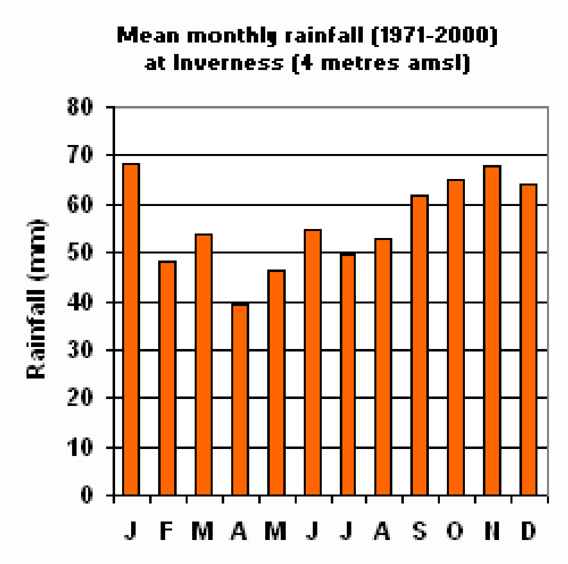
3 Review of antecedent conditions and rainfall

3.1 Introduction

The following section provides an overview of the wider antecedent conditions leading up to the flood events based on available sources of information.

Annual rainfall for Inverness and the two burns is approximately 750 mm. Average monthly rainfall at Inverness is shown in the Figure below.

Figure 3-1: Met Office average (1971-2000) rainfall at Inverness[4]



3.2 Antecedent conditions

July and August 2011 were wet months for much of north eastern Scotland with rainfall exceeding twice the July average in the region. Monthly rainfall totals were above average in both July and August and river levels were high. The River Ness closely approached its highest July daily flow in a 39 year data series[5].

Monthly rainfall totals for July were 211 mm at Culloden. This equates to over a quarter of the annual rainfall falling in July and is 400% greater than the long term July average. This is supported by the Met Office plans that shows an area of above average rainfall (>200%) for the months of July and August for the Inverness region.

Specific rainfall events occurred on the 8-10 July, 16 July and the 6-7 August. The latter two lead to flooding on the Inverness East burns. River flows on the Mill Burn (recorded at the SEPA gauge at Diriebught) illustrate these 3 specific rainfall and the resulting high river flows (Figure 3-2).

4 http://www.metoffice.gov.uk/climate/uk/ns/print.html

5 CEH July Hydrological Summary for the United Kingdom. www.ceh.ac.uk/data/nrfa/nhmp/monthly_hs.html

Figure 3-2: July and August river flow data on the Mill Burn

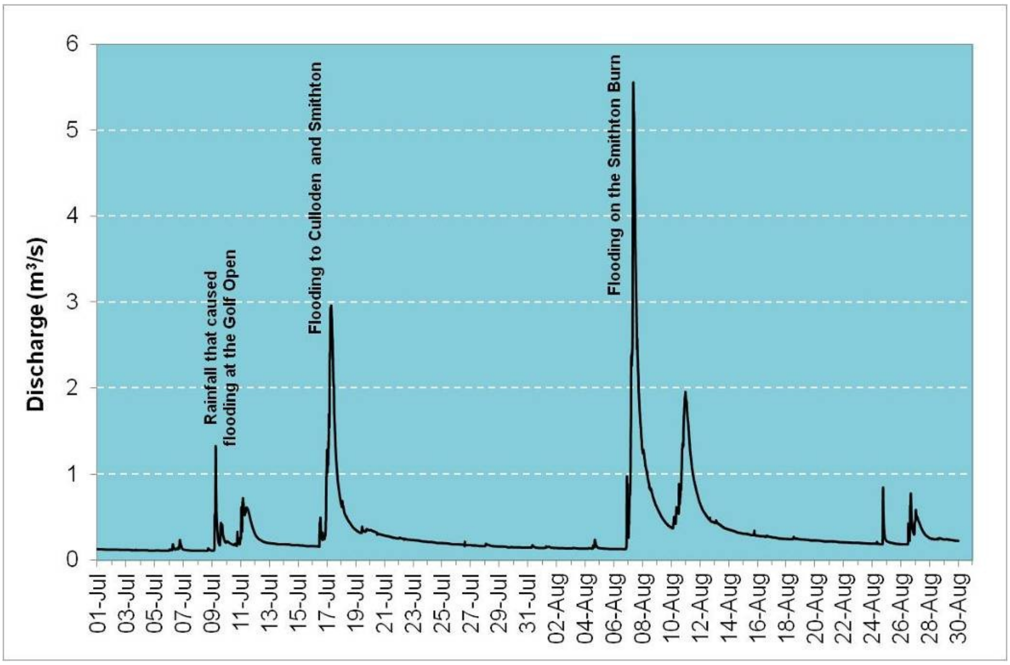
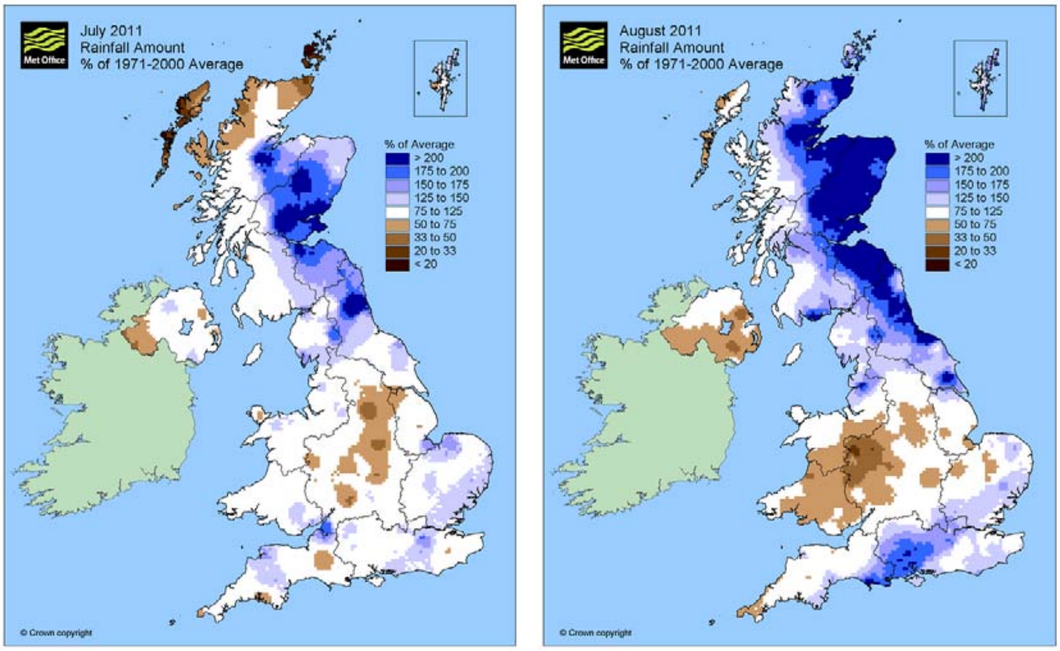


Figure 3-3: Met Office distribution of rainfall totals - % of 1971-2000 average



http://www.metoffice.gov.uk/climate/uk/anomacts/

3.3 Review of the July 2011 flood event

General situation and antecedent conditions have been reviewed by the Met Office with the following generic information on rainfall for the month as a whole over Scotland[6]:

> *"Alternating warm, settled weather and cooler spells with periods of rain and showers, some heavy and thundery. It was a wet month across many eastern areas, from the Borders to Inverness, with about twice the average in places".*

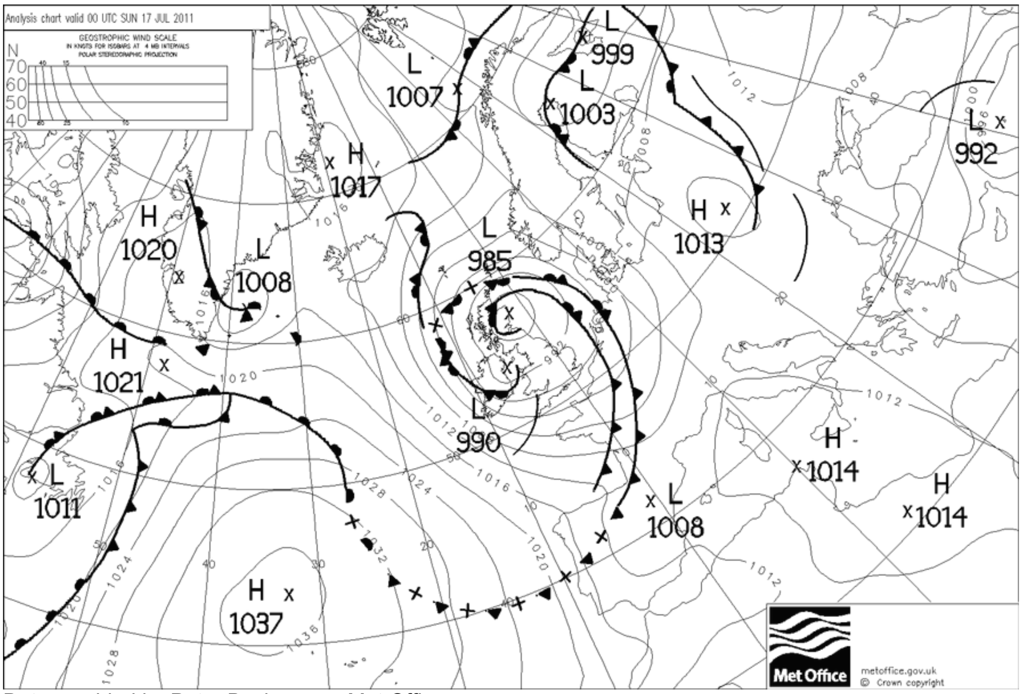
More specific information on the rainfall for the period between the 15th - 18th is provided for Scotland:

[6] http://www.metoffice.gov.uk/climate/uk/2011/july.html

"A dry and sunny start to 15th but it clouded over with rain spreading from the west. There was persistent rain near the east coast on 16th, but it was brighter further west. Heavy, slow-moving thundery showers broke out, with 29 mm was recorded at Strathallan (Perthshire) in 12 hours and reports of flooding in Perth. There were further heavy showers on 17th with isolated thunderstorms, and rain or showers again on 18th."

