APPENDIX H – DEVELOPMENT OF A RAINFALL TRIGGER THRESHOLD FOR DEBRIS FLOW

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H.1 METHODOLOGY AND SAMPLE RESULTS

Records of debris flow events identified by members of the Working Group were scrutinized for their suitability in terms of undertaking an analysis of the rainfall leading up to their occurrence. This produced a set of 16 events each of which met more than one of the following criteria:

- The debris flow had caused disruption at a known road location.
- The timing of the debris flow was relatively well-defined (in some cases, on main routes, there was good knowledge of timing).
- There was good coverage at the site of rainfall data from both gauges and radar.

The coverage of radar was considered of importance, as it is likely that any future general predictive model may rely more strongly on radar data. This is because rain gauge distribution in the Highlands and Islands is sparse, particularly tipping bucket rain gauges reporting by telemetry (Anon, 2006b) – which would be necessary for real-time information gathering.

The following rainfall information was extracted from records for each of the 16 events.

- Daily rainfall from the three stations closest to the location of the landslide, for a period of 150 days prior to the event. The rain gauges were selected based on the NGR of the debris flow: for each station a distance and bearing from the landslide location is given.
- Hourly rainfall from the tipping bucket rain gauge (TBR) closest to the landslide location for the 4-5 day period covering the time of the event. Distance and bearing information is also given.
- Radar measurements of rainfall intensity at intervals of five minutes (for 2km pixels) or 15 minutes (5km pixels) for the pixel square that includes the debris flow location. Similarly to the TBR data, the radar data covers a period of two to three days previous to and including the storm event.
- Radar measurements of rainfall intensity for a three by three array of pixels, which includes the debris flow location pixel at its centre.

Rain gauge data is summarised in Table H.1 and the location of debris flows and rain gauges, along with the coverage from Met Office weather radar installations is give in Figure 9.5.

Analyses of the storm events were carried out, generally for a period of 18 hours, and also for an antecedent period of 150 days prior to the event. The method is described below, in Section H.1.1, using the results for Event 1 as an example. The results for all 16 events analysed are presented in summary form and discussed in Section H.2.

Where possible, the storm rainfall information was analysed back from the point when the debris flow occurred, the assumption being that this time marks a point when an intensity or accumulation threshold which causes the debris flow process to occur had been reached. This information was not available for all events, so an initial time had to be chosen from the period of most intense rainfall. The hourly rainfall data from the most relevant TBR were examined to establish an initial starting point.

Table H.1 – Summary of information available for all analysed events.

Event Number, Location, Date (month/year)	NGR and Road Number	Daily Rain gauge Locations (Distance, km and bearing from landslide location)			Hourly Rain Gauge Location	Max. Hourly Rainfall, mm (gauge)	Time, Date of Max. Rainfall (gauge)	Max. Hourly Rainfall, mm (radar)	Time, Date of Max. Rainfall (radar)
		1	2	3					
1. L Carron, Strome-ferry Bp (10/01)	NG 910373: A890	Loch Carron (2.7 NNW)	New Kelso (6.4 NNE)	Plockton (11.5 WSW)	Lusa, Skye (24.0 SW)	3.6	1000, 30/10	5.8	1500, 29/10
2. Glen Croe, Rest & be Thankful (01/03)	NN 235071: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	5.4	0400, 25/01	6.7	0400, 25/01
3. Glen Croe, Rest & be Thankful (11/03)	NN 234072: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	7.4	0900, 29/11	10.5	1100, 29/11
4. Glen Croe, Rest & be Thankful (01/04)	NN 235070: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	3.0	1800, 18/01	5.4	1800, 18/01
5. Laide, Wester Ross (02/04)	NG 901924: Uncl	Sand 2 (1.2 SE)	Aultbea (5.6 WSW)	Poolewe (11.3 SSW	Aultbea (5.6 WSW)	4.6	0600, 05/02	2.7	0600, 05/02
6. Glen Kinglas (08/04)	NN 208096: A83	Clachan P.S. (3.7, NNW)	Glenfyne Lodge (6.0, N)	Lochgilpead (8.0, S)*(1)	Sloy (11.3, E)	9.4	2200, 08/08	13.7	2200, 08/08
7. Cairndow, Glenfyne (08/04)	NN 186115: A83	Clachan P.S. (1.8, NNE)	Glenfyne Lodge (5.3, NE)	Allt na Lairige (8.6, NE)*(2)	Sloy (13.6, E)	9.4	2200, 08/08	14.1	2200, 08/08
8. Dunkeld, Perth (08/04)	NO 005443: A9	Inver No.2 (2.5, SSE)	Meikle Tombane (7.0, SW)	Ballinluig (9.4, NNW)	Faskally (17.8 NNW)	17.6	1200, 09/08	13.1	1200, 09/08
9. Glen Ogle, Lochearnhead (08/04)	NN 573266 (N) / NN 576262 (S): A85	Killin, Mone-more (5.6, N)	Strathyre S.Wks. (10.0, S)	Ardtalnaig (18.1, NE)	Tyndrum No. 3 (21.4, W)	6.2	1100, 18/08	12.7	1700, 18/08
10. Pitcalnie, Easter Ross (08/04)	NH 804722: U150A	Tain Range (10.9, N)	Gleanies House (11.5, NE)	Hill of Fortrose (16.6, SSW)	Tain Range (10.9, N) *(3)	12.8	0400, 19/08	5.7	0200, 19/08
11. Eathie, Black Isle (08/04)	NH 775643: U231	Hill of Fortrose (8.3, SSW)	Nairn, Dunbar (13.9, ESE)	Tain Range (19.3, NNE)	Tain Range (19, NNE)	4.0	1600, 18/08 & 0500, 19/08	4.1	0100, 19/08
12. Avoch-Fortrose, Black Isle (10/04)	NH 717559: A832	Hill of Fortrose (1.9, NE)	Allangrange Hse (9.5, WSW)	Inverness (10.8 SSW)	Tain Range (29.0, NNE)	5.6	08:00, 21/10	3.8	0700, 21/10
13. Cnoc Fhionn, Shiel Br/Glenelg (12/04)	NG 876198: C46	Nostie (7.8, NNW)	Achnagart (9.7, ESE)	Plockton (15.4, NNW) *(4)	Skye Lusa (17.7, WNW)	5.6	07:00, 06/12	5.8	1100, 06/12
14. Letterfinlay, Loch Lochy (01/05)	NN250912: A82	Clunes Forest (5.3, WSW)	South Laggan no.3 (7.2, NE)	Braeroy Lodge (8.7, E)	Tulloch Bridge (16.3, SE)	5.0	19:00, 06/01	8.0	0300, 07/01
15. Inverinate-Morvich (09/05)	NG 944212: U152W	Achnagart (6.3, SSE)	Plockton (18.6, NW)	No Gauge	Skye Lusa (24.0, W)	15.6	17:00, 13/09	7.5	1600, 13/09
16. Kylerhea Glen, Skye (09/05)	NG 775208: C72	Skye Lusa (8.0, WNW)	Broadford, Rockbank (12.5, W)	Plockton (12.0, N)	Skye Lusa (8.0, WNW)	15.6	17:00, 13/09	5.0 (4.6)	0900, 13/09 (16:00, 13/9)

Timing for hourly rain gauge and radar maxima is for hour-ending. *Additional rain gauge information
(1) Allt Na Lairige (8.7, NNE). (2) Lochgilphead (10.0, S). (3) Kinloss (30.0 ESE). (4) Skye Lusa (17.7, WNW).

