

# Applications of Quantitative Risk Assessment for Debris Flow and Road Users

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**ABSTRACT:** Landslides have the potential to cause great disruption to transport networks, severing access for often remote communities to employment, education, health and social opportunities. However, their greater impacts are in potential loss of life for which fast-moving debris flows are of particular concern. A methodology for quantitative risk assessment to determine the annual probability of single and multiple fatalities resulting from the effects of debris flow on mobile road users has been developed. The methodology has been applied to three sites that encompass the range from high frequency-low magnitude to low frequency-high magnitude events. The methodology considers the probability of an event of a given 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 included. An additional methodology has been developed and applied at one site for a third scenario in which vehicles and road users are static in a car park. This includes a new metric to allow the temporal probability of a landslide impacting a person to be determined. The results are presented in terms of Personal Individual Risk (PIR) and in terms of the Frequency-Number (F-N) diagram, often referred to as the ALARP diagram. The application of the results to inform strategic responses to the extant risk and to suggest the level of landslide risk reduction appropriate to different sites is demonstrated.

**KEYWORDS:** Landslide, Debris flow, Road, Highway, Risk, Hazard.

## 1 INTRODUCTION

Fast-moving debris flows have the potential to be destructive to both buildings and infrastructure but, more importantly, to place the lives of people affected by them in jeopardy. Road users typically face two risk scenarios from such debris flows: that of a vehicle being hit by a debris flow and that of a vehicle hitting a debris flow (mobile elements at risk). However, at one site in Scotland car parks have been developed informally on the run-out materials from debris flows which introduces a third scenario of static elements at risk; people who are to all intents and purposes stationary potentially being hit by a debris flow.

The methodology for mobile elements at risk was developed for and applied at the A83 Rest and be Thankful which was believed to be the first full, formal quantitative risk assessment for debris flow risk to road users (Wong & Winter, 2018; Winter & Wong 2020); the methodology has been additionally applied at the A85 Glen Ogle (Winter 2018; Winter & Wong 2020) and A82 Glen Coe (Winter et al. 2024). The methodology for static elements at risk was developed for and applied at the A82 Glen Coe (Winter et al. 2024). This involves an assessment of the risk to people in those car parks being hit by debris flows.

The sites (Fig. 1) were selected from amongst the highest risk locations determined from the Scottish Road Network Landsides Study (Winter et al. 2005, 2008, 2013). In this paper we briefly describe the results of the QRAs, but not the methodology, and demonstrate how these are being and can be used to guide management and mitigations interventions to achieve landslide risk reduction. The citations contained herein allow the reader to access highly detailed information on the debris flow hazards, including the known history, the methodologies developed for each of the three scenarios, as well as the application and derivation of probabilities of loss of life for each of the three scenarios, as appropriate, at each site.

## 2 HAZARDS

The study sites represent areas with both high frequency, low magnitude events (A83 Rest and be Thankful) hazards and low frequency, high magnitude hazards (A85 Glen Ogle) with the A82 Glen Coe having areas characteristic of both categories.

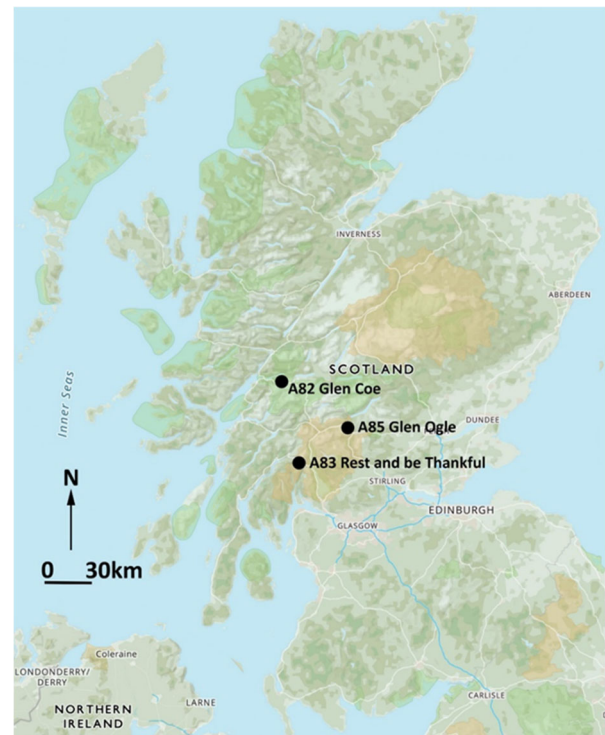


Figure 1. Figure 2. Map of Scotland (without Orkney and Shetland) showing the three sites. Ordnance Survey, base mapping, © Cro6n Copyright. All rights reserved Scottish Government 100020540, 2025.

