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An Extended and Updated Technical Evaluation of Wig-Wag Signs at the A83 Rest and be Thankful

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Contents

Executive Summary

The Scottish Road Network Landslides Study made a number of recommendations for landslide management and mitigation. Amongst these was that 'wig-wag' signs could be suitable at sites with specific conditions, particularly those sites at which debris flow events occur on a regular basis. Such signs incorporate a standard rockfall/landslide red warning triangle, flashing lights, and a sub-plate that that warns of 'Higher risk when lights flash'.

A trial of such signs commenced on the A83 in 2011 and was centred on the section of the route that includes the Rest and be Thankful. As part of this trial it was intended that a detailed technical and perceptual evaluation of the signing arrangements be undertaken. An initial technical evaluation, after two years of operation, and a perceptual evaluation were undertaken. This report extends and updates the technical evaluation to four years of operation and examines the efficacy of the operation of the wig-wag signing arrangements at this location. The previous perceptual evaluation explored the perceptions and attitudes of road users to these specific signs.

It is broadly concluded that the trial has had a satisfactory outcome; 15 of the 17 debris flow events (almost 90%) that occurred during the period of the trial were within a period when the lights were activated, or most likely activated in the two cases when the time/day of occurrence is not known with precision. The two events that did not occur during such a period were of a somewhat different character, but must nonetheless be seen as 'false negatives'.

The period during which the lights were activated and were not associated with a debris flow event corresponds to between 12% and 19% of the days of the year; this is significant but is considered to be broadly acceptable in the light of the rainfall triggers that are currently available to determine the timings of switch-on and switch-off.

The results of the previously reported driver perception element of the work indicate that, in general, desired behaviours are promoted by the use of the signs.

The A83 Rest and be Thankful locality is known for the frequency with which debris flow events occur, much more than any other part of the trunk road network in Scotland. It is thus well-suited to the use of this type of temporal warnings. The potential application of wig-wag signs to other parts of the network is limited and any proposals should be the subject of detailed location-specific assessment.

The evidence presented in this report supports the continued use of the wig-wags and the continued promulgation of messages about desired behaviours to the non-local driver target audience.

1 Introduction

Landslides in the form of rainfall-induced debris flows are a common occurrence in Scotland. The events of August 2004 which adversely affected the Scottish trunk road network led to the Scottish Road Network Landslides Study (Winter et al. 2005; 2009; 2013a).

The overall purpose of that study was to systematically assess and rank the hazards posed by debris flows and to put in place a management and mitigation strategy for the Scottish trunk road network. The ranking system allows lengths of the network subject to risk from debris flow events to be prioritised for action.

The approaches to management and mitigation were based upon exposure reduction and hazard reduction respectively (Winter et al., 2009). There are many forms of landslide management and mitigation (e.g. VanDine, 1996) and a strategic approach to landslide risk reduction has been developed (Winter, 2013; 2014). This particular approach is intended to provide a common lexicon and to allow a clear focus on outcomes from such activities whilst avoiding an overemphasis on individual processes and techniques. This approach ought to be of particular value to those who fund such works, including infrastructure owners and local governments. Management involves the reduction of the exposure of road users to the hazard by means of either:

1) education;
2) geographical (non-temporal) warnings; or
3) response (including temporal, or early, warnings).

Mitigation primarily, but not exclusively, involves reduction of the actual hazard by means of:

a) works to engineer or protect the elements at risk;
b) remediation of the hazard to reduce the probability of failure; or
c) removal, or evacuation, of the elements at risk.

One of the recommendations put forward by Winter et al. (2009) was that a form of temporal warning sign incorporating a standard rockfall/landslide red warning triangle, flashing lights and a sub-plate that warns of 'Higher risk when lights flash' (i.e. during periods of high rainfall) might be suitable for sites where debris flow events occur on a regular basis. Such signs are colloquially known as 'wig-wags' and also provide a permanent geographical warning (Winter, 2014), thus fulfilling a risk management function under both items (2) and (3) above, as part of an overall landslide risk reduction strategy (see also Figure 1).

The debris catch fences (item (a) above) that have been installed above the road have undoubtedly reduced the overall risk between Ardkinglas and just west of Cairndow but the wig-wags remain, alongside media and other information and education activities, an important part of the overall landslide risk reduction strategy (Winter, 2014) in the area. The fences in isolation reduce the hazard for the relatively small events that occur at the highest frequency but do relatively little for the lower frequency higher magnitude events that also occur. It is also important to understand that the area (length of road) covered by the wig-wag signs is substantially greater than the length of road that is, or could reasonably be, covered by active mitigation measures such as fences and catch pits for example.

The context of the suitability of the wig-wag signs in this specific location is important. The wig-wag signs are suited to this location because the events are relatively small and occur regularly – the signs are thus likely to be well-understood as is strongly suggested by the perceptual evaluation (see Section 4). At other locations (e.g. A85 Glen Ogle, A82 Glencoe) where the frequency of events is measured in decades, rather than in months to one-year as at the A83 Rest and be Thankful, and the events tend to be of much greater magnitude such signs would have little meaning. There are no other known sites on the Scottish trunk road network at which wig-wag landslide warning signs would, currently, be considered suitable for application.

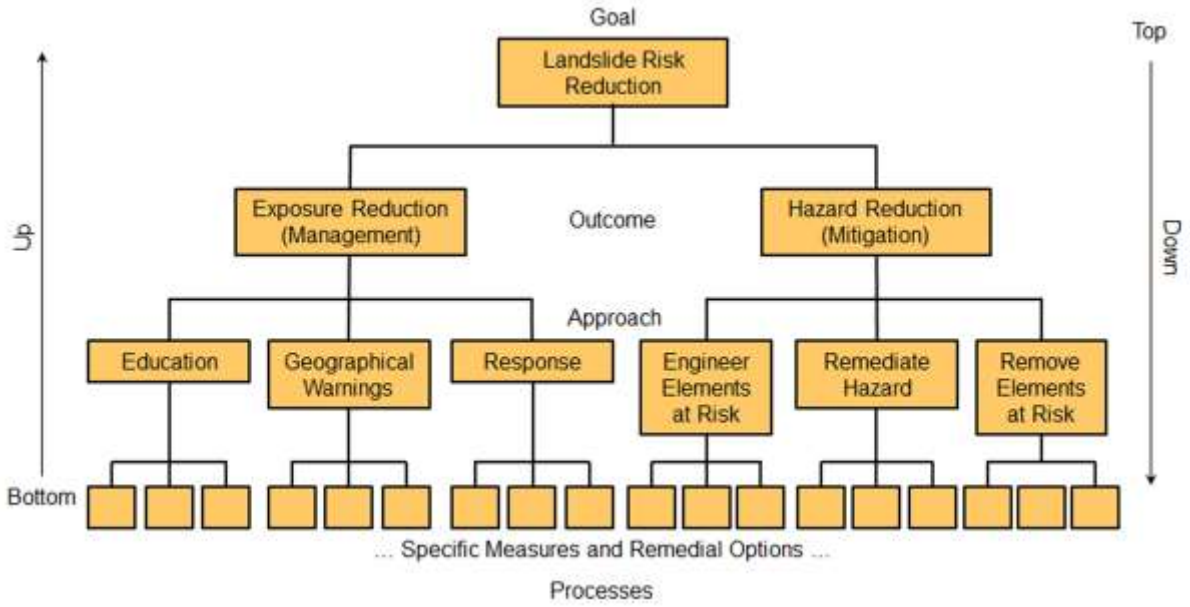

Figure 1. Classification for landslide management and mitigation to enable a strategic approach to risk reduction (from Winter, 2014).

At the A83 Rest and be Thankful, the application of the strategic approach to landslide risk reduction is extensive and incorporates either exposure or hazard reduction actions. Exposure reduction (or management) may involve:

1) education: leaflets indicating desired driver behaviours and offering information about the wig-wags and other risk reduction measures;
2) geographical (non-temporal) warnings: the wig-wag signs when switched off (or on); or
3) response (including temporal, or early, warnings): the wig-wags when switched on.

Hazard reduction (or mitigation) may involve:

a) works to engineer or protect the elements at risk: debris catch fences and other direct protection measures such as catch pits;
b) remediation of the hazard to reduce the probability of failure: planned future vegetation planting with the express purpose of reducing instability (Winter & Corby, 2012); or

c) removal, or evacuation, of the elements at risk: the temporary use of the Old Military Road diversion that moves traffic further away from the debris flow risks at the Rest and be Thankful.

A two-year trial of the wig-wag signs commenced on the A83 in January 2011 and was extended prior to the signs being made permanent in December 2014. The terms of the trial approval required that the effectiveness of the signs should be monitored and that the results should be incorporated into a report. The aims of the monitoring, as determined by Transport Scotland, were as follows:

- *Technical evaluation:* Determine the efficacy of the wig-wag switch-off/switch-on protocol in terms of its alignment with actual events and also to assess the rainfall threshold used for the switch-on.
- *Evaluation of drivers' attitudes and behavioural responses:* Explore the attitudes held by local and non-local drivers towards landslide wig-wag signs on the A83 in terms of their perceived meaning and their impact on road safety.

An initial technical evaluation, after two years of operation, and a perceptual evaluation (Winter et al., 2013b) satisfied those aims. This report extends and updates the technical evaluation to cover four years of operation and examines the efficacy of the operation of the wig-wag signing arrangements at this location. The previous perceptual evaluation explored the perceptions and attitudes of road users to these specific signs.

This report presents the technical evaluation for the years 2011 to 2014 (Section 3), building on the evaluation for 2011 and 2012 presented by Winter et al. (2013b). The evaluation of drivers' attitudes and behavioural responses (perceptual evaluation) to the wig-wag signs is summarised here in Section 4. Pertinent background information is presented in Section 2 and conclusions are drawn and recommendations made in Section 5.

2 Background

2.1 Debris Flows and the Trunk Road Network

The Scottish Road Network Landslides Study (Winter et al., 2005; 2009; 2013a) was instigated in response to the rainfall-induced landslide events of August 2004. The rainfall experienced in Scotland in August 2004 was substantially in excess of the norm. Some areas of Scotland received more than 300% of the 30-year average August rainfall (source: www.metoffice.gov.uk), while in eastern parts between 250% and 300% was typical. Although the percentage of the monthly average rainfall that fell during August reduced to the west, some parts still received 200% to 250%.

