Economic impacts of landslides and floods on a road network

Mike G. Winter[1, 2, *], David Peeling[3], Derek Palmer[4], James Peeling[3]

[1] Winter Associates, Kirknewton, Midlothian, U.K. formerly Transport Research Laboratory (TRL), Edinburgh, U.K.
[2] University of Portsmouth, Portsmouth, U.K.
[3] Transport Research Laboratory (TRL), Wokingham, U.K.
[4] Formerly Transport Research Laboratory (TRL), Wokingham, U.K., now Independent Transport Economist, U.K.
* Corresponding author: mwinter@winterassociates.co.uk

ABSTRACT

Even in the absence of serious injuries and fatalities, landslide and flood events can have significant socio-economic impacts. These include the severance of access to and from relatively remote communities for services and markets for goods; employment, health and educational opportunities; and social activities. The economic impacts can be classified as: direct economic impacts, direct consequential economic impacts, and indirect consequential economic impacts. In addition, the vulnerability shadow cast can be extensive, and its geographical extent can be determined by the transport network rather than the relatively small footprint of the event itself. Using a number of debris flow events and a flood event in Scotland this paper places values on the economic impacts of landslides and floods. It also demonstrates the widespread impact of the events by means of the vulnerability shadow that is cast.

KEYWORDS

landslides; floods; hazard; risk; economic; social

Received: 17 May 2019
Accepted: 15 October 2019
Published online: 18 November 2019

Winter, M. G., Peeling, D., Palmer, D., Peeling, J. (2019): Economic impacts of landslides and floods on a road network. AUC Geographica 54(2), 207–220
https://doi.org/10.14712/23361980.2019.18

1. Introduction

A series of debris flows associated with monthly average rainfall substantially in excess of the norm occurred in Scotland in August 2004. The resulting landslides affected important parts of the trunk (strategic) road network, linking both cities and smaller, remote communities. Notable events occurred (Figure 1) at the A83 between Glen Kinglas and north of Cairndow (9 August), the A9 north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August). While there were no major injuries, 57 people had to be airlifted to safety at A85 Glen Ogle when they became trapped between two major debris flows.

The A83 Rest and be Thankful site, while not affected in August 2004, has been extremely active in recent years with multiple debris flow events and road associated closures; in particular events in 2007 (Figure 2), 2008, 2009, 2011, 2012, 2014, 2015, 2017 and 2018 had an adverse effect on the travelling public. As a result the area has become the focus of not only concern but also of extensive landslide risk reduction activities, in the form of both management and mitigation and. a study was commissioned to assess and make recommendations on potential landslide remediation actions at the Rest and be Thankful site (Anon. 2013a; Winter, Corby 2012).

The rainfall-induced landslides occur in thin deposits of weathering products and other debris overlying rock that frequently dips out of the slopes which may be at angles of up to around 36°. Detailed descriptions of events are available (Winter et al. 2006), as are approaches to hazard and risk assessment (Winter et al. 2005, 2009, 2013), and approaches to management and mitigation (Winter 2014a, 2016). The links with rainfall are described by Winter et al. (2010, 2019).

In the absence of serious injuries and fatalities to those involved, the primary impacts of these events were economic and social. Such impacts include the

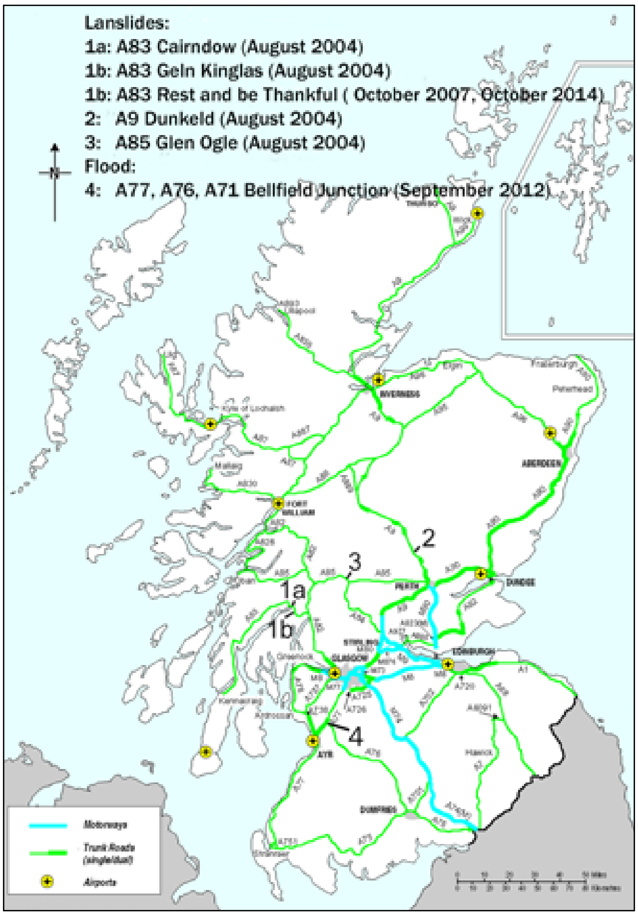

Fig. 1 Map showing the strategic road network in Scotland. The locations of the three main debris flow event groups that affected the trunk road network in Scotland in August 2004 (1, 2, 3) are shown (from Winter et al. 2009). The locations of the later A83, 2007 and 2014, landslides are coincident with the 2004 event at this scale and the A77, A76, A71 Bellfield Junction flood event from 2012 is also shown. The locations for the events correspond to those shown in Figures 4 (1b), 9 (2), 10 (3) and 11 (4).

Fig. 2 View of the debris flows above and below the A83 on the approach to the Rest and be Thankful (location approximately that of 1b in Figure 1). 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.

cost of delays and diversion on transport networks and the severance of access to and from relatively remote communities for services and markets for goods; employment, health and educational opportunities; and social activities.

In 2004 for example, the A83, carrying up to 5,000 vehicles per day (all vehicles two-way, 24 hour annual average daily traffic, AADT) was closed for slightly in excess of a day, the A9 (carrying 13,500 vehicles per day) was closed for two days prior to reopening, initially with single lane working under convoy, and the A85 (carrying 5,600 vehicles per day) was closed for four days. The traffic flow figures are for the most highly trafficked month of the year (July or August). Minimum flows occur in either January or February and are roughly half those of the maxima reflecting the importance of tourism and related seasonal industries to Scotland's economy. Substantial disruption was thus experienced by local and tourist traffic, and goods vehicles.

This paper describes a study to assess the economic impacts of selected debris flow events in Scotland, based on the scheme set-out by Winter and Bromhead (2012). The impacts of floods can be assessed using the same set of principles and metrics and the impacts of one such event are also reported here.

2. Economic impacts

Due to the major contribution that tourism makes to Scotland's economy the impacts of road closures can be particularly serious during the summer months, during which period debris flows usually occur in July and August. Nevertheless, the impacts of any debris flow event occurring during the winter months, between October and November, and in January when debris flow usually occurs, should not be underestimated and events are arguably more frequent during the winter. Not surprisingly, the debris flow events described created a high level of interest in the media in addition to being seen as a key issue by politicians at both the local and national level. Indeed, the effects of such small events which may, at most, directly affect a few tens of metres of road cast a considerably broader vulnerability shadow (Winter, Bromhead 2012), which defines the geographical extent of the impacts of landslides and floods. The qualitative economic impacts of such landslide (and flood) events include:

- the loss of utility of parts of the road network,
- the need to make often extensive detours in order to reach a destination,
- the severance of access to and from relatively remote communities for services and markets for goods; employment, health and educational opportunities; and social activities.

