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

A85 Glen Ogle

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Contents

Abstract

This report presents a Quantitative Risk Assessment (QRA) for the impact of debris flow on the A85 road at Glen Ogle in Scotland. The methodology was developed and first used on the A83 Rest and be Thankful site, also 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 overall risk to society is expressed using the F-N diagram and this shows that for numbers of fatalities between one and four that the annual risk falls into the ALARP (As Low As Reasonably Practicable) zone and that for numbers of casualties greater than four the risk falls into the Broadly Acceptable zone.

The potential effects of climate change on the frequency and magnitude of future events at the A85 Glen Ogle 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 to be Broadly Acceptable. In addition the societal risk would remain in the ALARP zone of the F-N diagram for lower numbers of fatalities (N=1 to 4) and in the Broadly Acceptable zone for higher numbers of fatalities.

The author is 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 results of a Quantitative Risk Assessment (QRA) study of landslide hazards on the south-west facing slopes of Beinn Leabhainn and Meall Buidhe that affect an approximately 5km-long section of the A85 Trunk Road in Glen Ogle in Stirling, Scotland.

The Scottish Road Network Landslides Study (Winter et al., 2009; 2013) evaluated the hazards and risks associated with landslides at a regional/national (pan-Scotland) scale and identified sites most at risk on the Scottish trunk road network. This has allowed the effective targeting of funds for implementation works. This work was undertaken within a qualitative/semi-quantitative framework.

At the highest risk sites identified, a Quantitative Risk Assessment (QRA) at key landslide sites that affect the Scottish trunk road network can 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 very limited event dataset available, and the calculation of the probability of a fatal (or near-fatal) event at this site.

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 the this work will help to better define the relations between the frequency and magnitude relations of landslide events, albeit only for those of magnitudes that are extant, and suggest a likely temporal framework for repeated events.

The first phase of the study developed the QRA methodology by considering the debris flow occurrence information currently available for the A83 Rest and be Thankful site (Wong & Winter, 2018). From this analysis the annual probability of an event of a given size was 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 demonstrated using the A83 Rest and be Thankful as a case study is herein applied to the A85 Glen Ogle site.

2 Study Area

The A85 at Glen Ogle is amongst the most highly ranked debris flow hazard sites in Scotland (Winter et al., 2009). There is a substantive history of instability in the Glen including the August 2004 debris flow events (Winter et al., 2005; 2006; 2009) and the rockfalls that closed the railway line on the west side of the Glen in 1965; the latter now functions as a walking and cycling route (see Section 5.1.3). The hillside to the east of the A85 is formed of the predominantly south-west facing slopes of Eildreach, Meall na Cloiche, Meall Buidhe and Beinn Leabhainn. The section of road defined is 4.99km long; it passes through Glen Ogle, over the pass at the head of Glen Ogle, past Lochan Lairig Cheile, and into the valley beyond. The hillside is subject to six-monthly visual and photographic surveys by the Operating Company which are reported annually to Transport Scotland.

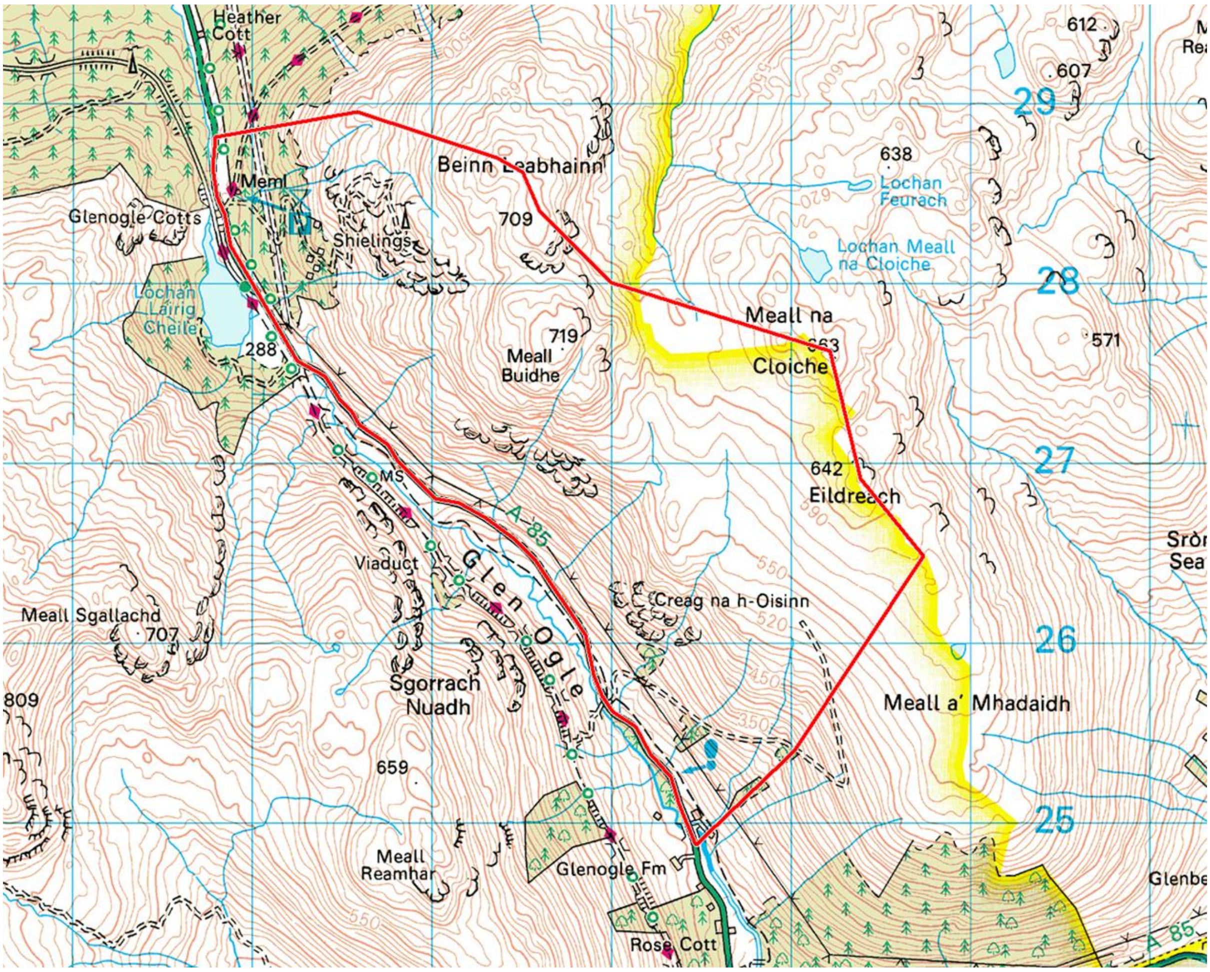

Figure 1. Location plan of the study area outlined in red (1:50,000, not to scale). Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

2.1 A85 Trunk Road

The A85 trunk road is a 139km-long single two-lane carriageway that connects the A9 at Perth in the east of Scotland with Oban in the west. A short stretch of non-trunk A85 connects the A9 with the A912 in the centre of Perth. The A85 runs east to west via

Crieff, Comrie, St Fillans, then along the north shore of Loch Earn to Lochearnhead, into Glen Ogle, then via Crianlarich, Tyndrum, Dalmally, then along the north shore of Loch Awe and through the Pass of Brander and past Cruachan Power Station to Taynuilt, before approaching the southern shore of the lower part of Loch Etive to Connel and then on to Oban, connecting with the A816 (non-trunk). The A85 supports the economic activities in the region including agriculture, forestry and fisheries, energy production, transport and storage, tourism, and public administration. (A short stretch of around 6.5km of non-trunk A85 connects the A90 at Dundee with the A991 in the city centre via the airport and the railway station.)

2.2 Road Through Glen Ogle

The section of the A85 trunk road through Glen Ogle is a relatively narrow single-carriageway and climbs north-westward from Lochearnhead at around 100m AOD. From Lochearnhead, the A85 runs to the west of Ogle Burn, which runs in the base of Glen Ogle, until the road crosses to the east flank of the glen after approximately 1.25km (150m AOD). From here the road runs above and to the east of Ogle Burn until the road levels out after around 5km. Here Ogle Burn becomes less significant and the road passes over it at around 300m AOD. Ogle Burn rises in the hills just to the east of the road at approximately 363m AOD. The road continues on the relatively flat ground that forms the pass between Glen Ogle and the valley to the north that in turn feeds into Glen Dochart and the road passes to the east of Lochan Lairig Cheile which drains to the north.

The section of road identified as being at higher risk in this area (Section A85-08 from Winter et al., 2009) extends approximately from the bridge crossing of the Ogle Burn (at 1.25km from Lochearnhead) over the pass and into the valley feeding into Glen Dochart. This area of interest for the study is defined in large part based on Winter et al. (2009), eliminating some marginal areas to the north, and also on taking account of the smaller area examined by Milne (2008) in which a large number of debris flows was identified.

The events that closed the A85 in Glen Ogle in August 2004 are located towards the mid-point of this section approximately 1.7km and 2.2km from the southern end of the section.

As a point of interest the part of the former Callander to Oban railway runs along the west flank of the slopes of Glen Ogle – this line was closed in 1965 (see Section 5.1.3) but now provides a series of excellent viewpoints for the eastern flanks of Glen Ogle. An old military road, dating from the 1700s, also runs through the glen.

2.3 Study Area

The hillside above the 4.99km-long section of road may be described in three parts. The first part, from the southern end of the section to the flanks of Meall Buidhe, is initially steep (around 28°) from road level to around the 500m to 550m contour where the slope slackens to around 5° or less. The second part, the south-west facing flank of Meall Buidhe is very steep at around 35° and the slope slackens only as the summit is approached. The third part, from the north of Meall Buidhe to the northern limit of the section is also relatively uniform at around 15° to 16°.

There are steep rocky exposures on the south-west facing flanks of Creah na h-Oisinn, Meall Buidhe and Beinn Leabhainn. Drainage channels incise the hillslope largely sub-perpendicular to the contours and extend below the A85 road level to reach Ogle Burn. While the drainage is in large part parallel there is some bifurcation, particularly of some of the larger stream channels and particularly on the lower reaches of the slopes. The width of the drainage channels intersecting the road section varies from 1m to more than 100m (allowing for the multiple debris pulses of the August 2004 debris flows that reached the road at slightly different positions: see Section 5.1.4), with an average of 12m.

Farm buildings are located just to the north of the bridge at the southern end of the section; the farm dwelling associated with these buildings appears to be located just inside the study area. Glenogle Cottages, which appear to comprise up to four dwellings are located just to the north of Lochan Lairig Cheile on the west side of the road.

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).

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 A85 at Glen Ogle as amongst the most highly ranked debris flow hazard sites in Scotland.

It has been observed that many Scottish debris flows are 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.

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). Glen Ogle 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). The A83 Rest and be Thankful site was identified as an area prone to debris flow and a pilot QRA methodology was developed for analysing and evaluating the landslide fatality risk posed to road users (Wong & Winter, 2018). The methodology developed for that site is adopted, and adapted where necessary, for the A85 Glen Ogle site.

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 12.5 to 11.5 ka BP (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.

Glen Ogle forms part of the southern Grampian Mountains; the flanks of the valley are relatively steep and in many places are formed of rock slopes. The maximum altitudes of the mountains that form these flanks are 719m and 709m AOD for Meall Buidhe and Beinn Leabhainn, respectively, on the east flank and 707m for Meall Sgallachd on the west flank (Milne, 2008).

