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The Quantitative Assessment of Debris Flow Risk to Road Users on the Scottish Trunk Road Network

A83 Rest and be Thankful

J C F Wong and M G Winter

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B Shearer

(Project Manager)

M G Winter

(Technical Referee)

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Abstract

This report presents the methodology developed for undertaking a quantitative risk assessment (QRA) for the impact of debris flow on roads. It also presents a first use of the methodology at the A83 Rest and be Thankful in Scotland. The methodology considers the probability of an event of a typical size, and the conditional probabilities of a vehicle being affected, given an event, and of damage (fatality) occurring given that the vehicle is affected.

Scenarios covering a vehicle being hit by a debris flow and of a vehicle hitting a debris flow are considered. The computed Personal Individual Risk (PIR) is used to calculate worst case fatality probabilities for commuters and logistics truck drivers; these fall within generally tolerable limits. The exception is the risk for the logistics truck driver risk which falls within the ALARP (As Low as Reasonably Practicable) zone. However, once the management and mitigation works are taken into account the risk is returned to a generally tolerable level.

The overall risk to society is expressed using the F-N diagram and prior to the implementation of mitigation measures being placed at the Rest and be Thankful show that for one or two fatalities the risk falls into the Unacceptable zone, while for higher numbers of casualties the risk falls into the ALARP zone.

When the mitigation measures are taken into consideration then the risk levels fall within the ALARP zone, indicating the value and effectiveness of the measures implemented. The timing of this work meant that only mitigation measures present as of October 2014 were taken into consideration. There has been significant work undertaken since that time to further reduce the risk at this site.

The potential effects of climate change on the frequency and magnitude of future events at the A83 Rest and be Thankful site are complex, and frequency and magnitude are coupled phenomena. However, a doubling of the frequency, for example, would lead to a doubling of the risk but the PIR values would still be considered Broadly Acceptable. The societal risk would, however, return to the lower reaches of the Unacceptable zone on the F-N diagram for low numbers of fatalities (N=1 or 2).

The authors believe that this is the first full, formal quantitative risk assessment for debris flow risk to road users.

The authors are conscious that the presentation of information relating to the probability of a fatality, or fatalities, at particular sites can be controversial. In addition, the use of internationally-recognised technical terms such as 'Broadly Acceptable' and 'Unacceptable', while necessary to the conduct of the work and the understanding of other professionals, may not help in the communication of such probabilities to a wider audience. It is important to note that the probabilities presented herein are low and, in addition, are not intended as a prediction. In contrast, their purpose is to build on earlier work on landslide hazard and risk and to assist in the making of effective investment decisions on risk reduction at appropriate sites and to an appropriate extent.

1 Introduction

This report presents the methodology and findings of a Quantitative Risk Assessment (QRA) study of landslide hazards on the slopes of Beinn Luibhean that affect a 1.7km-long section of the A83 Trunk Road on the approach to the Rest and be Thankful car park in Argyll and Bute, Scotland.

The Scottish Road Network Landslides Study (Winter et al., 2009) evaluated the hazards and risks associated with landslides at a regional/national (pan-Scotland) scale and identified sites most at risk. This has allowed the effective targeting of funds for implementation works. This work was undertaken within a qualitative/semi-quantitative framework.

With the most important sites identified, a Quantitative Risk Assessment (QRA) at key landslide sites that affect the Scottish trunk road network could be undertaken to facilitate direct comparison of landslide fatality risks on the trunk road with other published quantitative risk levels that society faces including those from road traffic accidents. The outcomes are set within the framework of the As Low As Reasonably Practicable (ALARP) approach which allows comparison with the levels of risk that the Health and Safety Executive deems acceptable in the nuclear industry (Anon., 1992; HSE, 2001), for example.

The work involved the estimation of frequency-magnitude relationships, as far as is possible using the limited dataset available and the calculation of the probability of a fatal (or near-fatal) event at a number of sites.

The outcomes will allow a greater degree of confidence in the spending decisions taken as well as giving a sound basis to such actions (and inactions) which will be valuable in the light of potential future landslide incidents and any associated injuries. There is also a strong link with work on economic impact assessment of landslides (Winter et al., 2014a; 2018) as this work will help to better define the relations between the frequency and magnitude of landslide events, albeit only for those of magnitudes that are extant, and suggest a likely temporal framework for repeated events.

The objectives of the study were to develop a QRA methodology by considering the debris flow occurrence information currently available for a selected site in Scotland. From this the annual probability of an event of a given size was to be determined.

The consequences of an event of a given magnitude were considered in terms of disruption or damage to the carriageway, and the vulnerability of road users determined in order to allow estimates of the annual probability of a fatality as a result of debris flow in the study area. The methodology has been demonstrated using the A83 Rest and be Thankful as a case study, a companion study assesses the risk at the A85 Glen Ogle (Winter, 2018).

2 Study Area

A83 Ardgartan to the Rest and be Thankful is amongst the most highly ranked debris flow hazard sites in Scotland (Winter et al., 2009). The hillslope overlooking the road is the south-west facing slope of Beinn Luibhean and has a particular history of instability (Jacobs, 2013a). Active monitoring and inspection of the slopes has been undertaken by the Operating Companies appointed by Transport Scotland since 2001 following a landslide at the south end of the Rest and be Thankful, where the A83 crosses the River Croe. Debris flow events have occurred in an area south-east of the Rest and be Thankful car park and the River Croe (Winter & Corby, 2012). In view of the above, the hillslope above this 1.7km-long road section was selected as the study area (Figure 1).

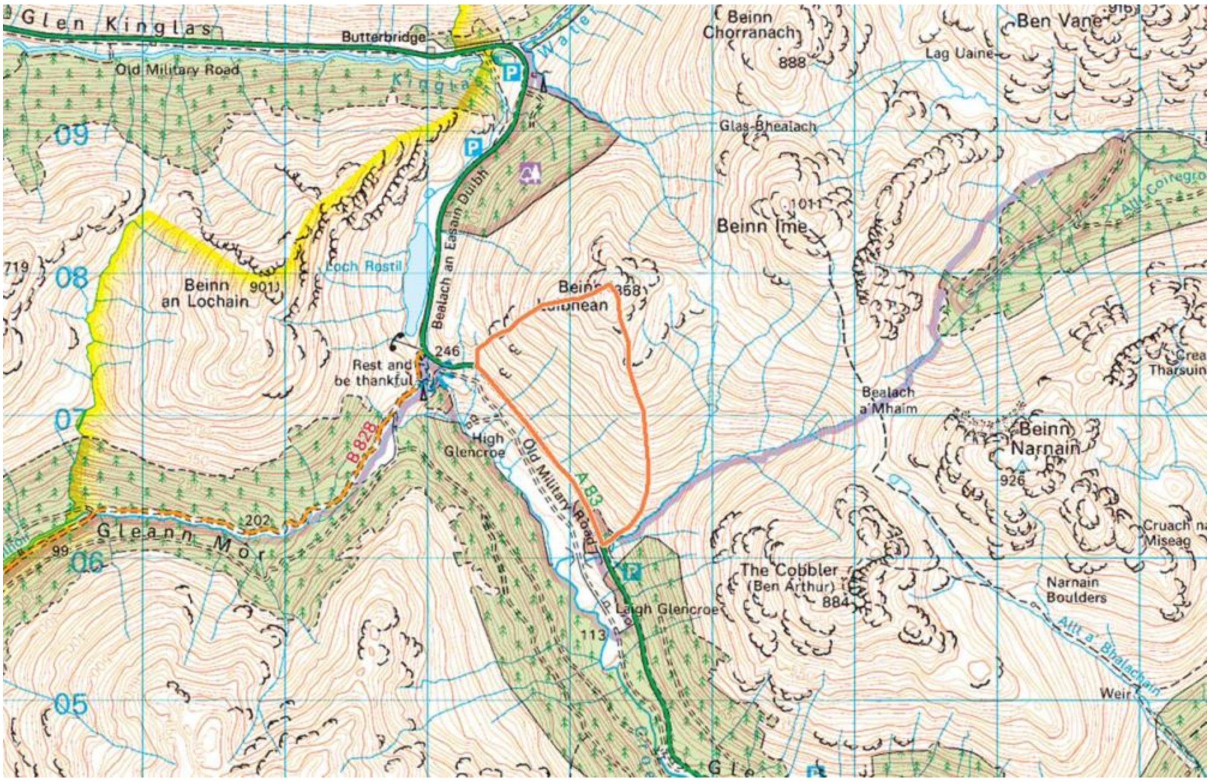


Figure 1. Location plan of the study area outlined in red (OS 1:50,000, not to scale). Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

2.1 A83 Trunk Road

The A83 trunk road is a 157km-long single two-lane carriageway connecting the A82 trunk road at Tarbet on Loch Lomond south-westwards to Campbeltown in Kintyre, connecting principal towns such as Inveraray, Lochgilphead, Tarbert and Campbeltown as well as other areas such as Dunoon and Cowal, Kintyre, and the islands of Islay, Jura and Gigha with the Scottish trunk road network. The 51km between Kennacraig and Campbeltown was trunked on 4 August 2014. The A83 supports the economic activities in the region including agriculture, forestry and fisheries, energy production, transport and storage, tourism and public administration.

2.2 Road Section between Ardgartan and the Rest and be Thankful

The section of the A83 trunk road between Ardgartan and the Rest and be Thankful through Glen Croe is approximately 7km long, starting from Ardgartan Village on Loch Long in the south-east towards the Rest and be Thankful car part in the north-west, near the junction with the B828. From Ardgartan the A83 (at 2m AOD) runs above and predominantly to the east of Croe Water, with only a small section of about 300m to the west, at the bottom of Glen Croe for about 3.3km to the junction with the Old Military Road at about 90m AOD. After this junction, the Old Military Road runs along the lower parts of the valley floor, while the A83 rises consistently at about 5^o towards the Rest and be Thankful car park at about 260m AOD.

Croe Water rises in the catchments to the south-west of Bealach a'Mhaim taking runoff from Beinn Luibhean (summit 858m AOD), Beinn Ime (1,011m), Beinn Narnain (926m) and The Cobbler (Ben Arthur) (884m). It intersects the A83 at approximately 180m AOD and 2km south-east of the Rest and be Thankful car park. The stream in Glen Croe to the north of that point is a tributary of Croe Water which rises in High Glencroe to the south of the Rest and be Thankful car park. The road between Croe Water and the Rest and be Thankful car park is overlooked by Beinn Luibhean whereas that between Ardgartan and Croe Water it is overlooked by The Cobbler (Ben Arthur).

The section of road identified of being at higher risk in this area (Section A82-02 from Winter et al., 2009) extends from just north of the Ardgartan turn at 45m AOD to 6.31km further north, just past the Rest and be Thankful car park at around 275m AOD.

The road closures at the A83 Rest and be Thankful generally occur on the south-west facing slopes of Beinn Luibhean overlooking the road section between where Croe Water passes under the A83 and a point approximately 500m south of the Rest and be Thankful car park (Figure 1). This hillslope was designated as the study area.

2.3 Study Area

In general, the 1.7km-long hillslope in the study area is planar towards the summit (Figure 1b), and the gradient varies from around 30^o to 36^o, averaging approximately 33^o. Above the middle part of the road section, an approximately 250m-long area of gentler slope (around 22.6^o) is evident between 550m to 600m AOD. This abuts the steeper rocky exposures (around 38.7^o) along a south-south-easterly spur extended from the summit of Beinn Luibhean. Numerous drainage channels incise the hillslope sub-perpendicular to the contours and extend below the A83 road level and the Old Military Road towards the tributary of Croe Water in the upper reaches of Glen Croe and High Glencroe. The width of the drainage channels intersecting the road section varies from 2m to 24m, with an average of 7.83m. No structure with human occupancy was found along the A83 Rest and be Thankful at the time of the Study. There is, however, one cottage located down slope of the Old Military Road at High Glencroe; this is understood to be occupied intermittently.

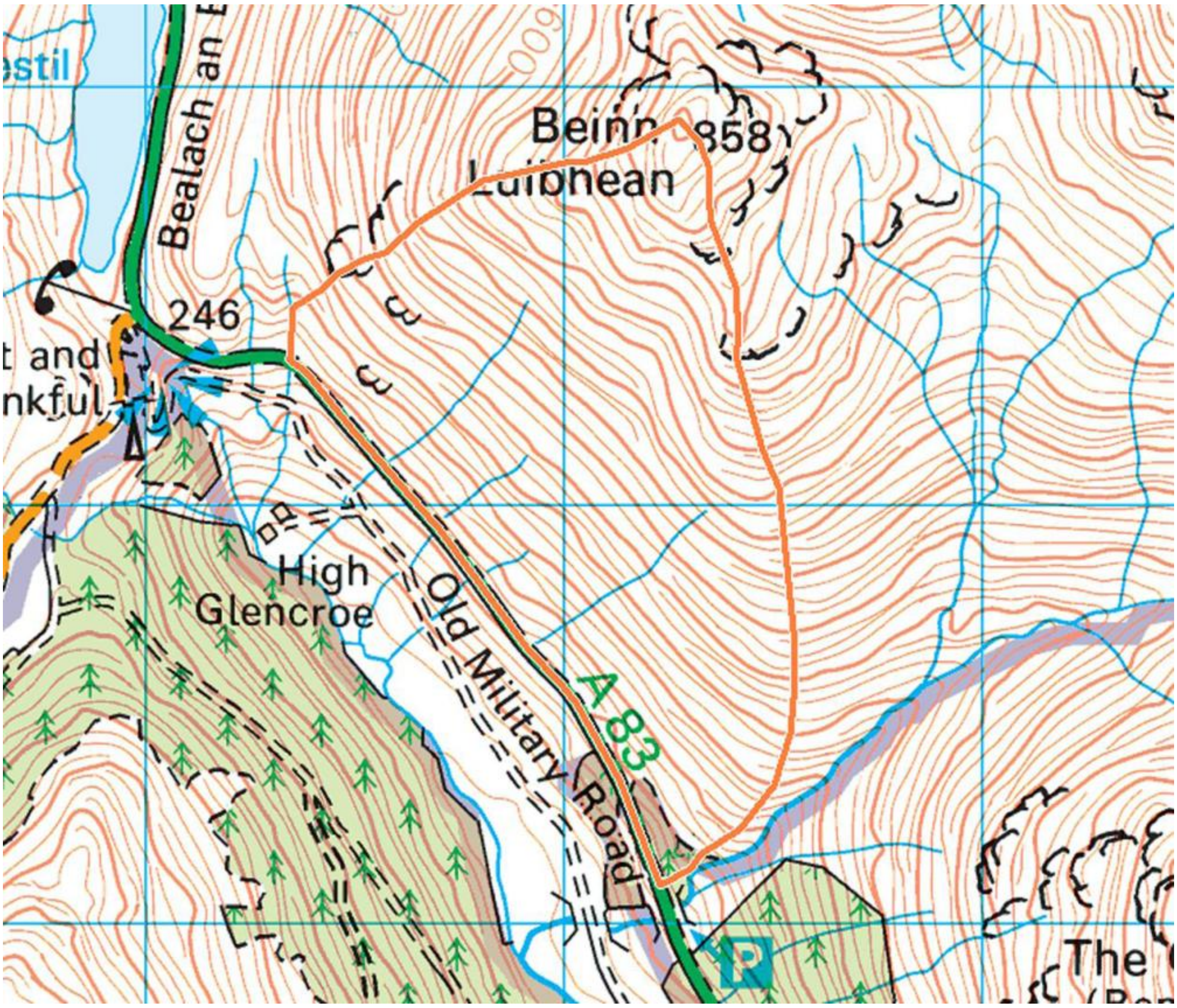


Figure 1b. Detailed location plan of the study area outlined in orange (OS 1:50,000, not to scale). Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

3 Desk Study

In Scotland there is a relatively high incidence of rainfall-induced debris flow. In August 2004 the rainfall was substantially in excess of the norm of up to 300% of the 30-year monthly average. The rainfall that triggered these events was both long lasting and intense although it is equally recognised that a relatively short-lived, high intensity storm can also trigger events (Winter et al., 2010).

Many of the observed cases show that failures were triggered as displacements of soil rafts that entered a stream channel, adding a substantial debris charge to already high and damaging water flows and resulting in substantial erosive power to entrain the loose materials over which it flows, giving rise to the potential for significant damage (Winter et al., 2005; 2006; 2009; Milne et al., 2009; Winter, 2019).

Although no major injuries were reported in the 2004 landslide incidents, two sequential debris flows along the A85 in Glen Ogle trapped 57 people who were airlifted to safety. In addition, disruption to the trunk road network has resulted in adverse socio-economic impacts to the relatively remote communities served by the road network (Winter et al., 2006; 2014a; 2018). Jacobs (2013a; 2013b) identified that the repeated closure of the A83 in the area of the Rest and be Thankful, and the need to use the diversion route via the A82, A85 and A819 between Tarbet and Inverary, increased journey times by about 45 minutes. The range of road users affected was comprehensive, ranging from public and school bus services, through haulage and private coaches to private cars. The disruption created economic loss to the local community and Jacobs (2013a; 2013b) reported that these were especially acute in the forestry and tourism industries.

Following the events of August 2004, Transport Scotland recognised the need to act and commissioned the Scottish Road Network Landslides Study (SRNLS) to ensure that in the future a system would be in place for assessment of the hazards and associated risks posed by debris flows. The first part of the study determined a way forward for dealing with such landslides events in the future (Winter et al., 2005) while the second part assessed and ranked the hazards and developed a management and mitigation strategy for the Scottish trunk road network (Winter et al., 2009). This latter part of the study identified the A83 Ardgartan to Rest and be Thankful site as amongst the most highly ranked debris flow hazard sites in Scotland.

Debris flow events at the A83 Rest and be Thankful are identified as occurring frequently, generally on an annual basis over the preceding 20 to 25 years, although the event magnitude was relatively small with a typical range of 200 and 1000m^3 (Winter et al., 2014b). Landslide management and mitigation measures include site-specific monitoring of rainfall, groundwater and slope movement; upgrading of culverts; installation of debris flow barriers and fences; road patrols; and annual slope inspections. In addition an alternative route along the Old Military Road that runs in the lower part of Glen Croe, downhill of the A83, has been provided. This is operated as an emergency diversion in the event of a road closure at the A83 Rest and be Thankful. A trial of 'wig-wag' signs as a temporal warning of a higher risk of rainfall-triggered debris flow events on A83 in the area centred on the Rest and be Thankful was also implemented from 2011 (Winter et al., 2013); these have been combined with extensive leafleting and more general publicity campaigns to promote desirable road user behaviours and responses to periods of higher risk. The planting of vegetation on the south-west facing slope of Beinn

Luibhean is planned for the future (Winter & Corby, 2012). These individual activities and actions sit within a strategic approach to landslide risk reduction (Winter, 2014).

In addition to the above landslide management and mitigation measures, Transport Scotland commissioned Jacobs to undertake the A83 Trunk Road Route Study to identify and appraise potential options to minimise the effects of road closures on the local communities and road users due to landslides in the area (Jacobs, 2013a; 2013b). The Part A report commented on the history of hillside instability both above and below the road between Ardgartan and the Rest and be Thankful car park within Glen Croe. In particular landslides on the slopes near the Rest and be Thankful car park, led to road closures for a total period of 34 days on six separate occasions between 1 January 2007 and 31 October 2012 (Jacobs, 2013a). Four additional landslides that occurred on 19 November 2012, 3 October 2013, 6 March 2014 and 28 October 2014 after this period also resulted in road closures. The report recommended that additional debris flow barriers, drainage improvement works and hillslope vegetation would be cost-effective options to reduce the occurrence of road closures related to debris flow and to reduce the risk to road users.

It has been observed that many Scottish debris flows were triggered by short intense rainfall events preceded by periods of heavy antecedent rainfall. A wide variety of international approaches to the back analysis and forecast of landslide events resulting from rainfall were researched and the rainfall data based on rain gauges and rainfall radar for 16 debris flows events in Scotland were used to develop a tentative debris flow trigger threshold for Scotland (Winter et al., 2009; 2010). It was identified that sufficient rainfall over a period of 288 hours (12 days) to 2 hours before an event would create conditions in which debris flow was highly likely. Nevertheless, it was noted that the Scottish rain gauge network was developed mainly for synoptic meteorological and flood observations, and more specific purposes such as water resources and hydroelectric power. The rain gauge network was therefore sparse in areas of interest for debris flow forecast. In some cases, the distance of the rain gauge from the landslide location exceeded 20km. Furthermore, although the rainfall radar system covers some areas of interest at a resolution of 2km, most are resolved at only 5km. Roberts et al. (2009) stated in relation to an analysis in an area with 5km radar resolution that rainfall amounts estimated by the [UK] radar network were generally less than those measured by gauges and distributed somewhat differently. Having identified the Rest and be Thankful to be one of the sections of the major road network most frequently affected by debris flows, two rain gauges were installed in the area and commissioned in April 2012 (Winter et al., 2013).

