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RESEARCH

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Quantitative risk assessment for static and mobile road users: methodology and application at A82 Glen Coe, Scotland

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Abstract

Background In August 2004 a series of debris flows caused significant disruption to the Scottish (strategic) Trunk Road Network. The subsequent Scottish Road Network Landslides Study identified a number of sites considered to be at highest risk. Some of these sites have been the subject of formal quantitative assessment of the risk from debris flow to mobile road users in vehicles. The A82 in Glen Coe has the added complication that two car parks have developed on debris fans exposing significant numbers of people to the risk while, they are essentially static and largely outside their vehicles.

Methodology The risk to road users is determined using a previously developed probabilistic methodology for mobile road users (mobile elements at risk) and a new and related methodology developed for static road users (static elements at risk) is described and applied. Within the latter, an entirely new metric of Annual Average Daily Visits is used to allow the temporal component of the probability of a landslide impacting a person to be determined given the occurrence of an event.

Results While Personal Individual Risk is at an acceptable level, including for frequent users, the risk presented to society as a whole presents a rather different picture; this is largely due to the number of visitors. The results assess the overall, societal risk for mobile elements at risk as As Low As reasonably Practicable, being at a similar level to other sites, albeit with a higher risk associated with higher numbers of fatalities. The results for the static elements at risk on the other hand suggest that the risks are classified as Unacceptable for higher numbers of fatalities. The assessment of the total societal risk, for mobile and static elements at risk, at the A82 Glen Coe suggests As Low As Reasonably Practicable for low numbers of fatalities but classify as Unacceptable for higher numbers of fatalities (around 20 to 250).

Keywords Landslides, Debris flow, Hazard, Risk, Road, People, Quantitative risk assessment

Introduction

The Scottish Road Network Landslides Study (SRNLS) was executed in response to a series of debris flow events that caused significant disruption to the Scottish (strategic) Trunk Road Network (TRN) in August 2004 (Winter et al. 2005; Winter et al. 2008; Winter et al. 2013). The study identified a series of sites as being of higher hazard and therefore of potentially higher risk. Amongst those were the A83 Rest and be Thankful and the A85 Glen Ogle site which were subject to formal Quantitative Risk Assessment (QRA) for the effects of debris flow

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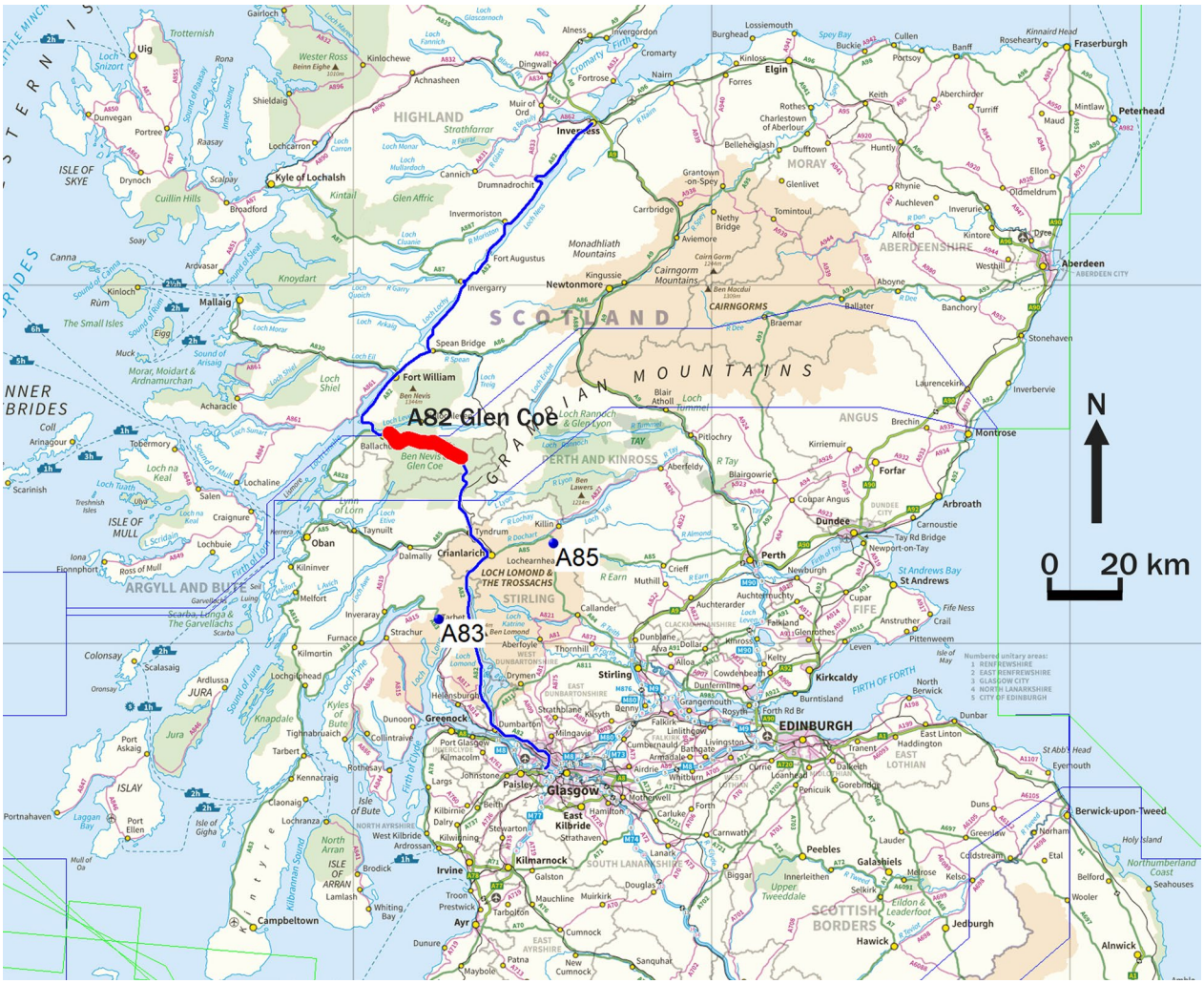

Fig. 1 Partial map of Scotland showing the A82 route in Blue and the Separate Assessment for the A82 in Glen Coe in Red. The locations of the A83 (Rest and be Thankful) and A85 (Glen Ogle) sites referred to in the text are also shown. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2024. All rights reserved. Ordnance Survey Licence number 100046668

on moving traffic (Wong and Winter 2018; Winter 2018; Winter and Wong 2020). The A82 in Glen Coe (Fig. 1) was also highlighted as a result of the debris flow hazards and the scree and talus slopes that persist above parts of the road. This site is characteristically different as not only are there risks posed to moving traffic, vehicles and road users but two car parks have developed in the highest hazard area to allow access to viewpoints, hiking trails and climbing routes; in addition, a large number of tourist buses stop at this location. Prior to the study up to nine coaches and minibuses had been observed in the two car parks at any one time and total numbers of people present at the two car parks were estimated at up to around 250 at any one time. The risk at this location is thus somewhat different to those more typically encountered in a road environment.

In this paper the approach to defining the risk to the road using public in moving vehicles in Glen Coe and to road users who stop at the two aforementioned car parks is described. The QRA for mobile elements at risk is undertaken using the methodology developed and reported by Winter and Wong (2020) while a new methodology, based on that approach, has been developed for static elements at risk. Consequently, this QRA for the A82 comprises two main parts:

(1) An assessment of the risk to road users that do not stop at the car parks, which is based on the methodology developed and reported by Winter and Wong (2020) and
(2) An assessment of the risk to those road users that stop at the car parks using a newly-developed methodology.

These two assessments might usefully be described as pertaining to mobile road users (or mobile elements at risk) and to static road users (or static elements at risk), respectively. Clearly those who stop at the car parks are exposed to both the mobile and the static risk. While the methodology for static road users is new it follows the same principles as that for mobile road users. This is important as in order to obtain a complete picture of the risk to road users it is necessary to combine the results from the two assessments.