However, because the TBR rain gauge was, in most cases, at some distance from the landslide location (sometimes in excess of 20 km), the hourly radar rainfall record at the radar pixel covering the debris flow location was also inspected to select the timing of the maximum fall. This information is recorded in Table H.1. Where a clear start time from either rainfall intensity or time of debris flow events was not readily identifiable, this may have introduced some discrepancy in the results; to some extent this has been taken into account in the interpretation of the results. The detailed examination of storm rainfall depth and intensity is made using the radar data from the pixel containing the landslide location. Radar pixels cover fixed grid locations on either a 2 km or 5 km grid, depending on the distance from the observing radar. The coverage of the rainfall radar network in Scotland is shown in Figure 9.5. Although there are a number of ways in which errors can arise in radar rainfall estimation, it is considered that using radar represents a consistent approach. The use of TBR data introduces the problems that the gauge locations are variable in respect of landslide location and intervening topography, as well as distance and aspect. This, in addition to any movement in the rain producing system, may introduce unquantifiable errors in quantity and timing.

H.1.1 Results for Event 1

The radar data were processed to provide the cumulative rainfall from the storm event, and the average intensity over the various fixed intervals, as shown in Table H.2.

Table H.2 – Storm rainfall summary for radar pixel at Stromeferry, Loch Carron, Event 1.

Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
Total Rainfall (mm)	1.7	3.0	5.9	11.3	13.5	15.6	15.8	28.0	47.5
Rainfall intensity (mm/hr)	6.6	5.9	5.9	5.7	3.4	2.6	2	2.3	2.6

The rainfall intensity was divided by mean annual precipitation (1961-1990) to provide the intensity/MAP function shown in Table H.3.

Table H.3 – Storm rainfall summary for radar pixel at Stromeferry, Loch Carron, Event 1.

Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
Intensity/MAP	0.339	0.303	0.303	0.293	0.175	0.134	0.103	0.118	0.134

Mean annual precipitation values were provided by the Met Office for two standard periods 1961 to 1990 and 1971 to 2000. The value used in calculations is that for the closest daily rainfall station, for the 1961 to 1990 period. There are some differences in the figures for the two periods: the former was chosen as there is a view that this figure is less influenced by the extremes experienced in the 1990s, and may be less affected by the early manifestations of human-induced climate change. For the reference rain gauges used, the 1971 to 2000 average is consistently greater than the 1961 to 1990 average by between 3% and 5%, which will not however have a significant influence on the intensity/MAP values.

The analysis of the antecedent daily rainfall was carried out by calculating cumulative rainfall totals over fixed periods prior to the date of the debris flow event. Where possible the analysis of the antecedent daily data was carried out for the rain gauge nearest the debris flow location. Where this gauge had missing data, data for the next nearest rain gauge were used. Table H.4 shows an example of the antecedent data tabulation.

Table H.4 – Antecedent rainfall and intensity, New Kelso daily rain gauge, Event 1.

Antecedent days	1	2	4	6	8	12	18	25	50	75	100	150
Rainfall total (mm)	33.4	39.6	61.4	66.2	70.0	74.0	96.0	152.6	270.8	415.0	516.0	674.6
Intensity (mm/hr)	1.39	0.83	0.64	0.46	0.36	0.26	0.22	0.25	0.23	0.23	0.22	0.19
Intensity/ MAP (%)	0.0715	0.0424	0.0329	0.0236	0.0187	0.0132	0.0114	0.0131	0.0116	0.0178	0.0221	0.0289

Three analyses were carried out on the daily rain gauge data. Firstly, the interval data were reversed to give an incremental total commencing at T-150 (Day 0) up to the day before the debris flow event (e.g. Table H.5). Secondly the interval data was converted to an average intensity over the relevant period (mm/hr). Finally the intensity was converted to a dimensionless function, intensity/MAP by dividing intensity by the mean annual precipitation (MAP), the result being expressed as a percentage (see Table H.4).

Table H.5 – Antecedent rainfall (from T-150 days), New Kelso daily rain gauge, Event 1.

Day	0	50	75	100	125	132	138	142	144	146	148	149
Incremental rainfall (mm)	0.0	158.6	259.6	403.8	522.0	578.6	600.6	604.6	608.4	613.2	635.0	641.2

The data contained in Tables H.2 to H.5 are also presented graphically. Figure H.1 shows the plots for storm rainfall, as accumulation and average intensity (Table H.2). Figure H.2 shows cumulative antecedent rainfall (Table H.5). Figure H.3 shows a log-log plot of intensity against duration for the combined storm and antecedent period (Tables H.2 and H.4). Figure H.4 is a log-log plot of the intensity function and combines storm and antecedent intensity data (Tables H.3 and H.4). Where feasible, a best-fit straight line was fitted.

Because radar data were used for the storm period analyses, spatial variability was examined by comparison with a three-by-three array of local radar pixels. Radar information was extracted at five or 15-minute intervals, as appropriate to the distance from the radar source. A data array for the storm duration was also analysed for the same time intervals as the intensity and accumulation analyses. Tabulations for each storm were prepared, as shown in Table H.6. The data from Table H.6 is presented graphically to compare the 18-hour accumulation in the grid array, as in Figure H.5. The location of the landslide is shown in the central pixel (5) in Figure H.5. Further data from the other events are presented in H.2.1.

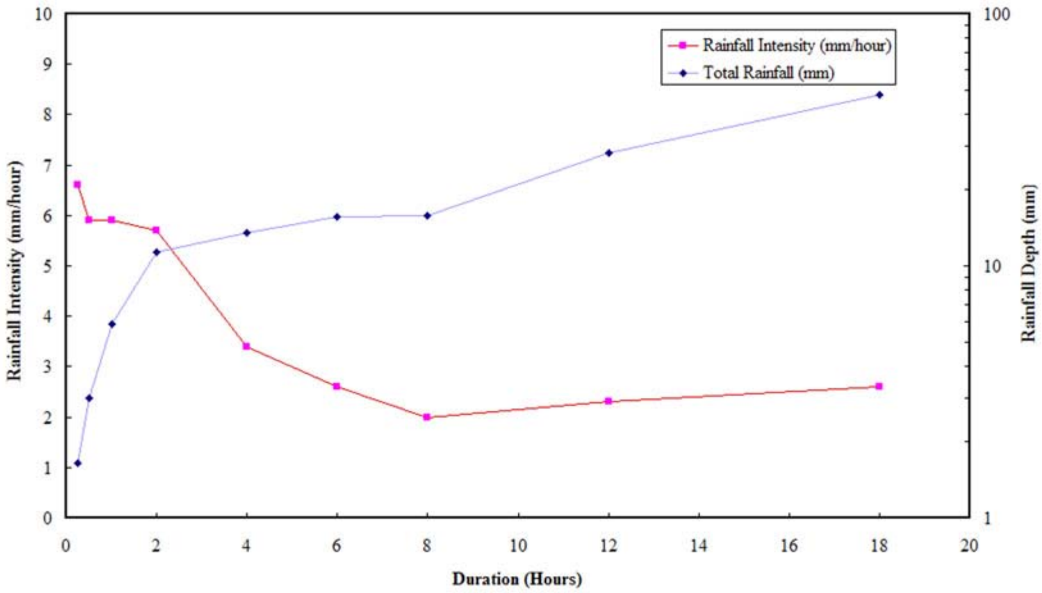

Figure H.1 – Storm Rainfall Intensity and Accumulation, 5 km radar for Event 1.