The lithology is dominated by impermeable upper Dalradian metamorphic rocks, particularly Quartzose-Mica-Schists (Ben Lui Schist Formation) formed from marine shales during the Caledonian Orogeny (*c*. 410 Ma BP) (Craig, 1991; Trewin & Rollin, 2002). Tills deposited during the Dimlington Stadial (c. 27 ka to 13 ka BP) dominate the drift geology of Glen Ogle and these were heavily reworked by Periglacial activity during the cold climate of the Loch Lomond Stadial (c. 11 ka to 10 ka BP). Notwithstanding this, there is some debate as to whether Glen Ogle was itself affected by glaciation during the Loch Lomond Stadial. Thompson (1972) inferred the presence of a contemporaneous glacier flowing through the valley and terminating near the village of Lochearnhead at the south-eastern end of the valley. In contrast, Milne (2008) reports the personal communication of Golledge (in 2007) in which a prominent moraine ridge was reported near to Lochan Lairig Cheile (close to the north-western limit of the site) and was inferred to represent the limit of Loch Lomond Stadial ice in the valley. Much of the higher slopes of the eastern side of the valley decrease in gradient (see Section 2) to form a plateau morphology that is largely covered in peat deposits (Milne, 2008).

The digital aerial photography images taken in 2005 and 2006 show numerous, but nonetheless relatively well-spaced, stream channels that incise the hillslope largely sub-perpendicular to the contours and that generally pass through culverts below the A85 to reach Ogle Burn. While the streams are in large part parallel there is some bifurcation, particularly of some of the larger channels and particularly on the lower reaches of the slopes. In the southern and northern parts of the site the larger channels persist to the higher reaches of the hillside and the plateau-like areas below the summits of Eildreach, Meall na Cloiche and Beinn Leabhainn. The channels in the central part generally follow the high level valley structures around Meall Buidhe. A walkover along the road section on 3 February 2016 identified 21 drainage channels at road level. These drainage channels flow under bridge structures or are culverted under the A85 to allow continuation downwards towards the tributary of Ogle Burn in the valley floor.

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

5 Landslide Hazards

Glen Ogle has a history of instability and perhaps most prominent are the most recent events of August 2004.

5.1 August 2004

The August 2004 events were part of a series of events in Scotland that were the result of high rainfall; the monthly total was up to 300% of the monthly 30-year average but included intense storm events as well as significant antecedent rainfall (Winter et al., 2010). The events commenced at the A83 in Glen Kinglas and north of Cairndow on 9 August and continued at the A9 north of Dunkeld on 11 August. Following the A83 and A9 incidents, the rainfall in the area decreased for several days but on 18 August a short but exceptionally intense rainstorm occurred in west Stirlingshire and triggered two debris flows that blocked the A85 in Glen Ogle north of Lochearnhead. The southerly slip occurred first and, as advice was being offered to motorists by Trunk Road Operating Company staff, a second landslide occurred to the north of the first. Some 20 vehicles were trapped between the two debris flows, and 57 occupants were airlifted to safety by RAF and Royal Navy helicopters (Figure 2) (Winter et al., 2005; 2006; 2009).

Figure 2. Fifty-seven occupants of the 20 vehicles that were trapped between the two debris flows in Glen Ogle were airlifted to safety. (© Perthshire Picture Agency: www.ppapix.co.uk.)

The A85 trunk road through Glen Ogle is a relatively narrow single carriageway and climbs north-westward from Lochearnhead, at an elevation of approximately 100m AOD, to a pass at the head of the glen at around 300m AOD before descending into Glen Dochart to the north. From Glen Ogle Farm (approximately 1.25km from Lochearnhead) northwards, the road climbs up the eastern flank of the valley to the top of the pass; it is along this section that the most significant flows occurred.

The hillside above the road rises some 400m at approximately a variable angle but is steep in the areas of the 2004 debris flows (up to 35°). It is covered with bracken and heather with isolated boulders and areas of crags. Below the road the gradient of the slope decreases rapidly to the Glen Ogle Burn. The two slips followed steep streams that descend this hillside and are culverted beneath the road. The southerly stream descends through an area covered by heather and bracken while the northerly stream descends a partially rocky area of the hillside.

As a result of the exceptional rainfall, and possibly because of the addition of the high level of antecedent rainfall, the soils in the upper catchments to the streams became saturated, triggering slides into the headwaters of both streams. The culverts rapidly became blocked and debris spilled across the road (Figure 2) and down the slope beyond (Figure 3). Most of the debris came to rest on the slope below the road but a small proportion reached the Glen Ogle Burn. This burn was also in spate at the time and rapidly removed the debris that reached it.

Figure 3. View of the northern A85 Glen Ogle debris flow two days after the event, showing the sharp bend in the channel just above road level. (From Winter et al., 2009.)

5.1.1 Northern Flow

Both terrestrial and helicopter-based examinations of the northern flow (Figure 3) undertaken two days after the events indicated two independent sources. To the north is an arcuate scar from which a shallow translational slip broke away. The turf and upper soil travelled over the surface of the vegetation below and entered the upper part of the stream gully. However, scarring indicates that instability occurred independently at the very top of the gully. It is not known which instability occurred first although both slides appear to have generated only a relatively small amount of debris. The debris was, however, channelled into and down the steeply inclined bed of the stream and scoured the gully, removing turf and soil. It is likely that the volume of water and debris increased further down the gully and that the consequent damage was increased in areas closer to the road.

In the middle and lower parts of the flow, large and small boulders and trees were mobilised in addition to soil and turf. In that locality the schistose bedrock is generally encountered at shallow depths and scouring appears not to have been deep but rather to have spread laterally. However, it appears that bedrock was loosened in places in the area of a small waterfall a short distance above the road. The dominant component of the debris comprised fine particles but many cobbles and boulders were also in evidence. Several boulders of up to 10 tonnes were deposited on the road and one boulder, estimated at 90 tonnes, was deposited some 10m above the road. From eyewitness accounts it would appear that the debris reached the road in pulses. These were most likely associated with the temporary damming of the stream by debris or by new areas of instability in the stream banks. Similar observations were made regarding the August 1997 debris flow which affected the A887 at Invermoriston (Winter et al., 2005; Nettleton et al., 2005).

The west-flowing stream channel then takes a sharp, right-angled turn to the south approximately 10m before it reaches the road due to a bluff of rock. This outcrop steers the stream channel into a course that runs sub-parallel to the road before the stream makes another sharp, right-angled turn to the west to pass under the road by means of a high arched culvert and descends the lower slopes to the Glen Ogle Burn.

On the afternoon of 18 August the initial part of the debris flow followed the course of the stream. However, at some point the culvert became blocked with boulders up to 2m in size and fallen trees, causing the water and debris to flow over the road, largely destroying the parapet of the culvert. As the energy of the debris flow increased, it reached a point where some or all of it failed to negotiate the first corner and it swept over the rock bluff and crossed the road some 40m to 50m to the north of the culvert. An unoccupied Trunk Road Operating Company vehicle that had been parked in the lee of the spur was swept over the edge of the road and for some distance downslope before it came to rest against a tree (Figure 4). A wide debris fan was left on the slope between the road and Glen Ogle Burn (Figures 4 and 5).

5.1.2 Southern Flow

The failure in the southerly stream was less extensive than that in the northern, the erosion scar being both narrower and less deep. This may have been due to the flow having less momentum than the northerly flow as this stream appears to be less continuously steep. Much of the material was coarser than that from the northern slip, being predominantly cobble-sized (see Figure 2). Otherwise, the general mechanism appears to have been similar, although in this case there is no major bend in the stream. The culvert is smaller and rapidly became blocked and debris spilled across the road causing damage to the outer face of the culvert and the outer edge of the road.

Figure 4. A85 Glen Ogle showing the Trunk Road Operating Company vehicle that was swept away by the northern debris flow. (From Winter et al., 2009.)

Figure 5. The debris fan formed by the northern debris flow in Glen Ogle viewed from the A85 trunk road, looking towards Glen Ogle Burn and down the valley towards Lochearnhead. (From Winter et al., 2009.)

5.1.3 Elements of the August 2004 Events

The aerial photographs in Figure 6 have been digitally 'stitched' together to give more extensive coverage of Glen Ogle while Figure 7 gives a more detailed view of the main area of interest. Key features are marked on Figures 6 and 7 described in the figure heading for Figure 7.

Figure 6. Aerial photograph showing a large part of Glen Ogle. The image was made by stitching adjacent 1km by 1km tiles before cropping to give approximately 4km (vertical) by 3km (horizontal) coverage; north is to the top. (From Winter et al., 2009.)

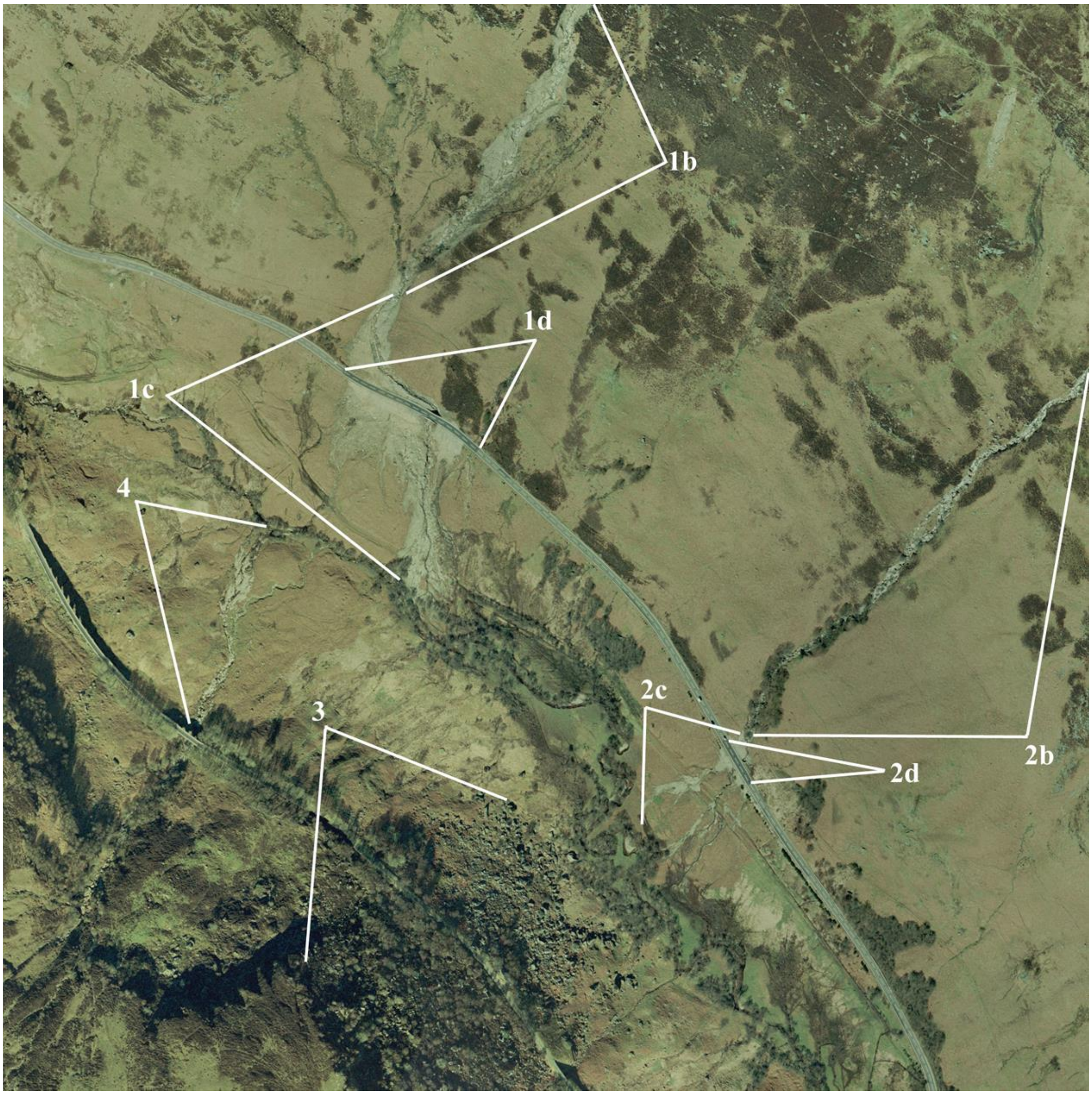

Figure 7. Aerial photograph showing the northerly (N) and southerly (S) debris flows that occurred in Glen Ogle in August 2004 with key features marked. The photograph represents a 1km by 1km square; north is to the top and the marked features are as for Figure 1, the south-west corner is located at National Grid Reference NN 570 260, or 2570 7260. (From Winter et al., 2009.)

