TRANSPORT SCOTLAND

SCOTTISH ROAD NETWORK LANDSLIDES STUDY:

IMPLEMENTATION

SUMMARY REPORT

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Transport Scotland, Edinburgh 2008

Cover Photograph (© Perthshire Picture Agency, PPA: www.ppapix.co.uk):

The A85 in Glen Ogle blocked by two debris flows on 18 August 2004. RAF and Royal Navy helicopters are pictured airlifting some of the 57 occupants from the 20 trapped vehicles to safety.

ISBN: 978-1-906006-37-2

The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

Produced for Transport Scotland by RR Donnelley B57645 10/08

Published by Transport Scotland, October 2008

Further copies are available from
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MINISTERIAL FOREWORD

The implications of landslides on the operation of the road network and thus on the economy of Scotland were brought into sharp focus in August 2004, when significant rainfall led to serious events on roads in the north and west of Scotland.

Improving communications, enhancing the country's transport infrastructure and supporting a stable economy are vital elements of the work of the Scottish Government and Transport Scotland. For these reasons the importance of advancing our understanding of landslides in Scotland was immediately recognised.

The Scottish Road Network Landslides Study, a programme of detailed research, began immediately after the events of 2004 and continues today. The study sets a benchmark in terms of the assessment of such large areas at relatively large scale.

The results documented here provide us with a comprehensive picture of the future risk of landslides in Scotland and the evidence that we require to properly plan for and manage that risk, reducing as far as possible the impact on our roads and road users.

This study has been delivered primarily by experts from Scotland's geotechnical community. They have drawn on their own international experience, and that of others, and experience from other disciplines, as appropriate. They have used technology in innovative ways to achieve the objectives of the study. The body of work produced places Scotland amongst other leading nations involved in the study of landslides and landslide management. I would like to thank all of those involved.

A number of the recommendations made in this study have already been taken on board and activities are underway in key locations to manage the exposure of road users to landslide hazards.

I believe that continued investment in this study, its recommendations and the associated study of the broader implications of climate change on the road network will ensure that Scotland is well placed to deal effectively with landslide events in the future.

Stewart Stevenson
Minister for Transport, Infrastructure and Climate Change

ABOUT THIS REPORT

In August 2004 Transport Scotland initiated the Scottish Road Network Landslides Study. This was in direct response to a series of landslides which had seriously affected the road network.

At the same time a second study, the Scottish Road Network Climate Change Study, was commissioned looking at the distinct, but related, issue of climate change and its broader impacts on the road network. This is a separate, but complementary, study and is not covered in this document.

The Scottish Road Network Landslides Study was divided into two parts. The first part was published in 2005 and was designed to gather and present background information about the landslides issue and put forward a plan for the second part of the study.

This second part of the study is concerned with facilitating the development of a landslides management plan and mitigation strategy for the Scottish trunk road network. This document is a summary of that second part of the Scottish Road Network Landslides Study.

1 INTRODUCTION

Transport Scotland instigated the Scottish Road Network Landslides Study in August 2004, when extensive and excessive rainfall caused a number of serious landslides which adversely affected the operation of the strategic road network.

During that month, some areas of central and western Scotland experienced levels of rainfall more than three times the average for the time of year including intense storms. As a result a large number of landslides – more specifically *debris flows*, a particular type of landslide – was experienced in the hills of Scotland. Among those which reached the trunk road network were those on the A85 in Glen Ogle, the A83 at Glen Kinglas and Cairndow, and the A9 north of Dunkeld.

Debris flows occur with some frequency in the hills of Scotland and although these only rarely affect the main road network, when they do they can have a major effect on communities, the economy and public safety.

Fortunately, during the events of August 2004 there were no injuries, but other factors were significant. Road closures and long diversions had the effect of restricting access to already relatively remote communities and were a substantial inconvenience to road users. This included tourist traffic, which is generally at its peak in the summer months when landslides can often occur.

In light of the above, and acknowledging that climate change may further increase the prevalence of landslides, Transport Scotland recognised the need to act.

The first part of the Scottish Road Network Landslides Study[1,2] considered the cause and effect of landslides and proposed the development of a system for assessing and ranking the hazards posed by debris flows. (A second study, the Scottish Road Network Climate Change Study[3,4], examined the distinct, but related, issue of climate change and its broader impacts on the road network) This system for assessing and ranking debris flow hazards has since been developed and applied across the entire coverage area of Scotland's trunk road network and the results are reported in this report on the second part of the study[5].

The objective of the study is to allow budget and resources to be focused on areas where debris flow hazards and impacts are most severe and where they can be effectively managed and mitigated to reduce the exposure to road users, while at the same time acknowledging that debris flows themselves cannot be prevented.

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[1] Winter, M. G., Macgregor, F. & Shackman, L. (Editors) 2005. *Scottish Road Network Landslides Study.* 119p. Edinburgh: The Scottish Executive.

[2] Winter, M. G., Macgregor, F. & Shackman, L. 2005. *Scottish Road Network Landslides Study Summary Report.* 27p. Edinburgh: The Scottish Executive.

[3] Galbraith, R. M., Price, D. J. & Shackman, L. (Editors) 2005. *Scottish Road Network Climate Change Study.* 100p. Edinburgh: The Scottish Executive.

[4] Galbraith, R. M., Price, D. J. & Shackman, L. 2005. *Scottish Road Network Climate Change Study Summary Report.* 31p. Edinburgh: The Scottish Executive.

[5] Winter, M. G., Macgregor, F. & Shackman, L. (Editors) 2008. *Scottish Road Network Landslides Study - Implementation.* 278p. Glasgow: Transport Scotland.

Section 2 of the full report[5] summarises the types of landslide that exist, the events that have been experienced in Scotland in recent years and the time of year during which these are most likely to occur.

Section 3 provides a brief overview of the actions which were undertaken in the immediate aftermath of the August 2004 landslide events.

Section 4 describes the methodology which was applied to devise the system of assessing debris flow hazards across Scotland. The use of this system essentially identifies the areas most susceptible to debris flow triggering.

Section 5 reports how this information was interpreted with the aid of other data and imagery to establish plausible flow paths from the susceptible zones identified in Section 4 and determine whether these debris flows might impact on the road network.

Using these findings the study progresses from desk-based work to actual site inspections to augment and verify the findings and modify the hazard scores. The methodology and results from these surveys are reported in Section 6.

Section 7 concludes the assessment of hazards posed by debris flows by considering the likely impacts of any flows on the road network, road users, communities and the economy. The results are presented as a listing of higher hazard sites in Scotland.

Section 8 outlines management and mitigation strategies which could be applied to or on the network. It draws on international experience and focuses on two key areas – reducing the exposure of road users through education, the use of signs and, where appropriate, temporary road closures; and reducing the hazard through engineering works.

Approaches which could be applied in the longer term are considered in Section 9. This looks in particular at methods for forecasting landslides from rainfall data and how such a system might be developed for Scotland.

Conclusions and recommendations for action and further investigation and study are outlined in Section 10.

Supporting information and detail is presented in a series of eight appendices.