A subjective increase in the frequency of intense rainstorms has been observed in recent years, resulting in presumed increases in the groundwater table on the hillside and an observed increase in the rate of water erosion and instability of the stream morphology. Such intense rainfall events have led to a larger number of landslides, in the form of debris flows, in the hills of Scotland (Winter et al., 2010). In broad terms the available climate change forecasts suggest that in the winter months when rainfall is expected to increase, landslide hazard frequency and/or magnitude may increase in Scotland in the future, whereas in the summer months the frequency may decrease, but with a possibility of increasing magnitude (Winter & Shearer, 2014a; 2014b). The Rest and be Thankful would therefore be likely to be subject to increased landslide activity and changing and potentially more complex patterns of landslide risk.

Risk is the term used to describe the likely scale and magnitude of future harm or adverse consequences arising from the impact of hazards such as landslides (Lee & Jones, 2014). The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment and Management defined landslide risk as a measure of the probability and severity of an adverse effect to life, health, property or the environment (ISSMGE, 2004). Burgman (2005) defines risk as "the chance, within a time-frame, of an adverse event with specific consequences" (from Dostál, 2008) and this temporal subtlety is reflected in Lee & Jones' (2014) definition of landslide risk as '*the potential for adverse consequences, loss, harm or detriment as a result of landsliding, as viewed from a human perspective, within a stated period and area'*. Lee & Jones also considered that '*risk assessment is not merely a new fad or fashion but a broader framework for considering the threat and costs produced by landsliding and for examining how best to manage both landslides and the risk posed by landslides'*.

Quantitative risk assessment (QRA) techniques have been used to quantify landslide risks posed to infrastructure and population as well as to perform cost-benefit analysis of risk mitigation strategies in many parts of the world (Bunce et al., 1997; Bunce, 2008; Cheng & Ko, 2008; ERM, 1998; Jaiswal et al., 2010; Wong et al., 2004). It allows the review of landslide hazards, diagnosis of risk distribution and characteristics, as well as the quantification of risk to life posed by the hazards for evaluation of risk tolerability and determination of risk management strategy (Wong et al., 2004). As the A83 Rest and be Thankful has been identified as an area prone to debris flow, a pilot QRA methodology was developed in this study for analysing and evaluating the landslide fatality risk posed to road users along this section of road based on the existing information available. The methodology developed is intended to be adapted for other high risk sites.

4 Geomorphology and Geology

Boulton et al. (2002) suggested that the frequent growth of ice sheets in the Quaternary has left the strongest mark on the landscape and in the terrestrial sedimentary record. Also, the ice sheets '*flowed radially outwards from centres in the Highlands and Southern Uplands and were powerful agents of erosion and deposition, moulding the uplands, removing earlier sediments from the lowlands, locally depositing great thickness of till directly from the ice, and depositing sand and gravel from meltwater rivers*'. Valleys and sea lochs were therefore eroded and deepened by repeated glaciations.

The study area has been subject to the waxing and waning of glaciers and ice sheets that has superimposed a large-scale erosional pattern on the landscape and shaped the relatively planar hillslope on both sides of Glen Croe. The last glacial period, the Loch Lomond Readvance, saw glacial retreat within the period 12,500 to 11,500 years before present (Ballantyne, 2012) and, although an ice dome developed over the west highlands, it is characterised by corrie and valley glaciers of the glaciated valley land system rather than by extensive ice sheets. The glacial till deposited on the hillslope was subsequently exposed and eroded, particularly along the subsequently formed gullies and drainage channels.

4.1 Superficial Geology

The hillslope above the A83 Rest and be Thankful is mainly covered by glacial till deposits, locally in the form of morainic deposits near the base of the hillslope (Jacobs, 2013a). There was no existing ground investigation data that defined the thickness of the superficial deposits on the hillslope. Based on mapping records (BGS, 2007), the source area of a landslide that occurred on 28 October 2007 comprised thin (<1m) and patchy cohesive subglacial till variably overlain by loose morainic debris and gravelly head. This thickness of superficial deposits was verified at many locations on the middle part of the hillslope in a field reconnaissance conducted on 9 October 2014.

The field reconnaissance also identified that various parts of the hillslope, particularly those at higher elevation where debris flow often initiates, are blanketed by topsoil or peat. The importance of water-bearing soils, particularly peat, as triggering materials for gully-constrained debris flows was acknowledged by both Winter et al. (2009) and Milne et al. (2009).

Signs of slope movements on the hillslope including failure backscarps, tension cracks, soil creep, soil rafts, unstable boulders, debris lobes and the parallel ridges of deposited debris (levées) that characteristically flank the tracks of debris flows are abundantly evident on the slope (Winter, 2019). The reworking of superficial deposits due to gravitational movements, by processes such as landslides and soil creep, has redeposited colluvium on the lower part of the slopes, resulting in an increased thickness of superficial deposits on the lower parts of the slope. This may mean that landslide events that trigger on the lower parts of the slope have the potential to be of greater magnitude than those that trigger more conventionally on the upper parts of the slope and become largely confined to stream channels where the volumes of material that can be potentially entrained may be less.

4.2 Solid and Structural Geology

The hillslope is predominantly underlain by the solid geology of the Beinn Bheula Schist Formation comprising pelite, semipelite and psammite formed during the Neoproterozoic Era approximately 542 to 1,000 million years ago. Plutons of pyroxene-mica diorite of the South of Scotland Granitic Suite intruded the Schist in the south-eastern part of the study area approximately 398 to 423 million years ago in the Devonian and Silurian Periods. Near the Rest and be Thankful car park, minor intrusions of lamprophyre dykes of the North Britain Siluro-devonian Calc-alkaline Dyke Suite. The bedrock has been subjected to folding and faulting, and two north-south trending faults in the Schist were mapped (Peach et al., 1903; Fettes et al., 1987).

4.3 Hydrology and Hydrogeology

The digital aerial photography images taken in 2007 show numerous water courses tributaries incising the middle part of the hillslope from 400 to 550m AOD in the study area. These drainage channels are in general 5 to 20m wide with maximum width exceeding 30m. Most of these tributaries merge into a main stream at or just below approximately 400m AOD and run sub-perpendicular to the contours to the valley bottom. A walkover along the road section on 3 October 2014 identified 26 drainage channels at road level. These drainage channels are culverted under the A83 to allow continuation downwards towards the tributary of Croe Water in the valley floor.

The Hydrogeological Map of Scotland indicates that the hillslope is underlain by crystalline basement rocks which offer little potential for groundwater storage and transport except in cracks and joints associated with tectonic features or weathering (Robins, 1988).

5 Landslide Hazards

As part of the term maintenance contract, Transport Scotland require the NW Operating Company to carry out active monitoring and inspection of the slopes at the A83 Rest and be Thankful. The available annual inspection reports (2005 to 2012) (BEAR, 2005; 2006 & Scotland TranServ, 2007; 2009; 2010; 2011; 2013) and field photographs of landslide events up to October 2014 were reviewed. A total of 16 debris flow events on the slopes above the road were identified. Three other debris flow events that occurred in January 2003, November 2003 and January 2004 in the Rest and be Thankful area, causing road disruption, were documented in a rainfall correlation assessment by Winter et al. (2009) and were also taken into account in modelling the landslide hazards in the study area. The details of the 19 events are tabulated in Table 1. Figure 2 shows the debris flow event locations where these are known. Information such as source location, source volume and deposition volume on and above the road section was available for most of the reported debris flow cases. The average figures for such landslides were used for those events for which information was not available.

Of the 19 events spanning 12 years from 2003 to 2014, twelve debris flow events resulted in debris deposition ranging from $2m^3$ to $1,000m^3$ at road level; in addition one event resulted in a piece of rock being deposited at road level while the debris deposits were not sufficiently mobile to reach the road and remained on the hillside. These thirteen events resulted in temporary road closures of variable duration. The debris of the other six recorded events was reported to have been deposited on the hillslope above the road without causing road disruption. Based on the available figures, the annual frequencies of debris flow occurrence on the hillslope and events in which the debris reaches the road are 1.58 and 1.08 per year respectively.

In reviewing the landslide records and field photographs of the twelve debris flow events that disrupted the road, it was found that the three events with a debris volume deposited at road level of less than $10m^3$ had only a minor effect on the road as might be expected from a minor washout (Figure 3). The other nine, more sizable events, resulted in considerable debris deposition on the road which caused significant disruption to traffic (Figure 4). For the rock fall case, although the fallen rock size of 0.13 m^3 is small in comparison with the debris flow volumes, it clearly had a significant effect on traffic (Figure 5). Given its impact force in falling from the hillside onto the road and the potential for impact with vehicles, this rock fall case was categorised with the more sizeable debris flow cases in the QRA.

The above information was determined from the available landslide records since 2003. There was no record of other debris flow events predating January 2003. No historical landslides are shown on the geological map published by the British Geological Survey (Peach et al., 1903; Fettes, et al., 1987). The digital aerial photography images of the study area, taken in 2007, were reviewed on the ArcGIS platform, and 224 probable recent and relict landslide scars with likely scarps and trails interpreted were identified (Figure 6). Earlier aerial photographs taken in 1988 and archived in the National Collection of Aerial Photography of the Royal Commission on the Ancient and Historical Monuments of Scotland were reviewed, but the study area was obscured by cloud such that the landslides that occurred between the 1988 and 2007 could not be identified by comparing the two sets of aerial photos. In this context it is clear that such events occurred prior to 2003, and the second author’s personal knowledge of such events goes back to around 1990, but details of times, dates and locations are not available in either records or from personal recall. It does, however, seems most likely that the frequency of such events at the A83 Rest and be Thankful has increased since the early-1990s.

Table 1. Details of 19 landslide events on the slopes above the A83 Rest and be Thankful.

No.	Information Source	Date of occurrence	Landslide nature	Location	Estimated source volume (m^3)	Estimated deposition volume on A83 (m^3)	Estimated width of deposition on A83 (m)	Road closure
1	Winter et al. (2009)	Jan 03	CDF	N/A	110*	200*	17*	Yes
2	Winter et al. (2009)	Nov 03	CDF	N/A	110*	200*	17*	Yes
3	Winter et al. (2009)	Jan 04	CDF	N/A	110*	200*	17*	Yes
4	BGS web report	28 Oct 07	CDF	NN23828 07142	300	227	25	Yes
5	TranServ annual report	2 Apr 08	CDF	224300E, 706700N	50	2.3	5	No
6	TranServ report	23 Oct 08	CDF	NN23770 07160	40	0	0	No
7	TranServ inspection report	23 Oct 08	CDF	NN24160 07170	8	0	0	No
8	TranServ annual report	8 Sep 09	CDF	NGR 223901 707208	375	500	30	Yes
9	TranServ annual report	24 Nov 09	CDF	NGR 223705 707106	50	0	0	No
10	TranServ Annual report	16 Feb 11	CDF	Near geotechnical feature G5	13	0	0	No
11	TranServ inspection report	1 Dec 11	CDF	NGR 223900 706720	63	55	10	Yes
12	Field photographs	22 Feb 12	CDF	N/A	25	0	0	Yes
13	TranServ inspection report	22 Jun 12	CDF	NGR 224394 707490	113	0	0	Yes
14	TranServ inspection report	29 Jun 12	CDF	N/A	40	0.13	0.5	No
15	Field photographs	1 Aug 12	CDF	N/A	75	450	25	Yes
16	Field photographs	19 Nov 12	CDF	N/A	60	10	8	Yes
17	Field photographs	3 Oct 13	CDF	N/A	110*	2	5	Yes
18	Field photographs	6 Mar 14	CDF	NGR 223783 707587	240	4.5	5	Yes
19	BEAR emergency report	28 Oct 14	CDF	N/A	110*	750†	50	Yes

Remarks:
CDF = Channelised debris flow.
* Estimated as the average from the other data available.
† 1,250 tonnes retained by the debris flow fence.

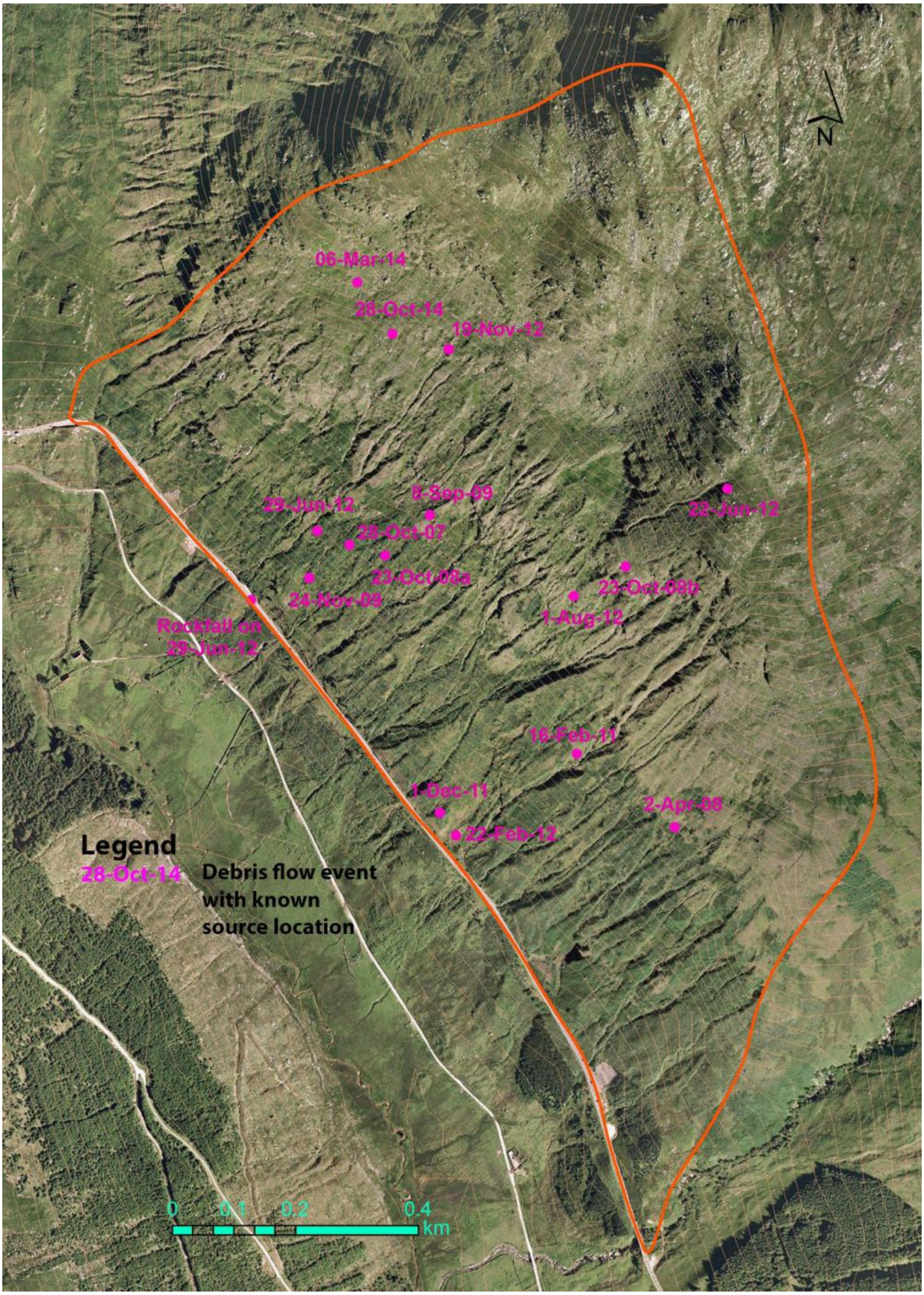


Figure 2. Debris flow events with locations known. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

Figure 3. Debris flow events with less than 10m^3 of deposits reaching the A83 Rest and be Thankful: Top-left, deposition from the 2 April 2008 event above the A83; Top-right, minor washout deposition from the 3 October 2013 event on the A83; and Bottom, minor washout deposition from the 6 March 2014 event on the A83. (Images courtesy of Scotland TranServ and BEAR Scotland.)

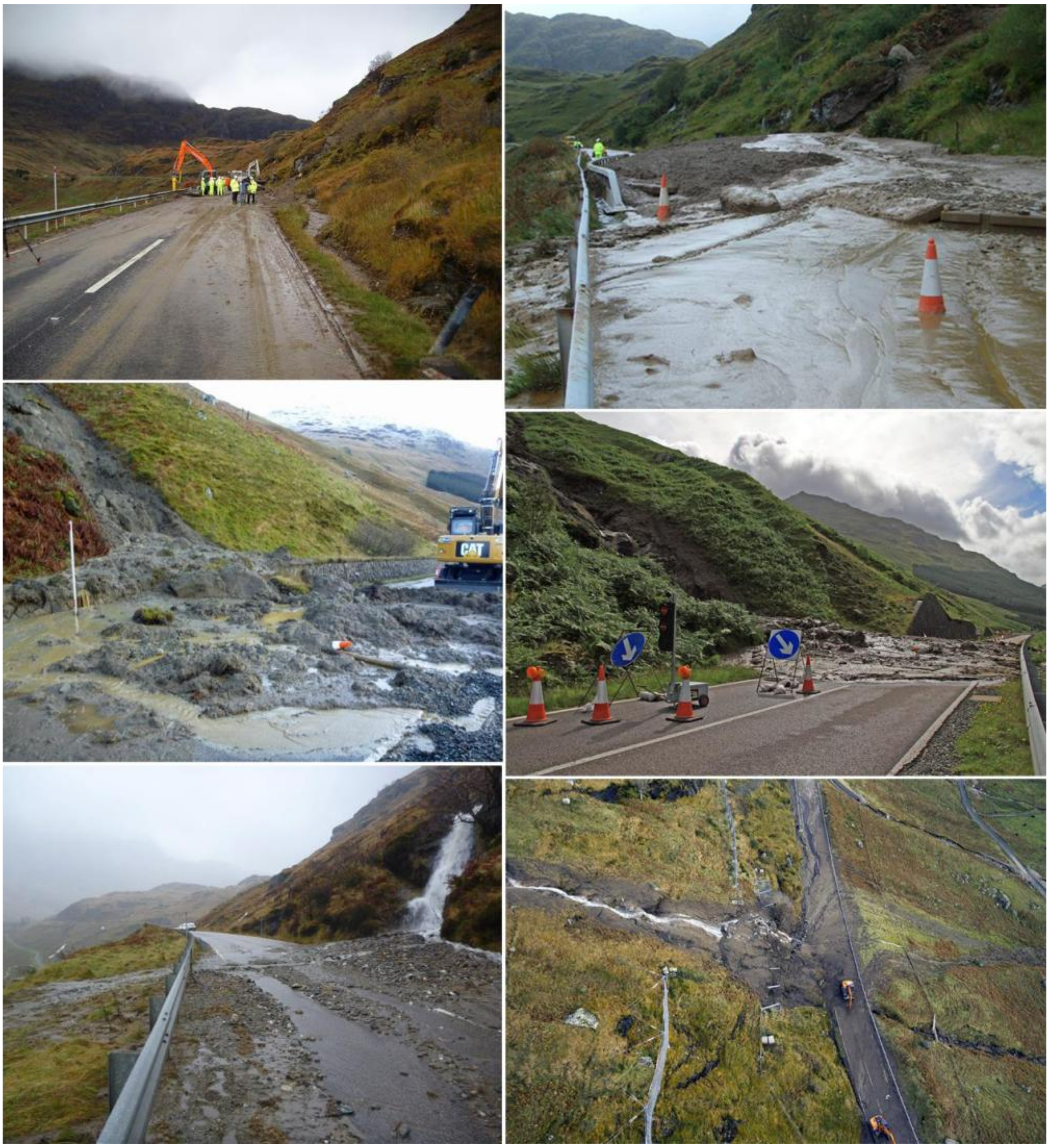


Figure 4. Debris flow deposits with more than 10m3 of deposits reaching the A83 Rest and be Thankful: Top-left, deposition from the 28 October 2007 event; Top-right, deposition from the 8 September 2009 event; Middle-left, deposition from the 1 December 2011 event; Middle-right, deposition from the 1 August 2012 event; Bottom-left, deposition from the 19 November 2012 event; Bottom-right, deposition from the 28 October 2014 event. (Images courtesy of Scotland TranServ and Sky View Video (Scotland).)