This general situation is supported by the surface pressure charts for the 17 July as shown below.

Figure 3-4: Met Office charts of surface pressure for 0000 hrs on Sun 17 July



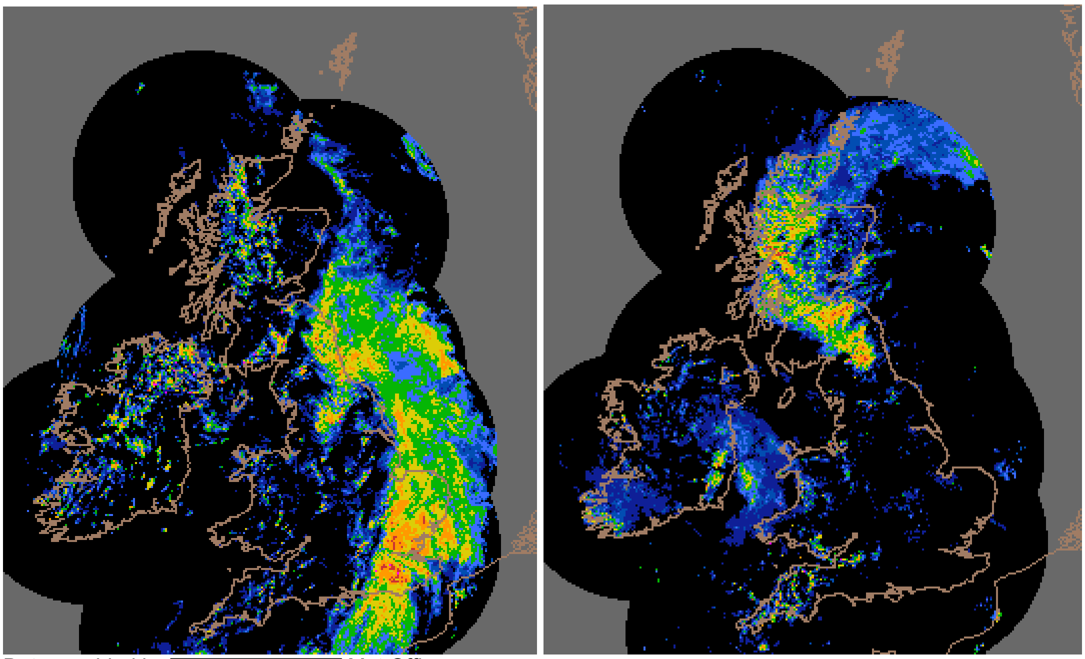
Data provided by Peter Buchannan, Met Office

3.3.1 Rainfall analysis

The rainfall event started between 11am to 1pm on the 16 July 2011 and lasted for approximately 20 hours. Analysis of the rainfall data suggests that there was a double peak of rainfall, with an intense period of rainfall at the start (11am on the 16 July) of the event that lasted for approximately 2-4 hours.

This double peak of rainfall is shown in the composite rainfall radar images for the UK (5km resolution) that shows the first peak as a fairly spatially isolated but intense rainfall shower followed by a more prolonged period of widespread rainfall from the south and east.

Figure 3-5: Met Office combined rainfall radar images at 1215 hrs on 16 July and 2230 on 16 July



Data provided by [redacted] Met Office

3.4 Review of the August 2011 flood event

General situation and antecedent conditions have been reviewed by the Met Office with the following generic information on rainfall for the month as a whole over Scotland[7]:

> *"A predominantly cloudy and rather cool month with showers and longer outbreaks of rain at times. Rainfall amounts were generally above average, particularly across the eastern half where over twice the average amount fell."*

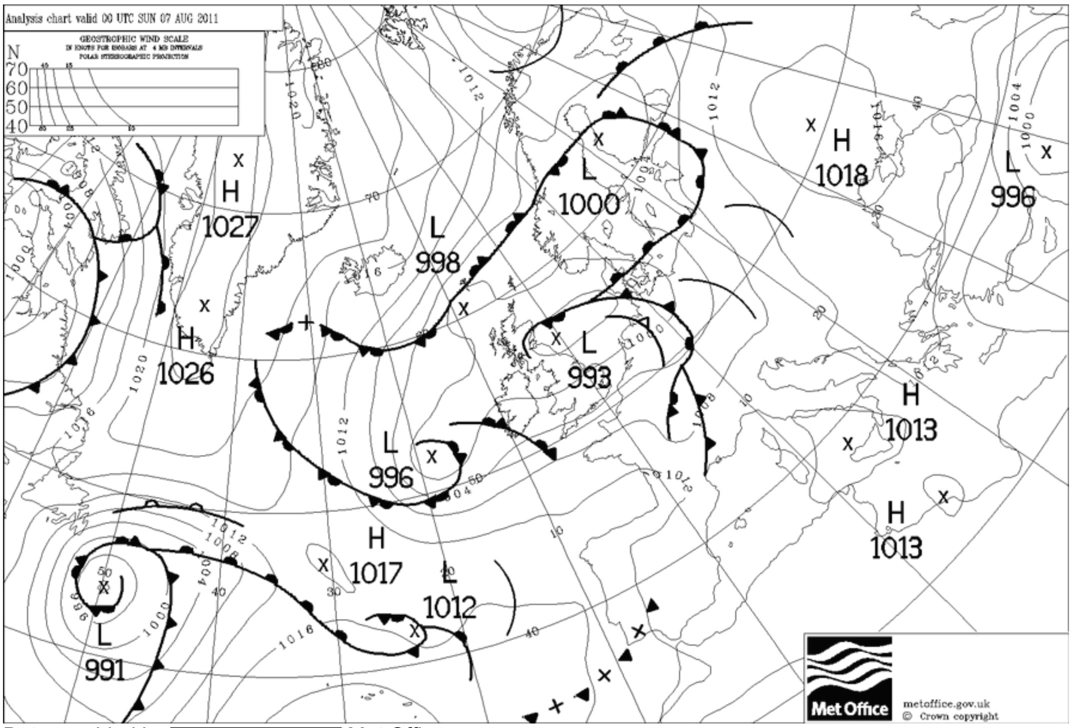
More specific information on the rainfall for the period between the 6th - 8th is provided for Scotland:

> *"Bright with a few showers on 6th but rain, occasionally heavy, spread into southern and eastern parts later. 24-hour totals to 0900 on 7th were widely in excess of 25 mm from the Borders to Inverness with 42.2 mm at Lentran (Highland), 46.8 mm at Kindrogan (Perth and Kinross) and 38.4 mm at Leuchars (Fife). Rain for most on 7th, heavy and prolonged, especially across the north and east with 24-hour totals again over 20 mm, including 33.6 mm at Lossiemouth (Moray) and 32.5 mm at Cupar (Fife). The rain became confined to the north-east on 8th, and it was brighter elsewhere with scattered showers."*

This general situation is supported by the surface pressure charts for the 7 August as shown below.

[7] http://www.metoffice.gov.uk/climate/uk/2011/august.html

Figure 3-6: Met Office charts of surface pressure for 0000 hrs on Sun 7 August



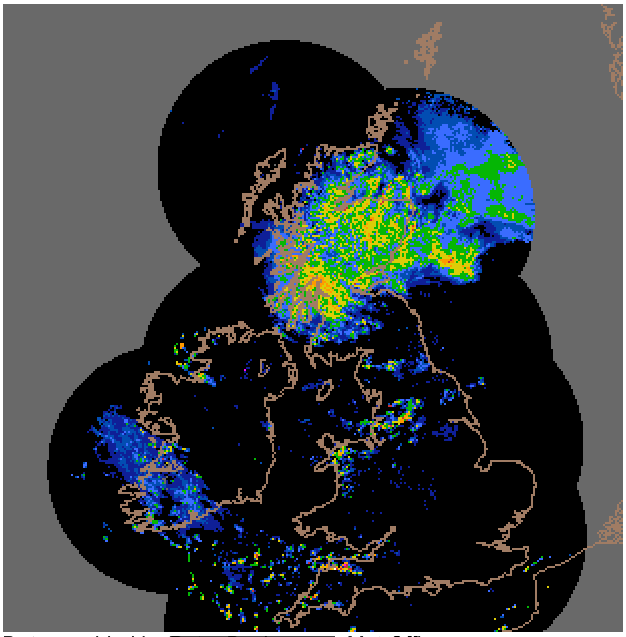
Data provided by [redacted] Met Office

3.4.1 Rainfall analysis

The rainfall event started at approximately 9pm on the 6 August and lasted for approximately 14 hours until 11 am on the 7 August 2011.

This rainfall event is shown in the composite rainfall radar image for the UK (5km resolution) that shows the widespread spatial coverage and intensity of rainfall over north east Scotland with higher intensity rainfall over Inverness and Moray.

Figure 3-7: Met Office combined rainfall radar image at 0315 hrs on 7 August



Data provided by [redacted] Met Office

3.5 Summary of antecedent conditions and rainfall

The following key findings are presented:

Variable	mm	% of annual
July average monthly rainfall at Inverness	50	-
August average monthly rainfall at Inverness	50	-
Average annual rainfall for both catchments	750	-
Total July rainfall recorded at Culloden Leannach gauge	211	28%
Total August rainfall recorded at Culloden Leannach gauge	152	20%
Total July & August rainfall recorded at Culloden Leannach gauge	363	48%

From the data available we can determine the following key findings:

- Average monthly rainfall for the area for July and August is approximately 50 mm.
- The average rainfall that fell for the months of July and August for the Inverness region was 200% of the long term average and may have been locally up to 400% of the long term average in the region of Culloden.
- A quarter of the yearly rainfall for the area fell in the month of July. Almost 50% of the total annual rainfall for Inverness fell at the Culloden Leannach raingauge over July and August.
- Within this period of above average rainfall for July and August specific rainfall events occurred on the 8-10 July, 16 July and the 6-7 August. The latter two led to flooding on the Inverness East burns.