The economic impacts of a landslide event that closes a road, and its associated vulnerability shadow, were summarized by Winter, Bromhead (2012), in three categories, as follows:

- direct economic impacts,
- direct consequential economic impacts,
- indirect consequential economic impacts.

Direct economic impacts: The direct costs of clean-up and repair/replacement of lost/damaged infrastructure in the broadest sense and the costs of search and rescue. These should be relatively easy to obtain or estimate for any given event, provided that records are still available.

Direct consequential economic impacts: These generally relate to 'disruption to infrastructure' and are really about loss of utility. For example, the costs of closing a road (or implementing single-lane convoy working with traffic lights) for a given period with a given diversion, are relatively simple to estimate using well-established models. The costs of fatal/non-fatal injuries and other incident accident costs may also be included here and may be taken (on a societal basis) directly from published figures. While these are set out for the costs of road traffic accidents, or indeed rail accidents, there seems to be no particular reason why they should be radically different to those related to a landslide or flood as all such incidents are likely to include the recovery of casualties from vehicles. Indeed, for events in which large numbers of casualties may be expected to occur, data for rail accidents may be more appropriate.

Indirect consequential economic impacts: Often landslide events affect access to remote rural areas with economies that are based upon transport-dependent activities, and thus the vulnerability can be extensive and is determined by the transport network rather than the event itself. If a given route is closed for a long period then confidence in, and the ongoing viability of, local business may be affected, for example. Manufacturing and agriculture (e.g. forestry in western Scotland), are a concern as access to markets is constrained, the costs of access are increased and business profits are affected and short-term to long-term viability may be adversely affected; in Jamaica a landslide on the B1 route in the Blue Mountains effectively severed local coffee production from the most direct route to the international market for that high value product (Figure 3). Perhaps of even more concern are the impacts on tourist (and other service economy) businesses. It is important to understand how the reluctance of visitors to travel to and within areas affected by landslides or floods is affected after an event that has received publicity and/or caused casualties and how a period of inaccessibility (reduced or complete) affects the short- and long-term travel patterns to an area for tourist services. Such costs form a fundamental element of the overall economic impact on society of such events. They are thus important to governments as they should affect the case for the assignation of budgets to landslide risk mitigation and remediation activities. However, these are also the most difficult costs to determine as they are generally widely dispersed both geographically and socially. Additionally, in an environment in which compensation might be anticipated, albeit often erroneously, those that have the best data, the businesses affected by such events, are also those that anticipate such compensatory events.

Typically analyses of the economic impacts of landslides and other natural disasters focus on the direct and/or indirect impacts, with the latter being generally analogous to direct consequential as set-out above (Schuster 1996; Highland 2006; Hearn et al. 2008; Chang, Nojima 2001; Bono, Gutiérrez 2011; Bil et al. 2015; Klose et al. 2015). Attempts to evaluate the indirect consequential impacts of such event are, at best, rare.

The vulnerability shadow cast can be extensive and its geographical extent can be determined by the transport network, including closures and diversionary routes, rather than the relatively small footprint of the event itself (Winter, Bromhead 2012). In the particular case of the event at the A83 Rest and be Thankful in October 2007 of the order of around 400 m^3 of material was deposited at road level with a footprint that closed a few tens of metres of the road (Winter 2014); the vulnerability shadow can be estimated to be of the order of 2,800 km^2 (total area approximately 3,500 km^2, 20% allowed for areas of sea) (Figure 4) which is, for

Fig. 3 Landslide on the B1 road at Section in Portland Parish, Jamaica. This event severed much of the local coffee production industry from the ports used to ship the product to market. (The picture is a photo-collage and some distortion is inevitable.)

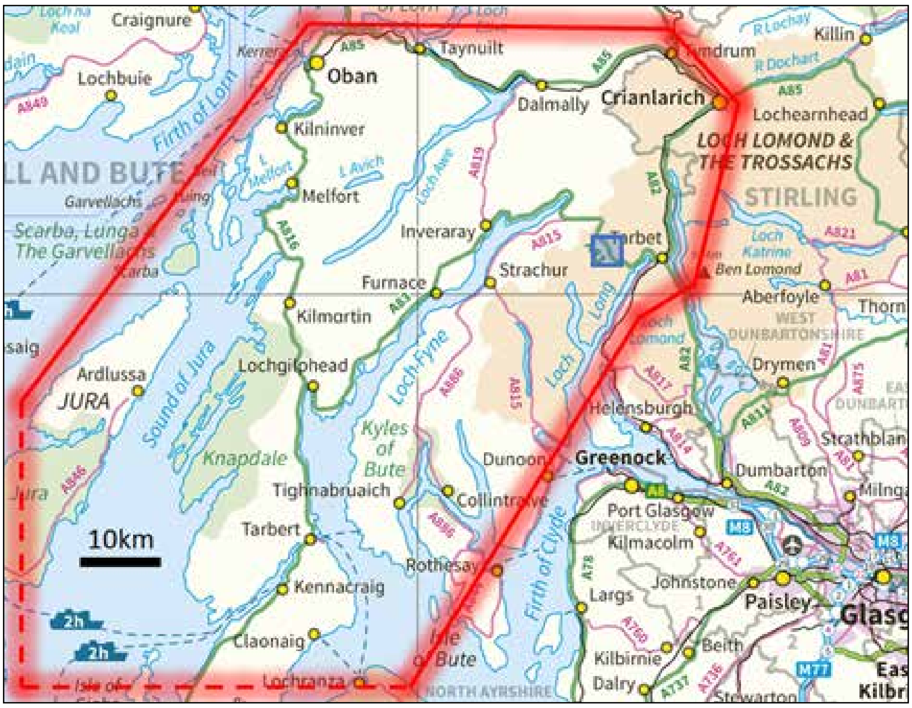

Fig. 4 A relatively small debris flow event (blue rectangle) closed the A83 at the Rest and be Thankful in October 2007; the vulnerability shadow that was cast (bounded in red) was extensive (Winter 2014a; 2014b). See Figure 1 (1b) for the event location in the wider geographical context. (Image based on OS Route Planner 2016 Map. © Crown Copyright. All rights reserved Scottish Government 100020540, 2019.)

the purpose of comparison, approximately two-and-a-half times the total land area of Hong Kong SAR.

The area has a population density of approximately 13 people/km^2 (www.argyll-bute.gov.uk) and the event thus had the potential to have had an economic impact upon up to approximately 36,400 people in Argyll, Bute, plus any transient (e.g. tourist) population.

It is instructive to make some simple comparisons with Hong Kong SAR, which has an average population density of around 6,500 people/km^2 (www.gov.hk). This dictates a much greater transport network density. Thus, and purely for the sake of comparison, in order to have an economic impact on the same number of people the vulnerability shadow cast need only be approximately 5.6 km^2 (2 km by 2.8 km, for example).