Background

The A82 links Scotland's largest city Glasgow, in the south, with its most northerly city Inverness, in the north, over a distance of 269 km of which all but 13 km forms part of the TRN. For the majority of its length, including through Glen Coe, the A82 comprises a 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 eighteenth century and with later roads constructed by Thomas Telford during the nineteenth century.

The A82 trunk road through Glen Coe runs from Rannoch Moor in the east at an elevation of approximately 315 m above ordnance datum (AOD) to Glencoe village in the west (5 m AOD). Glen Coe is generally considered to be one of the most important tourist destinations in Scotland (Fig. 2) and facilitates 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.

Instances of instability in Glen Coe are generally associated with high rainfall levels and the area experiences an average of 2371 mm per annum and annual minima and maxima of 1875 mm and 3016 mm, respectively. This compares to the capital of Scotland, Edinburgh with a 680 mm average, and a range of 448–892 mm.

Geology and hazards

A comprehensive account of the geological and geomorphological setting of the area, including Glen Coe, is given by Stephenson and Goodenough (2007). The area is a classic example of cauldron subsidence. The caldera at Glen Coe was formed after several eruptive phases, resulting in a down-faulted block within an elliptical ring fracture. The majority of the glen is situated on the down-faulted side (within the caldera) where thick sequences of basalt and andesites have been identified with ignimbrite phases.

During successive Quaternary glaciations, Rannoch Moor has been a persistent ice-sheet dispersal centre with ice sheets radiating out in all directions. This has resulted in the formation of major glacially-eroded troughs, including Glen Coe. Millions of years of erosion and intense glaciation have exposed the down-faulted sequences and surrounding fault intrusions at the present-day surface. Glaciers flowing westwards through Glen Coe were joined by smaller tributary glaciers from the corries to the south, scouring the valley floor and sides to create a classic 'U' shaped valley. Periglacial conditions have resulted in joint-bounded blocks detaching from the cliffs and accumulating on the slopes below. These are then transported downslope, particularly during periods of heavy rainfall, to form scree or talus slopes.

In Glen Coe, glacial moraines and morainic drift are present over the lower reaches of the slopes, with little or no drift cover at higher elevations. The Rannoch Moor area contains widespread glacial moraines and peat deposits.

The extant hazards are typically from the south-facing slopes to the north of the A82, other than in the extreme east and west of Glen Coe where the north-facing slopes to the south also come into play. The mountains to the north typically rise to elevations of up to around 900m to 950m. The slopes are steep with the those from road level to the summit of Meall Dearg, for example, averaging around 33° and being significantly steeper locally, while those to the summit of Am Bodach average almost 37° (Fig. 3).

Glen Coe was last glaciated from 11 to 10 ka BP (thousands of years before present), during the Loch Lomond Stadial, or Readvance (Woodcock 2000). The area would have been almost completely covered with ice, with the exception of the highest mountain peaks which would have protruded from the ice mass (Thorp 1981).

Mountainous areas that were glaciated during the Loch Lomond Readvance, including Glen Coe, were left in unstable, or metastable, conditions following the retreat of the ice and have been adjusting to the glacially induced changes in geomorphology since, with adjustments often occurring rapidly and/or over extensive areas (Ballantyne 1991, 2002). In some areas, equilibrium has been achieved while in others readjustment of the landscape in response to the retreat of the last glaciation continues; these types of geomorphic activity are termed 'paraglacial' processes. In the Highlands of Scotland,

Fig. 2 Glen Coe. Top: View from the East Car Park in Glen Coe; Middle: Glen Coe (facing west) from the Glencoe Mountain Resort; Bottom: Glen Coe (facing east toward the car parks) from Loch Achtriochtan. (All photographs by the first author.)

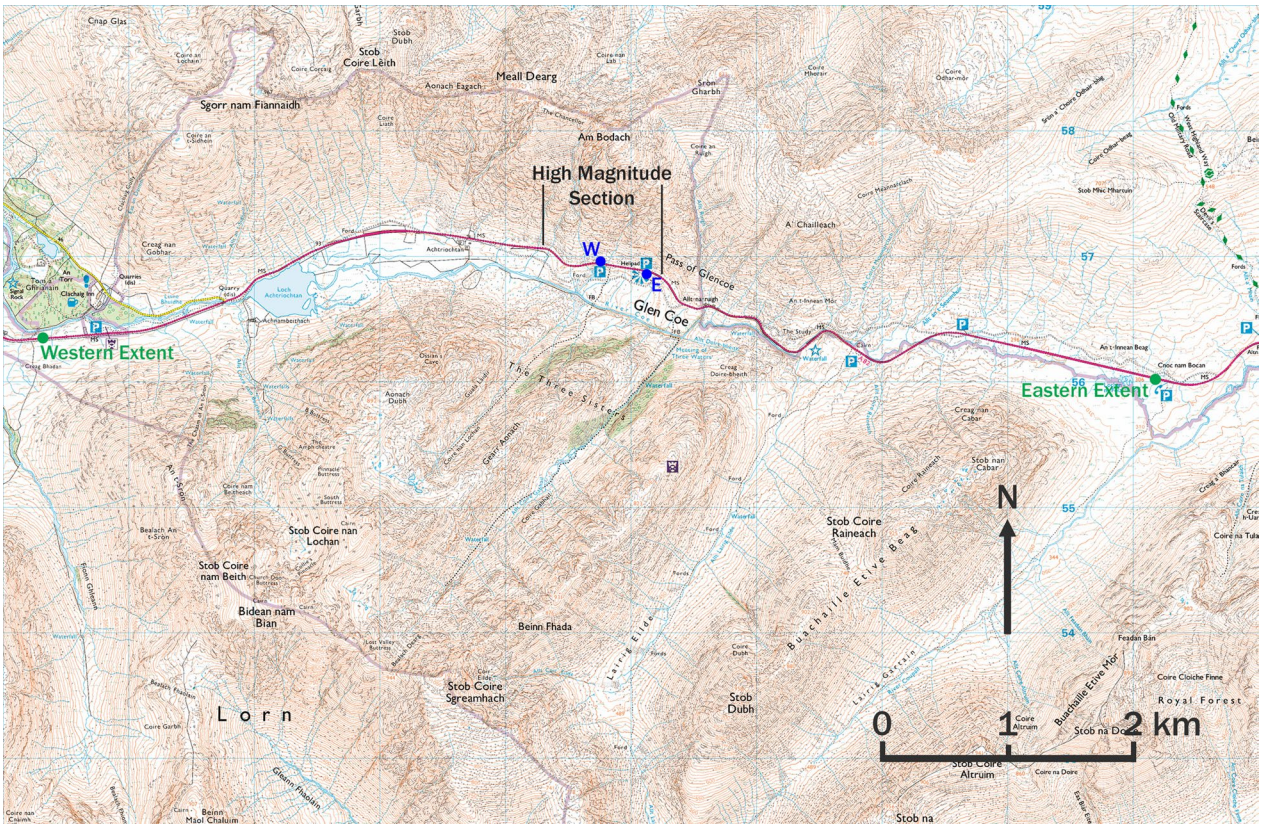

Fig. 3 The A82 Glen Coe showing the eastern and western extent of the area subject to QRA, the east (E) and west (W) car parks and the area subject to a higher event magnitude. Ordnance Survey the 1:25,000 map. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2024. All rights reserved. Ordnance Survey Licence number 100046668

readjustments principally occur on mountain slopes, particularly on the lower reaches, through three key processes (Ballantyne 1991):

1. Major rock slope failures.
2. Progressive accumulation of rockfall debris as talus slopes.
3. Reworking of drift or regolith by debris flow activity.

