flow downslope and are then culverted beneath the Old Military Road (OMR) before discharging into a larger stream that meanders through Glen Croe on the valley floor, before discharging into the Croe Water close to the south-east extent of the Study Area.

The single-track OMR runs parallel to the A83 close to the valley floor before traversing across the steep terrain to reach the Rest and be Thankful viewpoint. The OMR is often used as a temporary diversion for traffic when the A83 is closed following impact from a debris flow. Boulders have been deposited on the slopes and valley floor below the A83 trunk road, indicating that boulder fall from the upper slopes of Beinn Luibhean has crossed the A83 in the past before being deposited on the lower slopes.

Debris flow mitigation measures including debris flow barriers and a series of debris catch pits have been constructed immediately above the A83. The barriers constructed to date have been erected in a series of 'Phases'. A summary of mitigation measures currently in place as well as details of planned mitigation works are provided in Table 1-1. The locations of the debris barrier phases are shown on the site features plan, Drawing B-1 in Appendix B. It should be noted that the barriers designed with respect to debris flows, and not specifically to withstand the impact of individual boulders.

Table 1-1 Summary of natural terrain hazard mitigation measures at the Study Area

Natural terrain hazard mitigation measures	Date of construction	Planned works / comments
Phase 1 barrier	2010	Catch pit construction below phase 1 barrier due to commence October 2020. Phase 1 barrier reconstructed following the October 2018 debris floe and previous events.
Phase 2 barrier	2012	-
Phase 3 catch pit	2013	Phase 3 catch pit extended west to below Phase 7 barrier to increase pit capacity. Work completed summer 2019.
Phase 4 barrier	2013	Barrier reconstructed following 2014 debris flow.
Phase 5 barrier	2013	Catch pit construction due to commence in 2020
Phase 6 barrier	2013	Catch pit construction due to commence in 2020
Phase 7 barrier and catch pit	2013 (barrier), 2019 (catch pit)	-
Phase 8 barrier and catch pit	2013 (barrier), 2019 (catch pit)	-
Phase 9 barrier and catch pit	2013 (barrier), 2019 (catch pit)	-
Phase 10 barrier	2014	Phase 10 barrier reconstructed following the October 2018 debris flow.
Phase 11 barrier	2014	-
Phase 12 barrier	2014	-

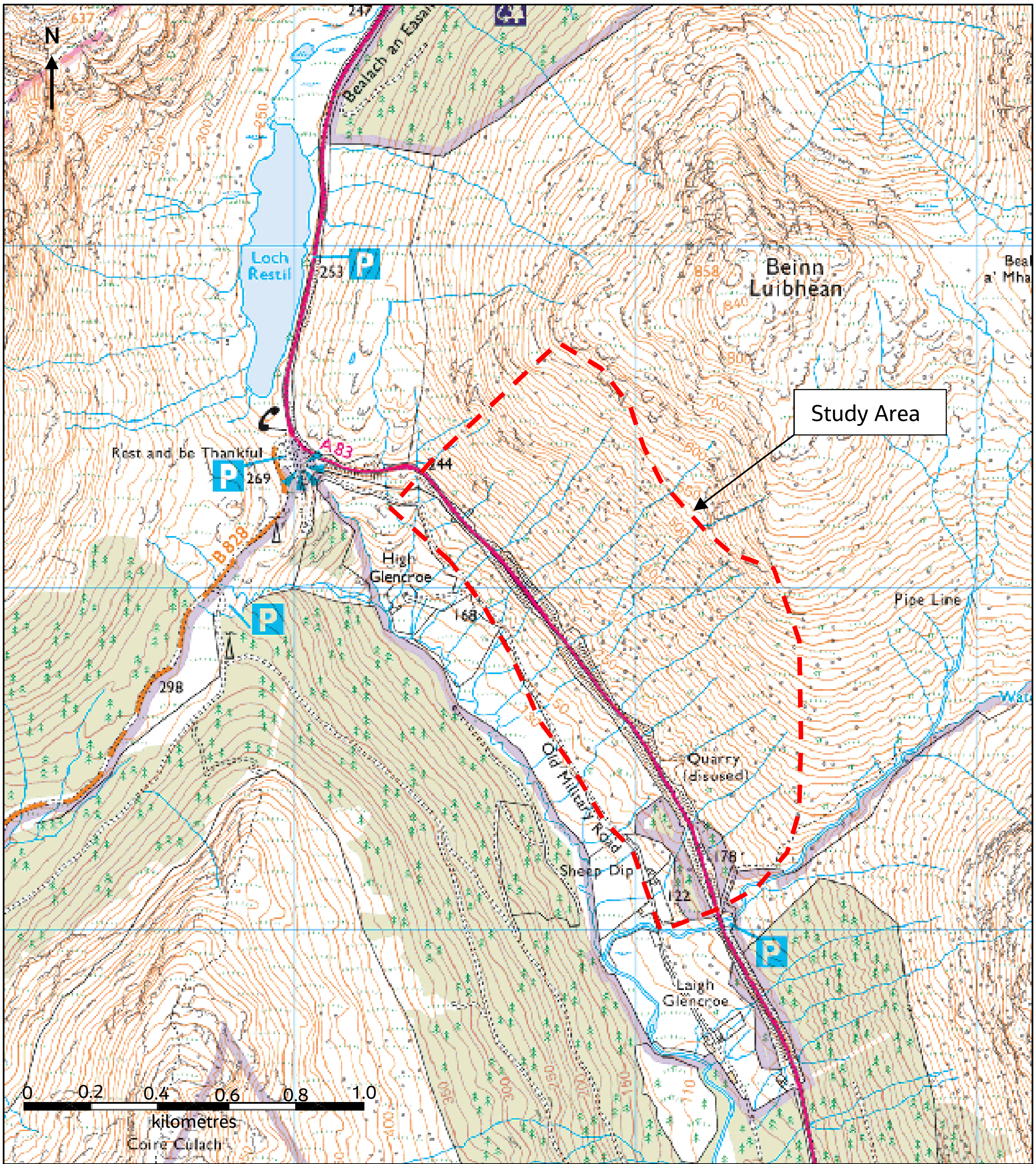

Figure 1-1 Study Area Location Plan

2. Desk Study

This section of the report presents the findings of desk study researches with regard to the geological, geomorphological and hydrological setting at the Study Area. This section also provides a summary of previously recorded natural terrain hazard incidents with a view of determining the history of occurrence of boulder fall events at the Study Area. The desk study information is also used to compile the preliminary boulder inventory which is essentially a list of known boulders and boulder locations across the site.

Data sources used to compile the desk study include the following:

- Published Ordnance Survey (OS) maps
- Published British Geological Survey (BGS) maps
- BEAR annual reports
- Landslide Inspection Reports
- Various technical reports on studies undertaken at the A83 Rest and be Thankful
- Terrestrial laser scanning LiDAR data provided by Newcastle University
- High-resolution digital photography of the Study Area (Transport Research Laboratory (TRL) 2017-2019)

2.1 Geological Setting

The published geological maps (BGS 1987, 1990) indicate that the Study Area is predominantly underlain by pelite, semi-pelite and psammite of the Beinn Bheula Schist Formation. A small area of igneous rock including diorite, tonalite and appinite is shown to outcrop adjacent to the eastern boundary of the site. Although a number of faults are indicated regionally on the geological maps, no faults are shown to be located within the Study Area.

Geological mapping indicates that the bedrock is overlain by Till. Some areas of the 1:50,000 maps record no superficial geological deposits, indicating that bedrock is at or close to the ground surface. In many areas, the Till surface is nothing more than a thin veneer resting on top of the bedrock, as observed from various debris slides over the years that have eroded gullies to expose the bedrock.

2.2 Geomorphological Setting

The deep u-shaped valley of Glen Croe was formed during the Quaternary Period when Scotland was affected by several phases of glaciation, the last being the Loch Lomond Re-advance, which ended approximately 11.7ka (Bickerdike et al, 2017).

During these phases of glaciation, Till was deposited on the valley sides, and locally morainic deposits were deposited on the lower slopes (Jacobs 2013). Since the last glacial period ended, colluvium has been deposited on the lower slopes as a result of gravity driven slope movements arising from the weathering, re-working and degradation of the Till deposits. Evidence of both recent and historical movement is widespread across the slopes through the presence of geomorphological features such as failure backscarps, tension cracks, terracettes, debris levees, and lobes of deposited failure material, including boulders.

The degradation of the Till on the slope has exposed numerous boulders that were originally contained within this material. Boulders are also present within the colluvium and are likely to have been transported downslope within debris material during previous events. It is anticipated that some of the boulders deposited on the slope may also have originated from rockfall as a result of progressive weathering of exposed rock outcrops on the upper slopes of Beinn Luibhean.

The slopes of Beinn Luibhean could be described as 'dynamic' due to the relatively rapid development of geomorphological features such as tension cracks, washout features and new drainage channels. The dynamic nature of the hillside is considered to contribute to landslide events that can trigger boulder fall or expose boulders within the Till.

2.3 Hydrological Setting and Drainage

The Study Area has been incised by numerous streams which drain the hillside, some of which have eroded down to, and exposed, the bedrock. The hillside above the A83 drains mostly into unlined drainage ditches running parallel to the road. In some areas, the streams flow into large catch pits, designed to collect debris in the event of a debris flow, before being culverted below the A83 and into the River Croe lower down the valley. Since slope stability issues have been identified within the Study Area there have been various interventions immediately above the A83 with the aim of improving drainage, including the construction of a cascade to prevent erosion, and enhancements to the culvert system. More recently the catch pits excavated provide increased drainage capacity during periods of inclement weather. At the time of writing, a hydrological study is being undertaken to look specifically at watershed and drainage capacity.

2.4 Previous Studies at A83 Rest and Be Thankful

Initial Studies (1999-2003)

The A83 within the Study Area has been affected by numerous natural terrain landslides within the last 20 years. This has resulted in road closures on a number of occasions. Landslides and boulder falls causing road closures have been documented and studied at the site since 1999; however, desk study researches indicate that natural terrain incidents have likely occurred in this area dating back to the 1930s when the A83 was constructed, but the locations and dates of these events are unknown. Wong and Winter (2018) suggest that it is likely that the frequency of landslide events at the Study Area has increased since the early 1900s.

Following concerns by the Scottish Government (formerly Scottish Executive) at the frequency of landslides in the area between 1999 and 2002, a study was commissioned to investigate the problems at the site, and to propose long, medium and short-term strategies to address the problems encountered.

The resulting soil assessment report (Babtie, 2003) highlighted 28 Geotechnical features that were of concern in terms of risk to the road. These included various features such as tension cracks, evidence of erosion, wash out features, etc. and were each assigned a Geotechnical feature number (G1 to G28) which were given a stability and risk rating. Two of the geotechnical features (G24 and G28) referred to potentially unstable boulders.

A detailed inspection of potentially unstable boulders was also carried out in October 2002 (Jacobs Babtie, 2003). The study focussed on boulders typically >1m^3 and identified approximately 50 potentially unstable boulders. The boulders were assigned a hazard rating and risk rating based on the physical properties of the boulders and the probability of the boulders reaching the road upon release. The final recommendations for boulder stabilisation were based on a site-specific hazard rating system. Six boulders were identified as having high risk of reaching the road (Tier 1). These boulders were identified for immediate stabilisation. Seventeen boulders were identified as having intermediate risk of reaching the road (Tier 2) where it was considered that failure was imminent in the short to medium term. The remaining boulders (Tier 3) were considered relatively stable in the short to medium term. The Tier 1 and Tier 2 boulders were stabilised between December 2002 and March 2003. The larger boulders were stabilised in situ, using dowels and netting, while smaller boulders were broken up using expansive grout, explosives, or hand breaking methods. In addition to the Tier 1 and Tier 2 boulders, an additional boulder, not previously identified during previous inspections, was stabilised at this time.

The remaining thirty Tier 3 boulders were not stabilised. These were considered to be relatively stable in the short to medium term and were recommended for future stabilisation. However, it was recommended that the stability of these boulders be reviewed by further site inspections, which should also include inspection of the remaining hillside for other boulders that have become potentially unstable during the intervening periods. A record of boulder locations identified during the 2003 boulder study, and the locations of geotechnical features G24 and G28 are provided on Drawing B-1 in Appendix B.

Annual Reporting (2005 – 2018)

Since the 2003 soil assessment of the slopes (Babtie 2003), annual reports have been compiled for the Study Area with the purpose of recording changes in the slope condition during the previous year and providing recommendations on further study and remedial works. The latest report available at the time of writing covers changes in the slope between 2017 and 2018.

The annual reports have typically been compiled using data from quarterly visual/photographic slope inspections with the aim of detailing changes to the slope and identifying new features which could indicate areas of instability. The quarterly inspections were undertaken from the forestry track on the opposite side of the Glen Croe valley using photographs and binoculars, and as such, did not involve detailed on-slope inspections. It is noted in the annual reports that it was not possible to determine the stability of boulders from the visual surveys. However, detailed observations have often been made in localised areas where emergency on-slope inspections have been carried out following failures. Results of the emergency inspections are also recorded as part of the annual reports.

A summary of observations relating to boulders that have been highlighted in the annual reports is provided in Table C-1 in Appendix C.

Emergency Inspection Reports

Emergency inspections are undertaken following landslide events (e.g. boulder fall, debris flows) that affect the A83 carriageway. These inspections provide detailed information on the failure such as dimensions, volume, location on slope, contributing factors and remaining instability concerns. At the time of the inspections, decisions are made on when it is safe to operate the trunk road and the OMR (if necessary), and recommendations are provided on any remedial works required to stabilise the hazard on the slope.

Available records indicate that at least 37 failure events have occurred since 1999. Of these failures, two have involved the movement of discrete boulders on the hillside which have directly impacted the A83 carriageway. An example of this is provided in Photograph A-2, Appendix A which relates to a boulder fall reported during an emergency inspection on 30 December 2015.

In many cases, potentially unstable boulders were identified following emergency inspections of debris flow events. In these cases, boulders within the debris material have been transported downslope within the debris flow (e.g. Photograph A-3), others have been released during soil disturbance and have moved independently of the flow (e.g. Photograph A-2), or have been exposed in the head and sides of failure scars (e.g. Photograph A-4). Bare landslide scars are at greater risk of erosion and emergency works have often been required to stabilise these boulders exposed within debris flow scars to reduce the risk to the A83 below (e.g. Photograph A-5).

The extensive information available on the natural terrain hazards that have occurred at the Study Area within the recent past, allows the development of a summary event timeline as in Table C.2. in Appendix C. Events that have involved boulder-falls, or where potentially unstable boulders have been recorded, are highlighted in *italics* in the table.

Potentially Unstable Boulder above Phase 10

A boulder was left potentially unstable following the debris flow on 28 October 2014. With a volume of approximately 105m^3 and approximate mass of 250 metric tons it was considered a potential hazard to the A83. Following a geophysical survey to determine the thickness of soil on which the boulder was resting, the boulder was stabilised using seven Kevlar tendons in March 2015.

Boulder Study, Jacobs 2016 – Phase 1 and 7 channels

Following landslides in December 2015 and January 2016 it was observed that a number of large boulders were present on the hillside above the Phase 1 and Phase 7 debris barriers. An exercise was undertaken by Jacobs to determine the hazard posed by these boulders. The condition of the boulders and the propensity to roll if disturbed was taken into consideration to determine the level of hazard. As noted in the unpublished report, the assessment was highly qualitative and subjective, based on engineering judgement. The assessment was considered using various factors including boulder size, shape, local topography, height above the road, and evidence of instability of the boulder or surrounding area.

A total of 45 and 11 individual boulders were identified that could potentially affect the Phase 1 and Phase 7 barriers respectively. Based on observations, a hazard rating was assigned to each boulder in respect of its potential to impact the Phase 1 debris barrier. The majority of boulders were assigned a hazard rating of low to low/medium, with five boulders assigned a hazard rating of medium to medium high. No boulders were designated as a high hazard.

Although this study was not published, the data was used to programme future works including a schedule of works for boulder stabilisation. The locations of boulders identified in 2015 are provided on Drawing B-1 in Appendix B.

2.5 Summary of recorded boulder movement

2.5.1 Pre-1999

While there is no documented evidence of boulder fall affecting the A83 prior to 1999, it can be assumed that periodic boulder fall from the slope is highly likely to have occurred. Some evidence of this includes the presence of boulders on the slope between the Old Military Road and the A83, and on the valley floor. These boulders are identifiable from various data sources. The earliest Ordnance Survey map of the area (1874, 1:10,560 scale), which was published prior to the construction of the A83, shows boulders to be present on the slopes immediately above the Old Military Road. Boulders resting on the lower slope below the current A83 alignment are also visible on modern data sources such as the LiDAR images and aerial photographs. The presence of these boulders indicates that there is likely to have been boulder fall from the hillside prior to the construction of the A83. However, the origins of each boulder cannot be determined, and the causation of boulder propagation is also difficult to determine without detailed fieldwork which is outside the scope of this study. Although it is likely that there was some discrete boulder fall, it is also possible that the boulders resting on the lower slope were entrained within a debris flow. Whichever the mechanism of failure, the presence of these boulders indicates that the current A83 alignment is likely to have been impacted by boulders prior to 1999.

2.5.2 Post-1999

There is recent evidence that boulder fall has occurred on the slopes above the A83 road within the Study Area. Evidence of this has been recorded in Geo-emergency reports, as well as from the Jacobs 2015 boulder survey.

Between 1999 and 2019, evidence from Geo-emergency reports and annual reporting from the site indicates that at least 40 natural terrain failures have occurred. Five of these events recorded discrete boulder fall, with four of the boulders impacting the A83. A summary of these events is provided in Table C.2 in Appendix C. Locations of post-1999 incidents provided on the site features plan, Drawing B-1 in Appendix B.

3. Literature Review

3.1 Boulder fall – description, triggering factors and boulder motion

3.1.1 Boulder description and origin

Ho and Roberts (2016) describe boulder fall as a hazard resulting from one, or several rock fragments being transported down slope by rolling, bouncing and sliding. It is believed that the boulders within the Study Area have originated from weathering or erosion of the glacial till in which they are contained. It is possible that some of the boulders may also originate from rock-fall events that have occurred as the rock outcrops and crags on the upper slopes of Beinn Luibhean have weathered over the years.

Some boulders resting on slopes above the road network in other areas of Scotland may have different origins from those noted above. Glacial erratics are boulders that have been transported by ice during glacial periods and have been deposited on the ground surface in a different location to where they originated as the ice melted. Erratics often comprise a different rock type compared to the underlying geology in the location in which they have been deposited. It is not believed that the boulders on the slopes of Beinn Luibhean comprise erratics.

3.1.2 Boulder fall triggering factors

It is considered that boulder fall could occur within the Study Area through two mechanisms. The first being slope movements, and the second through release of rock blocks from the weathering of rock outcrops. For the purpose of this study, only the first mechanism is being considered as rock fall analysis from cliffs is outside the scope of the brief.

It is widely recognised that high intensity short-term rainfall events are associated with triggering landslides and slope movements. However, as noted by Winter and Shearer (2013), longer term rainfall preceding a storm event has also been associated with slope instabilities occurring in Scotland.

It is considered that water infiltration into the soil and the resulting increase in porewater pressure is the main contributing factor with respect to soil slope movements which, in turn, causes the release of discrete boulders that are resting on, or are embedded within the soil. Water infiltration can be triggered by rainfall and by rapid snow melt. Other factors may also be applicable when considering the causes of soil movement, which can trigger the release of boulders from the slope. A list of factors which could be relevant for sites in Scotland are noted below. Factors that are unlikely to be relevant in Scotland, for example liquefaction due to seismic activity, have been omitted from the list.

- Increase in porewater pressure from intense/prolonged rainfall, or from snow melt – this can cause a release of a boulder through softening and deformation of the surrounding soil.

- Freeze thaw action on the soil – expansion occurs as moisture freezes within the soil. As the soil-ice melts, it contracts again. Numerous studies, e.g. Guo and Shan (2011), Cheng, Ge and He (2009) indicate that freeze-thaw cycles can contribute to shear strength reduction of the soil, and thus, increase the chance of soil movements that could trigger boulder fall.

- Fluvial erosion of exposed soil around a boulder – particularly for boulders located within existing drainage lines, or in channels formed during debris flows, further erosion of the channel sides causing the washout of finer soil particles that provide underlying support to the boulder may cause the boulder to release.

- Change in vegetation. Humphreys et al (2015) note that there are two mechanisms that can release boulders that are particularly relevant to land that is currently or has previously been forested. Root jacking occurs when tree roots can penetrate into rock crags or areas of scree. As the roots grow and expand, this causes blocks of rock or boulders to become dislodged. Deforestation may also have an effect on boulder stability. Boulders are often caught behind trees in areas where landslides have occurred in forested areas. Once the area of forest is cleared, the tree stumps retaining boulders on the slope will eventually decay. As decay continues, the boulders may become unsupported which could trigger release.

3.1.3 Boulder Motion

A summary of rockfall mechanics is provided by Dorren (2003) who details the down-slope modes of rockfall and how they come to rest. It is considered that much of the mechanics involved in the downslope movement of rock fall also applies to boulder fall. Dorren notes that the mode of motion is strongly influenced by the slope gradient. Free fall occurs on near-vertical slopes whereas bouncing occurs on slopes between 45 and 70 degrees, and at lower angles, boulders or rockfall particles are more likely to roll.

As boulders propagate downslope, energy is gradually lost due to impacts with the ground surface and they eventually come to rest. How quickly this occurs depends on several factors, including the underlying geology, vegetation cover, and slope morphology.

3.2 Hazard Assessment Methodologies

Lee and Jones (2014) describe hazard assessment as being the first active stage of a risk assessment and note that should a hazard involve the possibility of major or potentially highly destructive event, in this case the potentially destructive effects of boulder fall, then the assessment should concentrate on establishing the likely magnitude of the event, its character, time to onset, or speed of onset of the envisaged event. Following on from determining the hazards that are present, Lee and Jones (2014) recommend that this information is used to develop a hazard model, which should classify the threat of the hazard, and quantify the future frequency and magnitude.

Landslide hazard assessment methodologies are well developed in several countries around the world, especially in those that are prone to these events such as Switzerland and Hong Kong. Numerous studies and guidance documents have also been prepared across the world that relate to hazards associated with rockfall from cut slopes, e.g. TRL Rock Slope Risk Assessment (McMillan and Nettleton 1995), new priority classification system in Hong Kong (Wong, 1998), modified rockfall hazard rating system in Italy (Budetta, 2004), and Colorado Rockfall Hazard Rating System (Russel et al, 2008). However, comparatively little work has been undertaken to develop methodologies for the assessment of hazards specifically in relation to discrete boulder fall from natural slopes. In some cases, for example in Switzerland, guidance on the assessment of boulder fall hazards is incorporated in the assessments of landslide hazard as a whole, but there is no separate guidance for the assessment of boulder-fall hazard. On review of the available literature, The Hong Kong Special Administrative Region (SAR) appears to have the most well-developed guidance for boulder fall hazard assessment, and the frequency of boulder fall incidents over the years has allowed the phenomenon to be thoroughly studied. The prevalence of discrete boulders on slopes across Hong Kong SAR is largely due to deep tropical weathering of the igneous bedrock, leading to the formation of corestones within the weathered rock mass. Over time through geomorphological processes, the corestones weather out of the saprolite weathering product, that forms the matrix surrounding the corestones, to be exposed as boulders at the ground surface. Climatic conditions in Hong Kong, particularly the heavy rainfall that is often experienced during the typhoon season, is considered a triggering factor of boulder fall incidents over the years. The following sections outline current practice and methodologies developed for assessing natural hazards in Hong Kong and Switzerland.

3.2.1 Hong Kong Boulder Assessment Methodology

The Geotechnical Engineering Office (GEO) in Hong Kong, part of The Civil Engineering Department (CEDD) of the Hong Kong Government recognises the potential for boulder fall hazards to affect existing and proposed developments across the territory. Specific policy in relation to existing developments, both residential and commercial development as well as road infrastructure, is outlined in GEO Report 138, Guidelines for Natural Terrain Hazards (Ho and Roberts, 2016).

GEO Report 138 includes provision for assessing boulder fall hazards. Like most methodologies that have been developed for the assessment of natural terrain hazards, the Hong Kong guidance starts with the gathering of desk study information pertaining to the geological, topographical and geomorphological conditions at the site. Unlike most countries, Hong Kong has a territory-wide database of geotechnical information, Geo-Info, which is publicly available, and provides users with existing information about sites of interest. One of the available layers is a boulder field inventory. The inventory was prepared from data gathered when the whole of Hong Kong was mapped in terms of perceived geotechnical hazard from aerial photographs during the 1980s. The inventory does not record data on individual boulders, but instead groups areas of land with similar boulder densities into polygons and provides details of typical attributes such as boulder size and type. This allows users to ascertain whether there is a potential for boulder fall hazards at a particular site and to make provision for further study. Following on from this, a detailed inspection of boulder hazards from aerial photographs can be undertaken, with confirmatory field inspections thereafter to verify the data gathered during the desk study phase. GEO Report 138 recommends that, if boulder falls are considered to be a hazard, the evaluation of boulders during the field work should be at sufficient detail to allow assessment of the processes and the identification of potentially unstable boulders. The report recommends that the following data is gathered to allow subsequent assessment of likelihood of boulder fall initiation:

- Boulder shape
- Boulder volume
- Boulder location
- Slope gradient
- Exposure conditions
- Embedding material
- Surface drainage
- Vegetation cover
- Likely travel path of boulders in the event of failure

Following guidance on data to be gathered during the desk study and fieldwork, GEO Report 138 goes on to describe recommended methods for presenting the data. This includes a natural terrain hazard map showing boulder fall trajectories with the estimated distance that boulders will travel where numerical modelling is carried out. With regard to numerical modelling, the guidelines note that there are considerable limitations and uncertainties in the use of numerical models for the evaluation of boulder stability, and that the derived results should be carefully calibrated and should not take precedence over experience and judgement.

3.2.2 Switzerland

Natural terrain hazard incidents are also common in Switzerland, with six percent of the country being prone to slope instability (Latelin et al, 2005). In 1997, the National Platform for Natural Hazards was established to advise the federal council on natural hazards. Currently natural hazard events including rockfall are recorded in a digital database called StorMe at the Swiss Agency for the Environment, Forests and Landscape (PLANAT, 2005). The Swiss federal government requires Cantonal authorities to generate natural hazard maps and zoning of mass movements for their Canton, with the aim of restricting development in areas that are prone to natural hazards. The methodology for developing the hazard maps is provided in the "Code of Practice for Landslide Hazard and Land Use Planning" which was issued by the federal government in 1997. The guidelines produced can be used to assess all types of landslides and rockfall, including the potential for boulder fall. The hazard maps, which are available for almost all cantons in Switzerland (PLANAT, 2005) are then used as part of a three-stage process of risk assessment that is outlined in a 1999 Swiss Government document entitled 'Risk analysis for gravitational natural hazards'.

The Swiss guidelines for the integrated hazard management of landslides, rockfall and hillslope debris flows (Raetzo and Loup, 2016), describe the detachment of bedrock or unconsolidated material on a steep site as a 'fall'. For hazard identification purposes, falls are sub-divided into four categories by volume and size of the components. Thus, boulder fall of a certain size is treated in a similar manner as a similar size rock fall from a rock face. An extract from the Swiss guidelines showing the categorisation of rockfall hazards is provided in Figure 3-1. With respect to rockfall, the degree of hazard is also sub-divided into intensity categories as follows:

- Low <30kJ
- Medium 30-300kJ
- High - >300kJ

Intensity maps are then produced for rockfall hazard which form the basis for the development of the hazard maps. The hazard maps and associated technical reports that are produced contain detailed information on the causes, course, spatial extent, intensity and probability of occurrence. Hazard maps do not indicate what risks are associated with the rockfall processes. In terms of determining the degree of hazard, two parameters are used: intensity (described above), and probability. These parameters are visually summarised in a magnitude-probability diagram. The intensity-probability category is then used to populate the hazard maps. The magnitude-probability diagram along with an example of a hazard map provided in the Swiss guidelines is provided in Figure 3-2. It should be noted that the degree of hazard relates to land-use planning in general, rather than specifically for hazard to infrastructure.

Process	Diameter of the components	Volume	Velocity	Comment
Rockfall (*Steinschlag*)	<50 cm	-	<30 m/s	Usually individual rocks per event
Rockfall (*Blockschlag*)	≥50 cm	Vol.<100 m³	<30 m/s	Usually individual boulders per event
Rock avalanche (*Felssturz*)	-	Vol.>100 m³ and Vol.<1 million m³	10–40 m/s	Rock avalanche mass, usually the fall of a large number of rocks and boul-ders followed by their fragmentation. Rock avalanches can unfold in diffe-rent phases (partial avalanches).
Rock avalanche (*Bergsturz*)	-	Vol.>1 million m³	>40 m/s	Initial phase with compact rock avalanche mass. The process area involved, including the depositional area, can be very extensive.

Figure 3-1 – Classification of rockfall processes based on rock diameter and event volume, from Raetzo and Loup, 2016).

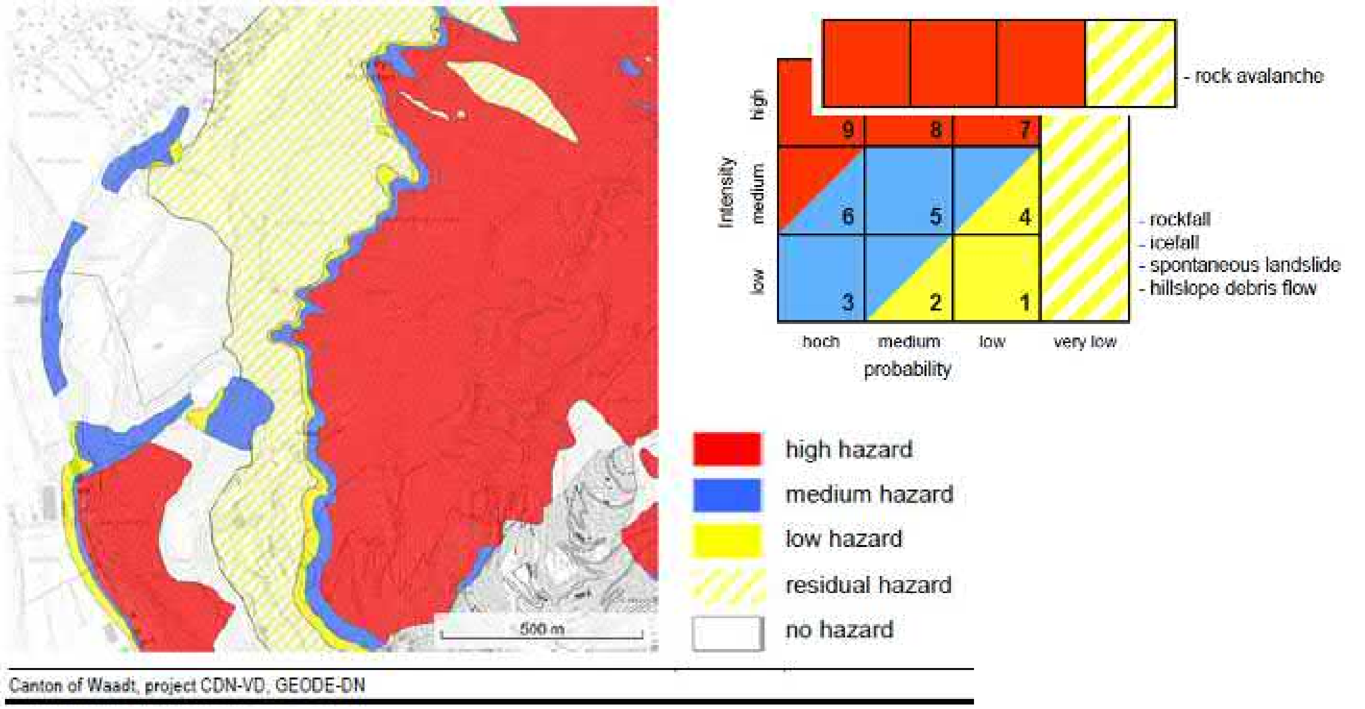

Figure 3.3 – Magnitude-probability diagram and example of rockfall hazard map from Canton of Waadt, (Raetzo and Loup, 2016).

3.3 Review of available run-out modelling software

Dorren (2003) notes that models can be useful tools to assess the risk posed by rockfall and summarised the abundance of modelling approaches. Jaboyedoff and Labiouse (2011) provide a history of rockfall trajectory modelling, which they note has been studied since at least the early 1960s.

Two-dimensional run-out modelling software has been commercially available since the 1990s. Examples of these include RocScience RocFall, and the Colorado Rockfall Simulation Programme (CRSP). Both have been widely used in industry for the purpose of modelling run-out distances, energy, speed and bounce height of dislodged boulders, or from rock fall. 2D trajectory models are based on the spatial domain derived from two axes, with a user-defined line of fall and do not take into account lateral variations in slope morphology. It is considered that 2D models are most suited to sites with a relatively uniform slope that display features of low geomorphological complexity.

Three-dimensional rockfall run-out modelling has been developed more recently following the advent of LiDAR data which is becoming more commonly utilised in slope stability studies. Jaboyedoff and Labiouse (2011) indicate that, when modelling in 3-dimensions, it is observed the more accurate the digital terrain model used, the further the spread of boulder trajectories across the slope. Early versions of 3D modelling software such as Rockfall Analyst, STONE and Pir3D provided advanced modelling techniques to study rockfall behaviour in 3D; however, these early models do not take boulder shape into consideration (Lan et al. 2010), which is considered to be a significant factor in boulder fall-paths. The following paragraphs describe three commercially available software packages that were considered for use in this study.

The program CONEFALL was developed by the International Independent Centre of Climate Change Impact on Natural Risk Analysis in Mountainous Area. (QUANTRERRA). The program is based on the simple theory that a block can propagate if the slope is sufficiently steep. The space where a block can propagate from a grid point (based on a DTM), is located within a cone of slope, with a summit placed at the source point. A diagram illustrating this concept is provided in Figure 3-3 below (Jaboyadoff, 2003).

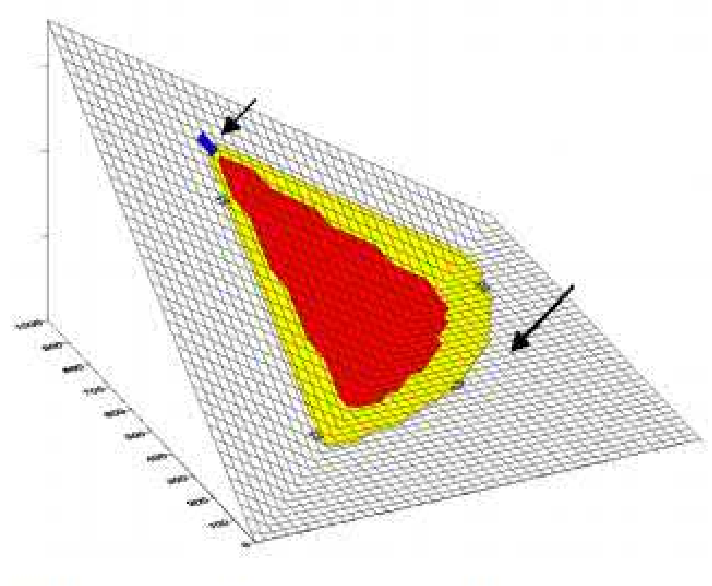

Figure 1.1 *Illustration of the potential propagation area of the blue pixel, using a cone slope of 35° and 40°.*

Figure 3-3 – Model illustrating potential propagation of a boulder in CONEFALL for a defined slope angle. Taken from program user manual (Jaboyadoff 2003).

The program RAMMS:Rockfall (Christen et al, 2012) was developed by the Institute for Snow and Avalanche Research, and the Swiss Federal Institute for Forest, Snow and Landscape Research. The model output calculates the run-out dynamics for rock blocks over a three-dimensional terrain using rigid body algorithms. Model input parameters focus on the individual rock shape and its frictional contact with a three-dimensional body, i.e. the slope. The main benefit of RAMMS:Rockfall is that it can take into consideration the geometries of the individual boulders, and this may be beneficial if the geometry of the boulders is highly variable across the area being assessed. Anecdotal evidence from other users of RAMMS:Rockfall indicates that a limitation of this software is that the integration of existing protection measures in the model is insufficient.

Rockyfor3D software (Dorren, 2016), developed by the International Association for Natural Hazard Risk Management (ecorisQ), calculates the trajectories of individual falling rocks in three dimensions. This simulation is based on a combination of physical algorithms and a stochastic approach, i.e. it creates a probabilistic process-based rockfall trajectory model. In order to achieve the desired simulation, the package needs consistent input data that represents the terrain in reality. The path, or trajectory, of the boulder is simulated as 3D vector data. In predicting fall trajectory, the software takes into consideration some of the possible impacts the obstacle may have on its path – including areas of forestry and any rockfall nets that are already in place. This aspect of the simulation may be of importance with respect to determining whether rockfalls will breach the existing debris flow barriers at the site. However, a limitation of this software is that individual trajectory information is not provided, so it is not possible to determine run-out distances for individual boulders.

Regarding 3D models, it is anticipated that both Rockyfor3D and RAMMS:Rockfall would be suitable options for the purpose of this study. The latter was selected for this study and it is considered to be more appropriate due to the function which allows the shape of the boulders to be modelled. It is anticipated that this will be a significant factor in determining the run-out distance in the event of a boulder fall. Furthermore, this model also has the capability to assess individual boulder trajectories which aligns with the aims of this project to assess the hazard from discrete boulders on the hillside.

4. Digital Elevation Model and Preliminary Boulder Inventory

4.1 Available Data and Data Interrogation

From previous studies on the hillside, it is known that there is a significant number of boulders on the hillside, ranging from dimensions of 0.3m diameter to in excess of 8m diameter. As such, it was envisaged that compiling an inventory of boulders in excess of 1.0m would yield a manageable amount of data and a minimum boulder size of 1.0m maximum dimension was selected for identification.

Several data sources were available during the study which lend themselves to the identification of boulders. A description of the data sources and the methods in which the data was interrogated to assess boulder locations is provided below.

4.1.1 Terrestrial Laser Scan

LiDAR data, captured and processed by researchers at Newcastle University and Northumbria University as part of a study into debris flows following storm Desmond in 2018, was made available for the purpose of this study. This data was captured to ensure that pre and post-event data was available for post-event analysis of a large debris flow event, essential for validating physical and numerical modelling approaches (Sparkes et al 2017, 2018). The LiDAR data covers the entire Study Area and was captured using a laser scanner at a monitoring stations set up on the forestry track on the opposite side of the valley from Beinn Luibhean. Using the LiDAR point cloud data, a 3-D digital elevation model (DEM) of the site was produced. The resolution of the point cloud data is 20cm with approximately 47.5 million individual points forming the DEM.

Although the DEM created from the terrestrial laser scan is of high resolution and is extremely detailed, the angle at which the data was captured from the opposite hillside has given rise to data shadows within stream channels, and behind other topographic features where the line of the scan has been obscured.

At project onset, it was envisaged that a deep-learning algorithm could be developed to automatically locate boulders from the DEM and that this would be used to populate the preliminary boulder inventory. The advantages of this method would be a significant reduction in the time taken to populate the inventory in comparison with a manual search of the DEM or the high-resolution photography. A deep-learning algorithm works by delineating certain attributes of a ‘typical’ boulder. Once the algorithm has been ‘trained’ to find these features in a small area, it can be used to search for similar features across the hillside. This technique has many applications and has been used to analyse various aspects of remote sensing data such as change detection and object recognition (Ma et al, 2019).

This method was trialled on the DEM created from the terrestrial laser scan of the site. While the algorithm was able to successfully identify some of the boulders on the hillside, it was an insufficiently significant proportion to be able to populate the preliminary inventory in detail. It is considered that coupling the laser scanning data with geo-referenced photogrammetry may have been more effective as this would have enabled the algorithm to search for boulders using changes in colour as well as identifying morphological changes that are typical of boulders on the slope. The algorithm also had difficulties in distinguishing between boulders and rock outcrops. This is partially due to the fact that the laser scan was taken from the opposite hillside and this orientation did not allow for the upslopeside of the boulders to be captured in the scan. An extract image of the DEM created from the terrestrial laser scan is provided in Figure 4-1.

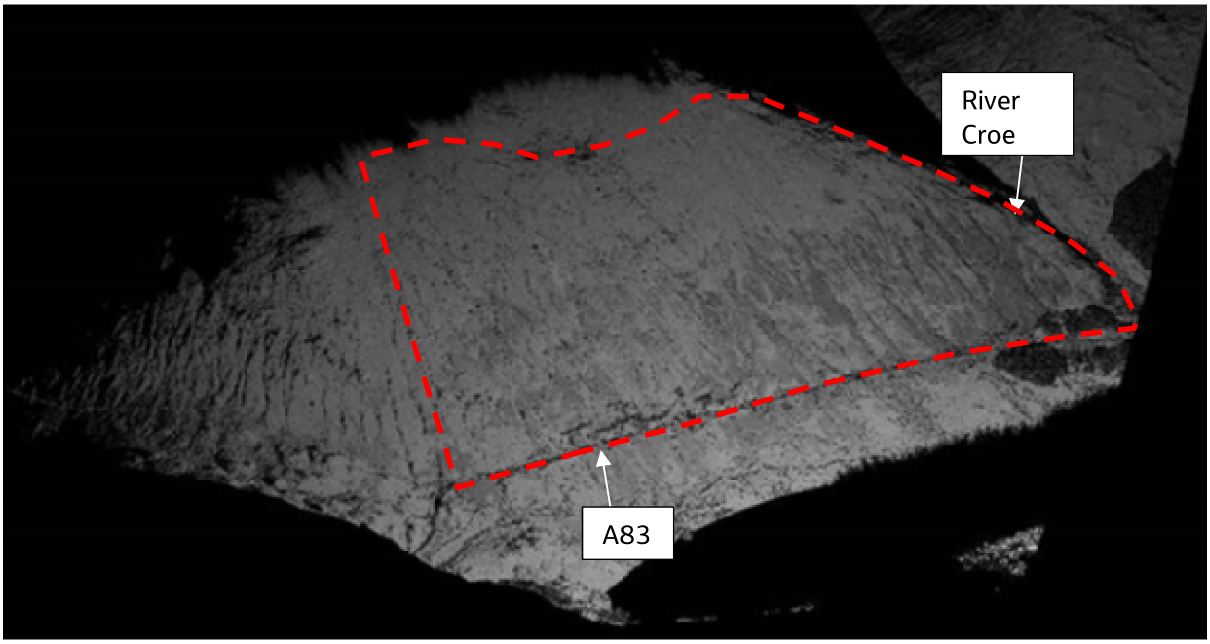

Figure 4-1: DEM of Study Area with Study Area boundary highlighted in red

4.1.2 High-resolution Panoramic Photography

High-resolution panoramic photography, captured by TRL (Winter et al. 2017, Winter & Ferreira 2019), was also provided for the study. This data was originally captured for the purpose of determining differences in the hillside geomorphology between photo-sets and has primarily been used for identifying potential instabilities on the hillside and other hazard and risk assessment activities. Similarly to the terrestrial laser scan data, the panoramic photographs were taken from the forestry track on the opposite site of the valley from Beinn Luibhean. The photographs are of high enough resolution to identify individual boulders on the hillside. At the time of writing, the most recent photographs available were taken on 30th April 2019. Unfortunately, cloud cover on this date was low, and the upper portions of the Study Area are obscured. Photographs captured during better weather on 15th November 2017 provide full coverage of the Study Area. However, debris flows that occurred in October 2018 disturbed the hillside above the Phase 1 and 7 debris barriers, and as such, the number of boulders identified on the November 2017 photographs is unlikely to truly reflect the number and location of boulders in parts of the Study Area.

Due to the nature of the photographs, compiling the preliminary boulder inventory using this data source could not be automated and the photographs were manually examined to identify boulder locations. Although a more time-consuming method, examination of the photographs identified a greater number of boulders when compared with boulders identified using the deep-learning algorithm and the terrestrial laser scanning data. However, a limitation of the photographs is that boulder size is difficult to assess due to the lack of reference points on the hillside. Boulders that were estimated to be in excess of 1.0m diameter are considered within the preliminary inventory.

A further limitation of the preliminary inventory compiled using the high-resolution panoramic photographs is that exact boulder locations were difficult to assess due to the panoramic nature of the photograph. Difficulties were experienced when trying to transpose the boulders identified from the cross-valley panoramic viewpoint, to a plan view of the site for fieldwork purposes.

An example of the high-resolution panoramic photography used to identify boulder locations is provided in Photograph A-7 in Appendix A.

4.1.3 Unmanned Aerial Vehicle (UAV) Survey

A UAV photogrammetry survey of the Study Area above the Phase 1 and 7 debris barriers was undertaken by GeoRope Ltd following the October 2018 debris flows. This has allowed a full-colour DEM to be produced in this area.

The DEM can be visually interrogated to identify boulder locations, and boulder sizes can be measured from the geo-referenced model. An extract from the model is provided in Figure 4-2.

As the images were captured aerially, boulders can be viewed from all angles, meaning that it is easier to distinguish boulders from rock outcrops in comparison to the other data sets trialled.

While the data can be interrogated manually in order to count the number of boulders present, it is envisaged that a deep-learning programme could be utilised more effectively in comparison with the terrestrial laser scan DEM, as the photogrammetry data set would potentially allow more effective delineation of attributes of a typical boulder due to the presence of colour which may allow more comprehensive 'training' of the model to identify boulders from the surrounding landscape.