Figure 5. The fallen rock onto the A83 Rest and be Thankful associated with a debris flow event on 29 Jun 2012. (Image courtesy of Scotland TranServ.)

Hungr et al. (1999) suggested that landslide record data may be limited due to underreporting, incomplete recording and inadequate record intervals which result in missing information particularly on landslide volume and underrepresentation of low-frequency, high-magnitude events. That said, the objective of the study was to analyse and evaluate the landslide fatality risk posed to road users at the A83 Rest and be Thankful based on available information. Given the landslide patrols that have been commissioned in recent years, it was considered that the debris flow events with deposits hitting the road within the study area should have been adequately identified and recorded.

As a first step to ensure that a comprehensive knowledge of debris flows, road network and their interaction was fully captured, a landslide susceptibility map showing the hazard potential of debris flows was prepared in the SRNLS for systematically assessing and ranking the hazards posed by debris flow and developing a management and mitigation strategy for the Scottish trunk road network (Winter et al., 2009). The landslide susceptibility map comprises five main components, namely availability of debris material, water conditions, land cover, proximity of stream channels and slope angle based on existing data sources. Notwithstanding this, Winter et al. (2009) took a semi-quantitative/qualitative approach to the development of a regional (Scotland) susceptibility map and details of previous landslides were not considered (as such details were limited). The level of information was therefore not sufficient for sophisticated hazard modelling such as debris run-out mobility. Figure 7 shows an overlay of the SRNLS debris flow susceptibility map on the debris flow events with source locations known in the study area.

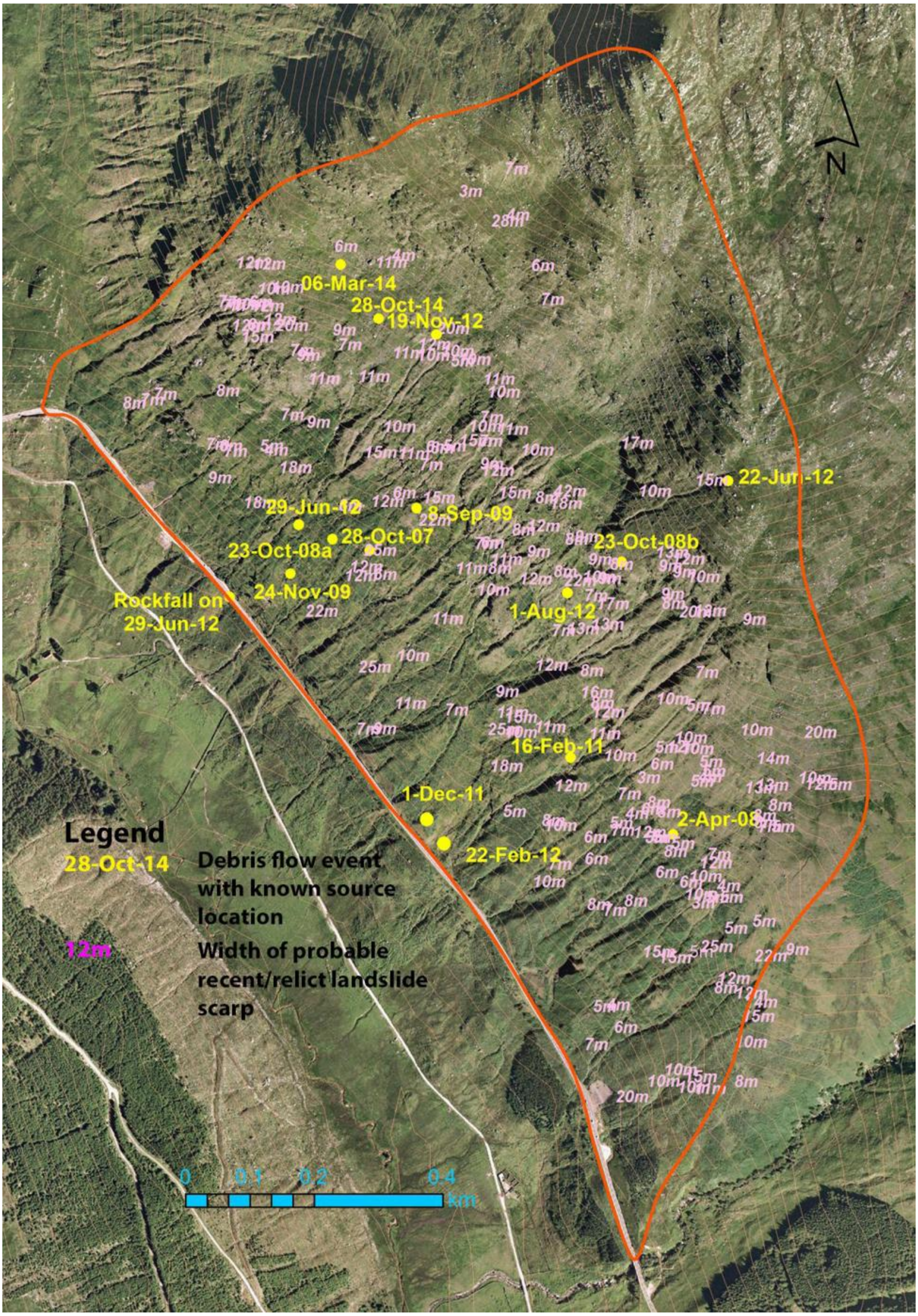


Figure 6. Locations of probable recent and relict landslide scars identified on the GIS platform. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

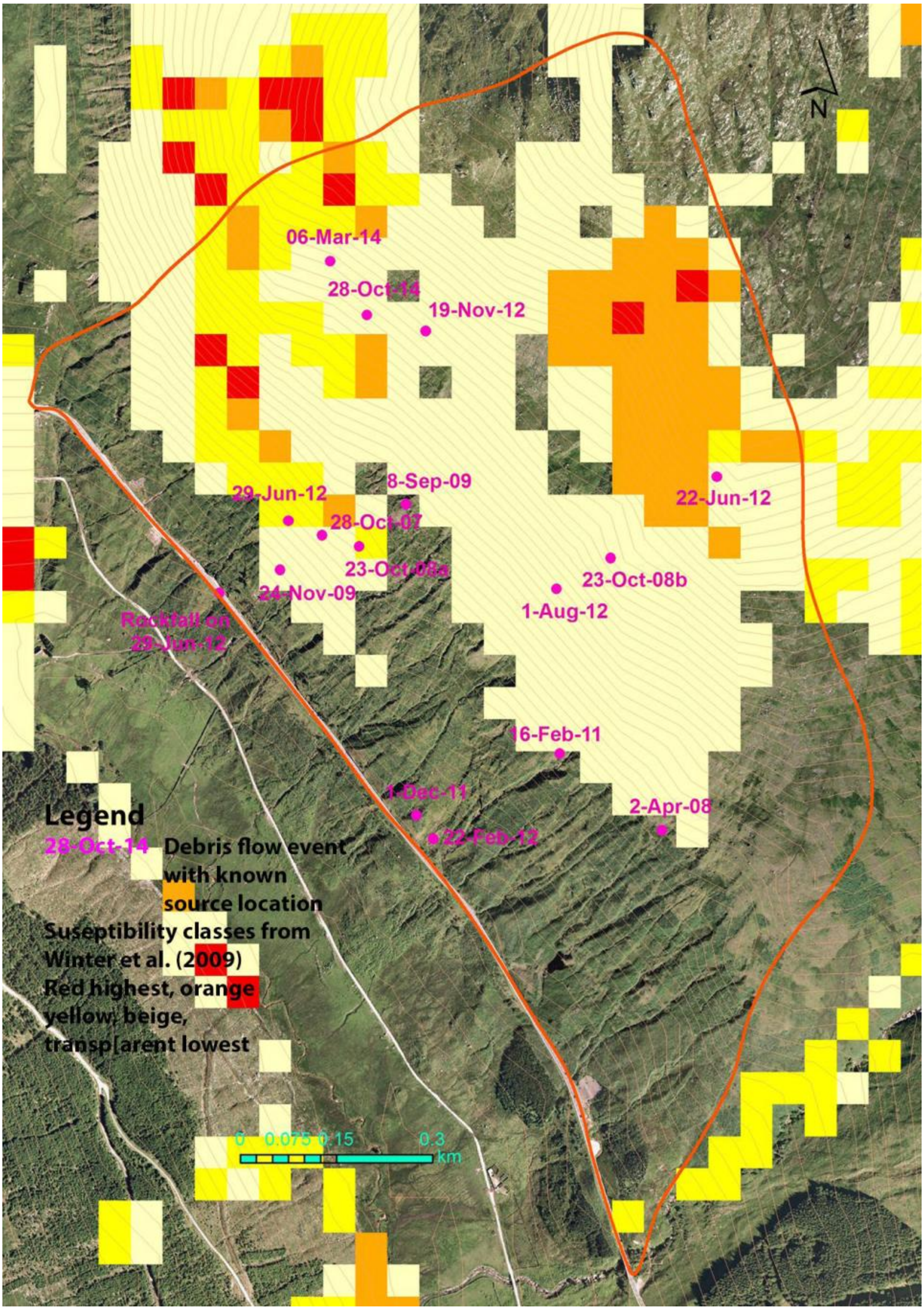


Figure 7. Debris flow susceptibility map (Winter et al., 2009) showing locations of known debris flow sources. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

6 QRA Methodology

The key objective of this QRA Study was to determine the fatality risk to road users due to debris flow hazards within the study area based on available information. The study thus focusses on the A83 leading to the Rest and be Thankful, treating the vehicles and associated road users as the elements at risk. The road infrastructure was not considered as an element at risk, but see also Winter et al. (2014b) and Section 6.3.1. Although out of the scope of the study it is worth noting that there were no structures with human occupancy identified along the stretch of A83 (see also Section 2.3 which identifies a single cottage some way downslope of the Old Military Road).

The benefit of adopting a risk-based approach is that it could provide a systematic landslide risk assessment framework to enhance the openness, objectivity and consistency of judgements (Lee & Jones, 2014). The estimated risk levels also could be compared with existing and relevant risk criteria for major hazardous installations handling dangerous chemicals, for example, and provide an approach for Cost Benefit Analysis (CBA) for risk management (ERM, 1998). This is particularly useful for prioritising and decision-making with respect to resource allocation for landslide risk reduction purposes, comparison of different sites, and for providing comparisons with other known and relevant risks.

Landslide risk assessment presents major challenges as it requires the numerical expression of the chance of future landsliding (and other uncertain events) and as Lee (2009) puts it "… Many projects take the view that risk management decisions must be made even if we don't know the 'true' probability. In this context the numerical expression of chance should be a best estimate judgement, based on the available knowledge." As Suzanne Lacasse put it in her, as yet unpublished, 2015 Rankine Lecture, "QRA is the systematic application of engineering judgement".

Based on The Royal Society's definition (1992), risk is defined as a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of occurrence. Hazard is a situation that in particular circumstances could lead to harm. Risk is expressed as the product of the probability of a hazard and its adverse consequence:

$$Risk = Probability\ (landslide\ event) \times Consequences \tag{1}$$

Adverse consequences might include accidents, loss of life, damage to property, services and infrastructure, environmental impacts and associated financial losses (Lee, 2009). The 'bow-tie' diagram (Figure 8) is often used in the risk assessment process, and is a representation of all the initiators and consequences of a particular scenario, together with the safety barriers that are in place to prevent, control or mitigate the event (HSE, 2006).

This analytical method highlights that the focus of hazard assessment should not be solely on just the annual probability of a landslide event on a hillslope, but also on whether the event would reach and damage the elements at risk, and the vulnerability of those elements to damage. Lee & Jones (2014) developed the following simple conditional probability:

$$Risk = P(Event) \times P(Hit|Event) \times P(Damage|Hit) \times C \tag{2}$$

where *P(Event)* is a measure of the expected likelihood of a landslide event per year, *P(Hit|Event)* is the annual probability of a vehicle 'hit' given that a landslide event occurs which involves both spatial and temporal probabilities of affecting the elements at risk,

P(Damage|Hit) is the annual probability of damage given that a 'hit' has occurred, as a measure of chance between 0 and 1, and

C is the consequences as a result of the landslide event.

For the purposes of this work 'Damage' is taken to represent the fatality of one or more road users and effectively encompasses the concepts of both 'Damage' and 'Consequences' and Equation (2) becomes:

$$Risk = P(Event) \times P(Hit|Event) \times P(Fatality|Hit) \quad (3)$$

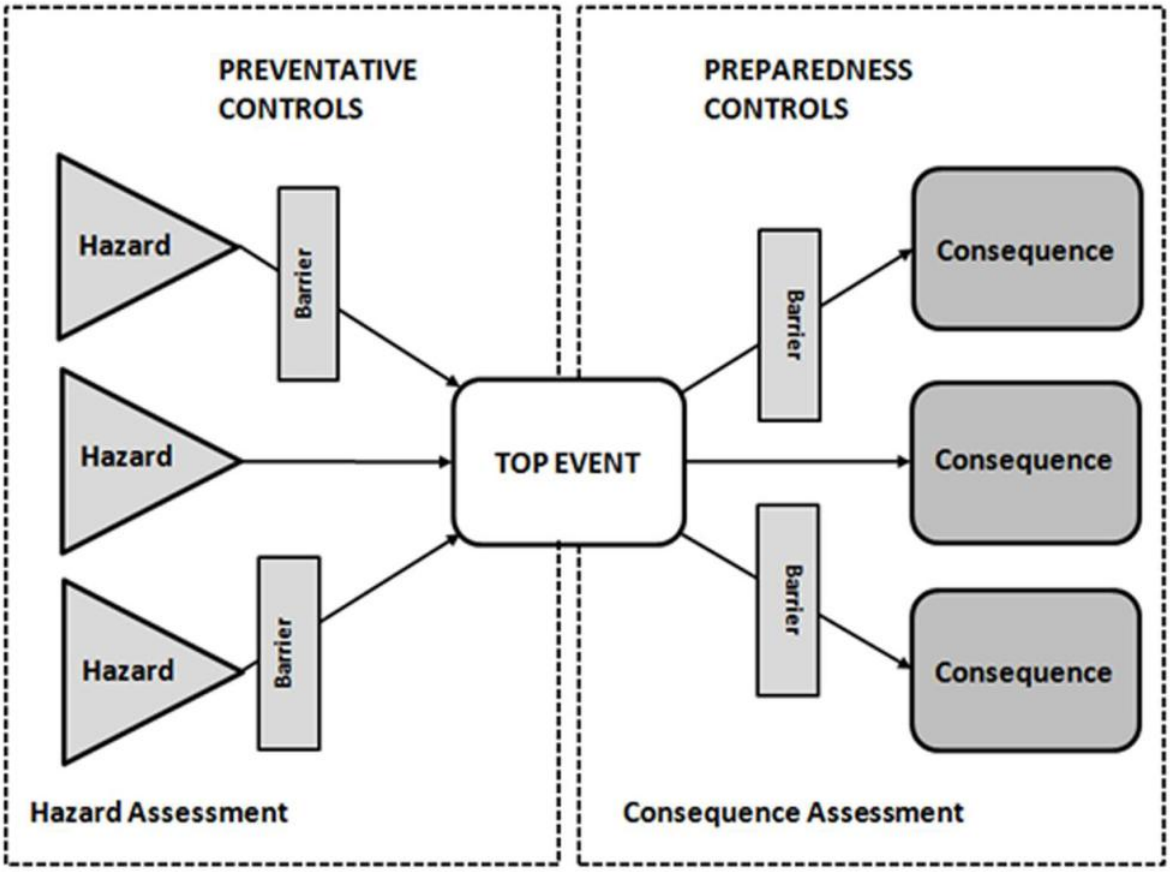


Figure 8. The risk assessment 'bow-tie' diagram (from Lee & Jones, 2014).

6.1 P(Event)

The debris flow hazard, or P(Event), is expressed as the annual probability of occurrence determined from historical records; this expressly assumes a uniformitarian approach in which the past is considered to be a guide to the future. It may be argued whether or not the past pattern of natural processes is an adequate guide to the future and whether, for instance, the anticipated, but necessarily qualitatively expressed, increase in landslide frequency due to climate change in Scotland suggested by Winter et al. (2010) and (Winter & Shearer, 2014a; 2014b) (see also Section 3) should be accounted for. The main argument against accounting for such changes is, of course, that the uncertainty associated with climate change is, most likely, considerably greater than that associated with past events.

The key benefit of this uniformitarian approach is in describing landsliding uncertainties associated with the random occurrence of events such as rainfall and groundwater conditions over time as well as incomplete knowledge or understanding of the circumstances leading to a debris flow event. In addition, statistical analysis of the historical landslide occurrence data as the outputs from the slope system within the study area was considered effective in revealing, practically at least, the current landslide fatality risk along the road section based on the current level of understanding and information. In much the same way that a qualitative approach has been used to assess the likely changes in landslide frequency and magnitude due to climate change a similar approach can be used to assess the likely changes in the quantitative risk (see Section 8).

Inevitably, judgement was exercised in a number of areas, including in the determination of which data was representative, or appropriate, to the aim of this Study. From the landslide inventory in Table 1 covering the 12-year period spanning from 2003 to 2014, thirteen out of nineteen recorded events resulted in road closures. Notwithstanding this, as discussed in Section 5 above, it was identified that only those nine debris flow events with debris volume exceeding $10m^3$, and the debris-flow-related rock fall case, caused appreciable disruptions to the road and posed significant risk to the road users and were thus considered in the QRA.

Accordingly, the probability of annual occurrence, or frequency, of debris flow events causing disruption to road users at the A83 Rest and be Thankful was determined as follows:

Frequency of debris flow events causing disruption to road users

$$= \text{Number of recorded landslides / time period (years)} \quad (4)$$

$$= 10/12 \text{ years}$$

Giving a frequency of 0.83 events per year.

It is noted that the period of 12 years for which records are available is relatively short compared to that available and used for other similar studies, such that the probability of low-frequency, high-magnitude events might be underestimated. Nevertheless, the P(Event) calculated was considered the best estimate based on existing information for the purpose of this study and the scarcity of such low-frequency, high-magnitude events can be extrapolated over a much longer period of approximately 26 years, albeit that this is still shorter than that used for many other studies, from the second author's experience.

6.2 P(Hit|Event)

When a debris flow occurs on the slopes above the road in the study area, the potential elements at risk are the moving vehicles using the road and the associated road users (i.e. the drivers and passengers). P(Hit|Event) is the conditional probability of a 'hit' on a non-stationary object per year given the occurrence of an event; it is the product of two components, namely P(Wrong Place) and P(Wrong Time) (Lee & Jones, 2014). P(Wrong Place) quantifies the spatial probability of a vehicle exposed to a hazard on a single trip in a year, whereas P(Wrong Time) indicates the temporal probability associated with a vehicle passing through the 'Wrong Place' on that trip. The product of P(Wrong Place) and P(Wrong Time) gives rise to P(Hit|Event) quantifying the probability of a 'hit' associated with a debris flow event.

6.2.1 P(Wrong Place)

P(Wrong Place) is expressed as the spatial probability of an element at risk being in the danger zone on a single trip per year where it could be damaged by a debris flow or deposit (i.e. the length of vehicle as a fraction of the length of the debris flow hazards in the study area). While the precise calculation of P(Wrong Place) differs for the two distinct risk scenarios considered (see below), it is determined by two parameters, namely the length of the element at risk (i.e. average vehicle length) and the length of road section exposed to debris flow hazards, for both cases, as follows:

$$P(Wrong\ Place) = \frac{L_v}{L_H} \tag{5}$$

where L_v is the length of the vehicle, and
L_H is length of debris flow hazards in the study area.

The actual vehicle length is a variable by class of vehicle. The value used is therefore the average weighted by the proportion of vehicles in each class; this is thus representative of the traffic. In determining an average vehicle length, the Annual Average Daily Flow (AADF) information available on the Transport Scotland website (http://www.transport.gov.scot/map-application) was reviewed. The nearest data point for the study area is at 'JTC08338 - A83 West of Arrochar'. The most recent full set of data that was available at the time the work was conducted indicated that the AADF in both directions through the study area was 4,039 vehicles in 2010; this was split into six vehicle classes (figures in brackets denotes the proportion), as follows:

- CCE1-motorbike (1.55%).
- CCE2-car/van (87.98%).
- CCE3-car+trailer (0.94%).
- CCE4-light goods van (LGV)/rigid heavy goods vehicle (HGV) (5.77%).
- CCE5-HGV (3.72%).
- CCE6-bus (0.06%).