Key:
1. North debris flow: (a) potential source areas, (b) debris track, (c) runout/ debris fan and (d) subsequent carriageway repair.
2. South debris flow: (a) potential source areas, (b) debris track, (c) runout/ debris fan and (d) subsequent carriageway repair.
3. Historic rock falls.
4. Other debris flows assumed to have occurred in August 2004.

Of particular interest, are the different elements of the August 2004 debris flows. A number of other features may also be seen including the carriageway repairs subsequent to the debris flows and the rockfalls/rock slides that cross the old railway line on the west side of the glen. The railway line was closed in 1965 when the line, already scheduled for closure, was blocked by one or more major landslides. It is believed that these may have been one or both of the rock-based landslides illustrated in Figure 6. Figure 7 is a single 1km by 1km image; the original orthographic digital aerial photographs were supplied as 25cm resolution JPEG images with both JGW and TAB files for the purposes of geo-referencing by Getmapping. Both the north and south debris flows at Glen Ogle are annotated on Figures 6 and 7, but note that the source areas appear only in Figure 6.

The work by Milne (2008) includes a detailed field evaluation of the 2004 events at Glen Ogle (Figure 8) and identified additional debris flow events on both the east and west flanks of the valley in addition to those that affected the A85 trunk road. Both channelised and open hillslope debris flows were initiated and the former typically formed where the initial failure entered a bedrock gully rather than being initiated by the failure of the gully walls or the mobilisation of material in the bed of the gully within the gully. Nine channelised debris flows reached the lower slopes of the valley, two of which crossed the A85 trunk road as described above.

Debris flows initiated to the south of the two events that reached the A85 trunk road were affected by the presence of a farm track. The farm track redirected and concentrated the flow such that at the foot of the slope it was comparable in size to the southerly flow. However, the A85 was not affected as the road is relatively distant from the slope foot at this location (Milne, 2008) and the material mobilised was insufficiently mobile to persist over longer run-out distances. Milne (2008) reports a total of around 30 debris flow initiation events in Glen Ogle of which 12 were on the west flank of the valley.

5.1.4 Past Events

There is also evidence of past debris flow activity in the upper reaches of Glen Ogle and Milne (2008) illustrates debris deposits in the valley (Figure 8). Figure 9 also illustrates what may be debris deposits from one or more such events located to the north-west of Milne's map. However, this geomorphological evidence has been substantially reworked and is unlikely, for example, to be sufficiently intact to allow dating of the deposits to assist with the determination of frequency-magnitude relations. Notwithstanding this, all of the directly observable debris flow evidence presented by Milne (2008) was from August 2004. However, Milne (2008) also reported that Wilson (2006) identified landslide scars on aerial photographs from the 1940s and 1950s that are no longer clearly discernible in the field or on more recent aerial photographs. A brief examination of imagery archived in the National Collection of Aerial Photography of the Royal Commission on the Ancient and Historical Monuments of Scotland broadly confirmed this conclusion. Milne (2008) also reports that the August 2004 debris deposits and landslide scars were rapidly colonised by vegetation reducing the visibility of debris flow forms.

This essentially means that it is possible to infer that there was a gap of between 45 years (1959 to 2004) and 64 years (1940 to 2004) between major debris flow events. Of course, it is not known when the scars observed by Wilson (2006) were formed or indeed whether these events triggered debris flows that reached the road. The estimate of a return period of around 45 to 64 years is therefore, in all likelihood, somewhat conservative.

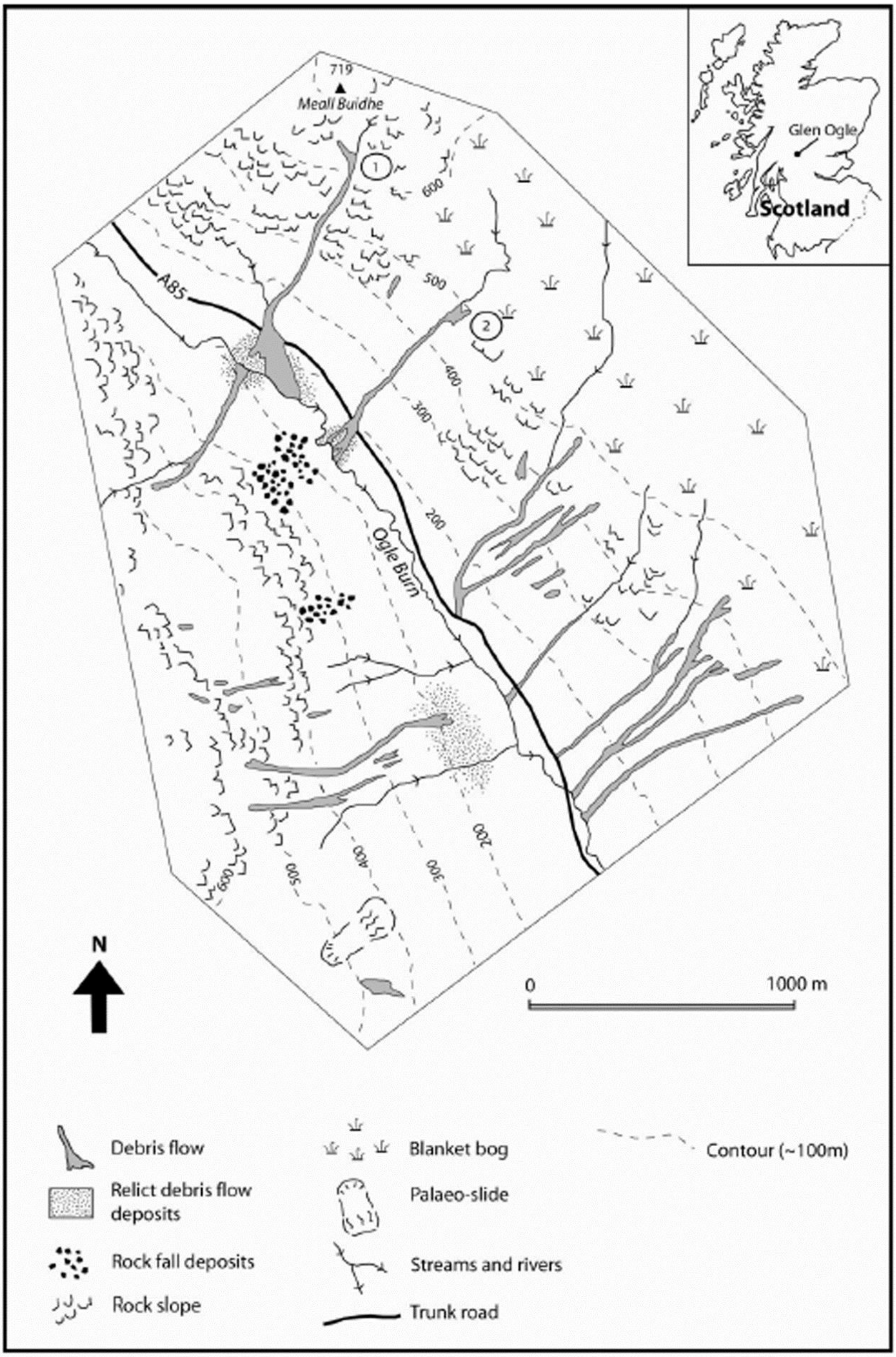

Figure 8. Geomorphological and location map of Glen Ogle showing debris flows generated on 18 August 2004; (1) and (2) on the map represent the northern and southern flows, respectively, described above. (From Milne, 2009.) A more detailed geomorphological map of the northern debris flow is in Milne et al. (2010).

It is also worth noting that, at the time of writing, more than 11 years have passed since the 2004 events at Glen Ogle without recurrence. Notwithstanding this there were media and social media reports of a landslide event at the A85 Glen Ogle on 30 December 2015 (associated with Storm Frank); whilst it is understood that the road was closed it appears that this was due to flooding and not as a result of a landslide.

These return periods (45 and 64 years) correspond to a frequency of between 0.02222 and 0.015625 per annum, which should be doubled to give 0.04444 to 0.03125 per annum, in the light of the two events that reached the road at Glen Ogle in 2004.

Figure 9. A possible relict debris deposits in the upper reaches of Glen Ogle. The possible deposits are clearly delimited in this image by the change in vegetation. Image dated August 2011.

Table 1. Details of known landslide events at the A85 Glen Ogle.

No.	Information Source	Date of occurrence	Landslide nature	Location	Estimated source volume (m^3)	Estimated deposition volume of fan (m^3)	Estimated width of deposition on A85 (m)*	Road closure
1	Winter et al. (2009); Milne et al. (2009)	18 August 2004	CDF	NN 57400 26650 (257400 726650)	280	8,500	127	Yes
2	Winter et al. (2009); Milne et al. (2009)	18 August 2004	CDF	NN 57700 26300 (257700 726300)	285	3,200	38	Yes

Remarks: CDF = Channelised debris flow.

* Estimated from high resolution post-event aerial photography (Figure 10). These channel widths include the multiple debris pulses that reached the road at slightly different positions in August 2004.

As part of the term maintenance contract, Transport Scotland requires the NW Operating Company (currently BEAR) to carry out visual and photographic surveys of the A85 Glen Ogle site every six months and to report the results of these annually. These surveys have not reported any major movements or other signs of instability since the debris flow events of August 2004. Figure 10 shows the major signs of debris flow in the study area superimposed on the aerial photography. This shows a total of 19 debris flows on the hillside in the area of interest of which two are those from 2004 that reached the road.