Long lasting and intense rainfall led to a large number of landslides, in the form of debris flows, in the hills of Scotland. Critically, some of these affected important parts of the major road network, linking not only cities but also smaller, remote communities. Notable events occurred at the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August) (Figure 2).

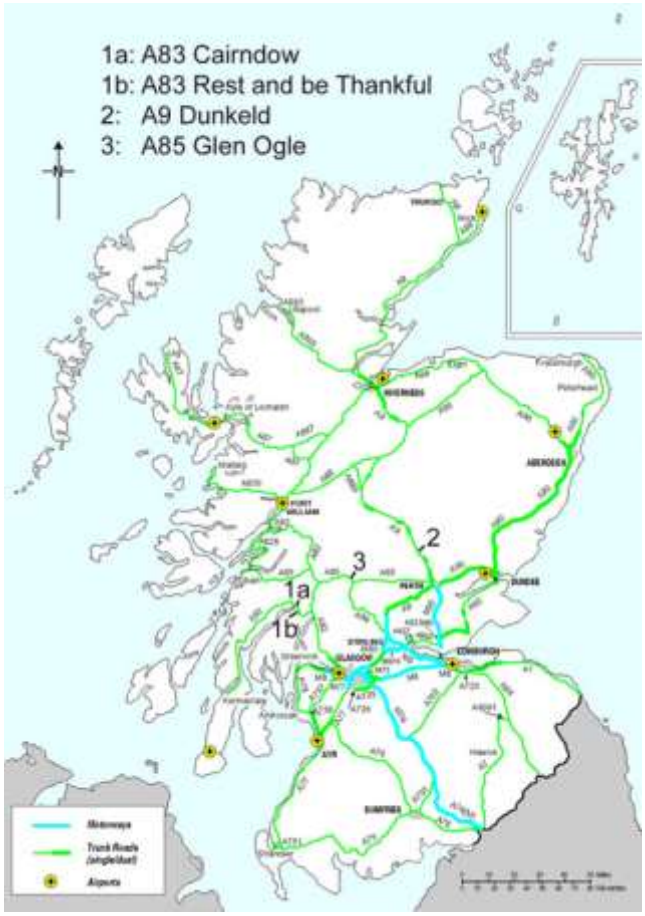

Figure 2. Map showing the trunk road network, including motorways, in Scotland. The locations of the three main debris flow event groups that affected the trunk road network in Scotland in August 2004 are shown.

Subsequent analysis of radar data indicated that at Callander, 20km from the A85 events, 85mm of rain fell in four hours on 18 August. Some 48mm fell in just 20 minutes and the storm reached a peak intensity of 147mm/hour. The 30-year average August

rainfall varies between 67mm on the east coast and 150mm in the west of Scotland (Anon., 1989).

While there were no major injuries, some 57 people were taken to safety by helicopter after being trapped between the two main debris flows on the A85 in Glen Ogle. However, the real impacts were social and economic, in particular the severance of access to and from relatively remote communities. 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.

The events of August 2004 are described by Winter et al. (2006). These events are by no means unique and further debris flows have affected both the A9 and the A83, for example, since August 2004. The event pictured at the A83 in Figures 3 and 4 occurred at around 0330 hours on Sunday 28 October 2007. Figure 3 illustrates the event and the surrounding hillside; the photograph is taken from the opposite side of the valley and evidence of numerous past events can be clearly observed. Figure 4 illustrates the event in more detail and it is clear that the system of mass movement comprises two discrete but related events. The flow above the road commenced with a relatively small slide (or slides) into an existing drainage channel. This then triggered the movement of a large amount of marginally stable material in and around the stream channel depositing an estimated 400 tonnes of material at road level. This material blocked the open drain which carries water along the upslope side of the road to a series of culverts beneath the road. While the material from above the road had limited impact upon the slopes below the road, water diverted from the drain was channelled across and over the edge of the road causing some significant undercutting of the slope below and associated deposition further down the hill as can be seen in Figure 4.

Due to the major contribution that tourism makes to Scotland's economy the impacts of such events 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, during which debris flow usually occurs between October/November and January, should not be underestimated. 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, affect directly a few tens of metre of road cast a considerably broader vulnerability shadow (Winter & Bromhead, 2012); Winter (2014) estimated the boundaries of the vulnerability shadow cast as illustrated in Figure 5.

Figure 3. View of the hillside above and below the approach to the Rest and be Thankful from the east (from NGR NN 23160 06559 on the opposite side of Glen Croe). Not only can the event dated 28 October 2007 be clearly seen but evidence of numerous past events can be seen on the surrounding hillside.

Figure 4. View of the debris flows above and below the A83 on the approach to the Rest and be Thankful (from NGR NN 23160 06559 on the opposite side of Glen Croe). The head scar is at approximately 370m AOD, the A83 at 240m AOD and the old road at 180m AOD.

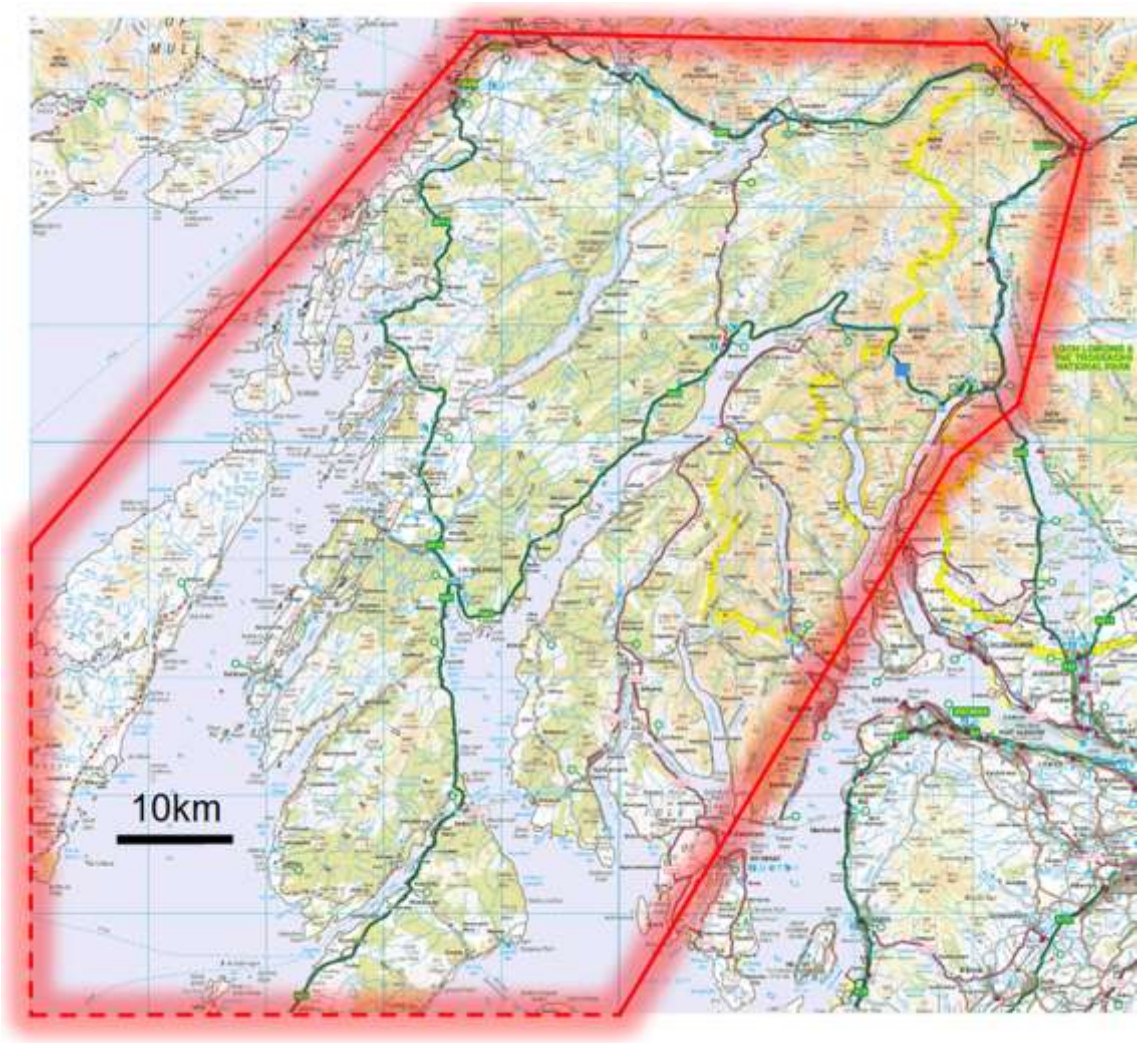

Figure 5. A relatively small debris flow event (blue square) closed the A83 at the Rest and be Thankful in October 2007; the vulnerability shadow that was cast (bounded in red) was extensive.

The A83 Rest and be Thankful site has been extremely active in recent years with multiple debris flow events and associated closures and events in 2007, 2008 and 2009 had an adverse effect on the travelling public. Subsequent events in 2011 and 2012 have continued this trend. This has meant that the area has become the focus of not only concern but also of extensive landslide management and mitigation activity. This culminated in a study being commissioned to assess and make recommendations on potential landslide remediation actions (Anon., 2013; Winter & Corby, 2012).

2.2 Wig-wag Signs

The installation of trial wig-wag signs was one of the options recommended by Winter et al. (2009) as part of the overall management strategy. The wig-wag signs (Figures 6 and 7) provide both permanent geographical signing and temporal warning of potential landslides as part of a landslide risk reduction strategy (Winter, 2014).

The design of the wig-wag signs used in this setting incorporates both a static landslide warning sign and lights that flash during periods of heavy rainfall, to indicate an elevated risk of landslide (Figures 6 and 7). Such signs are commonly used to indicate the presence of school crossings or ice, both of which have a clear temporal aspect and are

eminently suited to the use of flashing lights when such risks are at a higher level than at other times (i.e. at school start and end times, and during periods of cold weather, respectively).

Figure 6. Standard design of landslide wig-wag warning sign.

Figure 7. Wig-wag warning sign in operation.

A two-year trial of such signs was approved, originally for commencement on 21 April 2009 (this was later revised to 1 October 2010 and then to 1 November 2010) and this was subsequently extended for a period of one-year, before being made permanent in December 2014. The trial commenced in January 2011 and the area was defined as the

A83 between Ardkinglas and a point to the west of Cairndow just before the turn to the Achadunan Brewery (Figure 8).