4 Recorded rainfall and gauged river flow analysis

4.1 Rainfall analysis

The analysis of rainfall data is essential to determine the event rarity of the storm events that caused the flooding. The estimation of a return period of a rainfall observation can be carried out using FEH methodologies for any area of the mainland UK if the rainfall duration, rainfall depths and the location is known.

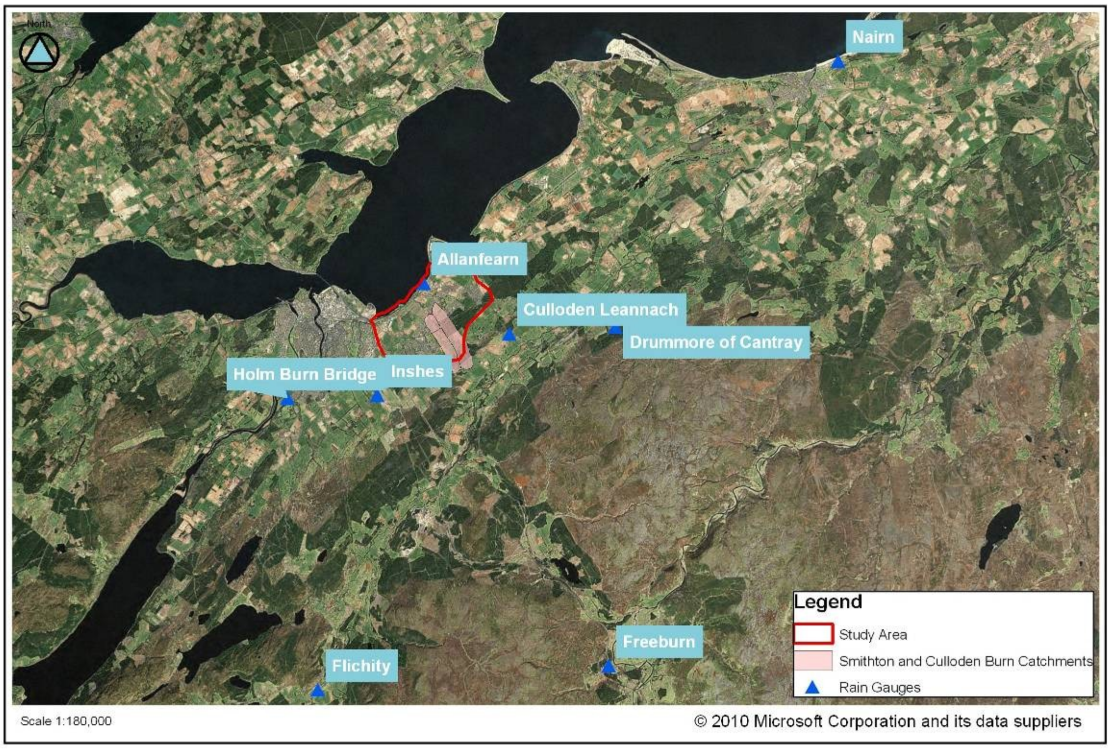
4.1.1 Rainfall data

Rainfall data has been obtained from SEPA for a number of nearby gauging stations in the region of Inveress - Nairn. Data for the following rain gauges has been provided by SEPA for the two key flood events around the 16-17 July and 6-7 August. The location of each of these rain gauges is shown in Figure 4-1 below.

Table 4-1: SEPA rain gauges used in analysis

Gauge	Location	Type	Elevation (mAOD)	Distance from Culloden (km)	July data provided	August data provided
Allanfearn	NH711474	TBR	5	1	1-21 July	5-8 August
Drummore of Cantray	NH798454	TBR	210	8	15-18 July	5-8 August
Flichity	NH663289	TBR	220	18	15-18 July	5-8 August
Inshes	NH690423	TBR	130	5	15-18 July	5-8 August
Nairn	NH899575	TBR	5	21	15-18 July	5-8 August
Culloden Leannach	NH750451	Daily	150	3	1-31 July	1-31 August
Holm Burn Bridge	NH649421	Daily	20	8	1-31 July	1-10 August

Figure 4-1: Location of SEPA rainfall gauges



4.1.2 Recorded daily rainfall totals

Daily rainfall data (9am to 9am) for each gauge is provided in the tables below. The difference in total rainfall depths between gauges illustrates the very localised nature of the rainfall events.

Table 4-2: Daily rainfall totals for July

Date	Allanfearn	Culloden Leannach	Inshes	Drummore of Cantray	Flichity	Nairn	Holm Burn Bridge
15-Jul	0.4	1.7	0.6	0.6	0.4	0.4	0
16-Jul	33.0	79.5	32.6	37.0	30.4	10.2	19.2
17-Jul	15.6	-	24.2	21.4	20.6	6.6	20.0
18-Jul	1.6	-	2.6	0.0	0.2	0.2	1.2

Table 4-3: Daily rainfall totals for August

Date	Allanfearn	Culloden Leannach	Inshes	Drummore of Cantray	Flichity	Nairn	Holm Burn Bridge
5-Aug	0.0	0.0	0.2	0.4	0	0.2	0.2
6-Aug	9.6	67.5	8	3.6	8.2	3.4	16.4
7-Aug	50.8	16	61.2	34.4	35.2	35.8	52.2
8-Aug	2.2	2	4.4	4.0	8.6	1.6	5.4

4.1.3 Spatial distribution of rainfall

The spatial distribution of rainfall has been assessed by plotting the cumulative rainfall totals for each of the TBR gauges. These are shown for the July and August events in Figure 4-2 and Figure 4-3 below.

Figure 4-2: July cumulative rainfall

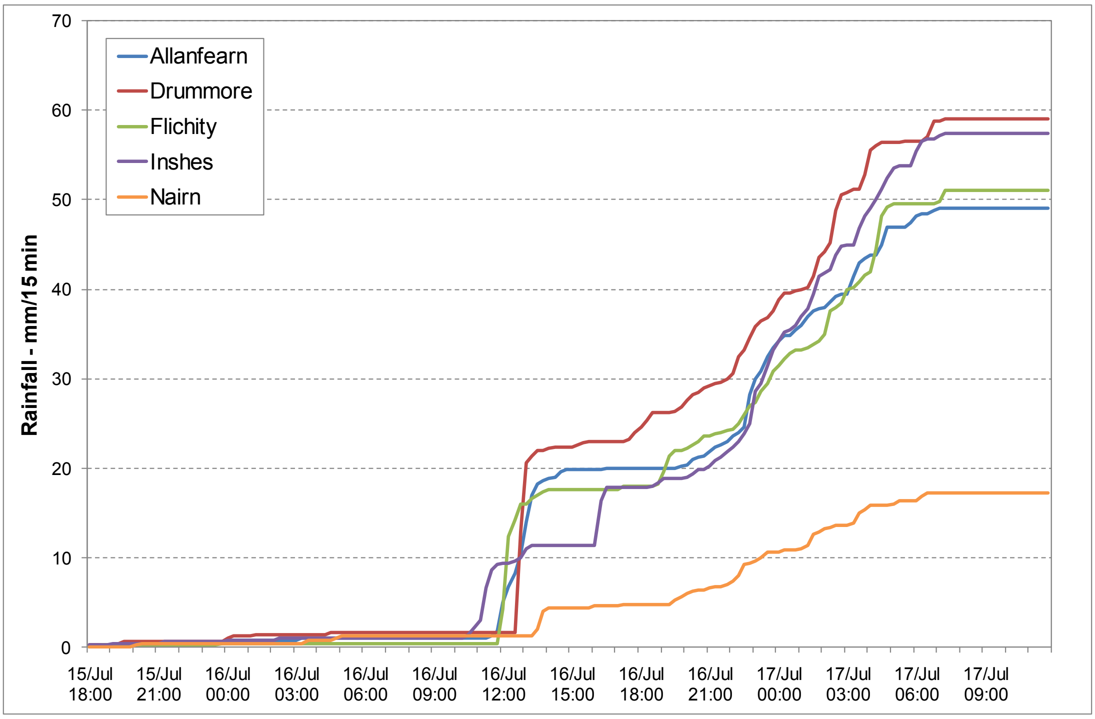
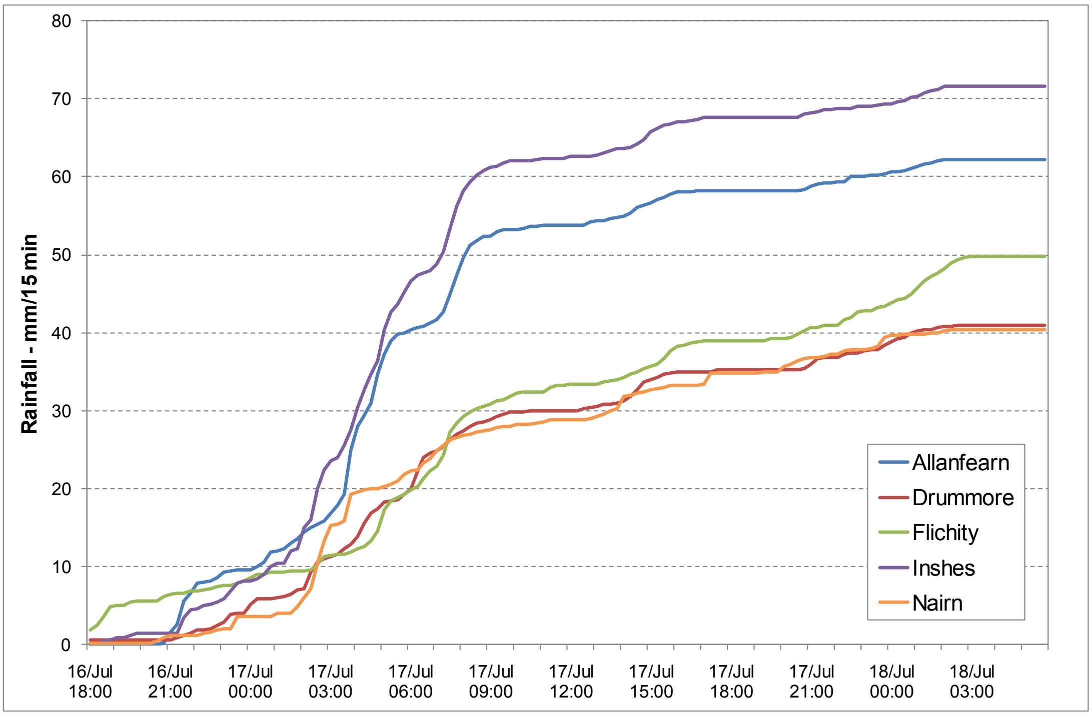


Figure 4-3: August cumulative rainfall



The above charts suggest that for the July event the rainfall totals and intensity were relatively uniform across the area other than at Nairn to the east were much lower rainfall totals were observed. For August it is clear that the area to the west and north of the Culloden received significantly higher rainfall totals than the other rain gauges.