### 2.1 A83 Rest and be Thankful

The A83 trunk (strategic or national) road is a 157 km-long two-lane single-carriageway connecting the A82 trunk road at Tarbet on Loch Lomond south-westwards to Campbeltown in Kintyre, connecting principal towns such as Inveraray, Lochgilphead, Tarbert and Campbeltown as well as other areas such as Dunoon and Cowal, Kintyre, and the islands of Islay, Jura and Gigha with the Trunk Road Network (TRN). The A83 supports the economic activities in the region including agriculture, forestry and fisheries, energy production, transport and storage, tourism and public administration.

The glacial context of the wider site is described by Finlayson (2020) and an account of the operational management activities and processes that are applied at the site is given by McMillan & Holt (2019). The A83 Rest and be Thankful site has been extremely active in recent years with multiple debris flow events and associated closures; events in 2007 (Fig. 2), 2008, 2009, 2011, 2012, 2013, 2014, 2015, 2016, and 2018, 2020 and 2021 had an adverse effect on the travelling public. This has meant that the area has become the focus of not only concern but also of extensive landslide management and mitigation activity and currently the site is subject to feasibility, planning and design for major landslide risk reduction works.

The event frequency determined for the A83 site was 0.83 per annum for event magnitudes typically between 10 and 1,000m<sup>3</sup>. It should be noted that post-2018 the magnitude of events at this site accelerated and major infrastructure works are now in the pipeline to reduce the risk.



Figure 2. View of the debris flows above and below the A83 on the approach to the Rest and be Thankful. The head scar is at approximately 370 m Above Ordnance Datum (AOD), the A83 at 240 m AOD and the Old Military Road (OMR) at 180 m AOD.

## 2.2 A85 Glen Ogle

The A85 trunk road is a 139km-long two-lane single-carriageway that connects the A9 at Perth in the east of Scotland with Oban in the west. The A85 supports the economic activities in the region including agriculture, forestry and

fisheries, energy production, transport and storage, tourism, and public administration.

The section of the A85 trunk road through Glen Ogle is a relatively narrow single-carriageway that climbs northwestward from Lochearnhead at around 100m AOD. From Lochearnhead, the A85 runs to the west of Ogle Burn to the pass at the top at approximately 363m AOD.

Two major debris flow events closed the A85 in August 2004 (Winter et al. 2005, 2006) and these are located towards the mid-point of this section approximately 1.7 and 2.2km from the southern end of the section. The debris flow events at the A85 Glen Ogle were amongst the most notable events that occurred in August 2004 and along with other events at the A83 between Glen Kinglas and to the north of Cairndow, and at the A9 to the north of Dunkeld led to the Scottish Road Network Landslides Study (Winter et al. 2005, 2008, 2013). At Glen Ogle, while there were no major injuries, 57 people had to be airlifted to safety when they became trapped between the two major debris flows.

As a point of interest, 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 but now provides a series of excellent viewpoints for the eastern flanks of Glen Ogle.

Fig. 3 identifies both the August 2004 debris flows and other evidence of debris flow using information from (Winter et al. 2006; Milne et al. 2009, 2010). As is the case for the A83 site it is clear that the debris flow events on the hillside above the A85 are largely coincident with stream channels.

The event frequency determined for the A85 site was between 0.03125 and 0.04444 events per annum of a magnitude of between 3,000m<sup>3</sup> and 10,000m<sup>3</sup>, with the higher frequency taken forward for analysis.

## 2.3 A82 Glen Coe

The A82 trunk road links Scotland's largest city Glasgow, in the south, with its most northerly city Inverness, over a distance of almost 270km. For the majority of its length, including Glen Coe, the A82 comprises a two-lane single-carriageway road that broadly follows historic routes with contemporaneous upgrades to some of the busier sections. The historic routes include the military roads constructed through the Highlands by General Wade and Major Caulfeild in the 18th century and with later roads constructed by Thomas Telford during the 19th century.