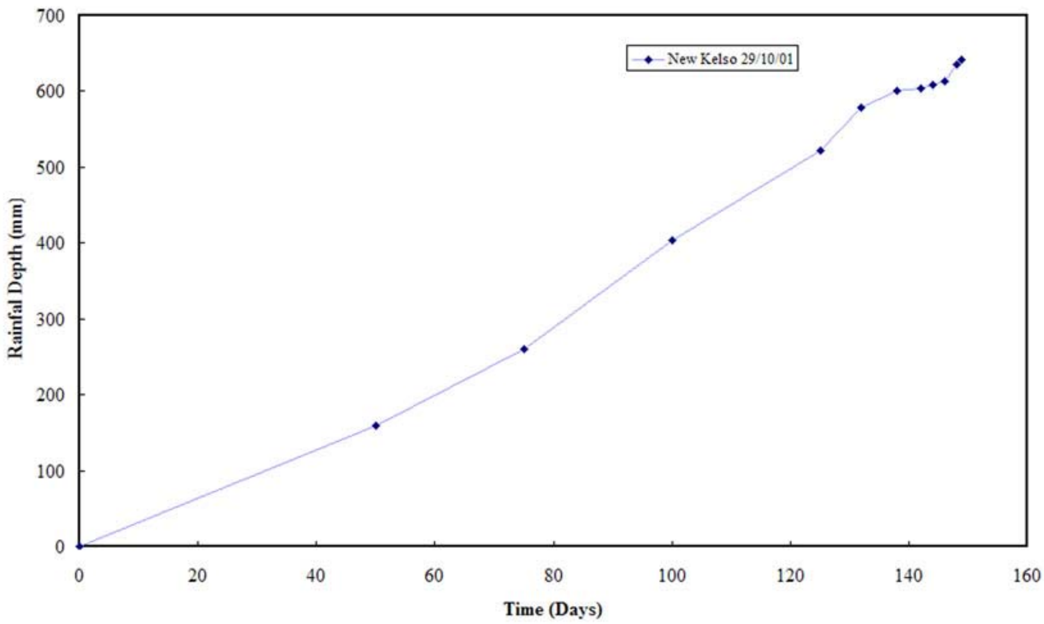

Figure H.2 – Graph of Cumulative Antecedent Rainfall, Event 1.

Table H.6 – Storm rainfall accumulation (depth-mm and duration) for each radar pixel.

Pixel / Duration	1	2	3	4	5	6	7	8	9
18 hour	56.3	31.3	67.6	52.4	47.6	54.0	50.5	40.7	88.3
12 hour	33.0	17.5	34.1	31.8	28.0	30.3	31.5	25.4	49.4
8 hour	19.8	10.4	16.8	18.4	15.8	16.6	17.9	14.8	26.8
6 hour	19.6	9.8	16.8	18.2	15.7	16.6	17.9	14.8	26.8
4 hour	17.5	8.8	13.8	15.5	13.4	13.2	13.6	11.8	22.1
2 hour	15.2	7.3	12.7	11.6	11.3	12.3	11.6	9.4	19.4
1 hour	7.7	3.9	6.5	6.0	5.9	6.4	5.9	4.8	10.0
30 minutes	4.2	2.0	3.4	3.1	3.0	3.2	2.9	2.3	5.0
15 minutes	2.2	1.1	1.7	1.7	1.6	1.7	1.5	1.3	2.5

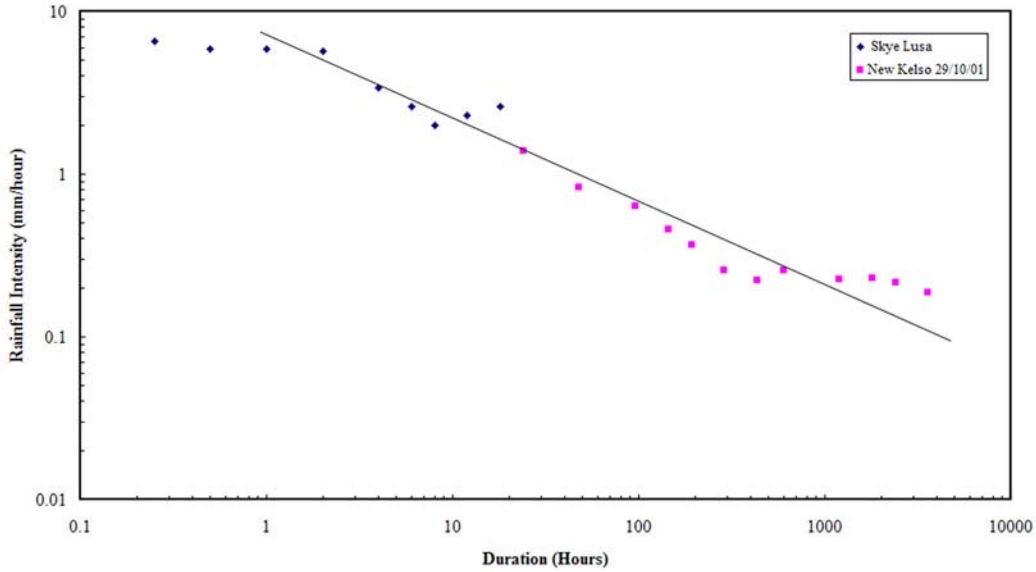

Figure H.3 – Combined storm and antecedent period rainfall intensity, Event 1.

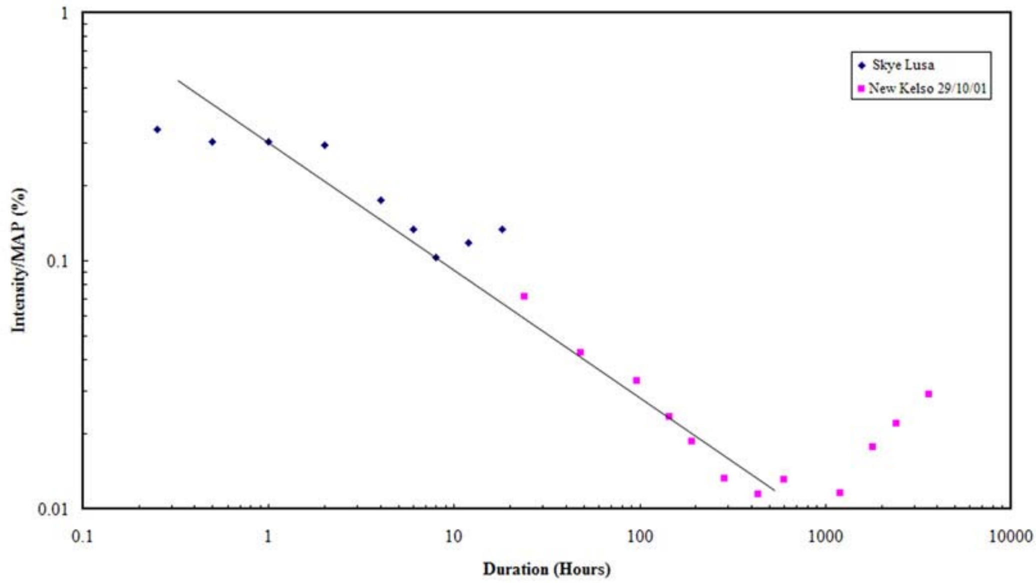

Figure H.4 – Intensity/MAP Function for storm and antecedent period, Event 1.