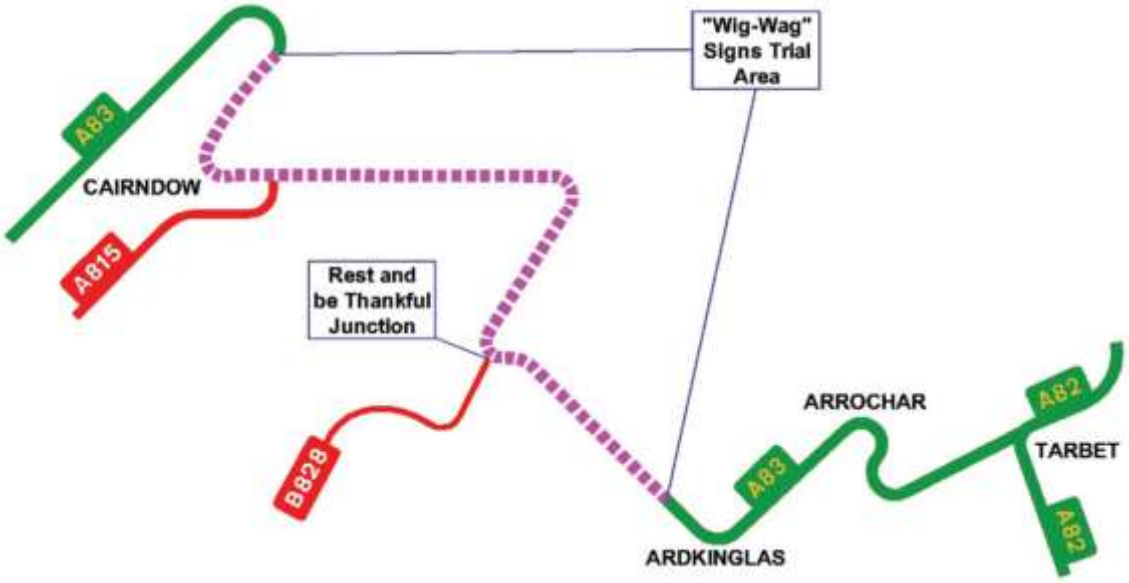

Figure 8. Wig-wag warning sign trial location.

A total of six signs was installed, three each for eastbound and westbound traffic. The sign plates are permanently visible to drivers and the flashing lights are switched on remotely, using mobile telecommunications technology, in response to warnings (or forecasts) of heavy rainfall. When the lights are switched on, to indicate a period of higher risk (of landslides), a notification is placed on the Traffic Scotland website (www.trafficscotland.org); such notifications are frequently broadcast both locally and nationally.

The wig-wag signs are switched on by the Traffic Scotland Control Centre in response to Heavy Rainfall Warnings. These are predicated upon meteorological forecasts that suggest that one or other of two threshold values is likely to be exceeded. The thresholds are defined by the Met Office as follows:

- 25mm in a 24 hour period, or
- 4mm/hour in a three hour period.

The lights then flash from the time that the forecast period commences until six hours after the forecast period finishes; the six hour period was agreed, at the outset of the trial, as the best estimate of the period over which the residual risk would persist. The content of a typical Heavy Rainfall Warning is shown in Box 1. The warning is also emailed to the Operating Company who consult with Transport Scotland and make a decision on whether landslide patrols should be activated, although it should be noted that these operate in daylight hours only.

The wig-wags have prompted diverse views from road users and local residents. The promulgation of messages in the media, when the lights are switched on, along the lines of "There is a higher risk of landslides at the Rest and be Thankful … nothing has happened but drivers should be advised to take care …", may erroneously send out the message that mid-Argyll is effectively closed for business at such times. Such a message was not stated in the recommendations made by Winter et al. (2009); what was

contained in those recommendations was that such signs should be used to alert drivers to the need to take extra care. The actions that drivers should take were detailed in Appendix F of Winter et al. (2009) and repeated and reinforced in leaflets issued jointly by Transport Scotland and Scotland TranServ. These leaflets included the following messages:

> "*These new [wig-wag] signs will flash when there is a higher risk of a landslide, alerting drivers to take extra care while continuing their travel on the road.*
>
> "*Our aim is to keep roads open as safely as possible and you can help make your trip even safer by:*
>
> - *planning your journey in advance at www.trafficscotland.org*
> - *checking the weather forecast before you set off*
> - *allowing extra travel time*
> - *being alert for water or debris on the road*
> - *listening for travel bulletins and looking for roadside messages displayed on Variable Message signs*
> - *avoid stopping on bridges or next to water courses in mountainous areas*
> - *planning your stops in towns and villages rather than the open roadside*
>
> "*For more information about the Landslide Action Plan and Wig-Wag trial visit http://www.transportscotland.gov.uk/.*"

Box 1: Rainfall Warning Service for A83 Wig-Wag Signs

Heavy Rainfall Warning

Warning Number 3
Valid From: 0900 on 13th May 2012
Valid Until: 2100 on 13th May 2012
A83 Rest and be Thankful (Ardgartan to Cairndow)

Applicable Criteria:
1. Rainfall accumulation of 25mm in a 24hour period, or
2. Rainfall expected to fall at a rate of 4mm/hour or more, giving a total of 12mm or more within 3 hours.

Action:
Switch ON Wig-Wags at: 0900 on 13th May 2012
Switch OFF Wig-Wags at: 0300 on 14th may 2012

Issued by: [redacted]

It is clear that from the outset of the trial there were three aspects to the wig-wag signs, as follows:

1) The standard fixed-plate rockfall/landslide warning red triangle sign which is used internationally to indicate risks of both rockfall and other types of landslide.
2) The flashing lights that are activated during periods of heavy rainfall.
3) The notifications that were posted on the Traffic Scotland website and thus picked up and promulgated more widely by the media.

In the following section an evaluation of the technical success, or otherwise, of the mechanisms and procedures used to trigger the flashing, wig-wag, lights is presented.

3 Technical Evaluation

The technical evaluation assesses, both qualitatively and quantitatively, the success or otherwise of the procedures and methodologies used to switch the wig-wag signs on and off. In order to evaluate success of the initiative what should be assessed is whether the wig-wags were switched on too frequently when debris flow events did not occur – 'false positive' – and switched off when debris flow events did occur – 'false negative'.

However, it is important to note that the flashing lights indicate a higher risk of debris flow occurrence, not a certainty of an event, and that their absence indicates a lower risk period, not a zero risk state. In this context it should be clear that the phrases 'false positive' and 'false negative' are used as shorthand.

3.1 Data Assessment

A number of data sets were compiled for the period 1 January 2011 to 31 December 2014, unless stated otherwise, as follows:

- Rainfall data from a Vaisala rain gauge located adjacent to the A83 carriageway on the easterly approach to the Rest and be Thankful (data for 2011 only).
- Rainfall data from a Scotland TranServ rain gauge located adjacent to the A83 carriageway on the easterly approach to the Rest and be Thankful (2011 and 2012 only).
- Rainfall data from a SEPA rain gauge station located to the south of the B828 near to the beginning of the forestry road that traverses the west side of Glen Croe (Station Name: Rest and be Thankful; Station number: 485490; National Grid Reference: NN 22835 06967) (data from 29 April 2012).
- Rainfall data from a SEPA rain gauge station located to the east of the A83 on the westerly approach to the Rest and be Thankful opposite the northern end of Loch Restil (Station Name: Loch Restil; Station Number: 485489; National Grid Reference: NN 23249 08496) (data from 29 April 2012).
- The days on which Heavy Rainfall Warnings were in operation for the Rest and be Thankful area (these were supplied by Net Weather until 23 November 2011, by Met Office from 24 November 2011 until 12 March 2013 and by MeteoGroup thereafter). This data set was supplied by BEAR Scotland and shows differences from the data set supplied by Scotland TranServ and reported by Winter et al. (2013b).
- The times for which snow warnings were in operation for the Rest and be Thankful area (these were supplied by Net Weather until 23 November 2011, by Met Office from 24 November 2011 until 12 March 2013 and by MeteoGroup thereafter).
- The days on which landslide patrols were active. (This is presented for information only and does not form part of the technical evaluation.)
- The days on which the flashing lights on the wig-wag signs were activated. This data was sourced from BEAR Scotland and shows differences from the data set supplied from Scotland TranServ and used in the previous evaluation (Winter et al., 2013b).

- The times and dates of debris flow events in the area. This data set is from a variety of sources including from TRL records and BEAR Scotland records which update those used by Winter et al. (2013b).

The data are presented in Figures 9, 10, 11 and 12 for 2011, 2012, 2013 and 2014 respectively and the debris flow events that occurred during this period are summarised in Table 1. The Heavy Rainfall Warnings, snow warnings, landslide patrols and wig-wag sign activations are plotted on a daily basis: thus a point appears on Figures 9 to 12 even if the event to which it refers covers only a small part of the day. For debris flow events of uncertain date of occurrence each possible date of occurrence is shown.

The location of the Vaisala and Scotland TranServ rain gauges in close proximity to the A83 carriageway may mean that the measurements recorded are influenced by spray from passing vehicles. Certainly there are a number of spikes during 2011 (Figure 9) that are illustrated by one or other of the data sets, Vaisala or Scotland TranServ, but not the other. In addition, the Scotland TranServ data set shows some spikes that are not shown by either of the SEPA rain gauges that were commissioned on 29 April 2012 (Figure 10).

In the time during which they have been in operation the two SEPA rain gauges reported broadly similar results (Figures 10 to 12). Indeed, it is generally rather difficult to observe the data from the Loch Restil gauge in Figures 10 to 12 as it is largely visually obscured by that from the Rest and be Thankful gauge.

Road closures, including those that were a result of landslide activity, are excluded from the data illustrated in Figures 8 to 11 as such closures are usually complete for only part of the road and are often for only part of the day. For example, closures during the period 2011 to 2012 were typically between Ardkinglas and the A83-B828 junction (Figure 8) and over the winter of 2011-12, for example, were mainly during the hours of darkness. Road closures thus reduced rather than eliminated the function of the wig-wag signs.