It is not suggested that the economic impacts would be similar for events with vulnerability shadows of these diverse sizes in Argyll, Bute and Hong Kong. However, it is clear that the low density/dispersed network in Argyll, Bute dictates a large vulnerability shadow while the much more dense/less dispersed network in Hong Kong means that the vulnerability shadow will be much less extensive, with the possible exception of events that affect critical infrastructure corridors, as more alternative routes will exist and will be more proximal to the event (Winter 2014b).

As part of this work (Winter et al. 2018), the vulnerability shadow has been evaluated using knowledge of the local transport networks and the socio-economic activity associated with the network that has been built up over a period of 30 years. This includes a holistic evaluation of major nodes, origins and destinations and includes both experience and knowledge gleaned from formal surveys (e.g. Winter et al. 2013).

The economic impact and the vulnerability shadow are concepts that apply equally to other discrete climate driven events, such as floods, that may close parts of the road network. Both landslides and floods are generally thought to be likely to increase in frequency as a result of climate change (Galbraith et al. 2005; Anon. 2011; Winter et al. 2010; Winter, Shearer 2013).

Notwithstanding the above, it is clear that for some events the hazard itself, and not the transport network or, more pointedly, its density, that determines the location, shape and extent (morphology) of the vulnerability shadow. It is therefore important to recognise that the morphology of the vulnerability shadow caused by other types of event (e.g. glacial lake outburst floods), may be determined by the nature of the hazard itself.

An example in which the hazard itself determines the vulnerability shadow is that of the Seti River debris flow in Nepal (Figure 5). On 5 May 2012 a major event caused significant erosion and deposition in the river channel over an approximate 40 km length. The event was thought to have resulted from a failed landslide dam. However, subsequent inspection of satellite imagery and aerial photography (Petley, Stark 2012; Petley 2014), and more detailed site inspection and investigation (Dahal , Bhandary 2013) led to a rather different conclusion; that the event was a debris flow initiated by part of a 22 Mm^3 rock avalanche originating on the slopes of Annapurna IV entering the upper stream channel at high speed. An estimated 71 people lost their lives at Kharapani, some 20 km north of Pokhara. The vulnerability shadow was constrained by the dimensions of the hazard flow within the stream channel, extending beyond these bounds only where infrastructure was damaged, including the footbridge at Kharapani.

Fig. 5 Residents of Kharapani located on the platform in the middle distance on the Seti River, Nepal, were among fatalities from the 5 May 2012 debris flow event. The abutment of the suspended footbridge is on the platform.

3. Methodology

3.1 Direct Economic Impacts

Direct economic impacts should be the most straightforward to determine. Indeed, this has generally proved to be the case with relatively recent events that occurred within the currency of existing network operation contracts. Thus, data relating to the 2007 and 2014 A83 Rest and be Thankful events were readily available from the company responsible for the operation of roads in this north-west part of Scotland at the times of enquiry, as was data for the 2012 flooding event.

Data on direct economic impacts was generally collected from the records of the companies responsible for operating the road network. However, data from less recent events such as the landslide events of 2004 (Winter et al. 2005, 2006, 2009) proved more difficult to obtain largely as both the operators and auditors had changed since the events occurred; as Highland (2006) points out past data are generally labour intensive to retrieve.

The passage of time and the consequent lack of readily available records limited the resolution and reliability of the data that can be obtained for the 2004 events. What data has been obtained was derived from high level reporting documents to Scottish Ministers and Senior Civil Servants and covers all three of the event groups from August 2004 (A83, A9 and A85). This data has been interpreted and broken down to the best of the ability of the original authors and editors of the Scottish Road Network Landslide Study reports (Winter et al. 2005, 2009).

3.2 Direct Consequential Economic Impacts

Direct consequential economic impacts are related to ‘disruption to infrastructure’ and concern loss of utility or the costs imposed on road users. For example, the costs of closing a road (or implementing single-lane working with traffic lights) for a given period with a given diversion, are relatively straightforward to estimate using well-established models. The costs of fatal/non-fatal injuries and incident damage only accidents are also included here and may be taken (on a societal basis) directly from published figures (Anon. 2013b). While these are set out for the costs of road traffic accidents (figures are also available for rail accidents) there seems to be no particular reason why they should be radically different to those related to a landslide or flood as both are likely to include the recovery of casualties from vehicles. Indeed, for events involving large numbers of casualties, it can be argued that data relating to railway accidents may be more appropriate. In all of the cases presented here the accidents have been non-injury accidents (damage only) and the numbers of vehicles involved have been estimated from contemporaneous photographs taken by the first author and others.

If a road is closed, either fully or partially, as a result of an event some or all of the users of that route will have to take an alternative, diversionary route, which may be significantly longer than the primary route. Even if no diversion is necessary, then the capacity of the road will likely be reduced (e.g. through a lane closure or the imposition of a speed limit) meaning that queues form, particularly at peak times, slowing the traffic flow. These effects can significantly increase road users’ journey times. It is also pertinent to note that such queues if formed adjacent to areas of high landslide susceptibility can significantly increase the risks to the affected road users.

The QUADRO (QUeues And Delays at ROadworks) model provides a method for assessing the costs imposed on road users while roadworks are being carried out, considering:

- Delays to road users: the change in road users’ journey times, priced using the value of their time (e.g. cost to their employer’s business of the time spent travelling during the working day) based on the type of vehicle, its occupants and trip purpose.
- Fuel carbon emissions: the change in carbon emissions due to vehicle fuel consumption, based on average figures per litre of fuel burnt and costed using estimated abatement costs (see STAG and WebTAG) (Anon. 2012a, 2012b).
- Accident costs: the change in the occurrence of accidents, in terms of the additional delay caused and the direct costs (e.g. property damage, police time and insurance administration).

The program contains a model for allocating traffic to the diversion route if the site becomes overloaded, representing both the road users that queue through the site and those that take an alternate route in the case of a partial closure. The details of QUADRO, including all assumptions made in its calculations, are provided in the manual (Anon. 2015).

In order to model a road closure in QUADRO, a diversionary route must be defined. The QDIV (QUADRO Diversion) tool was used to model the standard diversionary routes used by the road operator.

QDIV requires each diversionary route to be defined in terms of a set of links (each defined as rural, urban, sub-urban or small town) that can be combined in series and parallel to build up a network. For each event, a simplified diversionary network schematic was developed and Google Maps was used to measure the length of each link (Winter et al. 2018). Traffic data, represented as annual average daily traffic (AADT), were sourced using data from the relevant Road Administrations.

Where information was not available (e.g. lane and verge widths), the default values suggested in the QUADRO manual were adopted. Classified traffic counts (i.e. split into different vehicle types), and therefore the proportion of heavy vehicles, were only

Table 1 Site parameters for the direct consequential economic impact analysis.