H.2 DISCUSSION OF RESULTS

The individual tables and graphs for Events 2 to 16 are not presented here, in the interests of conciseness. Summary data are tabulated in Section H.2.1 and presented graphically in both Section H.2.1 and in Figure 9.6. The data from Table H.6 is presented graphically to compare the 18-hour accumulation in the grid array, as in Figure H.5.

In discussing the analysed data it is important to recall the purpose of the analysis, namely to identify a lower threshold of rainfall intensity, across a range of rainfall durations, and which then defines the conditions likely to lead to debris flow events. Thus when examining any set of data it is important that scatter and 'outliers' on the low part of the graph are identified and dealt with as such. However, any 'outliers' amongst the high rainfall-intensity data have no influence on the threshold being developed and are therefore of relatively little significance in this exercise.

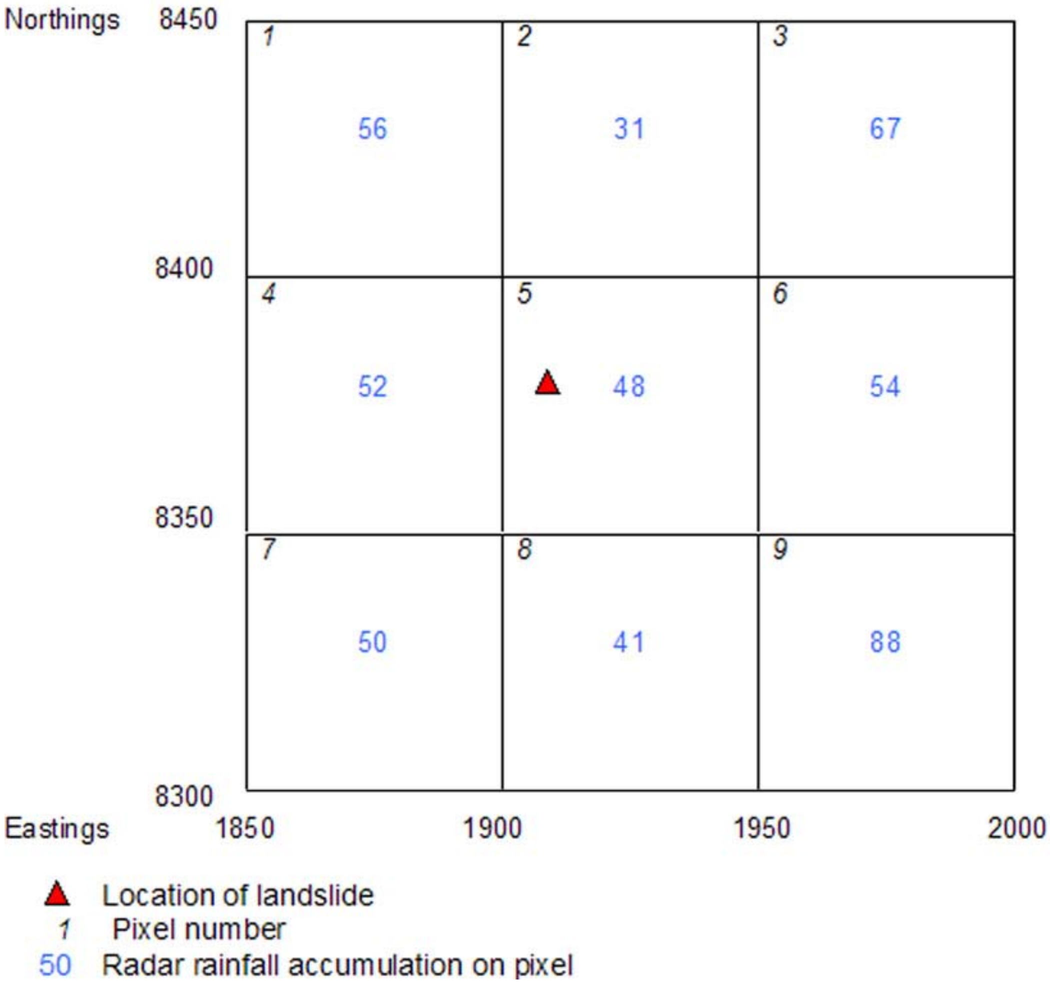

Figure H.5 – Grid analysis for 18-hour rainfall, Event 1.

H.2.1 General Discussion of Results

As might be expected, no consistent pattern emerged from the various analyses to identify what might be considered a typical event. Some events contained high intensity storm rainfalls, but many did not. Similarly there were some very high antecedent rainfall totals associated with events, especially for winter events. On the other hand, there were some – mostly summer events – where, although antecedent totals were high, the period closest to the storm did not contain high rainfall quantities. It may however be informative to compare summary statistics from the events, in anticipation that they may provide possible indicators for a future predictive approach (Table H.7).

Note that in Table H.7, the maximum intensity value is that for a five-minute radar measurement at the location of the pixel within the two hour period before the nominated event start-time.

The intensity-duration relations have been arranged in a number of combined plots. Figures H.6 and H.7 show the grouping of Events 1 to 8 and 9 to 16 respectively, largely to allow the use of symbols to identify the different events. Figure 9.6 combines the intensity-duration data as a scatter diagram (i.e. without recourse to the identification of the different events). It is this diagram and data that is used to determine the intensity-duration threshold. Overall, there was good grouping of data from most events: some of the data from below 1-hour (i.e. at the start of the storm) form outliers. Only Event 5 (Figure H.6) and Events 13 and 14 (Figure H.7) produced relations that plot separately from the rest of the group over a significant portion of the duration of the range. Indeed the data for Event 14 being of high intensity will not influence the trigger threshold selection process. The near event data (<1hour) for Event 12 also plots in a seemingly anomalous juxtaposition to the rest of the data (Figure H.7).

Table H.7 – Summary statistics from all events.