By summing the weighted lengths of the six vehicle classes (i.e. the product of the proportion and the average length of each vehicle type based on relevant models), the average vehicle length was calculated as 5.22m (Table 2). Despite the more exposed position of the motorbike rider, the CCE1-motorbike comprises a very small proportion of the overall traffic. It was thus grouped with the other vehicle classes to simplify the calculation for average overall length (Table 2), and no separate individual vulnerability was calculated for this vehicle/rider type.

Based on the landslide hazard model discussed in Section 5, the elements at risk in the study area are subjected to the debris flow hazards along the drainage channels on the hillslope. Given its channelised nature, the potential debris path could be confined to any of the existing drainage channels including topographic depressions on the hillslope, rather than the relatively planar or convex parts of the hillslope between depressions.

In order to determine the number and width of the drainage channels intercepting the road in the study area to define the length of 'Wrong Place', an exercise including interpretation of digital aerial images taken in 2007 on the ArcGIS platform and field verification was undertaken. The aerial photographic imagery that was available was orthographic, stereoscopic imagery was not available, and all interpretations were therefore undertaken in two-dimensions on the ArcGIS platform.

Table 2. Average length of vehicles based on AADF data.

Vehicle type	CCE1 motorbike	CCE2 car/van	CCE3 car+trailer	CCE4 LGV/rigid HGV	CCE5 HGV	CCE6 bus
Average AADF (no.)	63	3,553	37	234	150	2
Proportion of vehicle type (%)	1.55	87.98	0.92	5.77	3.72	0.06
Average vehicle length* (m)	2.237	4.501	10.292	8.060	17.625	13.075
Weighted vehicle length (m)	0.035	3.960	0.095	0.465	0.655	0.007
Σ Weighted vehicle length, L_v (m)	5.22					

* Calculated from a variety of web sources including manufacturer data.

A total of 25 drainage channels ranging from 4m to 20m in width at road level, and averaging 10.12m, were identified. In a field reconnaissance carried out on 3 October 2014, two out of the 25 drainage channels were found irrelevant (i.e. encompassed within the scope of another channel) whereas three new channels not identified in the GIS interpretation were included (Table 3). As a result, 26 drainage channels were identified in the field (Figure 9). After the field verification, the width of the drainage channels measured on the outside lane ranged from 2m to 24m, with an average width of 7.83m (L_s). Comparing this with the outcome of digital aerial image interpretation, it was apparent that the drainage channels less than 15m were over-measured on the ArcGIS platform, while those exceeding 15m were under-measured.

It was assumed that debris flow deposits on the slope could reach the A83 at any of the 26 drainage channels identified at any one time. Thus, the total length of the debris flow hazards in the study area (the denominator from Equation 5) was taken to be the aggregate of the 26 channel widths determined initially from the orthographic aerial photography and then modified during the field reconnaissance (see Table 3, i.e. 203.7m)

To model the consequence of a debris flow reaching the road based on the definition of P(Wrong Place) in Section 6.2 above, it was considered that a vehicle (and its occupants) could be damaged by two risk scenarios, as follows:

- Being hit by debris flow if the vehicle is within the debris path (Scenario A).
- Hitting deposit at the road level if the driver could not stop the vehicle in time (Scenario B).

While the average vehicle length is constant, the effective average vehicle length, or the length of road that any part of the vehicle occupies during a period in which it can be damaged is different for each of the two cases. It is this that is the numerator for Equation (5). In addition, the effective width of the channel increases as the deposits spread on reaching the road increasing the value of the denominator in Equation (5).

Table 3. Drainage channels at the A83 Rest and be Thankful.

Initial Drainage Channel Number (from GIS)	Width: from GIS (m)	Final Drainage Channel Number (field)	Width: field (m)	National Grid Reference	Remarks
-	-	1	5	NN 24180 06218	Identified in field
1	12	2	7	NN 24148 06310	
2	12	-	-	NN 24093 06407	The berm downslope of an old quarry site acts as a barrier to trap debris, deleted in field verification
3	16	3	6	NN 24003 06560	
4	12	4	8	NN 23970 06601	
5	15	5	24	NN 23951 06623	
6	20	6	24	NN 23922 06655	
7	8	7	5	NN 23882 06706	
8	9	8	7	NN 23853 06745	
9	8	9	8	NN 23824 06787	
10	15	10	17	NN 23795 06826	
11	5	11	2	NN 23772 06856	
12	12	12	6	NN 23742 06892	
13	17	12	8	NN 23718 06920	
14	15	14	10	NN 23695 06952	
15	5	-	-	NN 23675 06979	Deleted in field verification
16	5	15	5	NN 23659 07001	
17	5	16	2	NN 23641 07028	
18	10	17	5	NN 23593 07084	
19	6	18	2	NN 23578 07104	
20	6	19	5	NN 23539 07141	
21	10	20	19	NN 23515 07160	
22	4	21	3	NN 23483 07201	
-	-	22	7	NN 23465 07223	Identified in the field
-	-	23	3	NN 23416 07287	Identified in the field
23	5	24	2	NN 23411 07295	
24	5	25	4	NN 23368 07341	
25	10	26	11	NN 23348 07348	
		Total width of channels	**203.7**		
		No. of channels	**26**		
		Average width of channels, L_s	**7.83**		

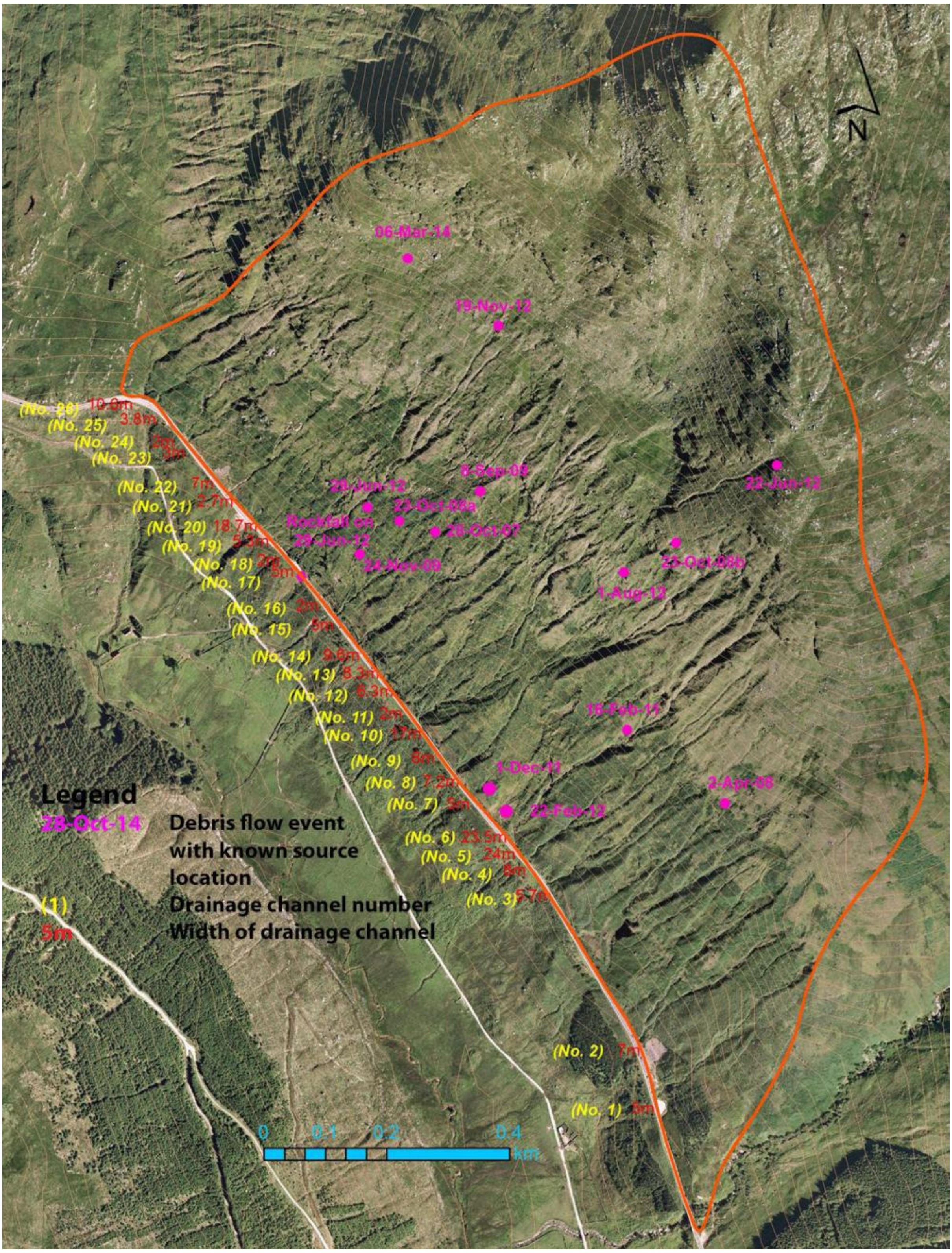


Figure 9. Locations of the drainage channels at the A83 Rest and be Thankful as confirmed by field reconnaissance. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

6.2.1.1 *Scenario A - Vehicle hit by a debris flow*

On reaching the road after leaving the drainage channel, the channelised debris flow deposits, having relatively fluid characteristics, would no longer be confined to the drainage channels and would thus undergo deceleration and spread out on the carriageway. Depending on the magnitude of the flow, some debris or slurry would continue to flow downslope across the road. The road has a 5° downwards gradient at the Rest and be Thankful from north-west to south-east and clearly in practice the debris would spread more widely on the downslope side and less so on the upslope side. However, to simplify the calculations it was assumed that the debris would spread outward equally at 45° on both sides of the channel intersection onto the carriageway.

For evaluating the landslide consequence under this risk scenario that a vehicle is hit by a debris flow, the individual length of the 'Wrong Place$_A$' at each channel was considered as the sum of the width of a debris flow (i.e. average width of drainage channels), the 45° spread of the debris flow on reaching the road, and the average length of a vehicle on either side of the spread (see Figure 10). This assumes a consistent level of damage if any part of the vehicle is hit by the flow. To simplify both the calculations, and the presentation thereof, the individual length of the 'Wrong Place$_A$' at each channel was taken at the middle of the carriageway which is the mean of those for the eastbound and westbound lanes.

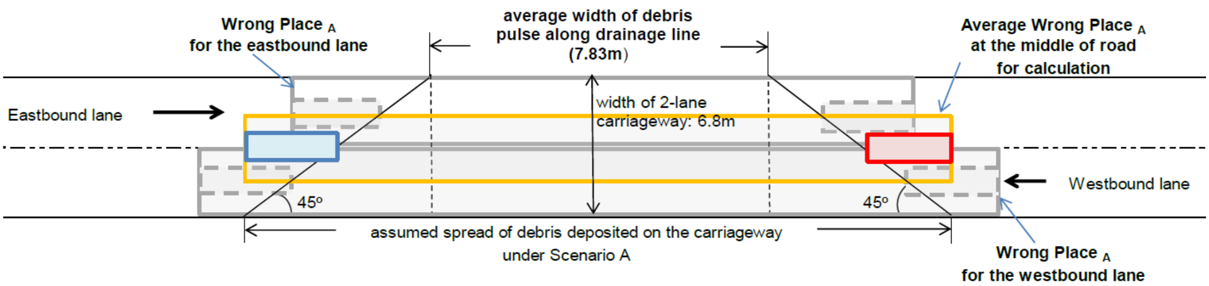


Figure 10. Wrong Place A for Scenario A.

Equation (5) may be modified from Figure 10 such that, *P(Wrong Place$_A$)*, which is speed independent, is:

$$P(Wrong\ Place_A) = \frac{L_v}{N_H(L_s + 2(0.5 \times W_C/\tan 45^o) + 2L_v)} \tag{6}$$

where N_H is the number of stream channels (26 from Table 3),
L_s is the average width of the stream channels (7.83m from Table 3), and
W_C is the width of the carriageway (6.8m from Figure 10 and Anon., 2013).

Which becomes:

$$P(Wrong\ Place_A) = \frac{5.22}{26(7.83 + 2(0.5 \times 6.8/\tan 45^o) + 2 \times 5.22)}$$

$$= \frac{5.22}{651.82} = 0.00801$$

6.2.1.2 *Scenario B - A vehicle hits debris deposited on road*

A vehicle outwith the zone defined by 'Wrong Place $_A$' would not be subjected to direct debris flow impact. However, such a vehicle may hit the debris deposited on the road section if it cannot be stopped in time. The normal vehicle speed limit along the road section is 60miles/h (97km/h), while that for trucks is 40miles/h (64km/h). However, the alignment of the road is such that normal speed tends to be lower on rainy days when debris flow could occur. Hence, an average of 50miles/h (80km/h) was taken as a representative speed for the QRA based on a field observation. Nevertheless, sensitivity analyses for the normal vehicle and truck speeds at 60miles/h (97km/h) and 40miles/h (64km/h) were carried out respectively. The Highway Code (Department for Transport, 2007) suggests that the total stopping distance comprising thinking and braking distances for a car travelling at 50miles/h would be 53m (Table 4). Assuming that the vehicle would not be damaged if it could stop before the deposition, 'Wrong Place$_B$' for this situation was therefore taken as the stopping distance before either side of the debris spread (Figure 11).

Table 4. Typical stopping distances (from Department for Transport, 2007).

Speed (miles/h)	**40**	**50**	**60**
Thinking distance, D_T (m)	12	15	18
Braking distance, D_B (m)	24	38	55
Stopping distance, D_S (m)	36	53	73

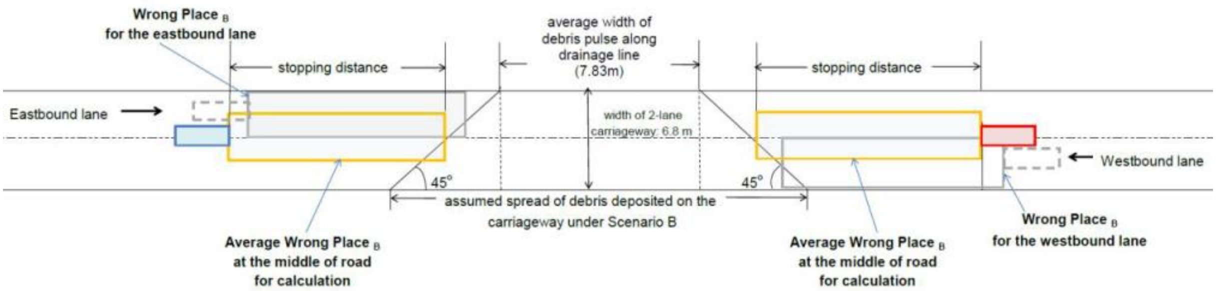


Figure 11. Wrong Place B for Scenario B.

The probably of a vehicle being in the 'Wrong Place$_B$' then becomes as set out in Equation (7) and Table 5:

$$P(Wrong\ Place_B) = \frac{L_v}{N_H . D_S} \tag{7}$$

where N_H and L_v have been previously defined (Equations 5 and 6, respectively), and D_S is the stopping distance at a given speed (the sum of the thinking and braking distances, Table 4).

Which becomes:

$$P(Wrong\ Place_B) = \frac{5.22}{26. D_S} = 0.20077/D_S$$

Table 5. *P(Wrong Place$_B$)*.

Speed (miles/h)	40	50	60
Length of vehicle, L_v (m)		5.22	
Stopping distance, D_S (m)	36	53	73
P(Wrong Place$_B$)	0.00557	0.00379	0.00275

6.2.2 *P(Wrong Time)*

P(Wrong Time) was defined as the temporal probability of an element at risk passing through the zone that debris flow hazards might affect on a single trip per year in the study area. As mentioned in Section 6.2 above, the element at risk (a vehicle) is a moving object and it is exposed to debris flow hazards only while it is this passing through the section of road where the hazards are extant. *P(Wrong Time)* was determined by two parameters (i.e. total length of 'Wrong Place' at the 26 drainage channels in either scenario and the vehicle speed (V_s) to express the exposure time in terms of a fraction of a year) (Equation 8 and Table 6):

$$P(Wrong\ Time_{A\ or\ B}) = \frac{Total\ length\ of\ Wrong\ Place_{A\ or\ B}\ at\ the\ 26\ Drainage\ Channels}{V_s.24\left(\frac{hours}{day}\right).365.25\left(\frac{days}{year}\right)}$$

(8)

Table 6. Calculation of P(Wrong Time) at different vehicle speeds for both Scenarios A and B.

Scenario	**Scenario A**			**Scenario B**		
Vehicle speed, V_s (in miles/h)	40	50	60	40	50	60
Vehicle speed, V_s (in m/h)	64,374	80,467	96,560	64,374	80,467	96,560
Total Length of Wrong Place $_{A\ or\ B}$ at the 26 drainage channels	651.82	651.82	651.82	936	1378	1898
P(Wrong Time$_{A\ or\ B}$)	1.155E-06	9.239E-07	7.699E-07	1.659E-06	1.954E-06	2.242E-06

* 1 mile = 1,609.344m

Note that the Wrong Place under Scenario B is strongly influenced by the stopping distance, which is itself speed-dependent.

6.3 P(Fatality|Hit)

P(Fatality|Hit), referred to as the human vulnerability (i.e. probability of a fatality given a coming together of vehicle and debris), was defined as a quantitative expression of probability of death given an impact with a debris flow event reaching the road. It represents the likelihood of death within the danger zones of the debris flow hazard (i.e. the 'Wrong Place' in either scenario).

AGS (2000; 2007) identified the following factors that determine human vulnerability in the context of landsliding and rock falls:

- Volume of the slide or fall.
- Type of slide, mechanism of slide initiation and velocity of sliding.
- Depth of the slide.
- Whether the debris buries the person(s).
- Whether the person(s) is in the open or enclosed in a vehicle or building.
- Whether the vehicle or building collapses when impacted by debris.
- The type of collapse if the vehicle or building collapses.

Nevertheless, there is limited available literature and damage data on the estimation of vulnerability related to road infrastructure to landslide (Winter et al., 2014b). Relevant previous area-specific studies resulted in a wide spectrum of vulnerability values without a readily promising figure for application, possibly due to the variations in the landslide settings, including topography, landslide types and magnitudes, traffic conditions and vehicle speed, as well as the methodologies in determining the values.

6.3.1 Scenario A - A vehicle being hit by a debris pulse

Given the limited information, expert judgement can play a key role in probability assessment, which has a long tradition in geotechnical practice where the available field and experimental data are often limited (Lee & Jones, 2014). Winter et al. (2014b) developed fragility relationships to represent three damage states (limited damage, serious damage and destroyed) of high-speed (50 to 70 mph or 80 to 110 km/h) and local (<30 mph or 50 km/h) roads to debris flow by relating landslide flow volume to damage probability with the consideration of the qualitative judgements of quantitative probabilities of 47 international experts. The derived fragility curves were compared to known damage states in the Republic of Korea and Scotland, including the A83 Rest and be Thankful site, and resulted in reasonable outcomes.

As noted in Section 5 above, the eight debris flow events with deposition volumes reportedly ranging from $10m^3$ to $500m^3$ at road level and the rock fall case, correspond to the serious damage and destroyed states of the fragility relationships. The deposition volume at road level does not always reflect the actual debris volume as the debris flow events may deposit material above road level and/or may continue downslope by passing through the existing culverts and/or over the road; it was thus considered reasonable to double the reported deposition volume for estimating the debris volume intersecting the road section for comparison with the fragility relationships described above. Using this assumption, the volume of the second largest recorded debris flow event occurred on 8 September 2009[1] and the total mobilised volume of material was

[1] This is considered to be a good representation of the events that typically occur at the A83 Rest and be Thankful site and is well within one order of magnitude of most of the major events and the largest event that occurred on 28 October 2014.

estimated to be around 1000m^3 (around 500m^3 at road level). By correlating this landslide volume to the fragility curve for high-speed roads (Winter et al., 2014b) (Figure 12), the conditional probabilities for no damage, limited, serious and destroyed damage states are around 0.7, 0.1(0.3), 0.18(0.2) and 0.02(0.02) (the probabilities of the damage states being met or exceeded are given in brackets) respectively.

These probabilities relate purely to the damage likely to be imposed on the infrastructure. The aggregate conditional probability of 0.2 under the serious and destroyed damage states to the road section is similar to the vulnerability value of 0.3 for destruction of roads by hillslope and distal debris flow given by Michael-Leiba et al. (2002).