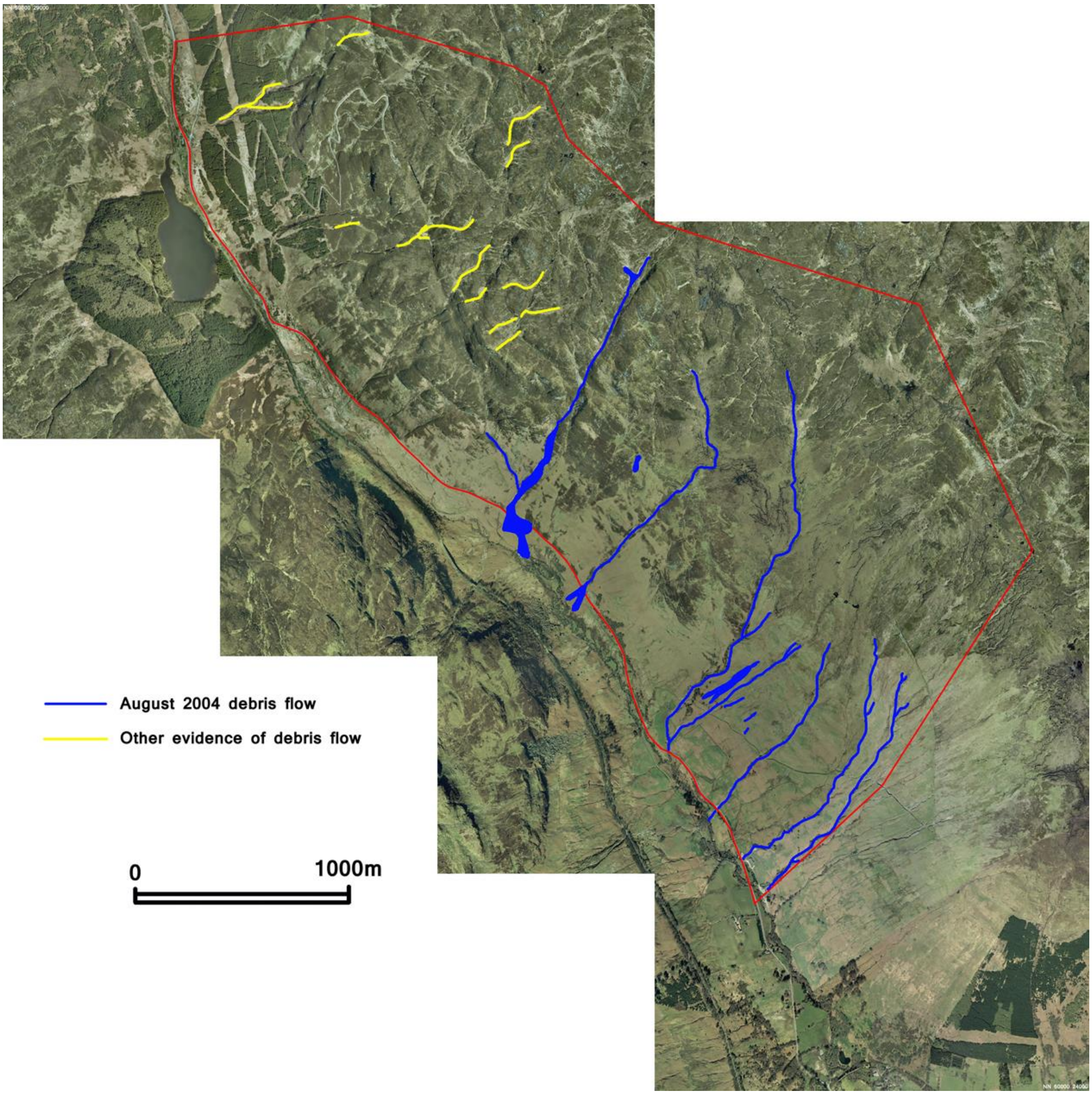

Figure 10. Debris flow events with known locations and signs of instability determined from the aerial photography. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

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, not least as the time period required in order to capture such data is significantly greater than the scale of a human lifetime. It also seems likely that high frequency, low magnitude events will be underreported as many such events will pass unnoticed. That said, the objective of the study was to analyse and evaluate the landslide fatality risk posed to road users at the A85 Glen Ogle 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 as part of 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 11 shows the SRNLS debris flow susceptibility map for the study area.

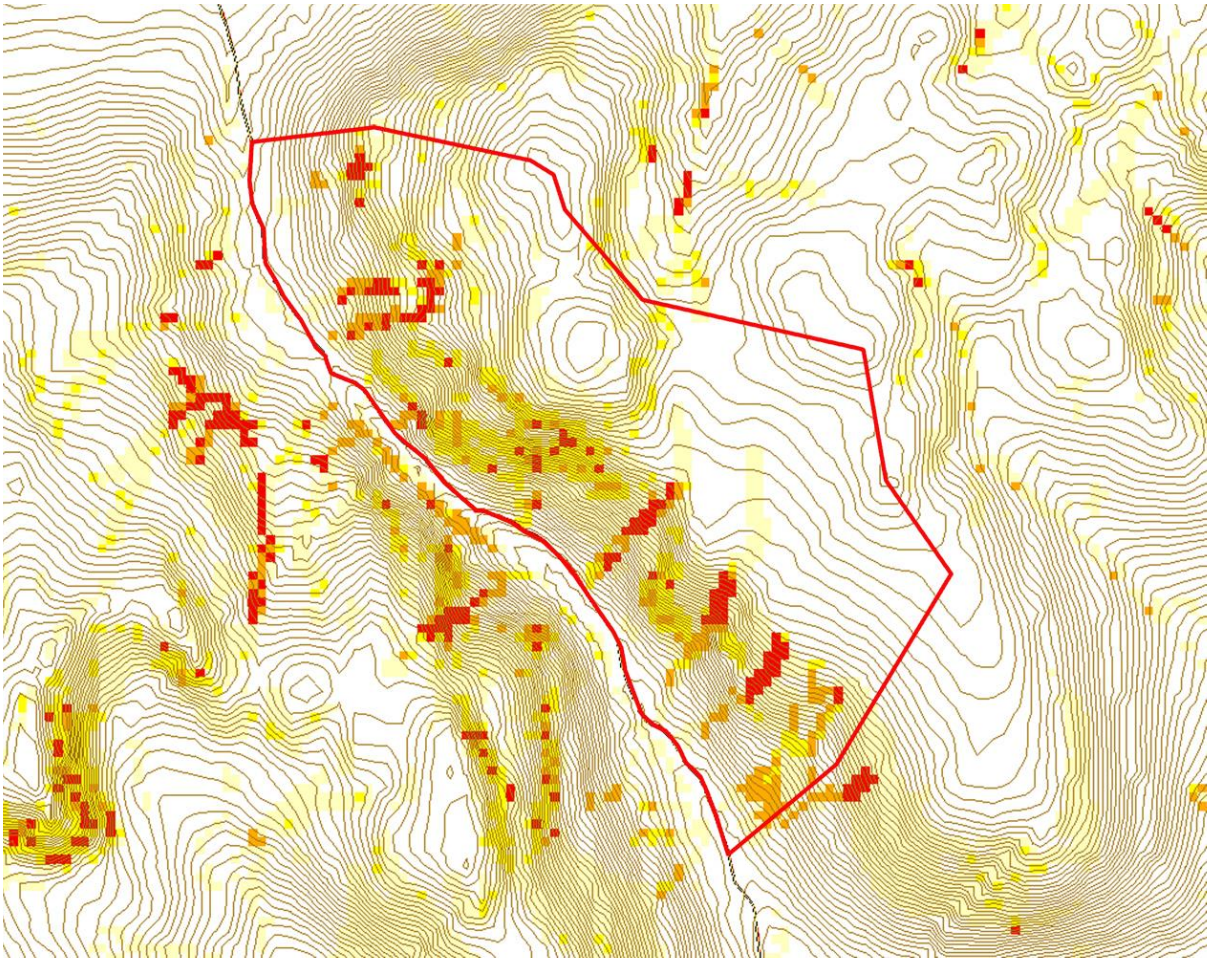

Figure 11. Debris flow susceptibility map (Winter et al., 2009) showing locations of known debris flow sources.

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 A85 in Glen Ogle, 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 although there were no structures, potentially with human occupancy, identified along this stretch of A85 (see also Section 2.3) these are at either end of the study area and are not specifically considered in the risk assessment.

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 12) 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:

$$Risk = P(Event) \times P(Hit|Event) \times P(Fatality|Hit) \tag{3}$$

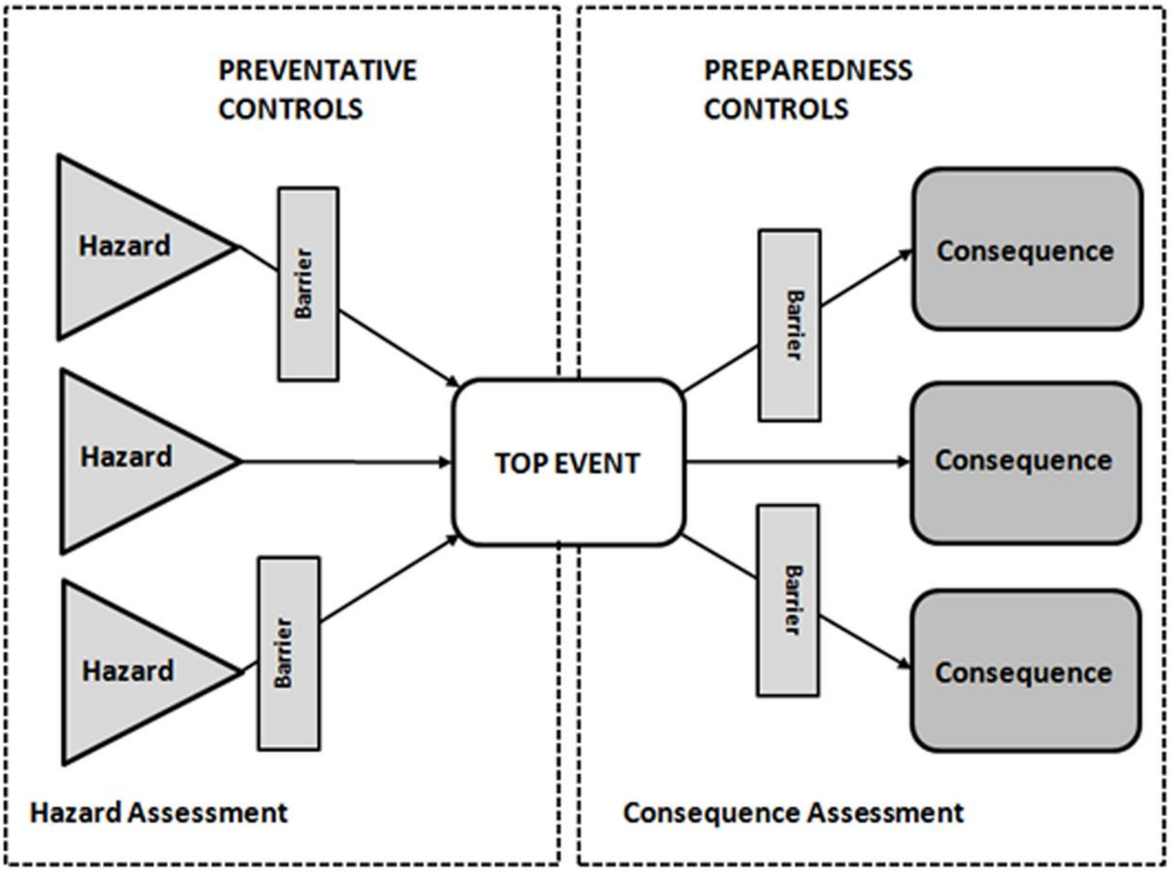

Figure 12. The risk assessment 'bow-tie' diagram (from Lee & Jones, 2014).

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 the frequency with which landslides might occur at Glen Ogle. In Section 5.1.4, the two 2004 events were taken as known and past evidence of mass movement on the hillside taken from Wilson (2006) indicates that previous events most likely occurred *at least* 45 to 64 years ago, as there is no certainly that the earlier events reached the road this is a conservative assumption.

Accordingly, the probability of annual occurrence, or frequency, of debris flow events causing disruption to road users at the A85 Glen Ogle was determined as follows:

Frequency of debris flow events causing disruption to road users, P(Event)
= Number of recorded landslides / time period (years) (4)
= 2/64 or 2/45 per annum

Giving a frequency of 0.03125 or 0.04444 events per annum.

P(Event) is taken forward as 0.04444 per annum in this study.

It is noted that the period of 11 years (2004 to 2015) for which detailed records are available is relatively short compared to that available and used for other similar studies. Typically this means that the probability of low-frequency, high-magnitude events might be underestimated, but the two events for which information is available at this location are of *relatively* high magnitude and there is an absence of information on smaller magnitude events that should occur at relatively high frequency. It may be that this indicates that the frequency is low and would in turn indicate that the frequency of the events considered here is high that is in fact the case. Alternatively it may be that low magnitude events at Glen Ogle simply do not tend to reach the road and are therefore not recorded. Nevertheless, the P(Event) calculated is considered to be the best estimate based on existing information for the purpose of this study and should be regarded as conservative.