Event No.	Max. Storm Intensity (mm/hr)	Ave. Intensity 0-2hrs (mm/hr)	Ave. Storm Intensity, 18 hrs (mm/hr)	Antecedent 4-Day Rainfall (mm)	Antecedent 12-Day Rainfall (mm)	Antecedent 50-Day Rainfall (mm)
1	6.6	5.7	2.6	70.2	90.4	328.0
2	8.6	5.14	2.61	46.4	141.8	213.2
3	10.2	7.01	1.56	50.1	156.1	277.9
4	8.9	5.19	1.19	34.6	195.3	476.5
5	6.6	2.22	0.77	77.8	110.8	379.9
6	23.4	8.39	5.75	62.3	70.7	300.8
7	50.0	11.42	6.37	62.3	70.7	300.8
8	7.0	3.71	1.64	144.5	183.2	285.8
9	44.8	12.35	2.37	22.7	121.6	231.7
10	10.6	4.4	1.55	34.2	38.8	82.8
11	7.8	2.75	1.25	63.8	67.6	153.0
12	4.4	1.94	1.03	18.4	51.9	177.9
13	3.1	1.41	0.15	76.9	118.4	513.3
14	9.4	7.33	6.59	189.7	317.3	742.5
15	9.6	6.81	1.78	9.3	38.8	329.6
16	5.7	3.75	1.21	30.6	49.0	294.0

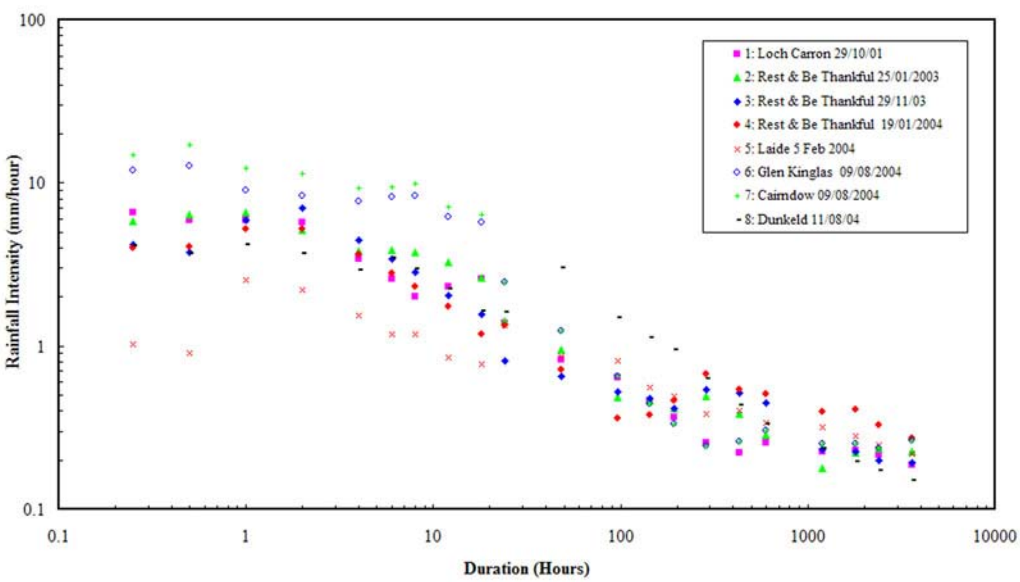

Figure H.6 – Combined plot of intensity versus duration for events 1 to 8.

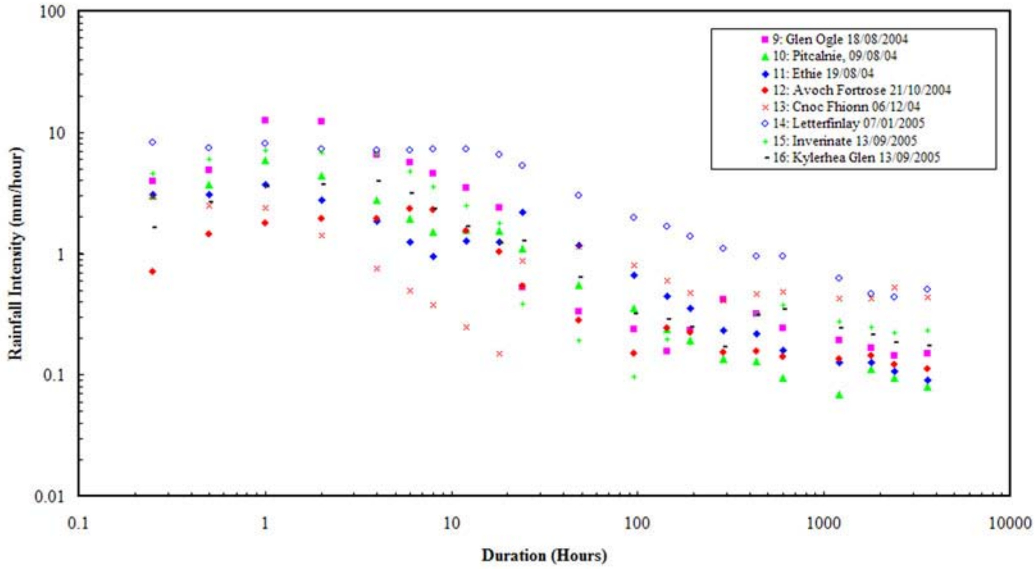

Figure H.7 – Combined plot of intensity versus duration for events 9 to 16.

As has been previously noted (Section 2.4), the occurrence of landslide events in Scotland may show some degree of seasonality, with events concentrated in late-summer (August-September) and in winter (November to February). Combined plots of intensity-duration relations for these sets of storms are shown in Figures H.8 and H.9. The single October event has been placed in the 'winter' set.

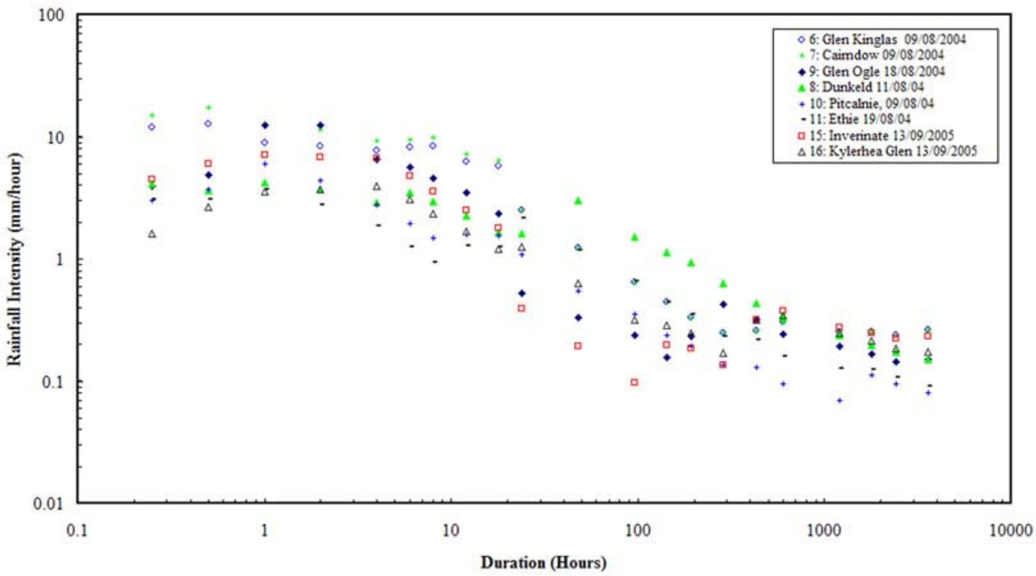

Figure H.8 – Combined plot of intensity versus duration for late summer storms.