The vulnerability of vehicles to damage in a similar situation is likely to be close to, or approaching unity even when the debris is very slow moving. If the vehicle were to be crushed or fully buried by a sizeable landslide then the vulnerability of the occupants might well be also close to unity (e.g. Wilson et al., 2005). Lee (2009) also suggested a vulnerability of 1.0 for people (walking) being hit by rockfall; this is reasonable as the subjects have no protection from the rock. Finlay et al. (1999) suggested that a vulnerability for passengers in a vehicle impacted by debris flow of between 0.9 to 1.0 would be appropriate if the vehicle were to be buried or crushed[2].

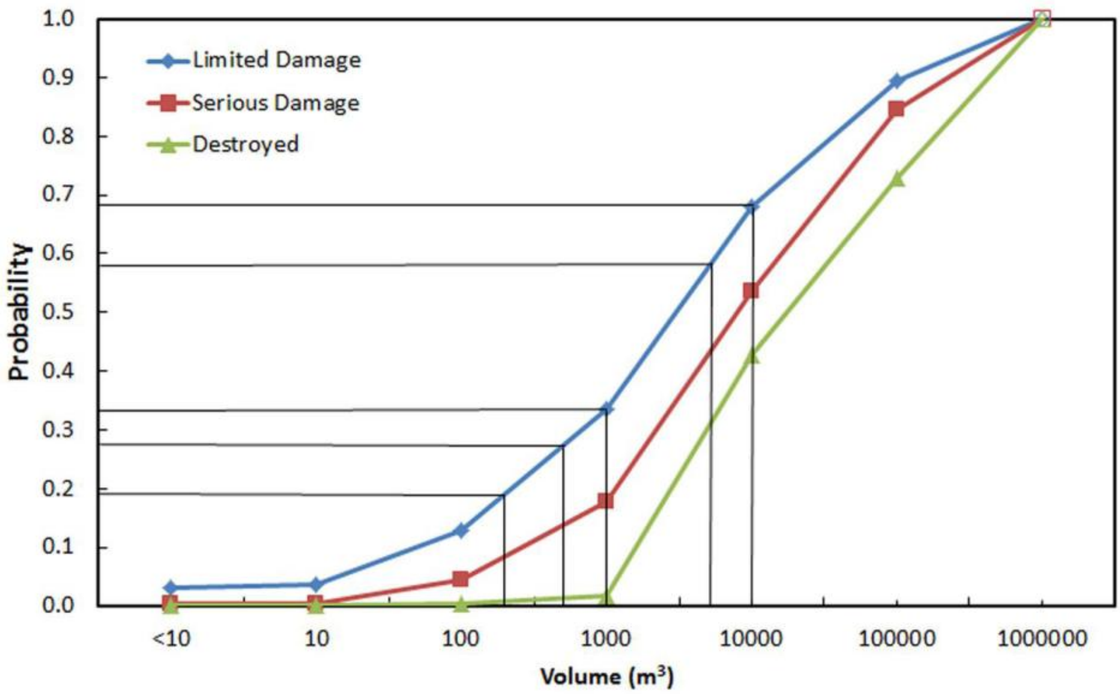


Figure 12. Fragility curve for a high-speed road (from Winter et al., 2014b).

However, when people are within a vehicle that is impacted by a rockfall or debris flow the vehicle may afford some degree of protection, particularly if the impact is to a part of the vehicle relatively remote from the human contents. The second author has near-direct (second-hand) experience of rockfall hitting a vehicle in Jamaica, an incident in

[2] Notwithstanding this there is a clear philosophical conundrum with assigning a probability of unity (1,.0) to such events in that this is a statement of the certainty of a consequence given an event; in this context it is considered that a 'x-nines' type approach (0.9, 0.99, 0.999, 0.9999, 0.99999 etc) is perhaps more consistent with reality. Similar arguments may be made against many assignations of a probability of zero (0.0) for which a 'y-zeros' (0.1, 0.01, 0.001, 0.0001, 0.00001, etc) approach might be preferable.

which the vehicle occupant was relatively uninjured albeit somewhat shaken. In terms of debris flow there have been a number of analogous cases in Scotland including when vehicles were damaged by debris at the A887 (1998), the A9 in 2004 (Winter et al., 2005) and, to a lesser degree, the A85 in 2004.

In addition, complete burial/crushing seems rather unlikely in the case of a 1,000m^3 flow, and (as noted above) the vehicle itself affords some protection to the occupants and some of the energy of the flow will be absorbed by movement of the vehicle. Michael-Leiba et al. (2002) suggested a vulnerability value for people (effectively pedestrians) to proximal debris fans of 0.5, while Finlay et al. (1999) suggested a vulnerability of 0 to 0.3 if the vehicle struck by a debris flow is damaged only. Interpolating data presented by Wilson et al. (2005) for a 1,000m^3 debris flow gives a vulnerability value of 0.23 for vehicle passengers to a debris flow impact. In this context a vulnerability value (i.e. $P(\text{Fatality}|\text{Hit}_A)$) of 0.25 for passengers in a vehicle seems appropriate for the purpose of this QRA taking account of the values suggested by both Finlay et al. (1999) and Wilson et al (2005).

6.3.2 Scenario B - A vehicle running into debris deposited on road

For the second scenario, in which a vehicle runs into the debris deposited on the road if the driver could not stop the vehicle in time, the degree of damage is very much speed dependent as is the probability of fatality of the vehicle occupants. Wilson et al. (2005) determined a site-specific vulnerability value of 0.003 for persons in a vehicle hitting landslide debris with a magnitude of 300 m^3 to 3000m^3 on a road on a coastal hillslope in Australia, using a workshop to capture expert judgement.

It was observed from a review of the records and photographs of the debris flow events along the Rest and be Thankful road section and other areas of Scotland that:

- The boulders tend to remain in the central portion of the deposits on the road, immediately below the drainage channel without flowing out towards the edges.
- Vehicles are likely to ride up over the edges of debris flow deposits on impact.
- The wet and fine portions of the deposition at the edges were found to be effective at retarding vehicles on impact.

The section of road at the Rest and be Thankful is relatively straight (see Figure 1) with a gentle gradient of 5^o. Based on site observation during the hours of daylight on a rainy day, the sightline was experienced to be 200m, such that the driver should notice the presence of deposits on the road from 200m to 0m distance. During the hours of darkness, the visibility from a vehicle depends on the light source used. The visibility under dipped and main beam headlights was tested to be approximately 75m and 150m respectively. Assuming an equal use of either headlight sources among the road users, the average night-time visibility of drivers would be the average of both situations, i.e. 112.5m. The assumption that daylight and darkness are in approximately equal proportion over a period of a year was also adopted giving an average sightline of 156.25m.

The probability of a vehicle hitting debris depends upon whether or not the driver could stop the vehicle in time. If the impact does occur, the human vulnerability would depend on the vehicle impact speed. Thus, the variation in speed from the initial vehicle speed (40mph, 50 mph and 60mph) reducing to 0mph within in the UK Highway Code stopping distance (comprising the sum of the thinking and braking distances), within the 156.25m mean sightline have been determined (Figure 13).

Subsequent discussions with TRL specialists on vehicle impact, based on the variation in vehicle speed within the mean sightline, led to the development of a speed-dependent human vulnerability curve. It was considered that the loose debris at road level could effectively act as a trap to decelerate a vehicle with impact speed lower than 20 to 30mph which would then be stopped before reaching the boulders in the central portion of the deposition. This effect, combined with in-vehicle features such as airbags and seatbelt pre-tensioners, would result in a minimal probability of injury and a very low probability of fatality. If the impact speed exceeds 20 to 30mph, the probability of the vehicle running over the deposits is increased due to the higher kinetic energy. However, the ramped shape of the deposits and the boulders in the central portion were considered likely to encourage a vehicle to launch and/or roll over after hitting the debris. Hence, the higher the impact speed would give rise to a higher risk of vehicle damage and therefore the human vulnerability.

Accordingly, the initial $P(\text{Fatality}|\text{Hit}_B)$ in a vehicle travelling at the speed limit of 60mph within the 156.25m sightline under Scenario B was assumed to have a value of 0.2. Depending on the initial vehicle speed, the initial human vulnerability values of 0.15, 0.1, 0.05 and 0.001 were assumed for 50, 40, 30 and 20mph on a more or less linear relation, and the a vulnerability of 0.0001 at 10mph and vulnerability was designated as zero at 0mph (Figure 14).

It was assumed that the vehicle speed would remain constant at the initial speed through the thinking distance (time) and then reduce towards zero through the braking distance (time) (Figure 13). $P(\text{Fatality}|\text{Hit}_B)$ should thus remain constant (given an impact) through the thinking distance and gradually reduce to zero through the braking distance as the vehicle is brought to a standstill. $P(\text{Fatality}|\text{Hit}_B)$ would be zero for the remaining part of the mean sightline beyond the stopping distance (as the vehicle is stationary).

Using this logic, the average $P(\text{Fatality}|\text{Hit}_B)$ within the average sightline for each initial vehicle speed of 40, 50 and 60 mph was normalised as 0.01536, 0.03264 and 0.05824 respectively (Table 7). These figures are somewhat higher, around one order of magnitude, than that reported by Wilson et al. (2005), 0.003, but do have the advantage of having been validated by experts in vehicle impact.

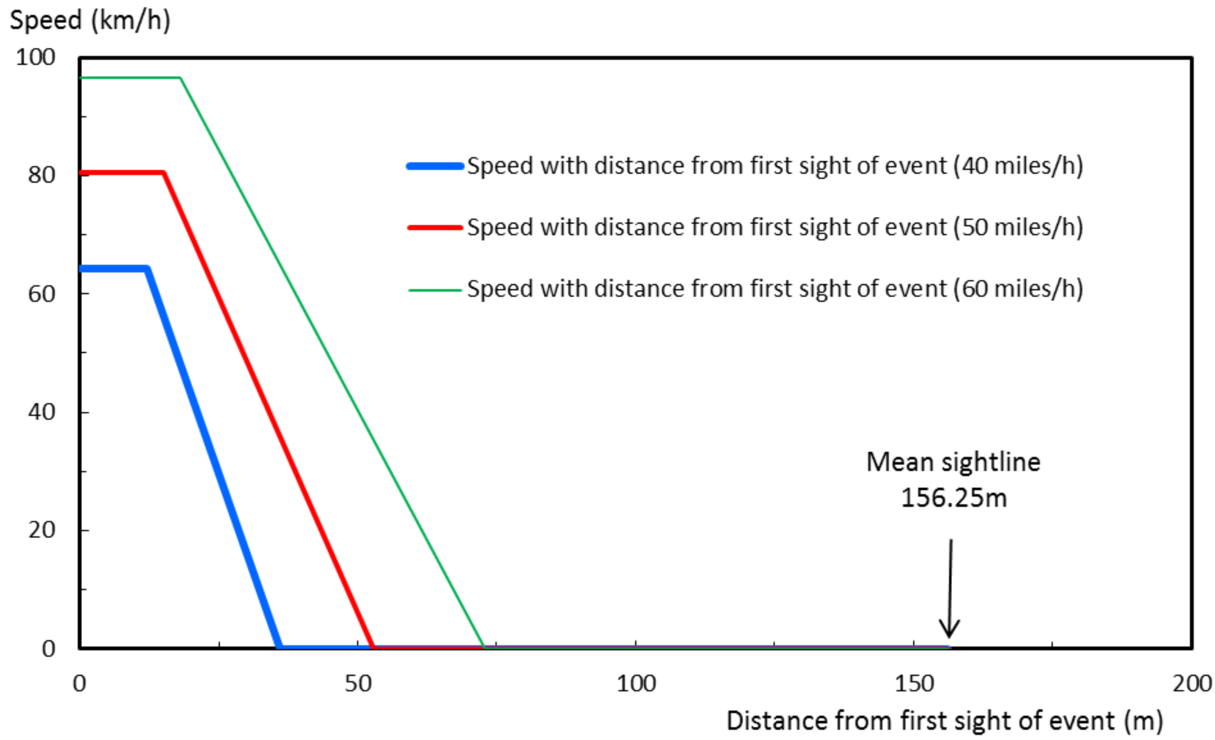


Figure 13. Vehicle speed variation within the 156.25m mean sightline for starting speeds of 40, 50 and 60 miles/h.

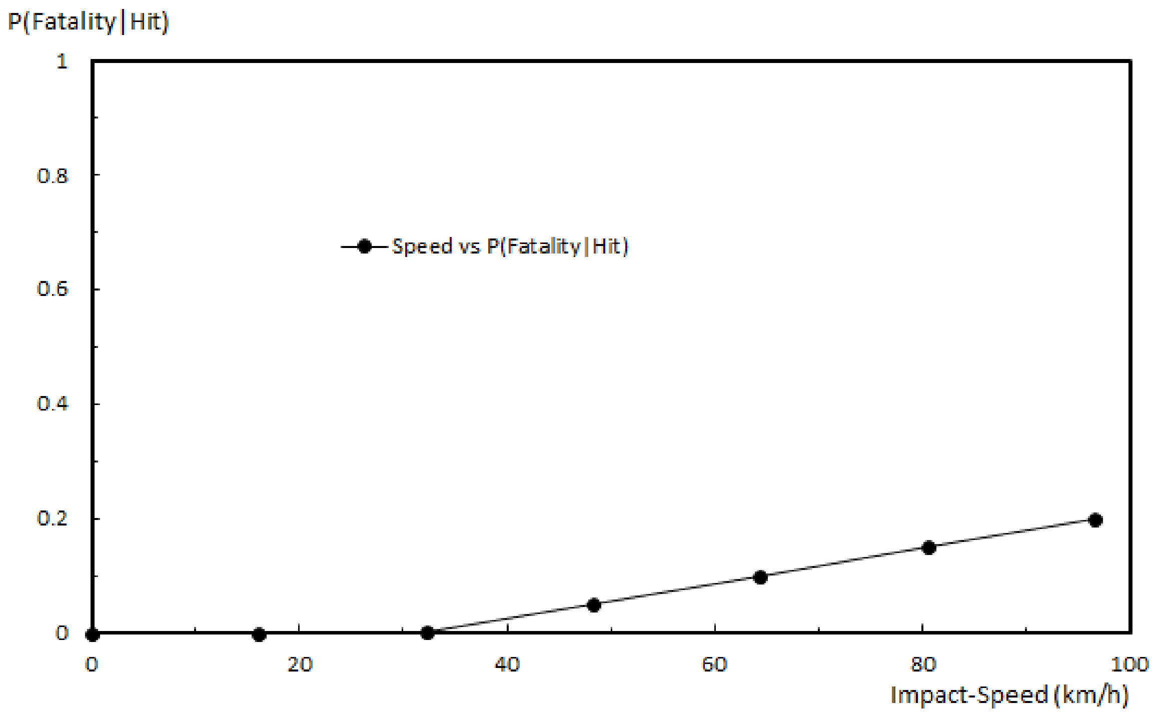


Figure 14. P(Fatality|Hit $_B$) at different initial vehicle speeds immediately prior to stopping.

Table 7. Calculation of mean P(Fatality|Hit $_B$).

Initial speed (km/h)	Distance from Event (m)	Vehicle Speed (km/h)	Assumed human vulnerability	Comments	P(Fatality| Hit $_B$)
64 (40 miles/h)	0	64	0.1	Initial vehicle speed at 64km/h	0.01536
	12	64	0.1	Thinking Distance at 64km/h	
	36	0	0	Total stopping distance from 64km/h to 0km/h	
	156.25	0	0	Assumed length of total sightline	
80 (50 miles/h)	0	80	0.15	Initial vehicle speed at 80km/h	0.03264
	15	80	0.15	Thinking Distance at 80km/h	
	53	0	0	Total stopping distance from 80km/h to 0km/h	
	156.25	0	0	Assumed length of total sightline	
97 (60 miles/h)	0	97	0.2	Initial vehicle speed at 97km/h	0.05824
	18	97	0.2	Thinking Distance at 97km/h	
	73	0	0	Total stopping distance from 97km/h to 0km/h	
	156.25	0	0	Assumed length of total sightline	

6.4 Personal Individual Risk

Given the mobility of the elements at risk (vehicles and their occupants) it is clear that the concepts of 'Individual Risk' (ERM, 1998) and of 'Location-specific individual risk' (Lee & Jones, 2014), representing the risk for a theoretical individual exposed to a hazard for 100% of the time (i.e. 24 hours per day, 365 days per year), are not relevant to this QRA study. In contrast the 'Personal Individual Risk (PIR)' (ERM, 1998) or 'Individual-specific individual risk (ISIR)' (Lee & Jones, 2014), taking into account the temporal and spatial conditions of exposure of the elements at risk to the hazard (i.e. present at different locations during different periods), is appropriate.

As a road user on a single trip in the study area would be subjected to both risk scenarios A and B, the total PIR is therefore the sum of the PIR under both scenarios. Tables 8 and 9 demonstrate the PIR calculation based on the workflow of Lee & Jones (2014) of a particular person under each risk scenario at different vehicle speeds on a single trip along the A83 Rest and be Thankful per year, which is summarised by Equations (9) and (10). The total PIR (single trip) of an individual in a vehicle at 50 mph is 1.742×10^{-9} per year.

$$P(Individual\ vehicle\ hit\ per\ year) = P(Event) \times P(Hit|Event) \tag{9}$$

$$P(Single\ trip\ per\ year) = P(Individual\ vehicle\ hit\ per\ year) \times P(Fatality|Event) \tag{10}$$

Table 8. Personal Individual Risk under Scenarios A and B on a single trip along the A83 Rest and be Thankful.

Probability	Details	Scenario A Initial Vehicle Speed (mph)			Scenario B Initial Vehicle Speed (mph)		
		40	**50**	**60**	**40**	**50**	**60**
P(Event)	Probability of annual occurrence of debris flow	0.83	0.83	0.83	0.83	0.83	0.83
P(Wrong Place)	Spatial probability of the vehicle within all 'Wrong Place' along the 26 drainage channels	8.006E-03	8.006E-03	8.006E-03	5.574E-03	3.786E-03	2.749E-03
P(Wrong Time)	Temporal probability of the vehicle within all 'Wrong Place' along the 26 drainage channels	1.155E-06	9.239E-07	7.699E-07	1.659E-06	1.954E-06	2.242E-06
P(Hit|Event)	P(Wrong Place)× P(Wrong Time)	9.246E-09	7.397E-09	6.164E-09	9.246E-09	7.397E-09	6.164E-09
P(Individual vehicle hit)	P(Event) × P(Hit|Event)	7.705E-09	6.164E-09	5.137E-09	7.705E-09	6.164E-09	5.137E-09
P(Fatality|Hit)		0.25	0.25	0.25	0.01536	0.03264	0.05824
PIR (Single trip per year)	P(Individual vehicle hit per year)× P(Fatality|Hit)	1.926E-09	1.541E-09	1.284E-09	1.184E-10	2.012E-10	2.992E-10

Table 9. Personal Individual Risk under Scenarios A and B on a single trip along the A83 Rest and be Thankful.

	Initial Vehicle Speed (mph) 40	50	60
PIR (Single trip under Scenario A per year)	1.926E-09	1.541E-09	1.284E-09
PIR (Single trip under Scenario B per year)	1.184E-10	2.012E-10	2.992E-10
Total PIR (single trip)/year	2.045E-09	1.742E-09	1.583E-09

Table 8 shows that P(Hit|Event) for risk scenarios A and B are identical given their different P(Wrong Place) and P(Wrong Time) values. It was found that the product of P(Wrong Place) and P(Wrong Time) would become the quotient of the vehicle length divided by vehicle speed in terms of year. Coincidently, this was also the case in determining the temporal spatial probability in other similar QRA studies such as Bunce et al. (1997) and Fell et al. (2005).

The PIR results determined with reference to the workflow of Lee & Jones (2014) were benchmarked with those determined using the method proposed by Bunce et al. (1997). They used the binomial theorem to determine the probabilities of impacts and no impact, and the outcomes of both approach were nearly identical; Table 10 gives a comparison of the two approaches to the determination of the PIR (single trip under Scenario A per year). This gives considerable support to the methodology and analytical method used in this study to examine and estimate the initiating events, hazards and consequences.

Table 10. Personal Individual Risk under Scenario A on a single trip along the A83 Rest and be Thankful using the approach in Bunce et al. (1997) for comparison.