Event	Number vehicles damaged	Traffic (AADT) (vehicles/day)[2]	HGVs (%)	Junction length (km)	Closure type(s)	Closure duration
August 2004: A83 Glen Kinglas to Cairndow (L)[1]	1	5,554	9	20	Full closure	2 days
August 2004: A9 N of Dunkeld (L)	5	13,864	18	18	Full closure, then shuttle working with convoy	2 days full 6 days convoy
August 2004: A85 Glen Ogle (L)	3	4,403	10	26	Full closure	4 days
October 2007: A83 Rest and be Thankful (L)	1	5,748	10	20	Full closure, then shuttle working[3]	15 days full 27 days shuttle[4]
September 2012: A77, A76, A71 Bellfield Junction (F)	0	6,400 to 13,800	6	0.3 to 4.9	A77: Full closure A76: Full closure then shuttle working A71 Full closure	25 hours 19 hours full 2 days shuttle 67 hours
October 2014: A83 Rest and be Thankful (L)	0	5,460	9.5	20 / 4[5]	Full closure (daytime) Full closure (night time) Convoy (daytime)[6] Convoy (night time)[6] Shuttle (daytime) Shuttle (night time) Shuttle (24 hours)	10 hours 28 hours 42 hours 56 hours 40 hours 42 hours 682 hours

[1] L = Landslide; F = Flood.
[2] Peak monthly figures, usually for August.
[3] Single-lane working with traffic light control.
[4] This figure represents the duration of the closure due to the instability and the immediate engineering works required to allow the reopening of the road. It is acknowledged that the road was subsequently subject to single lane working with traffic light control for a significantly longer period due to engineering works necessitated by the combination of this and subsequent events in the immediate vicinity.
[5] 20 km for full closure, 4 km for convoy working on the old Military Road (OMR).
[6] Using the OMR, the temporary diversion used when the A83 Rest and be Thankful road is closed.

available for some links; either the proportion from the closest link or a nominal 10% HGVs was assumed (Table 1).

It was assumed that all of the roads affected were rural all-purpose single carriageways with a speed limit of 96 km/h (60 mph), reduced to 48 km/h (30 mph) where part of the road remained open following the landslide or flood event, and that the length of the affected site in each case was 100 m. (The speed limit at the A85 site was reduced from the national speed limit of 96 km/h (60 mph) to 80 km/h (50 mph) in November 2015, more than a decade after the events and around the time that aspect of the study was completed.)

3.3 Indirect Consequential Economic Impacts

There is a wide range of possible approaches to estimating the indirect consequential economic impacts of landslides. These include:

- cost-benefit analysis,
- cost-effectiveness analysis,
- willingness to pay,
- multi-criteria analysis,
- methods based upon Transport Appraisal.

In addition, there are bespoke methods designed to address a particular set of circumstances (McLeod et al. 2005; Anon. 2013b) as described by Winter et al. (2018).

Surveys of businesses were undertaken in the areas of the 2004 A85 landslide; 2012 A77, A76, A71 Bellfield Junction flood; and A83 2014 landslide events. The surveys used questionnaires based on the Stated Preference approach that were mailed to respondents with follow up telephone calls to improve the response rate that varied between 20.8% (A5 Glen Ogle) 17% (A83 Rest and be Thankful) and 11.7% (A77, A76, A71 Bellfield Junction).

4. Results

4.1 Direct Economic Impacts

The available data is reported in Table 2, adjusted to 2012 prices.

Direct economic impacts include:

1. The direct costs of clean-up and the costs of search and rescue.
2. The repair/replacement of lost/damaged infrastructure in the broadest sense.

These might otherwise be described as ‘emergency response’ and ‘remedial works’, respectively as in Table 2.

Direct economic costs for the landside events range between approximately £250k and £1,700k. For the flood event in a more developed peri-urban part of Scotland the direct costs were relatively small (around £25k).

Table 2 Direct economic impacts (at 2012 prices).

Event	Emergency response	Remedial works	Total
August 2004: A83 Glen Kinglas to Cairndow	£395,043		£395,043
August 2004: A9 N of Dunkeld	£921,766		£921,766
August 2004: A85 Glen Ogle	£658,405		£658,405
October 2007: A83 Rest and be Thankful	£320,772	£1,372,629[1]	£1,693,401
September 2012: A77, A76, A71 Bellfield Junction	£16,756	£8,333	£25,088
October 2014: A83 Rest and be Thankful	£245,328	£0[2]	£245,328

[1] Comprises: debris barrier (including design, tender, award, construction and supervision) £425,446 (at 2012 prices); works prior to culvert replacement (including ongoing traffic management and carriageway protection, culvert design, geotechnical design and certification, ground investigation and diversion fibre optic telecommunications cable) £181,184; and culvert replacement (construction) £765,999. These works were undertaken in direct response to the October 2007 event and may thus be attributed to this event.

[2] While an extensive programme of remedial works has been undertaken at the wider A83 Rest and be Thankful site, some of which is focused on the location of the 28 October 2014 event, this was installed prior to the event and thus cannot be attributed to this event. In broad terms the remedial measures, including both management and mitigation measures (Winter 2014), worked as anticipated and would not have been expected to prevent a debris flow of this size from reaching the road.

4.2 Direct Consequential Economic Impacts

QUADRO enables the calculation of the costs of user delays and diversions, carbon emissions from vehicles and accidents associated with the road works, reporting the costs on the basis of an average day over a whole week (Table 3); the total costs for each site, taking into account the duration of the impacts, are summarised in Table 4. Implicit are assumptions regarding the costs of time (vehicle occupancy, journey purpose, and the value of time for both occupants and vehicles), vehicle operating costs (and associated carbon costs), and the value of accidents that occur within the section(s) of road under consideration (Anon. 2015) and the associated values are based on national statistics.

Careful consideration of the relative traffic levels, and closure type and duration (Table 4), reveals patterns that are broadly consistent with those that might be inferred intuitively, as follows:

– The costs of similar closures depend on traffic levels; costs being in proportion to traffic (A9 *cf.* A83 2004).
– Doubling the duration incurs higher costs, but may be reduced if the traffic levels are lower (A83 2004 *cf.* A85).
– A much longer duration increases the costs significantly (A83 2007).

Table 3 Incident accident costs (per vehicle) and QUADRO daily closure costs (at 2012 prices).

Cost (£)	August 2004: A83 Glen Kinglas to Cairndow	August 2004: A9 N of Dunkeld (Full closure/ shuttle working)	August 2004: A85 Glen Ogle	October 2007: A83 Rest and be Thankful (Full closure/ shuttle working)	September 2012: A77, A76, A71 Bellfield Junction (Full closure/ shuttle working)	October 2014: A83 Rest and be Thankful1 (Full closure/ convoy/ shuttle working)
Accident incident cost	2,520	2,520	2,520	2,520	2,520	2,250
Delay cost (daily)	84,071	270,885 / 135,339	71,679	88,040 / 461	1,548,624 / 94,363	168 to 83,427
Carbon cost (daily)	6,380	18,608 / 9,304	6,629	6,590 / 6	73,922 / 671	2 to 6,262
Accident cost (daily)	−4,360	−11,254 / −5,627	−4,494	−4,512 / 794	−38,568 / 7,564	−4,268 to 312

[1] The daily delay, carbon and accident costs for the October 2014 Rest and be Thankful event vary significantly, by several orders of magnitude, for the various types of closure described in Table 2 and accordingly only the range is reported here. Full details are given by Winter et al. (2018). The higher costs (lower daily accident costs) are for full closure and the lowest costs (highest daily accident costs) are for shuttle working.