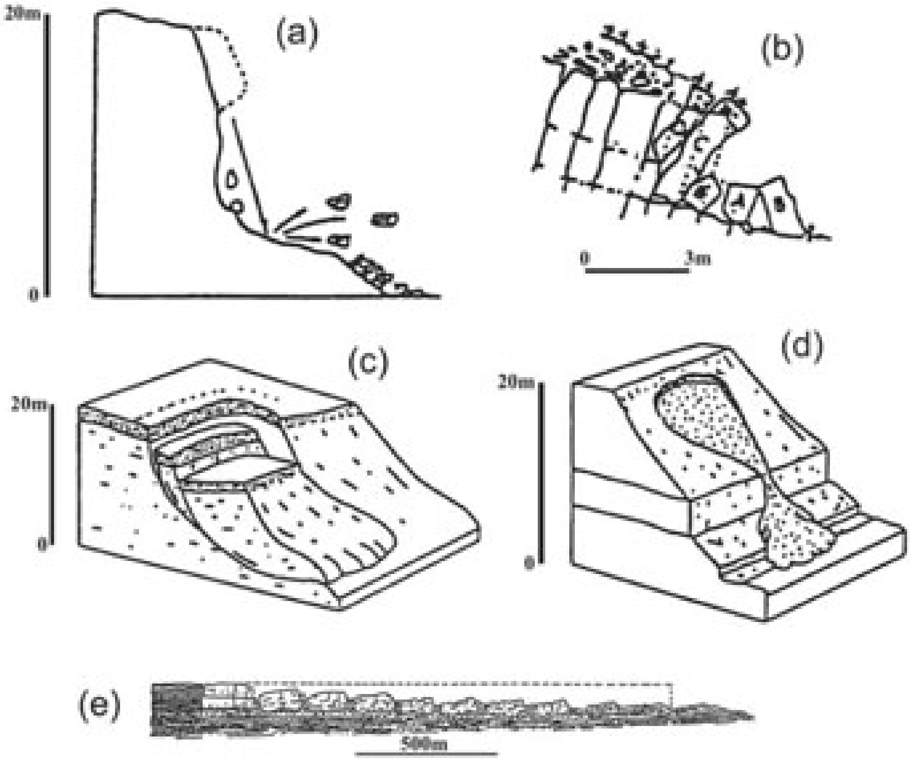
2 LANDSLIDE EVENTS

Landslides and Debris Flows

'Landslides' is a generic term used to describe a range of types of gravitational mass movement. Many systems have been proposed for the classification of landslides[6,7].

In order to adopt the correct approaches it is essential at the outset to analyse and understand the nature of the landslides which have occurred in Scotland.

Using the Varnes[6] system, landslides can be categorised into five main types - falls, topples, slides, flows and spreads. A sixth type – complex failure – is one in which one type of movement is followed by one or more of the other types.



Types of Landslides: a) falls, b) topples, c) slides, d) flows, e) spreads[8].

The recently observed landslides in Scotland have been typical of flow-type landslides. The initial trigger can be the slippage of a relatively small amount of material. This may lead to the erosion of material on the open hillside below or, as is

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[6] Varnes, D. J. 1978. Slope movement types and processes. In: *Special Report 176: Landslides: Analysis and Control* (Eds: Schuster, R. L. & Krizek, R. J.). Transportation and Road Research Board, National Academy of Science, Washington D. C., 11-33.

[7] Hutchinson, J. N. 1988. General Report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. *Proceedings, Fifth International Symposium on Landslides* (Ed: Bonnard, C.), **1**, 3-35. Rotterdam: Balkema.

[8] Escario, M. V., George, L.-A., Cheney, R. A. & Yamamura, K. 1997. Landslides: techniques for evaluating hazard. *Report of PIARC Technical Committee on Earthworks, Drainage, Subgrade (C12), 12.04B*. Paris: PIARC, World Road Association.

often the case, the material may enter an existing watercourse, leading to extra debris being added to an already rapid and potentially erosive flow of water. The fast-moving eroded material has sufficient energy to be damaging to any object in its path and will eventually be deposited lower down the hillside.

Debris flows are neither a recent phenomenon nor one which is limited to Scotland. They occur mainly as a result of the character of the hillside, the deposits (rocks and soils) which are present and the intensity and duration of rainfall. Debris flows are, generally speaking, not caused by the existence of infrastructure, and the fact that they impinge upon it is a matter of locality.

Landslide Events in Scotland

The landslide events of August 2004 which prompted the Scottish Road Network Landslides Study included debris flows on the A83 in the Cairndow area, the A9 to the north of Dunkeld and the A85 at Glen Ogle.

While there were no major injuries, at Glen Ogle 57 people had to be airlifted to safety when 20 vehicles became trapped between the two main debris flows. The real impacts of the events were economic and social, in particular the effects of the severance of access to relatively remote communities. The routes affected were closed for between one and four days affecting thousands of journeys and causing disruption to local road users, commercial vehicles and tourist traffic in the process.

Examples of landslides affecting the Scottish trunk road network. Top left: A83 Cairndow, August 2004. Top right: A9 North of Dunkeld, August 2004. Bottom left: A85 Glen Ogle, August 2004. Bottom right: A83 approach to Rest and be Thankful, October 2007.

A number of other landslide events, including debris flows, have occurred in Scotland in the intervening years, some affecting the main trunk road network and others affecting minor roads. The most serious of these recent events occurred on the eastern approach to the Rest and be Thankful in October 2007.

The particular geology and geomorphology of the Highlands combined with high rainfall makes this area particularly susceptible to landslides of many varieties. Landslides affecting the road network occur regularly in the region.

While most of these are usually small-scale events and relatively quick to clear, some more significant landslides have affected the main road network in recent times. Many of the roads affected are however B-class, C-class or unclassified routes and these are often the only access routes to and from communities. The lack of available diversion routes makes landslides in such parts of Scotland particularly disruptive.

Landslide Seasons

Debris flows mainly occur in Scotland in the periods July to August and November to January, with the latter period occasionally extending to October and February. There is, of course, no guarantee that such a pattern will continue, particularly with climate change studies anticipating that rainfall levels will increase in the winter but decrease during the summer and suggesting that the frequency of intense rain storms may increase.

3 RESPONSE TO THE 2004 EVENTS

The need to act in response to the events of August 2004 was recognised by Scottish Ministers.

Transport Scotland decided that a system should be put in place to allow the hazards of debris flow to be assessed. It was agreed that any system should also be capable of ranking the hazards in terms of their potential effect on trunk roads and road users. This would then allow budgets and resources to be appropriately directed to manage and mitigate debris flows in the future and reduce the consequences for the road network and road users.

The two-part landslides study was commissioned and this involved a wide range of experts as a Working Group. The initial study considered how a detailed review of the terrain adjacent to the trunk road network could be undertaken, outlined possible mitigation measures and management strategies and identified the immediate at-risk areas.

This work was published in a full report[1] and in summary[2] in 2005. The findings and recommendations of that report were used to develop the plan for part two of the study[5] which is reported in summary form herein.

Immediate Response

Areas of perceived hazard were identified by the team involved in the initial work of the study. This was primarily to identify sites which could be used to validate the emerging model for assessing debris flow hazard.

The sites identified, in no particular order, included:

- A83 Ardgarten to Loch Shira (29km).
- A84 South of Strathyre (8km).
- A85 Glen Ogle (6km).
- A87 Glen Shiel (18km, plus a possible further 17km).
- A82 Fort Augustus to Lochend (29km, plus a possible further 9km).
- A835 Ullapool to Braemore Junction (16km).
- A9 Dunkeld to Drumochter (22km).
- A95 Craigellachie (1km).
- A86 Spean Bridge (5.5km).
- A87 (Skye) Gleann Torra-mhichaig to South of Raasay ferry (1.5km).