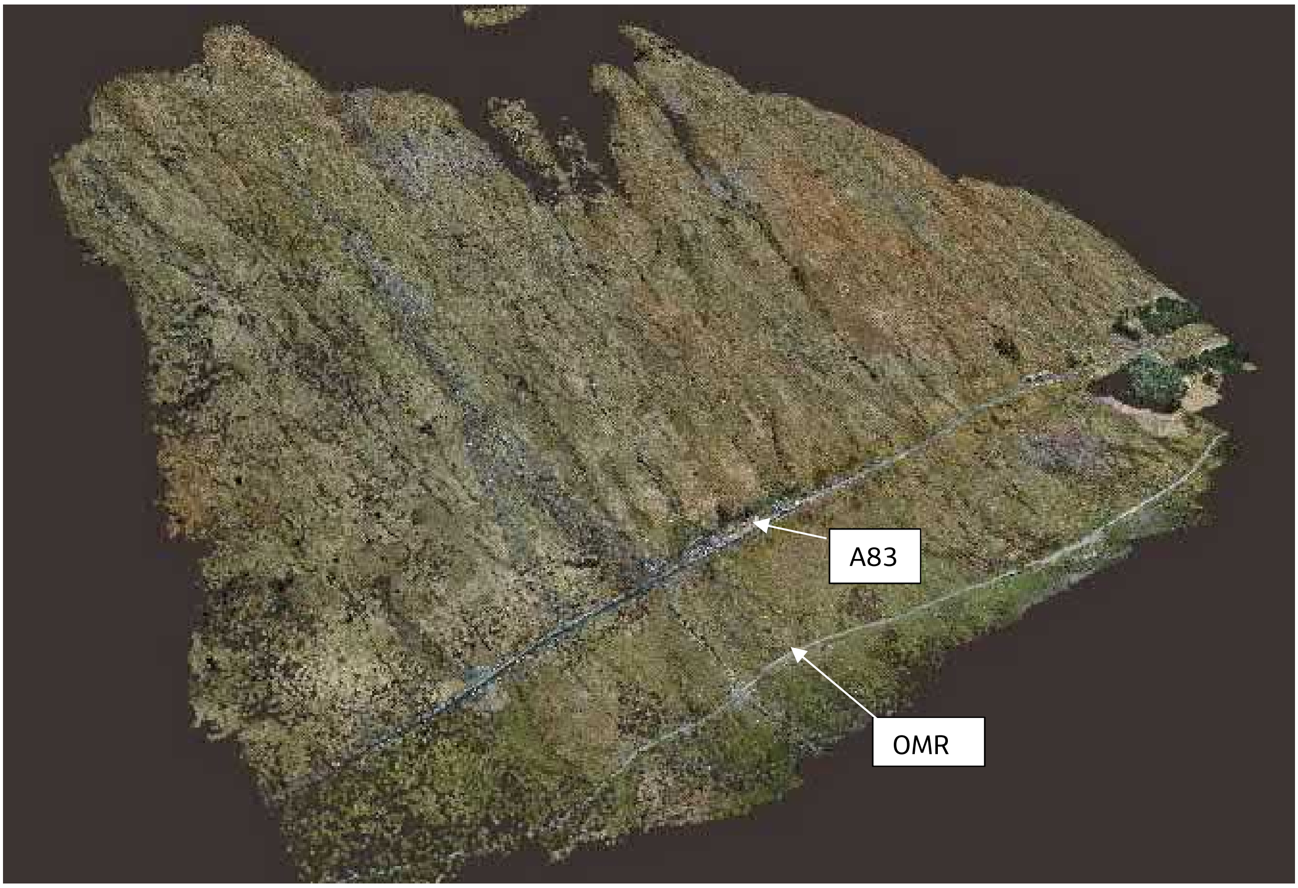

Figure 4-2 - DEM prepared using UAV photogrammetry

4.2 Preliminary Boulder Inventory (Detailed Study Area)

Due to the significant quantity of boulders on the slope within the Study Area, the boulder hazard study focuses on a smaller area of the site termed hereafter the 'Detailed Study Area'. The area of hillside chosen for detailed study is located immediately above the Phase 1 debris barrier and extends south to the drainage channel that flows towards the Phase 7 barrier. Several studies have been undertaken in this area following landslide activity in recent years and there is a considerable amount of existing information and datasets for the Detailed Study Area. The area selected for detailed study is detailed on Figure 4-3.

After comparing the three data sources outlined in Section 4.1, the preliminary boulder inventory was compiled by manually interrogating the Geo-rope photogrammetry DEM using the photogrammetry software Pix4Dmapper. This allowed boulder coordinates and elevations to be recorded. A measuring tool also allowed approximate boulder dimensions to be included on the preliminary inventory. Using this software, 126 boulders in excess of 1.0m maximum dimension were recorded. The locations of the boulders recorded in the preliminary inventory are shown on Drawing B-2 in Appendix B. Data included in the preliminary inventory including the boulder ID, coordinates and approximate maximum dimension is provided in Table C-3 in Appendix C.

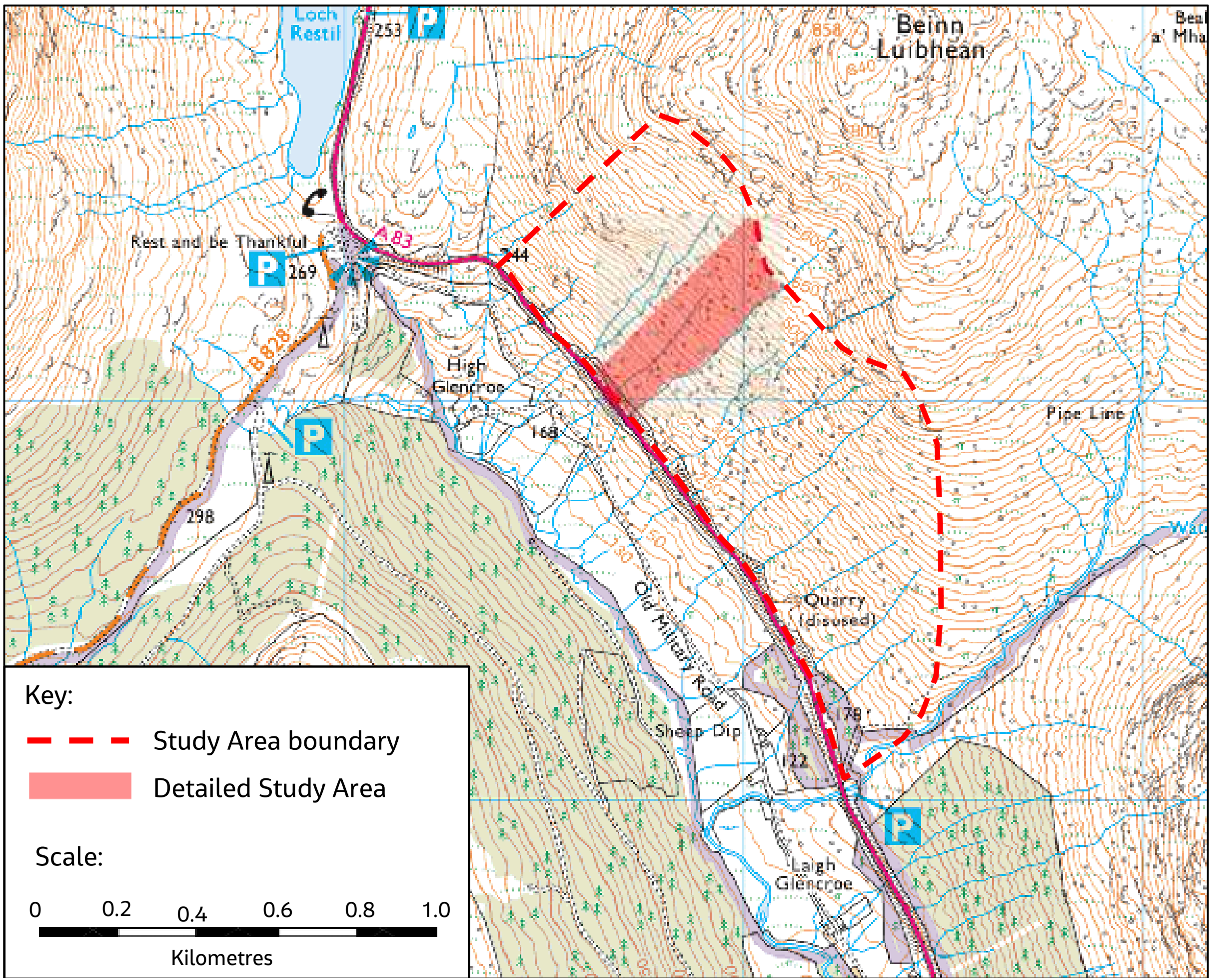

Figure 4-3 - Plan showing Detailed Study Area location

5. Fieldwork

5.1 General

Following preparation of the preliminary boulder inventory, fieldwork was undertaken to validate the results from the inventory and to update the inventory with respect to boulder properties that would be required as input parameters for the boulder fall-path modelling. The fieldwork was undertaken during eight separate site visits between September and November 2019.

5.2 Data Collection Methodology

Data gathering during the fieldwork for this study was streamlined using a tablet loaded with an ArcGIS Collector application. The Collector application allows map-driven forms to be created which allows project-specific field data to be collected. The application integrates with ArcGIS software, allowing other tasks to be completed, such as creating GIS-based drawings, without having to transfer data between operating systems.

The Collector application was pre-loaded with OS mapping and preliminary boulder inventory data, allowing for easy navigation via in-app GPS to a point of interest in the Detailed Study Area. When recording boulder data, the programme uses drop-down lists to select various attributes that are saved for each boulder. The application also has a function allowing geo-referenced photographs to be 'tagged' to individual boulders.

The type of data chosen to be included within the Collector application was based on the input parameters required for the fall-path modelling software, RAMMS: Rockfall, as well as other slope features that could be important during the hazard assessment. This included boulder shape and dimensions, release parameters (x,y,z coordinates), and evidence of slope instabilities that could relate to boulder fall triggering mechanisms, for example tension cracks.

A summary of the fields used with the Collector application for data collection is provided in Table C.4 in Appendix C. In addition to the boulder attributes logged within the application, at least one representative photograph was taken of each boulder, and a photograph looking down-slope of the boulder was taken with respect to verification of likely fall trajectories during the fall-path modelling.

5.3 Site Visit Observations and Final Boulder Inventory

At an early stage during the fieldwork, it was realised that there was a far greater number of boulders present on the slope in excess of 1.0m diameter than was identified during interrogation of the DEM. There appear to be several reasons for this. On many occasions, boulders were covered in vegetation and were either not recognised as boulders from the DEM, or the maximum dimension appeared smaller than the actual dimensions as the boulder was partially obscured. This led to some boulders being discounted from the preliminary inventory as the maximum dimensions appeared to be smaller than the 1.0m dimension threshold. On several occasions, boulders lying in close proximity to each other were observed as a single boulder on the DEM and were later confirmed as clusters of boulders during the fieldwork. True boulder dimensions were occasionally also obscured as they were covered in soil, particularly in areas where debris flows had recently occurred. This also led to some boulders being discounted from the preliminary inventory as the maximum dimensions appeared to be less than 1.0m.

During the fieldwork, 119 of the 126 boulders in the preliminary inventory were confirmed. Seven boulders were discounted due to either being confirmed as bedrock or as being smaller than the 1.0m diameter threshold.

An additional 335 boulders in excess of 1.0m dimension were identified during the fieldwork, bringing the total number of boulders identified within the Detailed Study Area to 454. The number of additional boulders identified equates to approximately three times the number of boulders in the preliminary inventory.

In some instances, several boulders were found to lie in very close proximity to each other in clusters. Where this occurred, a single point was recorded and the boulder with the maximum dimensions was recorded, noting the number of boulders within the cluster. The purpose of this was to improve efficiency during the fieldwork. To denote multiple boulders at the same location, these boulders have been allocated the same inventory number but a suffix, a, b, c, etc., has been added to the boulder designation. Each boulder within the clusters has been included in the total number of boulders identified in the Detailed Study Area.

With respect to boulder properties, many of the boulders were recorded as being tabular in shape. This is likely due to the nature of the schistose bedrock causing boulders to be formed along existing discontinuities.

In many cases, true boulder dimensions were obscured due to boulder embedment within the soil. Where this has occurred, a maximum visible dimension has been recorded, and the boulder has been noted as having a minimum dimension on the inventory. On rare occasions, boulders were embedded so that the boulder surface was flush with the ground surface and the third dimension could not be determined. On such occasions, the third dimension has been recorded as ‘undetermined’ in the boulder inventory.

In some cases, it was not possible to directly measure boulder dimensions due to them being located within steep inaccessible stream channels. On such occasions, boulder dimensions were estimated from a safe distance and any estimated dimensions have been noted as such in the inventory.

The additional boulders identified during the fieldwork as well as those confirmed from the preliminary inventory that were verified during the fieldwork, are provided on Drawing B.3 in Appendix B. A full list of the boulders and associated characteristics contained within the final inventory from the Detailed Study Area is provided in Table C.5 in Appendix C.

6. Fall-Path Modelling

6.1 Overview

RAMMS: Rockfall is a 3D rockfall simulation program that applies non-smooth (i.e. frictional), rigid-body mechanics coupled with hard-contact laws to predict rock trajectories in three-dimensional terrain (Leine et al., 2014). The software is designed to be used to predict rockfall velocity and runout for hazard mapping and planning of rockfall mitigation measures.

To date, most rockfall simulation programs have utilised simple rebound mechanics to describe the complex interactions between rocks and the ground (Bourrier et al., 2012). Within these programs, rock bodies consist of simplified shapes (e.g. spheres or ellipsoids), and the entire rock-ground interaction is parameterised and modelled using apparent coefficients of restitution, which work by reducing the entire rock-ground interaction to a single point in time and space (Caviezel et al., 2019).

RAMMS: Rockfall differs fundamentally from existing rockfall simulation programs because rock-ground interactions are parameterised by frictional operators that act at the rock surface. Compared to rebound models, the hard-contact, rigid-body approach used by RAMMS applies contact forces to the edges and corner points of rock bodies. This allows for rock shape to be accounted for in the rock-ground interaction, thus facilitating more complete modelling of the four primary modes of rock motion: falling, bouncing (i.e. jumping or skipping), rolling and sliding. According to Bartelt et all. (2016), modelling all four modes of rock motion is essential for realistic, self-consistent and risk-based rockfall hazard analysis.

Within RAMMS: Rockfall, rock bodies are modelled as convex hull polyhedrons, the shape and size of which can be acquired from remote sensing undertaken during field campaigns. This allows for the natural variability of rock shape and size, derived from different geological settings, to be accurately captured (Caviezel et al., 2019).

Another fundamental feature of RAMMS: Rockfall is the division of the terrain into a plastic, deformable scarring layer and a non-deformable, hard-contact slippage plane (Figure 6-1). This approach allows for rock-surface penetration, scarring, slipping and rebounding, and associated energy dissipation to be accurately accounted for, thus facilitating a more realistic model.

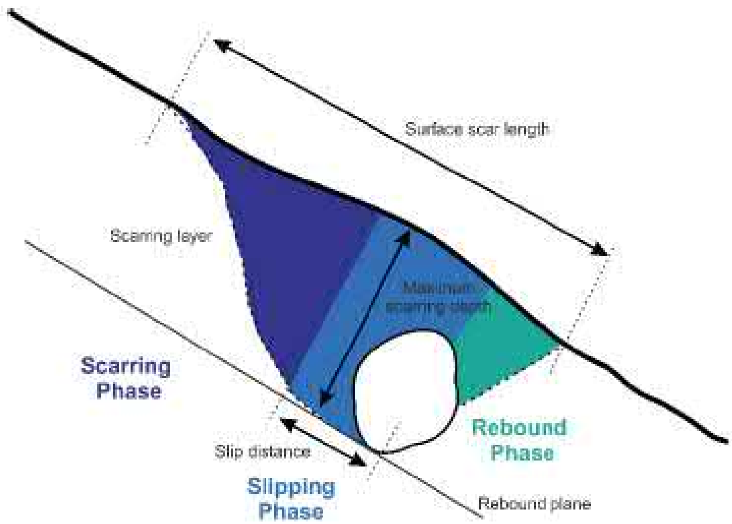

Figure 6-1: Illustration of the three distinct phases of rock-terrain interaction implemented in RAMMS: Rockfall – scarring phase, slipping phase, and rebound phase (Caviezel et al., 2019).

6.2 Input Parameters

This section describes the four primary input parameters required to undertake rockfall simulations using RAMMS: Rockfall. These include: Terrain Model, Rock Parameters, Terrain Parameters, and Release Parameters.

6.2.1 Terrain Model

RAMMS: Rockfall simulates the trajectories of falling rocks in three-dimensional terrain using high-resolution DEMs. How a rock moves downslope (i.e. runout trajectory, velocity, kinetic energy and jump height) is strongly influenced by its interaction with the terrain. Therefore, simulation results depend strongly on the resolution and accuracy of the topographic input data. To ensure that important terrain features are correctly represented by DEMs, a resolution of between 1m and 10m is recommended. Resolutions of less than 10m can lead to unrealistic simulation results, especially within the Beinn Luibhean Study Area, which comprises high levels of meso-scale roughness (i.e. features in the range of 0.1-0.5m).

Once topographic data has been converted into an ESRI ASCII grid, the DEM and its coordinate system form a simulation frame (O), in which four-sided planes (i.e. each defined by four coordinate pairs) form a tessellated terrain surface (Figure 6.2). The horizontal distance between coordinate pairs defines the model terrain resolution and therefore the accuracy with which the terrain morphology is represented (Bartelt et al., 2016). The properties of each plane can be varied to account for variable surface properties, such as hardness and roughness (e.g. forested areas can be defined as planes with enhanced drag).

To construct the simulation model of Beinn Luibhean used in this study, a high-resolution digital surface model (DSM) of the slope was captured using a terrestrial laser scanner (TLS) located on the opposite side of the valley (operated by Newcastle University). Following appropriate geo-referencing and pre-processing (e.g. DEM subsampling to facilitate the available hardware), the final DEM was found to comprise 12,380,820 nodes, with a spatial resolution of 0.2m (i.e. 25 times higher than the lowest resolution recommended by RAMMS), and therefore considered to be very high resolution.

As DSMs represent the surface of the earth surface and all objects on it, existing debris barriers constructed on lower sections of the Study Area were also incorporated into the simulation model as solid bodies. The possible effects of these structures on boulder trajectory reconstruction results are discussed in Section 6.5.

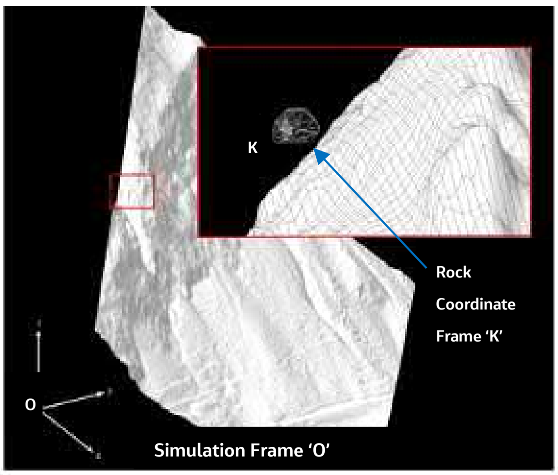

Figure 6-2: Simulation frame O, comprising a tessellated terrain surface with which rock bodies (K) can come into contact (Bartelt et al., 2016).

6.2.2 Rock Parameters

Rock bodies are introduced into the simulation domain (i.e. simulation frame O) as a cloud of points based in a coordinate system of the rock's origin. This coordinate frame (K) serves to map the rotations of the rock body (Figure 6-2). Rock body point clouds can be artificially generated or acquired from remote sensing undertaken during field mapping (e.g. 3D laser scanning or digital photogrammetry). Once generated or acquired, a convex hull polyhedron of the rock body point cloud is created by the model, allowing for its centre of mass and inertial tensor to be calculated (Figure 6-3). Bartelt et al. (2016) give details of the mathematical operations applied.

If no additional remote sensing is undertaken during field mapping in order to acquire unique rock body point clouds, RAMMS: Rockfall offers a *Rock Builder* tool to create realistic point cloud files from predefined rock shapes that are stored within a rock library. Given the effect rock shape has on modelling results, RAMMS: Rockfall recommends that the *Rock Builder* tool is used for simulations, as opposed to software generated spheres, cuboids or ellipsoids (Figure 6-3). The rock library contains three realistic rock shape classifications: equant, flat and long, each with predefined initial rock characteristics: dimensions, density, mass and volume. At present, the density, mass and volume of these rocks can be manually altered by the user; however, their field-measured dimensions cannot. Rock dimensions are automatically generated depending on the assigned rock shape classification and/or rock volume. As such, despite the interdependencies of density, mass and volume, it is not possible to vary the shape of these rocks to exactly match those recorded in the field, and a best-fit approach must instead be used.

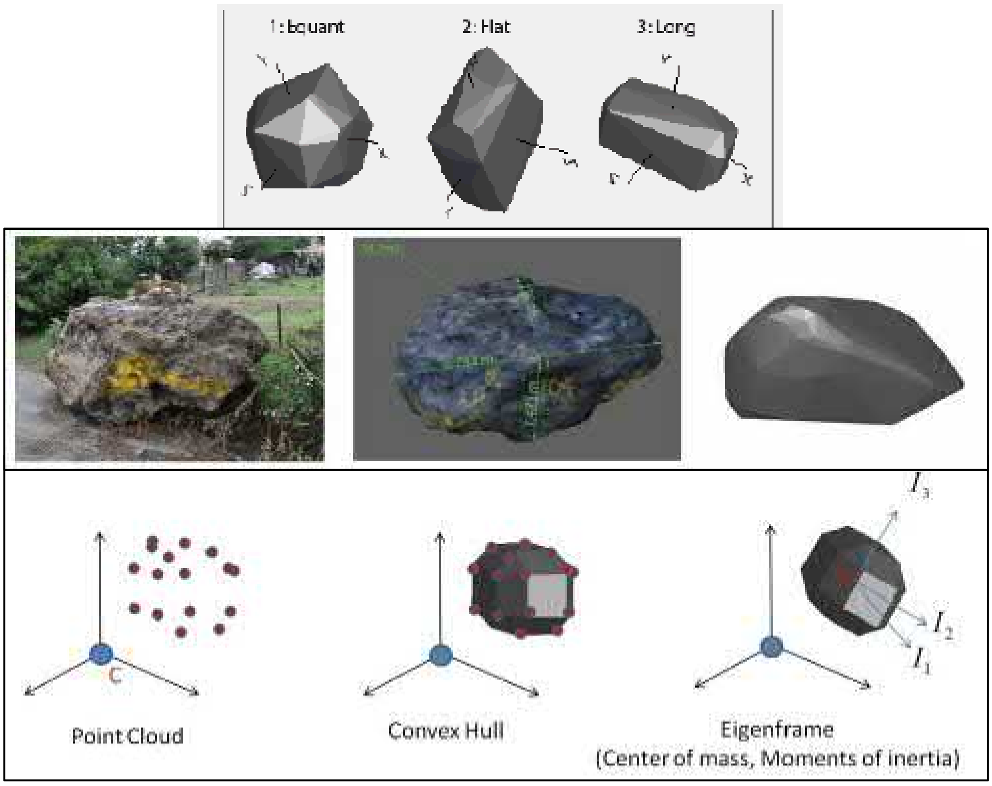

Figure 6-3: Equant, flat and long convex-hull polyhedrons that represent real boulders have been built using point clouds of Swiss boulders. These pre-built boulders can be used for modelling. Site-specific rock libraries can also be compiled if unique boulder point clouds are available (Bartelt et al., 2016).

6.2.3 Terrain Parameters

Eight predefined terrain categories, ranging from extra soft to extra hard, each with its own unique friction and drag forces, are contained within the program (Figure 6-4). Frictional forces act on the points of a rock surface that are in contact with the ground, and control when a rock slides, rolls or jumps. Drag forces act at the centre of the rock mass, in the opposite direction to movement, and account for terrain deformation during ground contact. These parameters (and therefore terrain material) have a considerable influence on the results of rockfall simulations.

If there is any uncertainty as to the terrain material of a given study area, Bartelt et al. (2016) recommend that the results of different terrain scenarios are compared. Following appropriate comparison and model calibration, a global terrain category can then be defined. For more variable study areas, shapefiles can optionally be used to delimit areas with differing terrain types.

Terrain	Mu_Min	Mu_Max	Beta	Kappa	Epsilon	Drag
Extra Soft	0.2	2	50	1	0	0.9
Soft	0.25	2	100	1.25	0	0.8
Medium Soft	0.3	2	125	1.5	0	0.7
Medium	0.35	2	150	2	0	0.6
Medium Hard	0.4	2	175	2.5	0	0.5
Hard	0.55	2	185	3	0	0.4
Extra Hard	0.8	2	200	4	0	0.3
Snow	0.1	0.35	150	2	0	0.7

Figure 6-4: Terrain material default parameter values. Bartelt et al. (2016) give further information on these parameters.

6.2.4 Release Parameters

Rockfall starting zones can be specified by setting a release point, drawing a release line, or defining a release area. As the definition and localisation of rockfall starting zones can have a significant influence on the results of a simulation, RAMMS: Rockfall recommends that reference information such as photographs, GPS measurements or field maps are used to more accurately define starting zones.

In addition to specifying rockfall starting zones, it is also possible to specify initial velocity, rotational velocity, and Z-Offset (i.e. the initial fall height of a rock measured from its centre of mass). If this information is not available, the software can automatically calculate the minimal offset that is necessary to initiate movement. To introduce variability into the rockfall simulation, it is also possible to specify the number of random release orientations of each rock. The number of random release orientations should seek to strike a balance between statistical reliability and processing time.

6.3 Preliminary Fall-Path Modelling and Sensitivity Analysis

Before undertaking detailed fall-path modelling, a series of sensitivity and preliminary rockfall trajectory analyses was performed. These analyses allowed for early calibration of the model through the identification of sensitive and non-sensitive input parameters, simplification of the model by allowing for model inputs that had little to no effect on the output to be fixed, and an overall increased understanding of the relationships between different input and output variables.

The findings of these analyses are summarised below.

6.3.1 Rock Parameters

Due to time and cost constraints, it was not possible to collect unique point clouds of each rock body identified during field mapping, leading to the use of the in-built rock library. The implications of this are discussed in Section 6.5.

Comparisons between the three pre-defined rock shape classifications stored within the rock library (i.e. equant, flat and long) revealed runout trajectory to be extremely sensitive to rock shape. Upon release from the same starting point (and with the same rock characteristics and number of random release orientations), equant and long boulders were found to have significantly longer and laterally variable runout trajectories than flat boulders, which were more readily stopped by gullies and other surface depressions. Equant boulders exhibited the most extreme runouts (both laterally and longitudinally).

Further comparisons also revealed rock velocity, kinetic energy and jump height to be highly sensitive to both rock shape and rock volume/mass. Upon release from the same starting point, equant and long boulders were found to have higher velocities, kinetic energy and jump heights than flat boulders throughout the entire trajectory. Once more, equant boulders exhibited the most extreme values, and did not appear to show significant reductions in velocity, kinetic energy or jump height until greater distances along the fall paths had been reached. Increases in rock volume/mass generally resulted in increases in velocity, kinetic energy and jump height (e.g. median kinetic energy values were seen to increase by over 1000% (1330kJ to 16650kJ) from the $1m^3$ to the $10m^3$ simulation – more than 10 times the increase that would be expected from the difference in mass alone).

Based on these early results, and in order to construct a more conservative model (in regards to run-out trajectory), attempts were made to match boulders identified and described during field mapping with either equant or long software shape classification boulders. During this process, efforts were made to ensure that the volume of each boulder measured in the field matched that of the software-generated boulder as closely as possible (Figure 6-5).

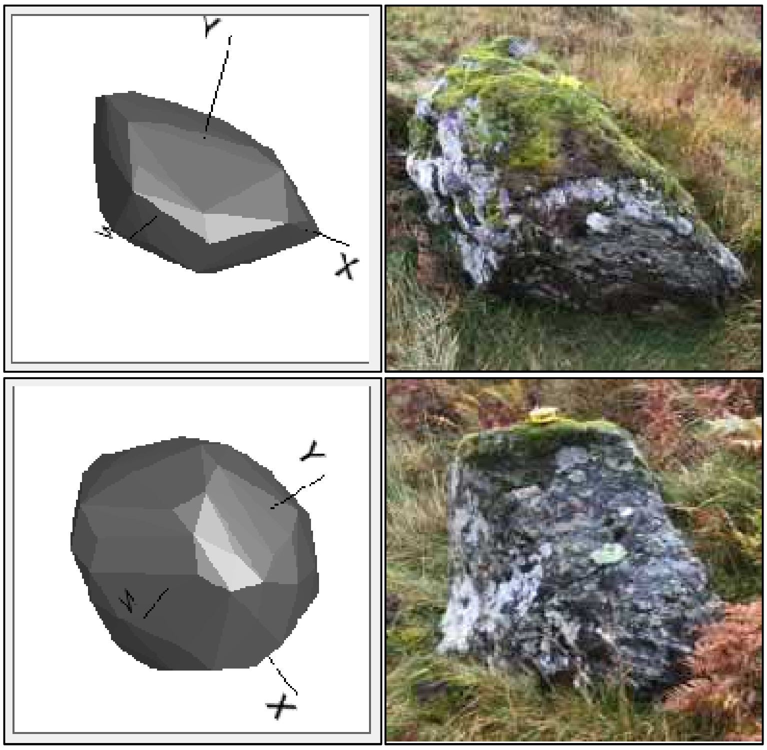

Figure 6-5: Boulders with a cuboid-like appearance were modelled using the long rock shape classification (top). Boulders with a shape that could be more closely approximated to a cube or a sphere (rather than a cuboid or cylinder) were modelled using the equant rock shape classification (bottom).

6.3.2 Terrain Parameters

Based on existing knowledge of the Beinn Luibhean slope, which has been studied extensively in recent years (e.g. Jacobs 2018a), it was possible to narrow the eight pre-defined terrain categories down to just two: medium hard and hard (Figure 6-6).

Subsequent comparisons of the influence of these two pre-defined terrain categories on the runout trajectory, velocity, kinetic energy and jump height of rockfall simulations found the influence on the model results to be negligible (e.g. the median velocity, kinetic energy and jump height values of a 1.4m^3 equant boulder, released from the same starting point on both terrain categories, were found to be within 3% of each other). The influence of the remaining pre-defined terrain categories on runout trajectory and intensity were found to be more significant (e.g. extra soft vs. extra hard terrain); however, none of these categories were suited to the Beinn Luibhean slope. Therefore, whilst it is possible to use shapefiles to delimit terrain areas with specific terrain materials (e.g. localised areas of hard terrain), this was not considered necessary for this Study Area and the model was instead simplified such that the entire slope comprised a global medium hard terrain. The possible effects of this model simplification are discussed in Section 6.5.

Medium Hard		Penetration depths are small. Ground is flat. Rocky debris is present. Shallow surface soil. Usually little (initial) vegetation.	Non-paved mountain roads, mountain meadow, pebble
Hard		Rocks jump over ground. Mixture of large and small rocks. Usually without any vegetation.	Rock scree, pebble, coarse rock, paved roads

Terrain	Mu_Min	Mu_Max	Beta	Kappa	Epsilon	Drag
Medium Hard	0.4	2	175	2.5	0	0.5
Hard	0.55	2	185	3	0	0.4

Figure 6-6: Terrain categories considered best suited to the Beinn Luibhean slope, and the associated default parameter values.

6.3.3 Release Parameters

All rockfall starting zones were specified by setting release points based on the OSGB (NGR) XY coordinates of boulders identified and described during field mapping. To further increase accuracy, these GPS measurement-based release points were also cross checked against high resolution terrestrial and aerial photography of the slope. Therefore, the definition and localisation of each rockfall starting zone was sufficiently accurate enough that the exploration of alternate starting zones was considered unnecessary.

However, in order to introduce some level of variability into each rockfall simulation, it was considered necessary to specify a number of random initial release orientations for each rock. Comparisons between different numbers of random initial orientations (i.e. 50, 100, 250, 500 and 1000) revealed runout trajectory to be moderately sensitive to initial orientation (e.g. increasing the number of random initial orientations from 100 to 1000 was not observed to have a considerable effect on the lateral runout of boulders, but did increase the longitudinal runout and, therefore the statistical probability of rocks reaching the A83.

Other comparisons of the influence of different numbers of random initial orientations on rock velocity, kinetic energy and jump height were found to have negligible effect, with mean values of each of these output parameters found to be within 1% of one another.

6.3.4 Final Input Parameters

Sensitivity and preliminary rockfall trajectory analyses were successful, allowing for early model calibration and simplification, and yielding an increased understanding of the relationships between different input and output variables. The outcomes of these analyses, along with the associated implications for subsequent detailed fall-path modelling, are summarised in Table 6.1.

Table 6-1: Summary of input parameters used for detailed rockfall trajectory reconstructions

Input Parameter		Sensitivity (Runout)	Sensitivity (Velocity/Kinetic Energy/ Jump Height)	Implication for Detailed Modelling
Rock	Shape	Very High	High	Long or equant rock library shape classification assigned based on field descriptions and photographs
	Volume/Mass	High	High	Model boulder volume matched to within 10% of field measurements
Terrain	Category	Low*	Low*	Global medium hard terrain material category applied to entire slope
Release	No. Random Orientations	Medium	Low	1,000 random initial release orientations for each simulation

*Low sensitivity observed between two pre-defined categories considered appropriate for the Beinn Luibhean slope (Medium Hard and Hard). High sensitivity observed between remaining categories (e.g. Soft vs. Hard).

6.4 Detailed Fall-Path Modelling

This section presents the findings of the detailed rockfall trajectory analyses, including calculated probability risk to the A83. All results are summarised in Table 6-5.

6.4.1 Justification of Boulders selected for Detailed Fall-Path Modelling

Of the 454 boulders identified and described during field mapping, 26 (i.e. 6%) were selected for detailed rockfall trajectory reconstruction (Figure 6-7). From the database, boulders were manually selected in order to ensure that a wide variety of rock and release parameters were considered. Field rock parameters include shape, volume/mass, level of embedment, and potential for instability. Field release parameters include rock position (i.e. proximity to drainage channels) and elevation on the slope.

An additional 10 software generated boulders (i.e. not based on real boulders identified and described during field mapping) were also constructed for secondary rockfall trajectory reconstruction, in order to further explore the effects of certain rock parameters (namely shape and extreme volume) on model output. The effects of these boulders are described in Table 6-4.

Figure 6-7: Release points of boulders selected for detailed simulation

6.4.2 Results

26 boulders (i.e. excluding the 10 software generated boulders) were selected for detailed fall-path modelling, resulting in a total of 26,000 simulations being performed (i.e. 1,000 random release orientations given to each of the 26 boulders).

Of these 26,000 boulder simulations, 152 reached the A83. 78 passed the A83, and 31 reached the Old Military Road (OMR). Out of the simulated boulders reaching the A83, 150 of these were equant and 2 were long (ID31). No long simulated boulders passed the A83 or reached the OMR. Reasons for these large differences and the important influence of boulder shape are discussed in Section 6.5. The simulation results are summarised in Table 6-2.

Table 6-2: Summary results of all detailed boulder simulations

	Reach A83		Pass A83		Reach OMR	
	Number	Percent	Number	Percent	Number	Percent
Total	152/26000	0.58%	78/26000	0.3%	31/26000	0.12%
Equant	150/11000	1.36%	78/11000	0.71%	31/11000	0.28%
Long	2/15000	0.01%	0/15000	0%	0/15000	0%

Of the 26 boulders selected for detailed modelling, the simulations indicate that 17 have the potential to reach the existing protection barriers installed above the A83 (i.e. at least one of the 1,000 random release orientations assigned to each of these 17 boulders reached the barriers during the simulations). Out of these 17,000 simulations, 2,470 were stopped at the barriers regardless of their velocity or kinetic energy values, and 4,338 passed the existing barriers, either through gaps between barriers or by jumping over them. However, whilst the simulation model can accurately account for the height of each barrier, it cannot account for their energy capacity, and instead treats them like any other area of terrain. The effects of barriers on simulation results are further discussed in Section 6.5. Further details of these results, including information on rock shape and percentage probability, are summarised in Table 6-3. Full results of all detailed simulations are summarised in Table 6-5.

Table 6-3: Numbers of boulder simulations passing and/or stopped by existing rockfall barriers

	Passing Barriers		Stopped at Barriers	
	Number	Percent	Number	Percent
Total	4338/17000	25.5%	2470/17000	14.5%
Equant	3891/17000	22.9%	2183/17000	12.8%
Long	447/17000	2.6%	287/17000	1.7%

In order to gain a better understanding of the relationships between the different input and output variables, further analyses of the statistical outputs from each detailed rockfall trajectory reconstruction were undertaken.

The primary goals of these additional analyses were to identify the factors which had the most significant impact on (1) the probability of a mobilised boulder reaching the A83 (i.e. runout distance), and (2) the intensity (i.e. average velocity, kinetic energy and jump height) of a mobilised boulder. As mentioned in Section 6.2.1, due to the nature of the DSM used for these analyses which represents the earth's surface and all objects on it, the effects of the existing debris barriers constructed on the lower sections of the Detailed Study Area were considered.

As anticipated, based on the results of the preliminary fall-path modelling and sensitivity analyses (Section 6.3), boulder shape was found to have the most significant influence on runout trajectory. Regardless of rock starting position (i.e. XYZ coordinates) or the average slope angle at the starting position, equant boulders were found to have significantly longer and more laterally variable runout trajectories than long boulders, in all cases. Figure 6.8 compares the runout trajectories of equant and long boulders with similar volume and mass characteristics (to within 3%), released from the same starting positions.

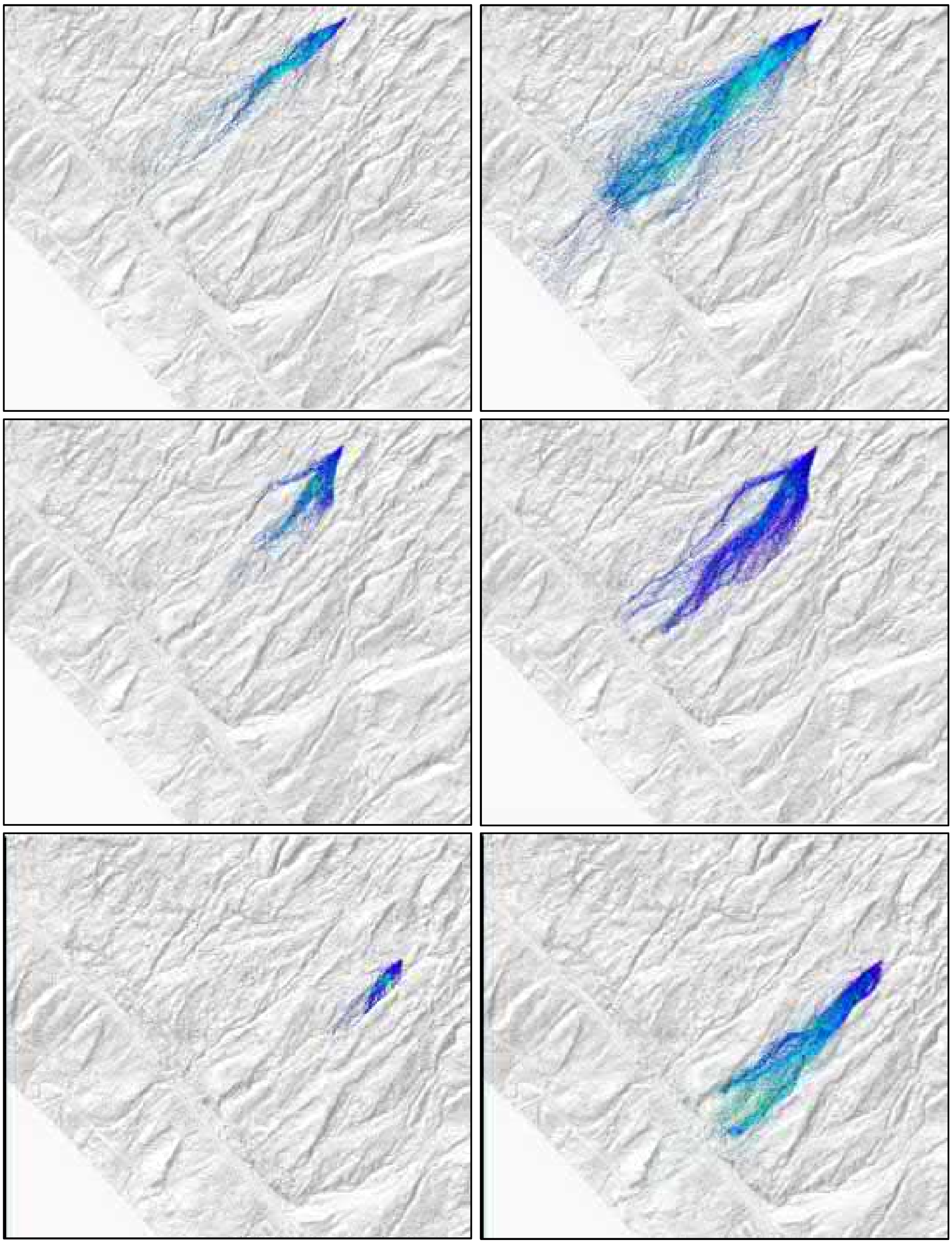

Figure 6-8: Comparison of runout trajectories of long (left) and equant (right) shape boulders with the same volume, mass and starting position characteristics.

Upon entering gullies or other surface depressions, long boulders were seen to experience a rapid loss of intensity (i.e. velocity, kinetic energy and jump height); this, in turn, resulted in a rapid transition of boulder mode of motion from bouncing to rolling or sliding. By comparison, equant boulders were not observed to experience such rapid loss of intensity, which is thought to have led to preservation of rotational velocity (and therefore gyroscopic forces), preservation of jumping and/or skipping motion, and therefore more extreme runouts. These results, including the influence of boulder mode of motion on runout trajectory, are further discussed in Section 6.5.

Boulder shape was also found to have a significant influence on intensity, with equant boulders generally seen to exhibit greater velocity, kinetic energy, and jump height values than long boulders of comparable volume. However, the impact of boulder volume and mass on intensity was not as significant as originally anticipated (e.g. during preliminary fall-path modelling, median kinetic energy values were seen to increase by over 1000% (1330kJ to 16650kJ) from the 1m^3 to the 10m^3 simulation). Indeed, increasing boulder volume was seen to have a moderate positive correlation with kinetic energy, but displayed no clearly identifiable correlation with velocity or jump height.

Instead, boulder volume was seen to have the strongest correlation with z-offset (i.e. the initial fall height of a rock measured from its centre of mass), with larger boulders requiring larger initial vertical movements in order to initiate movement. Apart from rock shape, z-offset was found to have the most significant impact on the intensity of a mobilized boulder; and was seen to result in a cascading effect between jump height, kinetic energy, and velocity. The influence of z-offset on boulder mode of motion and intensity is discussed further in Section 6.5. Further details of the relationships observed between input and output (including intensity) parameters are summarised in Table 6-4.

Table 6-4: Summary of relationships observed between different input and output parameters. For example, as input parameter Volume is increased, a strong positive correlation is observed with output parameter Z-Offset (i.e. larger volume boulders require a greater Z-offset value to become mobilised).

Output	**Z-Offset** (m)	Strong Positive	-	No influence	No influence	No influence	No influence
	Velocity (m/s)	No Correlation	No Correlation	-	Moderate Positive	Moderate Positive	Moderate Positive
	Rotational Velocity (rot s-1)	No Correlation	No Correlation	Moderate Positive	-	Moderate Positive	No Correlation
	Kinetic Energy (kJ)	Moderate Positive	Moderate Positive	Weak Positive	No Correlation	-	Strong Positive
	Jump Height (m)	No Correlation	Strong Positive	Moderate Positive	Weak Positive	Strong Positive	-
		Volume (m^3)	**Z-Offset** (m)	**Velocity** (m/s)	**Rotational Velocity** (rot s-1)	**Kinetic Energy** (kJ)	**Jump Height** (m)
		Input					
* At extreme, software-generated volumes (i.e. the 10 additional virtual boulders, described in Section 6.4.1), weak negative correlations were observed between volume and velocity, and weak positive correlations observed between volume and jump height.							

Table 6-5: Summary of results from detailed fall-path modelling.