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 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 traffic counters provide only gross (total) numbers of vehicles. The nearest potentially relevant traffic counter that does give a breakdown of vehicle classes is '108370 A82 Crianlarich (Core 903)', located between Crianlarich and Tyndrum, but this gives a zero count for motorcycles which is, at least, counter-intuitive for the A85 at Glen Ogle. It was therefore decided that the most effective and justifiable approach was to take the traffic data from 'A85(T) Glenogle Farm [16301 A85T 07]' which is located in Glen Ogle just to the south of the site but with no junctions between the counter and the northern limits of the site and to use the proportions of vehicle types derived for the A83 Rest and be Thankful site (Wong & Winter, 2018) using data from the traffic counter 'JTC08338 - A83 West of Arrochar'. The most recent data available for the A85 counter for 2010 showed apparent anomalies for the July data which was lower than would be expected so 2009 data was used instead; this gives a higher overall traffic count so may be considered conservative in that the calculated risk would be greater.

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 3,930 vehicles per day in 2009; and using the A83 data 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 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.

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.)	31	3,458	36	227	146	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.
Note that the proportions of vehicle types are taken from the A83 Rest and be Thankful study (Wong & Winter, 2018) in the absence of suitable available data in the A85 Glen Ogle area.

A total of 23 drainage channels ranging from 2m to 127m in width at road level, and averaging 11.5, were identified. In a field reconnaissance carried out on 3 February 2016, three out of the 23 drainage channels were found irrelevant (i.e. encompassed within the scope of another channel or with no expression on the hillside) whereas one new channel not identified from the Aerial Photography (AP) was identified (Table 3). As a result, 21 drainage channels were identified in the field (Figure 13). After the field verification, the width of the drainage channels measured on the outside lane ranged from 1m to 127m, with an average width of 12.0m (L_s). Wong & Winter (2018) reported more substantial differences between the desk-based and field measurements for the A83 Rest and be Thankful; for the work reported here, for the A85 Glen Ogle, a different desk-based measurement technique was used. Rather than examine the images in the GIS platform and interpret the position and size of channels once the positions of channels had been identified the AP was interrogated at the pixel level and the width of the each channel measured by the number of pixels it included. The physical dimension was then interpolated from the known size of the complete image and the corresponding number of pixels and a correction applied for the angle at which the stream passed through the pixel grid. While this technique appears to have been quite successful from a dimensional measurement point of view, it is also clear that some channels were not identified from the AP and others were identified that had no expression on the ground. It is clear that field verification remains a necessary exercise in order to fully understand the hydrological regime in addition to providing valuable insights into the hazards.

It was assumed that debris flow deposits on the slope could reach the A85 at any of the 21 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 21 channel widths, determined initially from the orthographic aerial photography and as then modified during the field reconnaissance (see Table 3, i.e. 252m)

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 out as they reach the road increasing the value of the denominator in Equation (5).

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 to the south-east of Locahn Lairig Cheile has an average 2.5^o downwards gradient in Glen Ogle 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^o on both sides of the channel intersection onto the carriageway.

Table 3. Drainage channels at the A85 Glen Ogle.

Initial Drainage Channel Number (from AP)	Width: from AP (m)	Final Drainage Channel Number (field)	Width: field (m)	National Grid Reference	Remarks
1	5	**1**	5	NN 58383 25084	
1A		**2**	1	NN 58337 25196	<1m
2	5	**3**	6	NN 58276 25287	
3	2	**4**	2	NN 58148 25469	N end of wall
4	6	**-**	-	-	No hillside expression
5	14	**5**	15	NN 58050 25566	
6	3	**6**	3	NN 57903 25793	Original 6/7 coalesce …
7	3	**-**	-	-	… just above road
8	5	**7**	3	NN 57828 26057	
9	38	**8**	38	NN 57669 26301	Southerly flow 2004
10	3	**9**	4	NN 57576 26451	
11	2	**10**	2	NN 57548 26473	Splits below culvert
12	127	**11**	127	NN 57385 26627	Northerly flow 2004
13	1	**-**	-	-	Road drainage
14	2	**12**	2	NN 57097 26766	
15	4	**13**	2	NN 56832 26980	
16	4	**14**	2	NN 56747 27079	
17	4	**15**	14	NN 56602 27198	
18	4	**16**	4	NN 56483 27353	
19	6	**17**	2	NN 56435 27424	
20	7	**18**	10	NN 56330 27510	Ogle Burn
21	3	**19**	2	NN 56066 27838	
22	5	**20**	2	NN 55967 27967	
23	11	**21**	6	NN 55788 28517	
Total width of channels			**252.0**		
No. of channels, N_H			**21**		
Average width of channels, L_s			**12.0**		

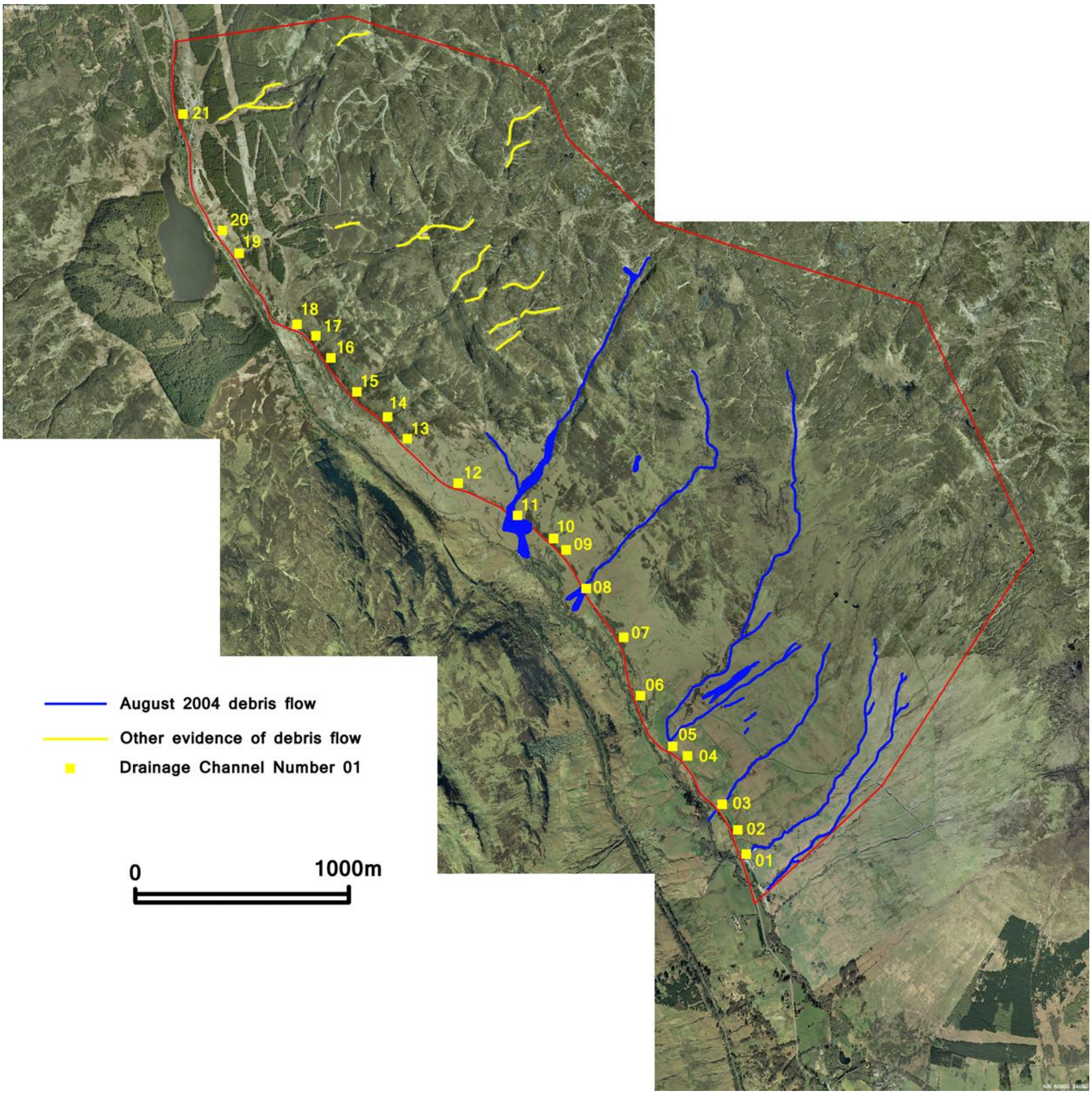

Figure 13. Locations of the drainage channels at the A85 Glen Ogle as confirmed by field reconnaissance. Base aerial photography reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2017. All rights reserved. Ordnance Survey Licence number 100046668.

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^o spread of the debris flow on reaching the road, and the average length of a vehicle on either side of the spread (see Figure 14). 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.

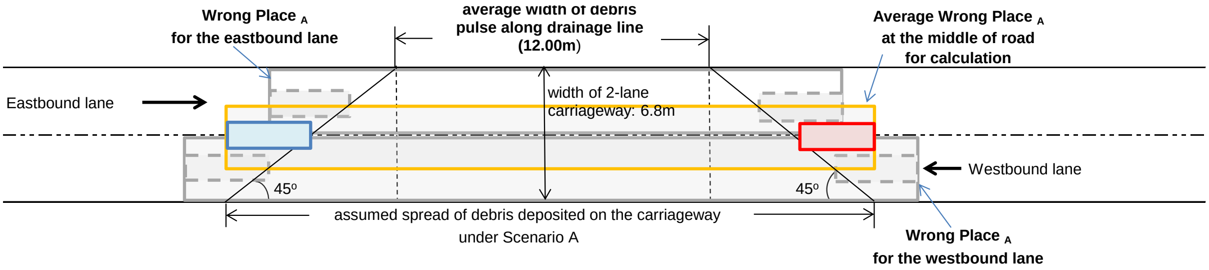

Figure 14. Wrong Place A for Scenario A.

Equation (5) may be modified from Figure 14 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 (21 from Table 3),
L_s is the average width of the stream channels (12.0m from Table 3), and
W_C is the width of the carriageway (6.8m from Figure 14 and observed from comparison with A83: Anon., 2013).

Which becomes:

$$P(Wrong\ Place_A) = \frac{5.22}{21(12.0 + 2(0.5 \times 6.8/\tan 45^o) + 2 \times 5.22)}$$
$$= \frac{5.22}{614.04} = 0.008499$$

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 15).

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

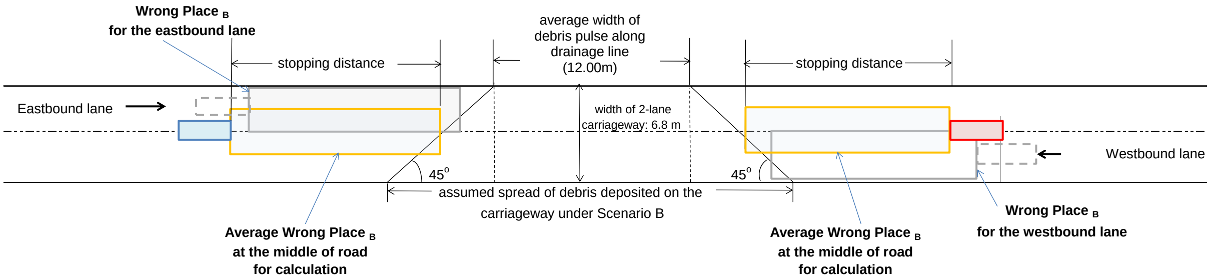

Figure 15. Wrong Place B for Scenario B.