Short-term actions recommended on a general basis included a significant programme of clearing vegetation and rocks from ditches, gullies, catchpits and culverts in the areas concerned and some new ditches being added at the crest of slopes.

It is worth noting that since August 2004 UK national drainage standards have been updated to cater for higher levels of water flow and these are now used in the design of all new roads and upgrades to existing roads.

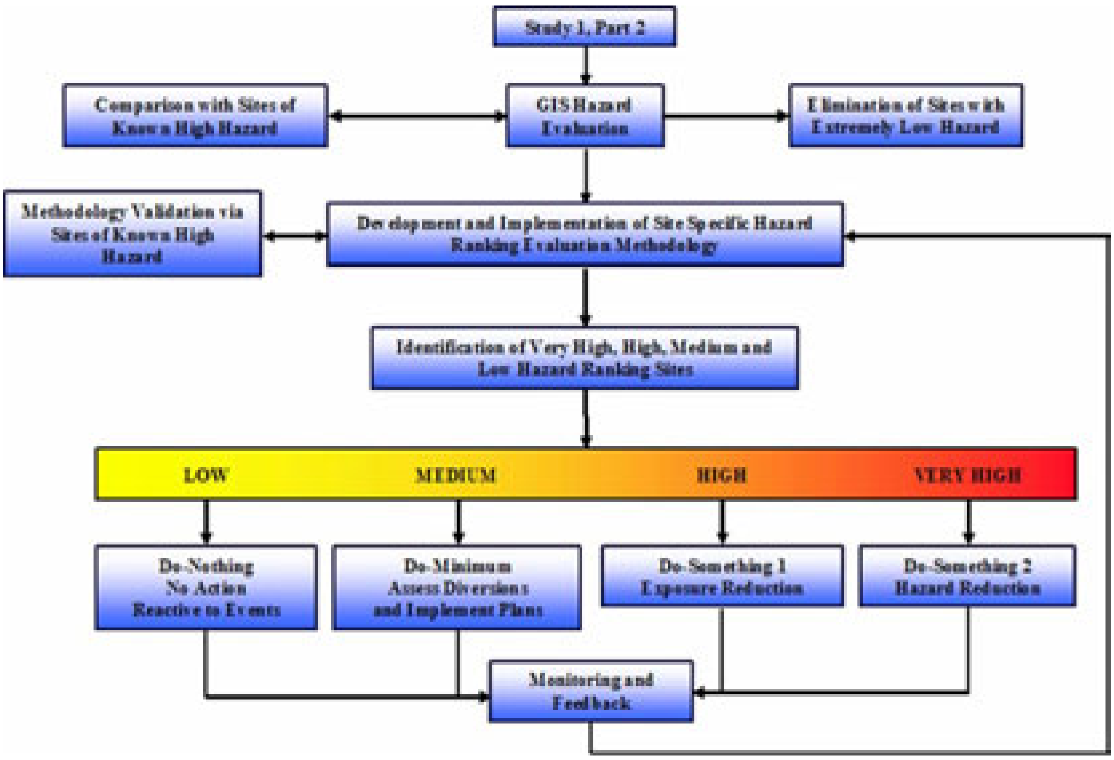
With regard to the specific areas of high hazard identified in the 2005 report a wide range of works have been progressed in addition to routine maintenance. These works include drainage improvements, culvert realignment and renewal, ditching and vegetation clearance, the ongoing installation of rain gauges, and road realignment within the context of the broader trunk road improvment programme.

Developing Future Management Options

The initial stage of the work may be divided into four elements and can be summarised as follows:

- Development of a debris flow hazard and exposure assessment system to provide a hazard ranking of 'at-risk' areas of the road network.
- Undertaking a computer-based GIS assessment as a first stage in the hazard assessment process.
- Undertaking site-specific hazard and exposure assessments of areas identified by the GIS as being of higher hazard.
- Identification and development of appropriate management processes for each category of hazard ranking.

The flowchart below presents an outline of the work undertaken. The initial stage of the process was to develop the methodology for the assessment of hazard and exposure to provide a hazard ranking, together with the selection of an appropriate management approach. The second stage was to test the methodology and apply it more widely to the trunk road network.



Outline flowchart of the current study.

Information Sharing and Dissemination

More than 40 separate activities have been undertaken to communicate the work to the public, Government and industry. These have included presentations to international conferences, articles in technical journals and the production of reports and a draft leaflet.

4 GIS-BASED ASSESSMENT

A Geographic Information System (GIS) is a means of capturing, storing, analysing and managing information about geographical locations. It is made up of layers of information including data relating to, for example, the contours of the land, buildings, roads and other landscape features. The information is recorded within a map-space defined by two horizontal coordinates and, where elevation is an issue, a third vertical coordinate.

Various forms of data relating to the susceptibility to debris flow triggering were reviewed and, if appropriate, selected for use in the model to assess for debris flow hazards.

Rainfall data were not included within the assessment, since rainfall sufficient to trigger debris flow in susceptible areas could occur anywhere within the study area.

Assessment of Debris Flow Potential

A large number of factors can trigger debris flows, but the five main ones are:

a) Availability of debris material.
b) Hydrogeological conditions.
c) Land use.
d) Proximity of stream channels.
e) Slope angle.

Information on these five factors was collected, scores assigned and weighted, and combined to produce a working model of debris flow hazard. The model was then validated by comparing its findings against the real occurrences of debris flows which have occurred in Scotland.

a) Availability of Debris Material

For debris flows to occur there must be material available and capable of being easily mobilised by water. Simplistically, granular materials are more likely to be involved in debris flows. Areas where the land contours could lead to the accumulation of such material were identified.

b) Water Conditions

There are two key considerations in respect of water and its impact on debris flows. The first is whether the ground, as described above, could be penetrated by either rainfall or overland water (as accounted for in item (a) above). The second is whether the underlying ground is sufficiently impermeable so as to ensure that excess water is retained in the surface deposits thus reduce their strength sufficiently to make debris flow more likely.

c) Land Use – Vegetation and Land Cover

Vegetation can help to stabilise slopes by reducing the amount of rainfall which penetrates the ground, soaking up moisture within the soil and reinforcing the ground through its root system. Loose, bare soil, on the other hand, is less stable and may provide a source of material for debris flow. Land cover information was thus used within the assessment with the lowest scores being given to woodland (representing higher stability), for example.

d) Stream Channels

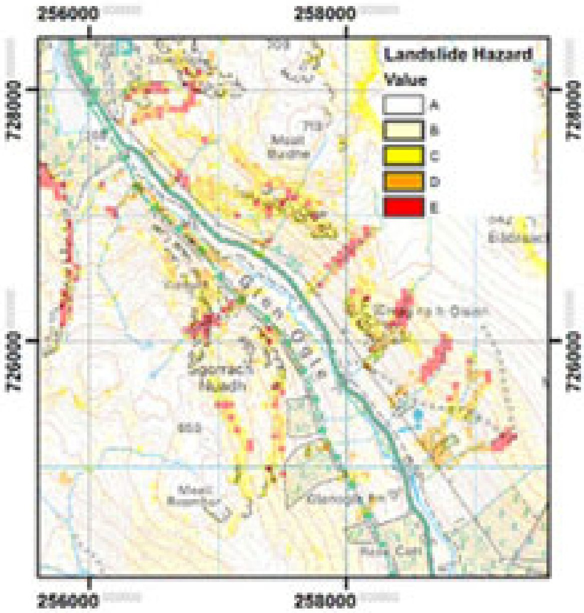
Stream channels are often associated with debris flows as they can help to focus the direction of water during heavy rainfall and supply large volumes of water that can mobilise available material. They may also collect debris from more moderate flows, forming dams of material in and around the stream which may then be mobilised as larger and potentially more destructive flows at a later date. Stream channels and the slopes to either side were therefore considered as potential debris flow trigger areas.

e) Slope Angle

The angle of a slope has been found to be one of the most significant indicators of debris flow potential. In simple terms the steeper the angle of a slope the more likely it is that a debris flow will occur, albeit that beyond an upper limit of slope angle the availability of material will be limited.