Boulder Properties					Simulation Results														
ID	Field Shape[(1)]	Model Shape[(2)]	Field Volume (m^3)	Model Volume (m^3)	Z-Offset (m)[(3)]	Reaches Barrier	No. Stopped at Barrier[(4)]	Reaches A83	No. Reaching A83[(4)]	Passes A83	No. Passing A83[(4)]	Reaches OMR	No. Reaching OMR[(4)]	Velocity (m/s) Mean/Max		Kin. Energy (kJ) Mean/Max		Jump Height (m) Mean/Max[(5)]	
5	T	L	0.4	0.4	0.71	Y	88	N	-	-	-	-	-	2.1	6.9	1.7	13.9	0.5	1.0
29	T	L	1	2	1.18	Y	104	N	-	-	-	-	-	3.2	10.9	19.4	166.4	0.8	3.7
31	C	L	4.7	5.4	1.64	Y	76	Y	2	N	-	-	-	6.3	22.9	189.8	1869.9	1.4	6.8
37	I	E	5.9	6.1	1.62	Y	437	Y	26	Y	4	Y	1	8.4	24.0	463.4	2816.8	1.7	-
52	T	L	3	7.2	1.72	Y	4	N	-	-	-	-	-	3.3	17.6	67.9	1325.3	1.1	6.2
67	T	L	2.1	2.8	0.98	N	-	N	-	-	-	-	-	3.6	13.5	14.1	155.8	0.7	3.1
89	T	L	3.6	3.8	1.38	N	-	N	-	-	-	-	-	2.5	11.4	19.7	289.8	0.9	2.9
91	I	E	5.3	6.2	1.63	Y	154	Y	37	Y	18	Y	9	8.2	28.2	497.4	4008.7	1.7	-
95	T	L	0.7	4	1.41	Y	2	N	-	-	-	-	-	4.0	20.5	60.2	1131.3	1.1	5.9
99	I	E	0.8	1	0.88	Y	75	Y	7	Y	2	N	-	5.1	17.4	27.5	234.7	0.8	5.4
103	I	E	1	1.4	1.05	N	-	N	-	-	-	-	-	2.4	8.7	7.6	78.5	0.7	2.0
125	I	E	6.4	8.3	1.79	Y	170	Y	1	N	-	-	-	3.5	15.4	121.4	1545.9	1.3	7.5
128	I	E	4.5	4.8	1.49	Y	468	Y	2	N	-	-	-	4.1	14.1	91.9	769.8	1.2	4.0
131	I	E	0.7	0.7	0.80	Y	176	N	-	-	-	-	-	4.1	14.7	13.8	127.5	0.7	7.7
150	T	L	1.5	1.9	1.16	Y	11	N	-	-	-	-	-	5.4	20.9	56.2	540.8	1.0	5.9
187	C	E	2.7	3.1	1.27	Y	241	Y	46	Y	31	Y	15	12.6	34.9	475.2	2949.7	2.1	-
193	T	L	0.5	1.3	1.02	N	-	N	-	-	-	-	-	6.1	22.4	44.1	445.9	0.9	7.1
200	T	L	0.4	0.5	0.70	N	-	N	-	-	-	-	-	3.9	19.3	7.3	128.7	0.6	5.1
211	I	E	2.2	3.1	1.29	Y	180	Y	22	Y	15	Y	3	9.2	31.5	297.3	2477.2	1.6	-
212	T	L	0.8	1.1	0.96	N	-	N	-	-	-	-	-	3.5	13.8	11.7	136.8	0.7	3.2
244	C	E	7.4	8.8	1.82	Y	114	N	-	-	-	-	-	7.2	27.7	502.9	7155.0	1.8	9.5
245	I	L	7.1	8.9	1.94	N	-	N	-	-	-	-	-	3.3	13.7	90.1	1128.5	1.5	4.3
253	T	L	3	9.3	1.97	Y	2	N	-	-	-	-	-	3.6	21.0	121.8	2793.0	1.4	5.8
259	T	L	2	4.3	1.52	N	-	N	-	-	-	-	-	2.9	15.3	35.5	655.8	1.0	3.5
270	T	L	0.9	1.1	0.97	N	-	N	-	-	-	-	-	3.1	11.7	10.3	103.1	0.7	2.5
290	I	E	9.7	9.8	1.86	Y	168	Y	9	Y	8	Y	3	8.6	28.0	760.2	5901.3	1.9	-

Notes:

(1) Field Shape: Rock shape recorded during field mapping. C: Cubic, I: Irregular, T: Tabular

(2) Model Shape: Rock shape classification selected for modelling. E: Equant, L: Long

(3) Z-Offset: The initial fall height of a rock measured from its centre of mass

(4) Numbers out of 1000

(5) Jump Height: Anomalous values removed. Such values (e.g. a maximum jump height of 3899m was calculated for ID187) are thought to be due to simulation errors (e.g. boulders 'falling' off the edge of the DEM)

6.5 Interpretation and Discussion of Results

6.5.1 Rock Size and Shape

The observation that rock size (i.e. volume) correlates inversely with likelihood of retardation is well documented (e.g. Evans and Hungr, 1993; Dorren et al., 2003; among others). Due to the lower kinetic energy values and higher likelihood of stopping in surface depressions, small rocks tend to retard more easily than large rocks.

Whilst the findings of this research are in line with those of previous authors (e.g. positive correlations were observed between rock volume and kinetic energy (Section 6.4)), increasing rock volume alone cannot explain the extreme runouts observed during detailed trajectory modelling. Instead, rock shape is indicated to have a more significant influence on likelihood of retardation and therefore runout trajectory, with long boulders found to retard more readily and abruptly than equant boulders, regardless of volume. These behaviours can be explained when considering rock mode of motion.

6.5.2 The Influence of Rock Z-Offset and Mode of Motion on Runout Trajectory

Once the minimum fall height required to initiate movement has been achieved, a rock will descend downslope in different modes of motion. These modes of motion strongly depend on average slope gradient, and include falling, bouncing (i.e. jumping or skipping), rolling and sliding (Ritchie, 1963; Dorren et al., 2003). Within RAMMS: Rockfall, the minimum fall height (i.e. z-offset) required to initiate movement and the average slope gradient are calculated automatically during statistical analysis. From the 26 boulders selected for detailed fall-path modelling, z-offset values of between 0.7m and 3.4m were calculated. In 24 out of 26 analyses, maximum slope angle was calculated to be above 70°, (effectively in freefall).

Based on the results of detailed fall-path modelling, the mode of motion of simulated boulders on the Beinn Luibhean slope is considered to be as follows:

Due to the initial z-offset required to initiate movement, all rocks begin to descend the slope in freefall. Freefall of rocks typically occurs on very steep slopes, where the slope gradient below the potential falling rock exceeds around 70° (Ritchie, 1963). During freefall, translation and rotation around centre of mass of the boulder occurs (Azzoni et al.,1995). Statistical analysis reveals that equant boulders generally experience greater rotational velocities than long boulders, suggesting that intensity of translation and rotation increases with rock roundness.

Following freefall rotation, both the direction and mode of motion of a falling rock can quickly change upon surface impact, compared with preceding directions (Dorren et al., 2003). If average slope gradient decreases in a down-slope direction, the mode of motion of a rock colliding with the surface will switch from freefall to bouncing. During the first bounce of a boulder previously in freefall, the boulder will either break, or at least 75% of the energy gained in its initial fall will be lost in that first impact (Evans and Hungr, 1993). Further, if the average slope gradient is less than approximately 45°, a rock will rapidly gather rotational momentum and the mode of motion of a bouncing rock will quickly transform into rolling. During rolling, only the rock faces with the largest surface area(s) maintain contact with the slope, resulting in centre of gravity of the boulder moving along an almost straight path, thereby causing the rock to experience rapid energy loss.

As the average slope gradient of Beinn Luibhean is around 35°, the mode of motion of most rocks was observed to transition rapidly from freefall to rolling in the early part of the trajectory (e.g. typically upon first contact with the surface). Small numbers of boulders were observed to transition from freefall to bouncing upon first contact; however, this was quickly transformed to rolling due to the relatively shallow average slope gradient. Following transition from freefall to rolling, long rocks were seen to experience rapid retardation, which is thought to be a result of the shape comprising fewer faces of larger surface areas, which more readily transfer momentum and energy into the ground surface on impact (Figure 6.5 top). By comparison, equant rocks, which comprise many edges of smaller surface areas (Figure 6.5 bottom), were seen to experience an increase in velocity, rotational velocity and jump height following initial transition from freefalling to rolling. This observed increase in intensity is thought to be a result of a greater surface area being in contact with the ground, which may cause preservation and development of additional rotational energy (in the form of momentum and gyroscopic force), and therefore promote another transition in mode of motion from rolling back into bouncing (i.e. in the form of skipping and jumping), even at average slope gradients of less than 45°. This re-initiation of bouncing is thought to be responsible for both the observed tendency of equant rocks to readily escape surface depressions (such as gullies), and the overall extreme lateral and longitudinal runouts.

Ultimately, the extreme runout trajectory and intensity values associated with equant boulders are largely dependent on the initial fall height (which, in turn, is a function of volume). As described in Section 6.4.3, further analysis of simulated statistical outputs reveals that z-offset has the most significant influence on the intensity of a mobilized boulder, often initiating a cascading effect between each parameter. However, based on existing knowledge of the Beinn Luibhean slope, the large z-offset values required to initiate freefall (i.e. sudden removal of up to 3.4m of underlying boulder material) automatically calculated by the software appear to be unrealistic. Shallow rotational and/or translational failures (which are predominant in this Detailed Study Area) are unlikely to result in the sudden removal of vertical columns of material, which raises concerns regarding software methodology, particularly the automatic z-offset function.

Unfortunately, as accounts of previous failures on the Beinn Luibhean slope are unable to quantify z-offset values, or observe boulder mode of motion in detail, it is not currently possible to better develop or refine the simulation model or its outputs. In order to do this, (i.e. incorporate a detailed back analysis into the model), it would be necessary to observe the mobilization of a discrete surface boulder in real time. This method would need to be capable of quantifying z-offset/volume of material lost from beneath a released boulder, using automated TLS with near real-time change detection using sequentially captured lidar point clouds (e.g. Kromer et al., 2017). Alternatively, the controlled mobilization of a boulder could be considered.

6.5.3 Modelling Rock Shape

The observation that different geological settings produce characteristic rock shapes has been well documented (Fityus et al., 2013). For example, a sequence of sandstones exposed to an extensional deformation regime will typically result in the formation of regularly spaced, orthogonal joint sets, which, in turn, will produce equant, cubic rock forms (Glover, 2015). More recently, thanks to advances in 3D rockfall simulation, the observation that specific rock shapes (characteristic of different geological zones) display distinctive runout behaviours, such as extreme jump heights and runout distances, has also been well documented (Caviezel et al., 2019).

One of the primary benefits of RAMMS: Rockfall is that real rock geometries representative of the different geological settings can be obtained by means of remote sensing undertaken during field investigations (e.g. by 3D laser scanning or digital photogrammetry). Unfortunately, due to the time and cost constraints, it was not possible to obtain unique rock body point clouds representative of the Beinn Luibheann Study Area during field investigation. Instead, all simulations were performed using pre-defined rock shapes (i.e. rock body point clouds) contained within the in-built rock library; which were acquired by means of remote sensing of real rocks from Swiss test sites Vallée de la Sionne and Illgraben.

Whilst the use of RAMMS: Rockfall's pre-defined rock shapes is considered superior to the use of software generated spheres, cuboids or ellipsoids (e.g. as used by alternative simulation programs), these rock bodies are ultimately characteristic of a geological setting that is entirely different to the Beinn Luibhean Study Area. This became evident during the early stages of rockfall inventory construction, where difficulties were found in matching the shapes and dimensions of boulders identified and described during field mapping with those contained within the rock library due to the natural variability caused by the differing boulder morphology. As it is not currently possible to manually alter the individual dimensions of rock library rock bodies, it was necessary to assume that measured boulder XYZ dimensions were interchangeable, and allow final rock volume (and therefore mass) to take precedence over dimensions.

In order to ensure that initial rockfall simulation conditions are as realistic and accurate as possible during future research, it is recommended that unique rock body point clouds of each rock be acquired during field investigation and subsequently modelled, as opposed to relying on rock geometries that are potentially unrepresentative of the geological setting being investigated.

6.5.4 Limitations and Next Steps

The main limitations of this research and suggested future developments, ranked in priority from low to high are summarised in Table 6-6.

Table 6-6: Summary of limitations of research and suggested future developments

Priority	Limitation	Suggested Future Development
Low	Terrain Material Based on existing knowledge of the Beinn Luibhean slope, and in attempt to simplify the model, the entire slope was given a global terrain material model of Medium Hard (Section 6.3.2). However, given the complexity of the rock-terrain interaction methodology applied by RAMMS: Rockfall (Section 6.1), and the possible effects of scarring, slipping and rebound on boulder mode of motion (Section 6.5.1); it is thought that this approach may have had an adverse (i.e. over-conservative) effect on predicted runout trajectories.	Ensure that slopes comprising complex and variable terrain types are appropriately delimited during simulation. Ensure that a variety of terrain scenarios are compared during sensitivity analysis, including a combination of different scenarios. Consider creating a custom terrain category based on results of in-situ testing.
Medium	Terrain Model (DEM) The simulation model of Beinn Luibhean was captured using a terrestrial laser scanner (TLS) located on the opposite side of the valley. Following appropriate processing, the final DEM was found to comprise over 12 million nodes, with a spatial resolution of 0.2m. The spatial resolution of the DEM used in rockfall simulation is fundamental in controlling rock-ground interactions, and therefore the results of trajectory modelling, with fine resolutions typically observed to decelerate and stop rocks much sooner than coarse resolutions. This is thought to be due to the representation of meso-scale surface roughness within the model, which is caused by single, small rocks and boulders or other small-scale terrain features (Buhler et al., 2016). For complex slopes such as Beinn Luibhean, which comprise localized areas of vegetation, debris from previous failures, surface tension cracks, etc., the representation of meso-scale roughness (i.e. in the range of 0.1-0.5m) is crucial. Therefore,	Ensure that slopes likely to experience complex rock-surface interactions (i.e. slopes with high levels of meso-scale roughness) are modelled using DEMs with enough resolution. Consider the use of aerial platforms for data acquisition, which have the potential to overcome the limitations associated with terrestrial methods (e.g. shadow zones); allowing for a more uniform and complete simulation model.

	whilst the DEM used in this simulation is considered to have a fine resolution, certain important meso-scale features may not have been well represented.	
High	Rock Parameters As discussed in Section 6.2, rock bodies used in detailed trajectory reconstruction were artificially generated by modifying pre-existing rock body point clouds contained within the in-built rock library. These pre-existing point clouds were acquired from remote sensing undertaken by the developers of RAMMS: Rockfall. Despite allowing for more realistic rock shapes to be used in simulation (as opposed to simple spheres, cuboids or ellipsoids), these rocks were acquired from a different site with a completely different geology. As such, it was not possible to recreate the boulders of Beinn Luibhean described during field mapping exactly.	Ensure that unique rock body point clouds of each rock to be modelled are acquired during field investigation by digital photogrammetry or 3D laser scanning, instead of relying on rock geometries that are unrepresentative of the geological setting being investigated (i.e. contained within the rock library)
High	Model Calibration Before undertaking detailed rockfall trajectory reconstruction, a series of sensitivity analyses were performed. These were successful in allowing for the identification of sensitive and non-sensitive parameters and an overall increased understanding of the relationships between different input and output variables. However, the lack of inventory data and associated knowledge of past rockfall events limited the overall confidence in the sensitivity analyses carried out.	Ensure detailed model calibration and sensitivity analysis is undertaken before performing trajectory reconstruction. Ensure that rockfall event data is captured and recorded within a systematic inventory system (e.g. within the Transport Scotland GIS system, associated with relevant information including images, reports, etc.).

7. Hazard Assessment

7.1 Methodology

7.1.1 Establishing the hazard

The term 'hazard' has been defined by Lee and Jones (2014) as "… a perceived peril, threat or possible source of harm of loss." Thus, boulders situated on a hillside above infrastructure or property that have the potential to cause harm or loss, such as those situated on Beinn Luibhean above the A83, can be considered a hazard.

Undertaking a hazard assessment is usually the first step in the risk assessment process. With respect to natural terrain hazards, defining the hazard is a two-step approach, taking both magnitude and frequency characteristics into consideration.

In recent years, risk assessment with respect to natural terrain hazards such as rockfall and landslides has gradually moved towards quantitative rather than qualitative assessments, albeit that semi-quantitative approaches are often more suited at a regional scale. However, with respect to boulder fall hazards, the data required to undertake a fully quantitative assessment is unlikely to be available for most sites as this requires detailed temporal information on previous boulder fall incidents, spatial data such as initiation and end termination positions, and the magnitude associated with the failure. As such, a semi-quantitative / qualitative approach has been developed for this study with the intention that this methodology, or an adapted version, can be applied to other sites.

With respect to assessment of hazard at the A83 Rest and Be Thankful site, a hazard matrix has been used. The hazard matrix considers probability and intensity of potential boulder falls at the site. The following paragraphs describe the methodology used in establishing boulder fall hazards using the hazard matrix based on Likelihood Class (L) and Intensity Class (V).

7.1.2 Likelihood Class (L)

The probability of a boulder reaching the A83 is determined by two main factors: whether boulder fall is likely to initiate, and the likely run-out distance upon initiation. These factors have been considered to determine a Likelihood Class, which will later feed into the hazard matrix. The Likelihood Class (L) is determined by applying factors A, B and C as defined in the following paragraphs.

Run-out Distance – Shape Factor, A

Based on the results of detailed modelling, boulder run-out distances are predominantly controlled by shape. Through undertaking the sensitivity analysis, it was found that tabular or flat shaped boulders are extremely unlikely to have significant run-out distances. As such, it can be considered that these boulders can immediately be categorised as low risk without further consideration in the matrix. The sensitivity analyses indicated that other boulder shapes have much longer run-out distances and thus are more likely to reach the A83 upon release from the slope. When considering shape, it is considered that equant or spherical boulders have a greater run-out length than long or irregularly shaped boulders. Thus, a Shape Factor, A, can be applied to boulders that are not flat or tabular in shape. Shape factors for each boulder shape are given in Table 7-1.

Table 7-1: Shape Factor, A

Boulder shape	Shape Factor, A
Flat / Tabular	N/A – automatically categorised as **low** hazard
Long, cylindrical, cubic	1
Irregular	2
Equant, spherical	3

Likelihood of initiation – Release Factor B, and Instability Factor, C

Based on the boulder-fall sensitivity analysis as well as observations from fieldwork, it is considered that boulder initiation is controlled by two factors: boulder magnitude and hillside instability. When considering boulder magnitude, it was observed during fall-path modelling that there is a positive trend between boulder volume and z-offset (initial free-fall) required to trigger movement. This relationship is shown in Figure 7.1. If real boulder fall events are considered, the Z-offset in the fall-path modelling broadly can be compared to the amount of soil displacement required to trigger a boulder movement: i.e. larger boulders require a greater amount of soil displacement, or potential energy, to trigger a failure than smaller boulders. Based on the equation of the curve on Figure 7-1, an approximate Z-offset can be applied to each boulder contained within the inventory.

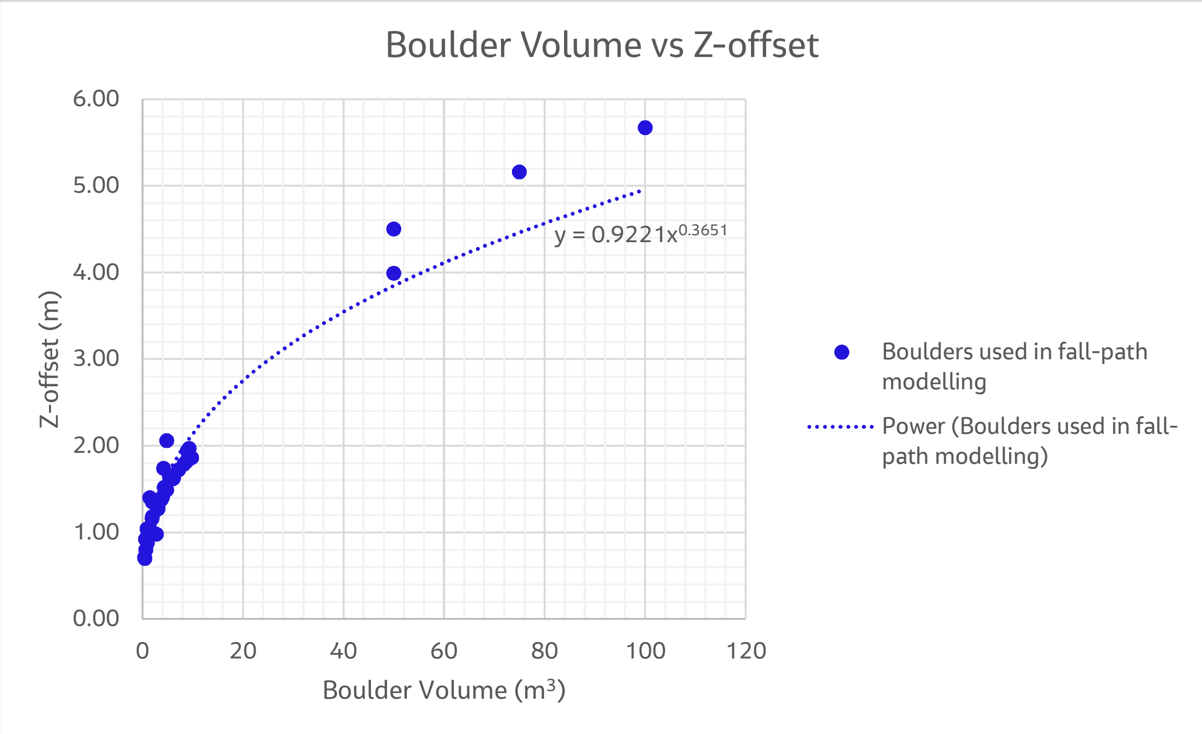

Figure 7-1: Power law relationship between boulder volume and Z-offset. In this functional relationship, a relative change in boulder volume results in a proportional relative change in Z-offset.

It can be observed from annual reporting, as well as numerous site visits to the Study Area, that small soil disturbances are more frequent than large debris flow events. Therefore, boulders that require a lower Z-offset to be mobilised are more likely to move than larger boulders that require a larger Z-offset. As such, by comparing the Z-offset required to trigger boulder falls of a certain volume, a likelihood of release factor, termed Release Factor B, can be applied to boulder volumes recorded in the inventory. Release Factor B can be calculated as shown in Table 7-2.

Table 7-2: Calculation of Release Factor B

Z-offset required to trigger movement	Equivalent boulder volume from modelling results	Comments	Release factor B
Up to 1.0 m	0 - 1.25 m^3	Likely to occur frequently. Causes may include tension crack formation, minor landslips, small washout failures.	3
1.01m – 2.50m	1.25 – 16 m^3	Likely to occur less frequently. Movement could occur during low volume debris flow events or open hillslope failures. May also occur due to localised channel washout during rainstorm events.	2
>2.50m	>16 m^3	Likely to occur rarely, mostly during large debris flow events.	1

Another factor to take cognisance of when considering the likelihood of boulder release from the slope, is whether any instabilities were recorded within close proximity to the boulder. Boulders in areas of instability (e.g. evidence of tension cracks or seepage that could cause washout of the soil beneath the boulder) are more likely to fail than boulders that are located on an area of hillside that shows no signs of instability. Evidence of instability is a feature that can be recorded during fieldwork and can potentially also be observed from remotely sensed data, depending on the data resolution. By allocating a factor to boulders that represent varying degrees of hillside instability this factor, termed Instability Factor C, can be accounted for in the hazard matrix. The instability factor categories that have been applied to boulders for this hazard assessment are given in Table 7-3.

Table 7-3: Calculation of Instability Factor C

Evidence of instability	Examples of observed instabilities	Instability factor C
No instability recorded	No instabilities recorded. Boulder is not located within a drainage channel.	1
Minor instability recorded	- Evidence of minor washout of soil below the boulder. - Seepage below the boulder. - Boulder located within stream channel	2
Significant instability/s recorded	- Tension cracks. - Evidence of recent boulder movement. - Evidence of active erosion or scour	3

By considering both Release Factor B and Instability Factor C, the likelihood of initiation is calculated as:

*Release Factor B * Instability Factor C.*

The likelihood matrix shown in Figure 7-2 considers the three factors (A, B and C) which can be relatively easily allocated to each boulder in the inventory, provided that basic boulder and on-slope features are recorded either during the fieldwork, or through interrogation of remotely sensed data. These factors are used to determine a Likelihood Class (L1, L2 or L3) which then feeds into a hazard matrix. The assessment of factors A, B and C which are used in the Likelihood matrix to calculate the Likelihood Class are described in Section 7.2.

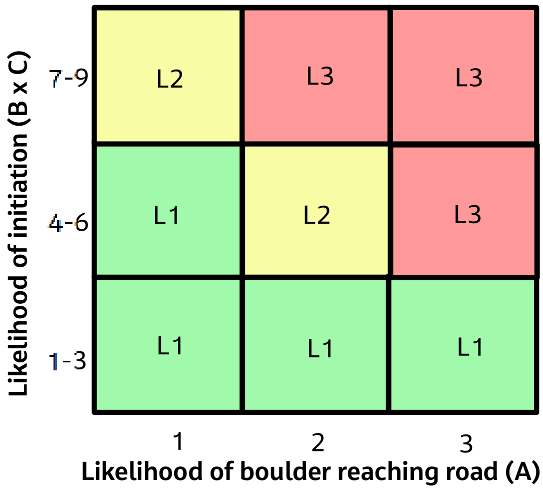

Figure 7-2: Likelihood Matrix used to calculate Likelihood Class

7.1.3 Intensity Class (V)

With respect to hazard intensity, it has been observed from the fall-path modelling, that kinetic energy and bounce heights typically increase with boulder volume. As such, it can be considered that the larger the boulder, the more destructive any potential impact will be should a boulder reach the A83 upon release. When considering intensity in relation to boulder hazard, a semi-quantitative / qualitative category has been assigned to boulders with respect to volume. These categories are referred to as Intensity Class V, and are noted in Table 7-4.

Table 7-4 Determination of Intensity Class

Boulder Volume	Potential effects upon impact	Intensity Class
0-0.5m^3	Boulder is comparatively small when compared with the size of a vehicle travelling along the A83. An impact to a vehicle will cause significant damage, but not necessarily to the entire vehicle. Depending on where the boulder hits the vehicle, impact may or may not cause an injury/fatality.	V1
0.5m^3 to 1.0m^3	It is considered that boulders of this size will cause a greater degree of damage to a vehicle on impact compared to Intensity Class 1. The likelihood of causing injury/fatality is considered greater in comparison to Intensity Class 1.	V2
>1.0m^3	It is considered that boulders of this size will cause a greater degree of damage to a vehicle on impact compared to Intensity Classes 1 and 2. The likelihood of causing injury/fatality is considered greater in comparison to Intensity Classes 1 and 2.	V3

7.1.4 Hazard Matrix

A hazard matrix has been used to enable classification of boulders within the boulder inventory in terms of the relative degree of hazard that they pose to the A83 road. The hazard matrix compares the intensity class and Likelihood Class given to each boulder to give a Hazard Rating of low, medium or high. The boulder hazard matrix used in this study to assign the Hazard Ratings is given in Figure 7-3.

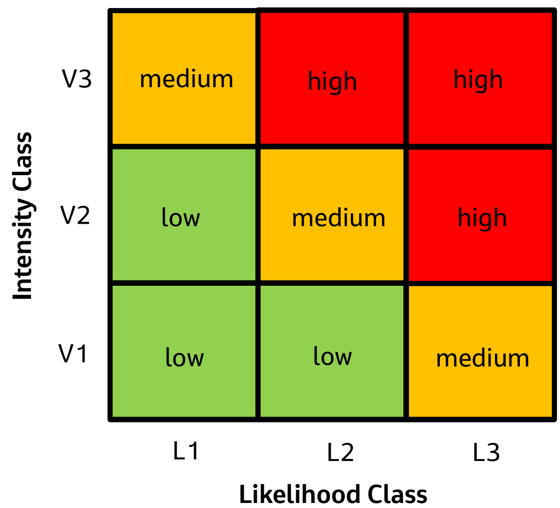

Figure 7-3: Boulder hazard matrix

7.2 Boulder Hazard Ratings in the Detailed Study Area

Using the methodology described in Section 7.1, a hazard rating has been given to boulders within the inventory. Out of the 454 boulders in the inventory, five could not be assigned a hazard rating as the volumes could not be determined during the fieldwork. Of the boulders where minimum dimensions are recorded due to a degree of embedment within the soil, the available dimensions have been used to calculate the volume. It is noted that this results in a degree of error within the hazard assessment; however, boulder volume is only one factor within a larger assessment of overall hazard.

Of the remaining 448 boulders that could be given a hazard rating, the results for each of the low, medium and high categories are given in Table 7-5 below.

Table 7-5 Results of boulder hazard assessment (Detailed Study Area)

Hazard Rating	Number of boulders within Detailed Study Area	Percentage of total (448 boulders)
Low	373	83.3%
Medium	65	14.5%
High	10	2.2%

Boulders designated as low hazard are generally tabular in shape. Of the boulders that are not tabular in shape, the boulders are not typically associated with significant existing instability features and tend to have a low volume, falling into the range of between $0.59m^3$ and $1.44m^3$.

Of the 65 boulders designated as medium hazard, all but four of the boulders fall into Likelihood Class L1 indicating that there is a relatively low chance of the boulder mobilising in most cases. However, the vast majority of the medium hazard boulders were given a V3 intensity class due to their large volume, so although the likelihood of boulder initiation is low, once mobilisation occurs, the intensity of the event is more severe.

Of the 10 boulders designated as having a high hazard rating, eight fall into Likelihood Class L2 and Intensity Class V3. Two boulders were found to fall into Likelihood Class L3. The boulders given a high hazard rating are also larger in size with all ten boulders recording an intensity class of V3.

7.3 Consideration of hazard across the rest of the Study Area

While a detailed boulder inventory has not been compiled for the entire Study Area, results from the boulder inventory and hazard assessment has been up-scaled in terms of relative area to give an approximation of hazard across the entire Study Area. This approximation assumes a relatively similar distribution of boulders across the rest of the slope and that slope angles are also broadly similar. While the distribution of boulders would require confirmation from further assessment of available data and / or fieldwork, it can be confirmed that average slope angles across the slope are not that dissimilar to those within the Detailed Study Area.

The area of the Detailed Study Area has been calculated as approximately $71{,}000m^2$ (7.1Ha), and the area of wider Study Area is approximately $807{,}000m^2$ (80.7Ha); the Detailed Study Area comprising 8.8% of the wider Study Area. Factoring these values, yields approximate numbers of boulders and resulting hazard assessment for the entire Study Area as given in Table 7-6 below.

Table 7-6 Indicative boulder hazard assessment for entire Study Area

Degree of Hazard	Number of boulders within Detailed Study Area (448)	Estimated number of boulders within the entire Study Area (5092)
Low	373 (83.3% of total)	4240
Medium	65 (14.5 % of total)	739
High	10 (2.2% of total)	114

8. Discussion on methodology used and application to other sites

8.1 Boulder inventory

8.1.1 Desk study and data gathering

In order to understand natural terrain hazard a desk study is an important first step to develop an understanding of the complexities of the Study Area, and the main influences on such hazards; this study of boulder hazards at the A83 Rest and be Thankful is no exception. Geology, geomorphology, hydrology and the history of previous events are important starting points for examination; the latter is particularly onerous when pre-existing formal event inventory information is limited.

As documented in Section 4 of this report, several methods of determining the locations of boulders (boulder inventory) using remotely sensed data were tested. The UAV survey which allowed a coloured DEM to be prepared using photogrammetry data proved to be the most successful method in terms of gaining precise locations of boulders. However, there were also deficiencies in this method, largely because boulders were partly obscured by vegetation or soil and their true dimensions could not be determined, thus causing boulders to be incorrectly omitted from the inventory. In this case, although time consuming and having to consider health and safety issues, undertaking confirmatory fieldwork to supplement the preliminary data obtained from the DEM was an invaluable part of compiling the boulder inventory.

Given the results of the sensitivity analysis on boulder shape undertaken as part of this study, a simple initial exercise to provide a high-level approximation of the degree of hazard for other sites could be to interrogate the available data at an early stage to identify the most common boulder shape on the hillside. A hillside with a high proportion of equant boulders is more likely to pose a hazard than a hillside with a larger proportion of tabular boulders.

With regard to other sites, if there is no existing data, careful consideration should be given to the suitability of the various remote sensing techniques available. If vegetation cover is not an issue and a high-quality DEM is available, then there could be justification to limit the duration of the required fieldwork. This is of particular note if the site is in a remote area where fieldwork could be extremely time-consuming to undertake and/or could pose concerns related to the safety of personnel. A summary of some of the common data collection techniques with the associated advantages and limitations is given in Table C.7 in Appendix C.

With regard to field mapping, recording boulder locations digitally was found to be particularly useful. This process assisted in ensuring that the fieldwork was undertaken systematically with no gaps in the spatial data collection and also resulted in data processing efficiencies following the fieldwork exercise.

Relevant features to be recorded during field mapping may need to be considered on a site-by-site basis depending on the specific hillside characteristics. Table C.4 at Appendix C provides a range of slope characteristics that can be used or amended as required for use during on site data collection.

8.2 Fall-path modelling

While the fall path modelling software used was found to have some limitations (refer to Section 6.5.4), undertaking a sensitivity analysis yielded valuable information on what parameters influence boulder fall trajectories within the Detailed Study Area. It was found that boulder shape has greater influence compared to the other factors. Furthermore, undertaking detailed fall path modelling on a selected number of boulders within the Detailed Study Area provided a means of determining the probability of boulders of various size and shapes reaching the A83 and the Old Military Road below.

When considering fall-path modelling on other sites, consideration should be given to undertaking a sensitivity analysis for parameters that were not relevant to this study. For example, slope angle is highly likely to have an effect on boulder run-out but was not considered in detail during this assessment due to the limited variation in average slope angle across the wider Study Area. Further factors such as tree cover and the presence of existing rock fall barriers could also be considered in a sensitivity analysis depending on individual site circumstances.

Consideration should also be given to the appropriateness of the modelling software on a site by site basis. While RAMMS: Rockfall was selected for this study, various software packages using a range of methodologies to simulate run-out are available. It may be a valuable exercise to compare the sensitivity of the various input parameters between different software products so that the most appropriate software can be selected.

8.3 Hazard assessment

For this Study Area, a relatively simple semi-quantitative / qualitative hazard assessment methodology was developed. This methodology was developed due to the lack of temporal data required to undertake a fully quantitative assessment. It was also recognised that in order to apply this methodology, or a version of it, to other sites such as Glen Ogle or Glen Coe, a quantitative method would not be suitable.

While the calculation of intensity class will be relatively straightforward for most sites, the calculation of probability class is likely to vary on a site by site basis. The methodology used to calculate probability class may vary depending on a site-specific sensitivity analysis undertaken. For instance, controlling factors on whether a boulder reaches the road (factor A in this study), could also relate to the presence of tree cover or existing rockfall barriers to name two examples.

With respect to boulder initiation, the Z-Offset categories which have been used to determine the likelihood of boulder initiation could be entirely irrelevant if rockhead is at or very close to the ground surface. Furthermore, the factors causing slope instability could have varying degrees of importance depending on site conditions. A site with a densely vegetated slope may not record features such as tension cracks or landslide scarps, and may have to re-think the scoring system to emphasise instability issues that could be common to that slope such as root-jacking.

Figure 8-1 provides recommendations for an outline methodology for undertaking boulder hazard assessments. It is intended that the approach used can be utilized and adapted as necessary depending on site specific characteristics.

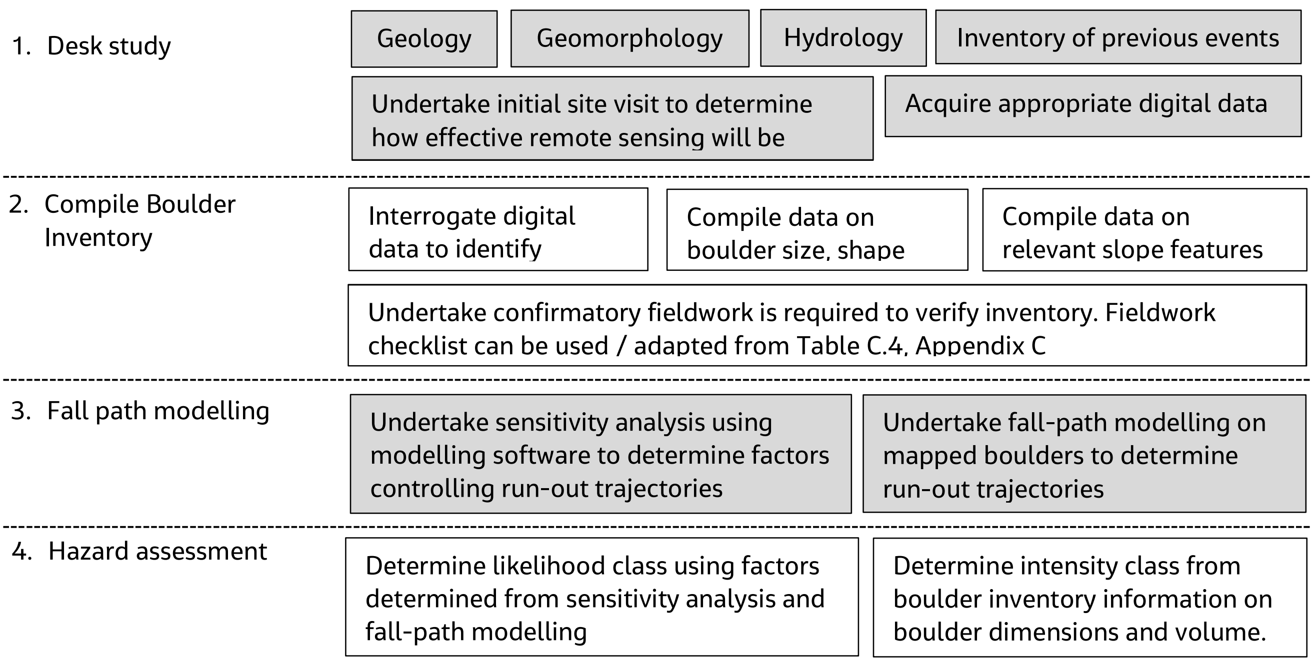

Figure 8-1: Outline methodology for determining boulder hazards

9. Conclusions and Recommendations

A boulder hazard study has been undertaken for a Detailed Study Area of 71,000m^2 as part of the hillside at the A83 Rest and Be Thankful, a section of trunk road which has been affected by several natural terrain hazards events in recent years including boulder fall (see Table C.2, Appendix C). The purpose of this study was to assess the hazard from isolated boulders on the slope and as such, boulders entrained within debris flows have not been considered.

Following a desk study exercise a preliminary inventory of boulders located on the hillside was compiled using remote sensing data. Fieldwork was then undertaken to validate the results from the inventory and to update the inventory with respect to boulder properties. An inventory of over 450 boulders was compiled. Data from the inventory was used to undertake a sensitivity analysis and fall path modelling to determine the boulder and hillside characteristics that are most likely to affect the probability of a boulder reaching the A83 upon release. The results from this exercise were used to develop a hazard matrix so that individual boulders on the hillside could be allocated a low, medium or high hazard-rating.

Using the methodology outlined in this report, it was found that the majority of boulders (83.3%), pose a low risk to the A83. Many of the boulders with a low hazard rating are tabular in shape which, as expected, exhibit shorter run-out distances upon failure when modelled in comparison to other boulder shapes. Of the remaining boulders on the hillside, 14.5% were allocated a medium hazard rating, and 2.2% a high hazard rating.

It was outside the scope of this study to carry out fieldwork across the entire Study Area. However, due to the broad similarities in slope angle and likely boulder distribution across the wider Study Area (807,000m^2), the total number of boulders (5092) as well as the approximate number of boulders within each hazard rating category (4240 low, 739 medium and 114 high) has been estimated.

Fall path modelling indicates that the debris barriers will provide some protection to the A83 from boulder fall. However, accurate modelling of the effect of the barriers taking account of the designed capacity was not possible using RAMMS: Rockfall. As such, the protection given by the presence of debris barriers at the slope toe has not been considered in the calculation of individual boulder hazard ratings in this hazard assessment.

While portions of the slope are protected by debris barriers and catch pits, these were designed for the purpose of reducing risk to the road from debris flows, rather than release of isolated boulders from the hillside. Further studies could be undertaken to determine whether the mitigation measures in place fully mitigate against the hazards posed by boulders. This could be assessed by comparing energy values calculated by the designer/supplier of the barriers with energies predicted by fall path modelling.

With respect to the boulder hazards identified at the A83 Rest and Be Thankful site, it is recommended that consideration is given to risk posed to road users from the hazards identified. This could be undertaken by developing a risk assessment, taking economic impact and loss of life into consideration. Furthermore, forestry planting of part of the slope has been programmed to be undertaken in 2020. It is recommended that the impact of trees on boulder hazards and run-out trajectory is considered to determine whether planting can be an effective method in hazard reduction.

With respect to application of the hazard assessment methodology used in this study to other sites, it is considered that the broad framework outlined in Section 7 of this report can be used, particularly on other parts of the trunk road network such as Glen Ogle or Glen Coe. This methodology could also be applicable to some Network Rail assets as well as other infrastructure such as overhead power lines where they are exposed to natural terrain hazards. A boulder inventory would generally be best determined using a UAV survey, but this would require some confirmatory fieldwork for completeness. When undertaking the hazard assessment, itis recommended that the methodology for calculating the Likelihood Class is considered on a site by site basis following fall-path modelling as fall-path distances as well as the likely release factors will largely depend on the local slope and boulder characteristics.

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Appendix A. Photographs

Photograph A-1: General view of the western portion of the Study Area. (Photograph from a series of time lapse images dated 02 October 2018).

Photograph A-2: Photograph of possible unstable boulder mobilised and deposited on the hillside following the 30 December 2016 debris flow.

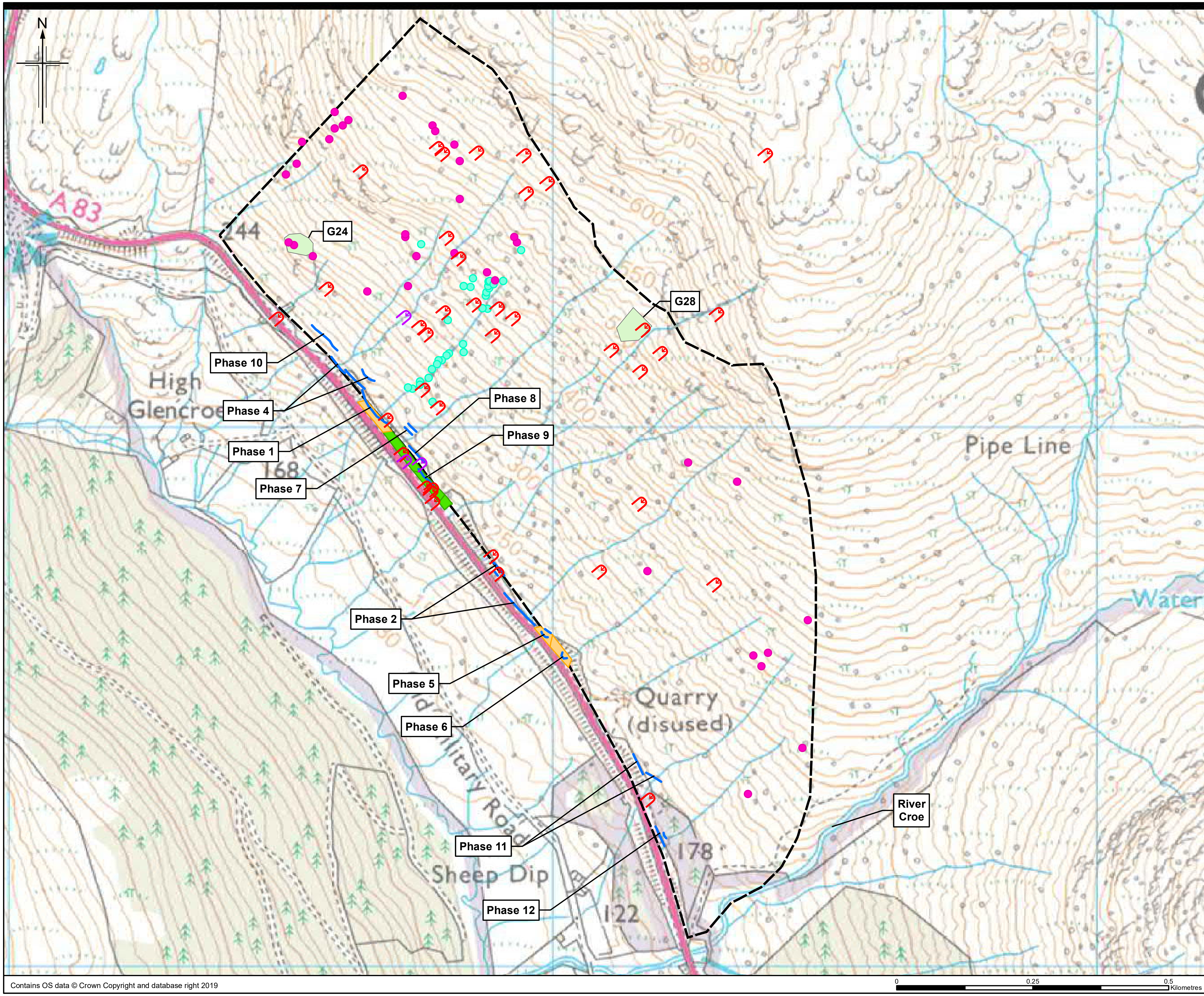
Photograph A-3: Photograph of the boulder that impacted the A83 on 30th December 2015 as a result of soil movement on the slope below the Phase 8 debris barrier.

Photograph A-4: Photograph of boulder exposed in the backscarp of the December 2015 debris flow.

Photograph A-5: Photograph of potentially unstable boulder identified following the December 2015 debris flow being drilled so that it can be broken up using explosives.

Photograph A-6: Photograph of a potentially unstable boulder following installation of a restraining system in 2015.