The A82 trunk road through Glen Coe is a relatively narrow single-carriageway that runs from Rannoch Moor in the east at an elevation of approximately 315m above ordnance datum (AOD) to Glencoe village in the west (5m AOD). With access to one of Scotland's ski resorts, multiple historic sites, and some of the best and most important hiking and climbing routes in the UK; Glen Coe is generally considered to be one of the most important tourist destinations in Scotland.

The complex structural geology (Stephenson & Goodenough. 20007), and the geomorphology and history of instability of Glen Coe (Ballantyne 1991, 2002; Brazier 1987, 1992; Thorp 1981) played a key role in informing the hazard analysis. The event frequency determined for the A82 site was 0.0870 events per annum for a longer stretch of road (8,500m) subject to lower magnitude (around 1,000m<sup>3</sup>) events and 0.0685 events per annum for shorter stretch of road (1,010m) subject to higher magnitude events (around 5,000m<sup>3</sup>). This latter frequency magnitude was also applied to the static elements at risk and the shorter stretch of road is illustrated in Fig. 4 along with the central section showing the car parks containing the static elements at risk.

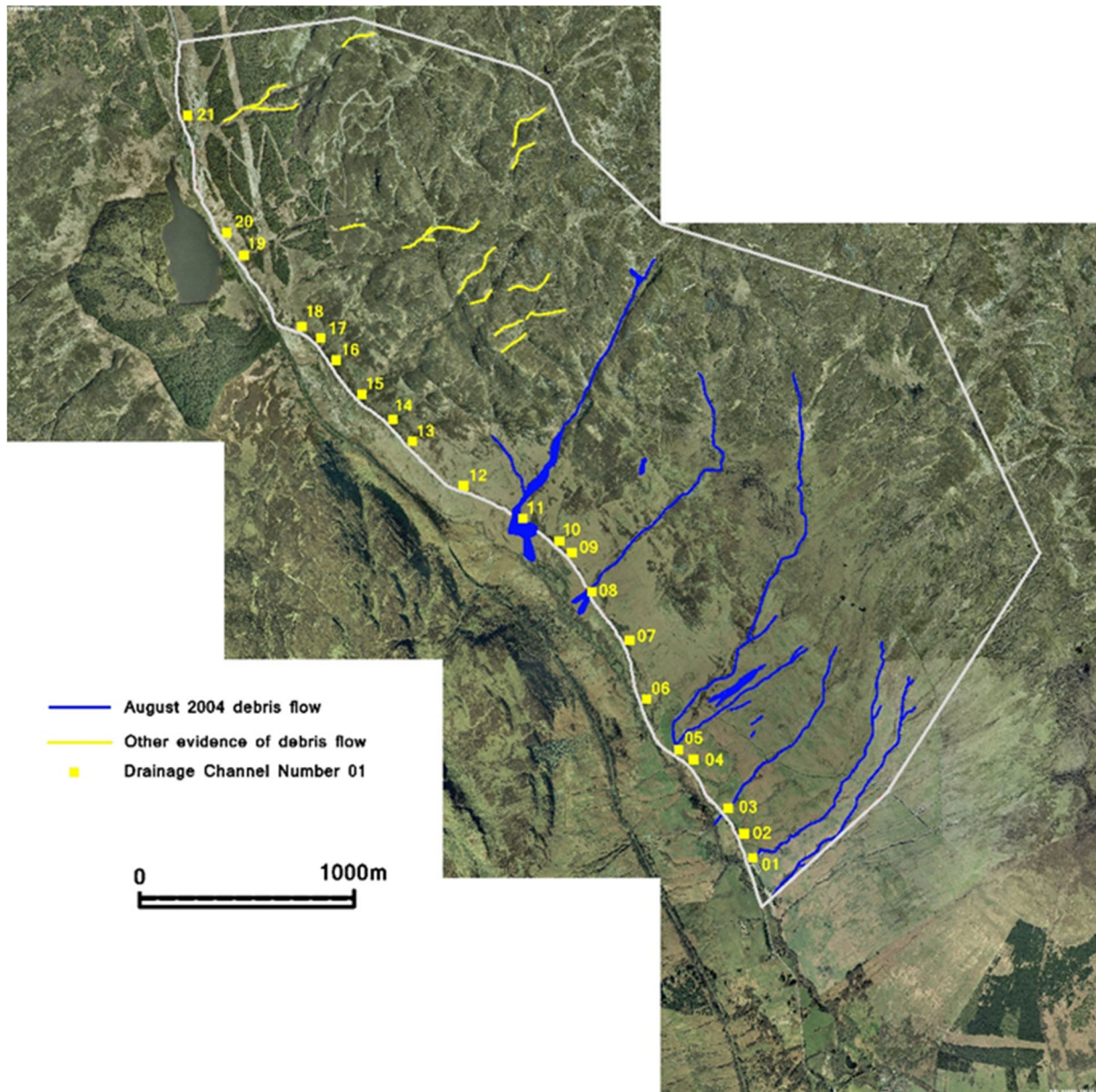