4.1.4 Daily rainfall totals and return period estimates

The Flood Estimation Handbook (FEH) provides a methodology to determine rainfall frequency estimates using a rainfall depth-duration-frequency model (a DDF model). This model is provided in the FEH CD-ROM v3 and can provide an estimate of the rainfall event at a given location based on observed rainfall durations and depths.

This methodology has been used to determine the rarity of the rainfall events at each gauge on a rainfall event and daily period. The results for the July and August floods are provided in Table 4-4 and Table 4-5 below.

It should be noted that this methodology gives an estimate of the event rarity based on available data for local rain gauges. The validity of these estimates are only as good as the data available. Therefore, whilst every effort has been made to use all available data, due to the highly localised nature of the summer rainfall events, there is still a degree of uncertainty that must be applied to determining the event rainfall over these relatively small catchments.

Table 4-4: Daily rainfall depths (mm) and return period (years) estimates for July

Duration	Allanfearn		Culloden Leannach		Inshes		Drummore of Cantray		Flichity		Nairn		Holm Burn Bridge	
	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP
Max daily total	33	2	80	**57**	33	1	37	1	30	1	10	<1	20	<1
Max 24hr total	48	6	80	**57**	56	**13**	57	7	51	3	16	<1	39	1
Max 2 Day total	50	2	81	**16**	57	3	58	2	51	1	17	<1	40	1
24 hour duration is the maximum during any 24 hour period and not necessarily 9am to 9am.														

Table 4-5: Daily rainfall depths (mm) and return period (years) estimates for August

Duration	Allanfearn		Culloden Leannach		Inshes		Drummore of Cantray		Flichity		Nairn		Holm Burn Bridge	
	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP	mm	RP
Max daily total	51	8	68	**25**	61	**19**	34	1	35	1	36	3	52	6
Max 24hr total	58	**16**	68	**25**	67	**31**	35	1	38	1	35	2	69	6
Max 2 Day total	60	5	84	**19**	69	9	38	1	44	1	39	1	74	5

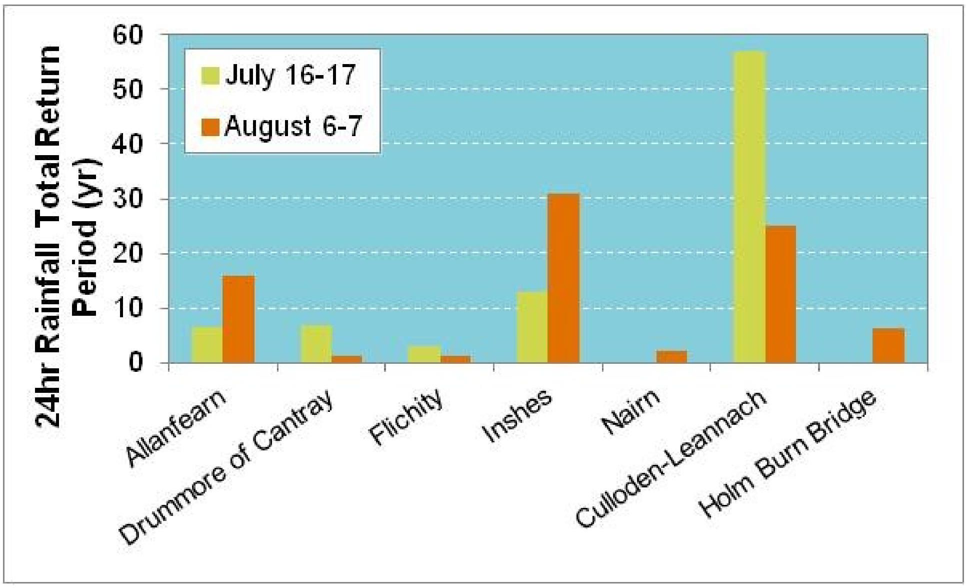
The above tables suggest that whilst the rainfall totals were similar, there was an increased intensity of rainfall and higher totals for the July event specifically over the Culloden daily gauge, with an estimated return period at the Culloden gauge of 57 years. The Culloden gauge recorded a daily total of 80 mm which is 20-30 mm higher than the next nearest gauges at Allanfearn and Drummore of Cantray only 5km away.

The daily rainfall depths over the nearby TBR gauges at Allanfearn, Drummore and Inshes generated a 6 year, 6 year and 13 year return period rainfall events respectively. The gauge located at Flichity recorded a similar depth but represents a smaller rainfall return period at this location due to its location in a more mountainous region further west and at a higher elevation than the site of interest. The recorded rainfall at Nairn was negligible.

The analysis of daily rainfall totals for the August event confirms that that the event was spatially variable with the greatest intensity of rainfall occurring over the northern portion of the region covering the Allanfearn, Culloden and Inshes rain gauges, each with a rainfall return period between 16-31 years. The rainfall return period for the Drummore, Flichity and Nairn gauges, whilst recording a daily total of 35-38 mm, do not represent a significant return period event at these locations.

The 24 hour daily rainfall return periods are presented in the Figure below.

Figure 4-4: Rainfall return period estimates for 24hour period



The above analysis suggests that both events were relatively highly localised with high return period rainfall depths being recorded over Culloden and to the west at Inshes in July and over the Inshes and Allanfearn for the August event. It is also of note that the rainfall events that caused the flooding were relatively short (sub daily) events.

4.1.5 Comparison with previous rainfall events

The following rainfall totals have been recorded in the past:

- 7/8 September 2002 - over 55 mm of rain (over half within a one hour period) fell during the night in Inverness and surrounding area.
- 24-26 September 1915 - approximately 92 mm of rain
- 25 September 1890 - approximately 90 mm of rain

Based on the above and assuming these fell over Culloden the following return periods are predicted:

- 7/8 September 2002 - 55 mm of rain in 12 hours = 41 years
- 7/8 September 2002 - 28 mm of rain in 1 hours = 60 years
- 24-26 September 1915 - 92 mm of rain in 3 days = 20 years
- 25 September 1890 - 90 mm in 1 day = 143 years

This suggests that historic flooding in the area of Inverness and Culloden has in the past generated significant rainfall events. Comparison with these events suggests that whilst they were high and intense rainfall events they are not unusual or excessive when viewed as part of a longer record.

4.1.6 Event rainfall analysis

It is worthwhile therefore assessing sub daily rainfall totals for those nearby gauges where recording is undertaken at 15 minute intervals. The graphical representation of this rainfall is shown in the figures below.

Figure 4-5: July rainfall totals

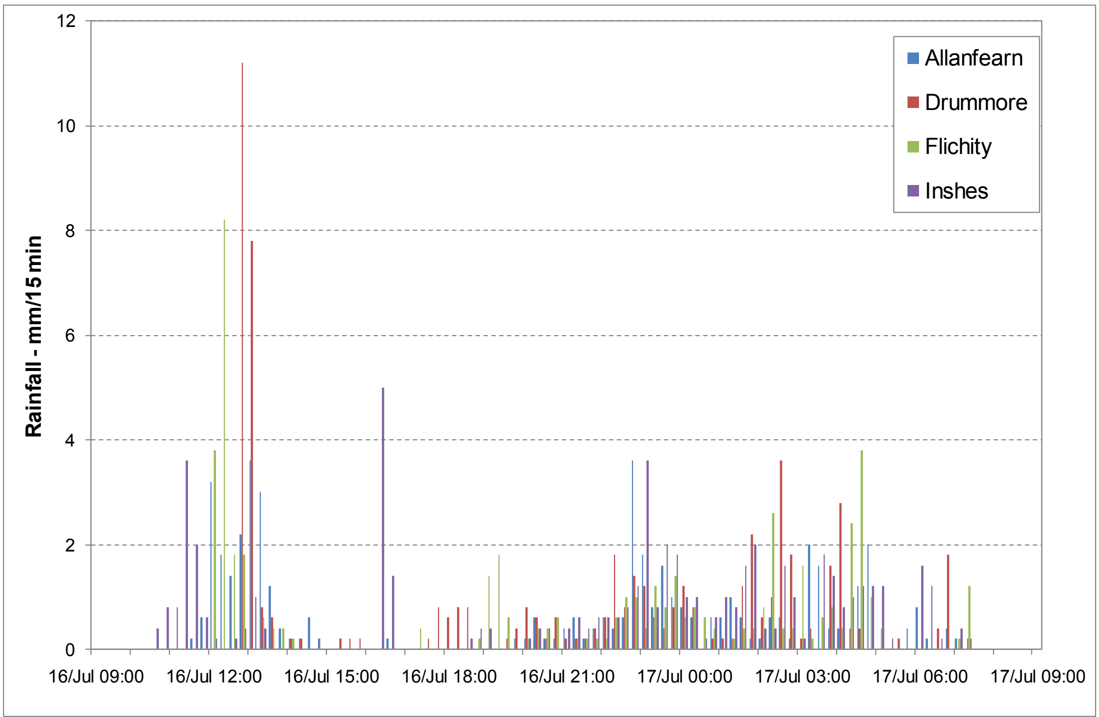
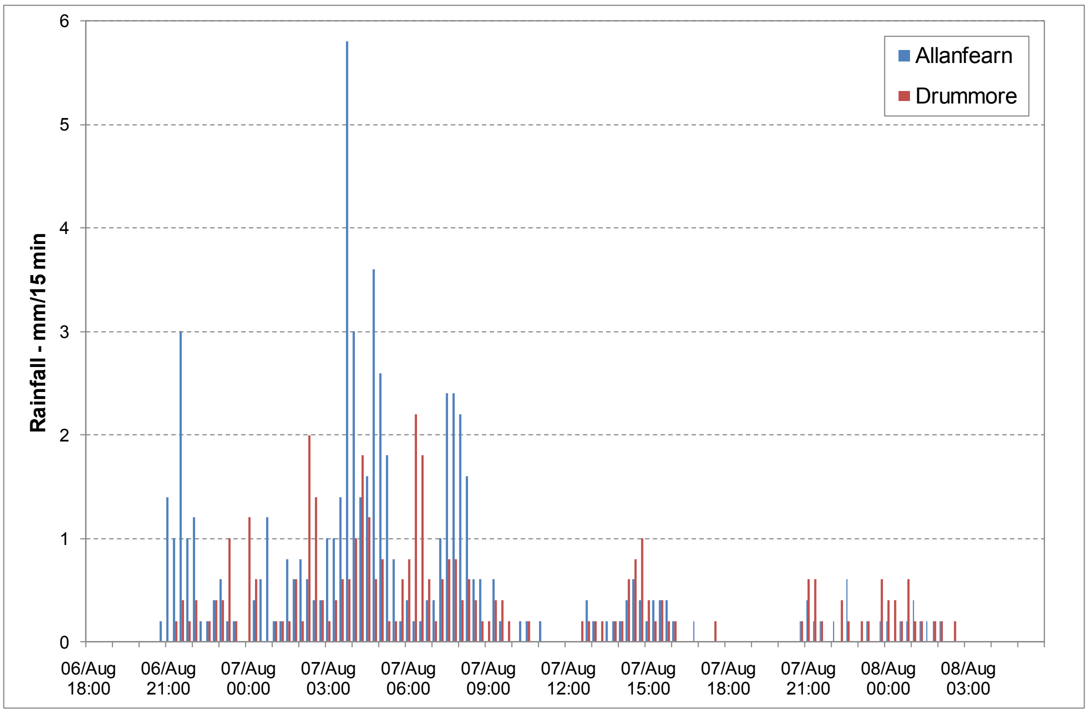