Drawing B-1



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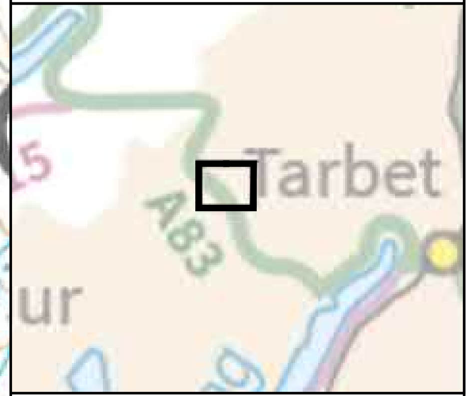

Legend

- Natural Terrain Hazard Event
- Boulder fall that impacted A83
- Boulder Location - 2003 Survey
- Boulder Location - 2015 Survey
- Geotechnical Features
- Debris Barrier
- Existing Catch Pit
- Proposed Catch Pit
- Study Area Boundary

Rev.	Rev. Date	Purpose of revision	Orig/Dwn	Checkd	Rev'd	Apprv'd
1	MAR 2020	For Issue	GB	JT	CAH	IWM
0	FEB 2020	Work in Progress	GB	JT	CAH	PC

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Client
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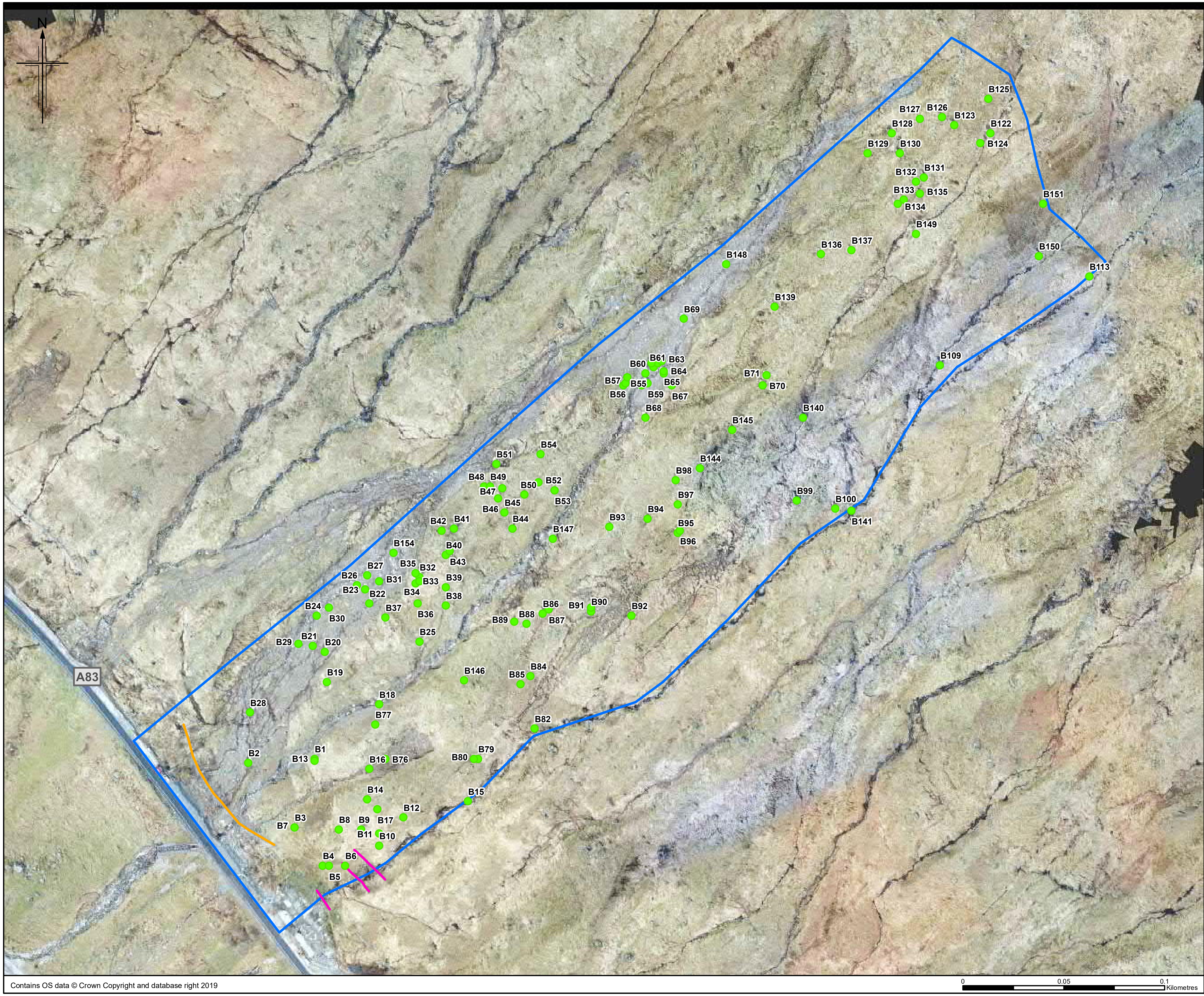
Project
Boulder Hazards Study

Drawing title
Site Features Plan

Drawing Status	DRAFT	
Scale	1:6,500 @ A3	DO NOT SCALE
Jacobs No.	B2359902	
BIM No.		
Drawing number	Drawing B-1	Rev 1

Drawing B-2



Legend

- Boulder Location
- Survey Area

Debris Barriers

- Phase 1
- Phase 7

Notes:

1. Background imagery courtesy of Geo-Rope Ltd.
2. Boulders included in the preliminary inventory are those identified from 2018 UAV survey data, observed to have a maximum dimension of 1.0m or greater.

Rev.	Rev. Date	Purpose of revision	Orig/Dwn	Checkd	Rev'd	Apprv'd
1	MAR 2020	For Issue	GB	JT	CAH	IVM
0	FEB 2020	Work in Progress	GB	JT	CAH	PC

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Project

Boulder Hazards Study

Drawing title

Preliminary Boulder Inventory: Boulder Locations

Sheet 1 of 1

Drawing Status	DRAFT	
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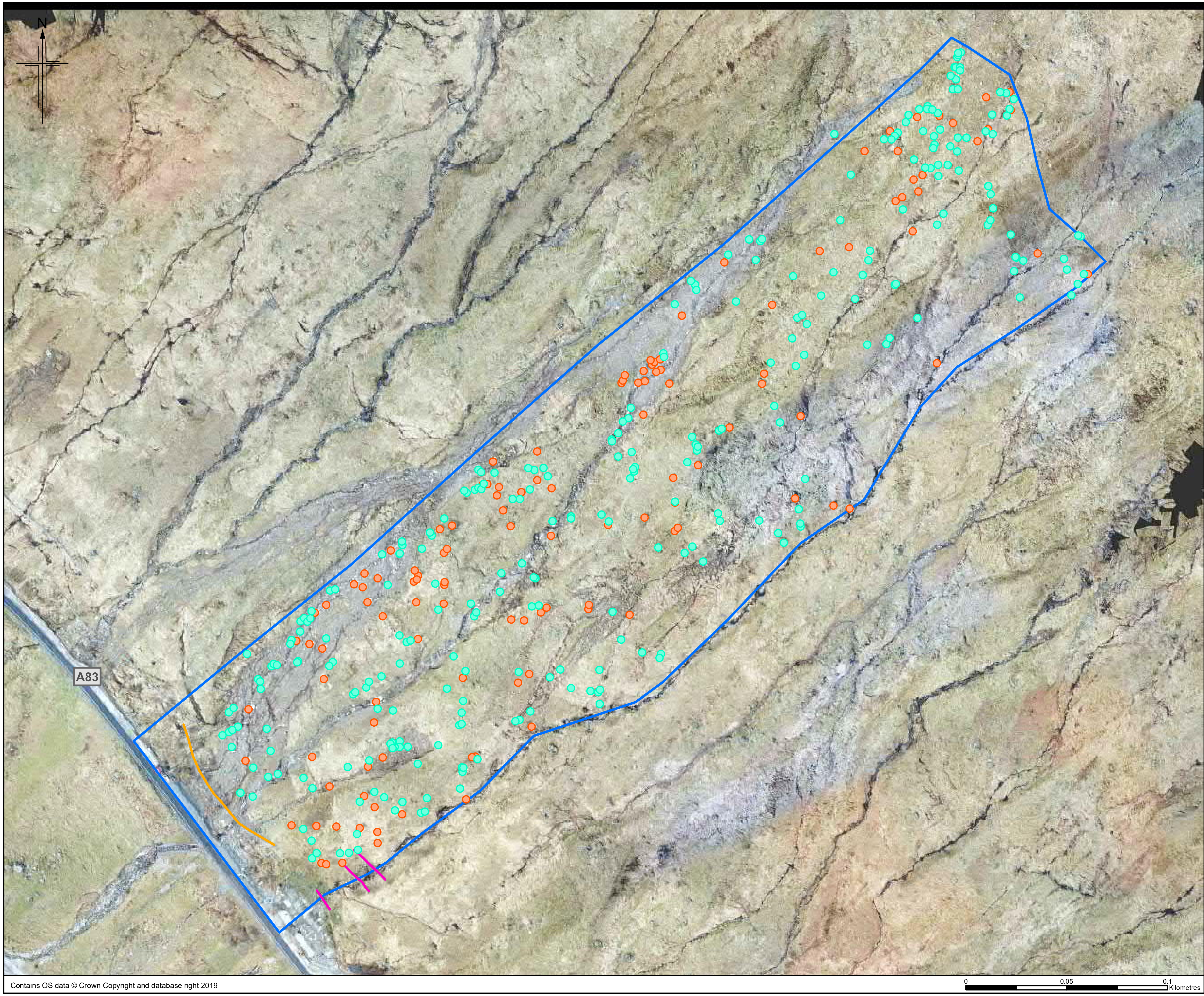
BIM No.		
Drawing number	Drawing B-2	Rev 1

Drawing B-3a



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Legend

Detailed Boulder Inventory

- Preliminary inventory boulders - confirmed during fieldwork
- Additional boulders identified during fieldwork
- Detailed Study Area

Debris Barriers

- Phase 1
- Phase 7

Notes:

1. Boulder locations determined using GPS. Typical accuracy +/- 6m.
2. Background imagery courtesy of Geo-Rope Ltd.

Rev.	Rev. Date	Purpose of revision	Orig/Dwn	Checkd	Rev'd	Apprv'd
1	MAR 2020	For Issue	GB	JT	CAH	IVM
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Boulder Hazards Study

Drawing title

Detailed Boulder Inventory: Boulder Locations

Sheet 1 of 3

Drawing Status	DRAFT	
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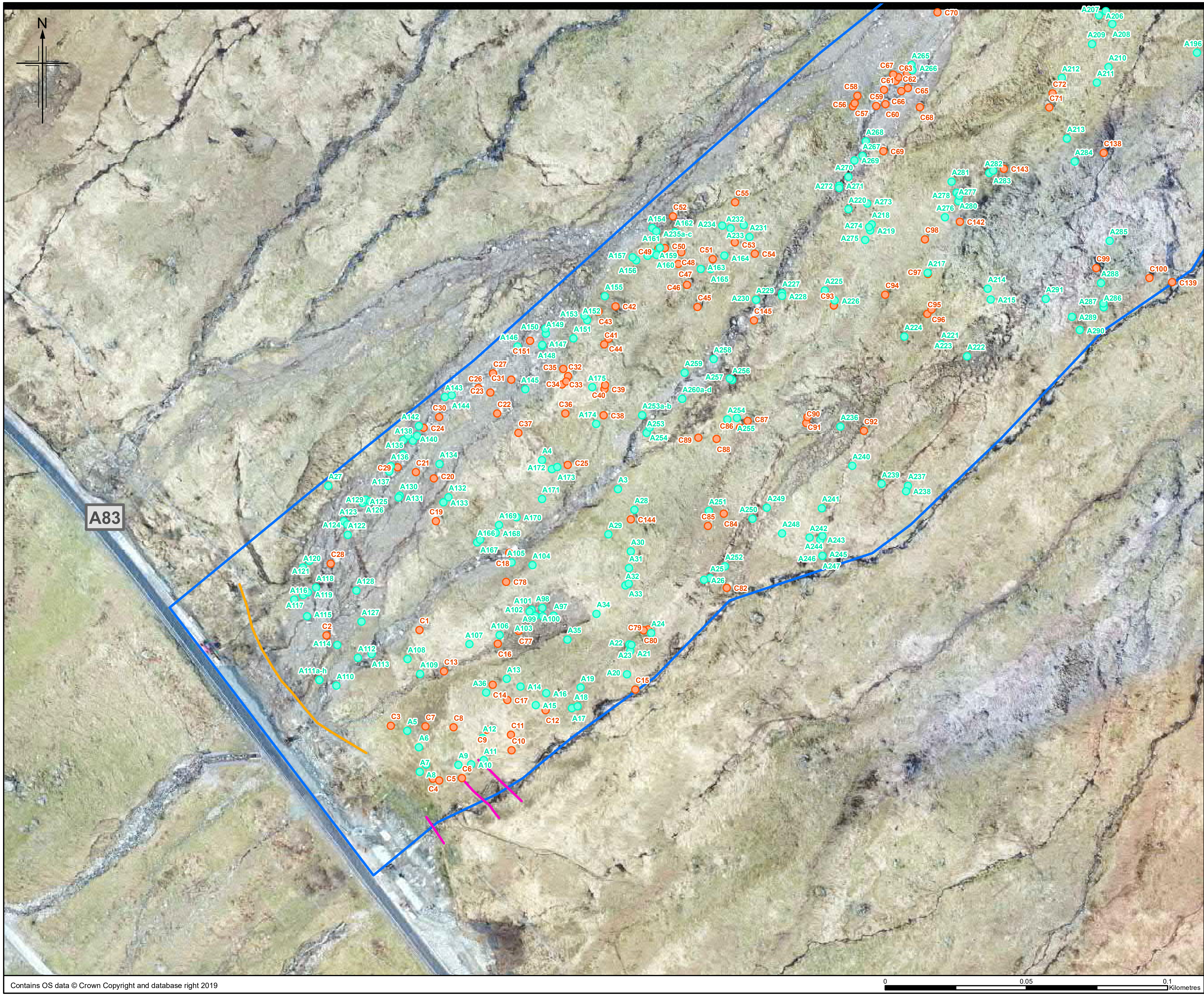
BIM No.		
Drawing number	Drawing B-3a	Rev 1

Drawing B-3b



Legend

Detailed Boulder Inventory

- Preliminary inventory boulders - confirmed during fieldwork
- Additional boulders identified during fieldwork
- Detailed Study Area

Debris Barriers

- Phase 1
- Phase 7

Notes:

1. Boulder locations determined using GPS. Typical accuracy +/- 6m.
2. Background imagery courtesy of Geo-Rope Ltd.

Rev.	Rev. Date	Purpose of revision	Orig/Dwn	Checkd	Rev'd	Apprv'd
1	MAR 2020	For Issue	GB	JT	CAH	IVM
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Project

Boulder Hazards Study

Drawing title

Detailed Boulder Inventory: Boulder Locations

Sheet 2 of 3

Drawing Status	DRAFT	
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Jacobs No.	B2359902	
BIM No.		
Drawing number	Drawing B-3b	Rev 1

Drawing B-3c

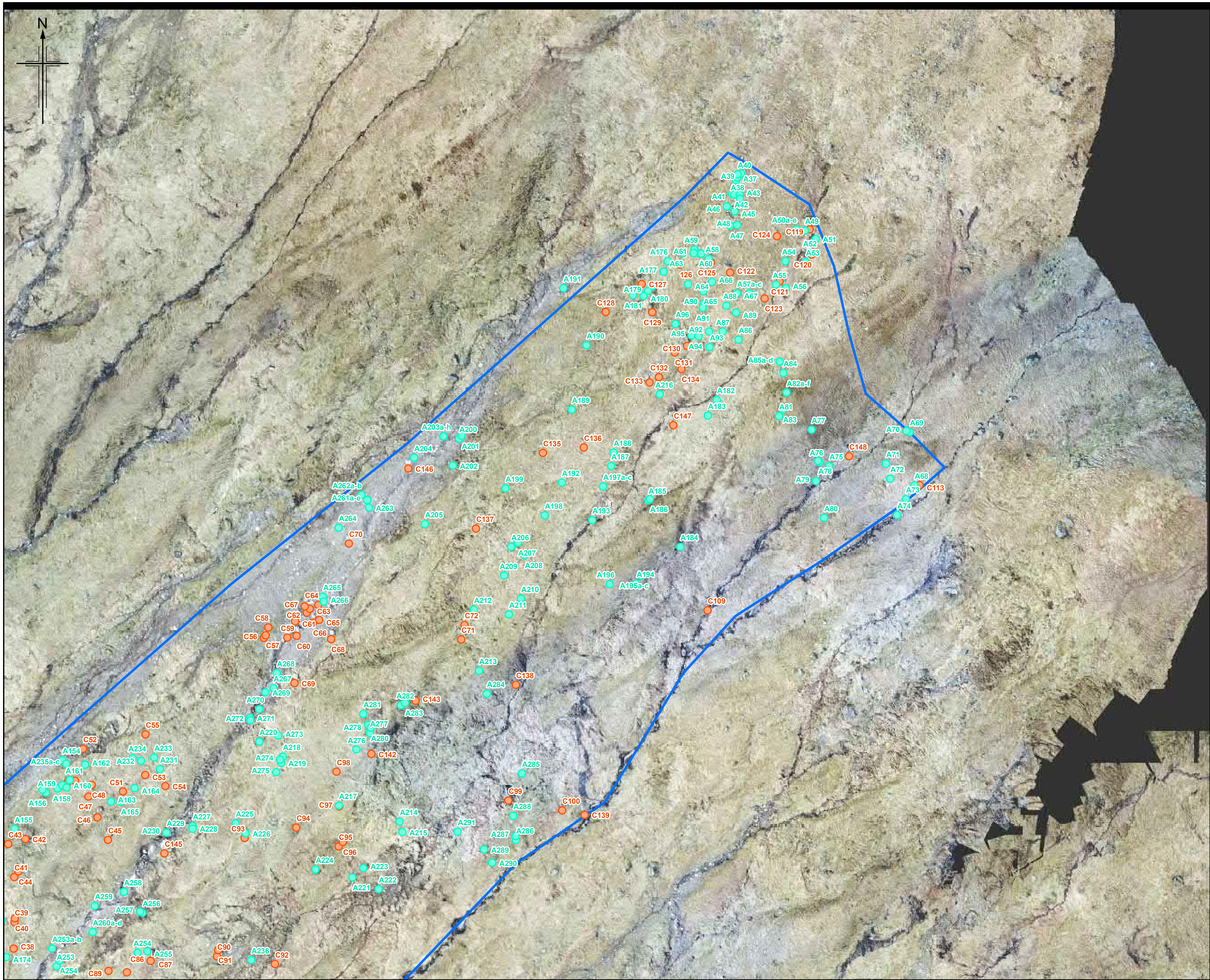
Legend

Detailed Boulder Inventory

- Preliminary inventory boulders - confirmed during fieldwork
- Additional boulders identified during fieldwork
- Detailed Study Area

Debris Barriers

- Phase 1
- Phase 7



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0 0.05 0.1 Kilometres

Notes:

1. Boulder locations determined using GPS. Typical accuracy +/- 6m.
2. Background imagery courtesy of Geo-Rope Ltd.

Rev.	Rev. Date	Purpose of revision	Orig/Dwn	Checkd	Rev'd	Apprv'd
1	MAR 2020	For Issue	GB	JT	CAH	IVM
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Boulder Hazards Study

Drawing title

Detailed Boulder Inventory: Boulder Locations

Sheet 3 of 3

Drawing Status	DRAFT		
Scale	1:1,250	@ A3	DO NOT SCALE
Jacobs No.	B2359902		
BIM No.			
Drawing number	Drawing B-3c		Rev 1

Appendix C. Tables

Table C.1 – Summary of boulder observations from A83 Rest and Be Thankful Annual Reports

Annual Report	Boulder observations
2005	Nine out of the 24 tier 3 boulders remaining on the slope after previous stabilisation works were identified for stabilisation. In addition, 5 additional boulders were identified during the inspection and were recommended for stabilisation.
2006	Tier 3 boulders identified in the 2003 soil slope assessment were inspected. Little or no change in condition was recorded, and none were identified as requiring further stabilisation. A further four potentially unstable boulders were identified, with only one considered to be a high risk to the A83 road below. Stabilisation of this boulder (No.58) was recommended.
2007	A stability study of four potentially unstable boulders highlighted in the 2006 annual report was undertaken. No stabilisation works were recommended.
2008-2009	A stability assessment was undertaken for the four potentially unstable boulders identified in the 2007 inspection report. A further two boulders located within areas of recent failures were also included in the assessment. No stabilisation works were recommended.
2009-2010	A boulder monitoring survey was undertaken which included an assessment of the stability of six boulders that had been identified as potentially unstable in 2008-2009 annual report. No stabilisation works were recommended.
2010-2011	A boulder monitoring survey was undertaken which included an assessment of the stability of six boulders that had been identified as potentially unstable in 2008-2009 annual report. No stabilisation works were recommended.
2011-2012	During the inspection of the slope following the 01/12/11 failure, it was observed that a boulder had fallen from an area of the hillside above the failure scarp where tension cracks were present. The boulder came to rest approximately 130m above road level. Boulders were recorded on the A83 carriageway on 29th June 2012. The boulder fall is believed to have been triggered by slope movements as a result of the 29th June 2012 landslide. The landslide itself did not impact the carriageway. At the time of the incident, no debris barrier was in place at this location. A boulder monitoring survey was undertaken which included an assessment of the stability of six boulders that had been identified as potentially unstable in 2008-2009 annual report. No stabilisation works were recommended.

Annual Report	Boulder observations
2012-2013	No report
2013-2014	A large potentially unstable boulder of approximately 300 tonnes was identified above the 06 March 2014 failure scarp. The boulder was left in situ with ongoing monitoring, but it was recommended that the boulder should be stabilised. Deterioration of Geotechnical Features G19, G22 and G26 was recorded. Large boulders were noted to be present within these features however, no comment was made on stability.
2014-2015	Works were undertaken to stabilise the large boulder above the 06/03/14 failure scarp. The boulder was stabilised by constructing an anchor and cable system designed to restrain the boulder in the event of slope movements. Further deterioration recorded in G19, G22 and G26, but no comment was made on boulder stability in these areas.
2015-2016	Potentially unstable boulders recorded in areas of the slope that are deteriorating. Boulder assessment recommended, particularly within the vicinity of Geotechnical Features 19 and 26. A large boulder (approximately 150 tonnes) was identified close to the source area of the 30/12/15 landslide. The hazard was mitigated by chemical breaking of the boulder during a road closure.
2016-2017	Potentially unstable boulders recorded in areas of the slope that are deteriorating. Boulder assessment recommended, particularly within the vicinity of Geotechnical Features 19 and 26.
2017-2018	Potentially unstable boulders recorded in areas of the slope that are deteriorating. Boulder assessment recommended, particularly within the vicinity of Geotechnical Features 19 and 26.

Table C.2: Summary of recorded boulder fall and landslide incidents at the Rest and be Thankful. Incidents in *italic text* indicate where boulder hazards have been observed. Rows with **bold text** indicate where discrete boulder fall has impacted the A83.

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
22/12/1999 (Mott MacDonald, 2000a)	*Boulder fall and debris flow*	*223725 E 706940 N*	*Yes*	*Unknown*	*Landslide resulted in large boulder being pushed off a rock face and on to the slope below. It did not impact the road. The boulder was considered unstable and was later split up using expansive grout.*
29/10/2000 (Mott MacDonald, 2000b)	**Boulder fall**	**223725 E 706940 N**	**Yes**	**Boulder impacted car and A83. Volume unknown.**	**Reactivation of 22/12/99 landslide which released a boulder that impacted a car on A83.**
03/12/2001 (4 No failure events) (Babtie, 2002)	Debris flow	Slip No.1 corresponds to (G1).	Yes	Slip 1 - Volume – 300 tonnes Scarp dimensions – 25 x 30m Scarp max depth – 1.5m Slips 2, 3 and 4 – dimensions and volume unknown.	Slip 1 – debris flow occurred after excessive rainfall. Boulder of approx. 15 tonnes within slipped material. A further three large washout failures were recorded during the same event (Slip 2, Slip 3 and Slip 4).
Estimated between late 2003 and March 2004 (Jacobs Babtie. 2005a)	*Debris Flow*	*223808 E 707338 N (G29)*	*No*	*Scarp height – 1.5-2m* *Scarp max width – 4m* *Debris run-out – 30-40m* *Volume - unknown*	*Unstable boulder noted at head of scarp. Boulder stabilised in March 2004.*
Estimated early 2006 (prior to 22/06/06)	Debris flow	224164 E 707092 N (G31)	No	Scarp height – 0.75m Scarp max width – 7m Debris run out – 30-40m Volume - Unknown	Concentrated water flow at head of scarp.

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
(Jacobs Babtie, 2006a)					
28/10/2007 (Scotland TranServ, 2007a)	Debris flow	223664 E 707000 N (where debris flow impacted road)	Yes – carriageway covered in 2.5m debris and trunk road closed for approximately 2 weeks	Scarp height – 6-9m Scarp width - 25m Scarp length – 40m Volume – 150m^3	Large debris flow even which also resulted in undermining the carriageway. Silt/Sand deposited on the OMR. Upper source area at 380m AOD.
02/04/2008 (Scotland TranServ, 2008a)	Debris flow	224300 E 706700 N	Yes	Volume – <2.5m^3 deposited on road	Debris accumulated in the former quarry below the slip, thus limiting the volume of debris impacting the road.
23/10/2008 (Scotland TranServ, 2008a)	*Debris flow*	*223770 E 707160 N*	*No – terminated approx. 15m above A83*	*Scarp height – 4.0m* *Max width – 7m* *Debris run out – 30-40m* *Volume – 75 tonnes*	*1.5m diameter boulder observed close to the backscarp.*
23/10/2008 *(Scotland TranServ, 2008a)*	Debris flow	224169 E 707169 N	No	Source area – 20m x 20m Debris run out – 50m	Not observed on site, identified from remote sensing data.
08/09/2009 (Scotland TranServ, 2009a)	Debris flow	223901 E 707208 N	Yes – A83 closed for several weeks	Volume – 1100 tonnes material deposited on A83 carriageway.	A large event depositing material on the A83 carriageway as well as the OMR below.
24/11/2009 (Scotland TranServ, 2009a)	Debris flow	223705 E 701106 N	No – terminated approx. 45m above A83	Volume – 500 tonnes	Debris flow did not channelise and flowed as a hillslope failure over a wide area (40-50m width approx.)
Feb 2011 (Scotland TranServ, 2011a)	Debris flow	G5	No	Small failure. Debris terminated a few metres downslope of the scarp	Identified during remote monitoring work on 16/02/2011. Debris did not

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
					channelise and remained a hillslope failure.
01/12/2011 (Scotland TranServ, 2013a)	Debris flow	223900 E 706720 N (G4)	Yes – road closed for 2 days during daylight hours, and 9 days at night time.	Debris run-out – approx. 35m (main scarp). Rafting extending 20m further up slope from main scarp. Debris volume 50m^3 deposited on A83 carriageway.	Translational failure. Drainage pattern above G4 noted to have changed, directing flow into feature G4.
22/02/2012 (Scotland TranServ, 2013a)	Debris flow	223900 E 706720 N (G4)	Debris did not impact A83 but road closed for 3 days as a precaution	Volume – 30-50 tonnes	Landslide patrol noticed silty water in G4 drainage channel. Soil lobes identified in 01/12/11 debris flow failed causing shallow landslide
22/06/2012 (Scotland TranServ, 2013a)	Debris flow	224394 N 707490 E	Debris did not impact A83 but road was closed for 1.5 days as a precaution	Source at 650mAOD Scarp width – 15m Scarp length – 15m	-
29/06/2012 (Scotland TranServ, 2013a)	**Debris flow and boulder fall**	**A83 carriageway at 224810 N (G18C above)**	**Yes – from boulder fall**	**Source at 340m AOD Estimated volume <1m^3. Debris flow did not impact A83 but mobilised 2 boulders which did impact the A83.**	**Boulder released from movement in debris flow area. Debris flow did not reach A83 but the released boulder impacted the road.**
01/08/2012 (Scotland TranServ, 2013a)	Debris flow	223779 E 706869 N	Yes – road fully closed to traffic until 3rd August, with a single lane operational afterwards.	Failure source – 350mAOD Scarp width – 15m Scarp length – 25m Volume – 650 tonnes of material blocked A83 during initial with a further 350	Failure source located below geotechnical feature G18. Several boulders mobilised in flow.

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
			Debris also impacted the OMR	tonnes deposited after a second failure overnight	
19/11/2012 (Scotland TranServ, 2013a)	Translational landslide	223494 E 707209 N (Stream north of barrier 1)	Yes – A83 closed for 1 day	Failure source – 50m AOD Failure volume – 150 tonnes deposited on A83 Scarp width – 10m Scarp length – 25m	Translational failure. Little erosive damage from flow within channel. Culvert blocked and flowing down carriageway allowing fines to be deposited on road.
03/10/2013 (Jacobs, 2015a)	Debris flow	223782 E 706850 N (Phase 9 debris barrier)	Yes	Failure volume – Exact volume not recorded. Indicated to be a washout failure of small volume.	Source of material in vicinity of G19. Impacted the area where Phase 9a barrier was being constructed.
03/10/2013 (Jacobs, 2015a)	Debris flow	223676 E 707011 N (Source at G18)	No. Material retained in Phase 1 debris barrier	Failure volume – 5m^3. Failure source – 223774 E, 707084N (G18)	-
09/01/2014 (Jacobs, 2015a)	Debris flow	223780 E 706875 N	No. Material retained in Phase 9a debris barrier	Failure volume – <2.5m^3 retained within Phase 9 barrier, and further material diverted to the neighbouring catch pit	Debris flow took similar route to 3/10/19 phase 9 failure and material originated from same source at G19
15/01/2014 (Jacobs, 2015a)	Debris flow	223768 E 706878 N	Yes – southbound carriageway	Failure volume – 45m^3, with 20m^3 affecting the carriageway	Failure occurred at bedrock interface on sidelong ground immediately above the carriageway.
06/03/2014 (Jacobs, 2015a)	*Debris flow*	*223495E 707189 N*	*Yes – A83 closed for 5 days*	*Failure volume – estimated total = <12.5m3 with approx. <5m3 impacting the carriageway.*	*Debris flow occurred immediately in advance of the planned construction of the Phase 10 barrier. Several potentially unstable boulders*

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
				Scarp dimensions – 10m x 12m x 2m	*were identified close to the scarp and within the channel (Dimensions up to 4m x 4.5m x 3.7m)*
28/10/2014 (Jacobs, 2016a)	Debris flow		Yes – A83 fully re-opened on 07/11/2013. Local diversion route (OMR) was in operation.	750 tonnes affected the carriageway with a further 1000 tonnes retained by the debris flow barrier. Failure scarp – 15m x 25m x 1.0m	Two additional small debris flows occurred on the same date in the Phase 7 and Phase 9 channels but did not impact the A83
15/01/2015 (Jacobs, 2016a)	Debris flow	223799 E 707495 N (Above Phase 10 barrier)	No – retained in barrier	Failure volume – 50-100 tonnes originating 350mAOD above phase 10 barrier. 5 tonnes retained in barrier. Run-out distance – 150m	Most of the debris was deposited on the slope, with only a small amount (5 tonnes) reaching the phase 10 debris barrier.
25/11/2015 (Jacobs 2015b)	Debris flow	Phase 7 barrier Termination coordinates: 223792 E 707026 N	No. Flow did not impact the barrier or the carriageway	Source height – 368m AOD Source width – 15m Scar length – 30m Source depth – 1m Run-out length – 100m	-
05/12/2015 (Jacobs 2016a)	Debris flow	223764 E 707058 N (Phase 1 barrier)	No impact on A83 however, road placed under temporary traffic lights while debris barriers were replaced.	Source height – 287m AOD Source width – 4-10m Source length – 20m Source depth – 2m increasing to 4m the following day after further erosion. Run-out length – 80m	Majority of debris flow material was retained in the phase 1 debris barrier.

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
				Failure volume – 100-200m^3 initially with further 400m^3 overnight.	
30/12/2015 (Jacobs 2016a)	*Debris flow*	*223696 E 707003 N (Phase 1 barrier)*	*Yes – phase 1 barrier breached and A83 closed. OMR in operation.*	*Failure run-out length – 275m* *Failure volume on carriageway – 150 tonnes*	*The debris flow breached the temporary phase 1 debris barrier which was in place after the 05/12/15 landslide. Two vehicles crashed into the debris. Large boulder near source area broken up by explosives. Several other boulders identified for hazard assessment.*
30/12/2015 (Jacobs 2016a)	**Boulder fall**	**Road below Phase 8 Barrier**	**Yes**	**Boulder Dimension – up to 1m diameter**	**Boulder fall associated with small slip in front of Phase 8 barrier. (See Photograph A-3)**
05/02/2016 (Jacobs 2016b)	*Debris flow*	*223799 E 707496 N*	*No. Material retained in Phase 10 barrier (23528 E, 707180 N)*	*Source height – 517mAOD* *Source width – 5m* *Source length – 20m* *Source depth – 1.0m in centre of scar* *Run out length – 350m*	*Large boulder (3m x 2m x 1m) identified as resting on slope above a 10m wide area of debris. No movement of boulder observed.*
11/10/2017 (Jacobs 2017a and 2018a)	Debris flow	223830 E 707300 N	No, material retained in Phase 4a barrier.	Source height – 528mAOD Source width - 7-10m Source length – 20m Source depth – 0.5m Run-out length – 300m Volume – Approx. 30-50m3	Debris impacted the phase 4a barrier. The majority of material was contained within the fence with only silt washing through the fence and on to the road.
November/ December 2017 (Jacobs geo-emergency	Debris flow	223930 E 707190 N	No	Source height – 415mAOD Source width - unknown Source length – 10m Source depth – 1.1m max	Landslide did not affect the A83. It was identified by Newcastle University during their monitoring activities.

Date (Report Reference)	Type of failure	Approximate source coordinates (Geotechnical Feature Reference)	Resulting disruption to A83	Approximate Dimensions and volume	Other observations / Summary of Event
inspection records, December 2018)					
August 2018 (Jacobs geo-emergency inspection records, August 2018)	*Landslide*	*223650 E 707460 N*	*No*	*Source height - 455mOD Source width – 5m Source length – 40m*	*Landslide did not affect the A83. Large boulder was released and travelled approximately 100m downslope breaking up en route and coming to rest at approximate NGR 223600 707390*
16-19 September 2018 (Jacobs 2018b)	Debris flow	223802 E 707201 N (scarp)	No	Source height – 371mAOD Source width - 7m Source length - 50m Source depth – 1m Run-out length – 50m.	Terrestrial laser scan undertaken by Newcastle university identified movement of a soil block over a period of four days. The failure did not channelise and the A83 was not affected. Several potentially unstable boulders were recorded in the vicinity of the failure scar. Comparison of time lapse footage indicated that one of the boulders had moved during the soil slip.
October 2018 (Jacobs emergency inspection records)	*Debris flow*	*Phase 1 Phase 4 Phase 10 (223799 707496)*	*Yes. Old military road diversion route also affected.*	*Several debris flows during a single rainfall event with a total estimated volume of 11234m^3*	*Many boulders mobilised during the failures, some of which were deemed to be a hazard and were subsequently stabilised. Catch fences provided some protection to the road but did not have adequate capacity for this failure event.*

Table C.3 – Preliminary Boulder Inventory

Boulder ID	Easting	Northing	Elevation (mAOD)	Maximum Dimension from DEM
B1	223714	707043	92.41	4.07
B2	223681	707041	73.78	2.32
B3	223704	707009	71.6	1.92
B4	223718	706990	76.46	1.3
B5	223721	706990	77.17	1.24
B6	223729	706991	80.48	1.46
B7	223716	707009	71.6	1.71
B8	223726	707009	85.79	1.15
B9	223737	707008	92.91	2.47
B10	223746	707000	91.89	1.63
B11	223746	707006	95.79	1.39
B12	223758	707015	105.31	2.18
B13	223722	707028	92.41	2.43
B14	223740	707024	101.85	2.41
B15	223790	707022	121.58	1.18
B16	223741	707038	103.83	1.74
B17	223745	707018	101.91	1.07
B18	223745	707070	119.27	2.05
B19	223720	707081	113.4	1.7
B20	223719	707097	119.15	1.77
B21	223712	707099	117.29	2.22
B22	223741	707120	143.41	2.59
B23	223739	707127	145.89	1.9
B24	223715	707114	125.97	1.91
B25	223766	707101	147.74	3.44
B26	223735	707129	143.81	1.49
B27	223740	707134	150.08	1.48
B28	223682	707066	89.06	2.51
B29	223706	707100	115.04	1.82
B30	223721	707118	130.83	1.6
B31	223746	707131	151.38	1.52
B32	223766	707133	162.75	2.92
B33	223764	707130	159.71	2.25
B34	223766	707131	160.59	1.84
B35	223765	707135	162.75	1.92
B36	223765	707120	152.83	1.2

Boulder ID	Easting	Northing	Elevation (mAOD)	Maximum Dimension from DEM
B37	223749	707113	142.74	2.39
B38	223779	707119	160.92	1.13
B39	223779	707128	164.6	1.57
B40	223779	707130	173.7	2.88
B41	223779	707144	180.48	4.31
B42	223783	707158	177.22	2.89
B43	223777	707156	174.62	1.84
B44	223781	707146	195.51	2.46
B45	223812	707157	195.74	2.15
B46	223808	707165	200.63	1.82
B47	223805	707172	202.97	1.54
B48	223806	707177	199.82	1.68
B49	223798	707178	200.4	1.2
B50	223801	707178	207.05	1.43
B51	223818	707174	204.47	2.4
B52	223803	707189	213.48	1.29
B53	223825	707180	214.8	2.49
B54	223832	707176	219.57	1.36
B55	223825	707194	250.11	1.27
B56	223867	707228	250.98	1.03
B57	223868	707229	253.12	1.15
B58	223869	707232	253.47	2.76
B59	223875	707228	255.59	2.09
B60	223879	707229	257.99	3.03
B61	223878	707234	260.67	1.77
B62	223882	707237	261.42	2.49
B63	223883	707239	263.47	1.76
B64	223886	707240	261.35	2.11
B65	223887	707235	261.4	1.35
B66	223884	707234	261.13	1.6
B67	223881	707239	261.53	1.59
B68	223891	707228	248.07	2.42
B69	223878	707212	285.18	2.29
B70	223897	707262	287.46	3.34
B71	223937	707228	289.07	1.71
B74	223938	707233	122.05	1.78

Boulder ID	Easting	Northing	Elevation (mAOD)	Maximum Dimension from DEM
B75	223749	707043	128.76	3.65
B76	223744	707060	108.65	1.52
B77	223795	707043	115.1	1.6
B79	223793	707043	136.53	2.5
B80	223823	707058	134.42	2.7
B82	223821	707084	151.03	1.62
B84	223816	707080	164.62	1.13
B85	223827	707115	160.23	1.11
B86	223830	707117	182.86	2.9
B87	223819	707111	186.02	3.34
B88	223812	707111	178.26	1.23
B89	223851	707116	173.48	1.43
B90	223851	707118	194.41	3.6
B91	223871	707113	196.3	2.38
B92	223860	707158	202.85	1.81
B93	223879	707162	217.22	3.01
B94	223894	707155	225.97	1.94
B95	223895	707156	227.59	1.73
B96	223894	707169	229.32	2.11
B97	223893	707181	237.29	1.17
B98	223953	707171	243.07	1.49
B99	223972	707168	262.45	5.79
B100	224023	707238	267.19	2.02
B109	224098	707282	330.05	3.96
B113	224059	707372	396.82	1.59
B117	224060	707363	414.22	1.83
B122	224049	707354	403.04	2.73
B123	224031	707357	398.78	2.83
B124	224044	707348	399.6	1.78
B125	224048	707370	409.45	2.25
B126	224025	707361	397.21	2.65
B127	224014	707360	387.31	2.17
B128	224000	707353	378.02	3.9
B129	223988	707343	366.46	1.99
B130	224004	707343	372.97	1.92
B131	224016	707331	377.42	3.12

Boulder ID	Easting	Northing	Elevation (mAOD)	Maximum Dimension from DEM
B132	224012	707329	374.01	1.81
B133	224006	707320	366.85	2.42
B134	224003	707318	364.52	1.71
B135	224014	707323	371.36	1.93
B136	223965	707294	333.29	2.08
B137	223980	707295	342.9	1.34
B139	223942	707267	306.21	2.09
B140	223956	707212	282.42	2.42
B141	223980	707166	273.01	3.92
B144	223954	707139	253.46	3.74
B145	223905	707187	267.86	2.23
B146	223921	707206	150.65	1.84
B147	223789	707082	201.97	5.27
B148	223832	707152	304.55	2.37
B149	223918	707288	360.91	2.41
B150	224011	707303	389.16	2.05
B151	224073	707292	401.71	2.28
B154	223753	707145	164.04	3.71

Table C.4 – Fields used in ArcGIS Collector application to record boulder attributes during fieldwork

Boulder ID	
Date	
Surveyors	
Boulder Legth	
Boulder Breadth	
Boulder Height	

Additional Notes:

Confirm boulder	✓ ×
Yes	
No	
Uncertain	
Boulder within Debris flow area?	✓ ×
Yes	
No	
uncertain	
Boulder Shape	✓ ×
Tabular	
Spherical	
Cubic	
Cylindrical	
Irregular	
Angularity	✓ ×
Very rounded	
Rounded	
Sub-rounded	
Sub-angular	
Angular	
Very angular	

Boulder embedded?	✓ ×
Yes	
No	
Embeddment material	✓ ×
Colluvium	
Glacial Till	
Top soil	
Undertermined	
Other (provide details)	
Evidence of instability	✓ ×
Tension cracks	
Terracettes	
Soil erosion	
Wash out feature	
Seepage	
Soil build-up behind boulder	
Landlside scarp	
Other (provide details)	

Slope vegetation	✓ ×
Grass / low shrubs above boulder	
Grass / low shrubs below boulder	
Bare soil above boulder	
Bare soil below boulder	
Bare rock above boulder	
Bare rock below boulder	
Bushes / small trees above boulder	
Bushes / small trees below boulder	
Hydrophillic vegetation above boulder	
Hydrophillic vegetation below boulder	
Trees / woodland above boulder	
Trees / woodland below boulder	
Other	
Surface drainage	✓ ×
Within drainage line (flowing)	
Within drainage line (dry)	
Within 5m of drainage line (flowing)	
Within 5m of drainage line (dry)	
Seepage / area of boggy ground	
More than 5m from drainage line	
Other (provide details)	