While numerous rock slope failures have been recorded across the Highlands of Scotland, Holmes (1984) found that the majority of these failures had occurred, or had deposited material, within the limits of Loch Lomond Readvance glaciers. It is therefore implicit that these failures occurred after glacial retreat. A spectacular example of rock slope failure is the Lost Valley (Coire Gabhail) in Glen Coe (Ballantyne 1991), the debris of which effectively blocked the valley mouth giving rise to the name by which it is now known. Similarly, talus cones that have developed within the limits of Loch Lomond Readvance glaciers are typically at the base of steep, high cliffs, are poorly vegetated, and have fresh debris lying over the slopes. Since glacial activity within these limits will have removed loose material, it is assumed, as above, that anything that has accumulated in these locations must have done so subsequent to glacial retreat (Ballantyne 1991).

Glen Coe exhibits recent and diverse slope movements. Brazier (1992) observed several Holocene debris slope features in Glen Coe as follows:

- Tracks and deposits of hillslope debris flows.
- Typically, small and discontinuous talus sheets.
- 'Cascades' of perched drift and talus which partially obscure lava ledges on Aonach Dudh (outwith the study area).
- Other rock fall features comprising:
    - Crag-scale rock failures.
    - The major rock slope failure that blocked the entrance of Coire Gabhail (outwith the study area).

Slope stability within Glen Coe has been known to impact the A82 in historic and recent times (Bailey and Maufe 1916; Brazier 1987). Significant hazards are extant on the slopes below the Am Bodach and The Chancellor, part of which coincide with not only the A82 road but,

particularly in the case of the former, also car parks that have evolved on debris fans (Fig. 3).

The length of A82 identified as being at higher risk by Winter et al. (2008) was 19.9 km. This has been reduced by successive hazard and risk assessments, including an initial part of this study, to focus on the highest hazard and risk section which is 9.5 km long from National Grid Reference (NGR).

- NN 21139 56045 (221139 756045 or Longitude −4.91993069522146, Latitude 56.6618856548596) in the east, to
- NN 12332 56351 (212332 756351 or Longitude −5.06362261956807, Latitude 56.661180707321) in the west.

As is typical in the UK, determining the frequency and magnitude of events at any given landslide site is a challenge due to the relative infrequency of events (Gibson et al. 2013; Winter 2019, 2020). On this occasion the frequency and magnitude had to be derived from a total of just nine events dating back to 1947, the details of which were in some cases limited.

The section of road is illustrated in Fig. 3. The event magnitude for the mobile elements at risk was taken as around 1000 m^3 with a frequency of 0.0870 events per annum for 8500 m of the road. A shorter section (1010 m in Fig. 3) was determined to be subject to a higher magnitude event of around 5000 m^3 with a frequency of 0.0685 event per annum. This short higher magnitude section coincides with the two car parks and the magnitude and frequency were also used for the static elements at risk. The magnitudes and frequencies were determined from (unpublished) contemporaneous accounts of events, observations of potentially mobile material on the hillsides, and the authors knowledge and recollections of events from the 1990s onwards and experience of other such events in other parts of Scotland (e.g. Winter et al. 2005; Winter et al. 2006; Winter et al. 2008; Winter and Wong 2020).

The mapped hazards are shown in aerial and panoramic photography for the central part of the study in Figs. 4 and 5, respectively. These demonstrate a significant degree of overlap between potential events in the shorter (1010 m) section.

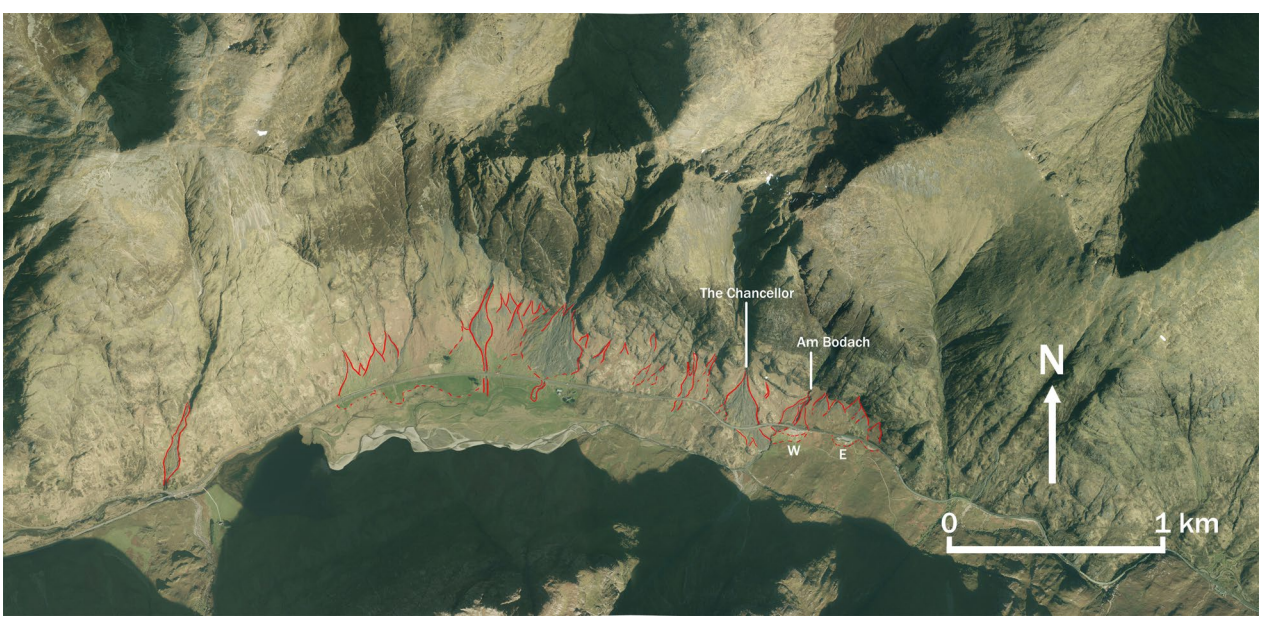

Fig. 4 Aerial photography of Glen Coe with significant debris fans marked in red, dashed lines indicate where fan boundaries are less well distinguished these are likely to be representative of less recent mass movements, imagery dated 2012. The image comprises of 18 1km square tiles (arranged six horizontally by three 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. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2024. All rights reserved. Ordnance Survey Licence number 100046668

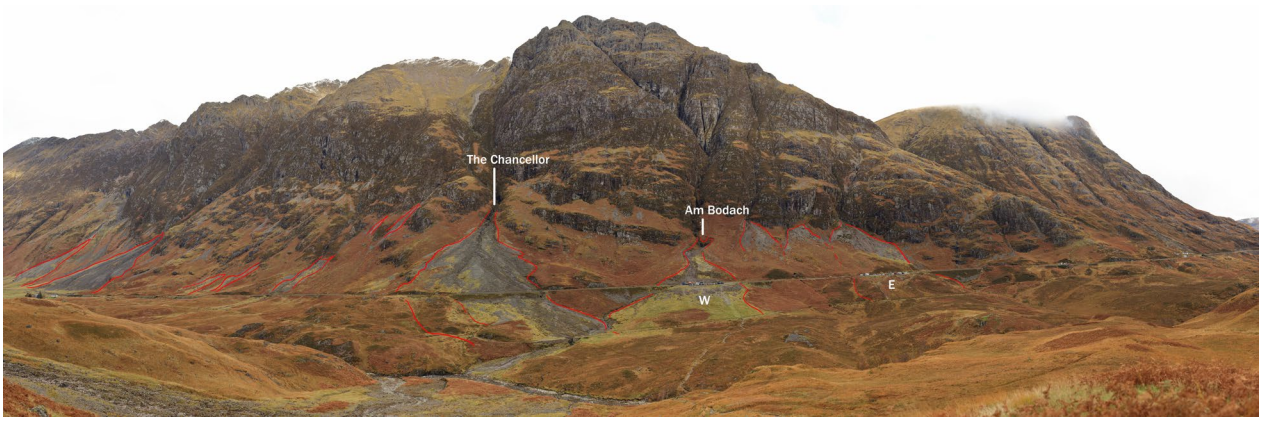

Fig. 5 High resolution panoramic imagery of Glen Coe in the vicinity of The Chancellor and Am Bodach with significant debris fans marked in red, imagery dated 30 October 2019. The image is a composite of 220 individual 50 mega-pixel images (arranged 20 horizontally by 11 vertically). The locations of 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 from NGR NN 16598 56386 (216598 756386) using techniques detailed by Winter et al. (2017) and Winter and Ferreira (2019)