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).

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$_B$)	0.006902	0.004688	0.003404

Which becomes:

$$P(Wrong\ Place_B) = \frac{5.22}{21.D_S} = 0.24857/D_S$$

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):

$$P(Wrong\ Time_{A\ or\ B}) = \frac{Total\ length\ of\ Wrong\ Place_{A\ or\ B}\ at\ the\ 21\ Drainage\ Channels}{V_s.24\left(\frac{hours}{day}\right).365.25\left(\frac{days}{year}\right)} \tag{8}$$

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 21 drainage channels	614.04	614.04	614.04	756	1113	1533
$P(Wrong\ Time_{A\ or\ B})$	1.088E-06	8.704E-07	7.253E-07	1.340E-06	1.578E-06	1.811E-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.

Wong & Winter (2018) developed figures for vulnerability based on the typically smaller events at the A83 Rest and be Thankful and here these figures are adapted for the larger events at the A85 Glen Ogle.

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

Given the limited available 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 Glen Ogle debris flow events with total deposition volumes reportedly ranging from 3,500m^3 to 8,500m^3 (Milne et al., 2009), correspond to the destroyed states of the fragility relationships. By correlating this landslide volume to the fragility curve for high-speed roads (Winter et al., 2014b) (Figure 16), the conditional probabilities for no damage, limited, serious and destroyed damage states are 0.4, 0.2 (0.6), 0.1 (0.4), and 0.3 (0.3) for the smaller 3,500m^3 event (notionally 5,000m^3) and 0.3, 0.15 (0.7), 0.15 (0.55) and 0.4 (0.4) for the larger 8,500m^3 (notionally 10,000m^3) event.

These probabilities relate purely to the damage likely to be imposed on the infrastructure. The aggregate conditional probabilities of 0.4 to 0.55 under the serious and destroyed damage states to the road section is somewhat higher than the vulnerability value of 0.3 for destruction of roads by hillslope and distal debris flow given by Michael-Leiba et al. (2002) as might be expected for these large events.

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[1].

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[1] 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.

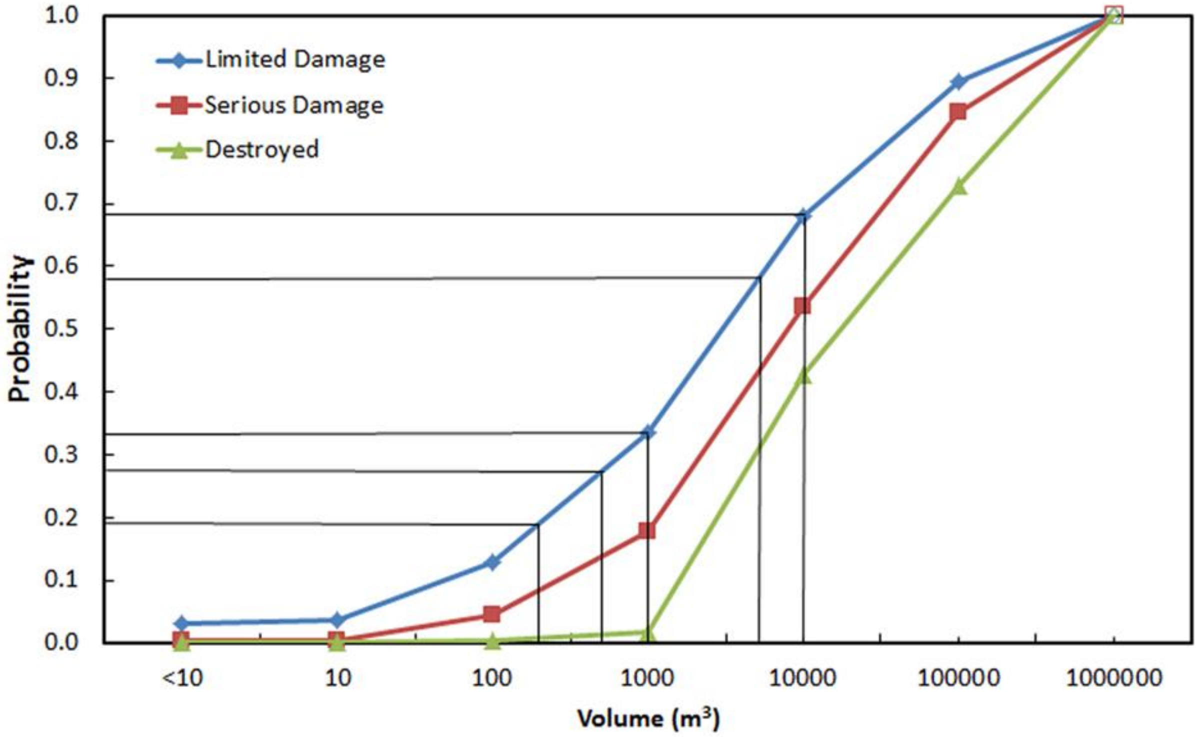

Figure 16. Fragility curve for a high-speed road (from Winter et al., 2014b).

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 author has near-direct (second-hand) experience of rockfall hitting a vehicle in Jamaica, an incident in 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, while significant burial and/or crushing is a possibility with debris flows of the order of 3,500m^3 to 8,500m^3, the images of the A85 events in 2004 (e.g. Figure 2) suggest that this is much less likely than, for example, a vehicle being entrained and swept downhill over the road. In addition, 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 a vehicle struck by a debris flow is damaged only. Wilson et al. (2005) suggest a vulnerability of unity for vehicle passengers subject to debris flow of 3,000m^3 or above; in the light of the forgoing this latter value seems very high and rather conservative. Certainly the evidence presented above suggests a much lower value, and a value of P(Fatality|Hit $_A$) of 0.3 seems appropriate for the purpose of the A85 Glen Ogle QRA.

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 300m^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.

In addition, video evidence of a car in Tennessee (USA) driving into a rockfall at speed gives some evidence that the probability of fatality in such scenarios may not be so high as might at first be assumed (https://www.youtube.com/watch?v=gBmE92n5mEI). Notwithstanding that the values reported by Wilson et al. (2005) seem to be very low and have no dependence upon speed.

The section of road at the A85 Glen Ogle is relatively straight (see Figure 1) with a gentle gradient of around 3^o. Based on site observations during the hours of daylight in a variety of weather conditions including rain day, the sightline was experienced to be generally 200m or more, 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 can 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 17).

Subsequent discussions with TRL specialists on vehicle impact, based on the variation in vehicle speed within the mean sightline, led to the development of speed-dependent human vulnerability curves, initially for events <1,000m^3 experienced at the A83 Rest and be Thankful (Wong & Winter, 2018) and subsequently for the larger events experienced at the A85 Glen Ogle. 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, higher impact speeds would give rise to a higher risk of vehicle damage and therefore the human vulnerability.

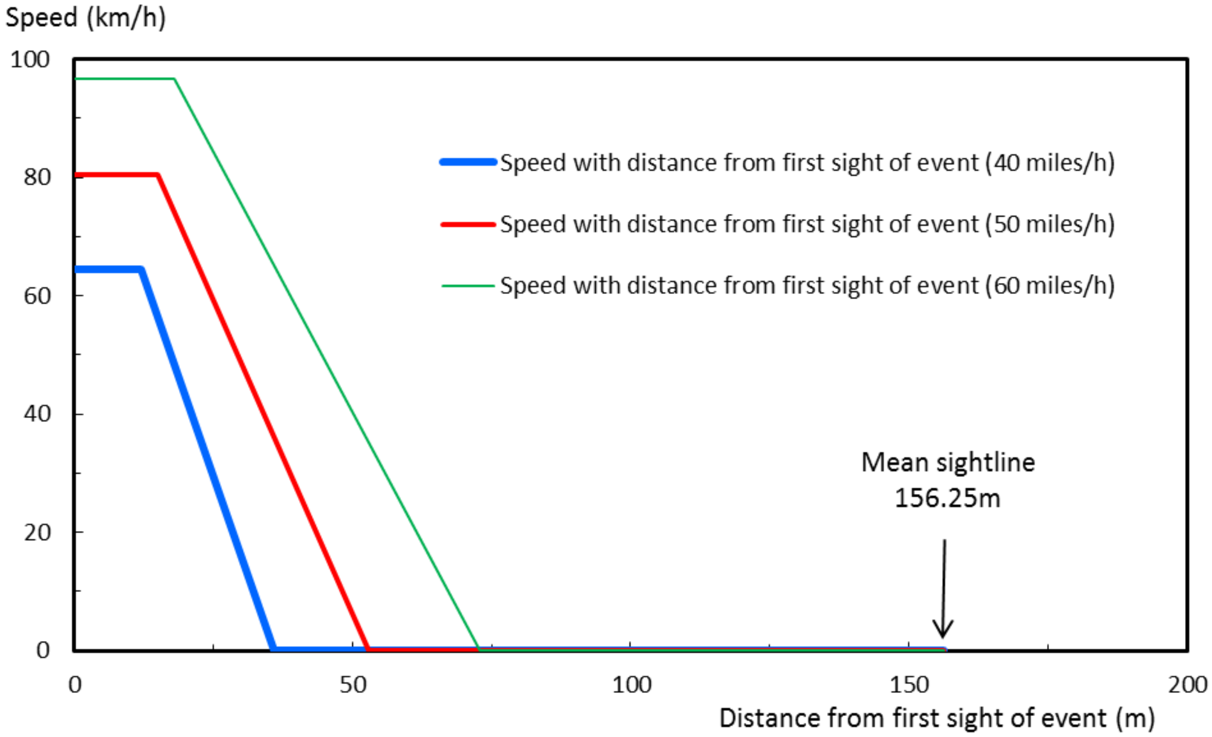

Figure 17. Vehicle speed variation within the 156.25m mean sightline for starting speeds of 40, 50 and 60 miles/h.

Accordingly, the initial P(Fatality|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 0.3. Depending on the initial vehicle speed, the initial human vulnerability values of 0.225, 0.15, 0.075 and 0.0015 were assumed for 50, 40, 30 and 20mph on a more or less linear relation, and a vulnerability of 0.0001 at 10mph and vulnerability was designated as zero at 0mph (Figure 18).

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 17). P(Fatality|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(Fatality|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(Fatality|Hit $_B$) within the average sightline for each initial vehicle speed of 40, 50 and 60 mph was normalised as 0.02304, 0.04896 and 0.08736 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.