Probability	Description	Initial Vehicle Speed (mph)		
		40	**50**	**60**
Nr	Probability of annual occurrence of debris flow: i.e. P(Event)	0.83	0.83	0.83
P(S:H)	Probability that a vehicle occupies the portion of the road section affected by a debris flow	8.006E-03	8.006E-03	8.006E-03
P(T:S)	Probability that a vehicle occupies the width of debris pulse at the same time as it falls towards the road section	1.155E-06	9.239E-07	7.699E-07
P(S)	Probability of one or more vehicles being hit (in an year) $P(S) = 1 - (1 - P(S{:}H))^{Nr}$	6.676E-03	6.676E-03	6.676E-03
P(L:T)	Probability of death given temporal impact, i.e. P(Fatality|Hit $_A$)	0.25	0.25	0.25
PAV	Annual probability of an accident to a particular vehicle P(S) x P(T:S)	7.710E-09	6.168E-09	5.140E-09
PDI	Probability of a death on an individual trip, i.e. PIR (Single trip under Scenario A) PAV x P(L:T)	1.928E-09	1.542E-09	1.285E-09
For comparison (this study): PIR (single trip under Scenario A)		**1.926E-09**	**1.541E-09**	**1.284E-09**

Individual drivers will use the section of road at the A83 Rest and be Thankful differing numbers of times. The PIR (single trip per year) (Table 9) is really only applicable to someone that uses the road once per year: for example, a tourist passing through the section of road and then returning by a different route. Of course, it may also be considered as the risk to which an individual is exposed on each journey through the Rest and be Thankful. Notwithstanding this, road users that use the road more frequently will be exposed to a commensurately greater level of risk.

In order to account for those who use the route more frequently, the travel patterns of daily commuters and local logistics truck drivers, such as those working in the forestry sector, were considered. The maximum PIR for each of these two types of road users (assuming single vehicle occupancy) is calculated in Table 11.

Table 11. Personal individual risk (PIR) of individuals most at risk.

Individual most at risk	Commuters	Logistics truck drivers
Travel pattern	One daily return trip on five days in 47 weeks per year	Two daily return trips on five days in 47 weeks per year
No. of journeys per year	2 x 5 x 47 = 470	4 x 5 x 47 = 940
Vehicle speed	60mph	40mph
Total PIR of fatality (single trip per year)	1.583E-09	2.045E-09
Maximum PIR of fatality = Total PIR of fatality (single trip per year) x No. of journey per year	7.440E-07	1.922E-06

The results show that the PIR levels of these two types of road user (around 1 in 1.35 million, commuters, and 1 in 520,000, logistics truck drivers) are less than the tolerable criteria of 10^{-4} fatalities per year (1 in 10,000) for members of the public in the UK who have a risk imposed on them (HSE, 2001; Lee & Jones, 2014). This same level of tolerable limit is also applied in many parts of the world, such as Hong Kong (Ho et al., 2000) and Australia (AGS, 2007). It is considered that the travel pattern for the logistics truck driver, and the associated risk, is at the high end of the level of risk that road users will be subject to at the Rest and be Thankful.

6.5 Societal Risk

Societal risk is a measure of the overall risk associated with a situation or system (ERM, 1998). It is the frequency and the number of people suffering a given level of harm from the realisation of specified hazards (IChemE, 1992), and a measure of the likely impact of hazard scenarios, not just on a particular type of individual (as in the case of personal individual risk) but on all individuals who may be exposed to the risk. The societal risk of fatality to road users at the A83 Rest and be Thankful was determined from Equation (11), which is taken from Lee and Jones (2014).

$$Societal\ risk = Individual\ risk \times Exposed\ population \tag{11}$$

The specific group exposed to the debris flow hazards are all road users in the study area, and their population size was determined based on official traffic records. As mentioned in Section 6.2.1 above, the AADF at the A83 Rest and be Thankful was 4,039 in 2010, corresponding to an annual flow volume of 1,475,245 vehicles by Equation (12) below:

$$Annual\ traffic\ flow = AADF \times 365.25(days/year) \tag{12}$$

In other words, the societal risk of a 'hit' to any vehicle at the A83 Rest and be Thankful per year, P(Any vehicle hit) is the product of P(Individual vehicle hit) and annual traffic flow.

The AADF statistics were analysed to determine the total number of each of the six constituent vehicle types in a year (Table 12). Single occupancy was assumed for CCE1-motorbike. For CCE2-car/van and CCE3-car+trailer, the occupancy was calculated based on the statistic classes (from 'One' to 'Five or more') in the AADF, with an average sum of six assumed for the class of 'Five or more', taking into account the occupancy from five-seater to eight-seater vehicles. The occupancies of CCE4-LGV/rigid HGV and CCE5-HGV were assumed to be two, considering the presence of a driver and a worker in most cases. For CCE6-bus, occupancy of 56 was adopted based on the relevant models of bus and coach.

Table 12. Numbers of people at risk in different vehicle types.

Vehicle type	Proportion of vehicle type	AADF Sub-category (where applicable)	Vehicle occupancy	Proportion of vehicle occupancy	Equivalent no. of vehicles travelling along the A83 RabT per year
CCE1-motorbike	1.55%	N/A	1	1.55%	22,878
CCE2-car/van	87.98%	One	1	56.31%	830,668
		Two	2	22.35%	329,671
		Three	3	6.07%	89,556
		Four	4	2.46%	36,342
		Five or More	6	0.79%	11,681
CCE3-car+trailer	0.85%	One	1	0.59%	8,715
		Two	2	0.23%	3,459
		Three	3	0.06%	940
		Four	4	0.03%	381
		Five or More	6	0.01%	123
CCE4-LGV/rigid HGV	5.77%	N/A	2	5.77%	85,175
CCE5-HGV	3.72%	N/A	2	3.72%	54,834
CCE6-bus	0.06%	N/A	56	0.06%	823

Assuming that the exposure to the risks associated with the debris flow hazards in the study area is equal for all vehicles, six consequence classes based on vehicle occupancy (1, 2, 3, 4, 6 and 56) were re-grouped from the statistics in Table 12 and the number of vehicles, annually, within each consequence class was calculated for Scenarios A and B. The number of probable fatalities (N) of each consequence class under Scenarios A and B was determined by multiplying the vehicle occupancy by P(Fatality|Hit).

Two definitions of N in the presentation of F-N curves were identified. Lee & Jones (2014) suggested that N should represent the probable fatalities: i.e. the product of the exposed population and P(Fatality|Hit), whereas the other adopted the number of people at risk: i.e. unfactored exposed population as N and considered the vulnerability factor in the calculation of F such as in Wong et al. (2004). The two approaches are considered in the following sections.

6.5.1 The approach of Lee & Jones (2014)

The calculations described below follow the approach set-out by Lee & Jones (2014) and are summarised in Tables 13 and 14.

Table 13. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario A based on the approach of Lee and Jones (2014). The consequence class simply refers to the different levels of vehicle occupancy.

Conse-quence class	No. of vehicles [2]	Vehicle occupancy [3]	P[Fatality| Hit $_A$] [4]	Probable fatalities in a 'hit' (N) [5]= [3] x [4]	Potential loss of life (PLL) per year [6] = [1]x[2]x[5]	Frequency of occurrence of N fatalities (f) [7]= [1]x[2]	Cumulative frequency of occurrence of N or more fatalities (F)
A1	862,260	1	0.25	0.25	1.329E-03	5.315E-03	9.094E-03
A2	473,139	2	0.25	0.5	1.458E-03	2.916E-03	3.779E-03
A3	90,496	3	0.25	0.75	4.184E-04	5.578E-04	8.620E-04
A4	36,723	4	0.25	1	2.264E-04	2.264E-04	3.042E-04
A5	11,804	6	0.25	1.5	1.091E-04	7.276E-05	7.783E-05
A6	823	56	0.25	14	7.098E-05	5.070E-06	5.070E-06
[1] P(Individual vehicle hit) = 6.164E-09 /year.				Total	3.612E-03		

Table 14. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario B based on the approach of Lee & Jones (2014). The consequence class simply refers to the different levels of vehicle occupancy.

Conse-quence class	No. of vehicles [2]	Vehicle occupancy [3]	P[Fatality| Hit $_B$] [4]	Probable fatalities in a 'hit' (N) [5]= [3] x [4]	Potential loss of life (PLL) per year [6] = [1]x[2]x[5]	Frequency of occurrence of N fatalities [7]= [1]x[2]	Cumulative frequency of occurrence of N or more fatalities (F)
B1	862,260	1	0.03264	0.03264	1.735E-04	5.315E-03	9.094E-03
B2	473,139	2	0.03264	0.06528	1.904E-04	2.916E-03	3.779E-03
B3	90,496	3	0.03264	0.09792	5.462E-05	5.578E-04	8.620E-04
B4	36,723	4	0.03264	0.13056	2.955E-05	2.264E-04	3.042E-04
B5	11,804	6	0.03264	0.19584	1.425E-05	7.276E-05	7.783E-05
B6	823	56	0.03264	1.82784	9.267E-06	5.070E-06	5.070E-06
[1] P(Individual vehicle hit) = 6.164E-09/year.				Total	4.716E-04		

Then, based on Equation (11), the societal risk in terms of annual potential loss of life (PLL) was calculated as the product of P(Individual vehicle hit), number of vehicles and probable fatalities (N) of each consequence class (Tables 13 and 14).

The frequency of occurrence of N fatalities (f) was calculated by multiplying P(Individual vehicle hit) by the number of vehicles of the respective consequence classes. The cumulative frequency of occurrence of N or more fatalities (F), was next calculated from the values of f (Tables 13 and 14), and F-N curves representing the societal risk of scenarios A, B, and A plus B plotted in Figure 15. This, widely used, diagram includes zones in which the risk level is considered to be Broadly Acceptable, Unacceptable, As

Low As Reasonably Practicable (ALARP) and a zone in which Intense Scrutiny of the risks is generally required.

The F-N diagram was introduced to landslide risk practice by the Hong Kong SAR Geotechnical Engineering Office (Ho et al. 2000; Lee & Jones 2014). The F-N diagram is also used by the UK Health & Safety Executive (Ale 2005), and Quinn & Davies (2004) give an example of the development of the development of alternative, more rapid, methods of the determination of societal risk from chemical processes. The concept of ALARP is fundamental to this and the line that defines the boundary between risks that are ALARP and those that are considered 'Unacceptable' mirrors that used by, for example, BC Hydro in Canada for risks related to the dams that it owns and operates (Lee & Jones 2014). The term 'Unacceptable' effectively defines those risks that are considered not to be as low as reasonably practicable and which society should not bear and should therefore be subject to risk reduction measures (see also Section 7). It is perhaps interesting that BC Hydro use 'tolerable' and 'intolerable' in place of 'Broadly Acceptable' and 'Unacceptable', reflecting the view that people do not accept risks but tolerate them (Lee & Jones 2014).

The societal risk in terms of PLL under Scenarios A, B and A plus B is summarised in Table 15.

Table 15. Societal risk in terms of annual Potential Loss of Life (PLL) for vehicle speed at 50mph based on the approach of Lee & Jones (2014).

	Scenario A	Scenario B	Scenarios A + B
Potential Loss of Life (PLL)/year	3.612E-03	4.716E-04	4.083E-03

It should be noted that the above (Lee & Jones, 2014) approach taken to determining PLL, averages many important factors such as P(Fatality|Hit), AADF and length of vehicle. Therefore some variation in the numbers reported should be anticipated. In particular, the variation in road user characteristics (e.g. the old, the young and other vulnerable road users), seasonal variations in traffic flows between the peak and non-peak seasons, and the seasonal variation in the proportions of different vehicle types are not fully-developed. Nevertheless, when compared with the scale of the debris flow events and the dimensions of the elements at risk, it is considered that this approach to the quantification of the risk is reasonable. In addition, the F-N curves developed enable differentiation of the risk level of road users in different consequence classes based on vehicle occupancy, which is the best estimate of the real situation based on the available information.

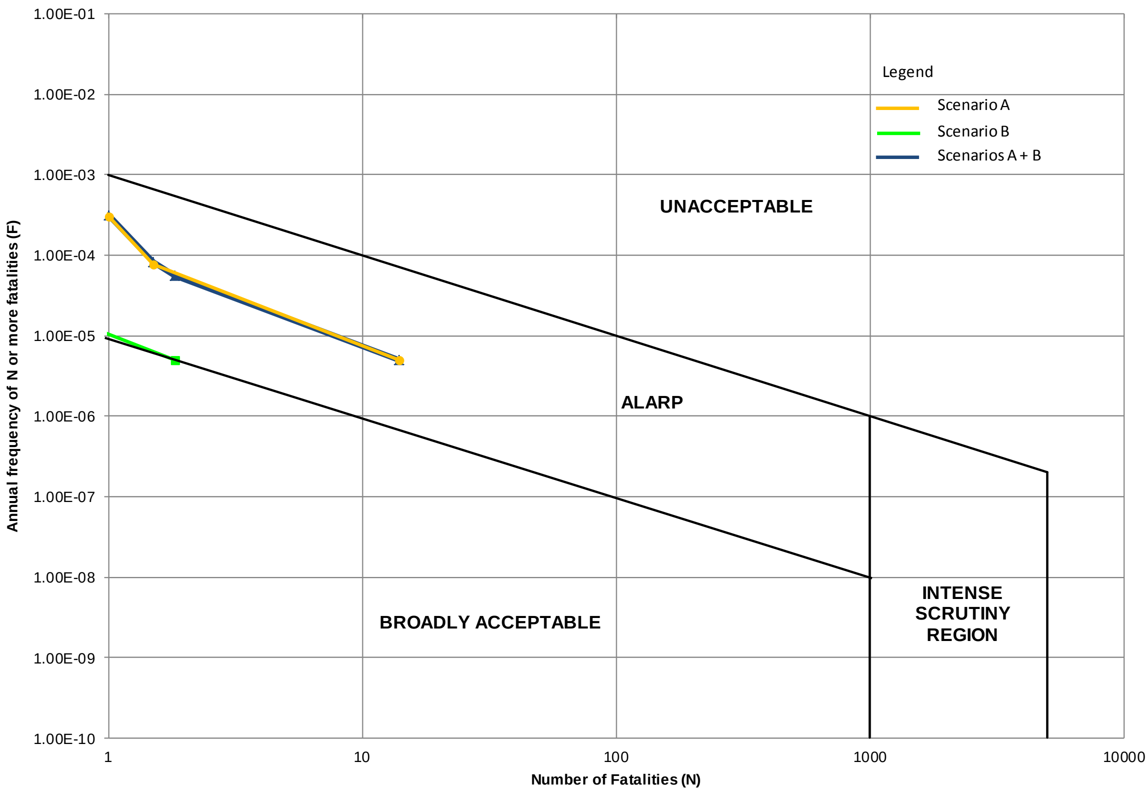


Figure 15. F-N Curves based on the approach of Lee and Jones (2014). Note that the line for Scenarios A and B combined is partly obscured by that for Scenario A.

6.5.2 The approach of Wong et al. (2004)

A F-N plot for vehicle speed at 50mph using the approach of Wong et al. (2004) was prepared for comparison (Tables 16 and 17, Figure 16).

Table 16. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario A using the approach of Wong et al. (2004)

Consequence situation	No. of people including driver in a vehicle (N) [2]	P(Fatality| Hit $_A$) [3]	No. of vehicles [4]	Frequency of occurrence of N fatalities [5] = [1]×[3]×[4]	Cumulative frequency of occurrence of N or more fatalities (F) [6]
A1	1	0.25	862,260	1.329E-03	2.273E-03
A2	2	0.25	473,139	7.291E-04	9.446E-04
A3	3	0.25	90,496	1.395E-04	2.155E-04
A4	4	0.25	36,723	5.659E-05	7.605E-05
A5	6	0.25	11,804	1.819E-05	1.946E-05
A6	56	0.25	823	1.268E-06	1.268E-06

[1] P(Individual vehicle hit) = 6.164E-09 /year

Table 17. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario B using the approach of Wong et al. (2004).

Consequence situation	No. of people including driver in a vehicle (N) [2]	P(Fatality| Hit $_B$) [3]	No. of vehicles [4]	Frequency of occurrence of N fatalities [5] = [1]×[3]×[4]	Cumulative frequency of occurrence of N or more fatalities (F) [6]
B1	1	0.03264	862,260	1.735E-04	2.968E-04
B2	2	0.03264	473,139	9.519E-05	1.233E-04
B3	3	0.03264	90,496	1.821E-05	2.814E-05
B4	4	0.03264	36,723	7.389E-06	9.929E-06
B5	6	0.03264	11,804	2.375E-06	2.540E-06
B6	56	0.03264	823	1.655E-07	1.655E-07

[1] P(Individual vehicle hit) = 6.164E-09 /year

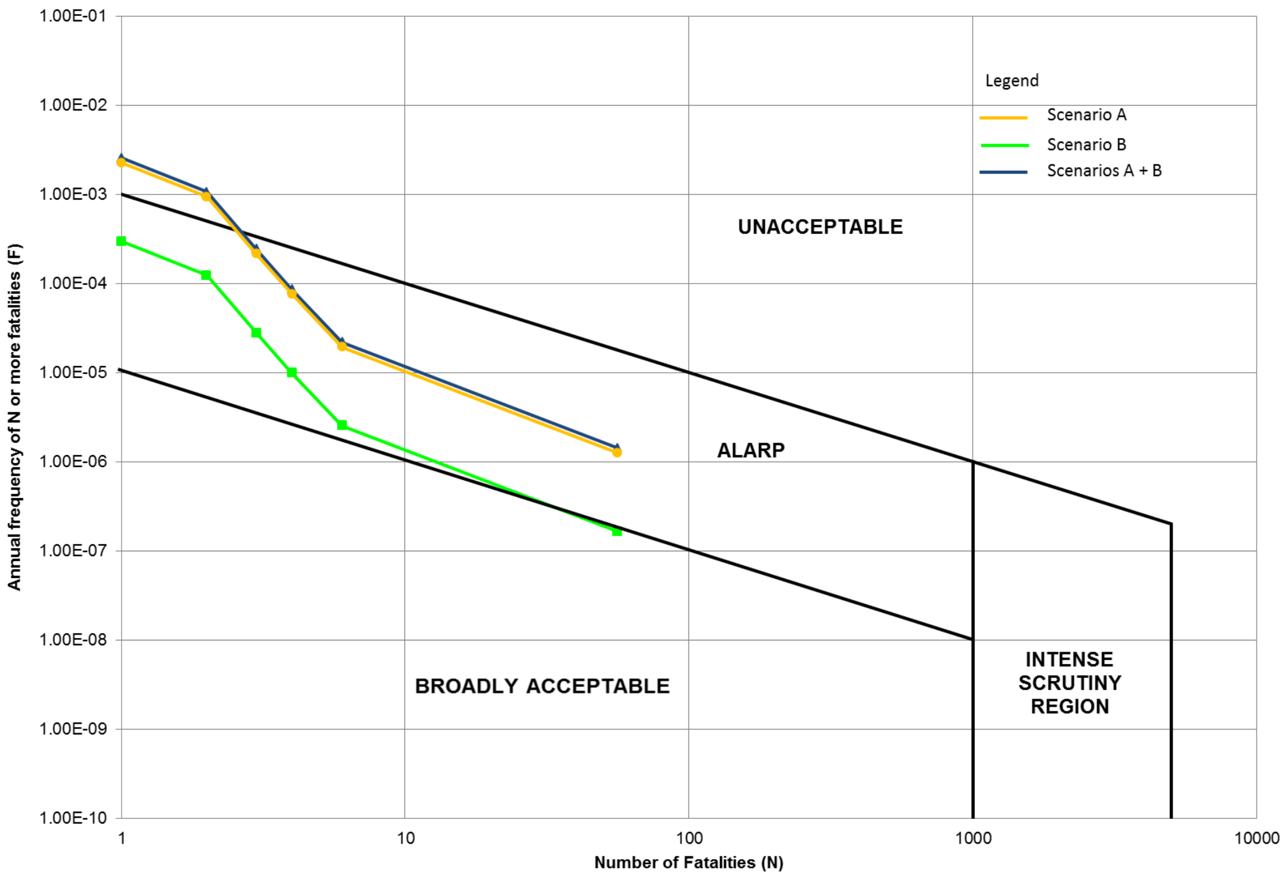


Figure 16. F-N Curves based on the approach of Wong et al. (2004).