3.2 Wig-Wag Switch-on Periods

It is clear from Figures 9 to 12 that both the number and duration of Heavy Rainfall Warnings and associated switch-on periods of the wig-wag signs is significant; this is particularly the case during November and December of 2011, June to August 2012, December 2013, and late-May to Early-June, October and December 2014. Certainly the number of these is significantly greater than the number of debris flow events and these may be described as 'false positives' (see above). Such 'false positives' may be defined in a number of ways. However, for the purposes of this evaluation two definitions have been used:

1) The number of times the wig-wag signs are switched on when a debris flow event does not occur.

2) The number of days (or part thereof) on which the wig-wag signs are switched on when a debris flow event does not occur.

In both cases the three days before and after a debris flow event have been excluded as the rainfall is likely to be associated with that event. In the case of definition (1), where a switch-on period encompasses part of the three day period either side of a debris flow event it is also not counted.

Table 1. Debris flow events during 2011, 2012, 2013 and 2014 in the A83 Rest and be Thankful area and Heavy Rainfall Warning and wig-wag status.

Time	Date	Event Description	Heavy Rainfall Warning and Wig-wag Status
Not known	On or before 16 February 2011	A small event at geotechnical feature G5, identified during routine inspection. Debris did not reach the carriageway. The exact date of the event is likely to have been some time before the inspection on 16th February 2011.	Heavy rainfall warning was not in force. Wig-wags not switched on. Note that a Heavy rainfall Warning was in force and the wig-wags were switched on, 4 February
Not known	11-12 September 2011*	A small event at Butterbridge in Glen Kinglas. It is not known if this event reached the carriageway.	Heavy Rainfall Warning in force. Wig-wags switched on.
Not known	4-5 October 2011*	A small event at the east end of Glen Kinglas that did not reach the carriageway.	Heavy Rainfall Warning in force. Wig-wags switched on.
Not known	29 November 2011	A small event at the west end of Loch Restil. It is not known if this event reached the carriageway.	Heavy Rainfall Warning in force. Wig-wags switched on.
07:12	1 December 2011	A significant event on the easterly approach to the Rest and be Thankful. Adjacent potential failure areas were associated with this event.	Heavy Rainfall Warning not in force (lapsed on 30 November 2011). Wig-wags not switched on.
12:14	22 February 2012	Failure of one of the potential failure areas identified adjacent to the December 2012 event, on the easterly approach to the Rest and be Thankful.	Heavy Rainfall Warning in force. Wig-wags switched on.
20:00	22 June 2012	A failure raft from a previous translational failure at the Rest and be Thankful was observed to be breaking up high on the slope. The event did not reach the carriageway.	Heavy Rainfall Warning in force. Wig-wags switched on.
Not known	On or before 29 June 2012	This relatively small debris flow did not reach the road although some small boulders did (this event may have occurred on 29 June or earlier) on the easterly approach to the Rest and be Thankful.	Heavy Rainfall Warning in force. Wig-wags switched on.

Table 1 (Continued). Debris flow events during 2011, 2012, 2013 and 2014 in the A83 Rest and be Thankful area and Heavy Rainfall Warning and wig-wag status.

Time	Date	Event Description	Heavy Rainfall Warning and Wig-wag Status
16:00	1 August 2012	A significant event on the easterly approach to the Rest and be Thankful.	Heavy Rainfall Warning in force. Wig-wags switched on.
07:15	19 November 2012	A significant event on the easterly approach to the Rest and be Thankful.	Heavy Rainfall Warning in force. Wig-wags switched on.
07:00	3 October 2013	A significant event in Glen Kinglas and Rest and be Thankful. Old Military Road used as detour.	Heavy Rainfall Warning in force. Wig-wags switched on.
16:45	15 January 2014	Rest and be Thankful. Shallow translational failure below debris flow barrier, approximately 90t reached carriageway.	Heavy Rainfall Warning not in force. Wig-wags not switched on.
11:30	23 February 2014	Glen Kinglas/Honeymoon Bridge, debris flow reached forestry car park but not the A83.	Heavy Rainfall Warning in force. Wig-wags switched on.
01:35	06 March 2014	Rest and be Thankful, deposits reaching both lanes of the A83.	Heavy Rainfall Warning in force. Wig-wags switched on.
01:00	08 June 2014	Tilt meter activation at the Rest and be Thankful, but apparently no movement either translational or debris flow.	Heavy Rainfall Warning in force on 07 June only. Wig-wags switched on.
12:15	06 October 2014	Glen Kinglas, a debris flow that washed a small amount of fines onto the road.	Heavy Rainfall Warning in force. Wig-wags switched on.
06:30	28 October 2014	Rest and be Thankful (and Glen Kinglas), the first 'live' test of the debris fences at the Rest and be Thankful.	Heavy Rainfall Warning in force. Wig-wags switched on.

* These events occurred overnight, hence the uncertainty regarding the day of occurrence.

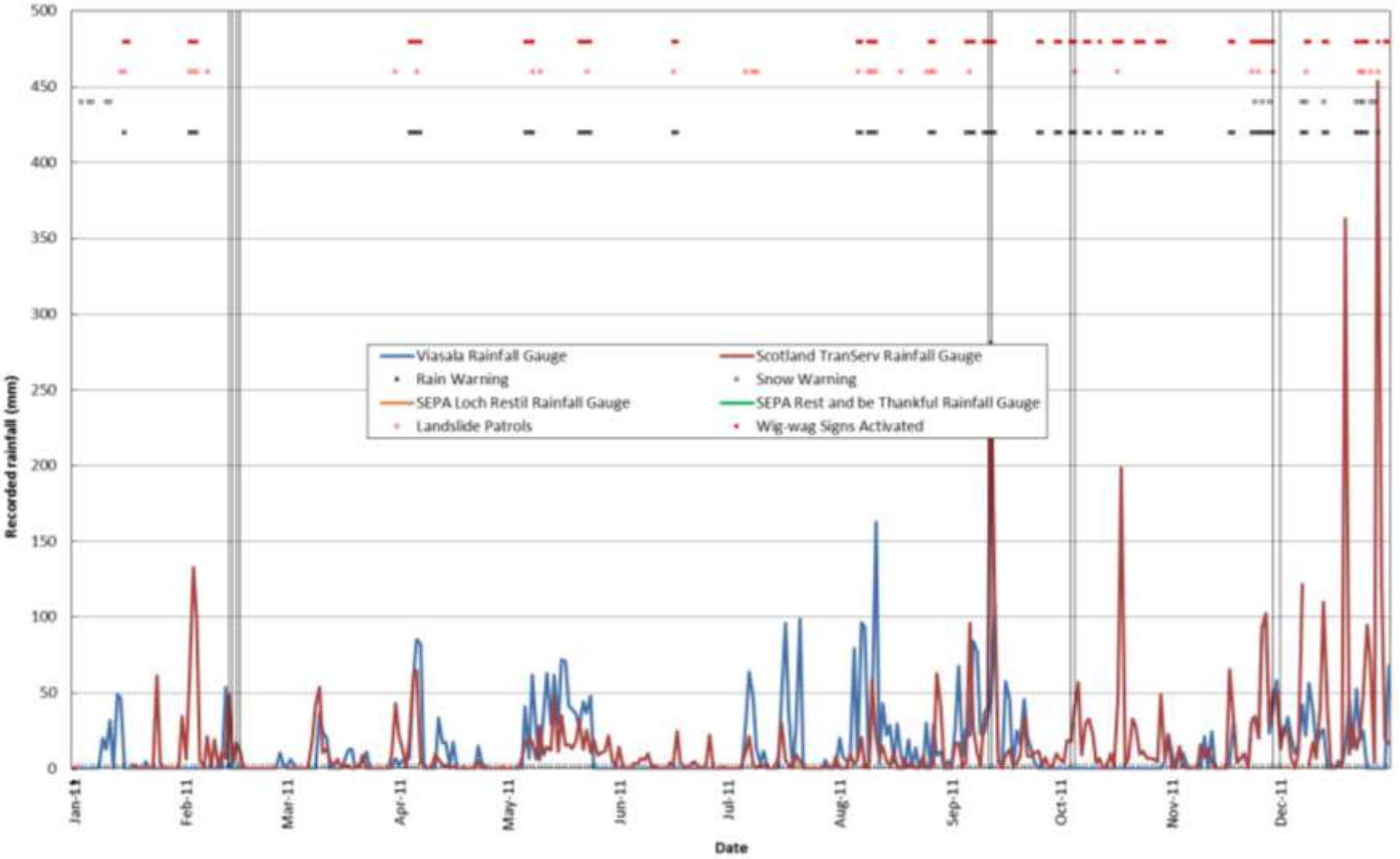

Figure 9. Rainfall data, weather warnings, landslide patrols and wig-wag switch-on periods for the Rest and be Thankful Rainfall for the period 1 January 2011 to 31 December 2011. Debris flow events are shown as vertical lines. (Note that the SEPA rainfall gauges were not activated until 29 April 2012.)