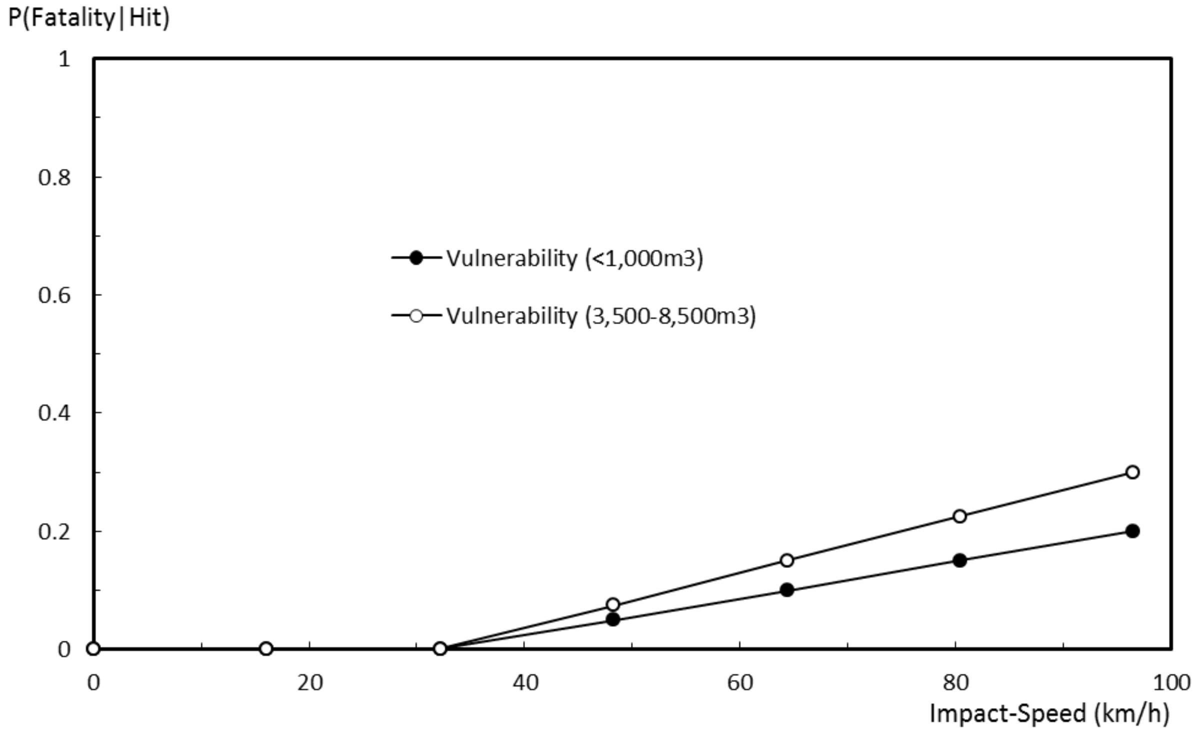

Figure 18. P(Fatality|Hit $_B$) at different initial vehicle speeds immediately prior to stopping.

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	0.15	Initial vehicle speed at 64km/h	0.02304
	12	64	0.15	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	0.225	Initial vehicle speed at 80km/h	0.04896
	15	80	0.225	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	0.3	Initial vehicle speed at 97km/h	0.08736
	18	97	0.3	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 A85 at Glen Ogle 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 1.147E-10 per year.

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

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

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) and is not only independent of the scenario but also of the site under consideration.

The PIR results determined with reference to the workflow of Lee & Jones (2014), Tables 8 and 9, were benchmarked with those determined using the method proposed by Bunce et al. (1997). They used the binomial theorem to determine the probabilities of impact 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 8. Personal Individual Risk under Scenarios A and B on a single trip along the A85 Glen Ogle.

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	0.04444	0.04444	0.04444	0.04444	0.04444	0.04444
P(Wrong Place)	Spatial probability of the vehicle within all 'Wrong Place' along the 26 drainage channels	8.499E-03	8.499E-03	8.499E-03	6.902E-03	4.688E-03	3.4049E-03
P(Wrong Time)	Temporal probability of the vehicle within all 'Wrong Place' along the 26 drainage channels	1.088E-06	8.704E-07	7.253E-07	1.340E-06	1.578E-06	1.811E-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)	4.109E-10	3.288E-10	2.740E-10	4.109E-10	3.288E-10	2.740E-10
P(Fatality|Hit)		0.30	0.30	0.30	0.02304	0.04896	0.08736
PIR (Single trip per year)	P(Individual vehicle hit per year)× P(Fatality|Hit)	1.233E-10	9.863E-11	8.219E-11	9.468E-12	1.610E-11	2.393E-11

Table 9. Personal Individual Risk under Scenarios A and B on a single trip along the A85 Glen Ogle.

	Initial Vehicle Speed (mph)		
	40	**50**	**60**
PIR (Single trip under Scenario A per year)	1.233E-10	9.863E-11	8.219E-11
PIR (Single trip under Scenario B per year)	9.468E-12	1.610E-11	2.393E-11
Total PIR (single trip)/year	1.328E-10	1.147E-10	1.061E-10

Table 10. Personal Individual Risk under Scenario A on a single trip along the A85 Glen Ogle 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)	0.04444	0.04444	0.04444
P(S:H)	Probability that a vehicle occupies the portion of the road section affected by a debris flow	8.499E-03	8.499E-03	8.499E-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	1.088E-06	8.704E-07	7.253E-07
P(S)	Probability of one or more vehicles being hit (in an year) $P(S) = 1 - (1 - P(S{:}H))^{Nr}$	3.793E-04	3.793E-04	3.793E-04
P(L:T)	Probability of death given temporal impact, i.e. P(Fatality|Hit_{A})	0.3	0.3	0.3
PAV	Annual probability of an accident to a particular vehicle P(S) x P(T:S)	4.126E-10	3.301E-10	2.751E-10
PDI	Probability of a death on an individual trip, i.e. PIR (Single trip under Scenario A) PAV x P(L:T)	1.238E-10	9.903E-11	8.252E-11
For comparison (this study): PIR (single trip under Scenario A)		**1.233E-10**	**9.863E-11**	**8.219E-11**

Individual drivers will use the section of road at the A85 Glen Ogle 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 Glen Ogle. 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. For commuters the calculation is made for speeds of both 60mph and 50mph as the speed limit for passenger cars changed during the project from the National Speed Limit of 60mph to 50mph, the latter coming into force on 9 November 2015 (Anon., 2015).

The results show that the PIR levels of these two types of road user (around 1 in 20 million at 60mph and 1 in 18.5 million at 50mph), commuters, and 1 in 3.5 million, logistics truck drivers) are considerably 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 A85 Glen Ogle. It is also instructive to compare the comparable risks at the A83 Rest and be Thankful (Wong & Winter, 2018) at 1 in 1.35 million for commuters and one in 520,000 for logistics truck drivers.

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	50mph / 60mph	40mph
Total PIR of fatality (single trip per year)	1.147E-10 / 1.061E-10	1.328E-10
Maximum PIR of fatality = Total PIR of fatality (single trip per year) x No. of journey per year	5.391E-08 / 4.987E-08	1.248E-07

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 A85 Glen Ogle 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 A85 Glen Ogle 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 A85 Glen Ogle 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 occupancy 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 A85 Glen Ogle per year
CCE1-motorbike	1.55%	N/A	1	1.55%	22260
CCE2-car/van	87.98%	One	1	56.31%	808238
		Two	2	22.35%	320769
		Three	3	6.07%	87138
		Four	4	2.46%	35360
		Five or More	6	0.79%	11366
CCE3-car+trailer	0.85%	One	1	0.59%	8480
		Two	2	0.23%	3365
		Three	3	0.06%	914
		Four	4	0.03%	371
		Five or More	6	0.01%	119
CCE4-LGV/rigid HGV	5.77%	N/A	2	5.77%	82875
CCE5-HGV	3.72%	N/A	2	3.72%	53353
CCE6-bus	0.06%	N/A	56	0.06%	800

Note that the proportions of vehicle types are taken from the A83 Rest and be Thankful study (Wong & Winter, 2018) in the absence of suitable available data in the A85 Glen Ogle area.

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 approach adopted the number of people at risk: i.e. unfactored exposed population as N and considered the vulnerability factor in the calculation of F (e.g. 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.

Consequence 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	838,978	1	0.3	0.3	8.274E-05	2.758E-04	4.719E-04
A2	460,363	2	0.3	0.6	9.081E-05	1.513E-04	1.961E-04
A3	88,052	3	0.3	0.9	2.605E-05	2.895E-05	4.473E-05
A4	35,731	4	0.3	1.2	1.410E-05	1.175E-05	1.579E-05
A5	11,485	6	0.3	1.8	6.796E-06	3.776E-06	4.039E-06
A6	800	56	0.3	16.8	4.420E-06	2.631E-07	2.631E-07

[1] P(Individual vehicle hit) = 3.288E-10 /year. Total 2.249E-04

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.

Consequence 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	838,978	1	0.04896	0.04896	1.350E-05	2.758E-04	4.719E-04
B2	46,0363	2	0.04896	0.09792	1.482E-05	1.513E-04	1.961E-04
B3	88,052	3	0.04896	0.14688	4.252E-06	2.895E-05	4.473E-05
B4	35,731	4	0.04896	0.19584	2.300E-06	1.175E-05	1.579E-05
B5	11,485	6	0.04896	0.29376	1.109E-06	3.776E-06	4.039E-06
B6	800	56	0.04896	2.74176	7.213E-07	2.631E-07	2.631E-07

[1] P(Individual vehicle hit) = 3.288E-10/year. Total 3.671E-05

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 19. 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 'Broadly 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	2.249E-04	3.671E-05	2.616E-04

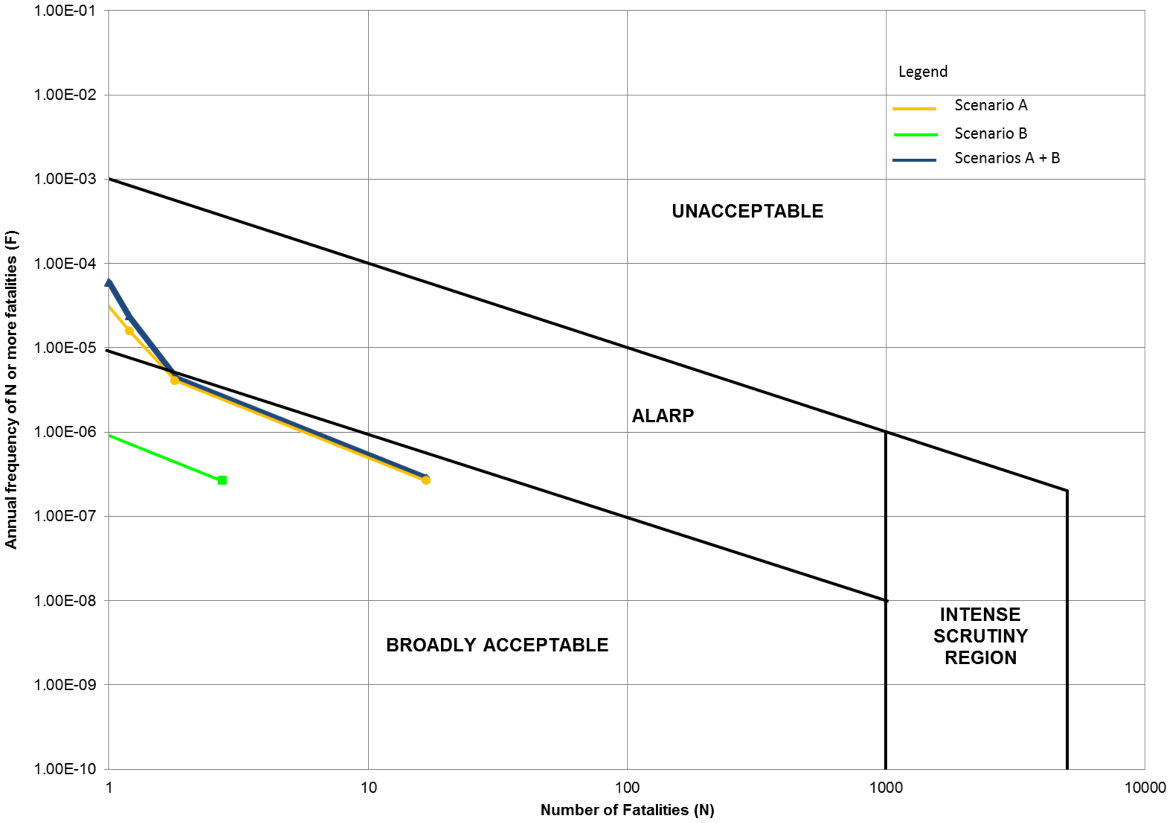

Figure 19. F-N Curves based on the approach of Lee and Jones (2014).