Table 4 Total incident accident costs and QUADRO total closure costs (at 2012 prices).

Cost (£)	August 2004: A83 Glen Kinglas to Cairndow	August 2004: A9 N of Dunkeld (Full closure/ shuttle working)	August 2004: A85 Glen Ogle	October 2007: A83 Rest and be Thankful (Full closure/ shuttle working)	September 2012: A77, A76, A71 Bellfield Junction (Full closure/ shuttle working)	October 2014: A83 Rest and be Thankful (Full closure/ convoy/shuttle working)
Accident incident cost	2,520	12,600	7,560	2,520	0	0
Delay cost	168,143	1,218,460	286,718	1,333,020	3,080,542	173,956
Carbon cost	12,762	83,737	26,514	99,029	151,669	9,164
Accident cost	−8,721	−45,288	−17,974	−46,247	−71,309	29,466
Total	**174,703**	**1,269,508**	**302,817**	**1,388,322**	**3,160,902**	**212,587**

Fig. 6 Word map of responses from survey respondents: A85 Glen Ogle, 18 August 2004 landslide.

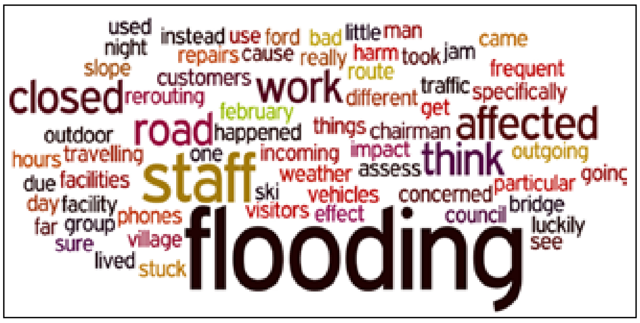

Fig. 7 Word map of responses from survey respondents: A77, A76, A71 Bellfield Junction Flooding: 21 September 2012.

Of particular interest are the negative costs (i.e. cost reductions) for traffic accidents during post-event diversions and/or restricted traffic flow. These reduced accident costs suggest a decrease in accident numbers and/or accident severity and seem most likely to be as a result of reduced traffic speeds leading to an increased opportunity to avoid accidents and lower severity when they do occur.

The landslide events were located in rural areas and their impacts are upon those areas and small towns and villages. Direct consequential costs range between approximately £180k and £1,400k for the landslide events. The latter costs are largely dependent upon the amount of traffic that uses the road and the duration of the disruption.

The flood event was located in a much more developed part of Scotland and on the edge of a town (Kilmarnock). The peri-urban flood location and much shorter event duration, places a different complexion on the direct consequential economic impacts which were more than twice those for the A83 2007 (c. £3,200k).

Notwithstanding this the impacts of the A83 event(s) should not be underestimated: those impacts were borne by a much smaller number of people over an extended period; the impacts on individuals and individual businesses seem likely to have been considerably greater. This part of the analysis also does not take account of the longer term indirect consequential economic impacts (see Section 4.3).

4.3 Indirect Consequential Economic Impacts

The surveys of businesses in the areas of these events provided cost information that could be interpreted in a number of ways and therefore gave a very wide range of potential results. The results did, however, provide useful qualitative information (Winter et al. 2018). For events of lesser impact, descriptors that relate to the hazard are used: 'landslide', 'flooding' and other words that describe the event itself are also to the fore (Figures 6 and 7).

In contrast responses to events of greater impact and or repetition such as at the A83 (Figure 8), at which a significant number of events and consequent closures have occurred over the past 20 years, tend to relate to the effects, risks, or impacts, that derive from the event. In this case the most frequently used word is 'road', with words such as 'closed', 'staff', 'visitors', 'due', 'access', 'tourism', 'minor' and 'island' also coming to the fore. These latter responses seemingly describe the consequences of the hazard, or the economic risks associated with the hazard, rather than the hazard itself, implying a greater economic impact or, at least, a greater awareness of the economic impact.

Fig. 8 Word map of responses from survey respondents: A83 Rest and be Thankful, 28 October 2014 landslide.

5. Vulnerability shadow

The vulnerability shadow for the October 2007 debris flow is described in Section 2 (Figure 4) and is estimated at around 2,800 km^2. This description holds for the event in 2014 also as the road closure was on the same link between the junctions with the A814 at Arrochar and the B828 immediately to the north of the Rest and be Thankful car park with no entry or exit routes to the A83 between.

While the 2007 and 2014 A83 debris flow events occurred to the east of the B828 (serving Lochgoilhead), the August 2004 events at the A83 were located to the west of the B828 in Glen Kinglas and further to the west, beyond the A815 (serving inter alia Dunoon) to the west of Cairndow (around 5 km to the north-west of the 2007/2014 events shown in Figure 4). Notwithstanding this, the differences in the diversions for the two sets of events were subtle and it is broadly considered that the extent of the vulnerability shadow was not dissimilar.