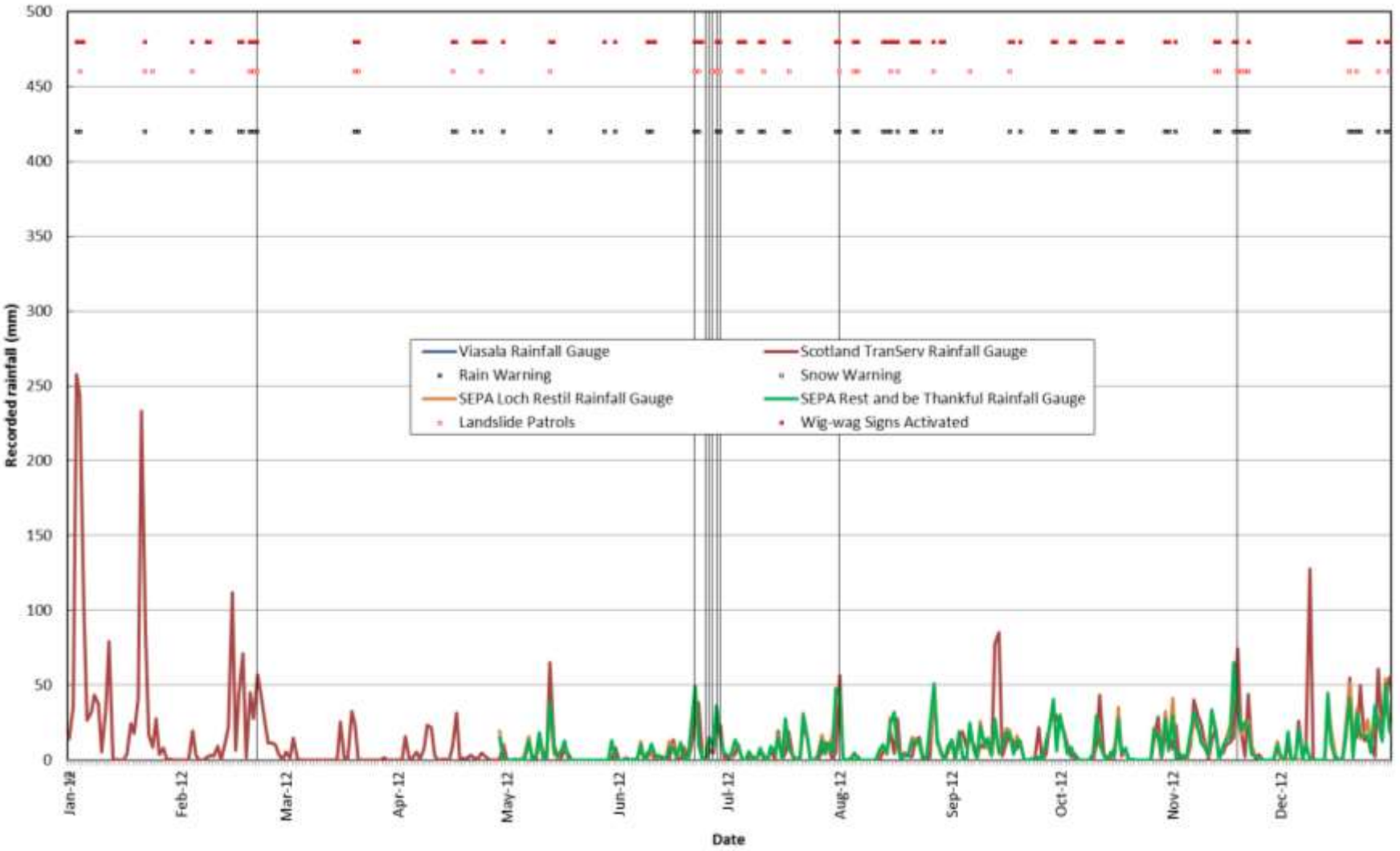

Figure 10. Rainfall data, weather warnings, landslide patrols and wig-wag switch-on periods for the Rest and be Thankful Rainfall for the period 1 January 2012 to 31 December 2012. Debris flow events are shown as vertical lines. (Note that the Vaisala rainfall gauge was not active in 2012.)

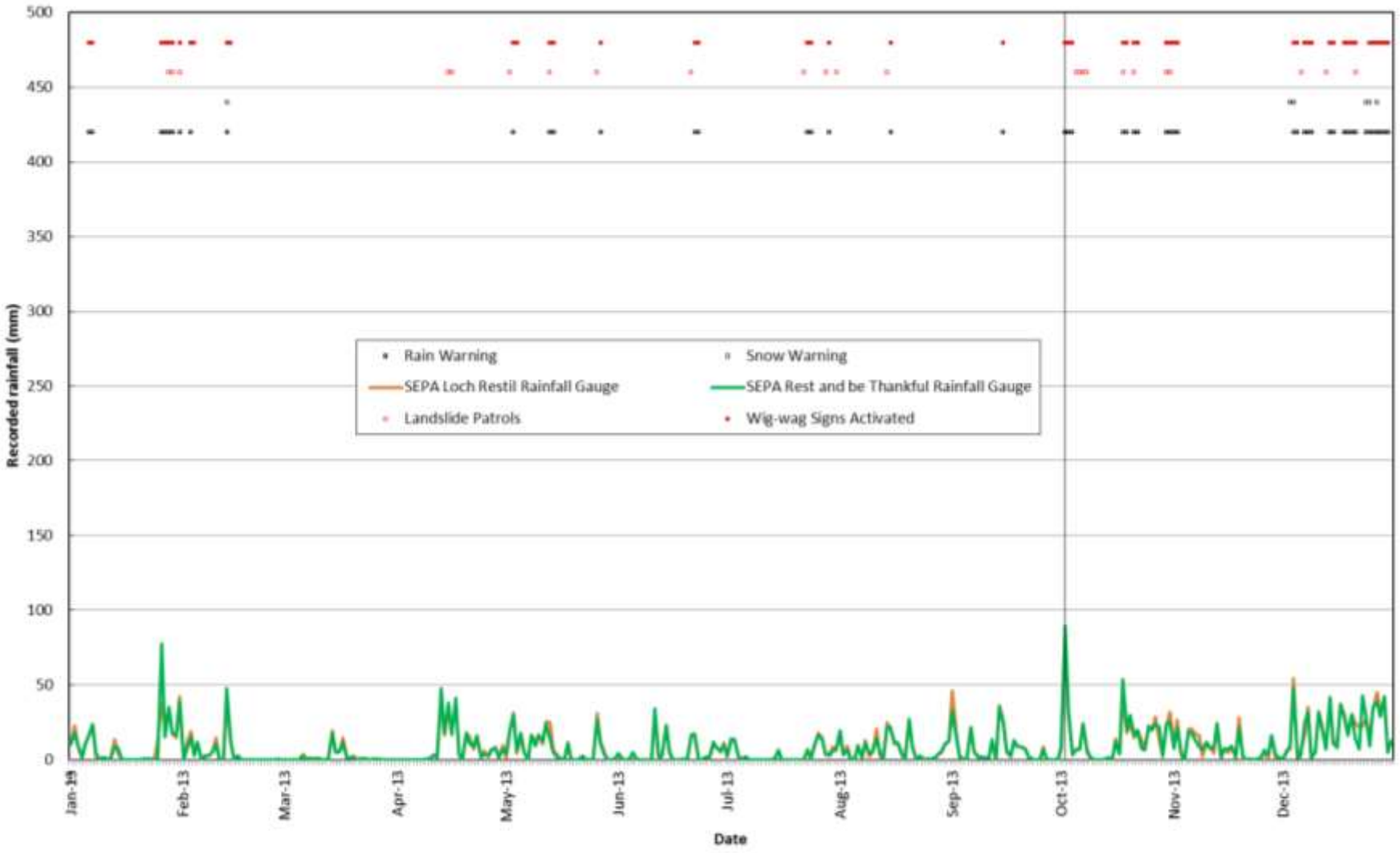

Figure 11. Rainfall data, weather warnings, landslide patrols and wig-wag switch-on periods for the Rest and be Thankful Rainfall for the period 1 January 2013 to 31 December 2013. Debris flow events are shown as vertical lines. (Note that the Vaisala and TranServ rainfall gauges were not active in 2013.)

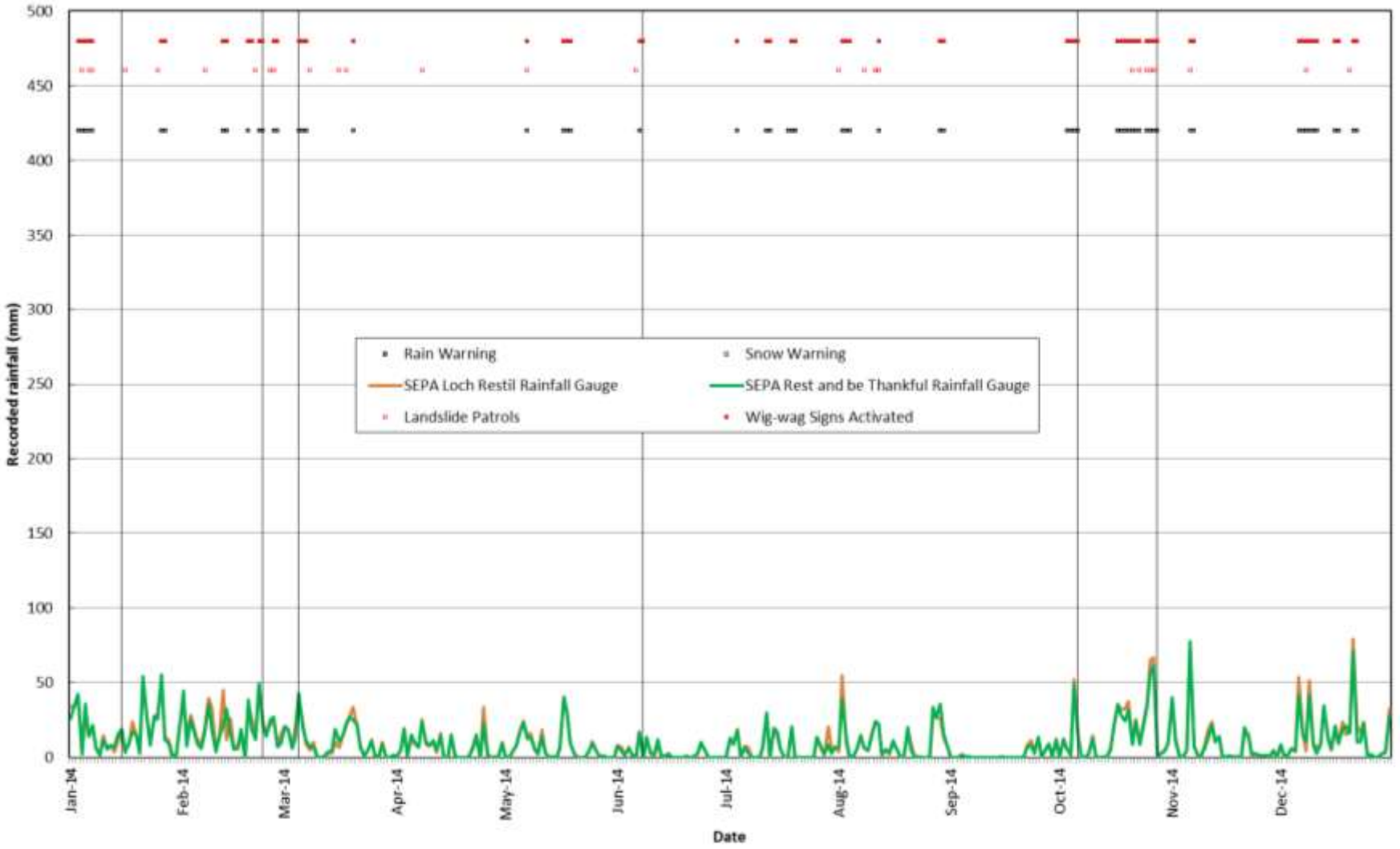

Figure 12. Rainfall data, weather warnings, landslide patrols and wig-wag switch-on periods for the Rest and be Thankful Rainfall for the period 1 January 2014 to 31 December 2014. Debris flow events are shown as vertical lines. (Note that the Vaisala and TranServ rainfall gauges were not active in 2014.)