Good grouping was achieved over the 'core' part of the time range, from two hours to 1,000 hours. At the early time ranges, the scatter was generally less that in the later time ranges, which may be explained by inaccuracies in the estimated time of the landslide events or, indeed, in terms of the maximum rainfall intensity. It may also be that the rainfall events did not contain very high, short-duration intensities. This is often a feature of rainfall systems over Scotland, in contrast to the higher intensities often experienced in southern England, which are associated with greater convective activity. The Inverinate data (Event 15) included some outliers in the 10 to 100 hour range, and also at the longer time ranges. The scatter tends to become wider at the longer time ranges, which is to be expected, as this period covers mid-summer, where extended dry periods can occur and would provide irregularities.

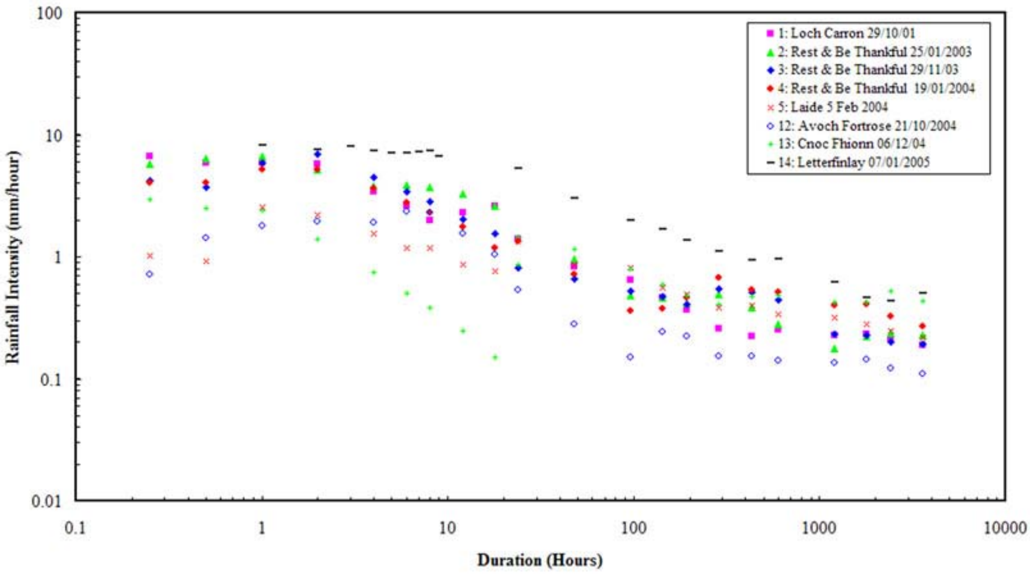

Figure H.9 – Combined plot of intensity versus duration for winter storms.

The winter data indicated less and more consistent scatter over the core range for most of the events, although there were some notable outliers above (Letterfinlay, Event 14), and below (Cnoc Fhionn, Event 13, and Avoch Fortrose, Event 12) the main group. The sub-2-hour data did not fit well with the rest of the relation, for the same reasons as mentioned above.

The influence of the wide difference in mean annual precipitation (MAP) between eastern and western locations has been noted in the discussion of individual events. Landslides in the Black Isle and Easter Ross locations have occurred in association with small-magnitude storm events in comparison other locations, and these may be the result of site influences, rather than rainfall. Plots have however been produced for groupings of ‘east’ and ‘west’ locations, in Figures H.10 and H.11.

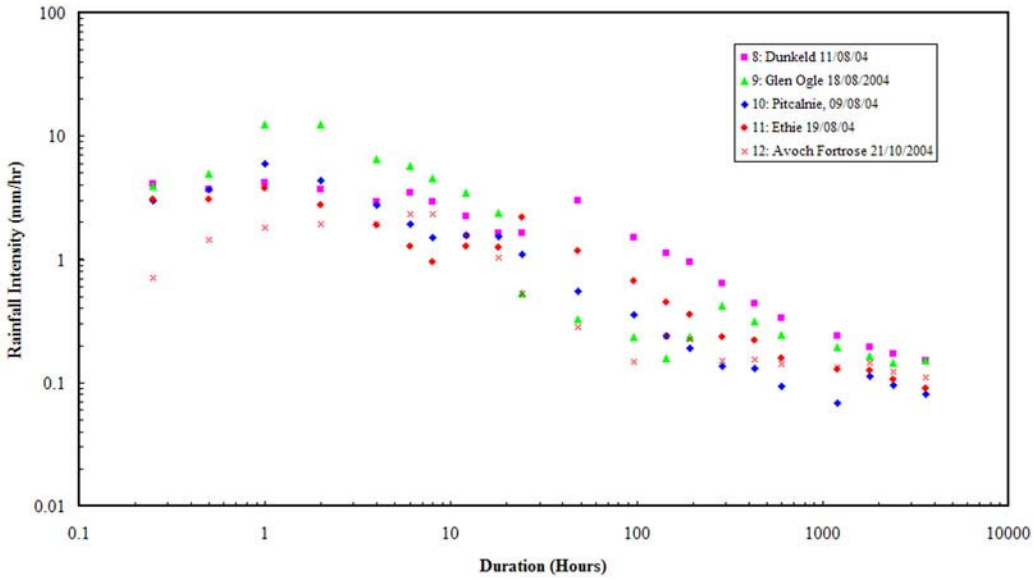

Figure H.10 – Combined plot of intensity versus duration for storms in the eastern areas.

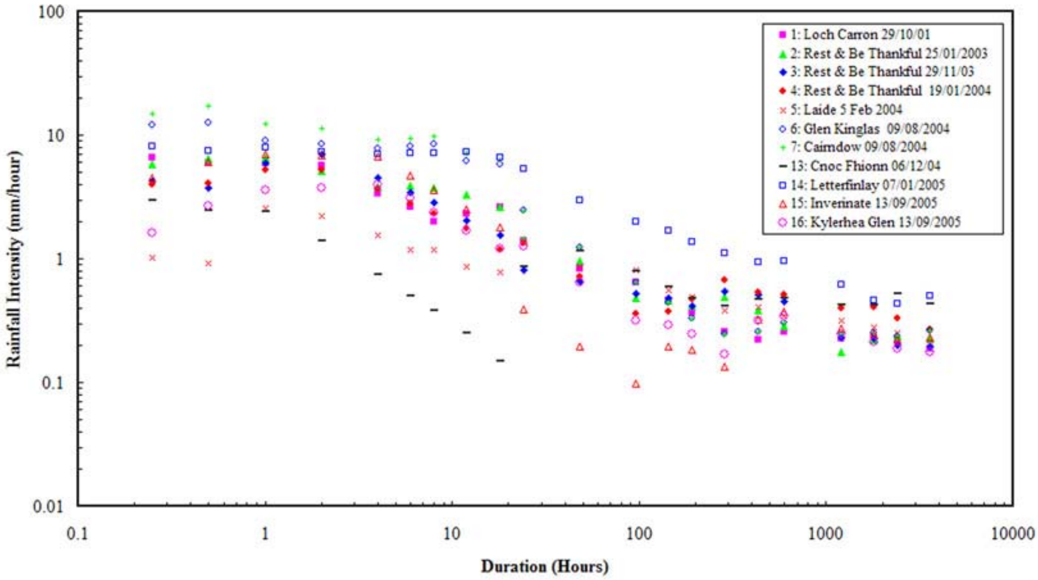

Figure H.11 – Combined plot of intensity versus duration for storms in the western areas.