Quantitative risk assessment

Both the existing method for mobile elements at risk (Winter and Wong 2020) and the new method for static elements at risk use the basic philosophy presented by Lee and Jones (2014). This was adapted and expanded as the scenarios under consideration dictated. Accordingly, a definition for risk analysis was taken as follows:

$$Risk = P(Event) \times P(Hit|Event) \times P(Damage|Hit) \times C \quad (1)$$

where

P(*Event*) is a measure of the expected likelihood of a landslide event per annum,

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' was taken to represent the fatality of one or more road users and effectively encompasses the concepts of both 'Damage' and 'Consequences' and Eq. (1) becomes:

$$Risk = P(Event) \times P(Hit|Event) \times P(Fatality|Hit) \quad (2)$$

It is important to note that P(*Hit*|*Event*) is defined as:

$$P(Hit|Event) = P\left(WrongPlace\right) \times P(WrongTime) \quad (3)$$

where

P(*Wrong Place*), the spatial probability of an element at risk being exposed to a hazard on a single trip or visit, and

P(Wrong Time), the temporal probability associated with an element at risk being in the 'Wrong Place' on that trip or visit.

For the mobile elements at risk, two scenarios were considered, that of a vehicle being hit by a debris flow that reaches the road (A) and that of a vehicle hitting a debris flow that has already reached the road (B). At the A83 Rest and be Thankful and A85 Glen Ogle sites, and in normal operational circumstances, the only major exposure is that related to moving vehicles and road users. There are, for example, no formal opportunities for stopping or parking within either of those two sites that could create risk to static elements at risk. As a result, these two scenarios are the only possibilities of fatality amongst road users that may be logically deduced.

For the A82 Glen Coe site, the existence of the two car parks introduces a third scenario for those vehicles and their occupants that stop, exposing these static elements at risk to a different form of risk. These two cases of static and mobile elements at risk are dealt with in the following sections.

Table 1 *PIR* for mobile elements at risk for combined Scenarios A and B at A82 Glen Coe

	Vehicle Speed: miles/h (km/h)		
	40 (64)	50 (80)	60 (97)
Low magnitude, long section	2.267E−10	1.932E−10	1.756E−10
High magnitude, short section	2.174E−10	1.879E−10	1.738E−10
Combined Sections	4.441E−10	3.811E−10	3.494E−10

Table 2 *PLL* for mobile elements at risk for combined Scenarios A and B at A82 Glen Coe

	Vehicle Speed: miles/h (km/h)		
	40 (64)	50 (80)	60 (97)
Low magnitude, long section	1.028E−03	8.763E−04	7.964E−04
High magnitude, short section	9.861E−04	8.522E−04	7.883E−04
Combined Sections	2.014E−03	1.729E−03	1.585E−03

QRA for mobile elements at risk

Table 1 shows the calculated results for Personal Individual Risk (*PIR*), the annual probability of a fatality resulting from a single journey, in the study area; these values were calculated from Eq. (2). The hazard frequency defines P(*Event*) while the values of P(*Hit*|*Event*) and P(*Fatality*|*Hit*) were calculated as described in detail by Winter and Wong (2020).

For clarity the results are presented in a combined form for both Scenario A (vehicle hit by a debris flow) plus Scenario B (vehicle hits a debris flow). Notwithstanding this, it is worth noting that, as reported by Wong and Winter (2018) and Winter (2018) for other sites, the risk associated with Scenario A is approximately one order of magnitude (ten times) greater than that associated with Scenario B.

The amount of traffic, defined by the Annual Average Daily Traffic (AADT: 5,530 vehicles/day),[1] along with data

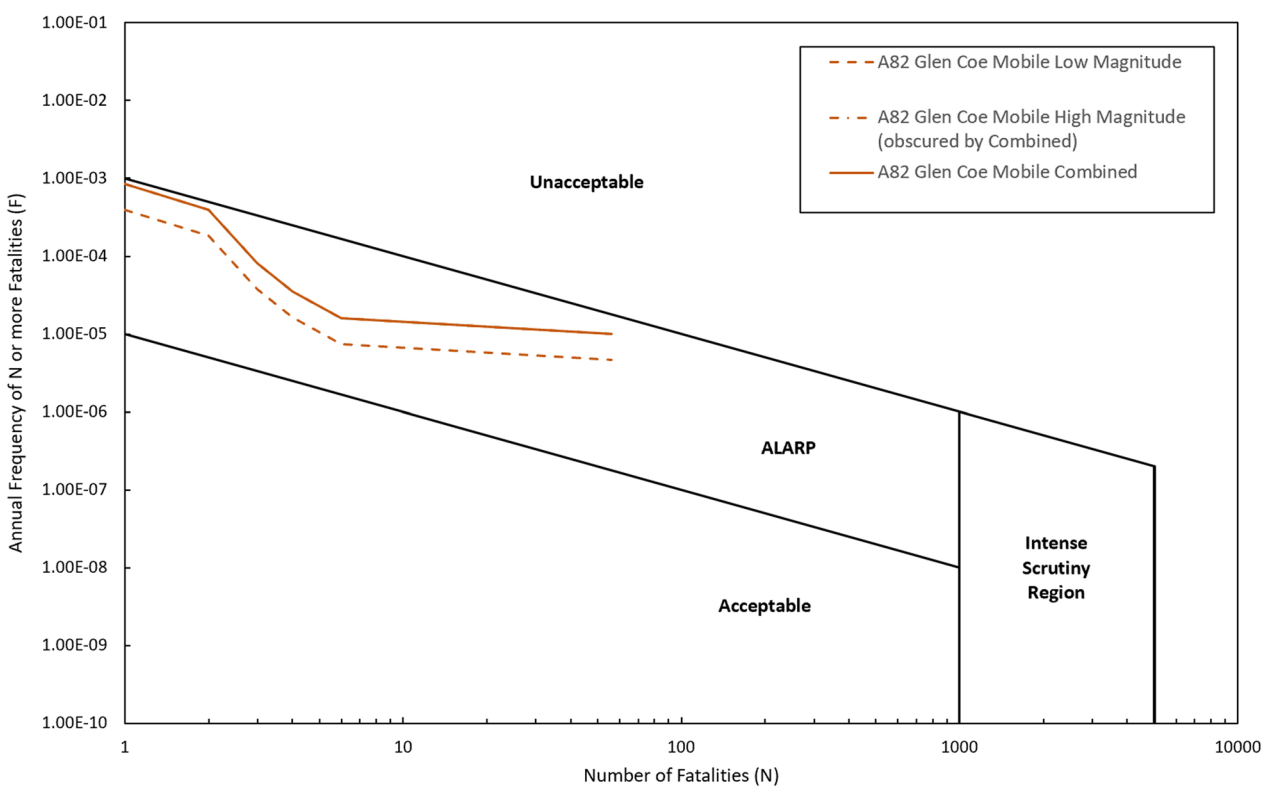

Fig. 6 *F-N* curves for mobile elements at risk for vehicle speeds of 80 km/h (50 miles/h) at the A82 Glen Coe for the longer low event magnitude section, the short higher event magnitude section and the two sections combined. Note that the Combined line obscures the Higher Magnitude line

[1] https://roadtraffic.dft.gov.uk/manualcountpoints/760. Note that the data was originally obtained from Traffic Scotland's National Traffic Data System, which is no longer accessible.

on vehicle types[2], and vehicle sizes and national vehicle occupancy rates (see Wong and Winter 2018) allows the Potential Loss of Life (*PLL*) to be calculated. This is the annual probability of a fatality from any journey made in the study area and represents the risk to society (Table 2). It is used to determine the *F-N* curve broadly following the approach of Wong et al. (2004) and as described in detail by Winter and Wong (2020). This plots the number of fatalities (*N*) against the annual probability of *N* or more fatalities (*F*) and the *F-N* curves for mobile elements at risk in the low magnitude and high magnitude sections along with the combined risk are illustrated in Fig. 6. Note that the risk associated with the high magnitude section is greater and is obscured in the figure by the combined risk.