The number of times that, and the number of days on which, the wig-wags indicated 'false positives' is detailed in Table 2.

Table 2. 'False positives' indicated by the wig-wag signs.

	2011	2012	2013	2014	Total
Number of times	21	33	21	19	94
Number of days	55	69	48	45	217
Percentage of total days	15%	19%	13%	12%	15%

This number of 'false positive' is certainly significant and it is noticeable that the wig-wags were switched on a significantly higher number of times in 2012 than in 2011, 2013 or 2014. However, the difference between the number of days that the wig-wags were switched on, while still greater for 2012 than 2011, 2013 and 2014, is not so significant, that is, the average switch-on period was shorter in 2012.

During 2011, 2012, 2013 and 2014 the wig-wags were switched on for between 12% and 19%, of the days of the year, when the switch-on period was not associated with a debris flow event (Table 2). Indeed, on some days the actual number of hours during which the wig-wags might be switched on can be very few: as an example, if a Heavy Rainfall Warning period started at 18:00 and ended at 22:00 on day 1, then the wig-wags would have been switched on until 04:00 on day 2 and two days would have been counted in Table 2, even though the actual duration of the switch on was only 10 hours. Also this is not considered exceptional given that the rainfall trigger thresholds are under development (see Section 3.4). It must be recognised that the Met Office (and Net Weather and MeteoGroup) Heavy Rainfall Warnings are not specifically purposed to forecast periods during which debris flows are more likely to occur but are a purely meteorological forecast that conform to an accepted definition of heavy rainfall.

There is a small number of days when there is a mismatch between the Heavy Rainfall Warnings in force and the wig-wag flashing lights being switched on. However, it should be noted that the wig-wag switch-on is intended to continue for six hours after the Heavy Rainfall Warning ceases (see also above) and therefore the wig-wag switch-on period may be shown in Figures 9 to 12 as being one day longer than the Heavy Rainfall Warning. In general this seems to explain the majority of the periods when the wig-wags were switched on when there was no Heavy Rainfall Warning in force. Other such instances of this scenario are most likely attributable to a reasoned decision to keep the wig-wags switched on during prolonged periods of particularly heavy rainfall (e.g. late-December 2011).

It should be noted that the mismatches between the wig-wags being switched on and Heavy Rainfall Warnings have been largely eliminated by the use of the new data sets supplied by BEAR Scotland and alluded to in Section 3.1.

In the west of Scotland 2011, 2012 and 2014 were wetter than the average while 2013 was slight wetter than the 1961 to 1990 average and slightly drier than the 1981 to 2010 average (Table 3). Clearly these are regional figures and may well mask more localised differences in the immediate Rest and be Thankful area. It is also worth noting that the annual average rainfall for the more recent period (1981 to 2010) is greater than that for the earlier period (1961 to 1990). While it may not be possible to attribute

this change to climate change, it is indicative of increased rainfall in more recent times in the West of Scotland.

Table 3. Annual rainfall figures for the West of Scotland (from Anon., 2015).

Year	Annual Rainfall (mm)	Percentage of 1961 to 1990 average	Percentage of 1981 to 2010 average	Number of Events from Table 1
2011	2,297.9	138	129	5
2012	1,913.2	115	107	5
2013	1,717.5	103	96	1
2014	2,020.7	121	113	6

Climate change forecasts suggest that winter rainfall may increase, and that storm rainfall (higher intensity/shorter duration) may be more prevalent throughout the year; associated landslide activity is likely to increase also (Winter & Shearer, 2013).

In broad terms the number of events experienced each year (Table 3) shows good correspondence with the amount by which the annual average rainfall is exceeded.

3.3 Debris Flow Events

Table 4 lists the known debris flow events for the period 2011 to 2014 (from Table 1) and compares their occurrence with wig-wag switch-on periods, Heavy Rainfall Warnings, and the use of landslide patrols.

Each event day, or possible event day, in Table 4 is represented by a vertical line in Figures 9 to 12.

In general, the more detailed data in Table 4 supports the observations that can be made from a visual inspection of Figures 9 to 12. That is, that debris flows generally occurred during periods when Heavy Rainfall Warnings were in effect and the wig-wags were switched on. There are four possible exceptions to this and these are described and discussed below.

Event dated on or before 16 February 2011: This was a small event at geotechnical feature G5 which was identified during a routine inspection (debris did not reach the carriageway). The exact date of the event occurrence is thus unknown but is likely to have been a short time before the inspection on 16th February 2011. It seems most likely that it coincided with the most recent period during which there was a Heavy Rainfall Warning (ending 4 February 2011) and during which period the wig-wags were switched on and rainfall levels were very high (100mm/day or more on each of 3 and 4 February). (High rainfall levels were also experienced at the Rest and be Thankful on 13 February but a Heavy Rainfall Warning was not activated and it is not clear whether this rainfall was highly localised or whether there was a malfunction of the measuring system.)

Event dated 1 December 2011: There was no weather warning current and the wig-wags were thus switched off at the time of this event (switch-off was at around midday on 30 November). The event occurred on the first day on which Met Office weather warnings were used, these having been issued by Net Weather up until 23 November 2011. This

change over in the source of the weather warnings is not thought to have adversely affected operation of the system. The fact that the landslide event occurred when there was not a Heavy Rainfall Warning active and the wig-wag signs were switched off means that it must be classed as a 'false negative'.

Table 4. Detailed Heavy Rainfall Warning, wig-wag and landslide patrol status for periods surrounding debris flow events: the day (or days, where this is not certain) of occurrence is highlighted.

On/before 16 February 2011	**13-Feb**	**14-Feb**	**15-Feb**	**16-Feb**	17-Feb	18-Feb
Wig-wags						
Heavy Rainfall Warnings						
Patrols						
11-12 September 2011*	09-Sep	10-Sep	**11-Sep**	**12-Sep**	13-Sep	14-Sep
Wig-wags		Y	Y	Y	Y	
Heavy Rainfall Warnings		Y	Y	Y	Y	
Patrols						
4-5 October 2011*	02-Oct	03-Oct	**04-Oct**	**05-Oct**	06-Oct	07-Oct
Wig-wags			Y	Y		
Heavy Rainfall Warnings			Y	Y		
Patrols				Y		
29 November 2011	26-Nov	27-Nov	28-Nov	**29-Nov**	30-Nov	01-Dec
Wig-wags	Y	Y	Y	Y		
Heavy Rainfall Warnings	Y	Y	Y	Y		
Patrols				Y		
1 December 2011	28-Nov	29-Nov	30-Nov	**01-Dec**	02-Dec	03-Dec
Wig-wags	Y	Y				
Heavy Rainfall Warnings	Y	Y				
Patrols		Y				
22 February 2012	19-Feb	20-Feb	21-Feb	**22-Feb**	23-Feb	24-Feb
Wig-wags		Y	Y	Y		
Heavy Rainfall Warnings		Y	Y	Y		
Patrols		Y	Y	Y		
22 June 2012	19-Jun	20-Jun	21-Jun	**22-Jun**	23-Jun	24-Jun
Wig-wags				Y	Y	Y
Heavy Rainfall Warnings			Y	Y	Y	
Patrols				Y	Y	
On/before 29 June 2012	**25-Jun**	**26-Jun**	**27-Jun**	**28-Jun**	**29-Jun**	30-Jun
Wig-wags				Y	Y	
Heavy Rainfall Warnings				Y	Y	
Patrols				Y	Y	
1 August 2012	29-Jul	30-Jul	31-Jul	**01-Aug**	02-Aug	03-Aug
Wig-wags			Y	Y		
Heavy Rainfall Warnings			Y	Y		
Patrols				Y		
19 November 2012	16-Nov	17-Nov	18-Nov	**19-Nov**	20-Nov	21-Nov
Wig-wags			Y	Y	Y	Y
Heavy Rainfall Warnings			Y	Y	Y	
Patrols				Y	Y	Y
3 October 2013	30-Sep	1-Oct	2-Oct	**3-Oct**	4-Oct	5-Oct
Wig-wags			Y	Y	Y	
Heavy Rainfall Warnings			Y	Y	Y	
Patrols						Y

Table 4 (Continued). Detailed Heavy Rainfall Warning, wig-wag and landslide patrol status for periods surrounding debris flow events: the day (or days, where this is not certain) of occurrence is highlighted.

15 January 2014	12-Jan	13-Jan	14-Jan	**15-Jan**	16-Jan	17-Jan
Wig-wags						
Heavy Rainfall Warnings						
Patrols					Y	
23 February 2014	20-Feb	21-Feb	22-Feb	**23-Feb**	24-Feb	25-Feb
Wig-wags	Y	Y	Y	Y	Y	
Heavy Rainfall Warnings	Y		Y	Y		
Patrols		Y				Y
6 March 2014	03-Mar	04-Mar	05-Mar	**06-Mar**	07-Mar	08-Mar
Wig-wags			Y	Y	Y	
Heavy Rainfall Warnings			Y	Y	Y	
Patrols						Y
8 June 2014	05-Jun	06-Jun	07-Jun	**08-Jun**	09-Jun	10-Jun
Wig-wags	Y		Y	Y		
Heavy Rainfall Warnings			Y			
Patrols		Y				
6 October 2014	03-Oct	04-Oct	05-Oct	**06-Oct**	07-Oct	08-Oct
Wig-wags	Y	Y	Y	Y		
Heavy Rainfall Warnings	Y	Y	Y	Y		
Patrols						
28 October 2014	25-Oct	26-Oct	27-Oct	**28-Oct**	29-Oct	30-Oct
Wig-wags	Y	Y	Y	Y		
Heavy Rainfall Warnings	Y	Y	Y	Y		
Patrols		Y	Y			

* These events occurred overnight, hence the uncertainty regarding the day of occurrence.