Table C-5 - Boulder Inventory and Hazard Assessment

Final Boulder Inventory for Detailed Study Area						Hazard Assessment								
Boulder ID	Boulder Shape	Evidence of instability 1	Evidence of instability 2	Surface Drainage	Notes	Approx. Volume	Z-offset	Shape Factor factor A	Release factor, B	Instability Factor C	Likelihood of initiation Score (B*C)	Likelihood Class	Intensity Class	Hazard Rating
B1	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	11.60	2.26	0.00	2.00	1.00	2.00	L1	V3	Low
B2	Spherical	Soil build up behind boulder	Seepage	Within 5m of DL (flowing)	No stability concerns	5.54	1.72	3.00	2.00	2.00	4.00	L3	V3	High
B3	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.86	1.35	0.00	2.00	1.00	2.00	L1	V3	Low
B4	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.78	0.84	0.00	1.00	1.00	1.00	L1	V2	Low
B5	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.81	0.85	0.00	1.00	1.00	1.00	L1	V2	Low
B6	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.24	0.55	0.00	1.00	1.00	1.00	L1	V1	Low
B7	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.12	0.96	0.00	1.00	1.00	1.00	L1	V2	Low
B9	Cubic	-	-	More than 5m from nearest DL	No stability concerns	5.60	1.73	1.00	2.00	1.00	2.00	L1	V3	Medium
B10	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.38	1.26	0.00	2.00	1.00	2.00	L1	V3	Low
B11	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.68	1.11	0.00	2.00	1.00	2.00	L1	V3	Low
B12	Tabular	-	-	More than 5m from nearest DL	No stability concerns	5.48	1.72	0.00	2.00	1.00	2.00	L1	V3	Low
B13	Tabular	Other (provide details)	-	Within drainage line (flowing)	Slight overhang. If scar eroded further, boulder may become loose.	6.83	1.86	0.00	2.00	3.00	6.00	L1	V3	Low
B14	Cubic	-	-	More than 5m from nearest DL	No stability concerns	4.79	1.63	1.00	2.00	1.00	2.00	L1	V3	Medium
B16	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	3.36	1.44	0.00	2.00	1.00	2.00	L1	V3	Low
B17	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Smaller tabular block sitting on top	0.36	0.64	0.00	1.00	1.00	1.00	L1	V1	Low
B18	Spherical	-	-	Within drainage line (flowing)	Within drainage line - could not measure safely. Measurements estimated	2.16	1.22	3.00	2.00	2.00	4.00	L3	V3	High
B19	Irregular	-	-	Within drainage line (flowing)	No stability concerns	1.94	1.18	2.00	2.00	2.00	4.00	L2	V3	High
B20	Tabular	Soil build up behind boulder	Wash out feature	Within drainage line (dry)	Within drainage line. Potential to fail in flood	1.21	0.99	0.00	1.00	3.00	3.00	L2	V2	Low
B21	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	1.94	1.17	0.00	2.00	1.00	2.00	L1	V3	Low
B22	Cubic	Soil build up behind boulder	Soil erosion	Within 5m of DL (flowing)	Soil below boulder is eroding. Potentially unstable if further soil removed	6.93	1.87	1.00	2.00	3.00	6.00	L1	V3	Medium
B23	Irregular	Wash out feature	Soil build up behind boulder	Within 5m of DL (flowing)	Washout below but no stability concerns	3.84	1.51	2.00	2.00	2.00	4.00	L2	V3	High
B24	Tabular	Wash out feature	Soil build up behind boulder	Within drainage line (flowing)	Potentially unstable	2.31	1.25	0.00	2.00	3.00	6.00	L1	V3	Low
B25	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	4.06	1.54	0.00	2.00	1.00	2.00	L1	V3	Low
B26	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.73	0.82	0.00	1.00	1.00	1.00	L1	V2	Low
B27	Tabular	-	-	More than 5m from nearest DL	Potentially unstable	2.27	1.24	0.00	2.00	3.00	6.00	L1	V3	Low
B28	Tabular	Soil build up behind boulder	Soil erosion	Within drainage line (flowing)	-	8.28	2.00	0.00	2.00	3.00	6.00	L1	V3	Low
B29	Tabular	Soil build up behind boulder	Soil erosion	Within 5m of DL (flowing)	Potentially unstable	0.99	0.92	0.00	1.00	3.00	3.00	L2	V2	Low
B30	Irregular	Wash out feature	-	Within 5m of DL (flowing)	Overhanging at front. Potentially unstable	0.42	0.67	2.00	1.00	2.00	2.00	L1	V1	Low
B31	Cubic	Soil build up behind boulder	Wash out feature	Within drainage line (flowing)	Potentially unstable	4.70	1.62	1.00	2.00	2.00	4.00	L1	V3	Medium
B32	Irregular	-	-	Within 5m of DL (flowing)	-	4.26	1.56	2.00	2.00	1.00	2.00	L1	V3	Medium
B34	Tabular	Seepage	-	Within 5m of DL (flowing)	-	9.59	2.11	0.00	2.00	2.00	4.00	L1	V3	Low
B35	Irregular	Other (provide details)	-	Within 5m of DL (flowing)	Boulder is overhanging	1.16	0.97	2.00	1.00	1.00	1.00	L1	V2	Low
B36	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.68	0.80	0.00	1.00	1.00	1.00	L1	V2	Low
B37	Irregular	Seepage	Tension cracks	Seepage/area of boggy ground	Potentially unstable if further soil movement due to tension cracks below	5.94	1.77	2.00	2.00	3.00	6.00	L2	V3	High
B39	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.92	0.89	0.00	1.00	1.00	1.00	L1	V2	Low
B40	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.25	0.56	0.00	1.00	1.00	1.00	L1	V1	Low
B41	Tabular	-	-	More than 5m from nearest DL	No stability concerns	4.90	1.65	0.00	2.00	1.00	2.00	L1	V3	Low
B42	Cubic	-	-	More than 5m from nearest DL	No stability concerns	61.01	4.14	1.00	3.00	1.00	3.00	L1	V3	Medium
B43	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	1.44	1.05	2.00	2.00	1.00	2.00	L1	V2	Low
B44	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.10	0.96	0.00	1.00	1.00	1.00	L1	V2	Low
B45	Tabular	-	-	More than 5m from nearest DL	No stability concerns	7.50	1.92	0.00	2.00	1.00	2.00	L1	V3	Low
B46	Tabular	-	-	More than 5m from nearest DL	No stability concerns	7.20	1.90	0.00	2.00	1.00	2.00	L1	V3	Low
B47	Tabular	-	-	More than 5m from nearest DL	No stability concerns	3.06	1.39	0.00	2.00	1.00	2.00	L1	V3	Low
B48	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.17	0.48	0.00	1.00	1.00	1.00	L1	V1	Low
B49	Tabular	-	-	More than 5m from nearest DL	Potentially unstable	0.61	0.77	0.00	1.00	3.00	3.00	L2	V2	Low
B50	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.95	0.91	0.00	1.00	1.00	1.00	L1	V2	Low
B51	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.58	1.09	0.00	2.00	1.00	2.00	L1	V3	Low
B52	Tabular	Seepage	Tension cracks	Within 5m of DL (flowing)	Potentially unstable if further erosion of the channel	3.02	1.38	0.00	2.00	3.00	6.00	L1	V3	Low
B53	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.06	0.94	0.00	1.00	1.00	1.00	L1	V2	Low
B54	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	7.00	1.88	0.00	2.00	1.00	2.00	L1	V3	Low
B55	Cubic	Tension cracks	Soil erosion	More than 5m from nearest DL	Potentially unstable if further erosion of scarp or washout	3.12	1.40	1.00	2.00	3.00	6.00	L1	V3	Medium
B56	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.31	0.60	0.00	1.00	1.00	1.00	L1	V1	Low
B57	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.61	0.77	0.00	1.00	1.00	1.00	L1	V2	Low
B58	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.15	0.97	0.00	1.00	1.00	1.00	L1	V2	Low
B59	Tabular	Soil erosion	-	Within drainage line (flowing)	Potential for instability if further erosion of the channel	3.78	1.50	0.00	2.00	3.00	6.00	L1	V3	Low
B60	Tabular	Soil erosion	Wash out feature	Within drainage line (flowing)	Potential for instability if further erosion of the channel	5.04	1.66	0.00	2.00	3.00	6.00	L1	V3	Low
B61	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	Boulder has drill holes. Potentially remains of stabilised boulder	12.96	2.35	0.00	2.00	2.00	4.00	L1	V3	Low
B62	Tabular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	2.25	1.24	0.00	2.00	3.00	6.00	L1	V3	Low
B63	Tabular	Soil erosion	-	Within 5m of DL (flowing)	No stability concerns	2.38	1.27	0.00	2.00	3.00	6.00	L1	V3	Low
B64	Irregular	-	-	Within drainage line (flowing)	Potential for instability if further erosion of the channel	2.16	1.22	2.00	2.00	2.00	4.00	L2	V3	High
B65	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	1.98	1.18	0.00	2.00	1.00	2.00	L1	V3	Low
B67	Tabular	Seepage	-	Within 5m of DL (flowing)	Potentially unstable if further erosion	2.08	1.20	0.00	2.00	2.00	4.00	L1	V3	Low
B68	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	7.34	1.91	1.00	2.00	1.00	2.00	L1	V3	Medium
B69	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	3.81	1.50	0.00	2.00	1.00	2.00	L1	V3	Low
B70	Tabular	Soil erosion	Soil build up behind boulder	More than 5m from nearest DL	Boulder has been stabilised by blasting but large fragments remain on hillside. Potential for instability if further erosion of the scar	10.08	2.14	0.00	2.00	3.00	6.00	L1	V3	Low
B71	Tabular	-	-	More than 5m from nearest DL	No stability concerns	3.43	1.45	0.00	2.00	1.00	2.00	L1	V3	Low
B72	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.80	0.85	0.00	1.00	1.00	1.00	L1	V2	Low
B77	Tabular	Seepage	Wash out feature	Within drainage line (flowing)	-	1.68	1.11	0.00	2.00	1.00	2.00	L1	V3	Low
B78	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.59	0.76	0.00	1.00	1.00	1.00	L1	V2	Low
B79	Cubic	-	-	More than 5m from nearest DL	Resting on boulder below	3.14	1.40	1.00	2.00	1.00	2.00	L1	V3	Medium
B80	Tabular	Other (provide details)	-	Other (provide details)	Potential ground movement below but no stability concerns	5.38	1.70	0.00	2.00	1.00	2.00	L1	V3	Low
B82	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.73	0.82	0.00	1.00	1.00	1.00	L1	V2	Low
B84	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	3.36	1.44	1.00	2.00	1.00	2.00	L1	V3	Medium
B85	Cubic	-	-	More than 5m from nearest DL	No stability concerns. Might be bedrock	1.44	1.05	1.00	2.00	1.00	2.00	L1	V2	Low
B86	Tabular	-	-	More than 5m from nearest DL	No stability concerns	5.76	1.75	0.00	2.00	1.00	2.00	L1	V3	Low
B87	Tabular	-	-	More than 5m from nearest DL	Overhanging but no stability concerns	11.76	2.27	0.00	2.00	1.00	2.00	L1	V3	Low

B88	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.72	0.82	0.00	1.00	1.00	1.00	L1	V2	Low
B89	Tabular	-	-	More than 5m from nearest DL	Potentially unstable if soil movement below but no immediate stability concerns	3.60	1.47	0.00	2.00	2.00	4.00	L1	V3	Low
B90	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.72	0.82	0.00	1.00	1.00	1.00	L1	V2	Low
B91	Irregular	Soil erosion	Seepage	Within 5m of DL (flowing)	Potential for instability if further erosion of the channel	5.31	1.70	2.00	2.00	3.00	6.00	L2	V3	High
B92	Tabular	Wash out feature	Soil build up behind boulder	Within 5m of DL (flowing)	Boulder has broken into 2 large pieces on movement in debris flow. Potentially unstable if further soil movement	5.94	1.77	0.00	2.00	3.00	6.00	L1	V3	Low
B93	Tabular	-	-		No stability concerns	4.41	1.59	0.00	2.00	1.00	2.00	L1	V3	Low
B94	Cubic	-	-	More than 5m from nearest DL	No stability concerns	6.48	1.82	1.00	2.00	1.00	2.00	L1	V3	Medium
B95	Tabular	-	-	More than 5m from nearest DL	Seems to have moved recently	0.66	0.79	0.00	1.00	3.00	3.00	L2	V2	Low
B96	Tabular	-	-	Within 5m of DL (dry)	No stability concerns. Seems to have moved recently	0.88	0.88	0.00	1.00	1.00	1.00	L1	V2	Low
B97	Tabular	-	-	More than 5m from nearest DL	Potentially unstable if further soil movement	0.67	0.80	0.00	1.00	2.00	2.00	L1	V2	Low
B98	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.81	0.85	0.00	1.00	1.00	1.00	L1	V2	Low
B99	Tabular	Seepage	Tension cracks	Within 5m of DL (flowing)	Potentially unstable if soil movement. Below tension crack	41.35	3.59	0.00	3.00	3.00	9.00	L1	V3	Low
B100	Cubic	-	Seepage	Within 5m of DL (flowing)	No stability concerns	3.32	1.43	1.00	2.00	1.00	2.00	L1	V3	Medium
B109	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	8.80	2.04	0.00	2.00	1.00	2.00	L1	V3	Low
B119	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	14.40	2.44	2.00	2.00	1.00	2.00	L1	V3	Medium
B120	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	2.56	1.30	0.00	2.00	1.00	2.00	L1	V3	Low
B121	Cubic	Soil erosion	-	Within drainage line (flowing)	No stability concerns	7.13	1.89	1.00	2.00	3.00	6.00	L1	V3	Medium
B122	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.42	0.67	0.00	1.00	1.00	1.00	L1	V1	Low
B123	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	1.96	1.18	0.00	2.00	1.00	2.00	L1	V3	Low
B124	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.84	0.87	0.00	1.00	1.00	1.00	L1	V2	Low
B125	Irregular	-	-	More than 5m from nearest DL	No stability concerns	6.38	1.81	2.00	2.00	1.00	2.00	L1	V3	Medium
B127	Cubic	-	-	More than 5m from nearest DL	Potentially unstable if soil movement	26.64	3.06	1.00	3.00	1.00	3.00	L1	V3	Medium
B128	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.32	1.02	0.00	2.00	1.00	2.00	L1	V2	Low
B129	Tabular	-	-		No stability concerns	0.34	0.62	0.00	1.00	1.00	1.00	L1	V1	Low
B130	Tabular	-	-	More than 5m from nearest DL	No stability concerns	11.02	2.21	0.00	2.00	1.00	2.00	L1	V3	Low
B131	Tabular	-	-	More than 5m from nearest DL	Overhanging. Potentially unstable if further erosion	1.08	0.95	0.00	1.00	2.00	2.00	L1	V2	Low
B132	Tabular	-	-		No stability concerns	1.19	0.98	0.00	1.00	1.00	1.00	L1	V2	Low
B133	Tabular	-	-		No stability concerns	0.68	0.80	0.00	1.00	1.00	1.00	L1	V2	Low
B134	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns but could slide if further soil movement	7.80	1.95	0.00	2.00	1.00	2.00	L1	V3	Low
B135	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Rebar in centre of boulder. Previously attempt to stabilise?	2.27	1.24	0.00	2.00	1.00	2.00	L1	V3	Low
B136	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.07	0.95	0.00	1.00	1.00	1.00	L1	V2	Low
B137	Tabular	-	-	More than 5m from nearest DL	No stability	2.80	1.34	0.00	2.00	1.00	2.00	L1	V3	Low
B138	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	12.50	2.32	0.00	2.00	1.00	2.00	L1	V3	Low
B139	Cubic	-	-	Within drainage line (flowing)	No stability concerns	3.00	1.38	1.00	2.00	2.00	4.00	L1	V3	Medium
B142	Tabular	-	-	More than 5m from nearest DL	No stability concerns	7.28	1.90	0.00	2.00	1.00	2.00	L1	V3	Low
B143	Tabular	-	-		No stability concerns	0.48	0.71	0.00	1.00	1.00	1.00	L1	V1	Low
B144	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.54	1.08	2.00	2.00	1.00	2.00	L1	V3	Medium
B145	Cubic	Wash out feature	Seepage	Within 5m of DL (flowing)	Potentially unstable if further soil movement below	62.40	4.17	1.00	3.00	2.00	6.00	L1	V3	Medium
B146	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	No stability concerns but could move if further erosion	6.86	1.86	0.00	2.00	2.00	4.00	L1	V3	Low
B147	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	9.50	2.10	1.00	2.00	2.00	4.00	L1	V3	Medium
B148	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	6.75	1.85	0.00	2.00	1.00	2.00	L1	V3	Low
B151	Tabular	Soil build up behind boulder	Wash out feature	Within drainage line (dry)	-	30.91	3.23	0.00	3.00	2.00	6.00	L1	V3	Low
A2	Tabular	-	-	More than 5m from nearest DL	-	1.95	1.18	0.00	2.00	1.00	1.00	L1	V3	Low
A3	Tabular	Landslide scarp	-	Within 5m of DL (flowing)	-	21.84	2.84	0.00	3.00	1.00	1.00	L1	V3	Low
A4	Tabular	-	-	More than 5m from nearest DL	-	1.92	1.17	0.00	2.00	1.00	6.00	L1	V3	Low
A5	Tabular	-	-	More than 5m from nearest DL	Potentially unstable - overhanging slope at base	0.35	0.63	0.00	1.00	3.00	2.00	L2	V1	Low
A6	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.98	0.91	0.00	1.00	1.00	1.00	L1	V2	Low
A7	Tabular	-	-		No stability concerns	0.63	0.78	0.00	1.00	1.00	0.00	L1	V2	Low
A8	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A9	Tabular	-	-	More than 5m from nearest DL	Surface exposure of boulder face. No stability concerns. 1m from channel barrier anchor phase 7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A10	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.29	0.58	0.00	1.00	1.00	0.00	L1	V1	Low
A11	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.06	0.94	0.00	1.00	1.00	0.00	L1	V2	Low
A12	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.47	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A13	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.86	1.35	0.00	2.00	1.00	0.00	L1	V3	Low
A14	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.08	0.95	2.00	1.00	1.00	1.00	L1	V2	Low
A15	Irregular	-	-	More than 5m from nearest DL	No stability concerns	0.44	0.68	2.00	1.00	1.00	1.00	L1	V1	Low
A16	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.17	0.48	0.00	1.00	1.00	0.00	L1	V1	Low
A17	Irregular	-	-	More than 5m from nearest DL	No stability concerns	2.16	1.22	2.00	2.00	1.00	2.00	L1	V3	Medium
A18	Unknown	-	-	More than 5m from nearest DL	Face of embedded boulder. No stability concerns	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A
A19	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.73	1.13	0.00	2.00	1.00	0.00	L1	V3	Low
A20	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.41	0.66	0.00	1.00	1.00	0.00	L1	V1	Low
A21	Tabular	Tension cracks	-		Signs of instability and recent movement	19.50	2.73	0.00	3.00	3.00	0.00	L1	V3	Low
A22	Tabular	Tension cracks	Landslide scarp	More than 5m from nearest DL	Evidence of recent movement and washout from below although dry at time of inspection	11.83	2.27	0.00	2.00	3.00	0.00	L1	V3	Low
A23	Tabular	-	-	More than 5m from nearest DL	No stability concerns	3.52	1.46	0.00	2.00	1.00	0.00	L1	V3	Low
A24	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.44	1.05	2.00	2.00	1.00	2.00	L1	V2	Low
A25	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.33	0.62	0.00	1.00	1.00	0.00	L1	V1	Low
A26	Irregular	Other (see notes)	-	Within 5m of DL (flowing)	Soil erosion at base of boulder and water flow at base	1.19	0.98	2.00	1.00	2.00	2.00	L1	V2	Low
A27	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.30	0.59	0.00	1.00	1.00	0.00	L1	V1	Low
A28	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.37	1.03	0.00	2.00	1.00	0.00	L1	V2	Low
A29	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.45	0.69	0.00	1.00	1.00	0.00	L1	V1	Low
A30	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Boulder flat against ground	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A
A31	Tabular	Tension cracks	-	More than 5m from nearest DL	Deep tension crack 3m above boulder location	0.26	0.57	0.00	1.00	3.00	0.00	L2	V1	Low
A32	Tabular	-	Tension cracks	More than 5m from nearest DL	Deep tension crack 3m above boulder location	0.48	0.70	0.00	1.00	3.00	0.00	L2	V1	Low
A33	Irregular	-	-	More than 5m from nearest DL	No stability concerns	6.50	1.83	2.00	2.00	1.00	2.00	L1	V3	Medium
A34	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.46	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A35	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.46	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A36	Tabular	-	-	More than 5m from nearest DL	No stability concerns	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A
A37	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.47	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A38	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.23	0.54	0.00	1.00	1.00	0.00	L1	V1	Low

A39	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.54	0.74	0.00	1.00	1.00	0.00	L1	V2	Low
A40	Cubic	Seepage	-	Within drainage line (flowing)	Potential for instability if erosion below boulder in drainage channel	2.46	1.28	1.00	2.00	3.00	6.00	L1	V3	Medium
A41	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A42	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A43	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.21	0.52	0.00	1.00	1.00	0.00	L1	V1	Low
A44	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.70	0.81	0.00	1.00	1.00	0.00	L1	V2	Low
A45	Irregular	-	-	More than 5m from nearest DL	No stability concerns	6.24	1.80	2.00	2.00	1.00	2.00	L1	V3	Medium
A46	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.88	1.36	0.00	2.00	1.00	0.00	L1	V3	Low
A47	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.67	0.80	0.00	1.00	1.00	0.00	L1	V2	Low
A48	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.36	0.64	0.00	1.00	1.00	0.00	L1	V1	Low
A49	Tabular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	1.52	1.07	0.00	2.00	3.00	0.00	L1	V3	Low
A50a	Tabular	-	-	Within 5m of DL (flowing)	One of 5 similar boulders stacked on top of eachother. No stability concerns	0.32	0.61	0.00	1.00	1.00	0.00	L1	V1	Low
A50b	Tabular	-	-	Within 5m of DL (flowing)	One of 5 similar boulders stacked on top of eachother. No stability concerns	0.32	0.61	0.00	1.00	1.00	0.00	L1	V1	Low
A50c	Tabular	-	-	Within 5m of DL (flowing)	One of 5 similar boulders stacked on top of eachother. No stability concerns	0.34	0.62	0.00	1.00	1.00	0.00	L1	V1	Low
A50d	Tabular	-	-	Within 5m of DL (flowing)	One of 5 similar boulders stacked on top of eachother. No stability concerns	0.35	0.63	0.00	1.00	1.00	0.00	L1	V1	Low
A50e	Tabular	-	-	Within 5m of DL (flowing)	One of 5 similar boulders stacked on top of eachother. No stability concerns	0.37	0.64	0.00	1.00	1.00	0.00	L1	V1	Low
A51	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	2.25	1.24	2.00	2.00	1.00	2.00	L1	V3	Medium
A52	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.20	0.51	0.00	1.00	1.00	0.00	L1	V1	Low
A53	Irregular	-	-	Within 5m of DL (flowing)	Triangular in shape. No stability concerns	1.43	1.05	2.00	2.00	1.00	2.00	L1	V2	Low
A54	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.78	0.84	0.00	1.00	1.00	0.00	L1	V2	Low
A55	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	0.95	0.90	1.00	1.00	1.00	1.00	L1	V2	Low
A56	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	1.26	1.00	0.00	2.00	1.00	0.00	L1	V2	Low
A57a	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns. One in cluster of 3 similar boulders.	0.67	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A57b	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns. One in cluster of 3 similar boulders.	0.67	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A57c	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns. One in cluster of 3 similar boulders.	0.67	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A58	Tabular	-	-	More than 5m from nearest DL	-	3.07	1.39	0.00	2.00	1.00	0.00	L1	V3	Low
A59	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.86	0.87	0.00	1.00	1.00	0.00	L1	V2	Low
A60	Irregular	-	-	More than 5m from nearest DL	No stability concerns	3.04	1.38	2.00	2.00	1.00	2.00	L1	V3	Medium
A61	Cubic	-	-	More than 5m from nearest DL	No stability concerns	5.76	1.75	1.00	2.00	1.00	2.00	L1	V3	Medium
A62	Cubic	-	-	More than 5m from nearest DL	No stability concerns	0.94	0.90	1.00	1.00	1.00	1.00	L1	V2	Low
A63	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.30	1.01	0.00	2.00	1.00	0.00	L1	V2	Low
A64	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.48	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A65	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.29	0.59	0.00	1.00	1.00	0.00	L1	V1	Low
A66	Tabular	-	-	More than 5m from nearest DL	-	0.36	0.64	0.00	1.00	1.00	0.00	L1	V1	Low
A67	Tabular	-	-	More than 5m from nearest DL	-	1.29	1.01	0.00	2.00	1.00	0.00	L1	V2	Low
A68	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.72	0.82	0.00	1.00	1.00	0.00	L1	V2	Low
A69	Irregular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	1.12	0.96	2.00	1.00	3.00	3.00	L1	V2	Low
A70	Tabular	-	-	Within drainage line (flowing)	No stability concerns	0.32	0.61	0.00	1.00	1.00	0.00	L1	V1	Low
A71	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.83	0.86	0.00	1.00	1.00	0.00	L1	V2	Low
A72	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.53	0.73	0.00	1.00	1.00	0.00	L1	V2	Low
A73	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.72	0.82	0.00	1.00	1.00	0.00	L1	V2	Low
A74	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	1.18	0.98	1.00	1.00	2.00	2.00	L1	V2	Low
A75	Tabular	-	-	Within 5m of DL (flowing)	-	0.31	0.60	0.00	1.00	1.00	0.00	L1	V1	Low
A76	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	1.58	1.09	2.00	2.00	1.00	2.00	L1	V3	Medium
A78	Unknown	-	-	Within drainage line (flowing)	No stability concerns	N/A	N/A	N/A	N/A	N/A	#VALUE!	N/A	N/A	N/A
A79	Tabular	-	-	Within 5m of DL (flowing)	-	3.10	1.39	0.00	2.00	1.00	0.00	L1	V3	Low
A80	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.72	0.82	0.00	1.00	1.00	0.00	L1	V2	Low
A81	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.16	1.22	0.00	2.00	1.00	0.00	L1	V3	Low
A82a	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A82b	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A82c	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A82d	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A82e	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A82f	Tabular	-	-	More than 5m from nearest DL	Cluster of 6 similar tabular boulders. No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A83	Cubic	-	-	More than 5m from nearest DL	No stability concerns	0.79	0.85	1.00	1.00	1.00	1.00	L1	V2	Low
A84	Tabular	-	-	More than 5m from nearest DL	No stability concerns	11.44	2.24	0.00	2.00	1.00	0.00	L1	V3	Low
A85a	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Cluster of four similar boulders	0.14	0.45	0.00	1.00	1.00	0.00	L1	V1	Low
A85b	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Cluster of four similar boulders	0.14	0.45	0.00	1.00	1.00	0.00	L1	V1	Low
A85c	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Cluster of four similar boulders	0.14	0.45	0.00	1.00	1.00	0.00	L1	V1	Low
A85d	Tabular	-	-	More than 5m from nearest DL	No stability concerns. Cluster of four similar boulders	0.14	0.45	0.00	1.00	1.00	0.00	L1	V1	Low
A86	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	3.57	1.47	2.00	2.00	1.00	2.00	L1	V3	Medium
A87	Cubic	-	-	More than 5m from nearest DL	Could roll down slope but would take a lot of movement to dislodge it. No immediate concerns	18.56	2.68	1.00	3.00	1.00	3.00	L1	V3	Medium
A88	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.19	0.50	0.00	1.00	1.00	0.00	L1	V1	Low
A89	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.50	0.71	0.00	1.00	1.00	0.00	L1	V1	Low
A90	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.45	0.69	0.00	1.00	1.00	0.00	L1	V1	Low
A91	Tabular	-	-	More than 5m from nearest DL	-	0.28	0.58	0.00	1.00	1.00	0.00	L1	V1	Low
A92	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.09	0.95	2.00	1.00	1.00	1.00	L1	V2	Low
A93	Tabular	-	-	More than 5m from nearest DL	-	1.14	0.97	0.00	1.00	1.00	0.00	L1	V2	Low
A94	Tabular	-	-	More than 5m from nearest DL	-	0.94	0.90	0.00	1.00	1.00	0.00	L1	V2	Low
A95	Cubic	-	-	More than 5m from nearest DL	No stability concerns	1.30	1.01	1.00	2.00	1.00	2.00	L1	V2	Low
A96	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.32	0.61	0.00	1.00	1.00	0.00	L1	V1	Low
A97	Irregular	Seepage	Soil build up behind boulder	Within drainage line (flowing)	Potential for failure if there is further erosion of scar.	0.60	0.77	2.00	1.00	3.00	3.00	L2	V2	Medium
A98	Tabular	Seepage	-	Within 5m of DL (flowing)	No stability concerns	0.77	0.84	0.00	1.00	1.00	0.00	L1	V2	Medium
A99	Irregular	Seepage	-	Within 5m of DL (flowing)	Potentially unstable if further erosion of scar	0.79	0.85	2.00	1.00	2.00	2.00	L2	V2	Medium
A100	Tabular	Seepage	Soil erosion	Within 5m of DL (flowing)	No stability concerns	2.31	1.25	0.00	2.00	1.00	0.00	L1	V3	Medium
A101	Tabular	Soil build up behind boulder	Wash out feature	Within 5m of DL (flowing)	Potential to fail if there is further erosion of the landslide scar.	0.62	0.78	0.00	1.00	3.00	0.00	L2	V2	Low
A102	Irregular	-	-	Within 5m of DL (flowing)	-	0.26	0.57	2.00	1.00	1.00	1.00	L1	V1	Low
A103	Irregular	-	-	Seepage/area of boggy ground	Sitting on smaller boulder less than 1m diameter. Potentially unstable if further soil erosion on scar	1.01	0.92	2.00	1.00	2.00	2.00	L1	V2	Low
A104	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	0.80	0.85	2.00	1.00	1.00	1.00	L1	V2	Low

A105	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.96	0.91	0.00	1.00	1.00	0.00	L1	V2	Low
A106	Tabular	Seepage	-	Within 5m of DL (flowing)	-	0.48	0.71	0.00	1.00	1.00	0.00	L1	V1	Low
A107	Tabular	-	-	Within 5m of DL (flowing)	-	5.98	1.77	0.00	2.00	1.00	0.00	L1	V3	Low
A108	Tabular	Seepage	-	More than 5m from nearest DL	No stability concerns	0.58	0.75	0.00	1.00	1.00	0.00	L1	V2	Low
A109	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	2.52	1.29	0.00	2.00	1.00	0.00	L1	V3	Low
A110	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.38	0.65	0.00	1.00	1.00	0.00	L1	V1	Low
A111a	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111b	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111c	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111d	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111e	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111f	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111g	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A111h	Tabular	-	-	Within drainage line (flowing)	Within cluster of 8+ boulders in stream >1.0m diameter. Largest measured	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A112	Cubic	Soil erosion	Landslide scarp	Within drainage line (flowing)	Potential for movement if further erosion.	1.96	1.18	1.00	2.00	3.00	6.00	L1	V3	Medium
A113	Tabular	Landslide scarp	-	Within drainage line (flowing)	Unsafe to take close up measurements within flowing drainage line. Potentially unstable in heavy stream flow but unlikely to impact road	1.47	1.06	0.00	2.00	3.00	0.00	L1	V3	Low
A114	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.76	0.83	0.00	1.00	1.00	0.00	L1	V2	Low
A115	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	2.28	1.25	2.00	2.00	1.00	2.00	L1	V3	Medium
A116	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	No stability concerns	0.70	0.81	0.00	1.00	1.00	0.00	L1	V2	Low
A117	Tabular	Seepage	-	Within drainage line (flowing)	No stability concerns	1.36	1.03	0.00	2.00	1.00	0.00	L1	V2	Low
A118	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns.	0.49	0.71	0.00	1.00	1.00	0.00	L1	V1	Low
A119	Tabular	Soil build up behind boulder	Other (provide details)	Within drainage line (flowing)	Root jacking from small trees. Boulder overhanging rock face.	0.62	0.78	0.00	1.00	2.00	0.00	L1	V2	Low
A120	Tabular	Soil build up behind boulder	Other (provide details)	Within drainage line (flowing)	-	4.22	1.56	0.00	2.00	2.00	0.00	L1	V3	Low
A121	Irregular	Seepage	Wash out feature	More than 5m from nearest DL	-	0.72	0.82	2.00	1.00	1.00	1.00	L1	V2	Low
A122	Irregular	Soil build up behind boulder	Seepage	Within 5m of DL (flowing)	Hydrophilic vegetation below boulder	8.25	1.99	2.00	2.00	2.00	4.00	L2	V3	High
A123	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.65	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A124	Tabular	-	-	More than 5m from nearest DL	-	0.18	0.49	0.00	1.00	1.00	0.00	L1	V1	Low
A125	Irregular	-	-	Within 5m of DL (flowing)	Potential for instability if further landslides occur	0.42	0.67	2.00	1.00	2.00	2.00	L1	V1	Low
A126	Irregular	-	-	Within 5m of DL (flowing)	-	0.20	0.51	2.00	1.00	1.00	1.00	L1	V1	Low
A127	Irregular	-	-	Within drainage line (flowing)	No stability concerns	1.55	1.08	2.00	2.00	2.00	4.00	L2	V3	High
A128	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	4.50	1.60	2.00	2.00	1.00	2.00	L1	V3	Medium
A129	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	10.34	2.16	2.00	2.00	1.00	2.00	L1	V3	Medium
A130	Tabular	-	-	Within 5m of DL (flowing)	-	2.11	1.21	0.00	2.00	1.00	0.00	L1	V3	Low
A131	Irregular	Wash out feature	Seepage	Within drainage line (flowing)	Potentially unstable	0.69	0.81	2.00	1.00	2.00	2.00	L1	V2	Low
A132	Irregular	-	-	Within 5m of DL (flowing)	-	0.59	0.76	2.00	1.00	1.00	1.00	L1	V2	Low
A133	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.66	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A134	Tabular	Soil erosion	-	Within 5m of DL (flowing)	-	0.19	0.50	0.00	1.00	3.00	0.00	L1	V1	Low
A135	Tabular	Soil build up behind boulder	Soil erosion	Within 5m of DL (flowing)	-	0.33	0.62	0.00	1.00	1.00	0.00	L1	V1	Low
A136	Tabular	-	-	Within drainage line (flowing)	Boulder overhanging in drainage line. Potential to move but unlikely to affect road	0.90	0.89	0.00	1.00	2.00	0.00	L1	V2	Low
A137	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.07	0.35	0.00	1.00	1.00	0.00	L1	V1	Low
A138	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.94	0.90	0.00	1.00	1.00	0.00	L1	V2	Low
A139	Irregular	Soil build up behind boulder	Seepage	Within drainage line (dry)	No stability concerns	0.64	0.78	2.00	1.00	2.00	2.00	L1	V2	Low
A140	Tabular	Soil build up behind boulder	Seepage	Within drainage line (flowing)	Potentially unstable if mobilised in flood	0.54	0.74	0.00	1.00	3.00	0.00	L2	V2	Low
A141	Irregular	Soil erosion	-	Within 5m of DL (flowing)	Potentially unstable if flood event occurs	0.65	0.79	2.00	1.00	3.00	3.00	L1	V2	Low
A142	Tabular	Soil build up behind boulder	-	Within drainage line (flowing)	No stability concerns	2.34	1.26	0.00	2.00	1.00	0.00	L1	V3	Low
A143	Tabular	Soil build up behind boulder	Seepage	Within drainage line (dry)	-	2.46	1.28	0.00	2.00	2.00	0.00	L1	V3	Low
A144	Tabular	Wash out feature	-	Within drainage line (dry)	No stability concerns	1.28	1.01	0.00	2.00	1.00	0.00	L1	V2	Low
A145	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	4.23	1.56	2.00	2.00	1.00	2.00	L1	V3	Medium
A146	Tabular	Soil build up behind boulder	Wash out feature	Within 5m of DL (flowing)	-	0.59	0.76	0.00	1.00	1.00	0.00	L1	V2	Low
A147	Tabular	Soil build up behind boulder	Wash out feature	Within 5m of DL (flowing)	-	0.25	0.56	0.00	1.00	1.00	0.00	L1	V1	Low
A148	Tabular	Soil build up behind boulder	Seepage	Within 5m of DL (flowing)	Unstable boulder resting above surveyed boulder.	0.50	0.72	0.00	1.00	2.00	0.00	L1	V2	Low
A149	Irregular	Soil build up behind boulder	Seepage	Within drainage line (dry)	-	1.13	0.97	2.00	1.00	2.00	2.00	L1	V2	Low
A150	Tabular	Soil build up behind boulder	Wash out feature	Within 5m of DL (flowing)	If underlying material were to wash out, the boulder would be at risk of instability.	1.51	1.07	0.00	2.00	2.00	0.00	L1	V3	Low
A151	Tabular	Seepage	Wash out feature	Within 5m of DL (flowing)	No stability concerns	2.90	1.36	0.00	2.00	1.00	0.00	L1	V3	Low
A152	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.29	0.59	0.00	1.00	1.00	0.00	L1	V1	Low
A153	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.10	0.40	0.00	1.00	1.00	0.00	L1	V1	Low
A154	Cubic	-	-	More than 5m from nearest DL	No stability concerns	0.81	0.85	1.00	1.00	1.00	1.00	L1	V2	Low
A155	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.18	1.23	0.00	2.00	1.00	0.00	L1	V3	Low
A156	Cubic	-	-	More than 5m from nearest DL	No stability concerns	1.76	1.13	1.00	2.00	1.00	2.00	L1	V3	Medium
A157	Tabular	-	-	More than 5m from nearest DL	-	0.97	0.91	0.00	1.00	1.00	0.00	L1	V2	Low
A158	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.54	1.08	0.00	2.00	1.00	0.00	L1	V3	Low
A159	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.50	1.07	2.00	2.00	1.00	2.00	L1	V3	Medium
A160	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.46	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A161	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.72	0.82	0.00	1.00	1.00	0.00	L1	V2	Low
A162	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.63	0.78	0.00	1.00	1.00	0.00	L1	V2	Low
A163	Cubic	-	-	More than 5m from nearest DL	No stability concerns	21.50	2.83	1.00	3.00	1.00	3.00	L1	V3	Medium
A164	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.31	1.02	0.00	2.00	1.00	0.00	L1	V2	Low
A165	Tabular	-	-	More than 5m from nearest DL	No stability concerns	10.92	2.21	0.00	2.00	1.00	0.00	L1	V3	Low
A166	Tabular	Soil erosion	-	Within drainage line (flowing)	Potentially unstable if further erosion of the channel	1.00	0.92	0.00	1.00	3.00	0.00	L2	V2	Low
A167	Tabular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	0.90	0.89	0.00	1.00	3.00	0.00	L1	V2	Low
A168	Tabular	Soil erosion	-	Within drainage line (flowing)	Potentially unstable if further erosion of the channel	1.01	0.92	0.00	1.00	3.00	0.00	L2	V2	Low
A169	Cubic	Soil erosion	-	Within drainage line (flowing)	No stability concerns. Could move within channel but unlikely to reach road	1.80	1.14	1.00	2.00	3.00	6.00	L1	V3	Medium
A170	Tabular	Soil erosion	Soil build up behind boulder	Within drainage line (flowing)	No stability concerns. Could move within channel but unlikely to reach road	3.34	1.43	0.00	2.00	3.00	0.00	L1	V3	Low
A171	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	No stability concerns	22.56	2.88	0.00	3.00	1.00	0.00	L1	V3	Low

A172	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.66	0.79	0.00	1.00	1.00	0.00	L1	V2	Low
A173	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.80	0.85	0.00	1.00	1.00	0.00	L1	V2	Low
A174	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.60	1.09	0.00	2.00	1.00	0.00	L1	V3	Low
A175	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.88	0.88	0.00	1.00	1.00	0.00	L1	V2	Low
A176	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.31	0.60	0.00	1.00	1.00	0.00	L1	V1	Low
A177	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.34	0.62	0.00	1.00	1.00	0.00	L1	V1	Low
A178a	Tabular	-	-	More than 5m from nearest DL	One of 2 boulders with similar dimensions lying next to eachother. No stability concerns	1.44	1.05	0.00	2.00	1.00	0.00	L1	V2	Low
A178b	Tabular	-	-	More than 5m from nearest DL	One of 2 boulders with similar dimensions lying next to eachother. No stability concerns	1.44	1.05	0.00	2.00	1.00	0.00	L1	V2	Low
A179	Tabular	-	-	More than 5m from nearest DL	No stability concerns	6.09	1.78	0.00	2.00	1.00	0.00	L1	V3	Low
A180	Cubic	-	-	More than 5m from nearest DL	No stability concerns immediately but could fail if soil movement	1.98	1.18	1.00	2.00	1.00	2.00	L1	V3	Medium
A181	Tabular	Seepage	-	More than 5m from nearest DL	No stability concerns	21.00	2.80	0.00	3.00	1.00	0.00	L1	V3	Low
A182	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	1.73	1.13	0.00	2.00	1.00	0.00	L1	V3	Low
A183	Tabular	-	-	More than 5m from nearest DL	Cluster of three similar boulders. No stability concerns	0.86	0.87	0.00	1.00	1.00	0.00	L1	V2	Low
A184	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.90	0.89	0.00	1.00	1.00	0.00	L1	V2	Low
A185	Cubic	-	-	More than 5m from nearest DL	No stability concerns. In scrap of historical landslide	0.99	0.92	1.00	1.00	1.00	1.00	L1	V2	Low
A186	Cubic	Soil erosion	Seepage	More than 5m from nearest DL	Potentially unstable if further erosion. Tension cracks around old scarp	0.79	0.85	1.00	1.00	3.00	3.00	L1	V2	Low
A187	Cubic	-	-	Within 5m of DL (flowing)	Potentially unstable if further erosion or slope movement of steep slope below	2.72	1.33	1.00	2.00	1.00	2.00	L1	V3	Medium
A188	Tabular	-	-	More than 5m from nearest DL	No stability concerns	3.02	1.38	0.00	2.00	1.00	0.00	L1	V3	Low
A189	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.79	0.85	0.00	1.00	1.00	0.00	L1	V2	Low
A190	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.24	0.55	0.00	1.00	1.00	0.00	L1	V1	Low
A191	Tabular	-	-	Within drainage line (flowing)	Potentially unstable if further soil erosion in channel	1.27	1.01	0.00	2.00	2.00	0.00	L1	V2	Low
A192	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.08	0.95	0.00	1.00	1.00	0.00	L1	V2	Low
A193	Tabular	Soil build up behind boulder	Soil erosion	Within drainage line (flowing)	Potentially unstable if further erosion	0.53	0.73	0.00	1.00	3.00	0.00	L2	V2	Low
A194	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.00	0.92	0.00	1.00	1.00	0.00	L1	V2	Low
A195a	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A195b	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A195c	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A196	Irregular	-	-	More than 5m from nearest DL	No stability concerns	1.18	0.98	2.00	1.00	1.00	1.00	L1	V2	Low
A197a	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A197b	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A197c	Tabular	-	-	More than 5m from nearest DL	One of 3 boulders with similar dimensions lying next to eachother. No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A198	Irregular	-	-	More than 5m from nearest DL	No stability concerns. Appears to be anchored- rebar in centre	1.76	1.13	2.00	2.00	1.00	2.00	L1	V3	Medium
A199	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.08	0.36	0.00	1.00	1.00	0.00	L1	V1	Low
A200	Tabular	Soil erosion	-	Within 5m of DL (flowing)	Potentially unstable if further erosion of the channel	0.36	0.64	0.00	1.00	3.00	0.00	L2	V1	Low
A201	Tabular	Soil erosion	Wash out feature	Within 5m of DL (flowing)	Potentially unstable if further erosion of the channel	0.48	0.71	0.00	1.00	3.00	0.00	L1	V1	Low
A202	Tabular	Soil build up behind boulder	-	More than 5m from nearest DL	Potentially has been weakened by blasting. Fractured. No stability concerns	4.68	1.62	0.00	2.00	1.00	0.00	L1	V3	Low
A203a	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203b	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203c	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203d	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203e	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203f	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203g	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A203h	Tabular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side off scar. Potentially unstable if further erosion of the channel	1.12	0.96	0.00	1.00	3.00	0.00	L2	V2	Low
A204	Irregular	-	-	Within drainage line (flowing)	One boulder in cluster of 8 similar boulders in channel and side of scar. Potentially unstable if further erosion of the channel	0.69	0.81	2.00	1.00	3.00	3.00	L2	V2	Medium
A205	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.11	1.21	0.00	2.00	1.00	0.00	L1	V3	Low
A206	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.54	0.74	0.00	1.00	1.00	0.00	L1	V2	Low
A207	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.22	0.99	0.00	1.00	1.00	0.00	L1	V2	Low
A208	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.78	0.84	0.00	1.00	1.00	0.00	L1	V2	Low
A209	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.13	0.44	0.00	1.00	1.00	0.00	L1	V1	Low
A210	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.77	0.84	0.00	1.00	1.00	0.00	L1	V2	Low
A211	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	2.20	1.23	2.00	2.00	1.00	2.00	L1	V3	Medium
A212	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.80	0.85	0.00	1.00	1.00	0.00	L1	V2	Low
A213	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.32	1.25	0.00	2.00	1.00	0.00	L1	V3	Low
A214	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.34	0.62	0.00	1.00	1.00	0.00	L1	V1	Low
A215	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.59	0.76	0.00	1.00	1.00	0.00	L1	V2	Low
A216	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.89	1.16	0.00	2.00	1.00	0.00	L1	V3	Low

A217	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.60	1.09	0.00	2.00	1.00	0.00	L1	V3	Low
A218	Tabular	-	-	More than 5m from nearest DL	No stability concerns	2.52	1.29	0.00	2.00	1.00	0.00	L1	V3	Low
A219	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.09	0.38	0.00	1.00	1.00	0.00	L1	V1	Low
A220	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.53	0.73	0.00	1.00	1.00	0.00	L1	V2	Low
A221	Cubic	Wash out feature	Soil erosion	Within 5m of DL (flowing)	Potentially unstable if further soil movement	39.15	3.52	1.00	3.00	2.00	6.00	L1	V3	Medium
A222	Tabular	Tension cracks	-	Within 5m of DL (flowing)	Potentially unstable if progressive soil instability	0.68	0.80	0.00	1.00	2.00	0.00	L1	V2	Low
A223	Tabular	-	-	Within drainage line (flowing)	No stability concerns	0.26	0.57	0.00	1.00	1.00	0.00	L1	V1	Low
A224	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.60	1.09	0.00	2.00	1.00	0.00	L1	V3	Low
A225	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.22	0.99	0.00	1.00	1.00	0.00	L1	V2	Low
A226	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.60	1.09	0.00	2.00	1.00	0.00	L1	V3	Low
A227	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	2.24	1.24	0.00	2.00	1.00	0.00	L1	V3	Low
A228	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	6.12	1.79	1.00	2.00	1.00	2.00	L1	V3	Medium
A229	Cylindrical	Soil erosion	-	Within drainage line (flowing)	Potentially unstable if further soil erosion	1.75	1.13	1.00	2.00	3.00	6.00	L1	V3	Medium
A230	Tabular	-	-	Within drainage line (flowing)	No stability concerns	5.60	1.73	0.00	2.00	1.00	0.00	L1	V3	Low
A231	Tabular	-	-	More than 5m from nearest DL	No stability concerns	3.97	1.53	0.00	2.00	1.00	0.00	L1	V3	Low
A232	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.24	0.55	0.00	1.00	1.00	0.00	L1	V1	Low
A233	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.61	0.77	0.00	1.00	1.00	0.00	L1	V2	Low
A234	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.23	0.54	0.00	1.00	1.00	0.00	L1	V1	Low
A235a	Tabular	Seepage	Soil erosion	Within drainage line (flowing)	One boulder in cluster of 3 similar boulders. Potentially unstable if further erosion of the channel	0.66	0.79	0.00	1.00	3.00	0.00	L2	V2	Low
A235b	Tabular	Seepage	Soil erosion	Within drainage line (flowing)	One boulder in cluster of 3 similar boulders. Potentially unstable if further erosion of the channel	0.66	0.79	0.00	1.00	3.00	0.00	L2	V2	Low
A235c	Tabular	Seepage	Soil erosion	Within drainage line (flowing)	One boulder in cluster of 3 similar boulders. Potentially unstable if further erosion of the channel	0.66	0.79	0.00	1.00	3.00	0.00	L2	V2	Low
A236	Tabular	Soil erosion	Seepage	Within drainage line (flowing)	Potentially unstable if further soil erosion	2.28	1.25	0.00	2.00	3.00	0.00	L1	V3	Low
A237	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.48	0.70	0.00	1.00	1.00	0.00	L1	V1	Low
A238	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.31	0.60	0.00	1.00	1.00	0.00	L1	V1	Low
A239	Cubic	-	-	Within 5m of DL (flowing)	No immediate concerns but potentially unstable if soil movement	18.72	2.69	1.00	3.00	1.00	3.00	L1	V3	Medium
A240	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.99	0.92	0.00	1.00	1.00	0.00	L1	V2	Low
A241	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	6.08	1.78	1.00	2.00	1.00	2.00	L1	V3	Medium
A242	Tabular	-	-	Within 5m of DL (flowing)	-	0.83	0.86	0.00	1.00	1.00	0.00	L1	V2	Low
A243	Tabular	-	-	Within 5m of DL (flowing)	Potentially unstable if soil movement	0.86	0.87	0.00	1.00	2.00	0.00	L1	V2	Low
A244	Cubic	-	-	Within 5m of DL (flowing)	Potentially unstable if soil movement. Overhanging at front	7.45	1.92	1.00	2.00	1.00	2.00	L1	V3	Medium
A245	Irregular	-	-	Within 5m of DL (flowing)	One boulder within cluster of 3. Largest measured. Potentially unstable if soil movement	7.07	1.88	2.00	2.00	1.00	2.00	L1	V3	Medium
A245a	Irregular	-	-	Within 5m of DL (flowing)	One boulder within cluster of 3. Largest measured. Potentially unstable if soil movement	7.07	1.88	2.00	2.00	1.00	2.00	L1	V3	Medium
A245b	Irregular	-	-	Within 5m of DL (flowing)	One boulder within cluster of 3. Largest measured. Potentially unstable if soil movement	7.07	1.88	2.00	2.00	1.00	2.00	L1	V3	Medium
A246	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.61	0.77	0.00	1.00	1.00	0.00	L1	V2	Low
A247	Tabular	-	-	Within 5m of DL (flowing)	-	0.13	0.44	0.00	1.00	1.00	0.00	L1	V1	Low
A248	Tabular	Seepage	Soil erosion	Within 5m of DL (flowing)	Recently moved. Potentially unstable if further soil movement	0.56	0.75	0.00	1.00	3.00	0.00	L2	V2	Low
A249	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.68	0.80	0.00	1.00	1.00	0.00	L1	V2	Low
A250	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	0.91	0.89	0.00	1.00	1.00	0.00	L1	V2	Low
A251	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns immediately but potentially unstable if further soil movement below	0.79	0.85	1.00	1.00	1.00	1.00	L1	V2	Low
A252	Cubic	Soil erosion	-	Within 5m of DL (flowing)	Looks like there has been some movement up to 20cm recently. Potentially unstable if further soil movement below	1.87	1.16	1.00	2.00	3.00	6.00	L1	V3	Medium
A253a	Tabular	Soil erosion	-	Within drainage line (flowing)	In channel, estimated dimensions. Potentially unstable if further soil erosion. 2 x boulders	3.00	1.38	0.00	2.00	3.00	0.00	L1	V3	Low
A253b	Tabular	Soil erosion	-	Within drainage line (flowing)	In channel, estimated dimensions. Potentially unstable if furth	3.00	1.38	0.00	2.00	3.00	0.00	L1	V3	Low
A254	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A255	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.84	0.87	0.00	1.00	1.00	0.00	L1	V2	Low
A256	Cubic	Soil erosion	Seepage	Seepage/area of boggy ground	Potentially unstable if further erosion	0.78	0.84	1.00	1.00	3.00	3.00	L1	V2	Low
A257	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	Overhanging. Potentially unstable if further erosion	3.88	1.51	0.00	2.00	3.00	0.00	L1	V3	Low
A258	Tabular	Soil erosion	-	Within drainage line (flowing)	Potentially unstable if further erosion of the channel	1.44	1.05	0.00	2.00	3.00	0.00	L1	V2	Low
A259	Tabular	Soil erosion	-	Within drainage line (flowing)	Potentially unstable if further erosion of the channel	1.95	1.18	0.00	2.00	3.00	0.00	L1	V3	Low
A260a	Tabular	Soil erosion	-	Within drainage line (flowing)	one boulder in cluster of four boulders in channel. Largest measured. Potentially unstable if further soil erosion of the channel	1.20	0.99	0.00	1.00	3.00	0.00	L2	V2	Low
A260b	Tabular	Soil erosion	-	Within drainage line (flowing)	one boulder in cluster of four boulders in channel. Largest measured. Potentially unstable if further soil erosion of the channel	1.20	0.99	0.00	1.00	3.00	0.00	L2	V2	Low
A260c	Tabular	Soil erosion	-	Within drainage line (flowing)	one boulder in cluster of four boulders in channel. Largest measured. Potentially unstable if further soil erosion of the channel	1.20	0.99	0.00	1.00	3.00	0.00	L2	V2	Low
A260d	Tabular	Soil erosion	-	Within drainage line (flowing)	one boulder in cluster of four boulders in channel. Largest measured. Potentially unstable if further soil erosion of the channel	1.20	0.99	0.00	1.00	3.00	0.00	L2	V2	Low
A261a	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One boulder within cluster of 5 boulders of similar properties. Potential to move if further erosion of landslide scar	1.73	1.13	0.00	2.00	2.00	0.00	L1	V3	Low
A261b	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One boulder within cluster of 5 boulders of similar properties. Potential to move if further erosion of landslide scar	1.73	1.13	0.00	2.00	2.00	0.00	L1	V3	Low
A261c	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One boulder within cluster of 5 boulders of similar properties. Potential to move if further erosion of landslide scar	1.73	1.13	0.00	2.00	2.00	0.00	L1	V3	Low
A261d	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One boulder within cluster of 5 boulders of similar properties. Potential to move if further erosion of landslide scar	1.73	1.13	0.00	2.00	2.00	0.00	L1	V3	Low
A261e	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One boulder within cluster of 5 boulders of similar properties. Potential to move if further erosion of landslide scar	1.73	1.13	0.00	2.00	2.00	0.00	L1	V3	Low
A262a	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One of two boulders of similar properties. Potential for movement if further erosion of landslide scar	1.90	1.17	0.00	2.00	3.00	0.00	L1	V3	Low
A262b	Tabular	Soil build up behind boulder	-	Within 5m of DL (flowing)	One of two boulders of similar properties. Potential for movement if further erosion of landslide scar	1.90	1.17	0.00	2.00	3.00	0.00	L1	V3	Low
A263	Tabular	Soil build up behind boulder	Soil erosion	Within 5m of DL (flowing)	Potential for instability if further erosion of the channel	0.97	0.91	0.00	1.00	3.00	0.00	L2	V2	Low
A264	Tabular	Soil build up behind boulder	Soil erosion	More than 5m from nearest DL	Potential for instability if further erosion of the debris flow	0.65	0.79	0.00	1.00	2.00	0.00	L1	V2	Low