Figure 3. Debris flow events with known locations and signs of instability determined from aerial photography. Locations of the drainage channels at the A85 Glen Ogle as confirmed by field reconnaissance are also shown. Ordnance Survey, base aerial photography, © Crown Copy-right. All rights reserved Scottish Government 100020540, 2026.

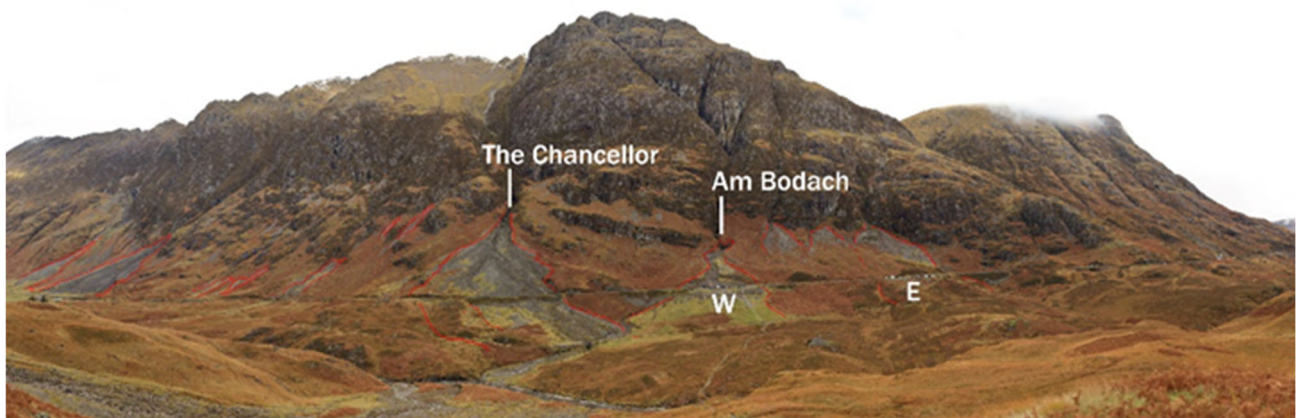


Figure 4. High resolution panoramic imagery of Glen Coe in the vicinity of The Chancellor and Am Bodach with significant debris fans marked in red, imagery dated 30 October 2019. The image is a composite of 220 individual 50 mega-pixel images (arranged 20 horizontally by 11 vertically). The locations of the Am Bodach and The Chancellor debris fans are indicated; 'E' indicates the location of the East Car Park and 'W' indicates the location of the West Car Park. The images were captured using techniques detailed by (Winter et al. 2017; Winter & Ferreira 2019).

## 2.4 Rainfall

Instances of instability at each of the sites are generally associated with high rainfall levels:

- Rest and be Thankful: annual average of 3,078mm; minima 2,050mm; maxima 3,673mm.
- Glen Ogle: annual average of 2,002mm; minima 1,590mm; maxima 2,773mm.
- Glen Coe: annual average of 2,371mm; minima 1,875mm; maxima 3,016mm.

The rainfall at these sites compares to those for Edinburgh, the capital of Scotland, with a 680mm average and with a range of 448mm to 892mm, and Glasgow, the largest city, with a 989mm average and a range of 664mm to 1,304mm.