However, the nature of this debris flow event was somewhat different to those that more typically affect the area. Typically the events start high on the hillside as a small translational slide that enters an existing stream channel and then if there is sufficient water, it erodes material from the stream walls and becomes a debris flow within that channel (more extensive descriptions of this process are given by Winter et al., 2005; 2006; 2009). The December 2011 event, being very close to the road effectively comprised only the translational slide phase and the translational slide itself appears to have been somewhat larger than is typical. It may also be that the six-hour period between the end of the Heavy Rainfall Warning and the switch-off of the wig-wags is insufficient for this type of larger scale translational movement.

Event dated on or before 29 June 2012: It is not known on which day this event which, beyond a few small rocks, did not reach the road occurred (see Table 1). As a Heavy Rainfall Warning was in force on 28 and 29 June these two dates seem to be the most likely dates of occurrence and also this would minimise the amount of time that the event went unobserved and unreported. The rainfall records also support this conclusion with rainfall in excess of the Heavy Rainfall Warning (daily) threshold of 25mm/day on 28 June (around 35mm/day) and rainfall somewhat below that level on 29 June (around 14mm/day); rainfall in the preceding days of 25 to 27 June was somewhat less at around 0, 15 and 8mm/day respectively. Notwithstanding this, the precise date of

occurrence cannot be confirmed with certainty and if, for example, the event occurred on 26 or 27 June then it would be a 'false negative'.

Event dated 15 January 2014: Like the event of 1 December 2011, this was an event that occurred very close to the road (below the level of the debris flow barriers) and approximately 90t reached the carriageway from a shallow translational slide. This is the form of many of the triggering events high on the slope and it may well indicate that the system in place is more effective at warning of the propagation of such events once they reach a stream channel and either become entrained or not. Another possibility is that the failure occurred as a result of disturbance during the installation of the debris flow barriers – while there is no direct evidence of this being the case it is a possibility that should not be completely discounted. A Heavy Rainfall Warning was not in force at the time and the wig-wags were not switched on which means this event must be classed as a 'false negative'.

3.4 Forecasting Considerations

The Scottish Road Network Landslides Study (Winter et al., 2005; 2009; 2013a) set-out the long-term aim of forecasting likely periods of higher landslide hazard. Work to date (Winter et al., 2010) has focussed upon the national rain gauge network and radar data to develop a tentative threshold for debris flow triggering (Figure 13).

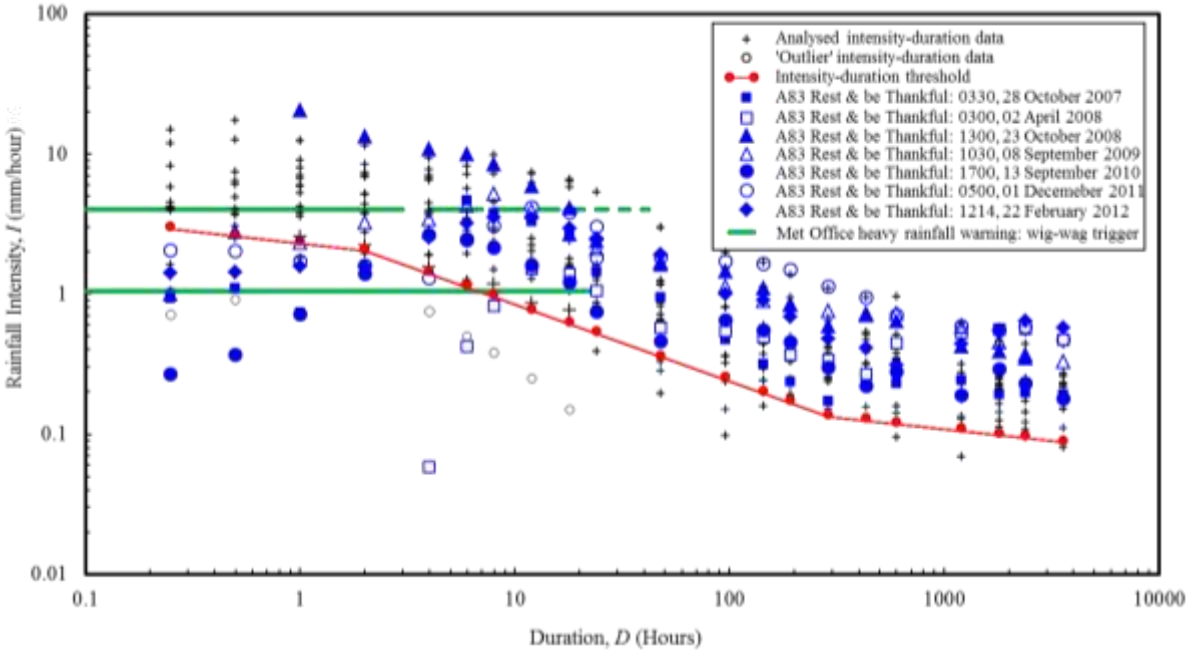

Figure 13. Tentative trigger threshold for Scottish debris flows in terms of rainfall intensity-duration showing events at the Rest and be Thankful that have been used for validation purposes. The wig-wag heavy rainfall warning triggers are also shown.

However, at an early stage it was noted that the rainfall gauge network in Scotland is sparse in areas of interest for debris flow forecasting, not least as the primary function of meteorological observation stations is the collection of synoptic data; simple rainfall stations are more usually used for specific purposes related to water resources and hydroelectric power, for example. In addition, while the rainfall radar system covers some of the areas of interest at a resolution of 2km, most are resolved at just 5km,

sufficient for the primary function of the weather radar network in monitoring precipitation patterns and their movement as input to general weather forecasting. Additionally, issues surrounding the performance of radar rainfall in mountainous, and indeed other, areas appear to be some way from being fully resolved. Roberts et al. (2009) state, in relation to an analysis performed in an area with 5km radar resolution that "… rainfall amounts estimated by the [UK] radar network were generally less than those measured by gauges and distributed somewhat differently".

In addition, comparison of the threshold in Figure 13 with similar thresholds from other parts of the world indicates that it may underestimate the amount of rainfall required to trigger debris flows (Figure 14). Indeed, the work by Cannon et al. (2007) on debris flow triggering in areas that have been subject to wild fires appears to support this. In such areas debris flows are generally considered to trigger with relatively little rainfall due to the hydrophobic nature of the ash left after the fires. The tentative rainfall threshold for Scotland suggests triggering at lower rainfall levels than those that would be expected to trigger debris flow in areas subject to wild fires (Figure 14). Notwithstanding this the rather short threshold for wildfires in Figure 14 also indicates that these events are caused by short duration/high intensity rainfall with relatively little influence from longer duration/lower intensity (antecedent) rainfall.

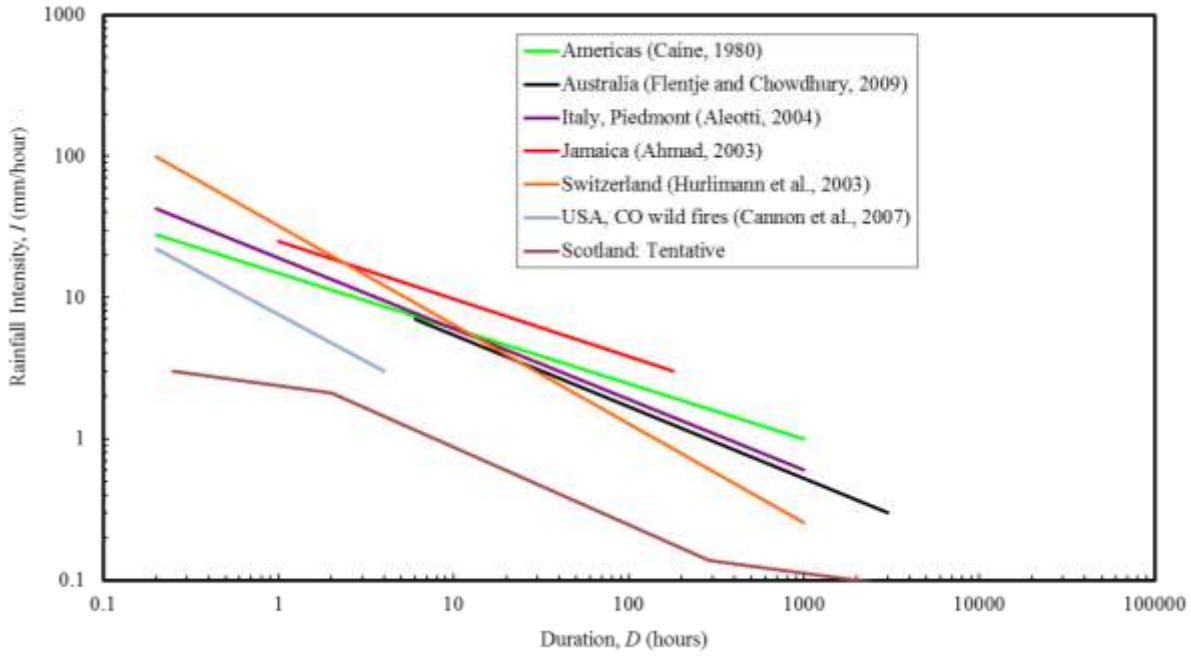

Figure 14. International rainfall intensity-duration trigger thresholds for rainfall-induced landslides showing the tentative threshold reported by Winter et al. (2009; 2010).

This may well be due to the fact that the rain gauge network in the UK generally and, more specifically, in landslide-prone areas of Scotland is not intended to provide data for the purpose of forecasting periods when landslides are more likely to be triggered by heavy rainfall.

Accordingly, two rainfall gauges were installed on land close to the A83 at the Rest and be Thankful and were commissioned on 29 April 2012. These were paid for by Transport Scotland but are operated by SEPA (see Figure 14). Ongoing work on rainfall thresholds will utilise the data from these rain gauges and assess rainfall events that do and do not coincide with debris flow events. This will allow the ongoing development of the tentative

rainfall threshold to better enable the forecast of likely periods of debris flow activity. The tentative threshold requires further consideration, validation and testing prior to the development and implementation of a procedure for its use in terms of issuing warnings of increased likelihood of landslide activity. It has been estimated that, given the frequency of such events in Scotland, around five years' worth of data may be required (Winter et al., 2009; 2010).