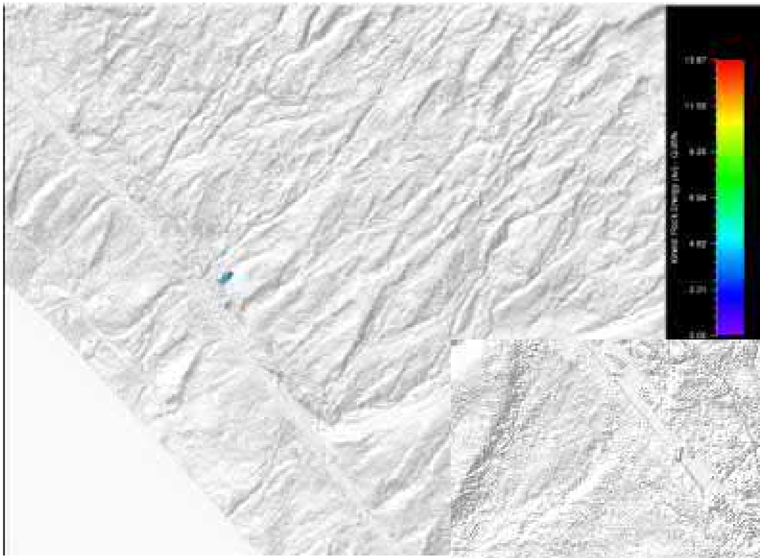
A265	Tabular	-	-	Within 5m of DL (flowing)	Several fragments of broken up stabilised boulder. Largest measured	0.55	0.74	0.00	1.00	1.00	0.00	L1	V2	Low
A266	Tabular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	1.68	1.11	0.00	2.00	3.00	0.00	L1	V3	Low
A267	Tabular	Seepage	-	Within 5m of DL (flowing)	No stability concerns	1.64	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A268	Tabular	Soil erosion	-	Within drainage line (flowing)	No stability concerns	1.90	1.17	0.00	2.00	3.00	0.00	L1	V3	Low
A269	Tabular	Soil erosion	-	Within drainage line (flowing)	Potential for instability if further erosion of the channel	1.40	1.04	0.00	2.00	3.00	0.00	L1	V2	Low
A270	Tabular	Soil erosion	Seepage	Within 5m of DL (flowing)	Potential for instability if further erosion of the channel	0.90	0.89	0.00	1.00	3.00	0.00	L2	V2	Low
A271	Cylindrical	Soil erosion	-	Within drainage line (flowing)	Potential for instability if further erosion	0.84	0.87	1.00	1.00	3.00	3.00	L1	V2	Low
A272	Tabular	Soil erosion	-	Within drainage line (flowing)	Potential for instability if further erosion	1.32	1.02	0.00	2.00	3.00	0.00	L2	V2	Low
A273	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.62	1.10	0.00	2.00	1.00	0.00	L1	V3	Low
A274	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.31	0.60	0.00	1.00	1.00	0.00	L1	V1	Low
A275	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.44	1.05	0.00	2.00	1.00	0.00	L1	V2	Low
A276	Irregular	-	-	More than 5m from nearest DL	No stability concerns	10.26	2.16	2.00	2.00	1.00	2.00	L1	V3	Medium
A277	Irregular	-	-	More than 5m from nearest DL	No stability concerns	12.12	2.29	2.00	2.00	1.00	2.00	L1	V3	Medium
A278	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.26	0.57	0.00	1.00	1.00	0.00	L1	V1	Low
A279	Tabular	-	-	More than 5m from nearest DL	No stabilitty concerns	0.20	0.51	0.00	1.00	1.00	0.00	L1	V1	Low
A280	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.50	0.72	0.00	1.00	1.00	0.00	L1	V2	Low
A281	Cubic	-	-	More than 5m from nearest DL	No stability concerns	200.72	6.39	1.00	3.00	1.00	3.00	L1	V3	Medium
A282	Tabular	-	-	More than 5m from nearest DL	No stability concerns	0.22	0.53	0.00	1.00	1.00	0.00	L1	V1	Low
A283	Tabular	Other (provide details)	-	More than 5m from nearest DL	Undercut. Resting on a rock outcrop	2.43	1.28	0.00	2.00	2.00	0.00	L1	V3	Low
A284	Tabular	-	-	Within 5m of DL (flowing)	No stability concerns	21.89	2.85	0.00	3.00	1.00	0.00	L1	V3	Low
A285	Cubic	-	-	More than 5m from nearest DL	No stability concerns	3.33	1.43	1.00	2.00	1.00	2.00	L1	V3	Medium
A286	Cubic	-	-	Within 5m of DL (flowing)	No stability concerns	10.35	2.16	1.00	2.00	1.00	2.00	L1	V3	Medium
A287	Irregular	-	-	Within 5m of DL (flowing)	No stability concerns	7.41	1.92	2.00	2.00	1.00	2.00	L1	V3	Medium
A288	Tabular	-	-	More than 5m from nearest DL	No stability concerns	1.09	0.95	0.00	1.00	1.00	0.00	L1	V2	Low
A289	Irregular	Tension cracks	Seepage	Within 5m of DL (flowing)	Tension crack below	5.85	1.76	2.00	2.00	3.00	6.00	L2	V3	High
A290	Irregular	-	-	Within 5m of DL (flowing)	Portion of boulder overhanging	9.66	2.11	2.00	2.00	1.00	2.00	L1	V3	Medium
A291	Tabular	Seepage	-	Within 5m of DL (flowing)	No stability concerns	0.82	0.86	0.00	1.00	1.00	0.00	L1	V2	Low

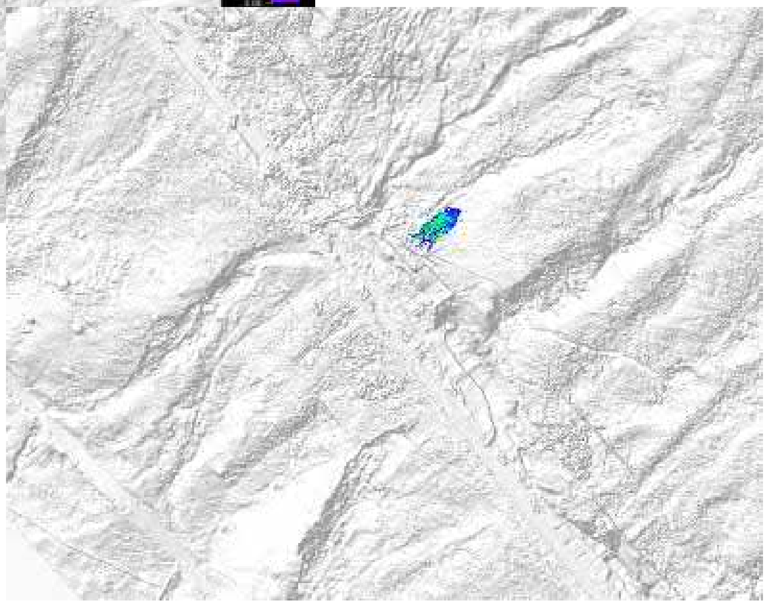
Table C.6 – Comparison of available data types

Data Type	Advantages	Disadvantages	Suitable Applications
Terrestrial laser scan	• High-resolution data can be specified • Resulting DEM can be used as a surface in fall-path modelling • Other geomorphological features can be recognised e.g. scarps, tension cracks • If data is of high enough resolution, individual boulder shapes could be obtained for use in fall-path modelling	• If not combined with photogrammetry, boulder identification may be limited • Limited use on sites with dense vegetation cover • Potential for 'blind spots' in data if complex site morphology	May be useful for hillsides with limited vegetation cover if laser scan data is used in combination with photogrammetry.
High resolution panoramic photography	• Boulders are easily identified on hillsides with limited vegetation	• Difficult to transfer boulder location to plan view due to panoramic nature of photographs • Allows measurement of boulders in two dimensions only • Additional survey data would be required if 3D fall-path modelling to be undertaken	May be suitable for relatively small sites that will not be severely affected by the panoramic nature of the photography.
Aerial Photography / Satellite imagery	• Boulders easily identified on open hillsides with limited vegetation • Boulder locations can be easily geo-referenced	• Allows measurement of boulders in two dimensions only.	May be suitable for hillsides with limited vegetation cover.
UAV photogrammetry survey*[1]	• Boulders are easily identified • Measurements over three dimensions can be taken • Resulting DEM can be used in fall path modelling • Geomorphological and other surface features such as bedrock can be identified • If resolution is high enough, individual boulder shapes can be obtained for use in fall-path modelling	• Vegetation cover such as trees may obscure boulder locations • Low vegetation cover can mask true boulder size	Open hillside with limited vegetation cover – e.g. scree slope, bare mountain terrain

	• UAV can be flown in areas that are inaccessible for site personnel		
Low flying, high specification UAV photogrammetry survey *[1]	• As above for general UAV photogrammetry but UAV can be flown through areas of forest so that there are no gaps in data for highly vegetated sites • Lower flight path can result in higher quality data	• Higher costs • Requires someone to fly the drone on the hillside	Could be undertaken on the majority of hillsides
*[1] within the limitations of the extant regulations			

Appendix D. Fall-Path Model Outputs





ID5 Simulation Results:

(Min/Mean/Max Values)

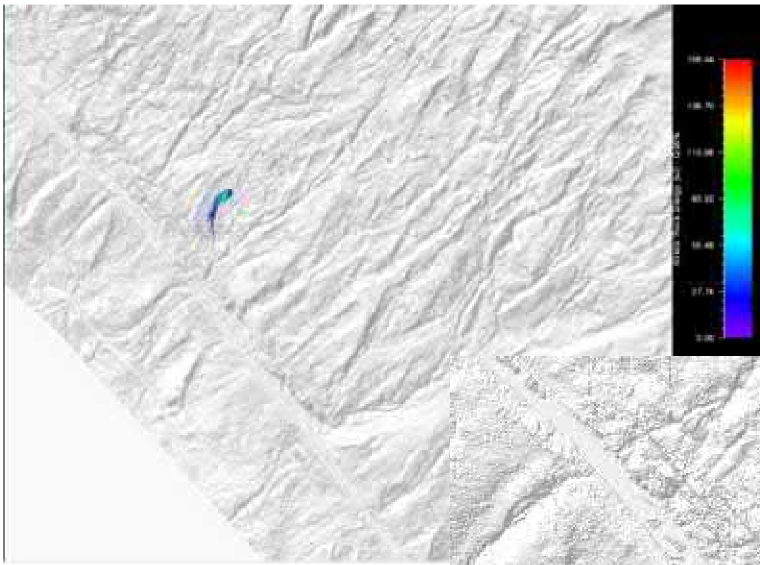
Jump Heights (m): -0.17 / 0.45 / 1.03

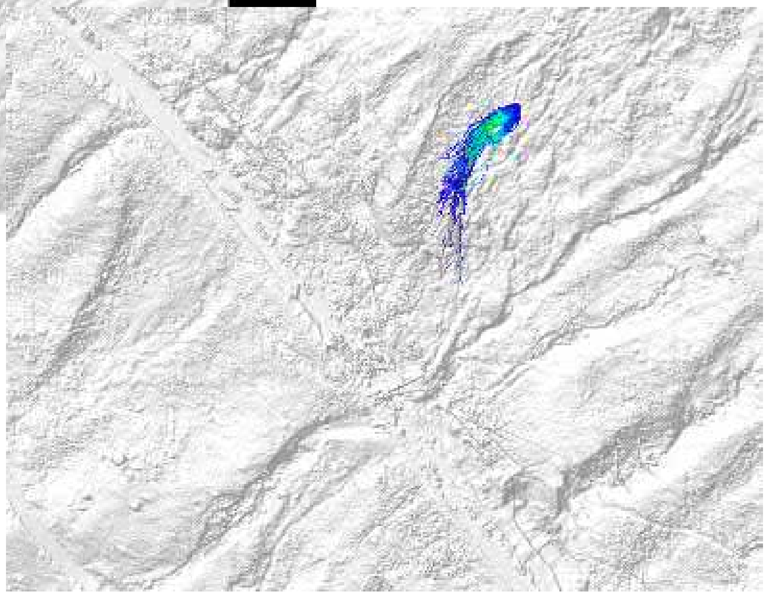
Velocities (m/s): 0.00 / 2.05 / 6.94

Kin. Energies (kJ): 0.00 / 1.73 / 13.87

Rot. Velocities (rot s-1): 0.00 / 0.73 / 2.50

Average Slope (Degrees): 27.08 / 32.62 / 90.00





ID29 Simulation Results:

(Min/Mean/Max Values)

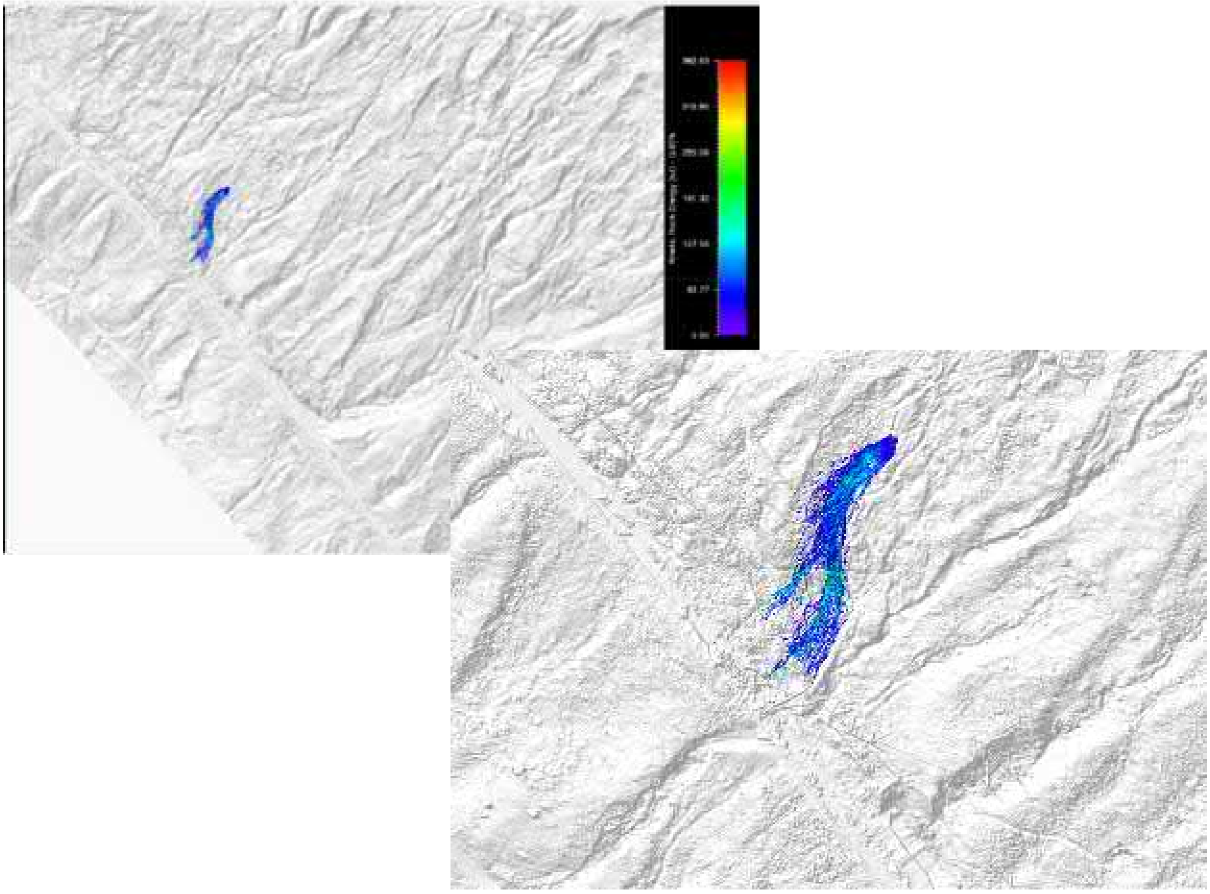
Jump Heights (m): 0.12 / 0.82 / 3.65

Velocities (m/s): 0.00 / 3.17 / 10.92

Kin. Energies (kJ): 0.00 / 19.43 / 166.44

Rot. Velocities (rot s-1): 0.00 / 0.65 / 3.16

Average Slope (Degrees): 27.04 / 38.90 / 90.00



ID29-B Simulation Results:

(Min/Mean/Max Values)

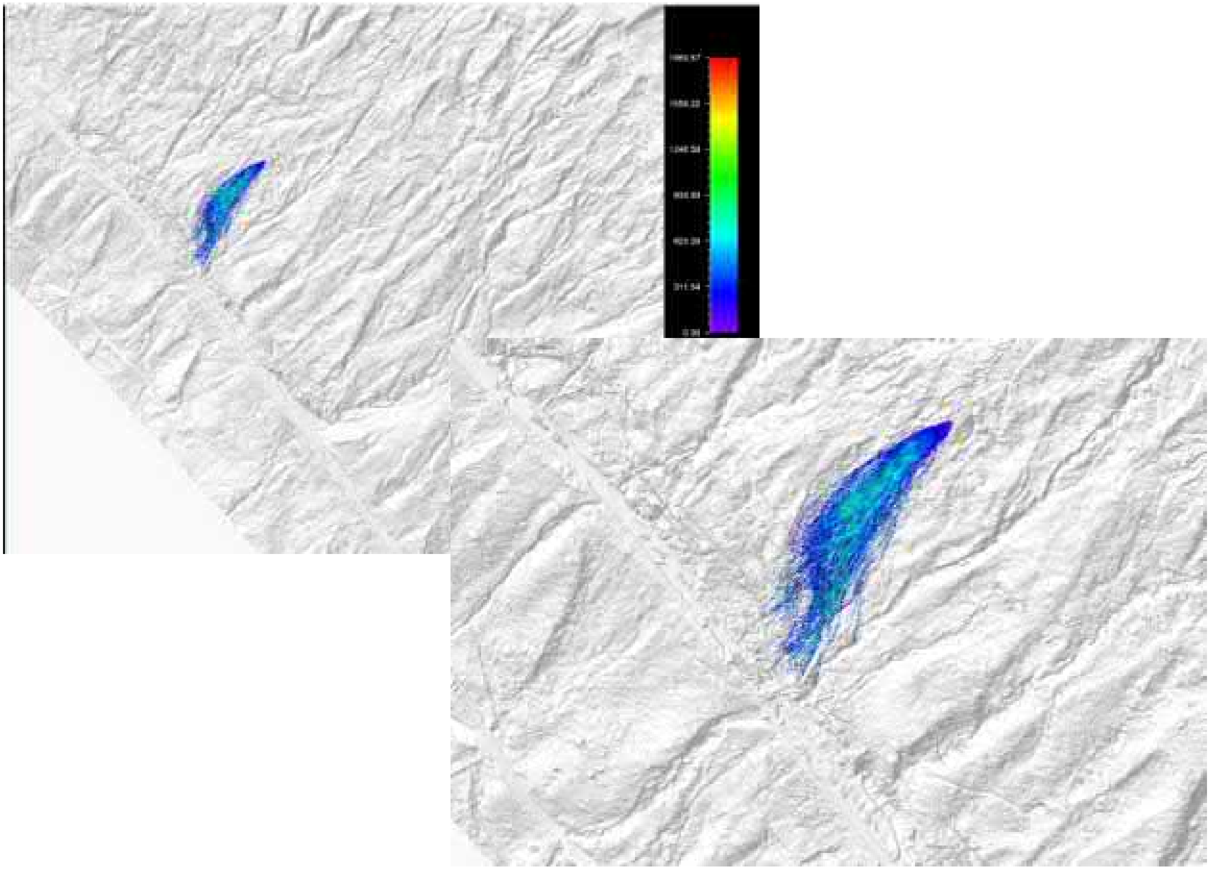
Jump Heights (m): -0.14 / 0.88 / 5.46

Velocities (m/s): 0.00 / 4.29 / 16.33

Kin. Energies (kJ): 0.00 / 34.44 / 382.63

Rot. Velocities (rot s-1): 0.00 / 0.90 / 3.09

Average Slope (Degrees): 19.29 / 32.86 / 90.00



ID31 Simulation Results:

(Min/Mean/Max Values)

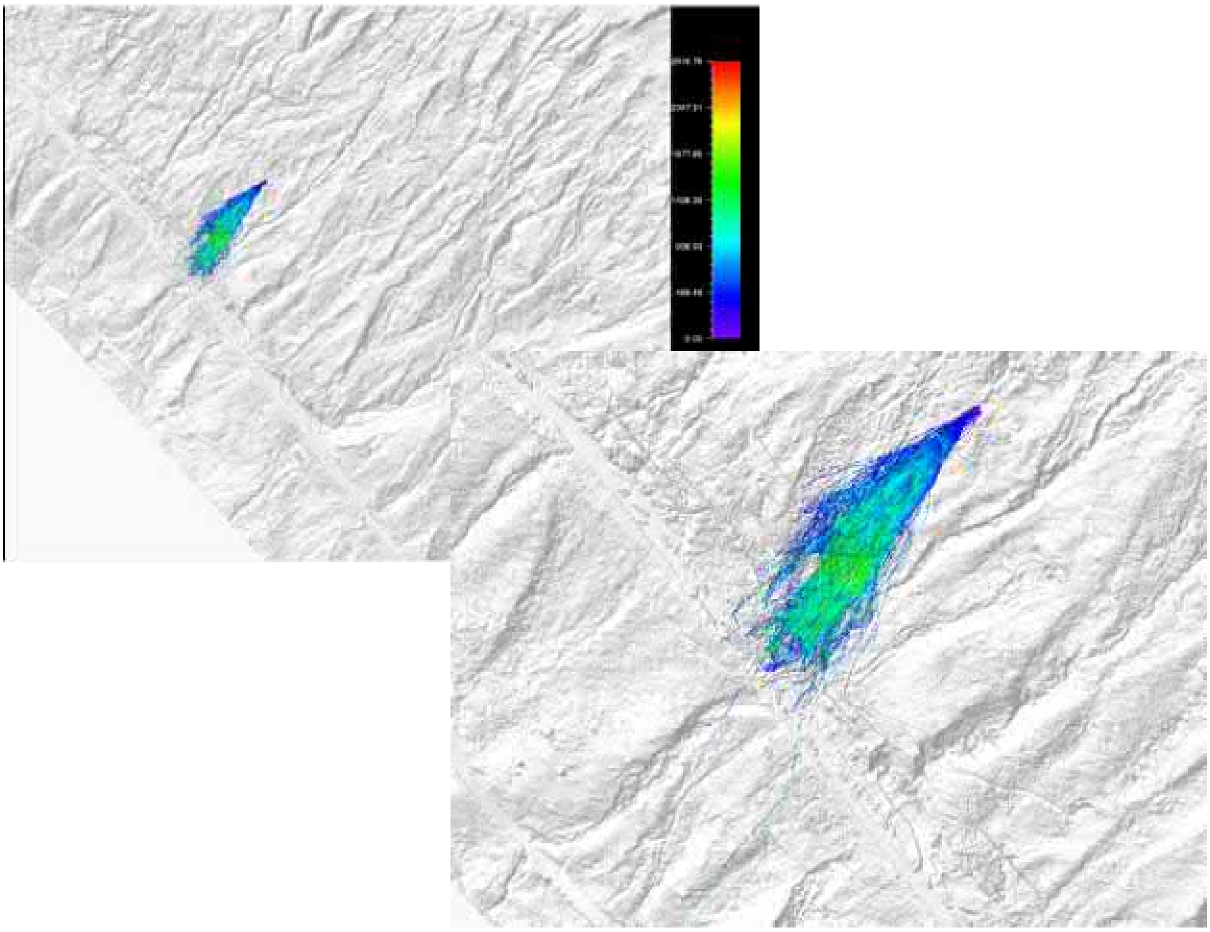
Jump Heights (m): 0.03 / 1.36 / 6.77

Velocities (m/s): 0.00 / 6.26 / 22.93

Kin. Energies (kJ): 0.00 / 189.78 / 1869.87

Rot. Velocities (rot s-1): 0.00 / 0.84 / 3.26

Average Slope (Degrees): 30.54 / 33.51 / 89.35



ID37 Simulation Results:

(Min/Mean/Max Values)

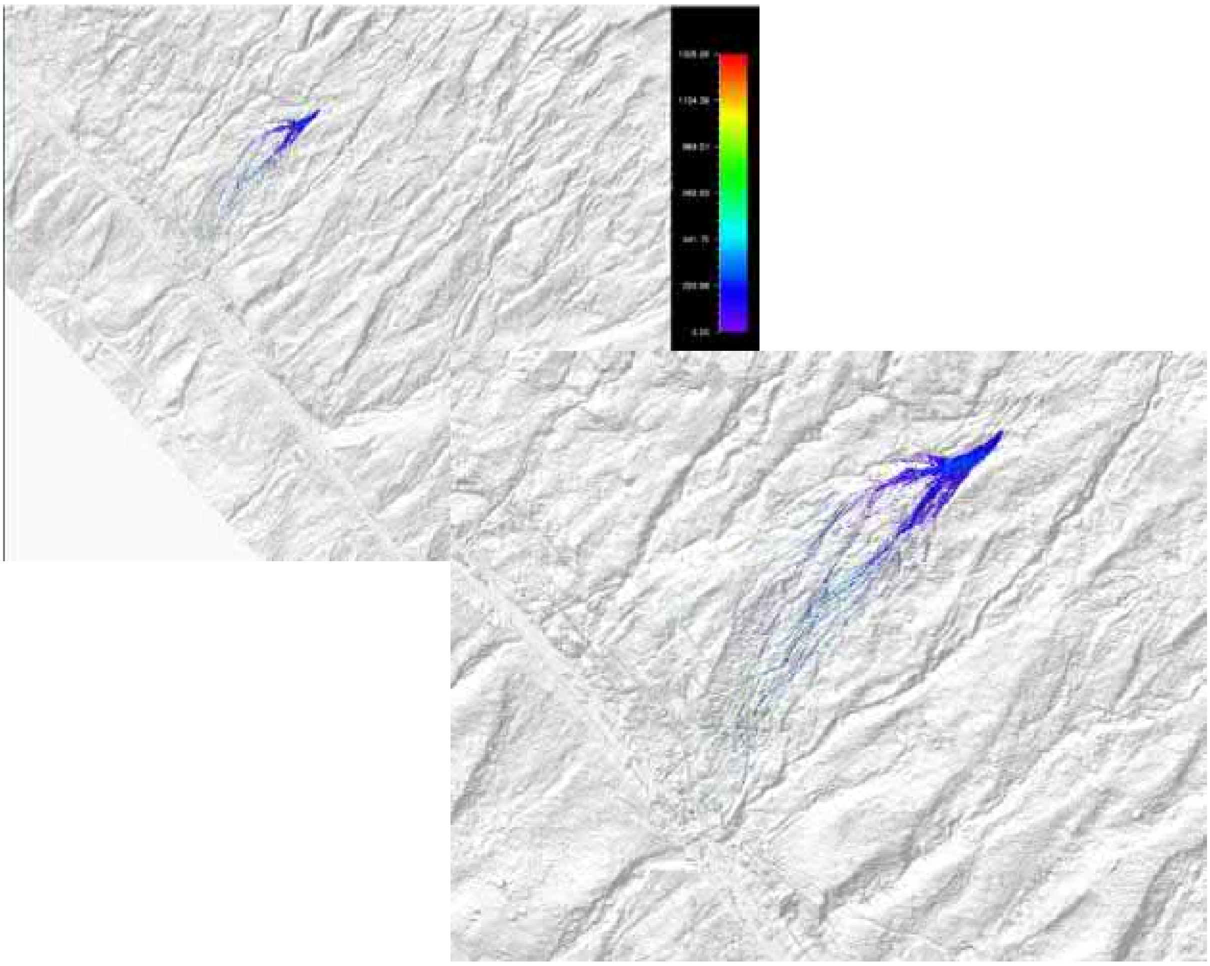
Jump Heights (m): -0.64 / 1.74 / 9.69

Velocities (m/s): 0.00 / 8.39 / 23.98

Kin. Energies (kJ): 0.00 / 463.40 / 2816.78

Rot. Velocities (rot s-1): 0.00 / 1.09 / 3.44

Average Slope (Degrees): 27.68 / 31.43 / 87.80



ID52 Simulation Results:

(Min/Mean/Max Values)

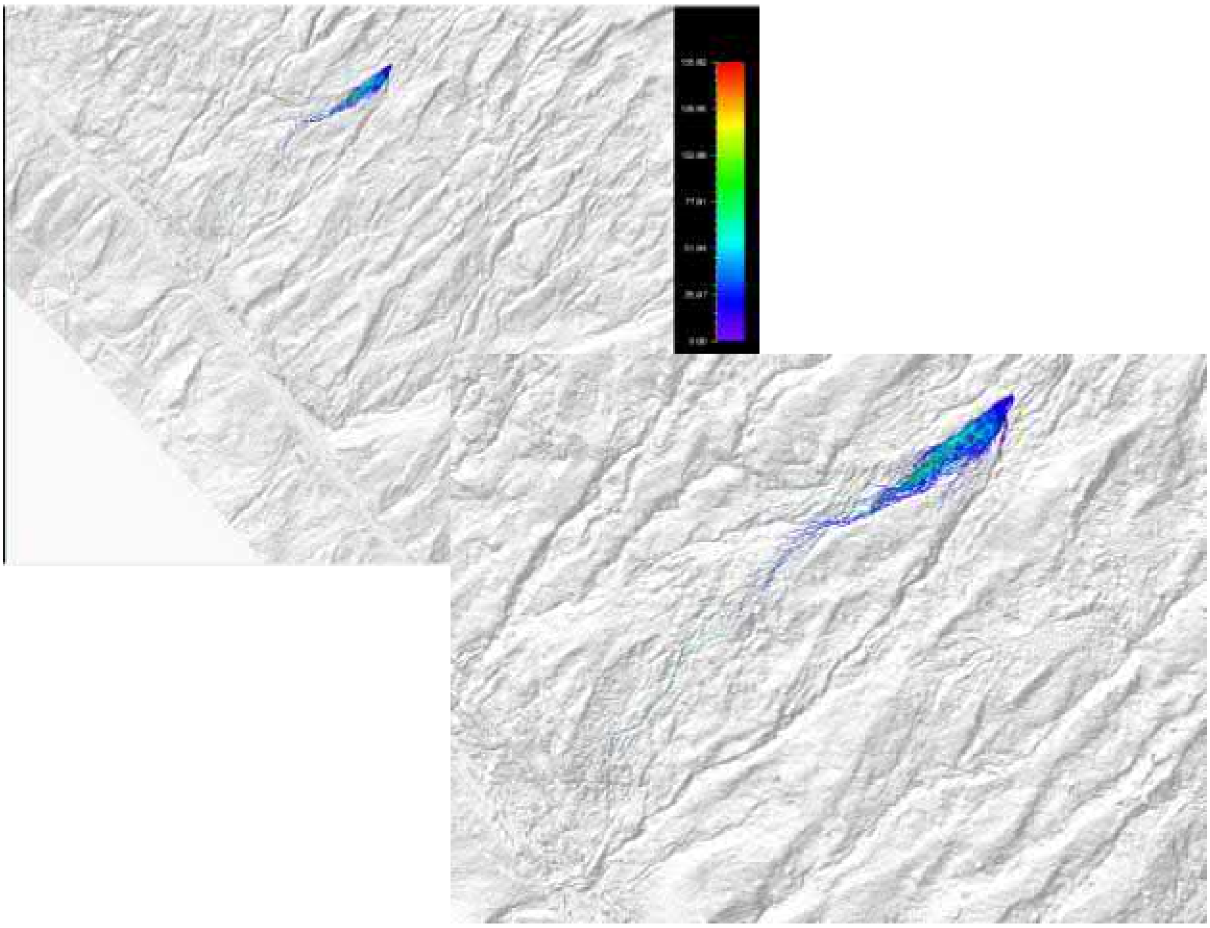
Jump Heights (m): 0.23 / 1.11 / 6.18

Velocities (m/s): 0.00 / 3.29 / 17.63

Kin. Energies (kJ): 0.00 / 67.93 / 1325.26

Rot. Velocities (rot s-1): 0.00 / 0.48 / 2.61

Average Slope (Degrees): 29.41 / 33.89 / 67.45



ID67 Simulation Results:

(Min/Mean/Max Values)

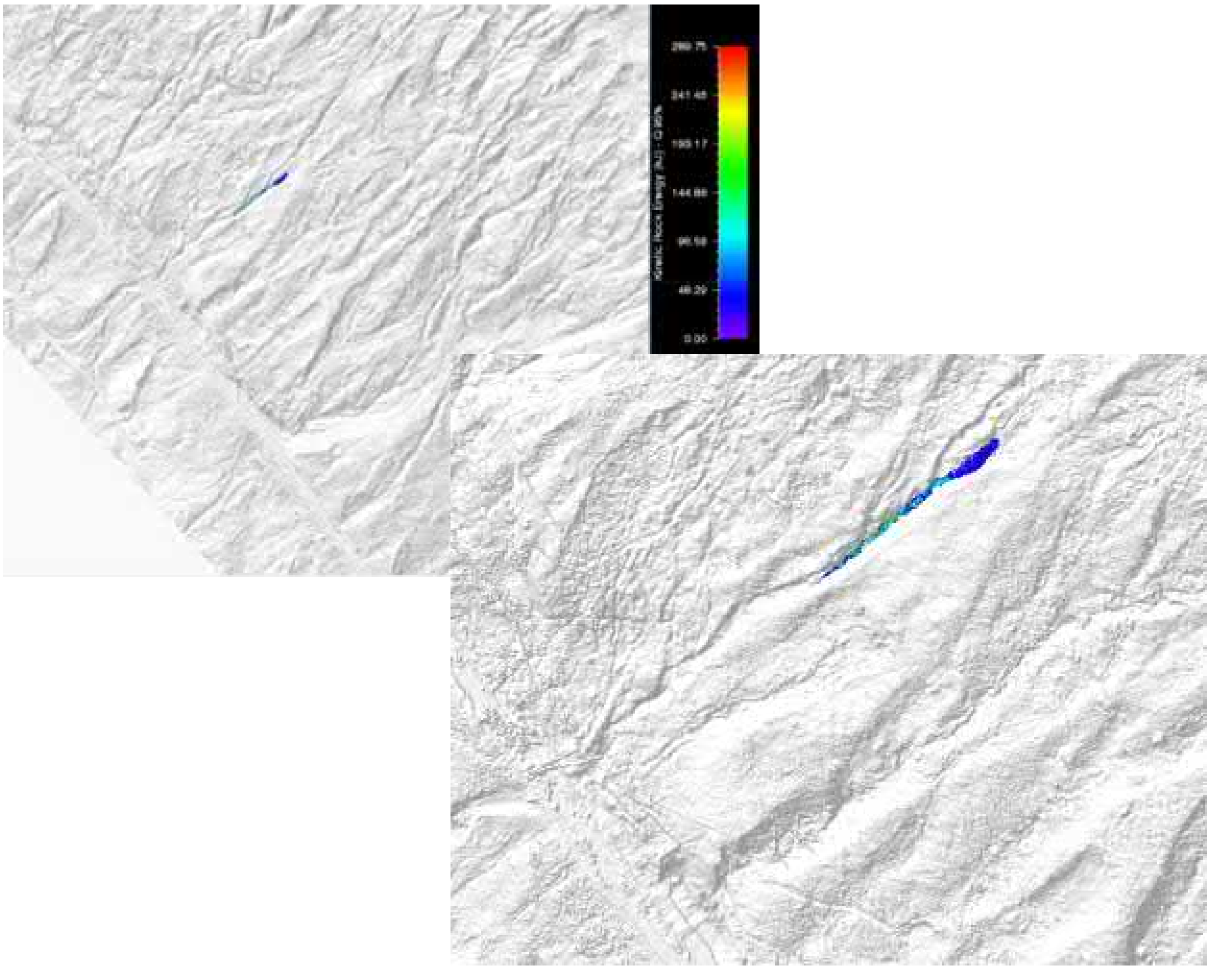
Jump Heights (m): 0.04 / 0.69 / 3.07

Velocities (m/s): 0.00 / 3.64 / 13.52

Kin. Energies (kJ): 0.00 / 14.11 / 155.82

Rot. Velocities (rot s-1): 0.00 / 0.85 / 3.84

Average Slope (Degrees): 27.51 / 31.10 / 84.82



ID89 Simulation Results:

(Min/Mean/Max Values)

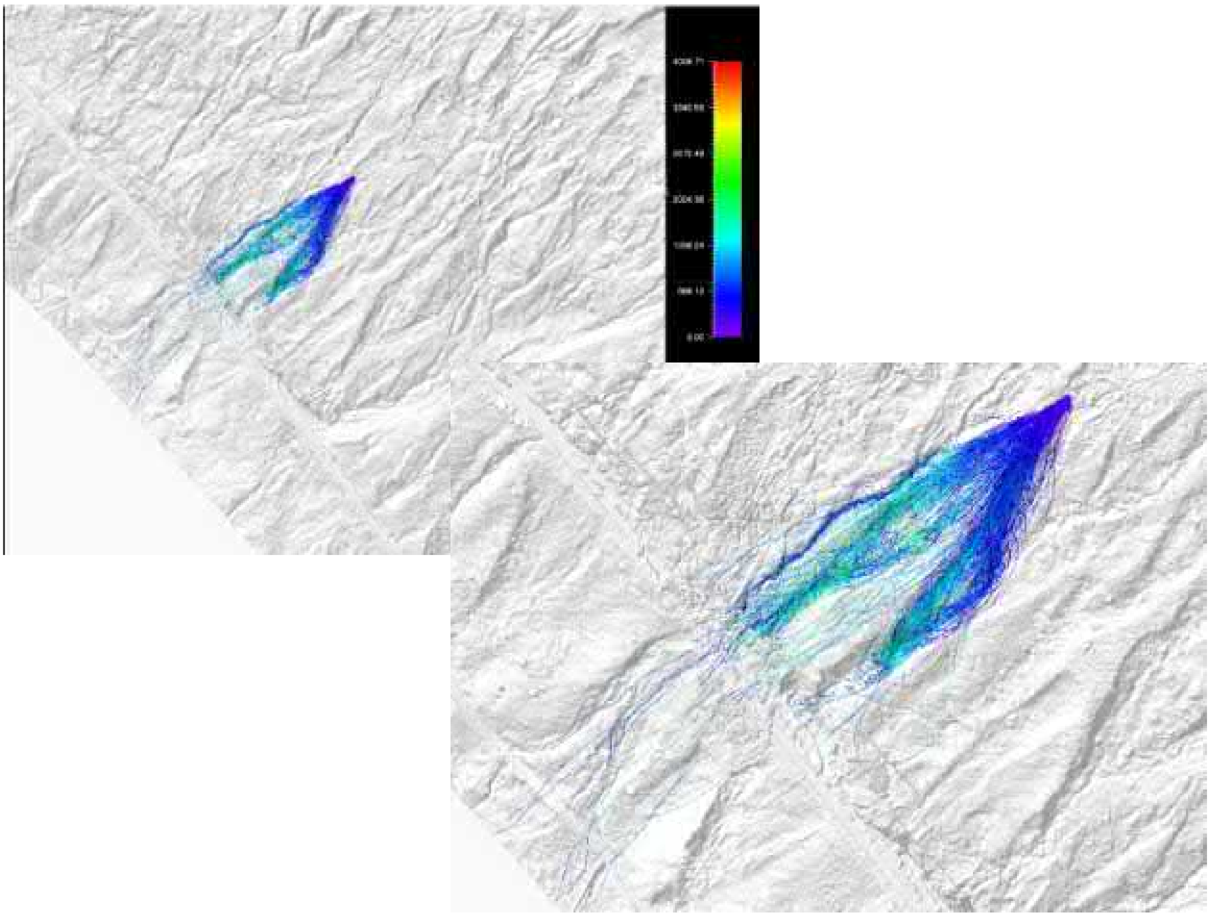
Jump Heights (m): 0.07 / 0.91 / 2.86

Velocities (m/s): 0.00 / 2.45 / 11.43

Kin. Energies (kJ): 0.00 / 19.66 / 289.75

Rot. Velocities (rot s-1): 0.00 / 0.47 / 1.75

Average Slope (Degrees): 28.90 / 32.70 / 84.96



ID91 Simulation Results:

(Min/Mean/Max Values)