QRA for static elements at risk

For the static elements at risk, P(*Wrong Place*) can be simply defined as the proportion of the hazard zone that that an element at risk (a person) occupies. The hazard zone comprised the two car parks with a combined length of 175m and the width of a person was taken as 0.45m both from measurement and a variety of readily-available web-based resources, giving a value of P(*Wrong Place*) of 0.000257.

The greater challenge is in determining an appropriate value of P(*Wrong Time*); whereas for the mobile elements at risk, vehicle speed determines the P(*Wrong Time*), the length of a visit determines P(*Wrong Time*) for visitors to the car parks. While for mobile elements at risk the AADT determines the number of people exposed, there was no such metric let alone statistics for visits to the car parks in Glen Coe. Accordingly, a survey methodology was devised to determine the number of visits and the average length of such visits.

The surveys entailed counting the number of people present in the car parks at 15-min intervals between the hours of 08:000 and 19:00, outside of these hours the car parks were found to be essentially unoccupied. Four surveys were undertaken on the following dates:

- Friday 23 August 2019.
- Monday 30 September 2019.
- Tuesday 29 October 2019.
- Wednesday 15 January 2020.

The dates were selected to be as neutral as possible, broadly followed the methodology for date selection set out in the Department for Transport's Road Traffic Estimates Annual Methodology Note.[2] Neutral days are considered to be those weekdays that are not a school holiday, or a public holiday between March and October. It seemed clear that using such days exclusively would overestimate visitor numbers during the winter and thereof overestimate the risk; the January survey was therefore also included and is considered essential in terms of the purposes of the study.

Informal observations, which involved simple visual assessments rather than formal counting, were made on days either side of the survey dates to provide a sense check on the patterns of the survey results. Figure 7 shows images from the four survey days although it should be noted that the pictures were taken during the quieter times of day when occupancies were at the lowest levels; the time pressure to capture the survey data precluded the taking of photographs during the busier times. Survey data is illustrated in Fig. 8.

The data for the individual days was then extrapolated to give data for a full year. It was assumed that each of the survey days was representative of the other days within that month allowing a total number of visits to be simply calculated for each of August, September, October, and January. The 2018 Great Britain Tourism Survey (GBTS) for Northern Scotland (Anon. 2018) gives percentages of annual visitor numbers for each month. Thus, using August as a base month the visitor numbers were calculated for the months that were not surveyed from the product of the August visitor numbers and the monthly percentage of annual visitors from the tourism survey.

The results were calculated in terms of 15-min equivalent visits. This coincided with both the survey interval and calculations that suggested that the average duration of a visit was between 10.3 min in January and 15.7 min in October with an average of around 14 min. This gives a value of P(*Wrong Time*) of 2.852E−05 (15 min divided by the product of 365.25 days/year, 24 h and 60 min).

The value of P(*Fatality*|*Hit*) logically varies across the site from the lower slopes of the mountain, across the A82 and the car parks. Past work (Wong and Winter 2018; Winter 2018), which was informed by discussions with specialists in vehicle and pedestrian impacts, was used to provide benchmarks of reasonably well-established values. Discussions amongst the project team were then used to determine values of P(Fatality|*Hit*) at other locations and in other scenarios as illustrated in cartoon style in Fig. 9, along with a commentary of those variations. A value of P(*Fatality*|*Hit*) of 0.01 was considered to be a valid representation of the risk to people in the car park. This allows the value of *PIR* to be calculated from Eqs. (2) and (3) and the previously defined values thereof as 5.021E−11 for a single visit.

The survey data was interrogated to calculate the number of Average Daily Visits was for each month as

[2] https://assets.publishing.service.gov.uk/media/63332990e90e0711d82ae0ed/annual-methodology-note.pdf

Fig. 7 Images from survey days. Top Left: 23 August 2019 East car park; Top Right: 23 August 2019 West car park; Middle: 30 September 2019 East car park; Bottom Left: 29 October 2019 East car park; Bottom Right: 15 January 2020 East car park

between 818 15-min equivalent visits per day for January and 3907 15-min equivalent visits per day in August. The number of Annual Average Daily Visits (AADV) average was calculated as 2309 15-min visits per day. This new AADV metric can be considered as broadly equivalent to the AADT metric used to articulate traffic flow. This corresponds to around 845,000 15-min equivalent visits annually. The *PLL* can then be calculated from the AADV and *PIR* as 4.234E−05 for all visits annually, representing the societal risk.

The results of the site surveys were used to determine the number of visits that coincided with mean occupation levels of 0, 3 (1–5), 13 (6–20), 60.5 (21–100), 150.5 (101–2000) and 201–300 (250.5) people. Note that for the hours outside the survey period the number of visits was assumed to be zero with the car parks effectively unoccupied; when combined with the unoccupied hours during the survey period this represented approximately 68% of the year when the car parks are effectively unoccupied.

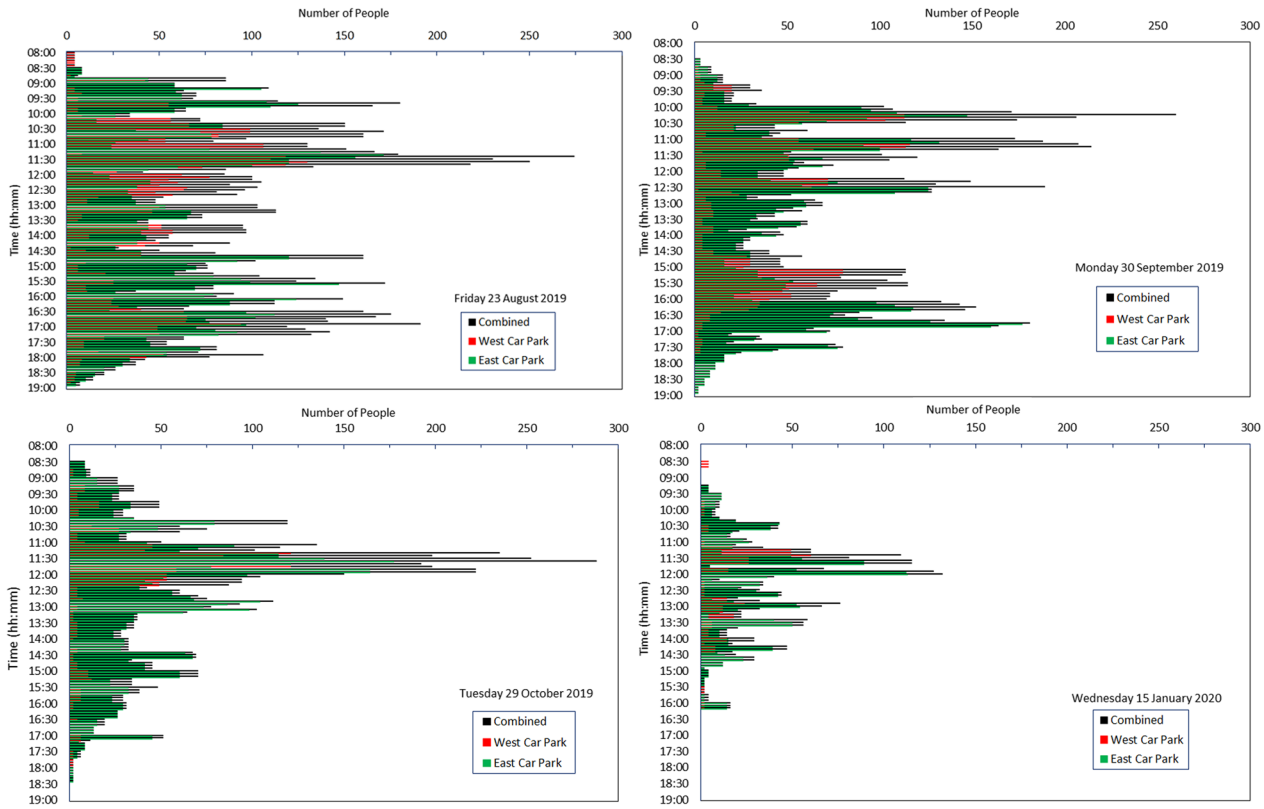

Fig. 8 Survey results showing the number of people occupying the car parks over time. Top Left: Friday 23 August 2019; Top Right: Monday 30 September 2019; Bottom Left: Tuesday 29 October 2019;' Bottom Right: Wednesday 15 January 2020