3.5 Discussion

There are four major considerations with respect to the technical evaluation of the wig-wag signs. These are as follows:

1) Periods when the wig-wags were switched on and a debris flow did not occur ('false positives').

It is clear from Table 2 that there was a significant number of 'false positives' and that these were of significant duration. With a forecast system of this nature, particularly one that is under trial and subject to ongoing development, 'false positives' are to be expected. There seems little doubt that given time the forecast values used to initiate switch-on of the wig-wag signs can be improved as set-out in Section 3.4. However, as also set-out in Section 3.4, this will take some time. The wig-wags were switched on for between 12% and 19% of the year when the switch-on period did not contain a debris flow event, for the years 2011 to 2014.

2) Debris flow events that occurred when the wig-wags signs were switched on.

A total of 17 debris flow events occurred during the four year period 2011 to 2014 in the Rest and be Thankful area. Of these, 13 occurred when a Heavy Rainfall Warning was in force and the wig-wags were switched on. A further two events (February 2011 and June 2012) seem most likely to have also occurred during the preceding warning period when the wig-wags were switched on although this cannot be confirmed with complete certainty as the debris flow did not reach the road. This would suggest that the events occurred around 12 days (February 2011) and between zero and one days (June 2012) prior to their discovery which, as neither reached the road and were therefore not easily observable, seems reasonable.

3) Debris flow events that occurred when the wig-wag signs were switched off ('false negatives').

The final two debris flow events (December 2011 and January 2014) occurred during a period when there was no Heavy Rainfall Warning in force and the wig-wag signs were not switched on. The possible reasons for this are discussed in Section 3.3 and centre around the somewhat different nature of these events compared to the more typical small translation slides that trigger debris flows high on the hillside. With respect to the December 2014 event, it is considered that the post-Heavy Rainfall Warning period during which the wig-wags remain switched on may benefit from being increased from the six hours at which it is currently set. It is recommended that this period be extended to 12 hours on a trial basis. While this is likely to improve the record by reducing the number of 'false negatives', inspection of Figure 9 reveals that there had been significant heavy rainfall in the preceding days and there may be a need for the current six hour period to be flexible depending upon the antecedent conditions. Introducing such flexibility is fraught with difficulties. Further development

work to refine the tentative rainfall intensity-duration threshold described in Section 3.4.

The above suggests that the wig-wags were switched on at the time of occurrence of almost 90% of the debris flow events at the Rest and be Thankful during the four-year period examined.

4 Perceptual Evaluation

The perceptual evaluation was reported in detail by Winter et al. (2013b) and only a summary is reported here.

The aim of this aspect of the research was to establish the impact of the installation of landslide wig-wag signs on the A83 Rest and be Thankful on driver behaviour and attitudes. A survey design was utilised to measure drivers' speed choice in response to a range of driving scenes including landslide and other wig-wag signs, whereby speed choice was considered a proxy for behavioural response. Road scenes were matched and digitally altered to allow direct comparison of participant responses where the sign was active (i.e. flashing), not active, and removed from the scene. Additional survey questions were asked. The face-to-face survey sought to answer the following research questions:

1. What is the effect of installing a landslide wig-wag sign on drivers' self-reported behaviours?
2. What effect does the type of sign (e.g. landslide wig-wag sign versus other wig-wag warning signs) have on drivers' behaviours?
3. What do drivers report they would do if they passed a wig-wag sign when the lights are flashing?
4. What do drivers think they should do if they pass a wig-wag sign when the lights are flashing?
5. Do drivers think the signs make the road safer and do drivers take the precautions that Transport Scotland publicised?
6. Are there differences between local and non-local drivers?

Overall results indicate that there is no effect on drivers' speed choice resulting from the presence of an inactive landslide wig-wag sign, and that the effect of activating the flashing lights on a landslide wig-wag sign is a reduction in chosen speed. This is a desirable outcome as it suggests that the installation of the signs has not resulted in any unexpected behavioural response from drivers and that drivers are responding as anticipated when the signs are activated (i.e. they are taking more care). This result was apparent for both local and non-local drivers, although non-local drivers' speed reductions to flashing landslide wig-wag signs are more pronounced. It should be noted that the pattern of responses to the flashing wig-wag landslide signs is not entirely consistent across all settings; in one of the four settings, speed choice was shown to increase with the presence of the landslide wig-wag sign with flashing lights. It is not clear why this setting would lead to such a behavioural response and further elucidation of the finding by testing a wider range of sign settings could be considered.

While the overall findings suggest that drivers' behavioural response to landslide wig-wag signs is in the desired direction (i.e. drivers reduce speed in response to a flashing landslide wig-wag sign) results indicate that the reduction in speed is not to the same magnitude as the reduction in speed to other wig-wag warning signs. Drivers' reduction in stated speed to both flashing ice warning and school wig-wag signs was found to be greater than that of landslide wig-wag signs. These differences by sign type could be for a number of reasons. For example it might suggest that drivers are uncertain of the correct response to a flashing landslide wig-wag sign and do not consider the risk of a landslide to be as immediate as that of either ice on the road or school children being

present. This interpretation is supported by what drivers report they would do if they passed a wig-wag sign when it was flashing. Almost every respondent reported that they would reduce their speed upon seeing a flashing school wig-wag sign, and 85% of respondents would slow down in response to a flashing ice warning wig-wag sign. In comparison, only 68% of respondents reported that they would slow down for a flashing landslide wig-wag warning sign. Interestingly, 13% of respondents reported that they would turn around or stop upon seeing a flashing landslide wig-wag sign and 2% of respondents reported that they would speed up. The lower consistency in stated responses for flashing landslide wig-wag signs suggests that the link between the risk factor being signalled (landslides) and the desired behavioural response (slow down) is not as obvious as it is for the 'ice' and 'school' risk factors. Presumably this is due to the immediacy of the threat in the landslide setting being less obvious than in the 'ice' and 'school' settings.

A similar pattern is present in the beliefs drivers stated about what they thought they *should* do when seeing a flashing landslide wig-wag sign. One-hundred per cent of drivers reported that they *should* slow down when passing a flashing school wig-wag sign. This drops to 92% of drivers for a flashing ice warning wig-wag sign and drops further to 83% for a flashing landslide wig-wag sign. A proportion of drivers believe that the correct response to passing a flashing wig-wag sign is to continue at the same speed (5%), turn around (5%), stop (5%) or speed up (1%). This is consistent with the proportions who report that this is what they *would* do and suggests that some drivers are unaware of the desired response, specifically for the landslide wig-wag signs. Further analysis revealed that this group of drivers are largely non-locals and may have therefore missed out on any marketing material disseminated when the signs were installed. It is possible that their behavioural response is a result of a lack of knowledge of the desired response rather than a deliberate act of non-compliance.

Of participants who drove the road regularly, the majority (71%) reported that they agreed that the signs had made the road safer (34% strongly agreed) although 18% disagreed with this statement (7% strongly disagreed). Over half of these drivers also reported following Transport Scotland's guidelines when using the A83 to check the weather forecast, allow extra time for their journey and listen to travel updates on the radio.

5 Conclusions and Recommendations

This report presents an evaluation of a trial of the use of wig-wag signs as a temporal warning of a higher risk of rainfall-triggered debris flow events on the A83 in the area centred on the Rest and be Thankful. This locality is known for the frequency with which debris flow events occur, much more than any other part of the trunk road network in Scotland. It is thus well-suited to the use of this type of temporal warning. The potential application of this approach to other parts of the network is limited and any proposals should be the subject of detailed location-specific assessment.

Seventeen debris flow events occurred during the period 2011 to 2014 in the Rest and be Thankful area. Thirteen of those occurred during periods when a Heavy Rainfall Warning was in force and the wig-wags were switched on and two more were most likely contained within that group, albeit that there is some doubt about the precise timing of these events.

The final two events occurred during periods when there was no Heavy Rainfall Warning in force and the wig-wag signs were switched off ('false negative'), the different nature of these events as set out in Sections 3.3 and 3.5 go some way towards may explaining this.

The above suggests that the wig-wags were switched on at the time of occurrence of almost 90% of the debris flow events at the Rest and be Thankful during the four-year period examined.

Nevertheless, there was a significant number of 'false positives'. These are to be expected with a system of this nature, particularly one that is under trial and subject to ongoing development. The wig-wags were activated during the period 2011 to 2014 on between 12% and 19% of the days of the year when the switch-on period was not associated with a debris flow event. There seems little doubt that the forecast values used to initiate switch on of the wig-wag signs can be improved as set-out in Section 3.4, albeit that this will take some time.

It should be noted that, work to further develop the currently tentative rainfall intensity-duration debris flow threshold is ongoing. That work is an important part of Transport Scotland's continuing programme of work on landslides for reasons that go beyond the operation of wig-wags. As part of this work a review of the post-Heavy Rainfall Warning period during which the wig-wags signs remain switched on should be undertaken. At the appropriate time the activation of the flashing lights on the wig-wag signs should be tied to the intensity-duration threshold rather than the Met Office Heavy Rainfall Warnings.

The results of the survey undertaken to evaluate driver perception of the wig-wags signs have established that overall, the installation of landslide wig-wag signs on the A83 does not appear to have had any negative effect on drivers' behaviour (as measured by speed choice) overall. Both local and non-local drivers who have experience of driving the A83 reported slower speed choice on average when landslide wig-wag signs are flashing, with non-local drivers reducing their speeds more than local drivers on average.

The evidence from both the technical and perceptual evaluations indicated that the wig-wag signs trial has a satisfactory outcome and that the flashing lights prompt generally desirable behaviours in the majority of cases. Notwithstanding this, there are areas for improvement and specific recommendations are made below.

It was recommended in the earlier report (Winter et al., 2013) that the wig-wag sign installations continue to be maintained and operated, and that the practice of notifying, on the Traffic Scotland website, the periods when the signs are activated be ceased; a recommendation that was implemented circa 2013.

Based on the two 'false negative' events (when a debris flow occurred but a Heavy Rain Warning was not in force and the wig-wags were not switched on) it is recommended that the post-Heavy Rainfall Warning period of wig-wag switch on be extended from six hours to 12 hours on a trial basis.

The evidence presented in this report supports the continued use of the wig-wags and the continued promulgation of messages about desired behaviours to the non-local driver target audience.

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