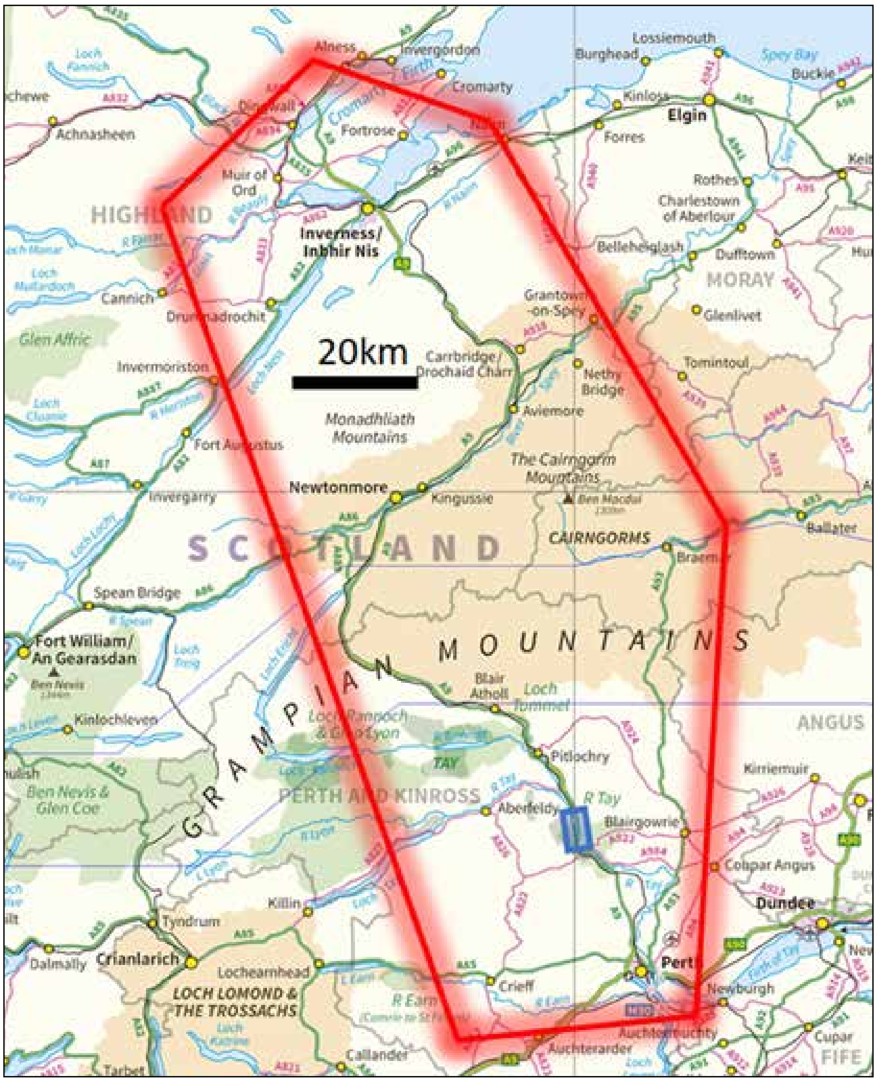

Fig. 9 Three main debris flow events (blue rectangle) closed the A9 N of Dunkeld on 11 August 2004; the vulnerability shadow that was cast (bounded in red) was extensive and reflects the importance of the A9, particularly to the communities to the north. See Figure 1 (2) for the event location in the wider geographical context. (Image based on OS Route Planner 2016 Map. © Crown Copyright. All rights reserved Scottish Government 100020540, 2019.)

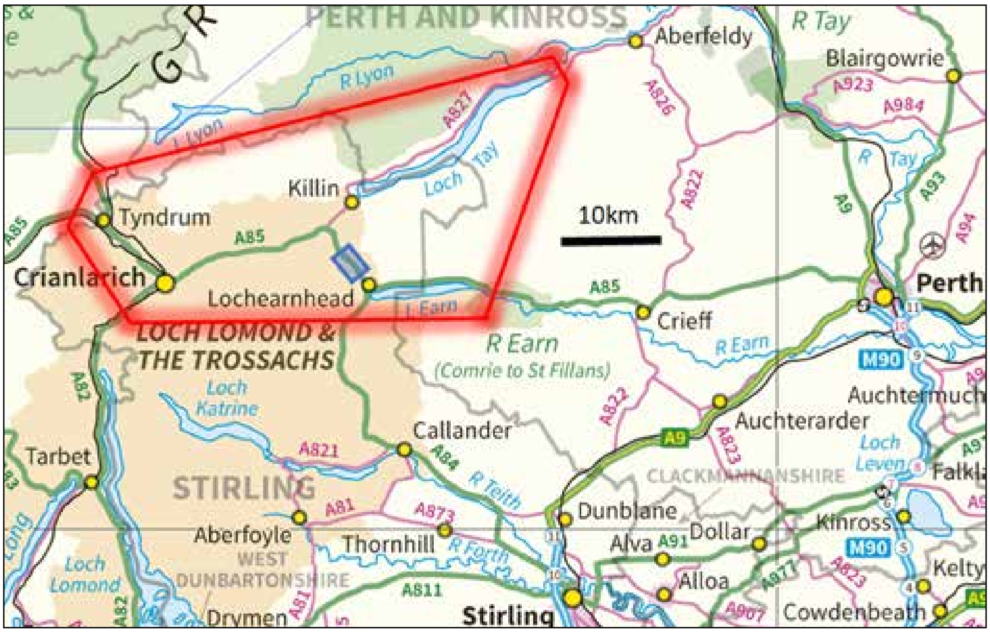

Fig. 10 Two debris flow events (blue rectangle) closed the A85 in Glen Ogle on 18 August 2004; the vulnerability shadow that was cast (bounded in red) was limited by the reasonably good range of alternative routes in the area. See Figure 1 (3) for the event location in the wider geographical context. (Image based on OS Route Planner 2016 Map. © Crown Copyright. All rights reserved Scottish Government 100020540, 2019.)

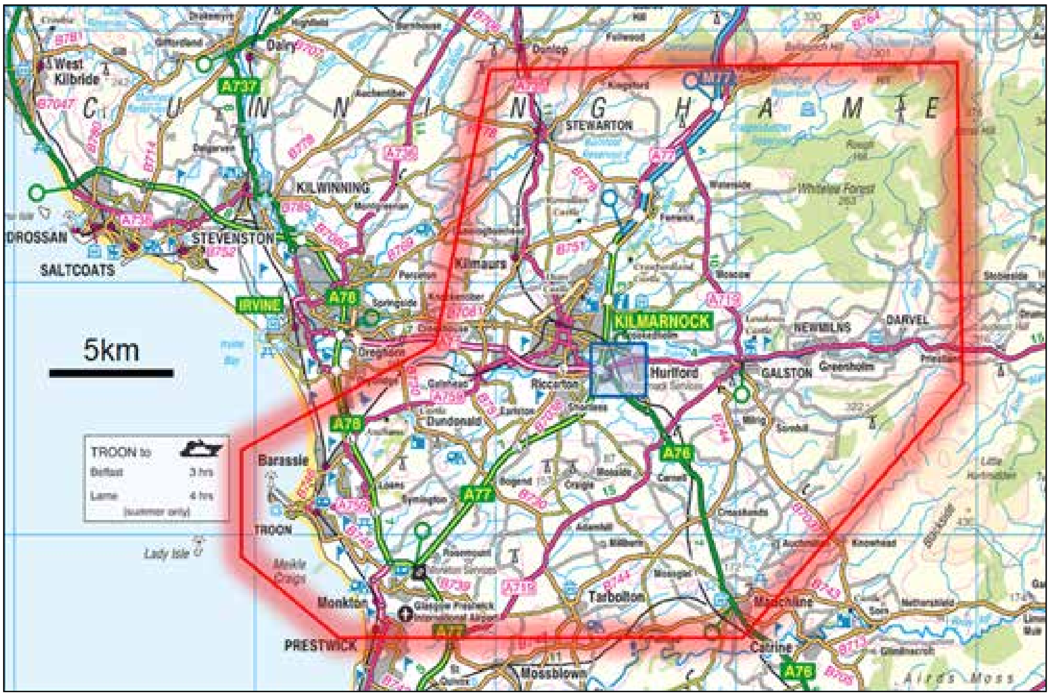

Fig. 11 Flooding at the A77, A76, A71 Bellfield Junction (blue rectangle) closed all three roads on 21 September 2012; the area of the vulnerability shadow that was cast (bounded in red) was limited by the availability of diversionary routes. See Figure 1 (4) for the event location in the wider geographical context. (Image based on OS 1:250,000 mapping. © Crown Copyright. All rights reserved Scottish Government 100020540, 2019.)

Those for the other 2004 events were estimated at around 8,000 km^2 (A9: Figure 9) and 800 km^2 (A85: Figure 10). The vulnerability shadow cast for the A9 debris flow events to the north of Dunkeld (11 August 2004) is significant (Figure 9), reflecting the importance of the A9 as the primary north-south route in Scotland, leading to the most northerly city of Inverness (population around 47,000) and numerous smaller communities along the route and to the north of Inverness, and the relative paucity of alternative routes and their commensurate length. The A85 Glen Ogle vulnerability shadow cast for the 18 August 2004 debris flow is, by comparison, relatively small (Figure 10). This, in turn, reflects the relatively central position of that area in Scotland and the existence and relative efficiency of alternate routes through and around the area.