Figure 4-6: August rainfall totals



The above figures indicate that the July event lasted approximately 20 hours with an intense period of rainfall at the start (11am on the 16 July) of the event that lasted for approximately 2-4 hours. The August event lasted slightly longer, although the main rainfall event occurred over a period of 15 hours starting at 9pm on the 6 August.

The total rainfall depths, durations and DDF return periods at each gauge have been determined for both the entire event and the shorter durations and are presented in Table 4-6 and Table 4-7 below.

The results of the DDF analysis suggest that the early peak for the July event did not generate a significant rainfall return period, but the whole event was more significant providing a return period of approximately 9-19 years depending on the gauge and slightly higher than the daily durations assessed in the section above.

The results for the August event suggest that the main first peak was the most significant in terms of return period with a rainfall duration of 28-44 years for the Allanfearn and Inshes rain gauges.

Table 4-6: Event rainfall depths (mm) and return period (years) estimates for July

	Allanfearn	Inshes	Drummore of Cantray	Flichity	Nairn	Culloden Leannach
First peak depth (mm)	18.8	10.4	20.8	17.2	-	N/A
Duration (hr)	3.8	3.25	2.0	2.5	-	N/A
DDF RP	2.7	1.01	6.0	2.0	-	N/A
Complete event depth (mm)	48.0	56.4	57.4	49.2	11	79.5
Duration (hr)	20.0	21.25	19.0	17.5	9	20
DDF RP	**9.1**	**16.4**	**10.7**	5.0	<1	**79**

It is clear from the above table that the general rainfall event for July occurred over an approximate 20 hour period. Therefore the estimate for the rainfall that fell over the Culloden Leannach rain gauge over a 24 hour period of 57 years is an appropriate estimate for this event. If we assume the slightly shorter rainfall duration of 20 hours however the estimated return period increases to 79 years.

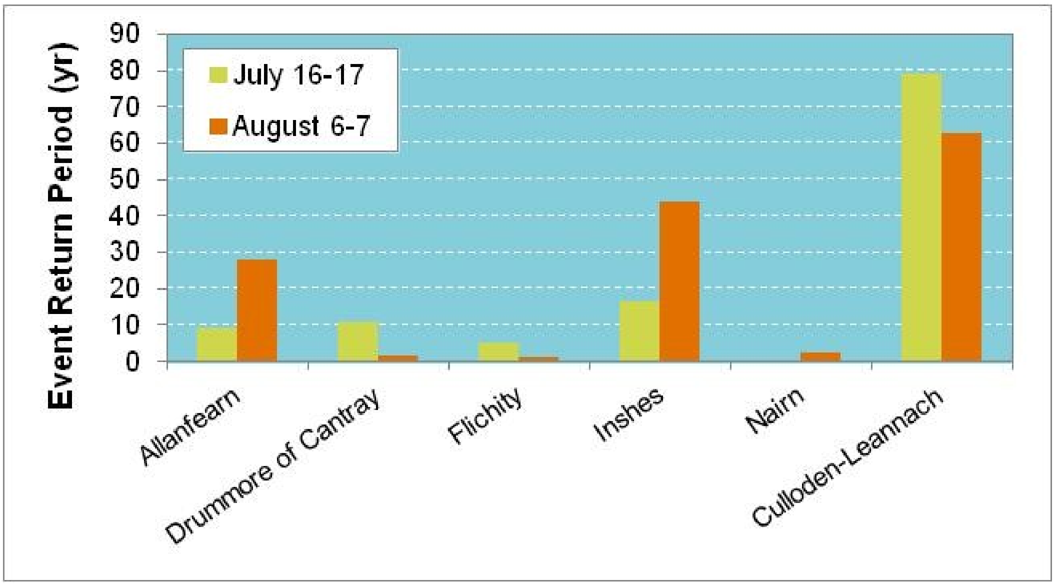
However, the majority of the rainfall for the August flood fell in a shorter period. It is therefore useful to assess what the 68 mm of rainfall that fell over the Culloden Leannach rain gauge would equate to in terms of return periods if we assume this shorter period.

Table 4-7: Event rainfall depths (mm) and return period (years) estimates for August

	Allanfearn	Inshes	Drummore of Cantray	Flichity	Nairn	Culloden Leannach
First peak depth (mm)	53.8	61.8	29.2	32.4	24.8	67.5
Duration (hr)	14.5	15.75	13.0	18.25	10.0	14.5
DDF RP	**28.0**	**44.0**	1.5	1.16	2.4	**63.0**
Complete event depth (mm)	62.2	71.4	40.4	49.8	36.4	N/A
Duration (hr)	29.5	32.0	29.8	35.0	25.0	N/A
DDF RP	**14.8**	**23.6**	1.3	1.48	2.5	N/A

The above tables are summarised in the Figure 4-7 below.

Figure 4-7: Rainfall return period estimates estimated by event duration

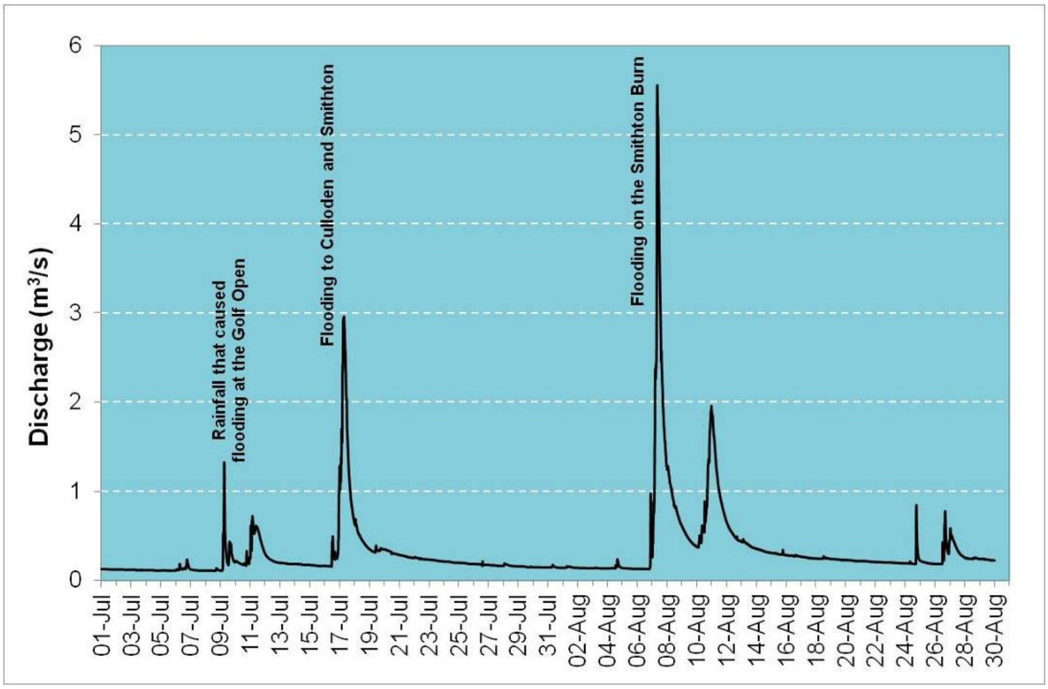


4.2 River flow analysis

The Mill Burn to the west of the area of interest is gauged at Diriebught and provides an assessment of the peak flows for this adjacent burn. The record of flows for July and August 2011 are provided in Figure 4-8 and illustrate that the August flood event was significantly higher on this catchment than the July event. Assuming that the rainfall for the two gauges were reasonably spatially consistent for both events, this would confirm broad findings of the above rainfall analysis.