Results of the Assessment

The five factors outlined above were scored and weighted within the GIS system. Combining the scores showed which areas had the greatest propensity for debris flows triggering.



Output from the GIS-based assessment showing areas of debris flow trigger potential. Red indicates the highest potential with shades of orange and yellow, and white indicating successively lower potentials.

Thereafter the information was interpreted in order to define hazards to the trunk road network and the analysis undertaken to rank the hazards in terms of the exposure of road users to the hazard.

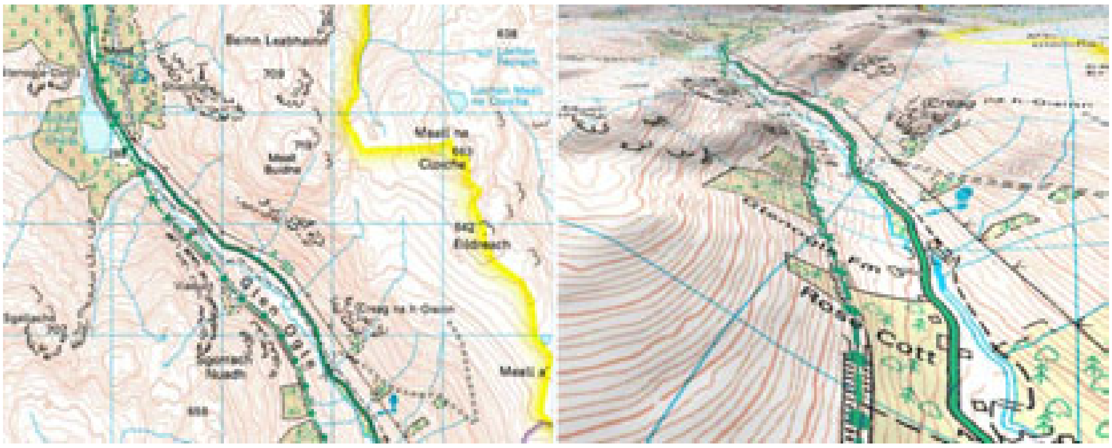
5 HAZARD ASSESSMENT AND HAZARD RANKING

This element of the study comprises two activities:

1. The desk-based interpretation of the GIS-based assessment which determines hazards on the trunk road network and associated site-specific assessments to give a hazard score.
2. The determination of the exposure of road users to the hazards identified, as in item (1) above, and the consequent ranking of the hazards to provide an analogue for the relative risk at each site.

Hazard Assessment

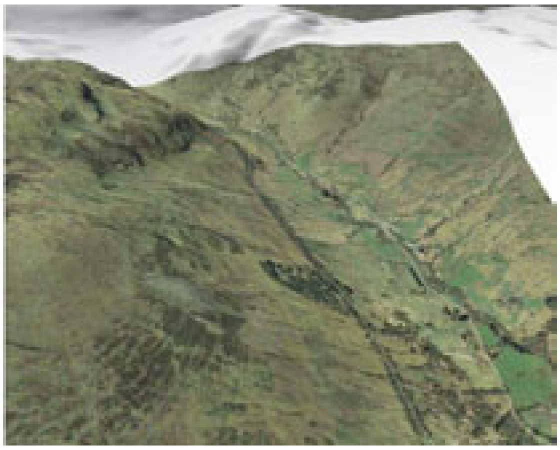
The debris flow hazards identified in Section 4 essentially relate to Scotland as a whole. The hazards extant on the Scottish trunk road network were determined using the GIS imagery, Ordnance Survey 1:50,000 mapping and low resolution aerial photography to understand plausible flow paths between hazard areas and the network. This highlighted the debris flow hazard areas in relation to the road network and shows which have the potential to affect the trunk road network – the main objective of the study.



Ordnance Survey mapping for Glen Ogle, presented conventionally in two-dimensions (left) and in draped over a digital elevation model (right) to illustrate relative heights. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

Additional imagery, maps and survey results were viewed alongside the GIS data created in Section 4 to enhance the understanding of the nature of the land in those areas and assess their proximity to the road network. Particular attention was paid to the land between the areas of potential debris flow triggering and the road in order to ascertain whether any debris flow might reach the road.

The Scottish trunk road network is made up of some 3,200km of road, ranging from motorways to single track roads. Of this just over 600km was thought to be potentially at risk from debris flows. These parts of the route were further categorised for severity of potential hazard and ranked as Priorities 1 to 4, where 1 is most severe and 4 is of lesser severity.



Low resolution aerial photography for Glen Ogle, presented conventionally in two-dimensions (left) and in draped over a digital elevation model (right) to illustrate relative heights. The white space represents limitations in the available coverage.

Two sections of the road network were highlighted for separate assessment – the A82 through Glen Coe and the A87 on Skye. These stretches of the network, totalling 46km in length, display particular characteristics which require a different type of assessment and were felt to require more specialist study. However, these sections continue to be included in the routes with higher hazard, in order to give a true reflection of their status, as summarised in the table below.

Outcomes from the interpretation of the GIS-based imagery.

	Route Lengths Assessed (km)	Percentage of Main Study Route Lengths (%)	Percentage of Trunk Road Network (%)
Priority 1	**135**	**22**	**4**
Priority 2	**154**	**25**	**5**
Priority 3	**160**	**26**	**5**
Priority 4	**112**	**19**	**4**
Separate Assessment	**46**	**8**	**1**
Total	**607**	**100**	**19**

The table above shows the breakdown of the road network by Priority. These priorities were used to set the sequence of the subsequent site inspections. These inspections were carried out in 2007 on the Priority 1 and 2 sites for which good quality aerial photography was available. The outputs form these inspections supplemented and validated the findings of the desk-based study.

The inspection process for each site began with the survey team studying high quality aerial photography and maps to allow them to familiarise themselves with the site and to highlight features which would be looked at in more detail during the site inspections itself.

Site inspections were conducted initially by driving the route which had been highlighted as a priority, observing and noting features and taking photographs to record the findings. Detailed site inspections in the form of walkover surveys up and down the slopes were then carried out at all locations to record more detail about the make-up of the hillsides adjacent to the roads. Any new features or recent unrecorded changes to the landscape, such as deforestation, were observed and incorporated into the assessment.

Each site was rated to take account of four main features:
1. Water (i.e. stream patterns, drainage, accumulation of water).
2. Instability (i.e. evidence of recent instability).
3. Slope / topography.
4. Vegetation and land-use.