6.6 Summary

Neither of the two approaches to determining societal risk is considered to be more correct than the other. However, the Lee & Jones (2014) approach produces values of N<1 which do not plot on the conventional F-N diagram. While the diagram could be extended to lower values of N, assumptions would need to be made regarding the extrapolation of the boundaries between the Broadly Acceptable, ALARP and Unacceptable zones. It is not entirely certain that a straightforward extension of these as straight lines would be appropriate. Indeed, in Hong Kong the Broadly Acceptable PIR (i.e. a single fatality) is set at 10^{-5} per year (or less) for new infrastructure and development and 10^{-4} per year (or less) for existing infrastructure and development (ERM, 1998). It is noteworthy that both methods plot broadly in the ALARP zone albeit that the Wong et al (2004) approach plots just into the Unacceptable risk zone for N values of 1 and 2 with the values for N = 3 and above being in the ALARP zone (Figure 16).

7 Management and Mitigation Measures

In response to the dynamic hillslope in the study area and the recommendations put forward by Winter et al. (2009), Transport Scotland has introduced a range of management and mitigation measures at the A83 Rest and be Thankful to reduce the risk posed to road users and to lessen the socio-economic impacts on the communities in the region. These include implementing a wig-wag system that provides warning of periods of higher risk (high rainfall) (Winter et al., 2013) and the installation of debris fences and a new catch pit. In addition, preventive ecological and related landslide mitigation options are being considered as supplementary measures to improve the stability of the slope-forming materials (Winter & Corby, 2012). The effectiveness of such mitigation measures in reducing the debris flow risk to road users along the 1.7 km-long road section in the study area is shown in an event tree diagram for 'bow-tie' risk assessment (Figure 17).

7.1 Flexible Barriers and Catch Pit

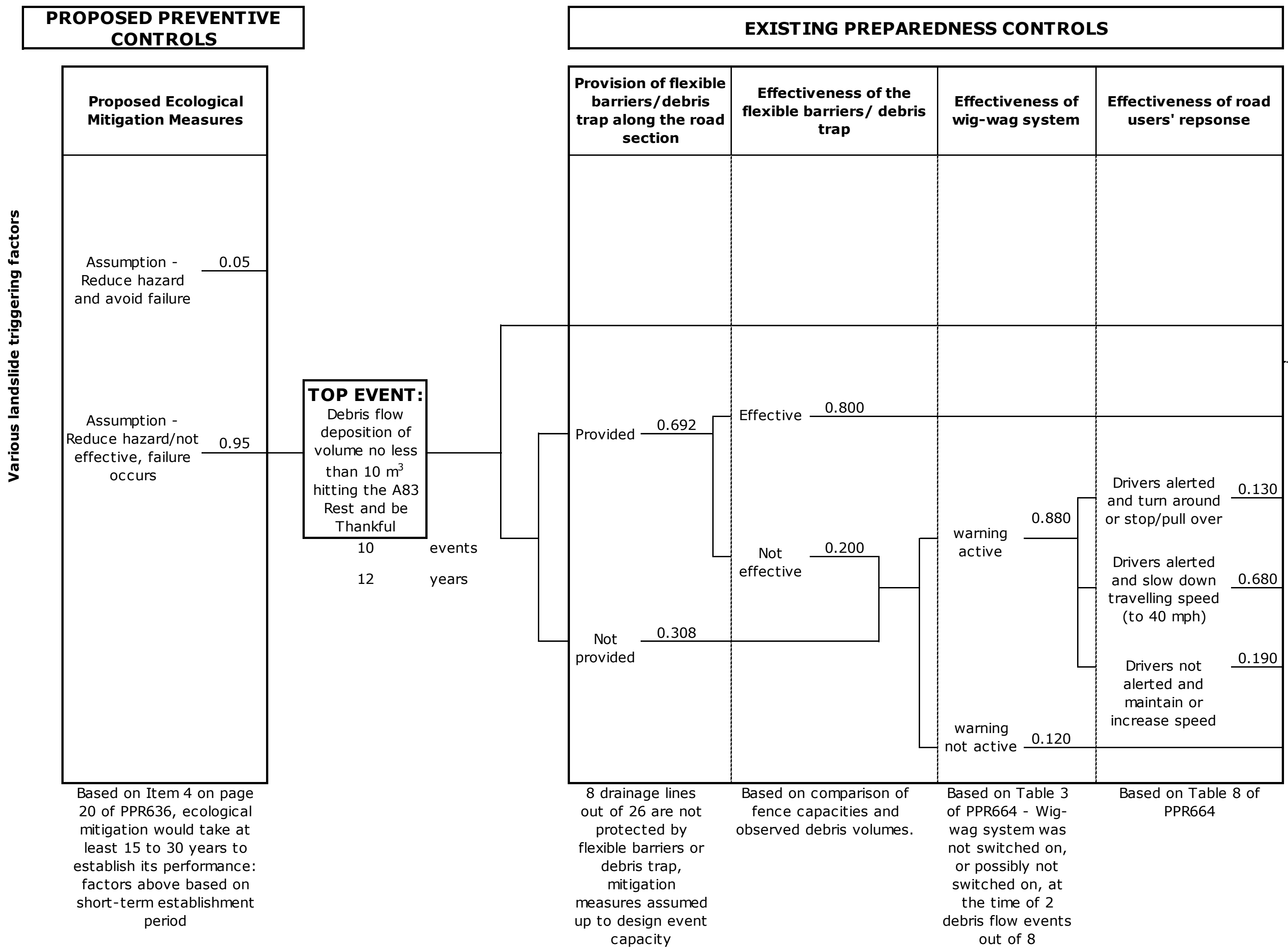
Approximately 700m of flexible barriers have been erected across 17 drainage channels on the hillslope above the road in the study area, in different phases, since 2010. A new catch pit was also formed below a drainage channel which had been previously subject to debris flow (Figure 18). The barriers and catch pit were designed individually to contain the amount of materials that were anticipated to reach the road through the drainage channels. The fences are designed to 'fail' by folding and allowing further material to pass when the capacity is exceeded (Figure 19). The design fence capacities vary between approximately 300m^3 and 1,250m^3 (corresponding to around 630 to 2,625 tonnes); some smaller additional fences with capacities of around 150m^3 (315 tonnes) are sited higher on gulley sides.

The 18 drainage channels protected by designed flexible barriers and the catch pit comprise 69% of the 26 identified channels (Figure 18). With the reduction in exposure length to debris flow hazard, the risk of debris flow posed to the road users at the A83 Rest and be Thankful may be expected to be reduced accordingly. This is illustrated by the source locations of the recorded debris flow events and the locations of the probable relict and recent landslides (Figure 18). The risk of debris flow between drainage channels nos. 2 and 3 would largely be contained by a berm downslope of the old quarry site.

Notwithstanding this, the performance of the flexible barriers was tested by the 28 October 2014 debris flow event that comprised approximately 2,000 tonnes (952m^3) of material; and estimated 750 tonnes (357m^3) reached the road and 1,250 tonnes (595m^3) was retained by the lower fence at this location (comprising part of the Phase 4 works). The fence pivoted at the base as the design load (450m^3 or 945 tonnes) was exceeded by a factor of around 1.3. Figure 19 shows that many large boulder-sized fragments were retained by the barrier and that the majority of the deposits at road level were muddy with some cobble-sized particles.

From this, it may be assumed that the effectiveness of flexible barriers at the A83 Rest and be Thankful would depend on whether the debris volume was greater or lesser than the design capacity. The debris flow events that caused disruption to road users, the estimated debris volumes on the hillside (double the reported deposition volume at road level, see Section 6.3.1) generally relate to the fence capacities.

Figure 17. Event tree diagram.



Consequence scenario	Outcome	Effects on the QRA based on vehicle travelling at 50/60 mph	Outcome probability of landslide risk to vehicles/road users at road level: Risk removed	#Risk reduced to a certain extent	Risk remained unchanged	Change in Societal risk in terms of Potential Loss of Life per year due to the proposed preventive and existing preparedness controls: Proposed ecological measures considered	Proposed ecological measures not considered
					Initial	**4.083E-03**	**4.083E-03**
	Preventive						
1	Ecological mitigation effects, debris flow does not occur, no damage	P (Event) and therefore the overall risk reduced	0.050			3.879E-03	4.083E-03
	Preparedness						
2	Debris flow occurs, deposits arrested by flexible barriers, no damage	Overall risk reduced by shortening P (Wrong Place)	0.554			1.731E-03	1.822E-03
3	Debris flow occurs and deposit hits the road, driver alerted by wig-wag warning to turnaround, stop or pull over	Overall risk reduced by a lower AADF	0.051			1.533E-03	1.613E-03
4	Debris flow occurs and deposit hits the road, driver alerted by wig-wag warning to slow down (to 40 mph)	Drivers would reduce the speed to 40 mph and the overall risk will be lowered		0.267		1.429E-03	1.504E-03
5	Debris flow occurs and deposits hit the road, driver not aware of the wig-way continues at same speed or speeds up	Risk level unchanged			0.075	1.429E-03	1.504E-03
6	Debris flow occurs and deposit hits the road, no wig-wag warning to alert driver	Risk level unchanged			0.054	1.429E-03	1.504E-03
				1.000			
					Final	**1.429E-03**	**1.504E-03**
					Reduction in risk	**65.00%**	**63.16%**

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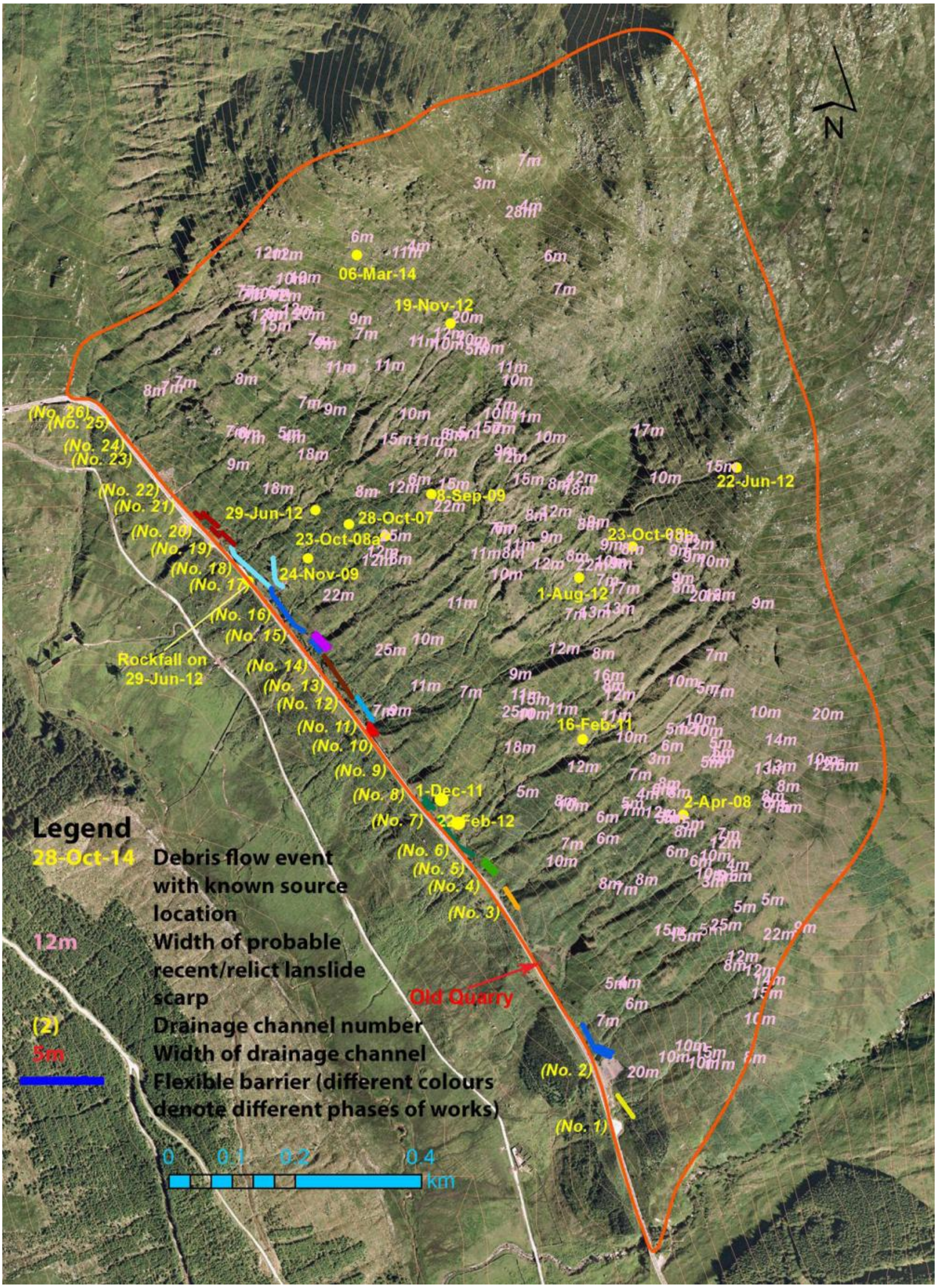

Figure 18. Locations of the flexible barriers and new catch pit. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

Considering this, the observed effectiveness of the fences in October 2014, and anticipated improvements to the existing fences[3] and effectiveness of the barriers in arresting debris can be conservatively estimated at 80%. It was thus assumed that the provision of flexible barriers and the catch pit could remove about 55% (i.e. 69% coverage × 80% effectiveness) of the landslide risk.

Figure 19. The 28 October 2014 debris flow event and damage to the flexible barriers at the A83 Rest and be Thankful. It is important to note that the barriers have performed in the manner that would be expected when the design load has been exceeded.

7.2 Wig-wag Signs

The installation of wig-wag signs was one of the options recommended by Winter et al. (2009) as part of the overall management strategy. The wig-wags are a form of temporal warning sign, incorporating a standard rockfall/landslide red warning triangle which acts as a permanent geographical warning, flashing lights and a sub-plate with a warning message of 'high risk when lights flash' during periods of high rainfall (Winter, 2014) (Figure 20). The wig-wag signs are operated by the Traffic Scotland Control Centre with the use of mobile telecommunications technology in response to Heavy Rainfall Warnings based on either of the following forecast thresholds:

- 25 mm rainfall in a 24-hour period, or
- 4 mm rainfall in a 3-hour period.

An initial two-year trial of this system was conducted on the A83 trunk road between Ardkinglas to a point west of Cairndow, which encompasses the Rest and be Thankful

[3]The Herald: 25 January 2015, accessed May 2016, http://www.heraldscotland.com/news/14228266.Additional___6_6m_to_boost_landslide_defences_at_Rest_and_Be_Thankful/.

(Figure 21). A total of six signs was installed; three each for the eastbound and westbound traffic. After activation at the beginning of a Heavy Rainfall Warning, the lights flash until six hours after the forecast period is completed, which was considered to be the best estimate of the period over which the residual risk would persist at the outset of the trial. The warning is also emailed to the Operating Company for the network to enable a decision to be made with Transport Scotland on whether landslide patrols should be deployed (these operate during daylight hours only).

Figure 20. Wig-wag warning sign in operation (From Winter et al., 2013).

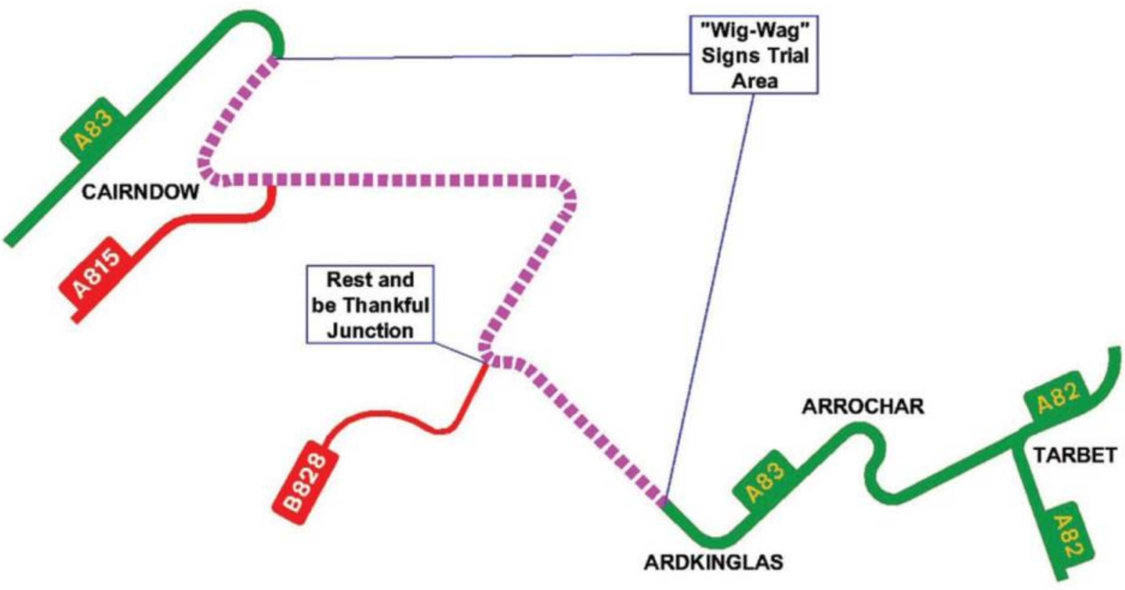

Figure 21. Wig-wag warning sign trial location.

In the evaluation of the two-year trial, Winter et al. (2013) examined the effectiveness of the scheme by correlating the response of the wig-wag system to eight debris flow events that occurred during 2011 and 2012. It was found that the system was not switched on at the time of one out of the eight events and that there was doubt surrounding the timing of the occurrence of another event that meant that the wig-wags might not have been switched on.

An extended and updated technical evaluation of the wig-wag signs (Winter & Shearer, 2017) covered the period 2011 to 2014 and encompassed 17 debris flow events, for which the wig-wags were switched on, or most likely to have been switched on, for 15 (88%) of the events.

Winter et al. (2013) also incorporated an evaluation of the perceptions of road users of the wig-wag signs by interviewing over 200 drivers. The normal speed limit of the road section is 60 mph (40 mph for heavy goods vehicles). When asked what they would do when the wig-wag signs were switched on, 68% of the interviewees responded that they would reduce their travelling speed, 13% that they would turnaround or stop, whereas the remaining 19% would continue at the same speed or even speed up.

Based on the interview outcomes, it was considered that turning on the wig-wag system would have the following influences on risk:

1) For the 13% of road users that would turnaround or stop, the risk would be removed under Scenarios A and B by not being exposed to 'Wrong Place $_{A/B}$' (Consequence Scenario 3 in Figure 17).
2) The 68% of road users that would lower their speed, would have a lower P(Fatality|Hit $_{B}$) for hitting deposits by reducing the travel speed to, say, 40 mph, but a higher P(Wrong Time $_{A/B}$) due to longer exposure times in both Wrong Places (Consequence Scenario 4). The response to another question in the questionnaire suggested that the average travelling speed under wig-wag signs was about 40 mph.
3) The risk levels of those 19% drivers not alerted by the wig-wag signs (Consequence Scenario 5) remained unchanged. (It is assumed that they would not increase their speed.)
4) In cases where the wig-wag signs were not switched on (Consequence Scenario 6) the risk levels remained unchanged.

From Figure 17, Consequence Scenario 3 corresponds to a 6% risk reduction. For Scenario 4, having considered the change in P(Fatality|Hit A and B) by lowering vehicle speed, the reduction in risk would be around 3%.

7.3 Proposed Ecological and Related Landslide Mitigation Options

Winter & Corby (2012) examined the use of a number of ecological and related landslide mitigation options for the hillslope above the Rest and be Thankful road section, as an aid to improved slope stability. The following three main benefits of planting were identified:

- Canopy interception (and attenuation) of rainfall and subsequent evaporation.

- Increased root uptake of water infiltrated into soil and subsequent transpiration via leaf cover.
- Root reinforcement by species with a mix of vertical or sub-vertical root penetration, rather than lateral roots that may form soil rafts that can subsequently fail in translational mode.

Potential dis-benefits of the ecological options were also identified in the assessment. The average gradient of the hillslope at around 36^{o} was found to be at the margin for forestation. Winter & Corby (2012) expressed the view that commercial forestry (plantation) was not suitable due to the:

- Subsequent need for harvesting (or deforestation, which had been identified as a triggering factor of the translational landslide at Loch Shira adjacent to the A83 trunk road near Inveraray in 1994).
- The potential for maturing trees to become a windthrow hazard.