Correspondence with SEPA regarding the quality of the gauge on the Mill Burn suggested that that is poorly calibrated for high flows. Therefore, whilst the relative difference in peak flows between events is useful as a donor comparison of the relative significance of the two flood events, no flood frequency analysis has been undertaken to estimate the magnitude of the flood on this burn.

Figure 4-8: Peak flow estimates on the Mill Burn for July and August

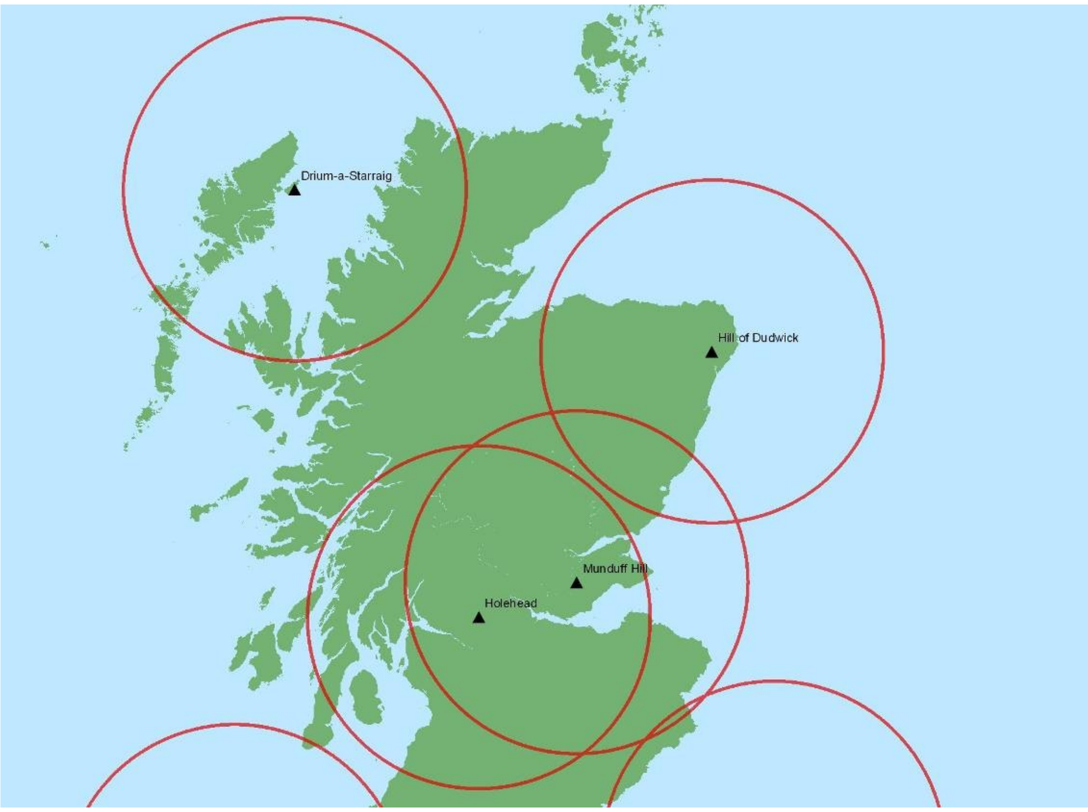


4.3 Radar Data

No suitable rainfall Radar data is available as the area of Inverness lies between the two main northern Scotland Radar stations at Stornoway and the Hill of Dunwick radar. High resolution Radar (1km and 2km grid resolutions) suitable to distinguish small scale spatial variations in rainfall intensities are only available at 50 and 100km distances from the Radar stations.

Therefore the area of interest is only covered by the 5km resolution UK composite coverage and unlikely to provide any high resolution supporting data to determine the spatial variation of rainfall intensities over this area.

Figure 4-9: Scottish Radar stations and the 100km (2km) rainfall resolution boundaries



4.4 Summary of rainfall and river flow analysis

From the data available and the above rainfall and FEH DDF analysis we can determine the following key findings:

- The July rainfall event had a uniform pattern over the region generating approximately 50-60 mm in a 24 hour period over the Inverness East area, but with locally intense cells that increased rainfall totals.
- The daily recording rain gauge at Culloden suggests that there was a localised higher intensity rainfall that generated 20-30 mm more than the surrounding area for the July event. This would have increased the rainfall falling over the upper catchment.
- Despite an intense period of rainfall at the start of the event, the July event lasted approximately 20 hours and resulted in rainfall return periods in the region of 9-16 years in the Inverness East area and contributing catchment areas.
- The rainfall return period locally in the region of the Culloden gauge is estimated to be approximately 80 years assuming the shorter duration witnessed at the surrounding tipping bucket recording rain gauges.
- The August rainfall event saw more intense rainfall distributed to the north and west of the Inverness East area with 50-60 mm rainfall depth occurring in a 15 hour period.
- The August rainfall event is estimated to have generated a rainfall return period in the region of 30-45 years, but may have been up to 63 years locally over the Culloden rain gauge.
- Flows on the adjacent Mill Burn catchment were higher for the August flood than the July flood and this reflects the locally heavier rain recorded to the west.

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5 Hydrology and peak flow estimates

5.1 Conceptual approach

Important inputs into estimations of flood hydrology include the analysis of historical events and the estimation of flood flows for a range of annual probabilities or 'design' events. Flood estimates for catchments of this size and type are typically undertaken using the Flood Estimation Handbook (FEH). The FEH offers three methods for analysing design flood flows; the statistical, rainfall-runoff and hybrid methods. In addition to these is the Revitalised Flood Hydrograph (ReFH) method.

- The statistical method combines an estimation of the median annual maximum flood (QMED) at the subject site with a growth curve, either derived from a pooling group of gauged catchments that are considered hydrologically similar to the subject site, or through single site analysis of a nearby gauge.
- The rainfall-runoff method combines design rainfall with a unit hydrograph derived for the subject site. This "design event" approach involves creating a design storm from the FEH rainfall statistics and running it through a simple catchment model to produce a design flood hydrograph.
- Hybrid methods intuitively involve a combination of the two.
- The Revitalised Flood Hydrograph Method (ReFH) was released in early 2006 and made some radical changes over the rainfall-runoff approach that aimed to improve confidence in the results.

The rainfall-runoff method is deemed the most appropriate method for estimating flows on the two burns due to the lack of any available gauged data (nationally and locally, there are few gauged catchments of this size from which to pool data) and the urbanised and small catchments. Furthermore, smaller catchments respond differently to rainfall.

Both the rainfall-runoff and ReFH method separate the flood hydrograph into a baseflow component and a storm runoff component. The baseflow represents the flow in the river before the event. The storm runoff is found by estimating the component of rainfall that contributes to rapid runoff (the net rainfall), then converting the net rainfall into a flow using the unit hydrograph.

5.1.1 Rainfall runoff method

The Rainfall-Runoff method involves constructing a simple unit hydrograph and losses model of the catchment, with three parameters:

- Time to Peak of the Unit Hydrograph (Tp) relating to the catchment response to rainfall,
- Standard Percentage Runoff (SPR) relating to the proportion of rainfall which directly contributes to flow in the river, and
- Base-flow being the quantity of flow in the river prior to the event.

These can be best estimated when there are rainfall and river level or flow data for a number of flood events. Where gauged flows or donor catchments are unavailable, these parameters are estimated using the catchment descriptors derived from the FEH CD ROM v3.

Standard FEH winter design storm profiles are appropriate for rural catchments (URBEXT < 0.125) as floods in Britain normally occur in the winter. On urban catchments however, the summer profile is more appropriate as floods normally occur in the summer and the rainfall events are more peaky and intense due to the nature of convective storms.

5.1.2 Revitalised Flood Hydrograph

This method has superseded the FEH rainfall-runoff method for most fluvial flood risk applications in England and Wales. However, whilst it was not initially calibrated fully across Scotland, due to the lack of Scottish gauges used within the analysis it has never been fully accepted by SEPA for work in Scotland.

5.1.3 Revised catchment areas

Catchment areas and other catchment parameters are derived from the FEH CD ROM v3. A comparison with the default FEH catchment areas, OS mapping and the site visits suggested that the catchment areas for the two burns are in error and needed amendments. The default and revised catchment areas are shown in Figure 5-1 below. A summary of the catchment areas is provided in Table 5-1.

Figure 5-1: Default FEH and amended catchment area boundaries

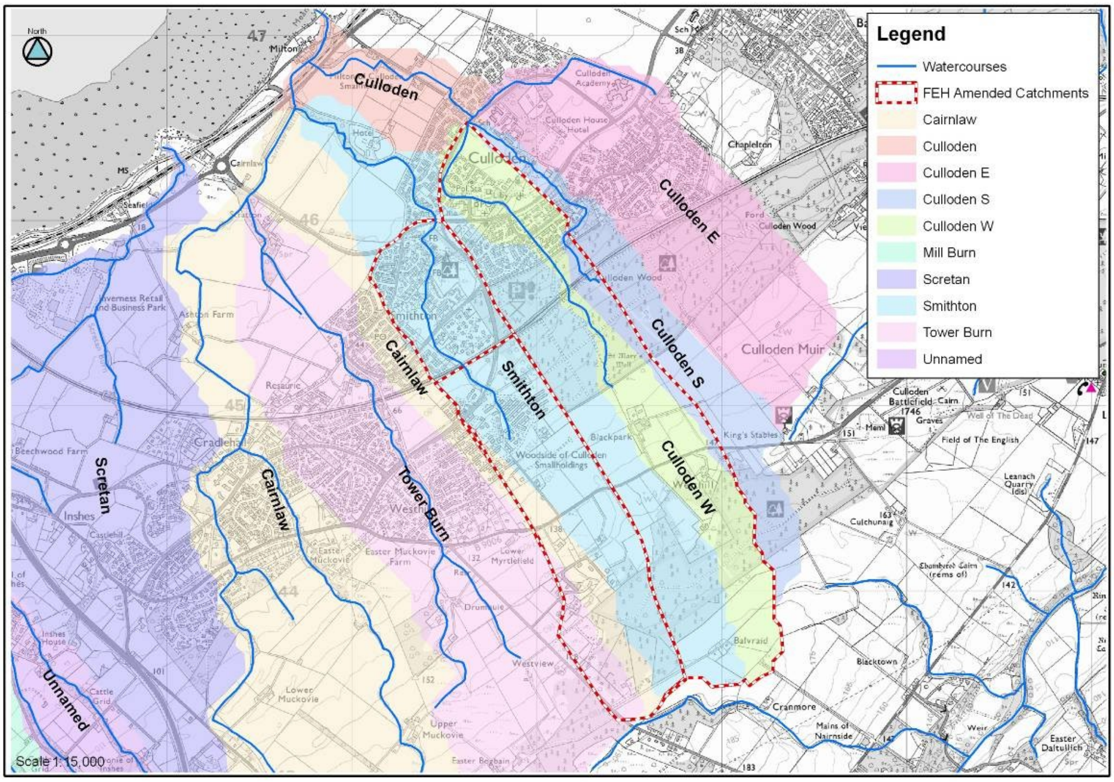

Table 5-1: Default FEH and amended catchment areas (km^2)