These scores were combined with the existing data to produce a finalised the hazard score for the particular stretch of road.

The assessments of the Priority 1 and 2 sites that took place in 2007 are intended to be part of an ongoing programme of site inspections that will be carried out over the coming years.

Hazard Ranking

As a final stage of the process, the data which had been collated and verified during the study was fed into a formula which would calculate the overall risk of debris flows to the road network and road users.

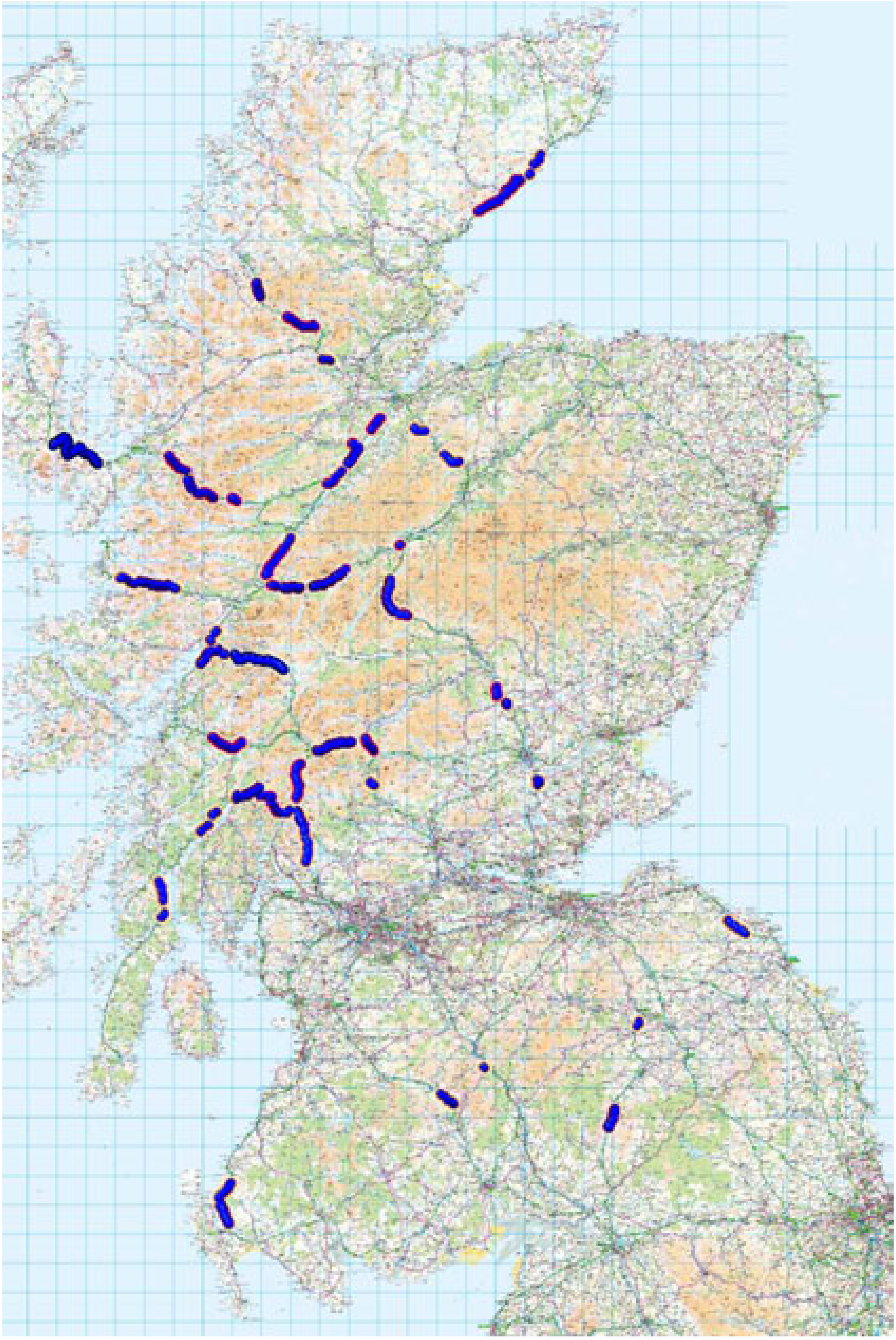
This formula factors in the hazards and the elements at risk, considering, for example, the level of traffic known to use certain stretches of road which effectively represents the risk to road users. Socio-economic factors are also incorporated, such as the length and viability of diversions in the event of the road being closed.

The map and table below show the sections of road which have the highest hazard rankings. A total of 67 sites are detailed, representing just over 380km of the trunk road network.

It is suggested that the GIS-based assessment and the associated interpretation should be refreshed approximately every 10 years to take advantage of any improvements in technology or data which will enhance the findings. It is also suggested that sites of higher hazard ranking should be subject to reassessment to take account of any changes on the ground.

Clearly debris flows are not the only hazards that may affect roads in Scotland and amongst the others are those presented by rock falls. Between 1994 and 1999 Transport Scotland (in a previous guise) initiated and operated a structured programme of rock slope risk assessment and management on the trunk road network.

A 2004 review recommended further action in this respect and Transport Scotland is currently assessing the future actions required to address those Hazard Rating surveys and re-inspections that remain to be carried out.



Map of Scotland showing the 67 highest hazard ranking sites in Scotland. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