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.

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 20).

Table 16. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario A using the approach of Wong et al. (2004). The consequence class simply refers to the different levels of vehicle occupancy.

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	0.3	838,978	8.274E-05	1.416E-04
A2	2	0.3	46,0363	4.540E-05	5.882E-05
A3	3	0.3	88,052	8.684E-06	1.342E-05
A4	4	0.3	35,731	3.524E-06	4.736E-06
A5	6	0.3	11,485	1.133E-06	1.212E-06
A6	56	0.3	800	7.892E-08	7.892E-08

[1] P(Individual vehicle hit) = 3.288E-10/year

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 for lower numbers of fatalities and in the Broadly Acceptable risk zone for higher numbers of fatalities.

Table 17. Calculation for plotting F-N curves for vehicle speed at 50mph under Scenario B using the approach of Wong et al. (2004). The consequence class simply refers to the different levels of vehicle occupancy.

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	838,978	1.350E-05	2.310E-05
B2	2	0.03264	46,0363	7.410E-06	9.600E-06
B3	3	0.03264	88,052	1.417E-06	2.190E-06
B4	4	0.03264	35,731	5.751E-07	7.729E-07
B5	6	0.03264	11,485	1.849E-07	1.977E-07
B6	56	0.03264	800	1.288E-08	1.288E-08

[1] P(Individual vehicle hit) = 3.288E-10/year

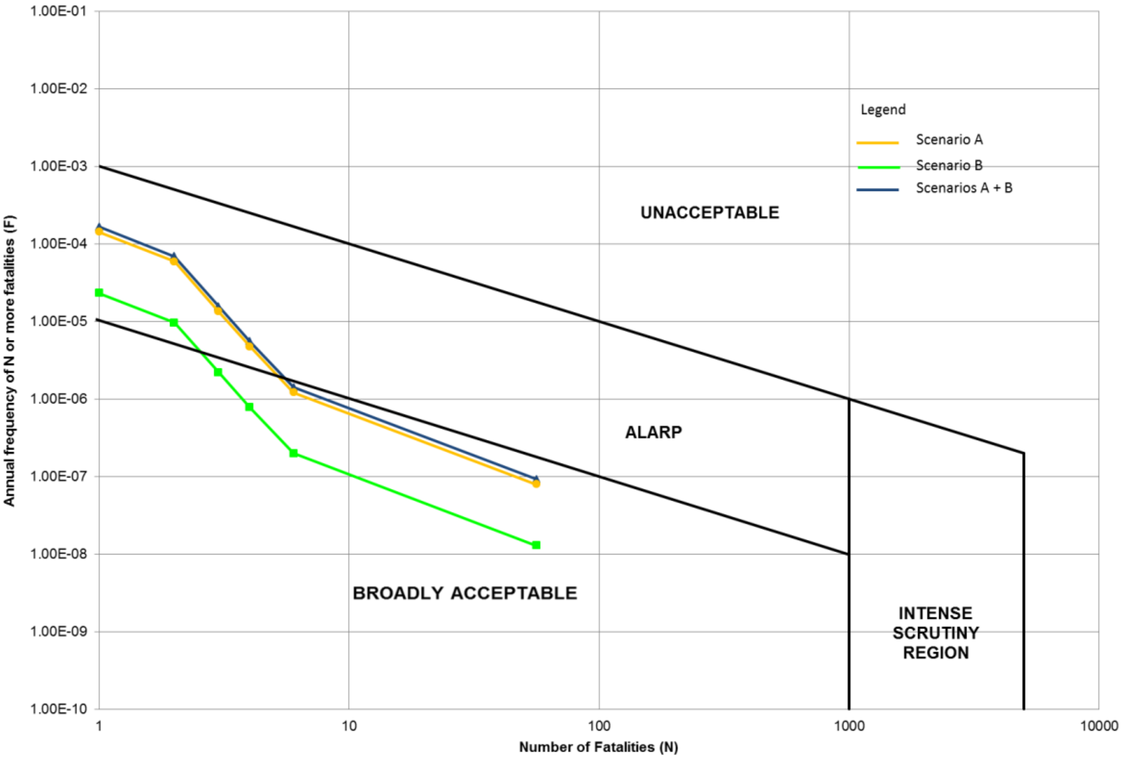

Figure 20. F-N Curves based on the approach of Wong et al. (2004).

7 Discussion

7.1 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) of fatality at Glen Ogle for a single trip (per year) which is speed dependent and varies from 1.328E-10 (40 mph), 1.147E-10 (50 mph) to 1.061E-10 (60 mph). Those who make multiple trips are exposed to a greater level of risk. Estimates of the annual probability of fatality for those most at risk have been made for commuters, at 4.987E-08 or an approximately 1 in 20 million chance (at the national speed limit of 60 mph) or 5.391E-08 or approximately 1 in 18.5 million at the revised speed limit for passenger cars in Glen Ogle of 50mph, and logistics truck drivers, at 1.248E-07 or an approximately 1 in 8 million chance (at the speed limit for heavy goods vehicles of 40 mph).

The values of PIR are considerably 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 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 21).

Overall the risk of a fatality (Scenario A plus B) from a debris flow shows a small decrease with 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.

7.2 Societal Risk

The societal risk from debris flow at the A85 Glen Ogle 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 at the A85 Glen Ogle. 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 ALARP 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 the risk levels plot broadly in the ALARP zone for lower numbers of fatalities and in the Broadly Acceptable risk zone for higher numbers of fatalities.

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 A85 Glen Ogle and, for an average traffic speed of 50mph, is 2.616E-04, which corresponds to one fatality every 3,822 years.

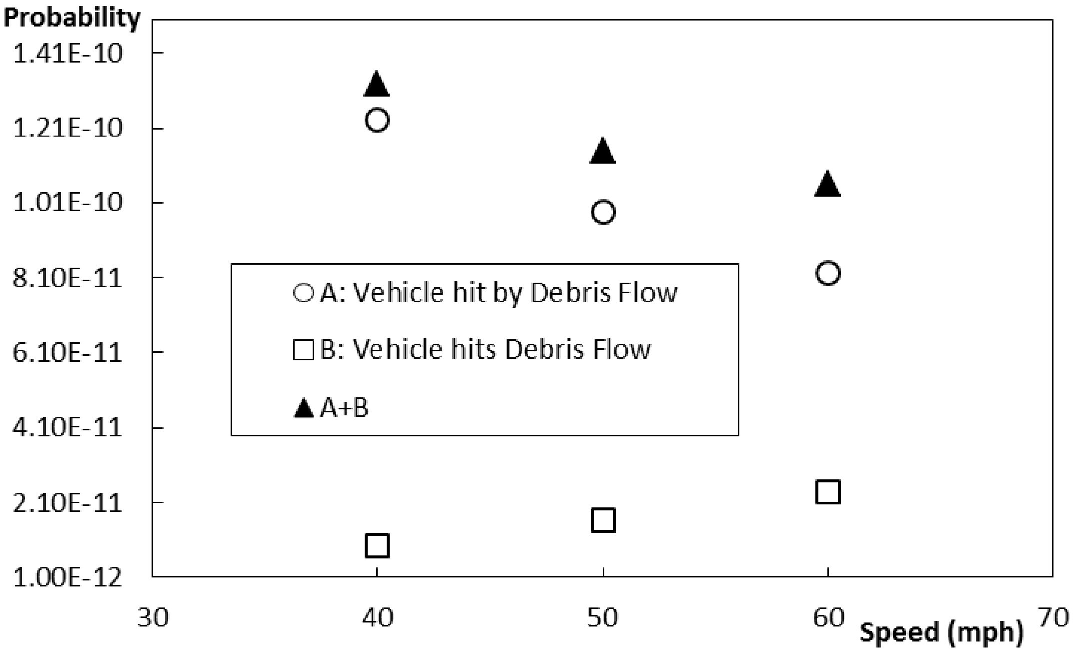

Figure 21. The variation of PIR for the two risk scenarios and total risk with speed.

7.3 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 1.248E-07 to 2.496E-07 (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 such 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 event frequency. A doubling of the event frequency would, however, still leave the societal risk within the ALARP zone for smaller numbers of fatalities and in the Broadly Acceptable zone for higher numbers of fatalities.

Of course, an assumption of the doubling of either frequency or magnitude is rather speculative and it must be remembered that frequency and magnitude are not completely decoupled; an increase in magnitude may leave less loose previously mobilised material to be entrained 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 such material and it may be less likely that a larger magnitude event will develop.

7.4 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 A85 Glen Ogle 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 described in Section 5 was compiled from various sources including Operating Company reports, field photographs and the author's own experience. The event frequency in particular is subject to uncertainty and the potential period between events was estimated to be between 45 and 64 years. The shorter period, corresponding to a higher event frequency of 0.04444 events per year and associated with a higher risk, was chosen for this study and the PLL corresponds to 2.616E-4 per annum or one life lost every 3,822 years. The longer period of 64 years leads to a lower frequency (0.03125 events per year) and an associated lower risk. If we apply this lower event frequency to the annual Potential Loss of Life (PLL), for example, then this reduces to 1.840E-04, which corresponds to one fatality every 5,335 years.

Conversely the period of 12 years since the most recent 2004 events would, if a further event (or events) were to occur in Glen Ogle in the near future, place a very different complexion on the event frequency and the resultant risk. A single event in 2016 would mean that three events had occurred in 12 years giving an event frequency of 0.25 events per year giving a PLL of 1.472E-03 or one fatality per 680 years. It should, however, be noted that there is no suggestion that this scenario is anything other than illustrative of the uncertainties involved in the analysis and there is certainly no suggestion that an event is imminent at the A85 Glen Ogle site.

Wong & Winter (2018) recommended that a more complete and systematic database of the landslide history of the A83 Rest and be Thankful site should be set up. The lack of long-term event information for the A85 Glen Ogle site reported on herein emphasises the need for this to be progressed on a Scotland-wide basis. This should be seen as a long-term project for sites such as Glen Ogle at which the frequency of events is low and a pan-Scotland system of reporting is recommended.

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 from 2004 to the present. In this context the possibility of underrepresentation of low-frequency, high-magnitude events (yet to occur or in the distant past) cannot be discounted. 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.

8 Summary

This report applies the methodology developed for undertaking a quantitative risk assessment (QRA) for the impact of debris flow on roads to the A85 at Glen Ogle.

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) of fatality at Glen Ogle for a single trip (per year) is speed dependent and varies between 1.328E-10 (40 mph), 1.147E-10 (50 mph) and 1.061E-10 (60 mph). Those who make multiple trips are exposed to a greater level of risk. Estimates of the annual probability of fatality for those most at risk have been made for commuters, at 4.987E-08 or an approximately 1 in 20 million chance (at the national speed limit of 60 mph) or 5.981E-08 or approximately 1 in 18.5 million at the revised speed limit for passenger cars in Glen Ogle of 50mph, and logistics truck drivers, at 1.248E-07 or an approximately 1 in 8 million chance (at the speed limit for heavy goods vehicles of 40 mph); these fall within generally tolerable limits.

The fact that the risk decreases with increasing speed must be set against the relatively low overall risk levels. 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 shows:

- that for one to four fatalities the annual risk falls into the ALARP zone and
- that for casualty number greater than four the risk falls into the Broadly Acceptable zone.

Potential Loss of Life (PLL), is the annual probability of a fatality being caused by debris flow at the A85 Glen Ogle is 2.216E-4, which corresponds to one fatality every 3,822 years or approximately one fatality every four millennia.

The potential effects of climate change on the frequency and magnitude of future events at the A85 Glen Ogle 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, also remain in the ALARP zone on the F-N diagram for low numbers of fatalities (N=1 to 4).

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