Burn	Default FEH	Amended	Difference
Culloden Burn West	0.870	1.438	0.57
Smithton Burn	1.790	1.835	0.05

5.2 Flow estimation

The FEH recommends that wherever possible, estimates of Tp and SPR should be based on gauged data rather than catchment descriptors. Where catchments are ungauged, the FEH recommends that Tp is estimated from a LAG analysis from a donor gauge/catchment and SPR is estimated from BFI (again calculated from a gauged donor catchment).

In this instance the Mill Burn to the west is a gauged catchment (gauged at Diriebught) which although much larger ($9km^2$), is suitably close to the subject site catchments and has comparable catchment descriptors. This gauge has therefore been tested for use as a donor gauge, although confidence in the gauge has been highlighted as an issue by SEPA[8].

SPR is closely related to baseflow index (BFI). The BFI measures the proportion of the long-term runoff that derives from stored sources. Determination of BFI on the Mill Burn was calculated by separation of the flow hydrograph into its rapid response runoff and baseflow

[8] Pers. Comm. Becky Thomson, SEPA

components using the procedure described in the IH report 108. SPR is then calculated using the following equation:

SPR = 72.0 - 66.5 BFI

Tp has been adjusted using the Mill Burn donor catchment by analysing the Tp from LAG (the time between the centroid of rainfall and the runoff peak). The procedure adopted is provided in the FEH[9] and is based on a flood event analysis of a number of gauged events on the donor catchment and subsequent adjustment at the subject sites (a number of peaks were analysed for the period between 2001-2011). The equation used is as follows:

Tp(0) = 0.879 LAG^0.951

The assessment of Tp at the Mill Burn and adjustment to the catchments of interest resulted in a substantial reduction in peak flows. Do to the poor quality of the flow estimates for this gauging station and the fact that this catchment is significantly larger than either of the two subject catchments suggests that the reliance on this estimate of Tp should be used with caution and may result in lower flow estimates and under design of future works. We have therefore provided results for the case with and without Tp adjustment in Table 8-3.

It is recommended that in this instance a precautionary approach is taken and the larger flood flow estimates are used before more detailed estimates (preferably using a short period of gauged data on the Culloden and Smithton Burns and some rainfall recorded within the upper catchment).

The ReFH does not recommend the use of donor sites. More recent research[10] has shown that using the closest available gauge from the ReFH calibration dataset as a donor site appears to offer no benefit on average in comparison with estimating parameters from catchment descriptors. As such the FEH RR revised method has been compared against the unadjusted ReFH methods. A summary of the full details of the methodologies undertaken are provided in Appendix F.

Table 5-2: Culloden Burn West peak flows calculated via the FEH Rainfall-Runoff and ReFH

Return Period	Annual Probability (AP) [%]	Rainfall-runoff with SPR adjustment (m^3/s)	Rainfall-runoff with Tp and SPR adjustment (m^3/s)	Revitalised Flood Hydrograph flow estimate (m^3/s)
2 year	50	0.73	0.46	0.49
5 year	20	1.05	0.65	0.63
10 year	10	1.26	0.79	0.74
30 year	3.33	1.67	1.05	0.91
50 year	2	1.93	1.19	1.01
75 year	1.33	2.10	1.29	1.09
100 year	1	2.25	1.37	1.15
200 year	0.5	2.63	1.59	1.33
200 year + cc	-	3.16	1.91	1.60
500 year	0.2	3.25	1.93	1.62

Table 5-3: Smithton Burn peak flows calculated via the FEH Rainfall-Runoff and ReFH

Return Period	Annual Probability (AP) [%]	Rainfall-runoff with SPR adjustment (m^3/s)	Rainfall-runoff with Tp and SPR adjustment (m^3/s)	Revitalised Flood Hydrograph flow estimate (m^3/s)
2 year	50	0.57	0.37	0.39
5 year	20	0.83	0.51	0.51
10 year	10	0.99	0.61	0.60
30 year	3.33	1.29	0.83	0.73
50 year	2	1.51	0.95	0.81
75 year	1.33	1.65	1.03	0.88
100 year	1	1.77	1.10	0.93
200 year	0.5	2.09	1.28	1.07
200 year + cc	-	2.51	1.54	1.28
500 year	0.2	2.59	1.56	1.31

[9] Flood Estimation Handbook, Volume 4, Chapter 2.2.5.
[10] Faulkner, D.S. and Barber, S. (2009) Performance of the Revitalised Flood Hydrograph Method. *J. Flood Risk Management*, in press.

A further assessment for the purposes of modelling was also undertaken to the catchment at the railway bridge crossing on the Smithton Burn, due to the change in catchment areas to this location. The results for this location are provided in below.

Table 5-4: Smithton Burn peak flows calculated via the FEH Rainfall-Runoff and ReFH

Return Period	Annual Probability (AP) [%]	Rainfall-runoff estimate to the confluence with the Culloden Burn West (m^3/s)	Rainfall-runoff estimate to the railway crossing (m^3/s)
2 year	50	0.57	0.46
5 year	20	0.83	0.67
10 year	10	0.99	0.80
30 year	3.33	1.29	1.04
50 year	2	1.51	1.21
75 year	1.33	1.65	1.32
100 year	1	1.77	1.41
200 year	0.5	2.09	1.65
200 year + cc	-	2.51	1.98
500 year	0.2	2.59	2.04

5.2.1 Summary and checks

A good check for flow estimates is the 1% AP (100 year) growth rate. The 100-year growth rate is typically between 1.8 and 3.0, with smaller catchments typically at the upper end of the scale.

The Smithton Burn 100 year growth curve is 2.97. The Culloden Burn West 100 year growth curve is 3.08. Both are similar and around the common range, suggesting a steep growth curve as would be expected for an upland and narrow catchment.

Small catchment hydrology is inherently uncertain without accurate flow gauges or local rainfall records to help calibrate design estimates.

5.2.2 Uncertainty and recommendations

Small catchment hydrology can be problematic for design due to the lack of observed data within these catchments. It is recommended that flows on the two burns are measured together with rainfall records within the catchments for a period prior to any design works to inform hydrological analysis and obtain best estimates of design flows on the catchment.

5.3 Comparison with previous estimates

It is important to consider the previous estimates for flood flows on the two burns as design works were carried out on these burns following the 2002 floods. The previous flood estimated undertaken in 2003 by Mouchel Parkman were estimated for the 1% AP flood (100 year) and are provided in the table below. The methodology used was not known.

Table 5-5: Comparison between current and previous assessments for the 1% AP flood (100 year)

Burn Return Period	Mouchel Parkman (2003) flow estimate (m^3/s)	Current flow estimate (m^3/s)	Difference (m^3/s)
Culloden Burn West	0.83	2.25	1.42
Smithton Burn	0.89	1.77	0.88
Note that the Smithton Burn has become more urbanised since 2002.			

This indicates that the current estimates of flood flows are more than the previous estimates by approximately 65% on the Culloden Burn West and 24% on the Smithton Burn. The reasons for this increase may be due to either changes in the catchment characteristics or the methodology used. The only catchment characteristics likely to change are the urbanisation within the catchment which has increased since 2003. Methodological changes shouldn't be significant as the standard rainfall-runoff approach has not changed since 2003. However, the changes may be due to the revised catchment areas or the amended SPR (run off) values used in this instance.

5.4 Discussion on peak flows

Flood events are sensitive to a number of factors such as storm (rainfall) depth or return period, storm profile, antecedent conditions and duration. The FEH Rainfall-Runoff approach recommends for design purposes a recommended storm return period that will yield a flood peak of required return period. For rural catchments the design rainfall return period is typically about 1.7 times higher than the flood return period[11]. Table 5-6 gives some common return period combinations from the FEH.

Table 5-6: Equivalent flow peak return periods for a given rainfall return period

Rainfall return period	8	17	50	81	140	247
Flood peak return period	5	10	30	50	100	200

It is not suggested that all rainfall events with a 50 year return period will yield a 30 year flood peak, but that a sufficient correlation exists to suggest these values are representative for a simplified methodology for the design case.

Based on these assumptions, it is reasonable to expect that the July and August rainfall events derived a flow return period of 9 years and 26 years respectively (corresponding to the 15 - 45 year estimates), and up to a 36 year flood corresponding to the 60 year rainfall event recorded at the Culloden rain gauge.

5.5 Event analysis

It is possible to estimate the flows during the event using the Rainfall-Runoff model and the recorded rainfall from the surrounding gauges. This gives a reasonable estimate but is vastly improved by local gauging and is reliant on the nearest rainfall data. This analysis has been carried out in ISIS using the Rainfall Runoff and ReFH units and similar adjustments to catchment areas and SPR as in the above analysis.

This has been done for both catchments and the available rainfall records for both the July and August events. The following results are provided. It should be noted that the rainfall records may not be sufficiently accurate to fully represent the spatial distribution of rainfall in the Culloden area. Therefore the analysis has been repeated by scaling the rainfall inputs to match the total rainfall depths observed and recorded at the nearest daily gauge of Culloden.