Sites with a hazard ranking score of 100 or greater.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Hazard Score	Exposure Score	Hazard Ranking (Risk) Score = Hazard × Exposure	Locality
A82-17	NW	NN 28766 96227	NN 21391 85632	13,400	**1**	**100**	**2.5**	**250**	Loch Lochy
A85-09	NW	NN 50672 28326	NN 38766 25266	12,900	**2**	**100**	**2.5**	**250**	Glen Dochart
A82-08	NW	NH 45761 19182	NH 43486 16747	3,410	**1**	**90**	**2.5**	**225**	N of Invermoriston
A82-37	NW	NN 34026 00456	NS 34556 97686	3,300	**1**	**90**	**2.5**	**225**	Inverbeg and N
A9-12	NW	ND 02175 14804	NC 93895 09663	10,200	**1**	**90**	**2.5**	**225**	S of Helmsdale
A9-35b	NW	NN 66562 72101	NN 69762 71546	3,310	**1**	**90**	**2.5**	**225**	N Glen Garry
A82-09	NW	NH 42981 16557	NH 42451 16667	581	**1**	**80**	**2.5**	**200**	Invermoriston
A82-26	NW	NN 05220 59568	NN 07550 58357	2,720	**2**	**80**	**2.5**	**200**	E of Ballachulish
A82-34	NW	NN 33296 20776	NN 31776 09196	13,500	**1**	**100**	**2.0**	**200**	N Loch Lomond
A85-08	NW	NN 58437 24970	NN 55677 29396	5,480	**1**	**100**	**2.0**	**200**	Glen Ogle
A9-11	NW	ND 08775 20794	ND 02860 15349	11,200	**1**	**100**	**2.0**	**200**	N of Helmsdale
A83-02	NW	NN 26901 03861	NN 23021 07837	6,310	**1**	**90**	**2.0**	**180**	Ardgarten to Rest & be Thankful
A83-04	NW	NN 23421 09592	NN 19096 09927	4,360	**1**	**90**	**2.0**	**180**	Glen Kinglas
A9-44	NW	NO 00212 47141	NO 00472 43871	3,320	**1**	**90**	**2.0**	**180**	N of Dunkeld
A87-19	NW	NG 64039 23632	NG 48718 29902	26,100	**Separate Assessment**	**90**	**2.0**	**180**	Southern Skye - N of Broadford
A82-36	NW	NN 31916 04456	NN 34026 00456	4,610	**2**	**70**	**2.5**	**175**	S of Tarbet
A9-35a	NW	NN 63982 83957	NN 64987 73046	11,900	**2**	**70**	**2.5**	**175**	S of Dalwhinnie
A83-06	NW	NN 19221 12717	NN 11260 08848	9,170	**2**	**85**	**2.0**	**170**	Clachan to Strone Point
A82-05	NW	NH 52566 28987	NH 49631 23632	6,770	**2**	**65**	**2.5**	**163**	S of Drumnadrochit
A77-11	SW	NX 05214 72439	NX 08694 63338	9,990	**2**	**80**	**2.0**	**160**	S of Glen App
A82-02	NW	NH 60696 39243	NH 57346 34993	5,520	**1**	**100**	**1.5**	**150**	N end of Loch Ness
A83-05	NW	NN 18406 11247	NN 19406 12512	1,620	**1**	**100**	**1.5**	**150**	Cairndow
A87-12	NW	NH 03370 12016	NG 96289 14946	8,620	**1**	**100**	**1.5**	**150**	E Glen Shiel
A87-15	NW	NG 94469 21121	NG 88269 26106	8,650	**1**	**100**	**1.5**	**150**	Loch Duich
A87-09	NW	NH 11495 10731	NH 09725 11731	2,080	**1**	**95**	**1.5**	**143**	W Loch Cluanie
A830-05	NW	NM 90195 80853	NM 76679 82314	15,500	**2**	**70**	**2.0**	**140**	Glenfinnan to Lochailort
A9-45	NW	NO 03452 41486	NO 04062 40886	877	**2**	**70**	**2.0**	**140**	S of Dunkeld
A82-27	NW	NN 10700 58212	NN 27671 52992	19,900	**Separate Assessment**	**90**	**1.5**	**135**	Glen Coe
A828-01	NW	NN 05175 59653	NM 99145 54983	8,540	**2**	**90**	**1.5**	**135**	W of Ballachulish
A835-07	NW	NH 38284 70387	NH 28554 73906	11,400	**1**	**90**	**1.5**	**135**	Lubfearn to W Loch Glascarnoch
A85-15	NW	NN 13191 28352	NN 03135 29863	12,400	**1**	**90**	**1.5**	**135**	Dalmally to W Pass of Brander
A86-12	NW	NN 25591 81307	NN 22966 81947	2,770	**1**	**90**	**1.5**	**135**	Inverroy to Spean Bridge
A87-13	NW	NG 96259 14951	NG 94614 17946	3,790	**2**	**90**	**1.5**	**135**	W Glen Shiel
A82-07	NW	NH 47461 21012	NH 46411 19822	1,620	**3**	**50**	**2.5**	**125**	N of Alltsigh
A82-16	NW	NN 29996 98177	NN 28981 96572	1,960	**3**	**50**	**2.5**	**125**	Loch Oich to Loch Lochy
A82-23	NW	NN 04505 66337	NN 03765 65377	1,260	**3**	**50**	**2.5**	**125**	N of Corran Ferry
A82-24	NW	NN 02295 63258	NN 02645 62728	688	**3**	**50**	**2.5**	**125**	S of Corran Ferry
A82-38	NW	NS 34556 97686	NS 35196 87156	11,100	**3**	**50**	**2.5**	**125**	N & S of Luss
A83-18	NW	NR 84819 80506	NR 86284 74006	7,040	**3**	**50**	**2.5**	**125**	S of Inverneill
A83-20	NW	NR 86794 69696	NR 86529 69066	687	**3**	**50**	**2.5**	**125**	N Tarbet
A9-24	NW	NH 72341 35783	NH 75841 34579	4,040	**3**	**50**	**2.5**	**125**	N of Loch Moy
A9-27	NW	NH 82171 26569	NH 87652 24074	6,660	**3**	**50**	**2.5**	**125**	Slochd
M90-09	NE	NO 14377 13430	NO 13887 15335	3,200	**3**	**50**	**2.5**	**125**	N of Glen Farg
A82-04	NW	NH 52391 30037	NH 50831 30172	1,590	**1**	**80**	**1.5**	**120**	Drumnadochit
A86-03	NW	NN 67317 95722	NN 67162 95417	357	**1**	**80**	**1.5**	**120**	Glentruim House
A86-09	NW	NN 48856 87552	NN 47661 86407	1,730	**1**	**80**	**1.5**	**120**	Aberarder (Loch Laggan)
A86-10	NW	NN 47516 86247	NN 37536 81267	11,600	**2**	**75**	**1.5**	**113**	Loch Laggan and Reservoir
A86-11	NW	NN 33266 80957	NN 27646 81067	6,180	**2**	**75**	**1.5**	**113**	Tulloch to Roy Bridge
A7-06	SE	NT 40762 02692	NY 38842 96252	7,160	**2**	**70**	**1.5**	**105**	S of Teviothead
A835-09	NW	NH 19553 80586	NH 18168 85540	5,320	**2**	**70**	**1.5**	**105**	S of Loch Broom
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	**3**	**50**	**2.0**	**100**	Penmanshiel to Howburn
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	**3**	**50**	**2.0**	**100**	N of Selkirk
A76-04	SW	NS 85832 04117	NS 81022 07857	6,570	**3**	**50**	**2.0**	**100**	S of Sanquhar
A77-10	SW	NX 09284 77378	NX 05214 72439	6,640	**3**	**50**	**2.0**	**100**	Glen App
A83-01	NW	NN 29616 05036	NN 28391 03881	1,760	**3**	**50**	**2.0**	**100**	W of Succoth
A83-07	NW	NN 11260 08848	NN 11395 10083	1,260	**3**	**50**	**2.0**	**100**	E Loch Shira
A83-10	NW	NN 04495 04203	NN 02915 03179	1,910	**3**	**50**	**2.0**	**100**	E of Auchindrain Folk Museum
A83-12	NW	NS 01725 99834	NR 98995 97649	3,550	**3**	**50**	**2.0**	**100**	W of Furnace
A83-21	NW	NR 86034 68451	NR 85284 68076	839	**3**	**50**	**2.0**	**100**	W of Tarbet
A830-04	NW	NM 90855 80478	NM 90205 80848	867	**3**	**50**	**2.0**	**100**	Glenfinnan
A830-06	NW	NM 76679 82314	NM 71574 84404	6,080	**3**	**50**	**2.0**	**100**	Lochailort to Prince's Cairn
A835-04	NW	NH 43565 58802	NH 40650 59367	3,110	**3**	**50**	**2.0**	**100**	S of Garve
A84-03	NW	NN 57047 14530	NN 58487 13465	1,900	**3**	**50**	**2.0**	**100**	N Loch Lubnaig
A9-09	NW	ND 15325 29325	ND 13145 25995	4,350	**3**	**50**	**2.0**	**100**	S of Dunbeath
A9-10	NW	ND 12010 23055	ND 11670 22435	1,110	**3**	**50**	**2.0**	**100**	Berriedale
M74-09	M74	NS 95997 16852	NS 96337 16502	492	**3**	**50**	**2.0**	**100**	Elvanfoot

6 MANAGEMENT OF HIGH AND VERY HIGH HAZARD AREAS

The purpose of determining a hazard ranking for stretches of the road network is to enable prioritisation of decision-making in terms of managing risks due to debris flow. At locations where the risk is deemed to require action, either the exposure of road users to the hazard or the hazard itself must be reduced.