These data were then used to calculate the annual frequency of *N* or more fatalities as shown in Table 3 and in Fig. 10.

Discussion

Personal individual risk

The values of *PIR* derived for the lower and higher event magnitude sections combined for the A82 in Glen Coe vary with vehicle speed (Table 4), as is case for the A83 Rest and be Thankful and A85 Glen Ogle sites with which the A82 is compared.

Vehicle speed is an important determinant of the resulting risk and for Scenario A (vehicle hit by debris flow) the risk decreases with increasing speed while for Scenario B (vehicle hits debris flow) the risk increases with increasing speed. As Scenario A is the major component of risk this means that the overall risk decreases with increasing speed. As Winter and Wong (2020) point out the higher fatality risk from a road traffic collision renders increased speed a wholly ineffective means of risk reduction.

The values of *PIR* (i.e. individual risk) are much lower than those levels of risk that are generally considered to be tolerable in the UK. These were described by Ale (2005) in the context of work by the UK Health & Safety Executive (HSE 1992). 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 10–03 per annum (1E−03 per annum or 1 in 1000 years). From this it was determined that members of the public could be exposed to an individual risk of 1E−04 per annum (1E−04 per annum or 1 in 10,000 years). It is immediately apparent that the *PIR* values at the A82 Glen Coe are considerably less than the tolerable criteria of 1E−04 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 and Jones 2014). This same tolerable limit is also applied in many other parts of the world, such as Hong Kong (Ho et al. 2000) and Australia (AGS 2000, 2007). The values of *PIR* for mobile elements at risk vary between 3.5E−10 and 4.4E−10 (or once every 2250–2800 million years) and remain broadly tolerable.

Similarly, the *PIR* for static elements at risk at 5.021E−11 falls well below the limits described above.

Frequent users

The *PIR* considers only a single journey through the A82 Glen Coe while many people will, of course, make

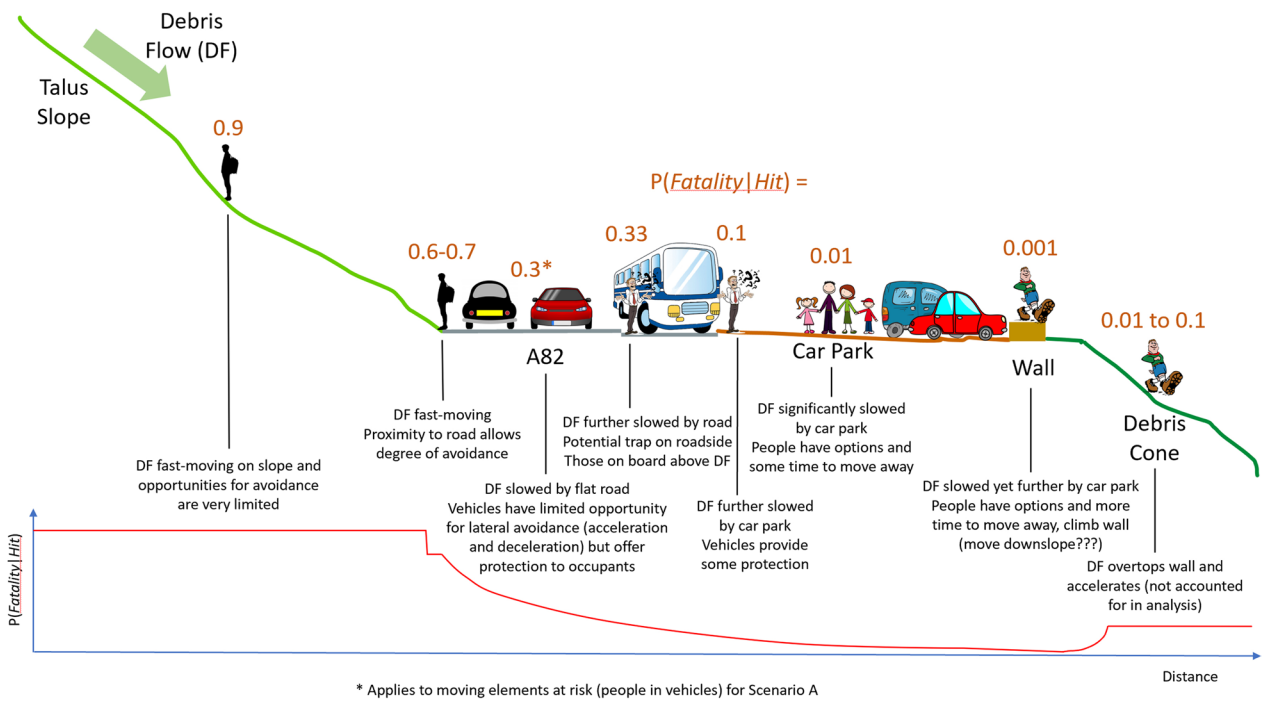

Fig. 9 Cartoon sketch showing hypothesised values of P(*Fatality*|*Hit*) in the Glen Coe car parks. The decay of the value of P(*Fatality*|*Hit*) with distance from the slope is shown in the plot at the bottom of the figure and a narrative that helps to illustrate the thought process involved in developing the values is also given

Table 3 Calculation of Frequency of *N* or more fatalities (*F*) for static elements at risk

Average occupancy in 15-miniute period, *N* consequence class	P(*Fatality*|*Hit*) [2]	No 15-min visits per year with Average occcupancy of *N* [3]	Frequency of occurrence of *N* Fatalities = [1] × [2] × [3]	Cumulative frequency of *N* or more fatalities (*F*)
3	0.01	3936	1.976E−07	4.338E−05
13	0.01	35,980	1.806E−06	4.318E−05
60.5	0.01	218,695	1.098E−05	4.138E−05
150.5	0.01	525,099	2.636E−05	3.039E−05
250.5	0.01	80,281	4.031E−06	4.031E−06

[1] P(Individual Person Hit) = P(Event) x (Hit|Event) = 5.021E−09

multiple journeys through Glen Coe. A typical tourist may, for example, make a return journey in any given year while walkers, climber and skiers may make perhaps half a dozen to a dozen return trips through Glen Coe each year. However, as at other sites some road users make more significant numbers of journeys through Glen Coe in a given year. In order to articulate the higher personal risk to such individuals Winter and Wong (2020) created two scenarios for frequent users: commuters (making two journeys per working day) and logistics truck drivers who make regular deliveries in the area (making four journeys per working day) (Table 5). For commuters the values of individual risk are given for 50 miles/h (80 km/h) and 60 miles/h (97 km/h), the latter being the speed limit for the A82 Glen Coe and the A83 Rest and be Thankful and the former being the speed limit for the A85 at Glen Ogle. For logistics truck drivers the values of individual risk are given for 40 miles/h (64 km/h), the National Speed Limit for goods vehicles in excess of 7.5 tonne maximum laden weight travelling on a single carriageway in Scotland (with the exception of a pilot 50 miles/h speed limit on parts of the A9 trunk road). It is clear that the individual risk to these high frequency road users remains broadly tolerable with values between 2E−07 and 4E−07 for the A82 Glen Coe and between 5E−08 and 2E−06 for all three sites in Table 5.