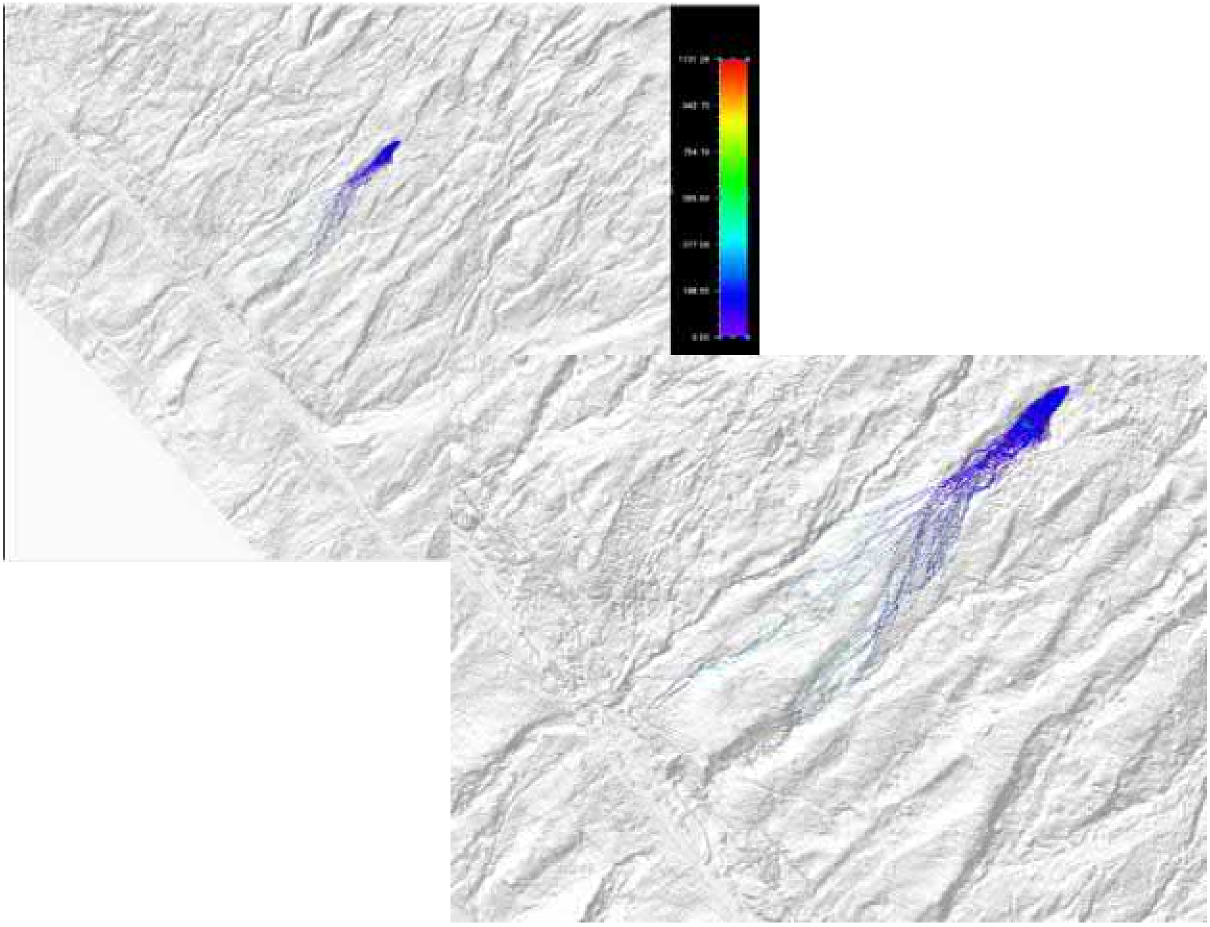
Jump Heights (m): -0.47 / 1.72 / 552.83

Velocities (m/s): 0.00 / 8.17 / 28.21

Kin. Energies (kJ): 0.00 / 497.41 / 4008.71

Rot. Velocities (rot s-1): 0.00 / 1.08 / 4.02

Average Slope (Degrees): 26.46 / 31.78 / 89.51



ID95 Simulation Results:

(Min/Mean/Max Values)

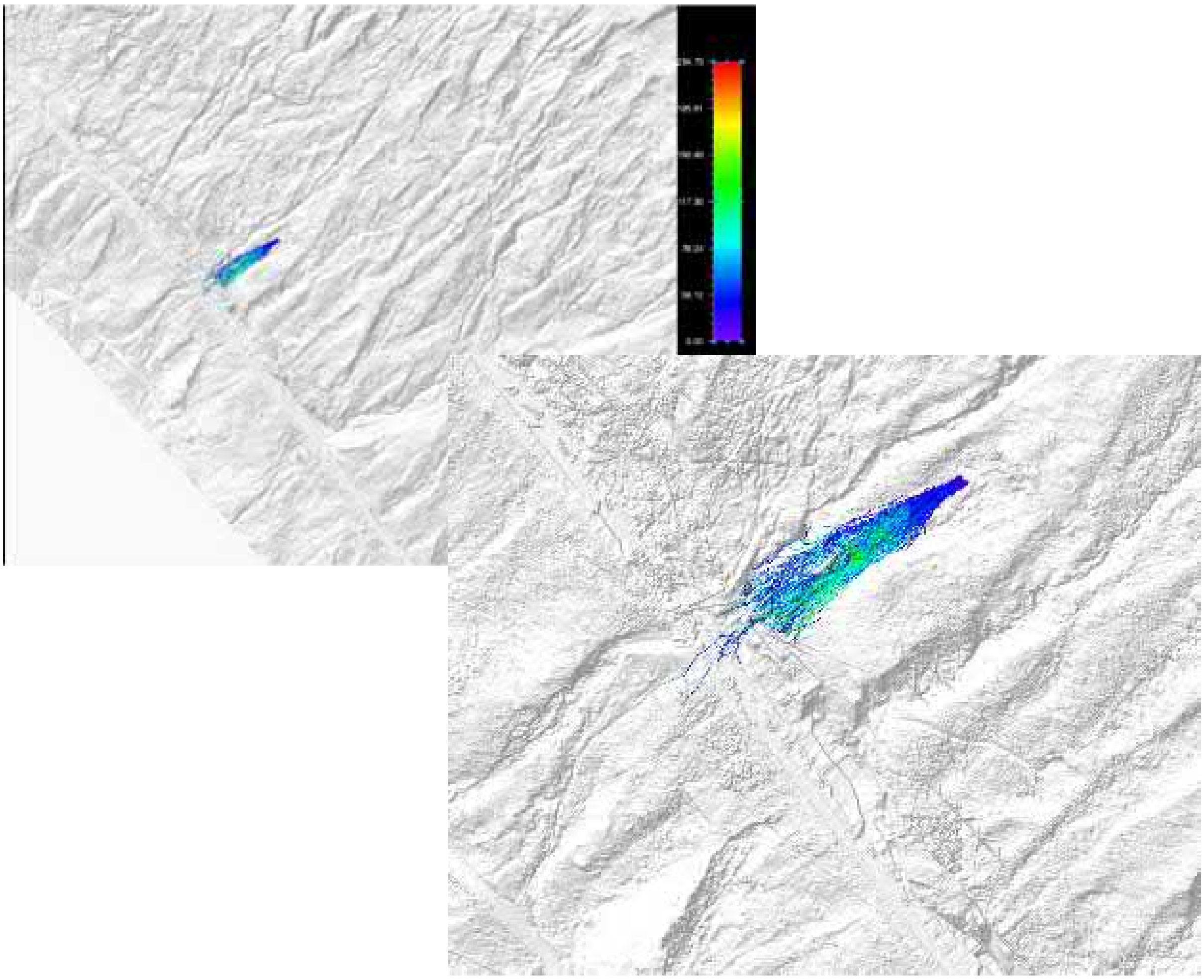
Jump Heights (m): 0.14 / 1.05 / 5.89

Velocities (m/s): 0.00 / 3.96 / 20.49

Kin. Energies (kJ): 0.00 / 60.17 / 1131.28

Rot. Velocities (rot s-1): 0.00 / 0.63 / 3.10

Average Slope (Degrees): 27.99 / 31.70 / 79.10



ID99 Simulation Results:

(Min/Mean/Max Values)

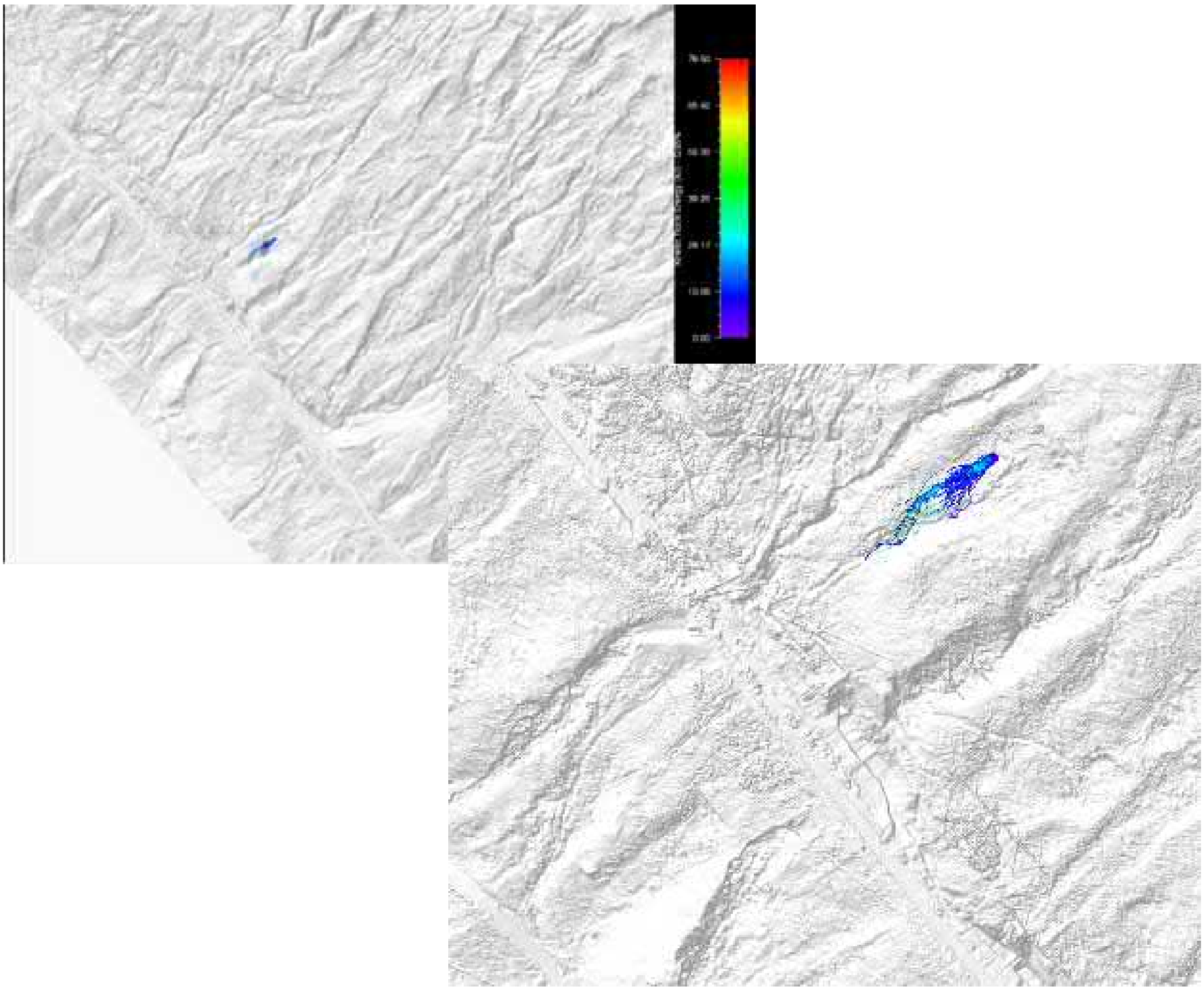
Jump Heights (m): -0.13 / 0.83 / 5.36

Velocities (m/s): 0.00 / 5.06 / 17.43

Kin. Energies (kJ): 0.00 / 27.53 / 234.73

Rot. Velocities (rot s-1): 0.00 / 1.30 / 4.25

Average Slope (Degrees): 28.82 / 33.10 / 89.80



ID103 Simulation Results:

(Min/Mean/Max Values)

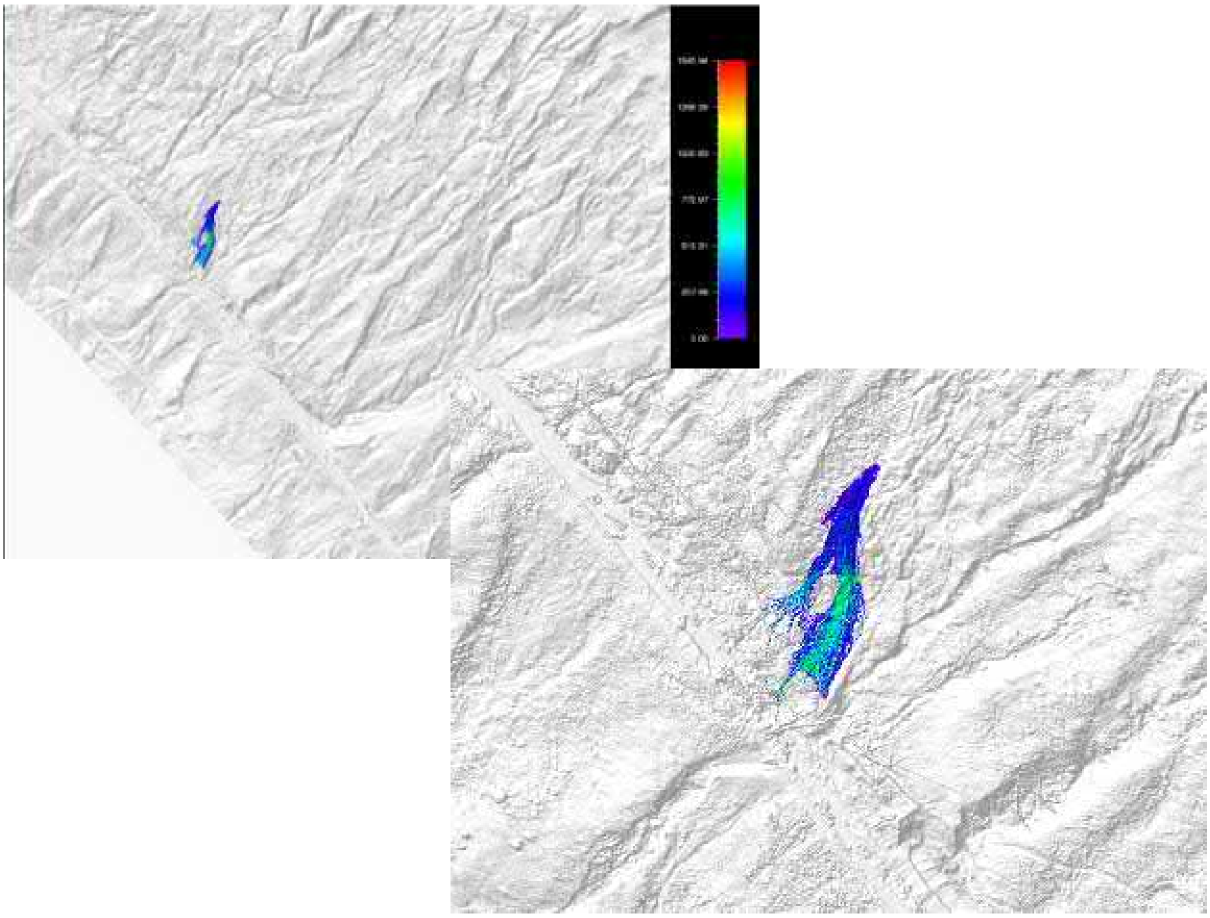
Jump Heights (m): -0.01 / 0.66 / 2.04

Velocities (m/s): 0.00 / 2.37 / 8.70

Kin. Energies (kJ): 0.00 / 7.62 / 78.50

Rot. Velocities (rot s-1): 0.00 / 0.58 / 2.20

Average Slope (Degrees): 28.14 / 56.18 / 90.00



ID125 Simulation Results:

(Min/Mean/Max Values)

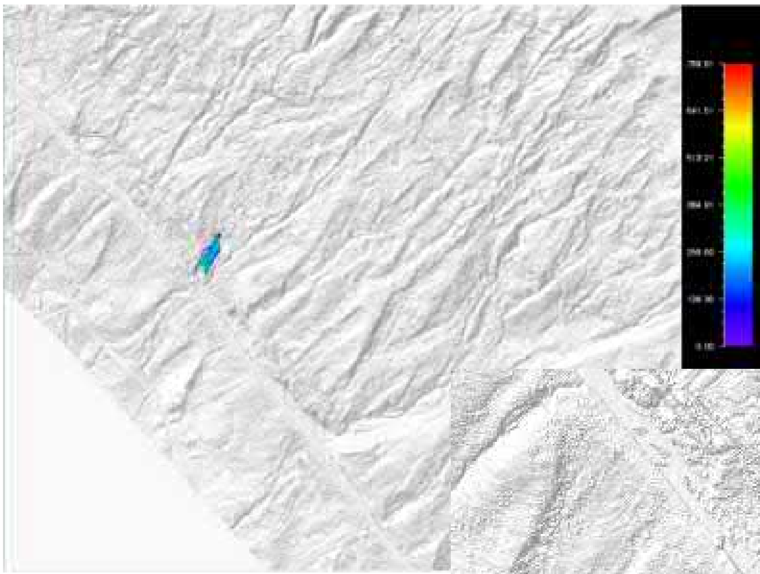
Jump Heights (m): -0.12 / 1.29 / 7.51

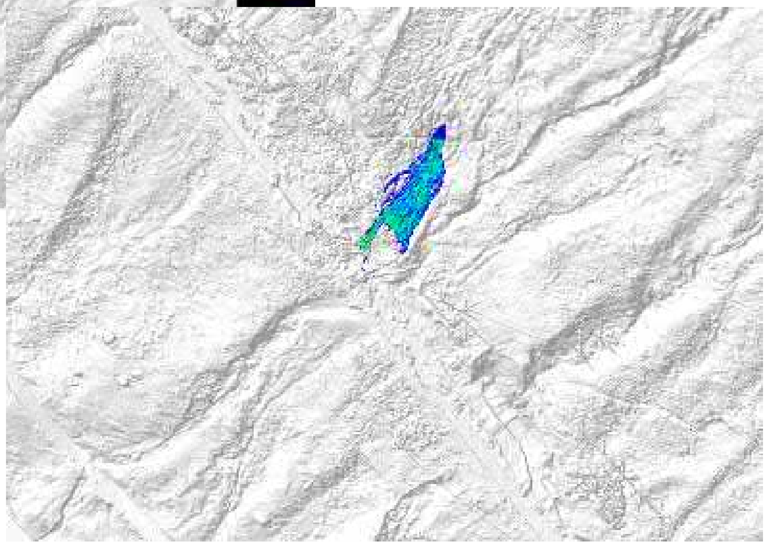
Velocities (m/s): 0.00 / 3.47 / 15.40

Kin. Energies (kJ): 0.00 / 121.42 / 1545.94

Rot. Velocities (rot s-1): 0.00 / 0.47 / 1.86

Average Slope (Degrees): 23.52 / 27.98 / 90.00





ID128 Simulation Results:

(Min/Mean/Max Values)

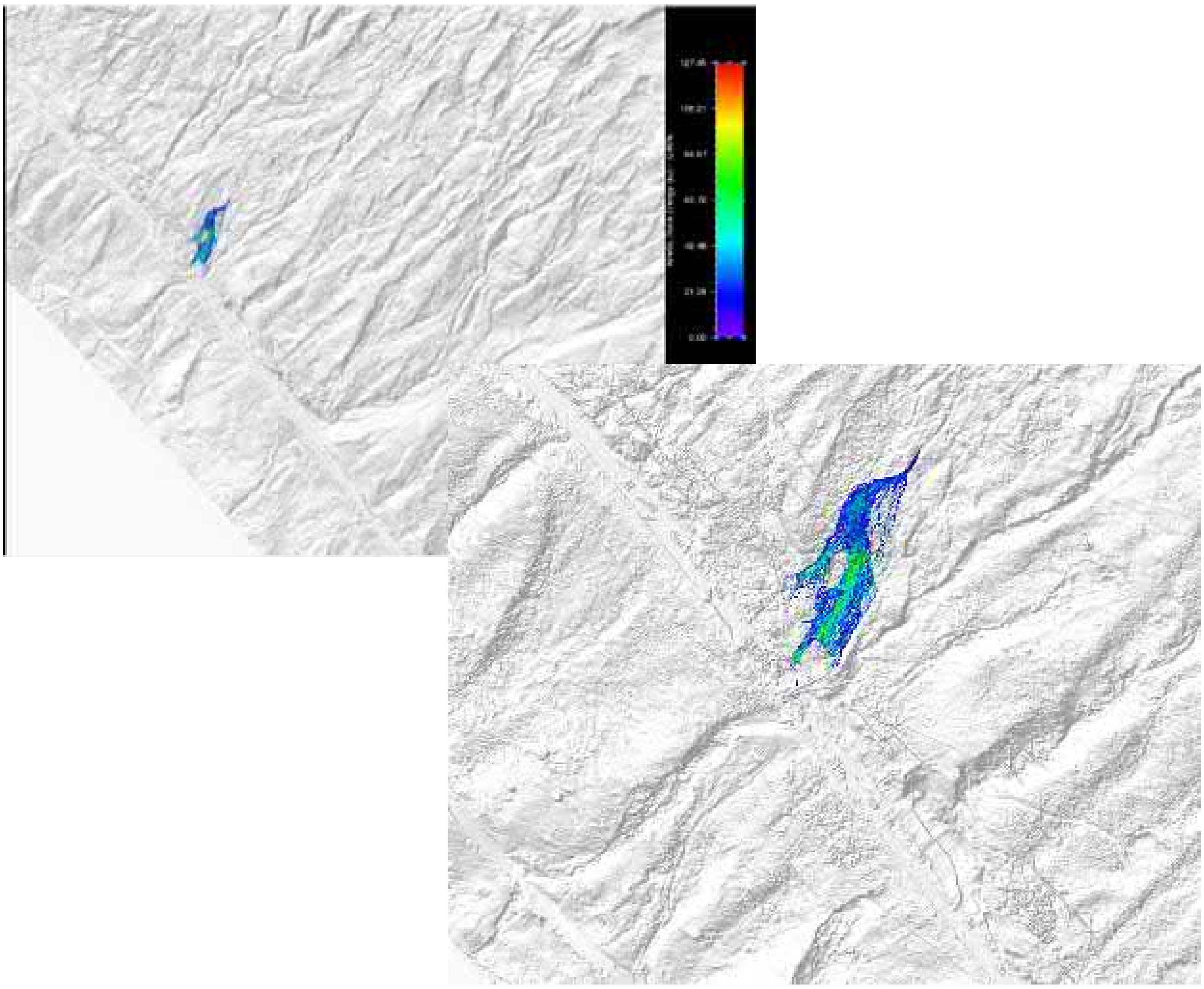
Jump Heights (m): -0.30 / 1.16 / 3.95

Velocities (m/s): 0.00 / 4.13 / 14.06

Kin. Energies (kJ): 0.00 / 91.93 / 769.81

Rot. Velocities (rot s-1): 0.00 / 0.63 / 1.93

Average Slope (Degrees): 25.08 / 28.22 / 64.14



ID131 Simulation Results:

(Min/Mean/Max Values)

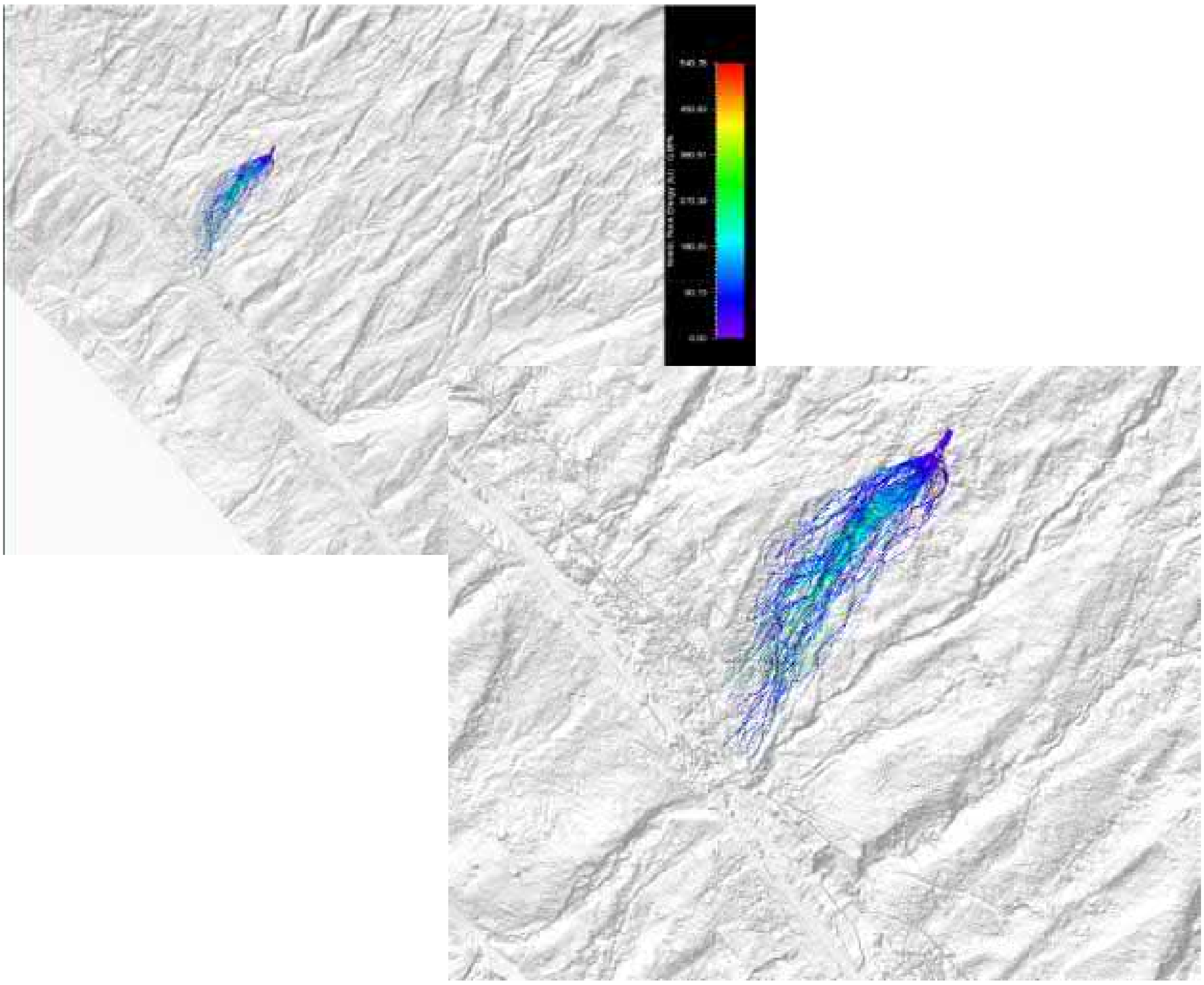
Jump Heights (m): -0.20 / 0.69 / 7.69

Velocities (m/s): 0.00 / 4.12 / 14.74

Kin. Energies (kJ): 0.00 / 13.77 / 127.45

Rot. Velocities (rot s-1): 0.00 / 1.13 / 4.12

Average Slope (Degrees): 26.29 / 30.01 / 81.00



ID150 Simulation Results:

(Min/Mean/Max Values)

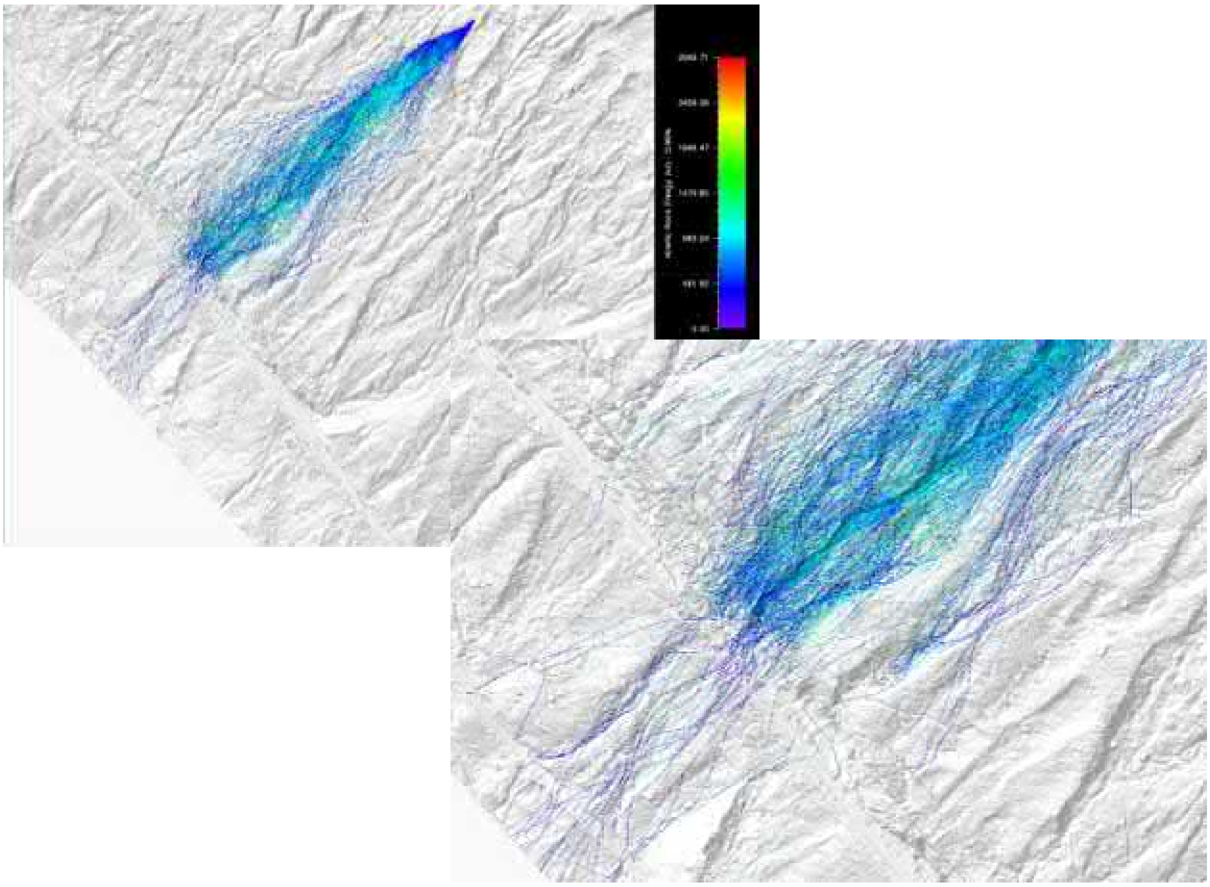
Jump Heights (m): 0.07 / 0.97 / 5.87

Velocities (m/s): 0.00 / 5.36 / 20.85

Kin. Energies (kJ): 0.00 / 56.15 / 540.76

Rot. Velocities (rot s-1): 0.00 / 1.05 / 5.27

Average Slope (Degrees): 26.19 / 33.35 / 90.00



ID187 Simulation Results:

(Min/Mean/Max Values)

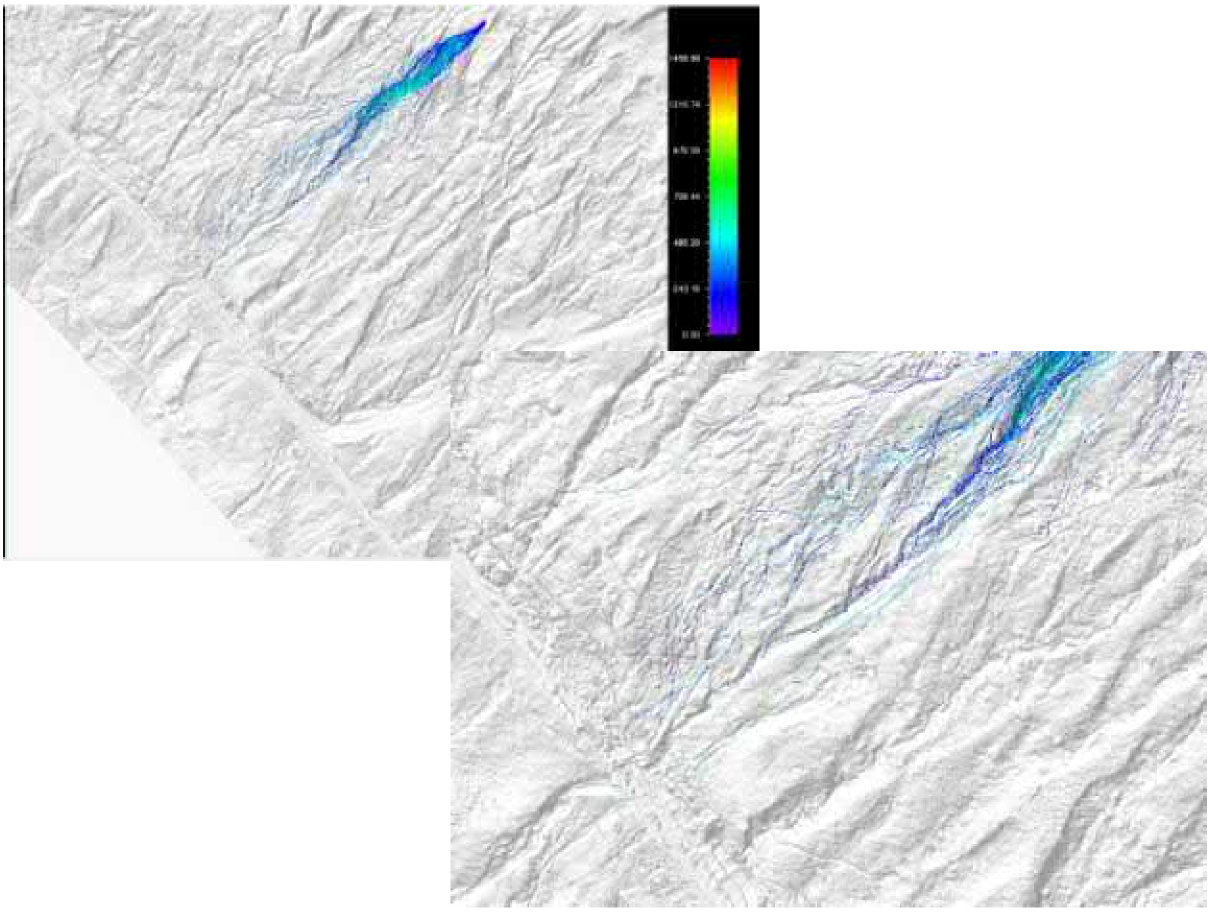
Jump Heights (m): -3.14 / 2.08 / 3899.36

Velocities (m/s): 0.00 / 12.56 / 34.93

Kin. Energies (kJ): 0.00 / 475.16 / 2949.71

Rot. Velocities (rot s-1): 0.00 / 2.34 / 6.70

Average Slope (Degrees): 29.81 / 32.14 / 80.67



ID187-B Simulation Results:

(Min/Mean/Max Values)

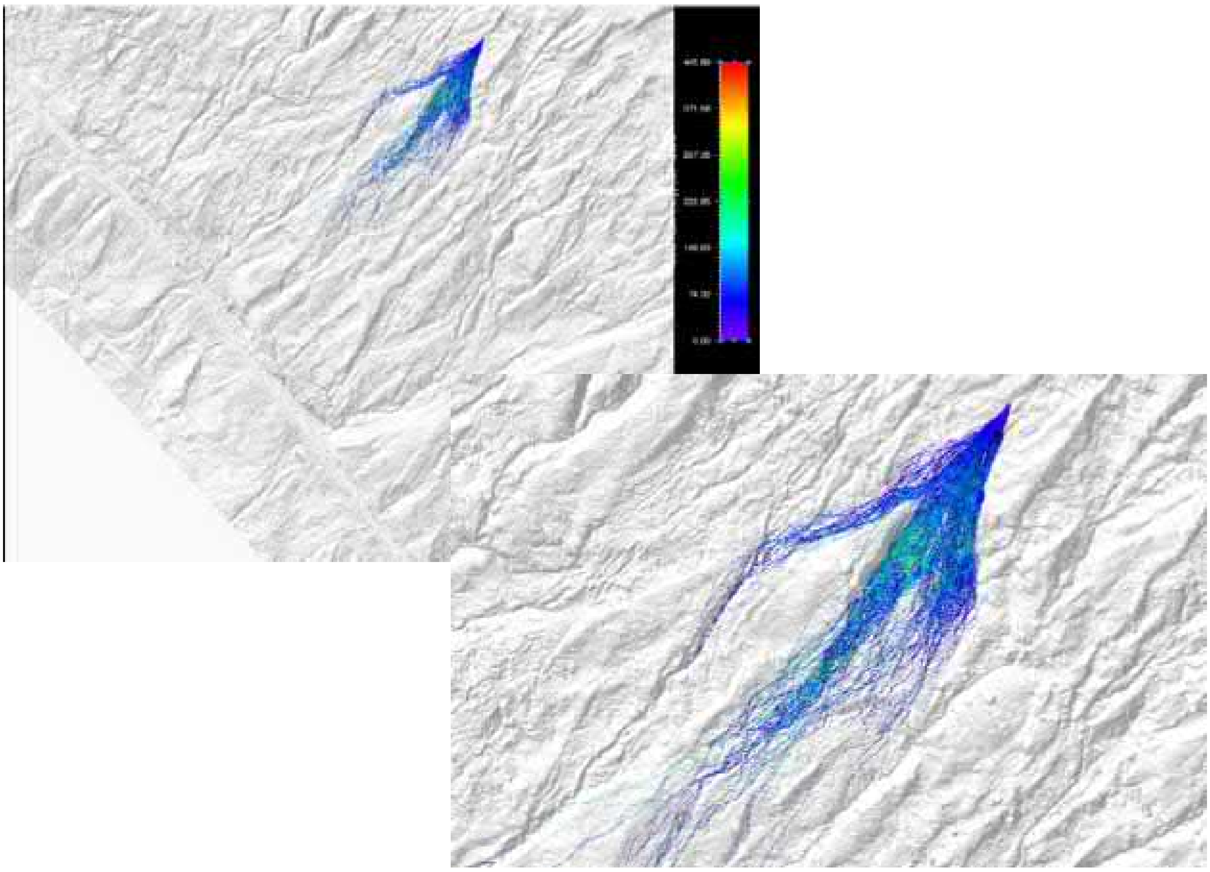
Jump Heights (m): 0.11 / 1.32 / 19.50

Velocities (m/s): 0.00 / 7.34 / 25.20

Kin. Energies (kJ): 0.00 / 165.61 / 1458.88

Rot. Velocities (rot s-1): 0.00 / 1.18 / 5.37

Average Slope (Degrees): 30.32 / 33.44 / 87.89



ID193 Simulation Results:

(Min/Mean/Max Values)

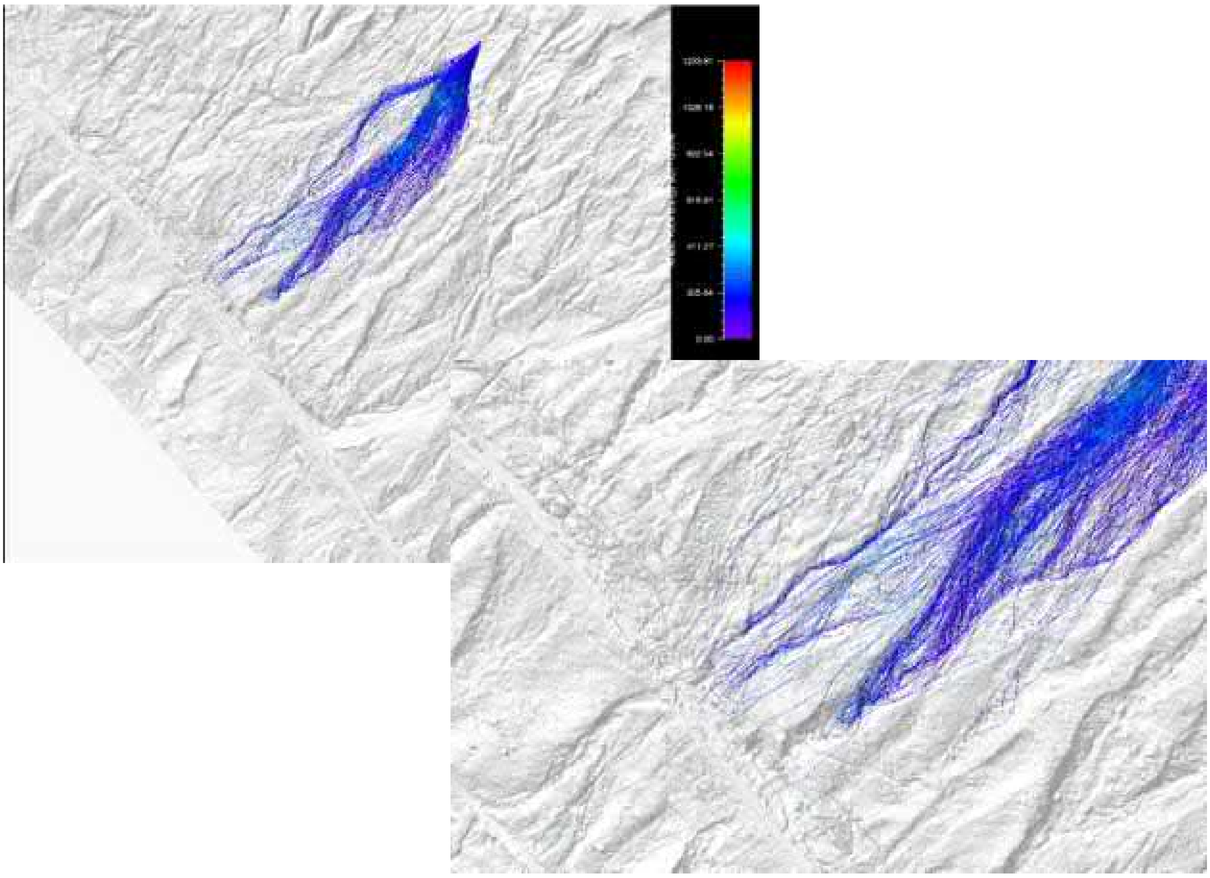
Jump Heights (m): 0.09 / 0.93 / 7.08

Velocities (m/s): 0.00 / 6.06 / 22.43

Kin. Energies (kJ): 0.00 / 44.11 / 445.89

Rot. Velocities (rot s-1): 0.00 / 1.33 / 6.34

Average Slope (Degrees): 29.65 / 32.83 / 85.45



ID193-B Simulation Results:

(Min/Mean/Max Values)

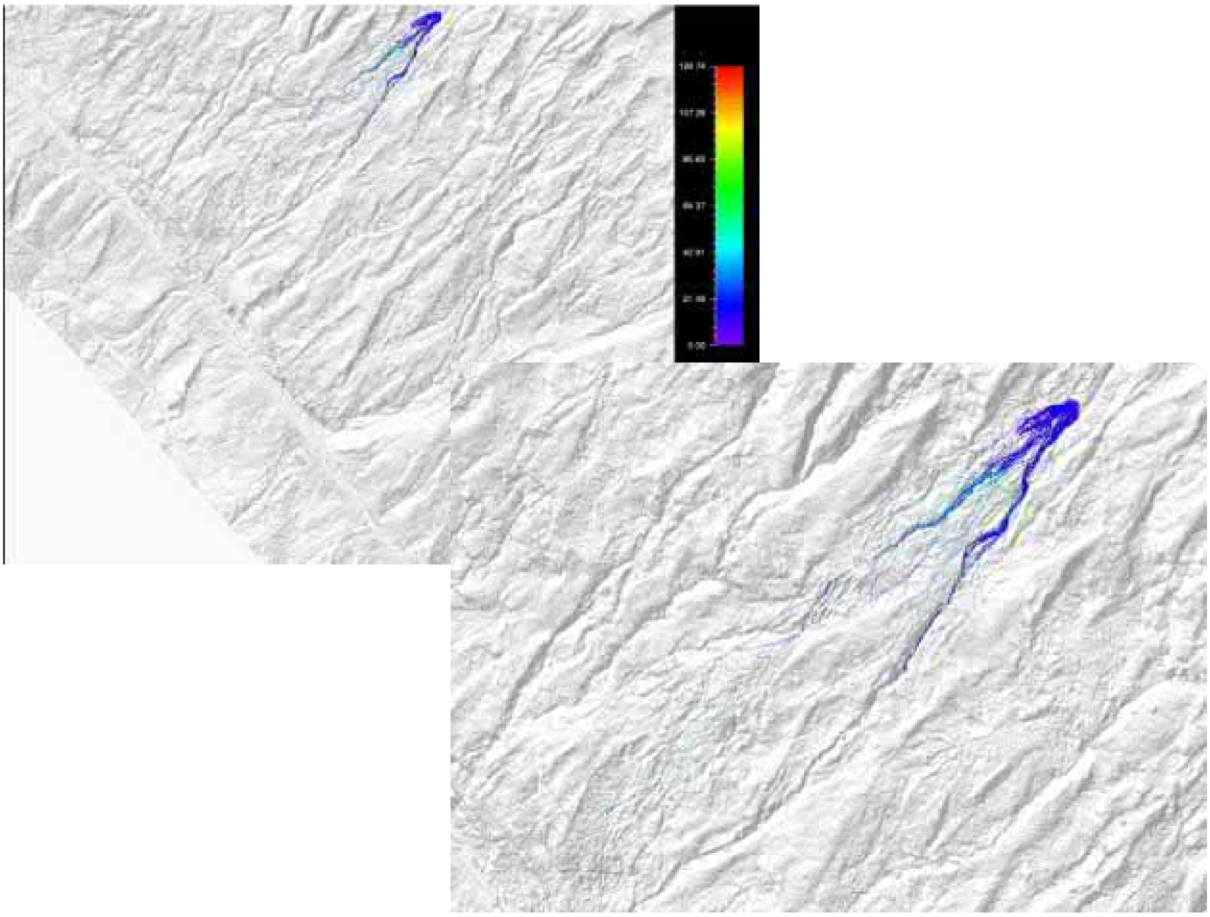
Jump Heights (m): -0.22 / 1.28 / 22.57

Velocities (m/s): 0.00 / 9.02 / 36.50

Kin. Energies (kJ): 0.00 / 97.95 / 1233.81

Rot. Velocities (rot s-1): 0.00 / 2.19 / 8.20

Average Slope (Degrees): 29.02 / 31.60 / 39.10



ID200 Simulation Results:

(Min/Mean/Max Values)