## 3 RISK

The detailed quantitative risk assessment methodologies are set out elsewhere for both mobile elements at risk (Wong & Winter 2018; Winter 2018; Winter & Wong 2020; Winter et al. 2024) and static elements at risk (Winter et al. 2024) and are based on typical approaches (Lee & Jones 2014; Wong et al 2014) to the annual risk of a fatality risk being the product of event, elements at risk and vulnerability, as follows:

$$\text{Risk} = P(\text{Event}) \times P(\text{Hit}|\text{Event}) \times P(\text{Fatality}|\text{Hit}) \quad (1)$$

where  $P(\text{Event})$  is defined as the annual frequency or probability of an event occurring at a given site,  $P(\text{Hit}|\text{Event})$  is the conditional probability of the event hitting a vehicle, and  $P(\text{Fatality}|\text{Hit})$  is the conditional probability of a fatality occurring as a result of the vehicle being hit.

It is important to note that  $P(\text{Hit}|\text{Event})$  is defined as:

$$P(\text{Hit}|\text{Event}) = P(\text{Wrong Place}) \times P(\text{Wrong Time}) \quad (2)$$

where  $P(\text{Wrong Place})$  is the spatial probability of an element at risk being exposed to a hazard on a single trip or visit, and  $P(\text{Wrong Time})$  is the temporal probability associated with an element at risk being in the 'Wrong Place' on that trip or visit.

$P(\text{Event})$  is derived from the inventory of known events over a given time period and the magnitude of the event which

feeds into  $P(\text{Fatality}|\text{Hit})$  is similarly derived from the inventory and records of past events.

### 3.1 Individual Risk and Frequent Users

The Personal Individual Risk (PIR) for mobile elements at risk, the risk of a fatality from a single journey, is low, in the  $10^{-10}$  to  $10^{-09}$  range, for all three sites for typical vehicle speeds of 40 (64), 50 (80) and 60 miles/h (97km/h). This increases to  $10^{-08}$  to  $10^{-07}$  for commuters who typically travel through a site twice daily on a working day; for logistics truck drivers who typically make double that number of journeys the risk increases to the  $10^{-07}$  to  $10^{-06}$  range (Winter & Wong 2020; Winter et al. 2024).

The PIR for static elements at risk, which is relevant only to the A82 Glen Coe site, is calculated from the surveyed mean visit duration,  $P(\text{Wrong Time})$  and the space occupied by a single person within the hazard zone,  $P(\text{Wrong Place})$ . The calculation of the temporal probability involved the development of an entirely new metric, Annual Average Daily Visits (AADV). The visitor surveys derived a 15-minute mean visit duration; geometrical elements related to the hazard and people were used to derive  $P(\text{Wrong Place})$ , while the derivation of  $P(\text{Fatality}|\text{Hit})$  is described in detail elsewhere (Winter et al. 2024). This methodology yields a value for PIR of between  $10^{-12}$  and  $10^{-09}$ . The annual PIR values for frequent visitors such as coach drivers and tour guides were calculated to be around  $10^{-08}$ .

While any fatality risk is undesirable these risks are low by any commonly applied standard.

### 3.2 Societal Risk

The annual risk to society of one or more fatalities is a much more important consideration, particularly in the consideration of the need to robustly allocate resources to landslide risk reduction activities (Winter 2014, 2016) that are usually in both high demand and short supply. The A83 Rest and be Thankful and A85 Glen Ogle demonstrate how this may be facilitated (Fig. 5).