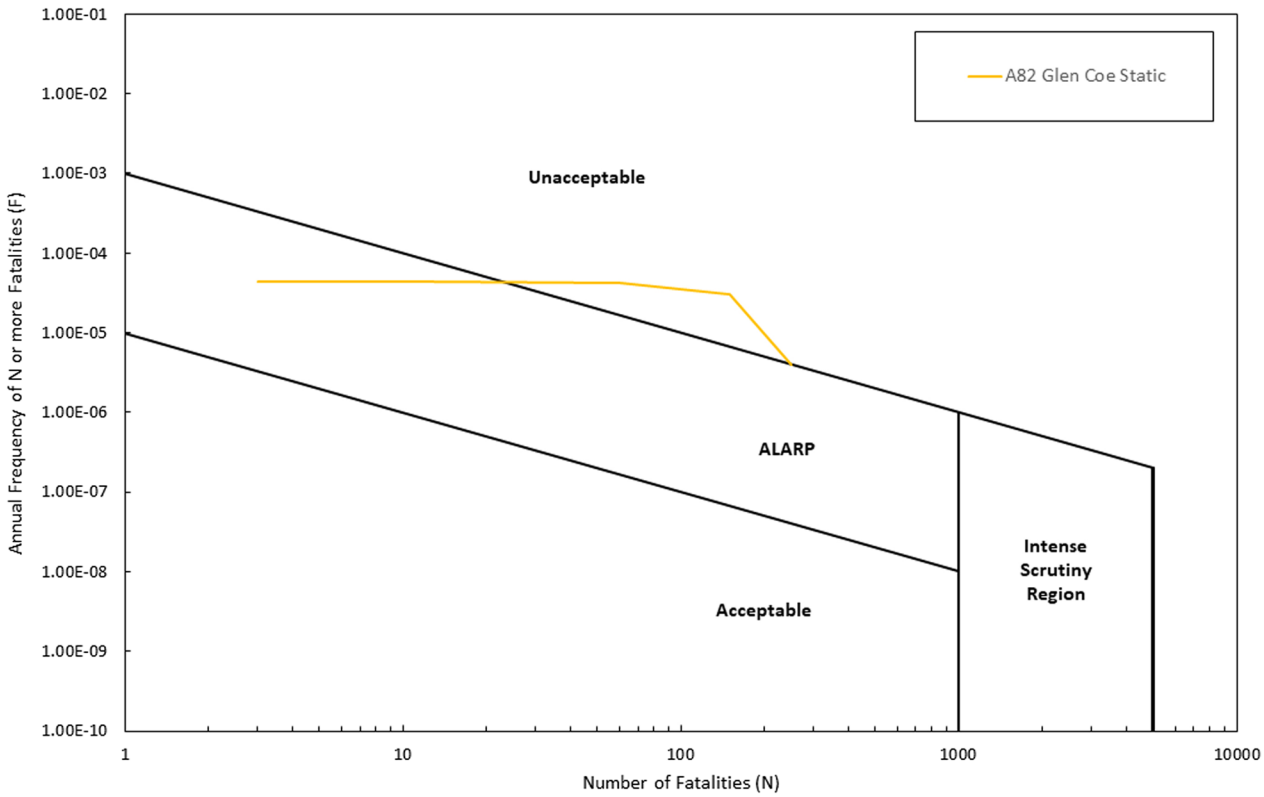

Fig. 10 *F-N* curve for static elements at risk for A82 Glen Coe

The *PIR* and individual risk to high frequency road users at the A82 in Glen Coe is approximately 3.3 times higher than that for road users at the A85 Glen Ogle (or the risk at Glen Ogle is approximately 30% of that at A82 Glen Coe). However, it is just over 20% of that for road users at the A83 Rest and be Thankful (or the risk at the Rest and be Thankful is approximately 4.5 times that at A82 Glen Coe).

Similarly, there are some static elements at risk, or users of the car parks, that make multiple visits in a year. While tourists and leisure-seekers will be among this group, those most at risk are considered to be coach drivers and tour guides. It is clear from the surveys conducted that for some this is a year-round activity, with potentially up to 47 weekly visits. It is recognised that such a pattern is rather unusual, but it does represent a personal-risk worst-case scenario and is strongly supported by conversations with coach drivers and tour guides during the surveys and other site visits. Assuming the value of P(*Fatality*|*Hit*) of 0.01, this gives a multi-visit *PIR* value for coach drivers and tour guides of 2.360E−09 (1 in 424 million years). However, observations during the survey suggest that most coach drivers, and tour guides, remain close to the road, where the value of P(*Fatality*|*Hit*) is arguably 0.1, giving a multi-visit *PIR* of 2.360E−08 (1 in 42.4 million years).

It is clear that the individual risk to those static elements at risk who visit the car parks once, with risk (*PIR*) at 5.021E−10 (around 1 in 2000 million years), and for higher frequency road users, with risk in the range from around 2.4E−09 to 2.4E−08 (1 in 40 million to 1 in 400 million years), is considerably less than the 1E−04 (or 1 in 10,000 years) commonly associated with being unacceptable; these risks can thus be viewed as broadly acceptable.

Table 4 *PIR* for mobile elements at risk/road users, single trip per annum, expressed as probability of occurrence of a fatality per annum; additional data for the A85 and A83 from Wong & Winter (2018) and Wong & Winter (2018)

Site	Vehicle speed: miles/h (km/h)		
	40 (64)	50 (80)	60 (97)
A82 Glen Coe	4.441E−10	3.811E−10	3.494E−10
A85 Glen Ogle	1.328E−10	1.147E−10	1.061E−10
A83 Rest and be Thankful	2.045E−09	1.742E−09	1.583E−09

Table 5 Individual risk for higher risk mobile elements at risk/road users, multiple trips per annum, expressed as the probability of occurrence of a fatality per annum; additional data for the A85 and A83 from Winter (2018) and Wong and Winter (2018)

Site	Commuters (470 journeys per annum)		Logistics truck drivers (940 journeys per annum)
	50 miles/h (80 km/h)	60 miles/h (97 km/h)	40 miles/h (97 km/h)
A82 Glen Coe	1.791E–07	1.642E–07	4.175E–07
A85 Glen Ogle	5.391E–08	4.987E–08	1.248E–07
A83 Rest and be Thankful	8.187E–07	7.440E–07	1.922E–06