The vulnerability shadow cast by the 21 September 2012 flooding event at the A77, A76, A71 Bellfield Junction (Figure 11) was smaller still at around 500 km^2 (the nearby town of Kilmarnock has a population of approximately 46,000). The road network in this area is much denser, and the population density is much higher, than that in the other areas studied and this leads to reasonable alternative routes, albeit with significant associated disruption to traffic.

6. Discussion

Highland (2006) (see also Schuster 1996; Schuster, Highland 2007; Highland 2012) concluded that records of landslides and their associated costs were inadequate and that a standardised approach to landslide loss inventory would reduce the cost, and improve the usability and availability of landslide loss information. Further work by Highland (2012) deals in more detail with both direct economic impacts and also some aspects of direct consequential and indirect consequential economic impacts, although these latter two are usually described in a qualitative manner. Highland describes decreased economic activity in some areas and increased economic activity in other areas (e.g. as a result of the Glenwood Canyon Rockfall) and both higher than usual flight costs and an increase in the incidence of charter aeroplane use between key locations on either side of the event.

A related study (Klose et al. 2015) collected data and modelled the costs incurred due to landslides that affected the federal road network in the Lower Saxon Uplands in NW Germany. The approach used the data collected at a local level to extrapolate direct costs for the region, using the results of a susceptibility assessment and an infrastructure exposure model. However, this study deals only with direct economic impacts and this degree of extrapolation across the network was not considered appropriate to the situation in Scotland where landslides occur relatively infrequently.

Hearn et al. (2008) deal with both direct and direct consequential economic impacts, but their approach to direct consequential impacts appears to be based on the assumption that all vehicles (and drivers and passengers) that would normally use the road for the period of the closure will wait for it to be reopened. While this might be appropriate for Laos, where the study was conducted, and reflects the morphology of the road network it does not account for either diversions or restrictions of traffic flow as are more normal in Europe.

The lack of a robust database of landslide events makes a quantitative national economic analysis difficult. Almost 40 landslides are reported in the media in the UK annually (38 in 2010) (Gibson et al. 2012). Anon. (2013a) noted that between 1 January 2007 and 31 October 2012, the A83 at the Rest and Be Thankful was closed five times as a result of landslides and these and other landslides have been enumerated and described (e.g. Winter et al. 2005, 2006, 2009) extensively in recent years. Despite this Dobbie et al. (2011) consider that landslides are rare in Scotland. Whatever the rarity or otherwise of such events, better data is critical to the effective management of risks, as highlighted for flood hazards and risks by the Association of British Insurers (Anon. 2010).

Importantly, this current work confirms Highland's (2006) assertion that past data for direct economic impacts are generally labour intensive to retrieve. The experience here has been that as people move on both knowledge and experience are lost but, even more critically, as contracts pass to new organizations data and information about events is lost.

The modelling of direct consequential economic impacts has not been attempted before and this throws up some interesting but rather unsurprising conclusions – not least that the total costs depend primarily on the amount of traffic affected and the duration for which it is affected. Notwithstanding this, it is important to recognize that where traffic levels are lower the network may represent a lifeline route with limited, complex/lengthy and/or no alternative routes.

Similarly, indirect consequential economic impacts are rarely evaluated. The surveys conducted for this work provided important and very useful qualitative data as set-out in Section 4.3 and represented in Figures 6,7 and 8. Indeed, some of the comments from the A85 Glen Ogle survey confirmed Highland's (2006) assertion that economic impacts need not only be negative, that some can be positive:

- "More people rented bikes to go and visit the landslide site. The landslide itself had little impact, it was the associated bad weather that was the problem - the main street was flooded" according to one retailer.
- Hoteliers also seem to have benefited as "[they were able to] put up people in the guest house who had been trapped in the glen (and who had been airlifted out) free of charge. The same happened in different places around Killin," which apparently "improved the image of the town."

Notwithstanding this an assessment that included indirect consequential impacts was reported as part of a route study of the A83 (Anon. 2013a) returning a figure of £286k per landslide at the A83 Rest and be Thankful. While this provides useful context, it is not entirely clear how much of that total would be accounted for by direct consequential impacts that were also included or for how long the impacts were assumed to endure.

The vulnerability shadow proved to be a useful tool to understand and articulate the extent of the socio-economic vulnerabilities and, indeed, the populations potentially affected.

The vulnerability shadows determined from the various events demonstrate that their extent is determined by the density of the network, and the linked availability and suitability of alternative routes. Clearly there is also a strong correlation between these factors and the population served by the routes and affected by the events; as the density of the network, and availability and suitability of alternative routes reduces so does the population served. This must of course be set against the fact that the lower density networks are often lifeline routes with few, if any, alternatives and their importance to a smaller population is amplified. The authors are not aware of this or a similar tool being used in other studies.

7. Summary and conclusions

This paper presents the results of a study to develop methods of obtaining data on the economic impacts of landslides and the associated extent of those impacts. The economic impacts of landslides are considered in three categories: direct economic impacts, direct consequential economic impacts, and indirect consequential economic impacts. This approach is also applicable to events that reflect relatively discrete closures including climate-driven flooding.

The work presented herein includes data for five Scottish landslide events that occurred between 2004 and 2014. Direct costs range between approximately £250k and £1,700k for the landslide event, while those costs for the flood event are relatively small. Direct consequential costs range between around £180k and £1,400k for the landslide events. The latter are largely dependent upon the amount of traffic that uses the road and the duration of the disruption. For a flood event in a more developed peri-urban part of Scotland although the direct costs were small but the direct consequential costs (c. £3,200k) much greater than for any of the landslide sites considered. It is also worth noting that flood event was of a relatively short duration compared to the high cost landslide event.

Work on indirect consequential impacts has provided valuable qualitative insights although meaningful quantitative data proved rather elusive.

The vulnerability shadow proved to be a useful tool to understand and articulate the extent of the socio-economic vulnerabilities and the populations potentially affected. They also aid in understanding and communicating the inter-relations between the density of the network, the linked availability and suitability of alternative routes.

Acknowledgements

Transport Scotland's funding of this work is gratefully acknowledged.

This paper is published with the permission of Transport Scotland and TRL Limited.

References

Anon. (2010): Fighting flood risk together. Association of British Insurers, London.

Anon. (2011): Scottish road network climate change study: UKCP09 update. Transport Scotland, Edinburgh. (Accessed February 2014: http://www.transportscotland.gov.uk/.)

Anon. (2012a): Scottish Transport Appraisal Guidance. Transport Scotland, Edinburgh. (Accessed February 2014: http://www.transportscotland.gov.uk/stag/home.)

Anon. (2012b): TAG UNIT 3.3.5: The Greenhouse Gases Sub-Objective, August. Department for Transport, London. (Accessed February 2014: http://www.dft.gov.uk/webtag.)

Anon. (2013a): A83 Trunk Road Route Study: Part A – A83 Rest and be Thankful. Final Report. Report prepared by Jacobs for Transport Scotland, 212p. (Accessed February 2014: http://www.transportscotland.gov.uk/road/maintenance/landslides.)