The group of eastern events showed a consistently good linear relation over the full duration range, apart from the first two hours. The general trend of the grouping for the eastern sites was much steeper than for the western group. This can be explained by the greater incidence and persistence of wetter conditions in the west of Scotland. Cnoc Fhionn (Event 13) and Inverinate (Event 15) produced low outliers over parts of the middle time range. Letterfinlay (Event 14) produced a range of high outliers, which is to be expected, as this storm included by far the highest antecedent rainfall total for all the events.

A method for 'Future Back Analysis' (Annex H.1), whereby a specially designed data-feed is available, has been developed to allow the analysis of future events to assist in the validation of the threshold developed in Section 9.5.

H.3 CONCLUSIONS

The analysis of rainfall leading up to debris flow events has successfully demonstrated methods for producing tabular and graphical outputs suitable for the consistent analysis of such events. The methods cover both the short-term behaviour of storm rainfall and the analysis of rainfall over an extended antecedent rainfall period.

Only Events 5, 12 and 13 produced relations for which a significant portion of the data plot was below the general mass and therefore indicate either a potentially lower threshold than might otherwise be expected or, more likely, that some of these data are outliers.

The work reported demonstrates the usefulness of analysing the rainfall intensities recorded at the radar pixel that covers the site location. Although having TBRs close to the site overcomes the problem of rain gauges being remote from the location, the use of radar data would provide a useful check, and also provides in-fill if any gaps occur in the TBR record. It is a straightforward process to request single or multi-pixel data retrospectively for the site from the Met Office, as these data are routinely archived at five or 15-minute intervals. The analysis of the data to produce into tabular and graphical output would be the same as for the

TBR data, but an extra step is required to convert the radar rainfall data), into an accumulation in mm over specified intervals. (The radar rainfall data is expressed as intensity (×32) in mm/hr over the time unit, five or 15 minutes.)

The analysis method can be adapted with only minor modifications to produce a spreadsheet for the input of data for future events. The final structure of the spreadsheet will depend on how the data is delivered from the field to a data archive, which in turn has to be updated and accessed at regular intervals.

ANNEX H.1 – SYSTEM FOR FUTURE BACK ANALYSIS

'Future Back Analysis' refers to the analysis of events that will be carried out once two new TBRs have been installed at a monitoring site, anticipated to be close to the Rest-and-be-Thankful landslide location. The TBR data will not be available in real-time (i.e. by telemetry), but will be archived by SEPA in a readily available database (referred to here as the core database).

To be compatible with the analysis of historic events, the TBR data needs to be converted to 15-minute clock hour units: i.e. 0900-0915, 0915-0930, and so on. In designing the analysis spreadsheet, it has been assumed that this initial processing from raw data will be carried out in the core database.

The 15-minute data will need to be downloaded at regular intervals to provide a project database, which can then be accessed to populate the spreadsheet. Given that requests for data will be on-demand after a reported event, or after a known incidence of heavy rainfall in the general area of the selected sites, it is suggested that the project database be updated monthly. Once an event needing analysis occurs, data from the end of the last complete month needs to be accessed from the core database. Access to and transfer of data from the core to the project database is to be agreed between TRL and SEPA.

The analysis of future events will largely follow the method used in the analysis of past events (using Tabulations 1 and 2), as follows:

i) The 15-minute data from the project database will be ingested into the first column of the spreadsheet.
ii) From this data array, the analysis start-time will be identified (either the maximum 15-minute accumulation in the storm event or the known time of landslide), and all daily data will be summed (for the standard period 0900-0900hrs GMT), and daily data out to T-150 will be placed in one column (Column 2).
iii) From this column, summations of data will be made for intervals over the storm antecedent period commencing at day T-1 out to T-150.
iv) Using this data, Tabulation 1 is constructed. Row 4 of the tabulation is the function of intensity/mean annual precipitation. The value for MAP will be obtained as a grid value for the site from the Met Office's NCIC (National Climate Information Centre) gridded national dataset of annual average rainfall or from the nearest long-term rain gauge.
v) The data in Row 2 of the tabulation is re-organised to produce cumulative totals of antecedent rainfall commencing at T-150 (Day 0) for periods of 50, 75, 100, 125, 132, 138, 142, 144, 146, 148, and149 days (Row 6).
vi) A graph (points and line) is constructed from Rows 6 and 7 of Tabulation 1: i.e. time in days versus rainfall accumulation (Graph 1).
vii) Using the 15 minute data in Column1, calculations will be carried out backwards from the start-time to provide cumulative totals at intervals of 15 and 30 minutes, and 1, 2, 4, 6, 8, 12 and 18 (or 24 hours if an extended continuous event is apparent).
viii) Using this data, Tabulation 2 is constructed.
ix) A graph (points and line) is constructed showing Rows 2 and 3 versus time (Row 1) (Graph 2).
x) Tabulation 1, Row 3 and Tabulation 2, Row 3 contain rainfall intensity data. This is to be plotted on a log-log scale against a combined time scale (0.25 hours to 150 days) using the intervals in Tabulation 2, Row 1 and Tabulation 1, Row 1 (Graph 3).

xi) Tabulation 1, Row 4 and Tabulation 2, Row 4 contain data for the function of intensity (mm/h) divided by mean annual rainfall (mean annual precipitation, MAP), expressed as a percentage. The two sets of data, time (Row 1, Tabulation 2 and Row 1, Tabulation 1) versus Intensity/MAP (%) are to be plotted on a single graph as points only, using logarithmic scales for both axes (Graph 4).

A summary of the spreadsheet data and products, presented as tables and graphs, is given below. The template for the spreadsheet data and tables are illustrated Tables H.8 to H.10.

Tabulation 1 – Table to be populated to allow the analysis of 150-day antecedent rainfall.

1	**Antecedent days**	1	2	4	6	8	12	18	25	50	75	100	150
2	**Rainfall total (mm)**												
3	**Intensity (mm/hr)**												
4	**Intensity (mm/hr)/MAP (%)**												
5	***Incremental rainfall from day-150***												
6	**Day from T-150**	0	50	75	100	125	132	138	142	144	146	148	149
7	**Incremental rainfall**												

Tabulation 2 – Table to be populated to allow the analysis of storm rainfall.

1	**Time before start point (hours)**	0.25	0.5	1	2	4	6	8	12	18
2	**Rainfall (mm)**									
3	**Rainfall intensity (mm/hr)**									
4	**Intensity/MAP (%)**									

Graph 1 – Antecedent Rainfall.
Cumulative rainfall (mm) versus time, T-150 to T0 (days), arithmetic scales.

Graph 2 – Storm rainfall, accumulation and intensity.
Rainfall intensity (mm/hr) and cumulative rainfall (mm) versus time 0 to 24 (hrs), arithmetic scales.