For these and other reasons the scheme at the Rest and be Thankful is focussed on non-commercial, low height, mixed native species broadleaf tree and shrub species with coppicing to reduce the windfall hazard. Notwithstanding this the positive effects of vegetation were expected to take between 15 to 30 years to fully establish and the rate of growth is also species-dependant.

Limited by the expected long-term effects of the ecological options and the uncertainties, a ballpark figure of 5% reduction in the likeliness of debris flow occurrence, P(Event), was assumed in the consequence model in Consequence Scenario 1 of the event tree diagram for the short- to medium-term establishment period (Figure 17) for the purpose of this Study. This figure is subject to change when further information is available once planting has taken place and an initial evaluation of the effects thereof have been undertaken.

7.4 Potential Risk Reduction by Mitigation Measures

By considering the performance of the existing mitigation measures (i.e. flexible barriers, debris trap and wig-wag system) it was found that the debris flow risk level could be reduced to around 63% (Figure 17) of that without mitigation measures. If the proposed ecological preventive controls were to be implemented an approximate further 2% reduction in risk level could be achieved in the short- to medium-term. This would increase as the vegetation became established.

The performance of the existing mitigation measures (risk reduced to 63%) was reviewed in the F-N graph for vehicle speed at 50mph (Figure 22). In Figure 15 the risk without the mitigation measures for N = 1 and 2 is within the Unacceptable zone. The introduction of the mitigation measures reduces the risk to a level whereby, for all values of N, the risk falls in the ALARP zone (for N = 1 the total risk is 9.47E-4, just within the 1.0E-3 limit). The short- to medium-term effects of the vegetation planting would reduce the total risk slightly further and it is reasonable to assume that the longer term effects associated with such an action would reduce the total risk further still.

This substantiates the appropriateness of the mitigation measures in reducing the debris flow risk to which road users are exposed at the A83 Rest and be Thankful.

The timing of this work meant that only mitigation measures present as of October 2014 were taken into consideration. There has been significant work undertaken since that time to further reduce the risk at this site.

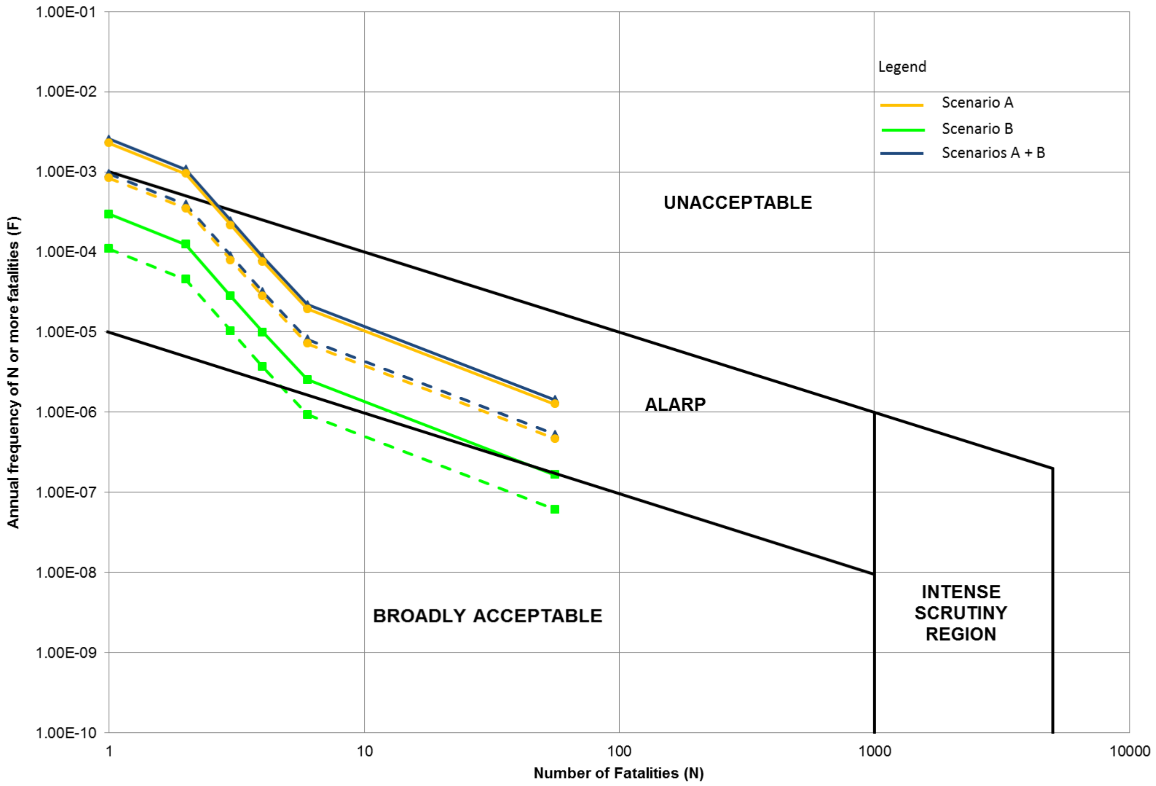

Figure 22. F-N Curve showing the risk reduction due to the existing mitigation measures. This is based on the Wong et al. (2004) approach; the Lee and Jones (2014) approach would yield lower levels of risk as is evident from Figures 15 and 16. Note that this does not include the effects of the planned, but as yet unimplemented, ecological mitigation works. Note that the lines for Scenarios A and B combined is partly obscured by that for Scenario A. Dashed lines represent the risk after the mitigation measures are taken into account.

8 Discussion

8.1 Individual Risk

In a comparison of risk regulation in the UK and the Netherlands, Ale (2005) noted that following the Sizewell B Enquiry the Health & Safety Executive (HSE) (Anon. 1992) described a tolerable risk level as one that is allowed to continue to exist somewhere in society. The highest tolerated risk at that time in the UK was that to miners and the individual risk to those workers was estimated to be of the order of 10^{-3} per year. From that it was derived that members of the general public could be exposed to an individual risk of 10^{-4} per year in the wider interests of society.

This compares to the computed Personal Individual Risk (PIR) for a single trip (per year) which is speed dependent and varies from 2.045E-09 (40 mph), 1.742E-09 (50 mph) to 1.583E-09 (60 mph). Those who make multiple trips are exposed to a greater level of risk and estimates for those most at risk have been made for commuters 7.440E-07 or 1 in 1.35 million (at the national speed limit of 60 mph) and logistics truck drivers 1.922E-06 or 1 in 520,000 (at the speed limit for heavy goods vehicles of 40 mph).

The values of PIR are generally lower than those that Lee & Jones (2014) suggest that the UK Health and Safety Executive currently use to define the upper (10^{-04}) and lower (10^{-06}) bounds of As Low As Reasonably Practicable for individual risk and may be described as Broadly Acceptable or tolerable. These risks are noticeably lower than those described by Ale (2005). The exception is the risk for the logistics truck driver risk which falls within the ALARP zone. However, once the management and mitigation works are taken into account the risk is returned to a generally tolerable level (approximately 7.1E-07).

The results for the two parts of this risk assessment (debris flow hitting vehicle and vehicle hitting debris flow) show, unsurprisingly and as noted above, that the resulting risk is vehicle speed dependent, albeit to a relatively small degree. It is important to apply these results in context. The larger overall risk of a debris flow hitting a vehicle (Scenario A) has a decreasing risk for higher speeds, while the overall lower risk of a vehicle hitting a debris flow (Scenario B) has an increased risk with increasing speed (Figure 23).

Overall the risk of a fatality (Scenario A plus B) from a debris flow shows a small decrease with increasing vehicle speed. It is important that increased speed is not seen, in any way, as an effective remedial measure, or tactic, for drivers to reduce the overall risk that they face on the road. It is important to recognise that increased speed also increases the (considerably higher) risk of a road traffic accident and reduces the control that a driver may have over the vehicle in the event of encountering a debris flow. It is clear that recommendations to drivers should focus on the balance of speed to driving conditions as such recommendations would in any other scenario.

8.2 Societal Risk

The societal risk from debris flow at the A83 Rest and be Thankful is dealt with in terms of the classic, and widely used, F-N diagram. There are two approaches to generating the data to be plotted on this diagram and neither is considered to be more correct than the other. In this study a speed of 50mph has been taken as an estimate of the average speed of traffic thorough the A83 Rest and be Thankful. The approach of Lee & Jones (2014) produces values of N that include some that are less than unity, the lowest value on the x-axis, which do not plot on the F-N diagram that has its lower bound value at unity. While it is not considered appropriate to extend the boundaries between Broadly Acceptable, ALARP and Unacceptable to accommodate lower values of N, it does seem likely that for the lower N values would plot just into the Unacceptable zone. Certainly the approach of Wong et al. (2004) produces results that are more suited to being plotted on the F-N diagram and a clearer picture emerges. The diagram shows that prior to the application of mitigation measures the risk levels for one and two fatalities (N=1 and 2) plot just into the Unacceptable zone, while the risks for higher numbers of fatalities plot in the ALARP zone.

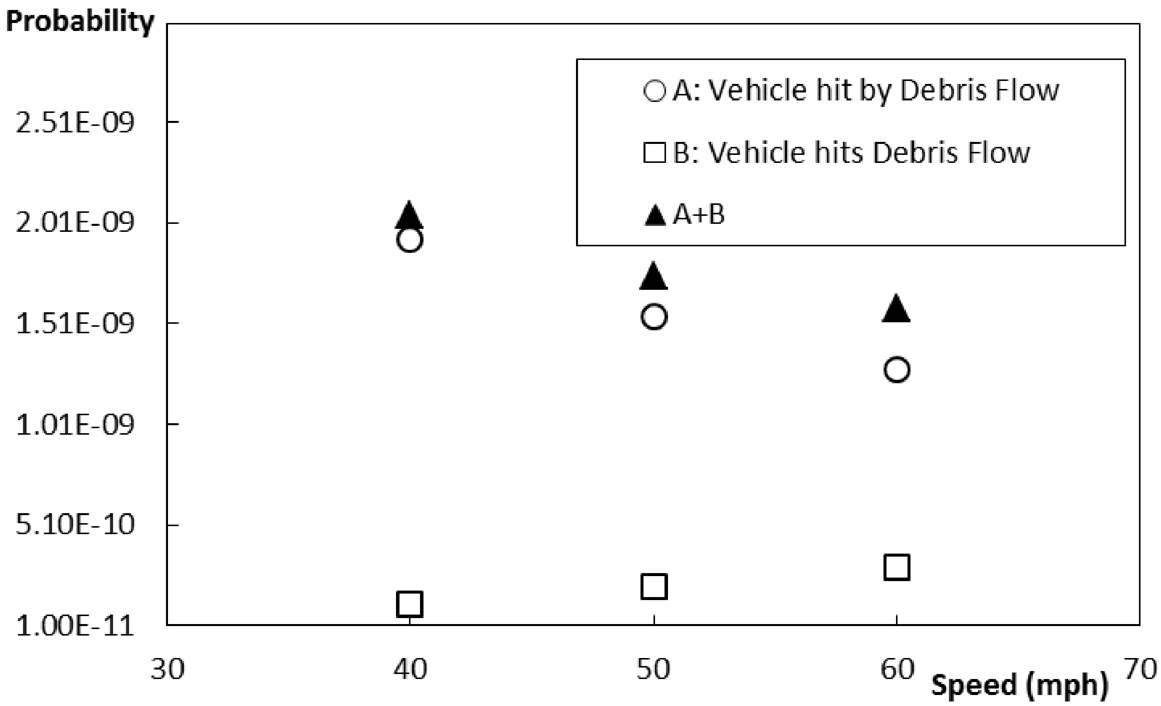

Figure 23. The variation of PIR for the two risk scenarios and total risk with speed.

The application of reductions to the risk levels in response to the mitigation measure implemented at the A83 Rest and be Thankful brings the value for N=2 into the ALARP zone and that for N=1 only fractionally into the Unacceptable zone. The intrusion of the latter into the Unacceptable zone is well within the limits of error of the study and thus the overall risk levels can be considered to be within the ALARP zone after mitigation. This indicates the value and effectiveness of the mitigation measures implemented.

The Lee & Jones (2014) methodology is particularly helpful in that it allows the ready calculation of a figure for the Potential Loss of Life (PLL). This is the annual probability of a fatality being caused by debris flow at the A83 Rest and be Thankful and, for an average traffic speed of 50mph, is 4.083E-03, which corresponds to one fatality every 245 years or approximately four fatalities per millennia.

Taking the estimated reduction in risk from Section 7.4, the fatality rate falls to less than two per millennium as a result of the mitigation measures, with a PLL of 1.504E-3 for the current mitigation measures (one fatality every 665 years) and 1.1.429E-3 for the current mitigation measures and the planned vegetation planting (one fatality every 700 years) in the short- to medium-term (the risk would decrease further in the longer-term as the vegetation became established).

8.3 Climate Change

In broad terms the available climate change forecasts suggest that in the winter months when rainfall is expected to increase, landslide hazard frequency and/or magnitude may increase in Scotland in the future, whereas in the summer months the frequency may decrease, but with a possibility of increasing magnitude (Winter & Shearer, 2014a; 2014b).

Increased hazard frequency, or P(Event), is relatively straight forward to deal with and Equation (3) suggests that doubling, for example, the frequency of event occurrence would double the risk. This would increase the risk to logistics truck drivers from 1.922E-06 to 3.844E-6 (at the speed limit for heavy goods vehicles of 40 mph), still well within the highest tolerated individual risk to workers of 10^{-3} per year, as reported by Ale (2005). Increases in hazard magnitude would have an influence on P(Damage|Hit), while P(Hit|Event) seems unlikely to change to a significant degree. This increase in P(Damage|Hit) seem likely to be greater in Scenario A than in Scenario B. Taking a lead from the fragility curves for road infrastructure in Figure 12, it seems reasonable to suggest that a doubling in the magnitude may lead to a doubling of the risk and a broadly similar outcome as for a doubling of the frequency. A doubling of the frequency of event would, however, return the societal risk to the lower reaches of the Unacceptable zone on the F-N diagram for low numbers of fatalities (N=1 or 2).

Of course, an assumption of the doubling of either frequency or magnitude is rather speculative and it must be remembered frequency and magnitude are not completely decoupled; an increase in magnitude leaves less debris and may lead to a decrease in the frequency, similarly an increase in the frequency may well mean that the channels are relatively clear of loose previously entrained material to be entrained and it may be less likely that a larger magnitude event will develop. Certainly, the larger event that occurred in October 2014 is not necessarily an indicator of future patterns of debris flow events at the Rest and be Thankful, but may well assist in understanding the longer term picture of frequency-magnitude at this location.

8.4 Limitations and Recommendations

It is important to note that the QRA technique is neither a neutral, nor is it an entirely objective, process such that the results could be value-laden and biased (Lee & Jones, 2014). As noted in Section 6, Suzanne Lacasse describes QRA as "… the systematic application of engineering judgement" in her, as yet unpublished, 2015 Rankine Lecture.

The QRA methodology and the pilot QRA for the A83 Rest and be Thankful reported herein were developed based on a review of the application of QRA in landslide studies in different parts of the world and the site-specific information available. The limitations identified in the study are summarised below and recommendations are made to improve the quality and accuracy of subsequent QRA work made.

The debris flow inventory in Table 1 was compiled from various sources such as preliminary landslide inspection records, Operating Company annual reports and field photographs. Inconsistencies in information such as the occurrence time, source location and debris volume were found. In order to establish a more complete database of the landslide history in the study area, it is recommended that the debris details summarised in this report should be reviewed and revised as and when more substantial records of landslides over a longer period become available. It also seems clear that a more systematic system of record acquisition and keeping in respect of landslides and debris flow is needed and that this should include the mapping of landslide events. In this context work to develop a simple recording system for landslide events has been instigated.

In addition, the frequency of landslide events, or P(Event), for the study area could only be determined from known debris flow records covering a relatively short period of 12 years from 2003 to 2014. In this context the possibility of underrepresentation of low-frequency, high-magnitude events (yet to occur) cannot be discounted. For instance, the higher event magnitude of the 28 October 2014 occurred at the end of the study and was about twice the size of the 8 September 2009 event, for example. The possibility of underrepresentation of high-frequency, low-magnitude events that are not detected and/or reported also could not be discounted. Such events are notoriously difficult to detect as often they will not reach infrastructure or, indeed, any other elements at risk and are difficult to detect remotely due to their small magnitude. Such 'invisible' events are often considered to be the explanation for the flattening of frequency-magnitude (FM) curves at the low frequency end. Notwithstanding this it is clear that only time and effective data acquisition and recording will allow the event record to be improved.

Limited by the lack of time series aerial photographs and small scale superficial geological mapping over the study area, the geomorphology and landslide history of the study area could not be assessed to reveal such potentially underrepresented events, not even for verification of the source location, debris path and run-out distance of the recorded events. Despite this, more than 200 recent and relict landslide scars were identified preliminarily on the GIS platform in 2-D based on the aerial photography taken in 2007. Nevertheless, 2-D interpretation cannot be as accurate as stereoscopic interpretation. Given that the study area is amongst the most highly ranked debris flow hazard sites on the Scottish trunk road network and its high landslide frequency, it is suggested that a remote sensing database be initiated to collate relevant information regarding the site. The database should include imagery from LiDAR and aerial photography over the study area with annual updates in view of the high landslide frequency and to tie-in with the regime of annual inspection reports to assist in stereoscopic interpretation for developing a better understanding of the drift geology, geomorphology, landslide history and susceptibility. This will benefit any relevant detailed study in future such as debris run-out mobility modelling for more robust input to the QRA. With the exception of stereo aerial photography capture, this recommendation is largely being addressed through ongoing work that will persist for three years, and will be reviewed thereafter.

Based on the details of the latest landslide on 28 October 2014, it is recommended that a review be conducted of the adequacy of the flexible barriers installed along the A83 Rest and be Thankful, particularly the gaps between drainage channel numbers 7 and 10 and numbers 20 and 26.

9 Summary

This report presents the methodology developed for undertaking a quantitative risk assessment (QRA) for the impact of debris flow on roads. It also presents a first use of the methodology at the A83 Rest and be Thankful in Scotland.

The methodology considers the probability of an event of a typical size and the conditional probabilities of a vehicle being affected, given an event, and of damage (fatality) occurring given that the vehicle is affected. Scenarios covering a vehicle being hit by a debris flow and of a vehicle hitting a debris flow are considered.

The computed Personal Individual Risk (PIR) at the A83 Rest and be Thankful for a single trip (per year) is speed dependent and varies between 2.045E-09 (40 mph), 1.742E-09 (50 mph) and 1.583E-09 (60 mph). Those who make multiple trips are exposed to a greater level of risk and estimates for those most at risk have been made for commuters 7.440E-07 (at the national speed limit of 60 mph) and logistics truck drivers 1.922E-06 (at the speed limit for heavy goods vehicles of 40 mph), which fall within generally tolerable limits The exception is the risk for the logistics truck driver risk which falls within the ALARP zone. However, once the management and mitigation works are taken into account the risk is returned to a generally tolerable level.

Risk decreases with increasing speed and it is important that increased speed is not seen, in any way, as an effective remedial measure, or tactic, for drivers to reduce the overall risk that they face on the road. It is important to recognise that increased speed also increases the (considerably higher) risk of a road traffic accident and reduces the control that a driver may have over the vehicle in the event of encountering a debris flow. It is clear that recommendations to drivers should focus on the balance of speed to driving conditions as such recommendations would in any other scenario.

The overall risk to society is expressed using the F-N diagram and prior to the implementation of mitigation measures being placed at the Rest and be Thankful shows:

- that for one or two fatalities the risk falls into the Unacceptable zone, while
- for higher numbers of casualties the risk falls into the ALARP zone.

When those mitigation measures in place as of October 2014 are taken into consideration then the risk levels fall within the ALARP zone, indicating the value and effectiveness of the measures implemented.

Potential Loss of Life (PLL), is the annual probability of a fatality being caused by debris flow at the A83 Rest and be Thankful, is 4.083E-03, which corresponds to one fatality every 245 years or approximately four fatalities per millennia. This reduces to 1.504E-3 (or one fatality every 655 years) when the current mitigation measures are considered.

The potential effects of climate change on the frequency and magnitude of future events at the A83 Rest and be Thankful site are complex, and frequency and magnitude are coupled phenomena. However, a doubling of the frequency, for example, would lead to a doubling of the risk but the PIR values would still be considered broadly acceptable. The societal risk could, however, potentially return to the lower reaches of the Unacceptable zone on the F-N diagram for low numbers of fatalities (N=1 or 2).

The authors believe that this study is the first full, formal quantitative risk assessment for debris flow risk to road users.

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