Anon. (2013b): Reported road casualties Scotland 2012. Transport Scotland, Edinburgh. (Accessed September 2015: www.transportscotland.gov.uk/statistics/reported-road-casualties-scotland-all-editions.)

Anon. (2015): The QUADRO 4 Manual, Part 2: The valuation of costs in QUADRO. (Accessed September 2015: http://tamesoftware.co.uk/manuals/manuals.html/.)

Bono F., Gutiérrez E. (2011): A network-based analysis of the impact of structural damage on urban accessibility following a disaster: the case of the seismically damaged Port Au Prince and Carrefour urban road networks. Journal of Transport Geography 19, 1443–1455, https://doi.org/10.1016/j.jtrangeo.2011.08.002.

Bíl, M., Vodák, R., Kubeček, J., Bílová, M., Sedoník, J. (2015): Evaluating road network damage caused by natural disasters in the Czech Republic between 1997 and 2010. Transportation Research Part A: Policy and Practice 80, 90–103, https://doi.org/10.1016/j.tra.2015.07.006.

Chang, S.E., Nojima, N. (2001): Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective. Transportation Research Part A: Policy and Practice 35, 475–494, https://doi.org/10.1016/S0965-8564(00)00003-3.

Dahal, R. K., Bhandary, N. P. (2013): Excursion guidebook for Pokhara Valley area. Unpublished.

Dobbie, K. E., Bruneau, P. M. C., Towers, W. (Editors) (2011): The state of Scotland's soil. Natural Scotland, Scottish Government, Edinburgh. (Accessed December 2012: www.sepa.org.uk/land/land_publications.aspx.)

Galbraith, R. M., Price, D. J., Shackman, L. (Eds.) (2005): Scottish road network climate change study. Scottish Executive, Edinburgh.

Gibson, A. D., Culshaw, M. G., Dashwood, C., Pennington, C. V. L. (2012): Landslide management in the UK the problem of managing hazards in a 'low-risk' environment. Landslides 10(5), 599–610, https://doi.org/10.1007/s10346-012-0346-4.

Hearn, G., Hunt, T., Aubert, J., Howell, J. (2008): Landslide impacts on the road network of Lao PDR and the feasibility of implementing a slope management programme. Proceedings, International Conference on Management of Landslide Hazard in the Asia-Pacific Region (Ed: Chigira, M.), 187-195. The Japan Landslide Society, Tokyo.

Highland, L. M. (2006): Estimating landslide losses – preliminary results of a seven-state pilot project. US Geological Survey Open File Report 2006–1032, USGS, Reston, VA, https://doi.org/10.3133/ofr20061032.

Highland, L. M. (2012): Landslides in Colorado, USA: impacts and loss estimation for the year 2010. US Geological Survey Open File Report 2012–1204, USGS, Reston, VA, https://doi.org/10.3133/ofr20121204.

Klose, M., Damn, B., Terhorst, B. (2015): Landslide cost modelling for transportation infrastructures: a methodological approach, Landslides, 12, 321–334, https://doi.org/10.1007/s10346-014-0481-1.

MacLeod, A., Hofmeister, R. J. Wang, Y., Burns, S. (2005): Landslide indirect losses: methods and case studies from Oregon, State of Oregon, Department of Geology and Mineral Industries Open File Report O-05-X, Portland, OR.

Petley, D. N. (2014): The Seti River debris flow in Nepal – what was the role of the smaller landslide downstream? (Accessed February 2014: blogs.agu.org/landslideblog/2014/02/07/seti-river/.)

Petley, D. N., Stark, C. (2012): Understanding the Seti River landslide in Nepal. (Accessed February 2014: blogs.agu.org/landslideblog/2012/05/23/understanding-the-seti-river-landslide-in-nepal/.)

Schuster, R. L. (1996): Socioeconomic significance of landslides, Landslides – Investigation and Mitigation: Transportation Research Board Special Report 247, 36–75, Washington, DC.

Schuster, R. L., Highland, L. M. (2007): The Third Hans Cloos Lecture, Urban landslides: socioeconomic impacts and overview of mitigative strategies. Bulletin of Engineering Geology and the Environment 66, 1–27, https://doi.org/10.1007/s10064-006-0080-z.

Winter, M. G. (2014a): A strategic approach to landslide risk reduction. International Journal of Landslide and Environment 2, 14–23.

Winter, M. G. (2014b): The vulnerability shadow cast by debris flow events, Engineering Geology for Society and Territory, Volume 6: Applied Geology for Major Engineering Works (Eds: Lollino, G., Giordan, D., Thuro, L., Carranza-Torres, C., Wu, F., Marinos, P. Delgado, C.), 641–644, Heidelberg: Springer.

Winter, M. G. (2016): A strategic approach to debris flow risk reduction on the road network. Procedia

Engineering 143, 759–768, https://doi.org/10.1016/j.proeng.2016.06.121.
Winter, M. G., Bromhead, E. N. (2012): Landslide risk: some issues that determine societal acceptance. Natural Hazards 62, 169–187, https://doi.org/10.1007/s11069-011-9987-1.
Winter, M. G., Corby, A. (2012): A83 Rest and be Thankful: ecological and related landslide mitigation options. Published Project Report PPR 636, Transport Research Laboratory, Wokingham.
Winter, M. G., Shearer, B. (2013): Climate change and landslide hazard and risk – a Scottish perspective. Published Project Report PPR 650, Transport Research Laboratory, Wokingham.
Winter, M. G., Macgregor, F., Shackman, L. (Eds.) (2005): Scottish Road Network Landslides Study. The Scottish Executive, Edinburgh.
Winter, M. G., Heald, A., Parsons, J., Shackman, L., Macgregor, F. (2006): Scottish debris flow events of August 2004. Quarterly Journal of Engineering Geology and Hydrogeology 39, 73–78, https://doi.org/10.1144/1470-9236/05-049.
Winter, M. G., Macgregor, F., Shackman L. (Eds.) (2009): Scottish road network landslides study: implementation. Transport Scotland, Edinburgh.
Winter, M. G., Dent, J., Macgregor, F., Dempsey, P., Motion, A., Shackman, L. (2010): Debris flow, rainfall and climate change in Scotland. Quarterly Journal of Engineering Geology and Hydrogeology 43, 429–446, https://doi.org/10.1144/1470-9236/08-108.
Winter, M. G., Harrison, M., Macgregor, F., Shackman, L. (2013): Landslide hazard assessment and ranking on the Scottish road network. Proceedings, Institution of Civil Engineers (Geotechnical Engineering) 166(GE6), 522–539, https://doi.org/10.1680/geng.12.00063.
Winter, M. G., Shearer, B., Palmer, D., Peeling, D., Peeling, J., Harmer, C., Sharpe, J. (2018): Assessment of the economic impacts of landslides and other climate-driven events. Published Project Report PPR, TRL, Wokingham.
Winter, M. G., Ognissanto, F., Martin, L. A. (2019): Rainfall thresholds for landslides: deterministic and probabilistic approaches. Published Project Report PPR 901, Transport Research Laboratory, Wokingham.