Exposure reduction has to be the main mechanism for reducing the risk due to debris flow. Physical intervention through engineering can reduce the hazard due to debris flow. But, such solutions are more intrusive and of higher cost – consequently it is anticipated that relatively few locations would justify this kind of expenditure.

Management of Exposure Reduction

The basic principle of exposure reduction is a straightforward three-stage process:

- *Detection:* identifying the occurrence of debris flows through observation and monitoring or by measurement and forecasting of rainfall, for example.
- *Notification:* notifying either the likely or actual occurrence of a debris flow to the relevant authorities.
- *Action:* proactive measures to reduce exposure to the road user, through, for example dissemination of information, signs, road closure or traffic diversion.

In the current situation it is considered that the Detection-Notification-Action (DNA) approach outlined above should be used on a reactive basis when debris flow events occur. There may be a case in the future for reacting to extremely heavy rain, but further work is required to better develop rainfall thresholds.

Introduction of a detection system which would flag up the likely occurrence of debris flows would be a longer term solution. It would require a significantly enhanced rainfall detection system across Scotland and even once this were in place some time would have to pass to allow adequate data to be collected and analysed to come up with a warning system of sufficient reliability. Such a system is discussed in the following Section 7.

Detection of Event Occurrence

The movement of slope material can be monitored in real time using a variety of instruments. Some problems associated with these techniques include identifying the optimal position for sensors and the possibility that some types of sensors could be triggered by livestock and hill walkers. Closed circuit television is another option to observe hill slope movements, although the use of patrol vehicles is likely to be a more practical, lower cost solution allowing greater coverage of the at-risk areas. It is worth noting, however, that these methods are only likely to be effective at spotting impending debris flows in daylight hours and in conditions of good visibility.

Importantly, the valuable role of the public in observing landslides and alerting the authorities using mobile communications technology should not be overlooked.

Notification of Event Occurrence

In the immediate aftermath of the occurrence of a debris flow event, notification must reach the Police, the Operating Company and the infrastructure owner. The decision must then be made rapidly as to appropriate actions (see below).

Action Following Event Occurrence

A number of options for action are available including closing the road and putting in place appropriate pre-planned diversion routes. It is important that road closures cover not just the stretch of road which has been affected but also any neighbouring stretches which may be affected by subsequent debris flows.

Road closures could be effected by installing barriers, similar to snow barriers, which are already in place on some of Scotland's roads. It is important that any such barriers are installed in locations where drivers can safely stop and turn back.

Warning the public of hazards is an important feature of any action programme. This includes, but is not limited to, traffic information websites showing real-time information, variable message signs and media announcements on TV, radio and web. It is suggested that press releases are prepared in advance for stretches of road which have a history of being affected by landslides.

Where variable message signs are used, it is important that they are suitably located, i.e. at a main junction well ahead of the affected stretch of road, to allow drivers to make an early decision whether to proceed or take a different route.

Examples of actions to reduce exposure of road users to debris flow hazards. Left: Barriers to effect road closures. Right: Variable message signs.

Appropriate wording for a variable message sign might include the following:

RISK OF WATER
ON ROAD AHEAD
PREPARE TO STOP

Following a closure, the road should only be reopened after a thorough inspection, undertaken once the bad weather has abated and the certainty that the hazard has passed.

Event Forecasting

Debris flows are generally triggered by heavy rainfall and forecasting and collection of rainfall data in real-time is therefore extremely valuable. A predictive system for Scotland based on monitoring rainfall is currently under development (see Section 7 herein). In parts of the world where landslide prediction systems are in place, landslide warnings are triggered once an agreed number of landslides is predicted to occur. The actions which follow are broadly the same as those which are put in place to respond to an actual debris flow.

There are, of course, some disadvantages to this system. The public may become desensitised to warnings if there are a large number of false alarms. Also, road closures have quite significant impacts and it may not be advisable to put closures in place in anticipation of a debris flow occurring.

Examples of Methods of Exposure Reduction

Road Signs

A review was undertaken of road signs used internationally to indicate the danger of landslides. Most countries use signs similar to those used in the UK, which depict rocks falling down a slope.

It is recommended that this graphic continues to be used on road signs in Scotland, with the possible addition of a plate underneath the triangular warning sign reading ‘Landslides’ and with the distance over which the landslide hazard exists (in miles or yards).

Proposed road sign.

Alternatively, signs could be placed at both ends of the hazardous stretch. The first sign could be with or without a plate underneath stating ‘Landslides’. The sign at the end of the hazardous stretch could state ‘End’ or have a score through the landslide symbol, indicating that the hazard has been passed.

Education

Signs which provide more detail about the nature of landslides and how they are generated could play a valuable role in helping to educate the public. Examples already exist of signs of this nature being successfully used in other parts of the world.

Such signs could be featured at National Park Gateways, service areas and the messages contained therein communicated in other forms.

A draft information leaflet explaining how landslides occur and what action the public should take is being drafted for the Transport Scotland website and other forms of dissemination.

Example of landslide hazard information sign.

Techniques for Hazard Reduction

A number of techniques for hazard reduction are available, ranging from relatively straightforward drain clearing to more extensive engineering works. The challenge is to identify which locations will benefit sufficiently from such techniques to justify the substantial expenditure and potential impact on the environment.

Road Protection

Road protection may take on a number of forms including the following:

- Debris basins to collect debris while allowing water to pass down the slope.
- Lined debris channels designed to carry debris and water underneath the road into a safe repository, such as a loch or the sea.
- Debris flow shelters which cover a section of road and arrest the material on the top of the structure.
- Debris flow overshoots which facilitate the passage of water and debris over the road.
- Barriers and fences, particularly flexible fences which are designed to catch debris but allow water to pass through.

Such approaches must take into account the speed, load and consequent energy of a debris flow and ensure that the engineering solution put in place can cope with this effectively.

Examples of debris flow hazard reduction techniques. Top left: Debris basin. Top right: Lined debris channel. Bottom left: Debris shelter. Bottom right: Fence.

Debris Flow Prevention

Options for retaining and stabilising the ground include retaining walls, anchoring or soil nailing. However, due to the widespread potential for debris flow, the instances in which such approaches are both practicable and affordable are rare. Effective drainage can, however, help reduce the potential for debris flow.

Road Realignment

The realignment of roads is usually undertaken to improve road safety and increase journey reliability. However, in locations where the debris flow hazard is deemed to be very high, road realignment may be a viable option provided that such actions fit with broader strategic route objectives.

Drainage

There are issues surrounding the maintenance of drainage and culverts in terms of debris flow management. In such localities culverts must be able to cope with debris as well as with water.