Graph 3 – Intensity versus Duration.
Rainfall intensity (mm/hr) versus time 0.1 to 150 days, log-log scale.

Graph 4 – Intensity/MAP function.
Rainfall intensity (mm/hr)/MAP (mm) as percentage versus time 0.1 to 150 days, log-log scale.

Table H.8 – Hourly rain gauge data.

04/10/2001		-	25													
05/10/2001	3.2		24													
06/10/2001	3.0		23													
07/10/2001	12.4		22													
08/10/2001	4.0		21													
09/10/2001	13.8		20													
10/10/2001	20.2		19													
11/10/2001	9.4		18													
12/10/2001	1.4		17													
13/10/2001	1.2		16													
14/10/2001	1.8		15													
15/10/2001	5.8		14													
16/10/2001	2.4		13													
17/10/2001	0.0		12													
18/10/2001	3.2		11													
19/10/2001	0.0		10													
20/10/2001	0.8		9													
21/10/2001	3.6		8													
22/10/2001	0.2		7													
23/10/2001	2.0		6													
24/10/2001	2.8		5													
25/10/2001	13.0		4													
26/10/2001	8.8		3													
27/10/2001	6.2		2													
28/10/2001	33.4		1	Table 2: Antecedent Rainfall at	New Kelso 29/10/01											
29/10/2001	90.6			Antecedent days	1	2	4	6	8	12	18	25	50	75	100	150
30/10/2001	25.4			Rainfall total (mm)	33.4	39.6	61.4	66.2	70.0	74.0	96.0	152.6	270.8	415.0	516.0	674.6
31/10/2001	5.8			Intensity (mm/hr)	1.39	0.83	0.64	0.46	0.36	0.26	0.22	0.25	0.23	0.23	0.22	0.19
Ave 1971-00		203.6		Intensity/MAP(%)	0.072	0.042	0.033	0.024	0.019	0.013	0.011	0.013	0.012	0.018	0.022	0.029
Total		333.4														
				Table 2A: Incremental rainfall from day -50												
				Day	0	50	75	100	125	132	138	142	144	146	148	149
				Incremental rainfall	0.0	158.6	259.6	403.8	522.0	578.6	600.6	604.6	608.4	613.2	635.0	641.2
				Antecedent Hours	24	48	96	144	192	288	432	600	1200	1800	2400	3600

Table H.9 – 15 minute radar rainfall data.

29/10/2001	13:05		n/a											
29/10/2001	13:10		n/a											
29/10/2001	13:15		5.2											
29/10/2001	13:20		n/a											
29/10/2001	13:25		n/a											
29/10/2001	13:30		6.2											
29/10/2001	13:35		n/a											
29/10/2001	13:40		n/a											
29/10/2001	13:45		5.1											
29/10/2001	13:50		n/a											
29/10/2001	13:55		n/a											
29/10/2001	14:00		6.2											
29/10/2001	14:05		n/a											
29/10/2001	14:10		n/a											
29/10/2001	14:15		5.7											
29/10/2001	14:20		n/a											
29/10/2001	14:25		n/a											
29/10/2001	14:30		5.2											
29/10/2001	14:35		n/a											
29/10/2001	14:40		n/a		Table 1. Analysis of 15 minute 5-km composite radar data from				Skye Lusa					
29/10/2001	14:45		6.6		Time before peak rainfall	0.25	0.5	1	2	4	6	8	12	18
29/10/2001	14:50		n/a		Total Rainfall (mm)	1.7	3.0	5.9	11.3	13.5	15.6	15.8	28.0	47.5
29/10/2001	14:55		n/a		Rainfall Intensity (mm/hr)	6.60	5.90	5.90	5.70	3.40	2.60	2.00	2.30	2.60
29/10/2001	15:00		5.7											
29/10/2001	15:05		n/a		Table 1A. Intensity Function for Storm									
29/10/2001	15:10		n/a		Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
29/10/2001	15:15		5.1		Intensity/MAP	0.3391	0.3031	0.3031	0.2929	0.1747	0.1336	0.1028	0.1182	0.1336
29/10/2001	15:20		n/a		Average Annual Rainfall (1961-90) =		1946.3							
29/10/2001	15:25		n/a		Time before peak rainfall (days)	0.01	0.02	0.04	0.08	0.17	0.25	0.33	0.50	0.75

Table H.10 – Gridded radar rainfall data: template for 15 minute rainfall data.

	Met	Office	-	Weather	Radar	Development				
	Crown	Copyright	2002							
You	requested	data	from	28/10/2001	12:00	to	31/10/2001	00:05		
Instantaneous	rainfall	values	in	units	of	mm	per	hour		
	EASTINGS	185000	190000	195000	185000	190000	195000	185000	190000	195000
	NORTHING	845000	845000	845000	840000	840000	840000	835000	835000	835000
200110281200		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281215		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281230		0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.4	0.0
200110281245		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
200110281300		0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.6
200110281315		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281330		0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281345		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281400		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281415		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281430		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281445		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281500		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281515		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281530		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281545		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281600		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281615		0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281630		0.1	1.4	2.4	0.0	0.2	1.1	0.0	0.0	0.0
200110281645		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281700		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281715		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281730		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281745		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281800		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
200110281815		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281830		0.3	0.0	0.0	1.2	0.4	0.0	1.2	0.9	0.0
200110281845		0.0	0.5	0.0	0.4	1.7	1.1	0.7	1.4	0.8
200110281900		0.6	0.0	0.6	2.0	0.8	1.2	1.6	1.5	1.5
200110281915		0.9	1.1	1.3	0.8	0.0	1.3	1.3	0.0	0.0
200110281930		1.3	1.0	1.0	1.6	1.3	1.5	1.3	1.2	2.8
200110281945		2.0	1.6	3.3	3.0	2.6	3.2	2.8	2.3	4.5
200110282000		1.8	1.3	3.4	2.2	1.6	2.4	2.2	1.4	3.2
200110282015		2.7	2.3	4.8	2.0	2.0	2.9	1.9	1.3	3.4
200110282030		2.7	1.8	4.3	2.6	1.9	2.4	4.3	2.6	3.6
200110282045		1.1	1.0	1.9	2.0	1.5	1.5	2.1	1.5	2.3
200110282100		2.5	1.5	3.6	2.3	1.4	2.1	1.8	1.3	2.2
200110282115		2.6	1.5	3.0	2.7	2.4	2.9	2.4	1.7	4.1
200110282130		4.3	2.4	5.5	3.3	3.3	3.6	2.9	2.3	5.1
200110282145		4.7	2.3	7.5	3.5	3.5	4.6	3.0	2.2	5.8
200110282200		4.2	2.3	5.4	3.6	3.2	4.2	3.4	2.7	6.7
200110282215		3.3	1.9	4.0	3.2	3.5	4.0	3.3	2.7	7.2
200110282230		4.3	1.9	4.6	2.9	2.7	3.1	3.0	2.3	5.5
200110282245		2.2	1.5	3.0	3.3	2.8	3.1	3.4	2.3	5.8
200110282300		0.4	0.7	0.0	2.4	1.8	0.0	0.9	0.0	0.0

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