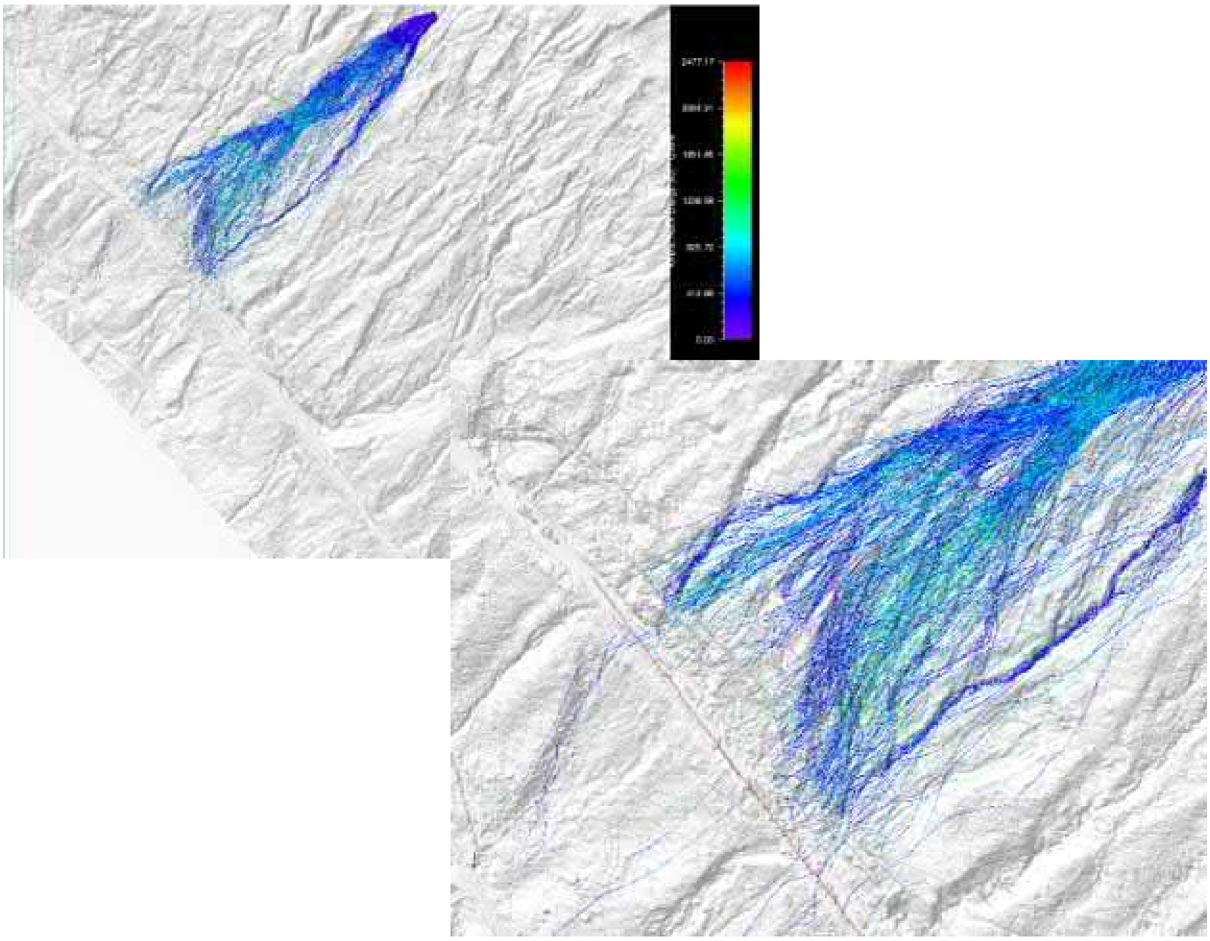
Jump Heights (m): 0.04 / 0.58 / 5.11

Velocities (m/s): 0.00 / 3.85 / 19.29

Kin. Energies (kJ): 0.00 / 7.32 / 128.74

Rot. Velocities (rot s-1): 0.00 / 1.14 / 7.04

Average Slope (Degrees): 26.84 / 30.19 / 85.45



ID211 Simulation Results:

(Min/Mean/Max Values)

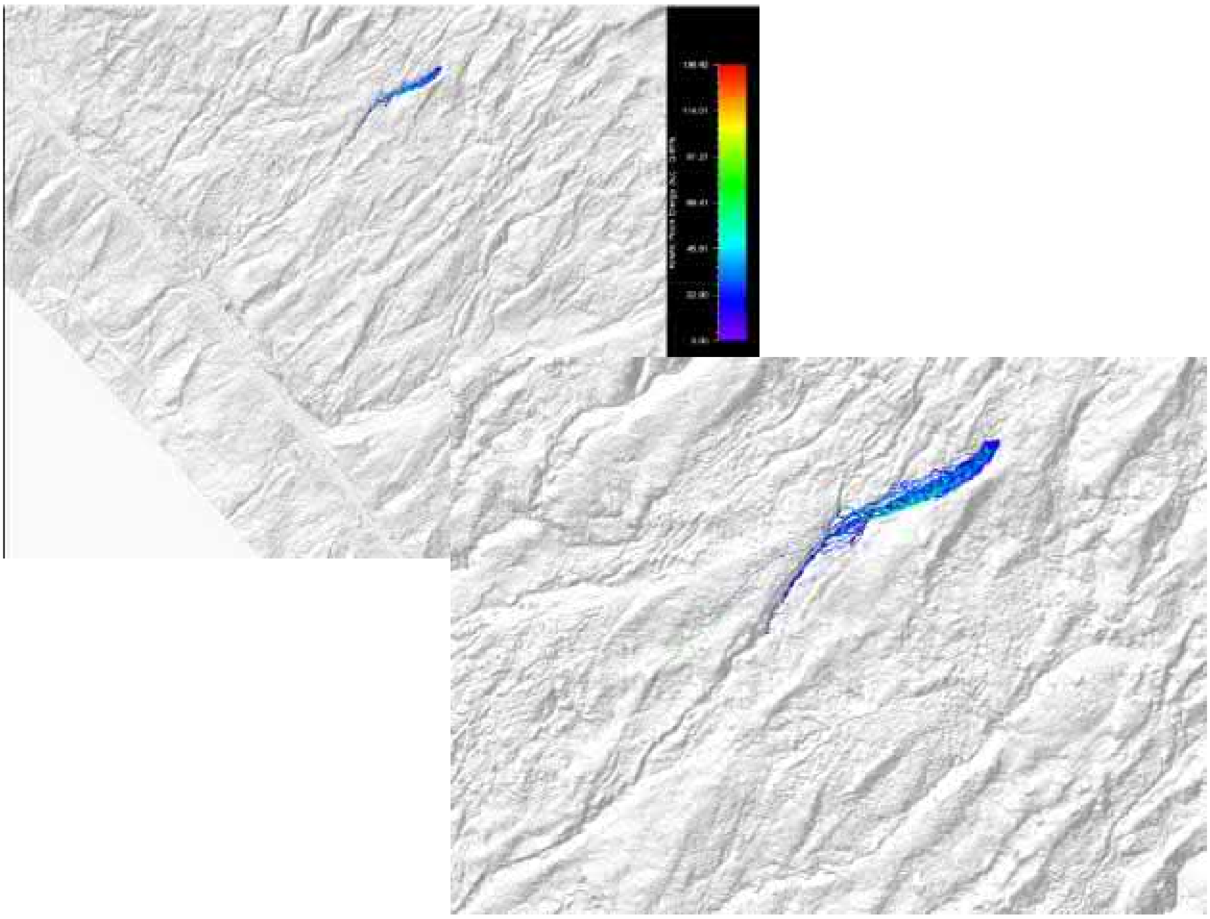
Jump Heights (m): -0.35 / 1.60 / 85.94

Velocities (m/s): 0.00 / 9.22 / 31.48

Kin. Energies (kJ): 0.00 / 297.34 / 2477.17

Rot. Velocities (rot s-1): 0.00 / 1.59 / 5.91

Average Slope (Degrees): 26.20 / 31.10 / 83.23



ID212 Simulation Results:

(Min/Mean/Max Values)

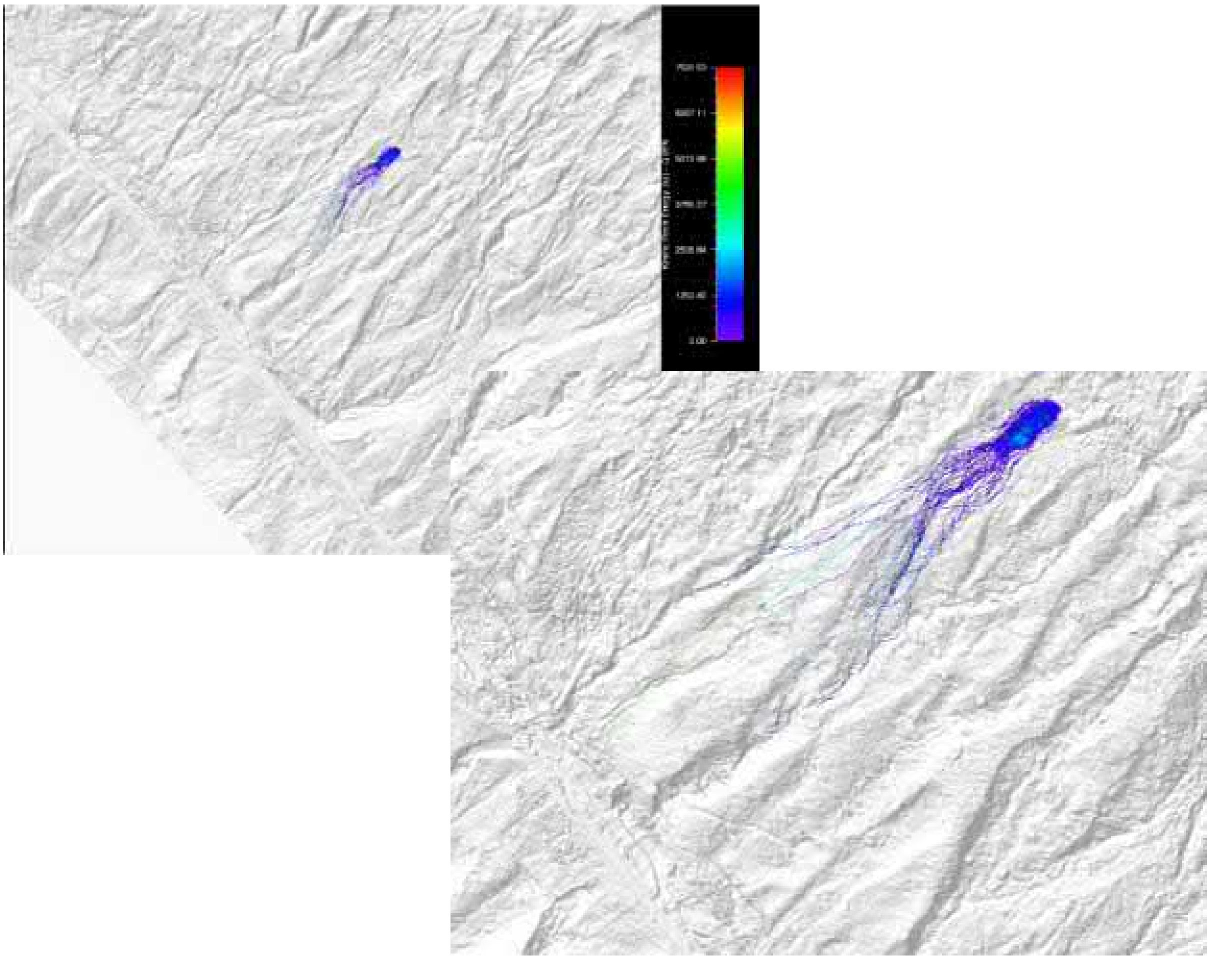
Jump Heights (m): -0.03 / 0.70 / 3.20

Velocities (m/s): 0.00 / 3.46 / 13.83

Kin. Energies (kJ): 0.00 / 11.74 / 136.82

Rot. Velocities (rot s-1): 0.00 / 0.84 / 3.96

Average Slope (Degrees): 30.41 / 33.67 / 77.59



ID221 Simulation Results:

(Min/Mean/Max Values)

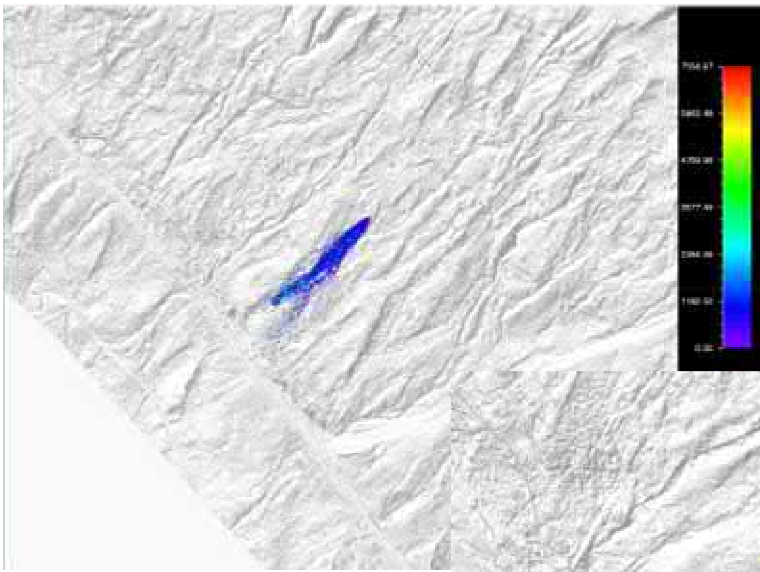
Jump Heights (m): -1.01 / 2.04 / 8.29

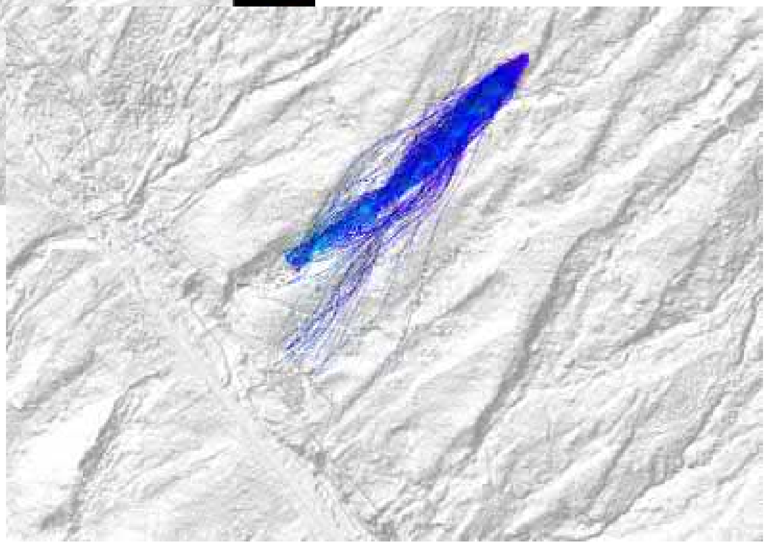
Velocities (m/s): 0.00 / 3.23 / 15.33

Kin. Energies (kJ): 0.00 / 474.38 / 7520.53

Rot. Velocities (rot s-1): 0.00 / 0.28 / 1.14

Average Slope (Degrees): 28.82 / 34.77 / 90.00





ID244 Simulation Results:

(Min/Mean/Max Values)

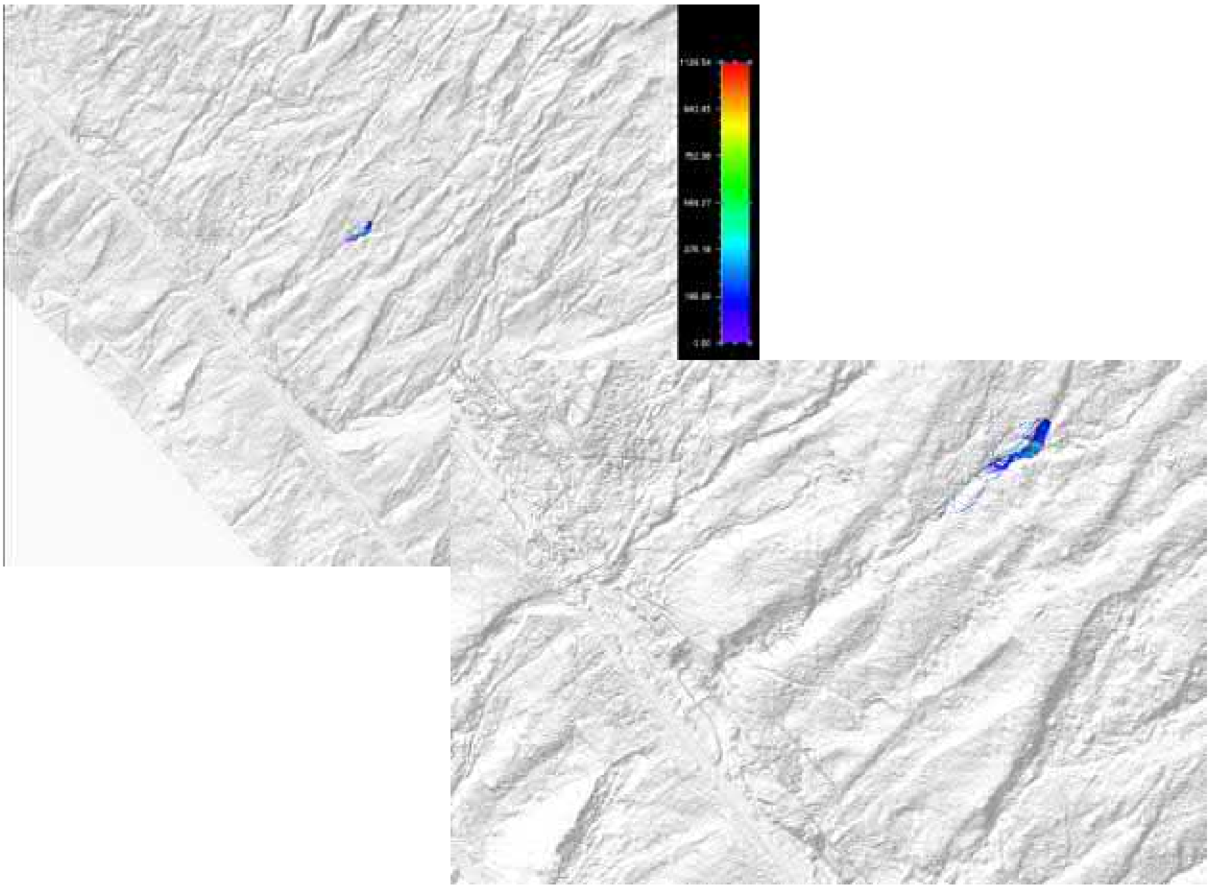
Jump Heights (m): -0.16 / 1.78 / 9.48

Velocities (m/s): 0.00 / 7.16 / 27.65

Kin. Energies (kJ): 0.00 / 502.88 / 7154.97

Rot. Velocities (rot s-1): 0.00 / 0.85 / 4.32

Average Slope (Degrees): 27.80 / 33.24 / 89.98



ID245 Simulation Results:

(Min/Mean/Max Values)

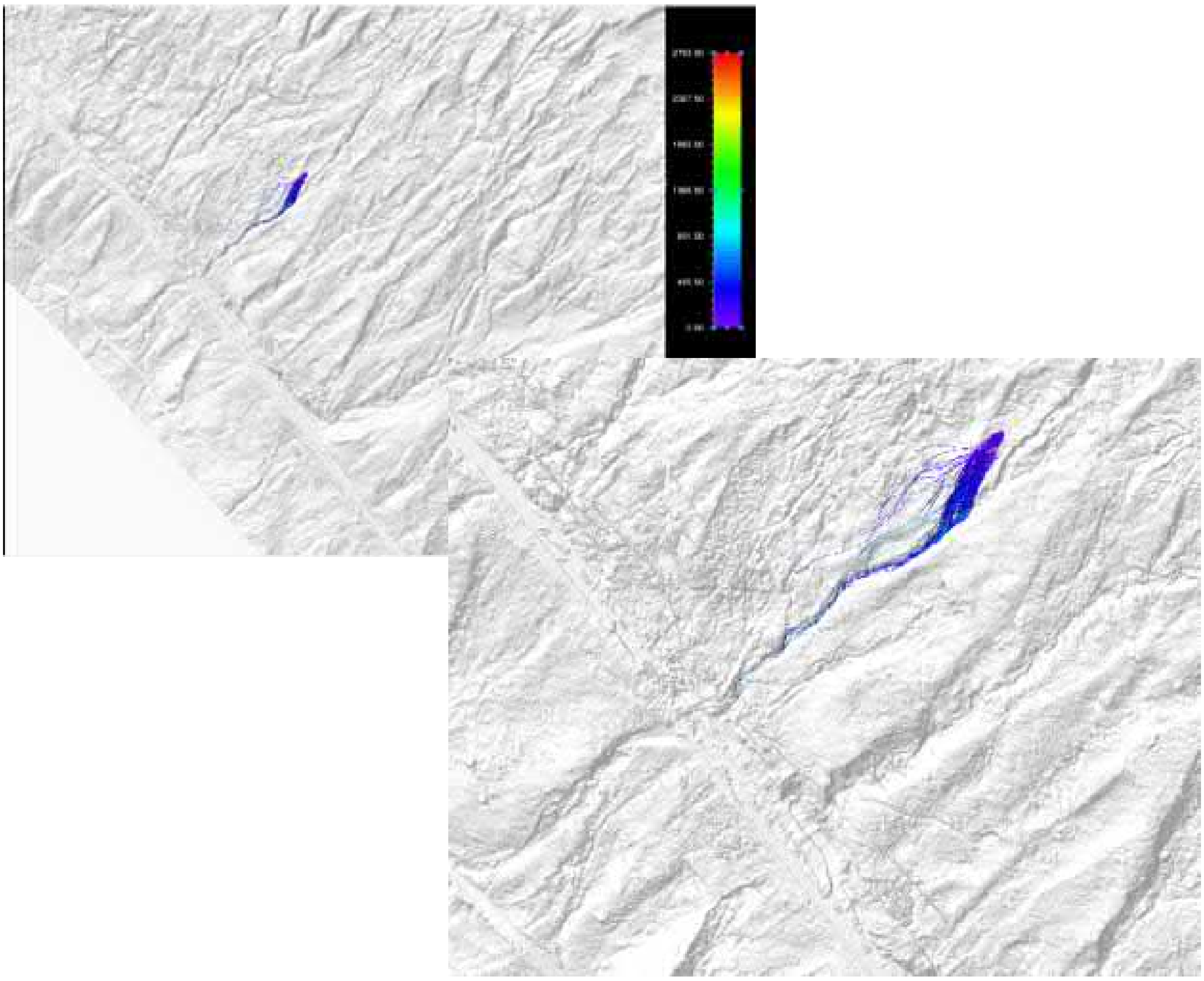
Jump Heights (m): 0.31 / 1.46 / 4.27

Velocities (m/s): 0.00 / 3.25 / 13.65

Kin. Energies (kJ): 0.00 / 90.13 / 1128.54

Rot. Velocities (rot s-1): 0.00 / 0.43 / 1.66

Average Slope (Degrees): 32.63 / 42.37 / 87.61



ID253 Simulation Results:

(Min/Mean/Max Values)

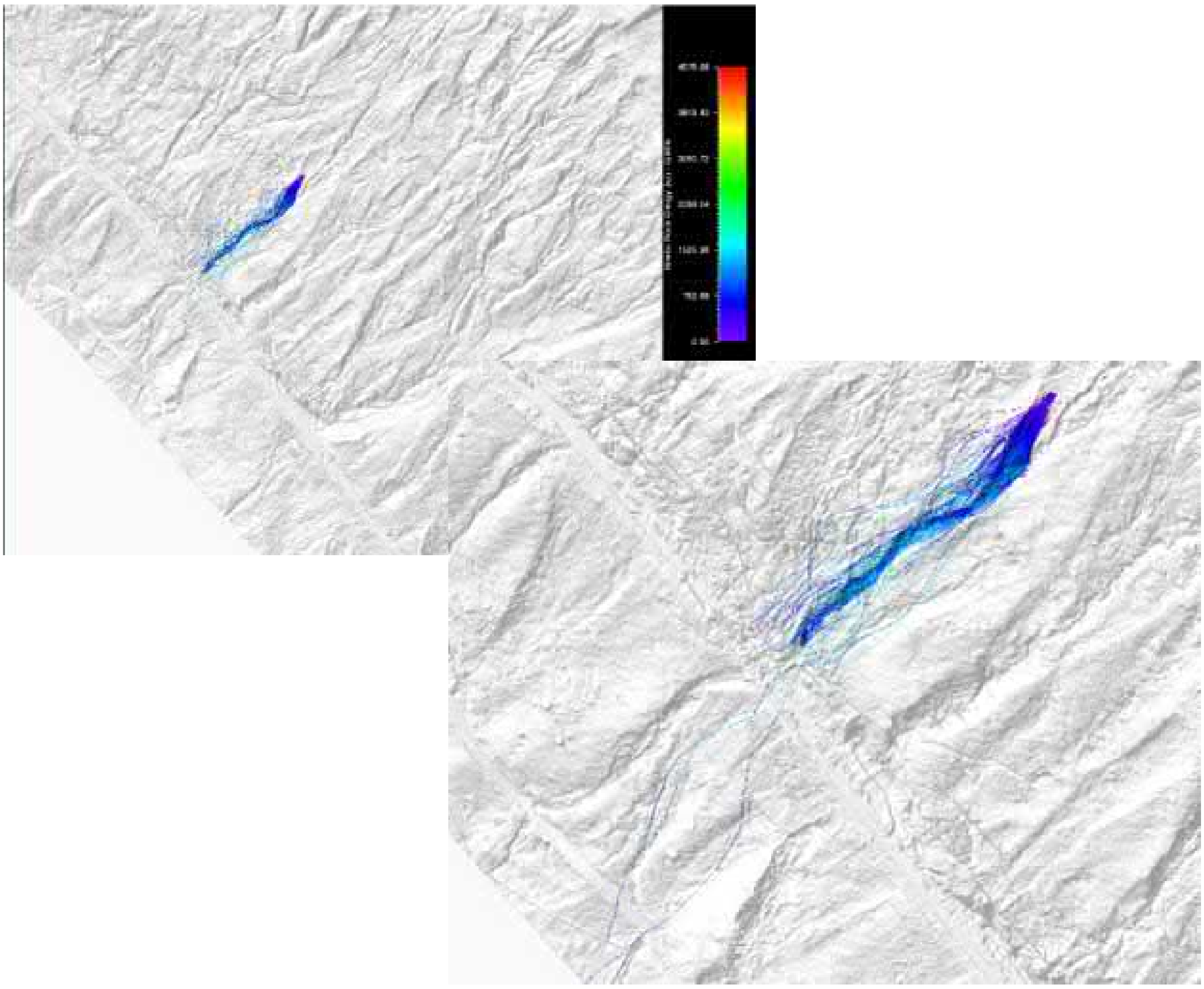
Jump Heights (m): 0.27 / 1.35 / 5.84

Velocities (m/s): 0.00 / 3.58 / 21.04

Kin. Energies (kJ): 0.00 / 121.81 / 2793.00

Rot. Velocities (rot s-1): 0.00 / 0.47 / 2.63

Average Slope (Degrees): 27.21 / 34.12 / 90.00



ID253-B Simulation Results:

(Min/Mean/Max Values)

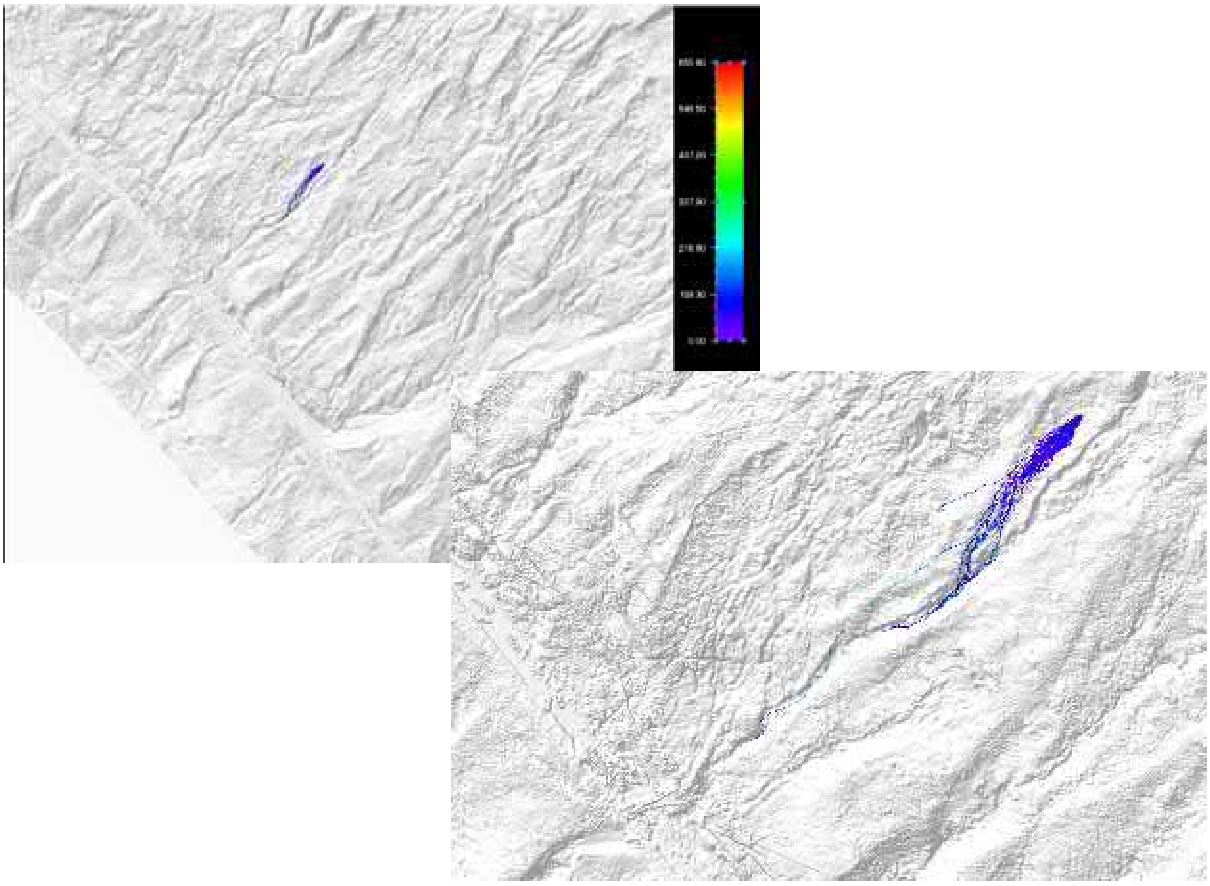
Jump Heights (m): -0.33 / 1.66 / 591.88

Velocities (m/s): 0.00 / 6.08 / 26.45

Kin. Energies (kJ): 0.00 / 343.09 / 4576.08

Rot. Velocities (rot s-1): 0.00 / 0.78 / 3.37

Average Slope (Degrees): 23.69 / 33.30 / 90.00



ID259 Simulation Results:

(Min/Mean/Max Values)

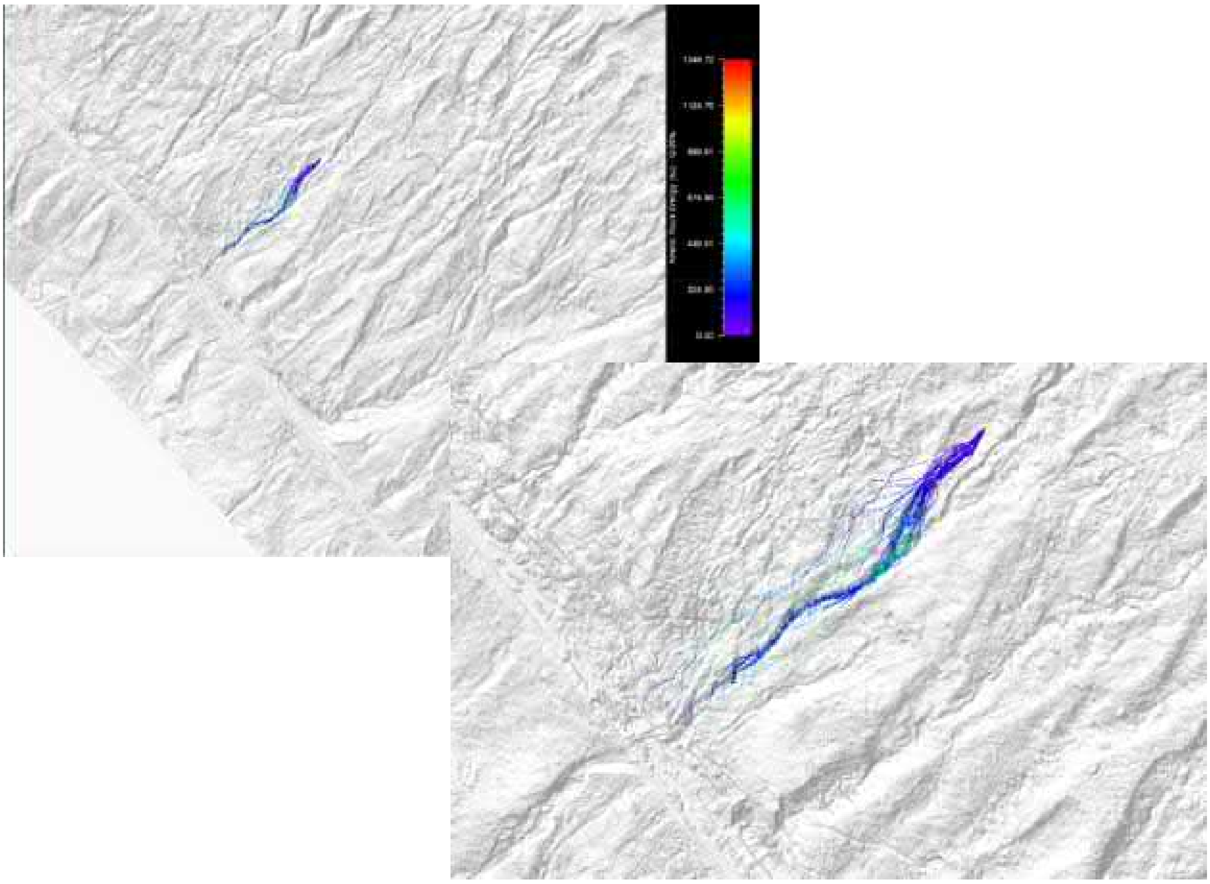
Jump Heights (m): 0.26 / 1.02 / 3.48

Velocities (m/s): 0.00 / 2.89 / 15.25

Kin. Energies (kJ): 0.00 / 35.51 / 655.80

Rot. Velocities (rot s-1): 0.00 / 0.50 / 1.86

Average Slope (Degrees): 0.52 / 86.62 / 90.00



ID259-B Simulation Results:

(Min/Mean/Max Values)

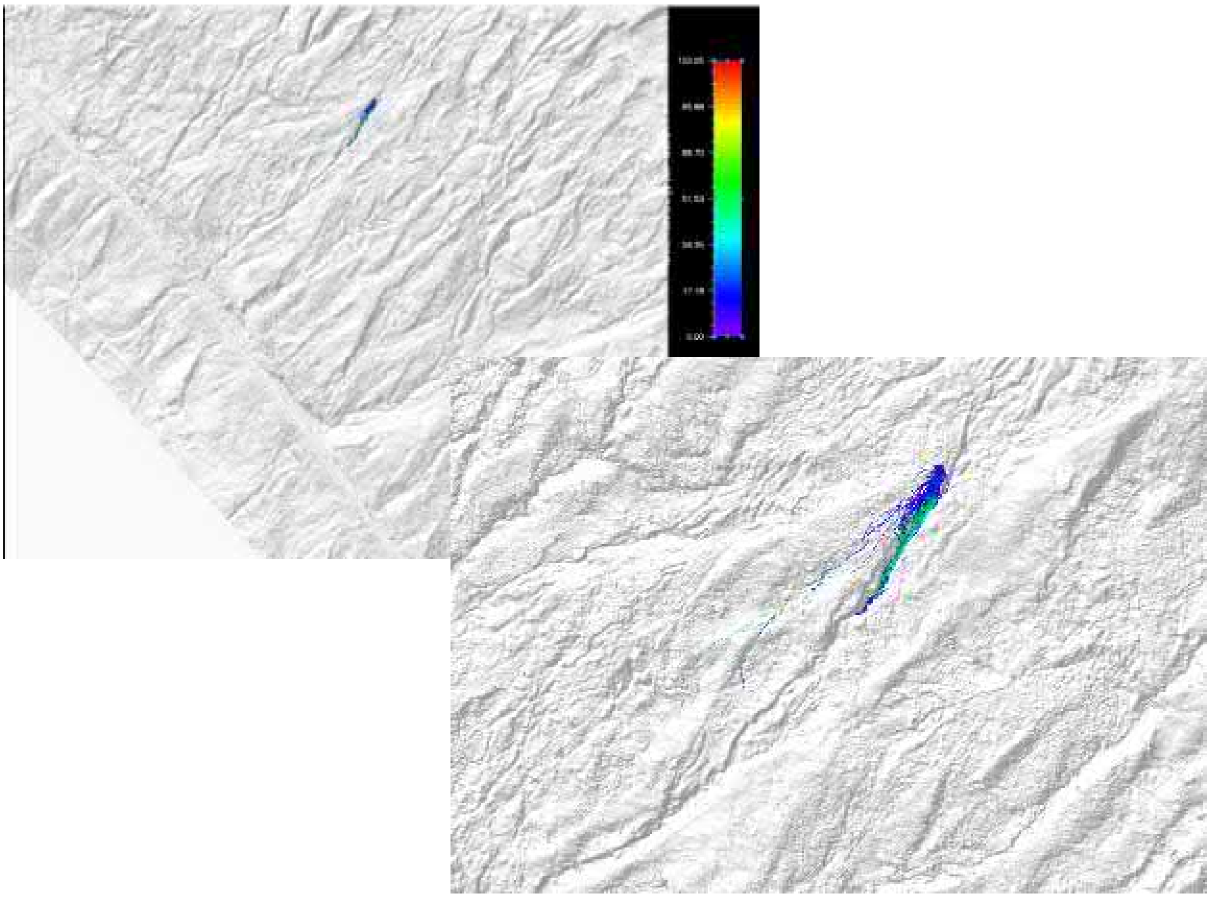
Jump Heights (m): 0.23 / 1.34 / 6.73

Velocities (m/s): 0.00 / 6.05 / 21.57

Kin. Energies (kJ): 0.00 / 158.18 / 1349.72

Rot. Velocities (rot s-1): 0.00 / 0.97 / 3.26

Average Slope (Degrees): -29.73 / 85.26 / 90.00



ID270 Simulation Results:

(Min/Mean/Max Values)

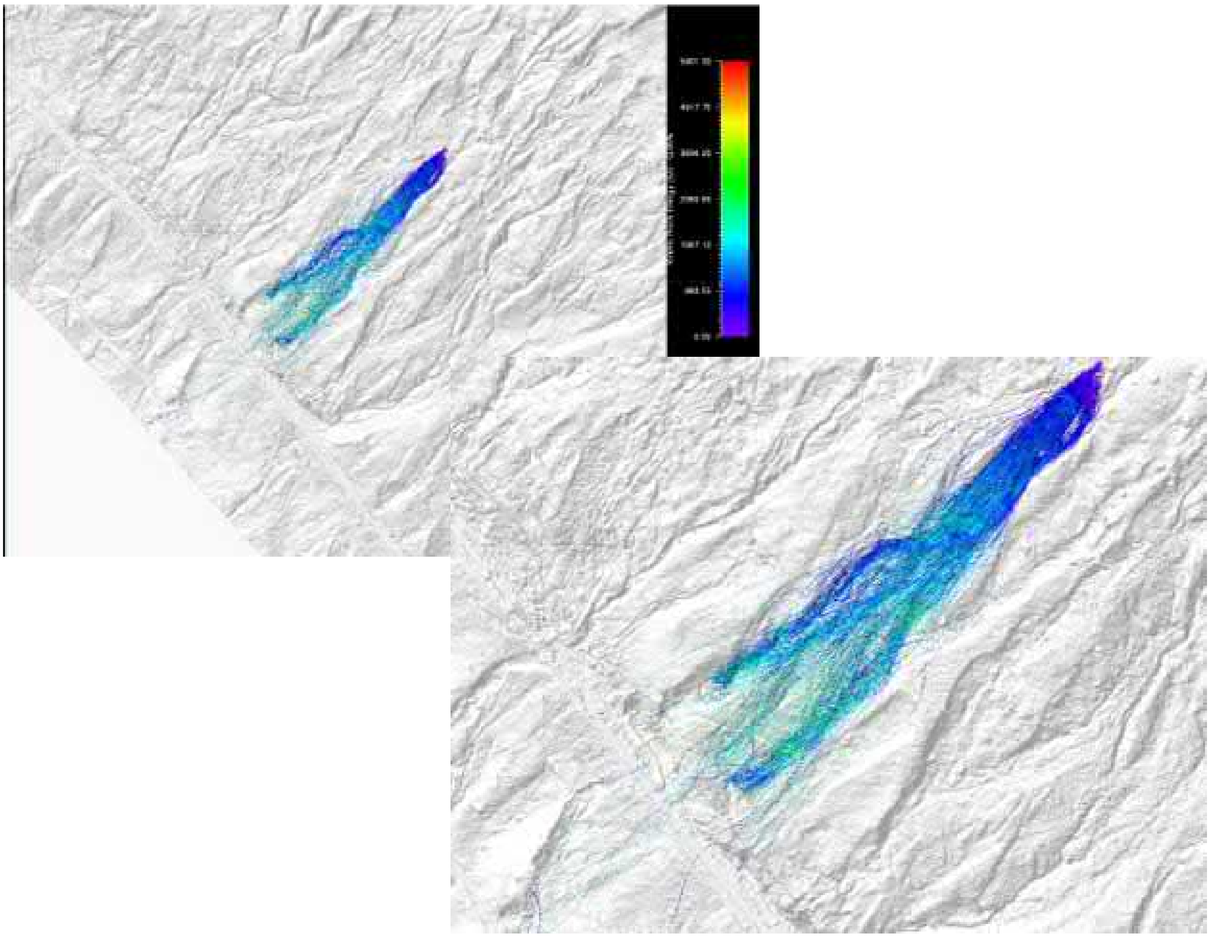
Jump Heights (m): 0.06 / 0.69 / 2.53

Velocities (m/s): 0.00 / 3.11 / 11.65

Kin. Energies (kJ): 0.00 / 10.26 / 103.05

Rot. Velocities (rot s-1): 0.00 / 0.76 / 3.03

Average Slope (Degrees): 24.73 / 35.44 / 90.00



ID290 Simulation Results:

(Min/Mean/Max Values)

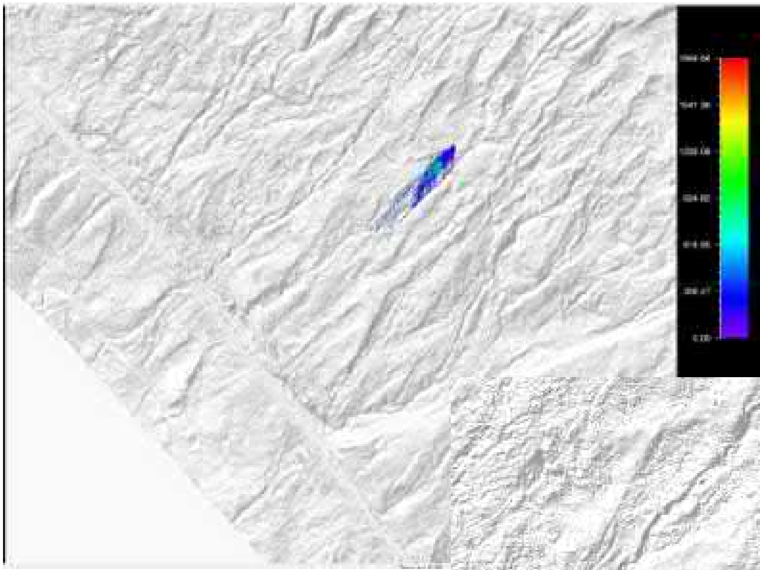
Jump Heights (m): -3.47 / 1.88 / 904.50

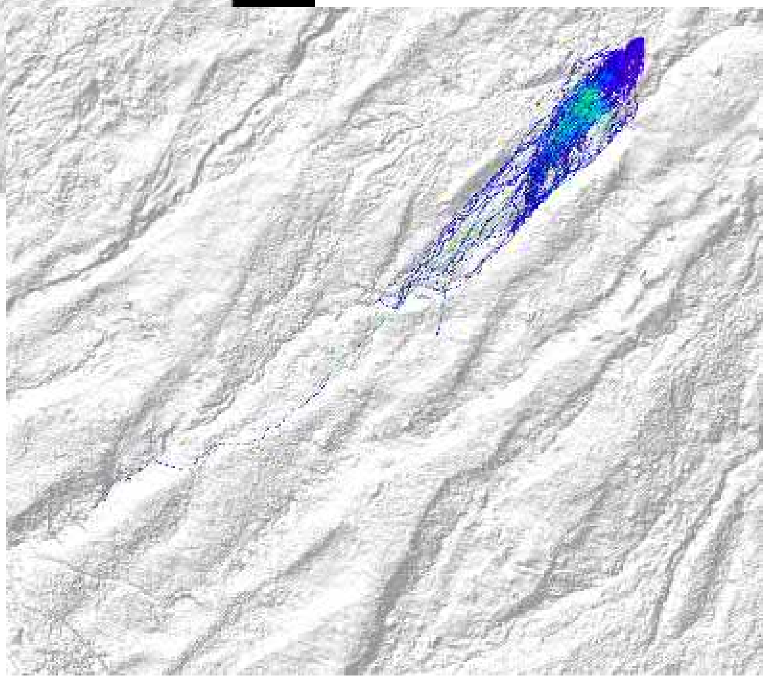
Velocities (m/s): 0.00 / 8.62 / 27.97

Kin. Energies (kJ): 0.00 / 760.17 / 5901.30

Rot. Velocities (rot s-1): 0.00 / 1.07 / 3.84

Average Slope (Degrees): 27.58 / 31.58 / 89.38





ID290-B Simulation Results:

(Min/Mean/Max Values)

Jump Heights (m): 0.21 / 1.38 / 4.08

Velocities (m/s): 0.00 / 3.72 / 15.98

Kin. Energies (kJ): 0.00 / 148.20 / 1849.64

Rot. Velocities (rot s-1): 0.00 / 0.46 / 1.86

Average Slope (Degrees): 27.26 / 34.09 / 89.42