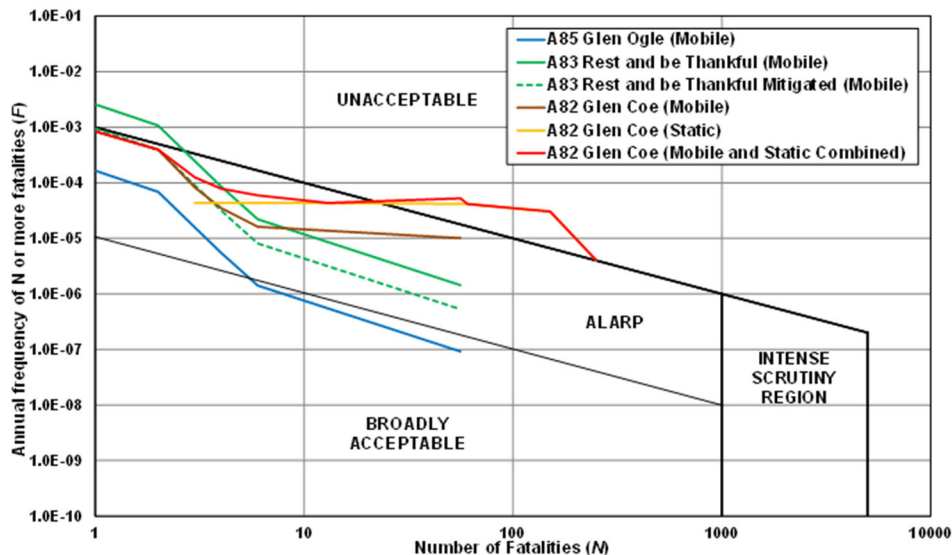


Figure 5. F-N curves based on the approach of [22] for the A83 Rest and be Thankful, before and after mitigation measures, A85 Glen Ogle and A82 Glen Coe, for both mobile and static elements at risk and those combined (Winter et al. 2024).

The results for the A83 Rest and be Thankful show that for low numbers of fatalities the risk resides within the Unacceptable zone while for high numbers of fatalities the risk resides within the ALARP zone. The risk at the A85 Glen Ogle

site is much lower with the risk for low numbers of fatalities in the ALARP zone and that for high numbers of fatalities in the Acceptable zone. This clearly indicates a prioritization of resources to the A83 site, and this is reflected in the curves for

A83 Mitigated which shows that when mitigation measures extant as of October 2014 were taken into account the risk resided wholly within the ALARP zone. This does not mean that the A85 site could be ignored and indeed it has not been with a number of studies being undertaken to better understand the likely future hazards and a regular monitoring programme being in place.

The risk for the A82 Glen Coe site for mobile elements at risk resides wholly within the ALARP zone although the risk for high numbers of fatalities is considerably higher than at the other sites. This is due to the large number of buses that use the route, both service buses and tourist buses. While the risk for static elements at risk resides within the ALARP zone for low numbers of fatalities it is definitely in the Unacceptable zone for higher numbers of fatalities. This picture is, of course, maintained when the risk for mobile and static elements at risk are summed with the risk residing in the ALARP zone for values of N from 1 to 23 and in the Unacceptable zone for greater values of N up to 250. These high values of risk are reflective of the high numbers of people using the car parks at peak times; a maximum of almost 300 people was recorded during the surveys conducted to determine visit numbers and durations.

The results for the A82 Glen Coe site tend to indicate that some degree of action is necessary to reduce the risk to road users at the A82 Glen Coe site. Given the high use rate of the two car parks their closure is unlikely to be an acceptable response. Accordingly, stakeholder consultation is ongoing with a view to reducing or eliminating the use of the car parks while improving the overall access to Glen Coe.

#### 4 CONCLUSIONS AND SUMMARY

The three sites discussed in this paper pass through some of the most iconic scenery in Scotland. This is especially so for the A82 in Glen Coe, which is one of the country's top tourist attractions and attracts walkers, climbers, sightseers and skiers in significant numbers.

Typically, the individual risk values associated with single trips and plausible multiple trips are relatively low and it is the large numbers of road users, the mobile elements at risk, that creates risk levels that are of greater concern to society as a whole. This is emphasized at the A82 Glen Coe site at which a proportion of the mobile elements of risk stop in car parks and are thus exposed to additional risk, as static elements at risk; this additional risk is largely driven by the duration of their visit which can, from observation range from a few minutes to several hours.

QRA has been demonstrated to be an undoubtedly powerful tool to analyze, understand and present the effects of landslides on society. It can be used to articulate the effects of landslide risk reduction measures, as is the case at the A83. In addition, it is extremely helpful in making the case for appropriate levels of intervention. At the A85 site the required level of intervention is relatively low while at the A82 site the case for a higher level of intervention is clearly articulated by the use of the F-N diagram.

The QRA process is, of course, considerably more time-consuming on a site-by-site basis than a less rigorous semi-quantitative assessment and demands significant resources. The associated costs mean that it is not generally possible, or appropriate, to apply QRA to a large number of sites and targeting the highest risk sites is necessary. This means that in the context of a transport network with multiple sites subject to landslide hazard and risk the existence and application of a semi-quantitative, regional assessment is a near-essential precursor to QRA. In addition, knowledge of the

infrastructure and its users is required, more so even than for the semi-quantitative regional assessment, in addition to high level knowledge of the physical processes (in this case debris flow).

It is essential that all elements of the risk equation are fully assessed, including the elements at risk and their vulnerability, rather than allowing a focus solely on the hazard,

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