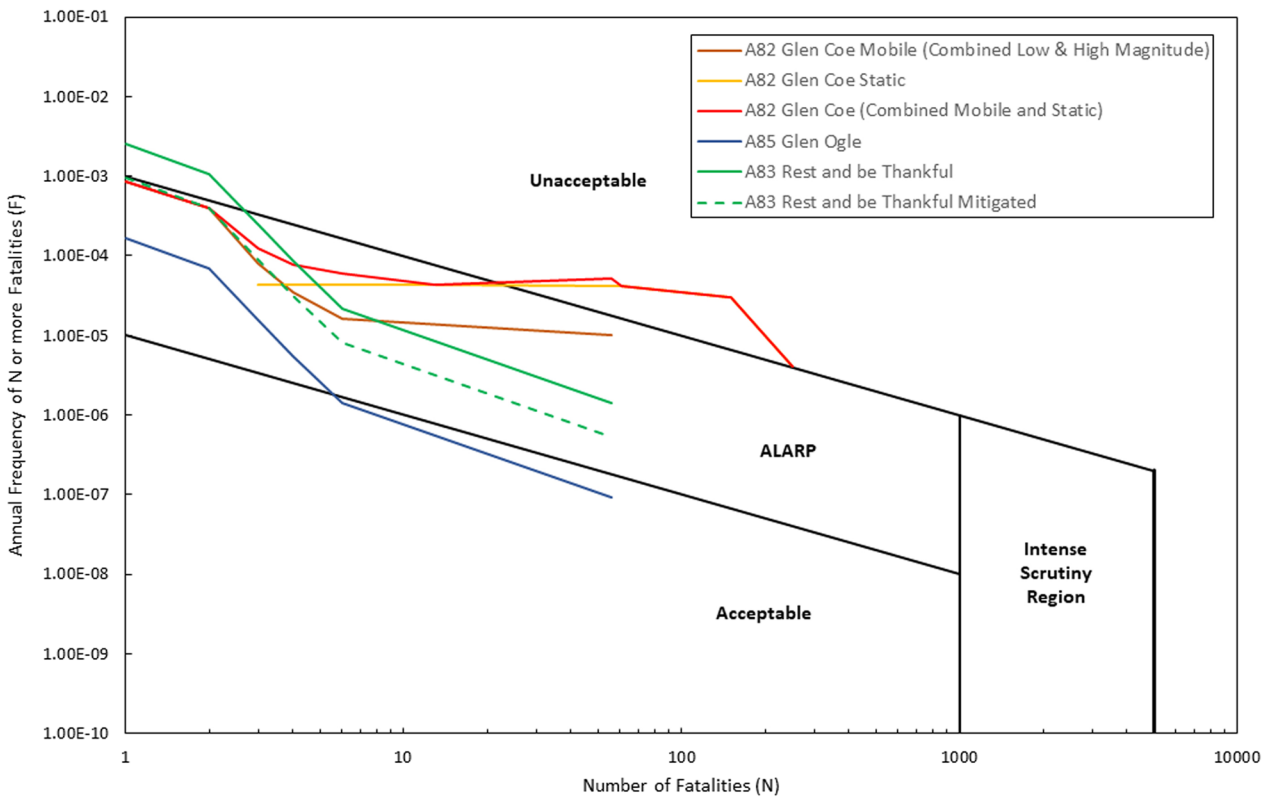

Fig. 11 *F-N* curves for static elements at risk, mobile elements at risk and mobile and static elements at risk combined for vehicle speeds of 80 km/h (50 miles/h) at the A82 Glen Coe. *F-N* curves for the A83 Rest and Thankful (unmitigated and mitigated as at October 2014) and A85 Glen Ogle are also shown for comparison

Societal risk

The *F-N* curves for the A82 Glen Coe, A83 Rest and be Thankful, and A85 Glen Ogle sites are all plotted on Fig. 11. Clearly, for mobile elements at risk at the A82 in Glen Coe, the risk resides entirely within the As Low As Reasonably Practicable (ALARP) zone. In contrast, that for the A83 resides in both the Unacceptable zone and the ALARP zone, albeit entirely with the ALARP zone when mitigation effective as of 2014 is considered, while that for the A85 bridges the ALARP and Broadly Acceptable zone.

The 'up-tick' in the *F-N* curve for the A82 site for higher values of N is due to the higher proportion of buses within the overall A82 traffic, compared to the A83 and A85 (1.19% compared to 0.06%, almost 20 times).

Figure 11 also shows the *F-N* curves for the A82 static elements at risk and the static and mobile elements at risk combined. The *F-N* curves, for values of $3 \leq N \leq 13$ plots

within the ALARP zone, while for higher values ($N \leq 250$) it plots in the zone in which the risk is considered to be Unacceptable. These values are due to the large numbers of visits that are made to the car parks annually; there are estimated to be 845,000 person visits annually with an average visit duration of around 15 min.

Total risk

Clearly there are two different risk scenarios for A82 road users in Glen Coe, as follows:

- Those who travel through Glen Coe but do not stop.
- Those that travel the A82 through Glen Coe and make a stop at the car parks.

The former are subject to the risk previously set out for mobile elements at risk while the latter are subject to the risks pertaining to both mobile and static elements at risk.

This gives total risk values for those that travel the A82 through Glen Coe (at 50 miles/h or 80 km/h) and make a stop at the car parks, assuming $P(Fatality|Hit) = 0.01$, as $PIR = 4.311E{-}10$ (or 1 in 2,300 million years) and $PLL = 1.834E{-}03$ or 1 in 545 years.

The calculated *PIR* for static elements at risk is generally towards the lower end of the values calculated for mobile elements at risk for any of the sites (A82, A85, A83) for which it has been calculated; this holds true also for those who make multiple visits including coach drivers and tour guides.

The *F-N* curves can also be combined for the mobile and static elements at risk to give a total risk for those that travel the A82 through Glen Coe (at 50 miles/h) and make a stop at the car parks as illustrated in Fig. 11. It is clear from Fig. 11 that the societal risk at Glen Coe is significant. The risk to road users who do not make a stop (mobile elements at risk) generally resides in the higher reaches of the ALARP zone, with a significant 'up-tick' for higher numbers of fatalities (N) that is of concern. The risk for static elements at risk resides in the upper part of the ALARP zone for lower values of N and in the Unacceptable zone for higher values of N. The total risk, for those who drive through Glen Coe and make a stop, follows a broadly similar pattern to that for static elements at risk. The most prominent feature of this pattern is that the risk is less acceptable for higher values of N. The probabilities for higher numbers of fatalities ($56 \leq N \leq 250$) are in the Unacceptable zone and for $13 \leq N \leq 150.5$ the probability (F) of those numbers of fatalities correspond to around 1 in 20,000–30,000 years.

It seems clear that the levels of risk related to those road users who make stops at the Glen Coe car parks are unacceptable and that some form of risk reduction is required.

Conclusions and summary

The A82 strategic road through Glen Coe is one of the most iconic driving routes in Scotland, and Glen Coe itself is a major leisure and tourist attraction and asset to the Scottish economy. The popularity of two car parks that have developed on the materials deposited by past debris flow events has led to concerns regarding the risk of both those who use the car parks as well as those who drive through Glen Coe.

A Quantitative Risk Assessment (QRA) has been performed for both mobile elements at risk, using a previously developed method, and for static elements at risk, using a new method. The latter includes the use of a new metric (Annual Average Daily Visits, AADV) that describes the number of visits and the duration of those visits to delineate the temporal probability of the elements at risk being in the wrong place, P(*Wrong Time*).

While Personal Individual Risk (*PIR*) is at an acceptable level, including for frequent users. The risk presented to society as a whole presents a rather different picture. This is largely due to the very high visitor numbers, equivalent to around 845,000 15-min equivalent visits per annum.

The results indicate that the societal risk for mobile elements at risk resides in the ALARP zone of the *F-N* diagram, being at a similar level to the A83 Rest and be Thankful site, albeit with a higher risk associated with higher numbers of fatalities. The results for the static elements at risk, while in the ALARP zone for lower numbers of fatalities, reside firmly in the Unacceptable zone of the *F-N* diagram for higher numbers of fatalities.

The total societal risk, for mobile and static elements at risk, at the A82 Glen Coe is at a level that corresponds to ALARP for low numbers of fatalities but Unacceptable for higher numbers of fatalities up to 250. This unacceptable level of risk indicates 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.

Abbreviations

AADT	Annual average daily traffic
AADV	Annual average daily visitors
ALARP	As low as reasonably practicable
AOD	Above ordnance datum
GBTS	Great Britain tourism survey
F-N	Frequency-number
NGR	National grid reference
PIR	Personal individual risk
PLL	Personal loss of life
QRA	Quantitative risk assessment
SRNLS	Scottish road network landslides study
TRN	Trunk road network

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Author contributions
MGW and GF conceptualised the study. MGW designed the study, developed the methodology and executed the study. TW managed the study, and advised and edited the internal (unpublished) report. GF secured the funding and directed the work. MGW wrote the paper; TW and GF reviewed and edited the paper. All authors read and approved the final manuscript.

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None.

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