First, routine inspection and clearing of drainage channels and culverts form part of the responsibilities of the Operating Companies and are seen as a priority on the trunk road network and its surroundings. The issue of more distant stream requires a degree of cooperation with land owners immediately adjacent to high hazard ranking areas of the trunk road network, in order that mutually beneficial improvements to the drainage regime may be undertaken.

Second, major systemic improvements to the drainage at road level, including enlarged/enhanced culverts and other drainage features to accommodate debris should be considered. Increasing such the capacity of drainage systems fits well with recent changes to UK National Standards implemented in response to anticipated climate change.

Land Management

The presence of forestry has been shown to help minimise debris flow in terms of both occurrence and magnitude. However, deforestation and logging can have an adverse effect on the drainage of a slope and destabilise the ground. Clear-felling is not as widespread in Scotland as it once was, and deforestation now tends to leave areas of trees intact, mainly for aesthetic reasons, but it is suggested that current practice be studied further to ensure that hillside stability, as well as visual appearance, is factored into future decisions concerning deforestation.

7 PROACTIVE DETECTION

One of the main factors influencing debris flow occurrence is water, with heavy and/or sustained rainfall in particular triggering the majority of landslide events. At present in Scotland the amount of rain falling during storm events, or in the period preceding the occurrence of a landslide, is relatively unquantified. It is generally accepted, however, that debris flows can be initiated either by long periods of rainfall or shorter intense storms.

Following the events of August 2004 it was concluded that a system of rain gauges should be installed at key locations in Scotland, with the intention of facilitating a greater understanding of the amount of rainfall which would cause instabilities at debris flow risk sites. Detailed scrutiny of the rainfall leading up to debris flow events would enable the development of a rainfall 'trigger level' above which it is likely that debris flow will occur. This would, in turn, allow the forecasting of periods during which such events might take place.

In the long term, a management strategy is required. This would include protocols for action, increased surveillance when predetermined levels of rainfall are exceeded and the potential for road closures to protect road users.

Forecasting Methods

Rainfall analysis is the most frequently adopted approach for forecasting landslides and worldwide observations have helped to identify the minimum and maximum volume of rain required over various periods of time to trigger these events.

It is widely accepted that Scottish debris flow events are usually preceded by extended periods of heavy, antecedent, rainfall prior to the storm that may trigger the event itself. Evidence of the influence of rainfall on landslide events has been gathered following events in many places in the world.

Scotland's rainfall patterns can be broadly divided into two zones covering the east and west of the country. The Met Office indicates that in the east rainfall generally peaks in August while in the west the maximum rainfall levels are reached during the wider period September to January. While rainfall levels in the west are relatively low in August they do increase from a low point in May.

Soil may therefore undergo a transition from a dry to a wetter state around August, leading to increased potential for debris flow and other forms of landslide activity at that time.

The analysis and interpretation of climate change models for Scotland suggests that there may be the potential for an increase in future debris flow activity in Scotland, as rainfall becomes more concentrated as well as becoming more intense (i.e. it is concentrated into fewer, higher magnitude events).

A Trigger Threshold for Scotland

Forecasting of conditions which could lead to debris flow is limited at present, as the rainfall gauge network in Scotland is sparse in most of the areas of interest. Although the existing system does cover some of the areas of interest, the outputs are not sufficiently detailed and more accurate data would be required.

Three hypothetical threshold levels have been outlined:

- A threshold level above which debris flow might be expected to occur.
- A lower threshold level at which a warning could be issued and action taken, giving adequate lead-in time for these to be effective.
- A still lower threshold level is set at which instruments are checked and key personnel alerted that conditions likely to lead to debris flow are developing, essentially the last step before issuing a warning.

Work has been undertaken to back analyse rainfall data from past debris flow events in order to develop a threshold level above which debris flow might be expected. Ongoing work is aimed at analysing more recent events in order to allow the further development and validation of this threshold level. The first such analysis, that of the storm which led to the debris flow event at the A83 Rest and be Thankful on 28 October 2007, indicates that the tentative debris flow threshold developed from the back analysis shows some promise for practical use.

High quality data from a variety of geographical locations will be needed in order to validate and/or change the threshold prior to its introduction as a management tool for the road network. Due to the frequency of such major events in Scotland, this process may take approximately five years.

8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Transport Scotland began a concerted programme of work following the major landslide events of August 2004, which had led to wide-ranging media and political interest. In general the events observed confirm that landslides typically occur in Scotland in two seasons, namely:

- Summer: July and August.
- Winter: November to January (with events sometimes occurring in October).

The work reported here forms the major component of Transport Scotland's response to the August 2004 events and builds upon an earlier report which described the background and objectives behind the work presented. The findings from the work have already been widely presented on both nationally and internationally.

The core of the work addressed by this report is the assessment and ranking of hazards presented by debris flows for the Scottish trunk road network.

The hazard assessment process involves the GIS-based spatial determination of zones of susceptibility which are then related to the trunk road network by means of plausible flow paths to determine specific hazard locations. This approach enabled the rapid analysis of large volumes of data. This desk-based approach to hazard assessment was then supplemented by site-specific inspections to give a hazard score for each site of interest.

The subsequent hazard ranking process involved the development of exposure scores predicated primarily upon the risk to life and limb, but also taking some account of the socio-economic impact of debris flow events. The exposure scores were combined with the hazard scores to give site-specific scores for hazard ranking from which a listing of high hazard ranking sites in Scotland was produced.

Processes for the management and mitigation of debris flow hazards have been developed and two approaches are described:

- Exposure reduction, which involves for example education, warning, signing and road closure.
- Hazard reduction, which includes engineering measures that protect the road, reduce the opportunity for debris flow to occur, or involve realignment of the road.

Most of the recommendations are based upon the reduction of the exposure of road users to debris flow hazards as a reaction to events and utilise lower cost and less environmentally intrusive approaches rather than the typically high cost, environmentally intrusive approach of specific hazard reduction. Exposure reduction is predicated upon the simple and easily-remembered, three-part management tool, Detection-Notification-Action (DNA).

Weather and climate are clearly key influences upon the triggering of debris flows in Scotland and climate change models generally indicate that such events may become more frequent and/or more intense in the future. In the longer term the ability to forecast debris flow from rainfall data is clearly desirable in order to allow, at least, the Detection and Notification aspects of the DNA process to be carried out in advance of events. In support of this, a rainfall-based analysis to develop, validate and refine a debris flow trigger threshold is under way.

The work presented in this report gives Transport Scotland the means to apply appropriate management measures to the sites of highest risk on the trunk road network.

Specific recommendations to achieve this and to further develop and improve the management process relate to:

- A series of management actions predicated towards exposure reduction.
- Opportunities for physical hazard reduction on new works and rehabilitation schemes.
- The vital role of the development of rainfall-monitoring systems and interpretative techniques to enable pro-active warning of debris flows to be brought into play in future years.
- The value of studying the ongoing effects of climate change on the prevalence of debris flows, of carrying out an evaluation of the economic effects of debris flow events, and working with the Forestry Commission in order to ensure that best practices are adopted in terms of forestry harvesting and hill slope stability.
- The need for a continuing site inspection programme to validate all four priorities of sites on the network, and the role of re-assessment and re-inspection at some time in the future.
- Consideration of actions relating to rock slope surveys.
- The need for separate assessment of scree-slope sections in Glen Coe and on Skye.

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RR Donnelley B57645 10/08

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ISBN 978-1-906006-37-2

9 781906 006372

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