Table 5-7: Estimated peak flows for the two catchments based on observed rainfall profiles for the July and August events

Catchment	Event	Peak flow (m^3/s)	Rainfall raised to nearest gauge (Culloden)
Culloden Burn West	July	1.0 (2-5 yr)	1.80 (30-50 yr)
Culloden Burn West	August	1.4 (10-30 yr)	1.77 (30-50 yr)
Smithton Burn	July	0.7 (2-5 yr)	1.31 (30 yr)
Smithton Burn	August	1.0 (10 year)	1.31 (30 yr)

Based on the above analysis the estimated return periods are between 2-5 year return periods for the July event and 10-15 year return periods for the August event. This is based on primarily the nearest TBR gauge at Allanfearn. However, if the Culloden scaled rainfall depths are used, the return periods increase to approximately a 30-50 year flood for both events.

5.6 Review of high flows on the Mill Burn

Using the 13 years of flow data recorded by SEPA on the Mill Burn an estimate of flows was made. The FEH Statistical method was employed using the single site analysis. The general logistic LMOM distribution growth curve was chosen as this gave the most robust estimate of flows. The flow estimates for the Mill Burn are shown in Table 5-8.

[11] ReFH are now the same!

These estimates were compared to the gauging station flow records at the SEPA gauging station. Maximum flows on the 16/17 July 2011 and 6/7 August 2011 were recorded at the SEPA gauging station as 2.9 m^3/s and 5.5 m^3/s.

Table 5-8: Estimated peak flows on the Mill Burn

Years	Annual Probability (AP)	Flow (m3/s)
1000 year	0.1%	27.33
200 year	0.5%	13.23
100 year	1%	9.66
30 year	3.33%	5.53
2 year	50%	1.15

The statistical flow estimation suggests that these events had a return period of approximately 8 and 29 years respectively. In the context of the annual maximum series of flow data recorded over the last 13 years there have been three occasions when flows have equalled or exceeded the event in August 2011 and 4 occasions for the event July 2011.

5.7 Climate change

SEPA's most recent guidance on the impact of climate change is to use a multiplication factor of 20%[12]. The potential effects of climate change on flow values have therefore been considered by multiplying the design flow for the 0.5% AP (200 year) flood by 20%.

Recent guidance for England and Wales[13] has provided regionalised estimates of how climate change will impact upon river flows through the next century based on the UKCP09 projections. Although this information does not support Scottish catchments at present the data is available for the Solway, Tweed river basins and Northumberland. These three regions are presented below to inform the choice of climate change estimates for the Inverness East Burns.

At the moment, current advice is to retain the use of SEPA's 20% increase for climate change for the 2080's. However, it is clear from the recommendations in use in England and Wales that the best estimate of climate change increase in flow by 2080 for Scottish catchments may be as much as 25-30% with a larger degree of uncertainty that should be tested further.

Table 5-9: Comparison between current and previous assessments

Region	Total potential change for 2020s	Total potential change for 2050s	Total potential change for 2080s
Tweed			
Upper range	25%	35%	35%
Best estimate	15%	20%	30%
Lower range	0%	5%	15%
Northumberland			
Upper range	25%	30%	50%
Best estimate	10%	15%	20%
Lower range	0%	0%	5%
Solway			
Upper range	25%	35%	65%
Best estimate	15%	20%	25%
Lower range	0%	5%	15%

5.8 Summary of hydrology

From the above assessment of peak flows we can determine the following key findings:

- A 0.5% AP peak flow on the Culloden Burn West is estimated to be 2.6 m^3/s. A 0.5% AP peak flow of the Smithton Burn is estimated to be 2.1 m^3/s.

[12] SEPA – Technical Flood Risk Guidance for Stakeholders, Version 2, 30th January 2008
[13] Environment Agency (2011). Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities.

- Peak flow estimation on small catchments is inherently uncertain. Without gauges on the burns and tipping bucket rain gauges within the catchment it is difficult to directly confirm a return period for both events.
- Current SEPA guidance suggests that flood estimates in Scotland should be raised by 20% when consideration of future climate change is considered. Current guidance for England and Wales suggests that a range of values should be considered, which in many cases exceed the historic and standard 20% value.
- Flows have been estimated to be similar on both burns and approximately 1.8 m^3/s and 1.3 m^3/s on the Culloden Burn West and Smithton Burn respectively.
- These flows are estimated to be equivalent to a return period of approximately 40 years and 30 years on the Culloden Burn West and Smithton Burn respectively. This would suggest that there is a good chance of flooding recurring on a number of occasions within the lifetime of any scheme.
- A comparison of recorded flows on the Mill Burn suggests that the July event was approximately an 8 year flood and the August Event a 30 year flood. This broadly matches with the rainfall analysis and gives confidence in the estimates provided, albeit with a known higher depth of rainfall further to the east at Culloden.
- It is recommended that flows on the two burns are measured together with rainfall records within the catchments for a period prior to any design works to inform hydrological analysis and improve the estimates of design flows.

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6 Flood events and impacts

6.1 On-site reports of flooding

The following section provides an overview of the July 2011 flooding, in the vicinity of the Smithton Burn and the Culloden Burn West, as detailed in information available from various sources.

6.1.1 Highland Council Post Flood Reports

Highland Council completed three post flood incident reports for the July 2011 event. Two of these reports cover residential areas in the Smithton Burn catchment (Murray Terrace and Smithton Villas), and the other a small residential area on the Culloden Burn West (Loch Lann Court). Each report contains general information on the flooding, photographs and an indicative flood map.

All three cover the July event. It is understood that flood incident reports for August were not completed as the mechanism and magnitude of the August flood was almost identical to the July event for the Smithton Burn.

6.1.2 Additional information from local community

45 questionnaires from the Smithton Burn and Culloden Burn West area were available following the July and August 2011 floods. Each of these was independently reviewed with the information collated and used to supplement the existing flood reports held by Highland Council.

Site walkovers undertaken on the 3 August, 18 August, 6-7 September and the public meeting on the 18 August provided an additional opportunity to gain information relating to flood mechanisms and flooding from the local community.

6.1.3 Scottish Flood Forum - Smithton and Culloden Flood Surgery

The Scottish Flood Forum has held a number of surgeries to offer help and advice and has undertaken a number of home visits within the affected community. Key concerns noted by the public include:

- Surface water run off
- Inadequate drainage
- Erosion to banks / sides of water course
- Flooding of property
- How to protect property from flooding
- Insurance cover, blight, premiums

The biggest worry was inadequate drainage in coping with the surface water with locals observing that gullies and water courses seemed unable to cope with the surface water run-off. The community is also aware of substantial debris that has been washed into the watercourses and although some of this has been removed, residents are still concerned about blockages leading further flooding.

6.2 Flood extents

Flood extents for the July 2011 event were estimated utilising the Highland Council post flood reports. These reports were supplemented with additional information from the local community in the form of questionnaires, onsite discussions and from the public meeting.

Following a review of all of the data available creation of an enhanced (using all available information) July 2011 estimated flood extents was possible. Figures showing the estimated flood extents are shown in Figure 3 to Figure 6.

6.3 Observed flood mechanisms, causes and impacts

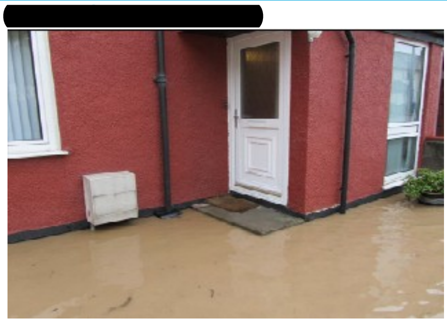
A summary and available photographs of the flood mechanisms, causes and impacts is provided in each of the following sections.

6.3.1 Culloden Burn West

Location	Culvert beneath garden of 20 Redburn Avenue
Event	July only
Mechanism	Culvert capacity exceedence and overland flow.
Cause	Culvert blockage due to woody material and sediment from woodland reach upstream.
Impact	Resulted in flooding to a number of properties on Loch Lann Court, Loch Lann Road and Ferntower Court.
Photos	Material removed from inlet  Culvert blocked during event  Water backing upstream of inlet  Overland flow onto Loch Lann Court  Flooding to [redacted]  Flow to side of [redacted]  Photos provided by [redacted]

6.3.2 Smithton Burn

Location	Culvert adjacent Murray Terrace
Event	July & August
Mechanism	Culvert capacity exceedence and overland flow onto Murray Terrace, Murray Road and Murray Place.
Cause	Erosion of watercourse upstream, sediment deposition and blockage of screen downstream. Possibly exacerbated by blockage of culvert at downstream end.
Impact	Resulted in flooding to a number of properties on Murray Terrace and Murray Place. Significant disruption to traffic due to ponding of water on Murray Road. Contributed to sewer flooding due to exceedence of surface water drainage capacities.
Photos	**Culvert blockage and overland flow**  **Screen cleared following July flood**  **Build up of sediment beneath railway culvert following August flood and sediment removed from channel**   **Ponding on Murray Road and Scottish Water surcharged manhole** 

Location	Culvert adjacent Murray Terrace
Event	July & August
Mechanism	Entry of overland flows into surface water drainage system and sewer capacity exceedence in Smithton Villas. Overland flow from Burn directly into Smithton Villas.
Cause	Overland flows from upstream (see above) and surface water. Exacerbated by low capacity of sewer system. Manhole surcharging on the footpath near Forbes Place led to an overland flow path into Smithton Villas. Burn capacity too low leading to with breach over low bank on left bank exacerbated overbank flows into Smithton Villas.
Impact	Resulted in flooding to a number of properties on Smithton Villas.
Photos	**Flooding to Smithton Villas** [redacted]   **Flooding to Smithton Villas** **Repaired bank were flooding occurred**   **Route of flooding from surcharged manhole near Forbes Place on walkway to Smithton Villas**   Some photos provided by [redacted]

Location	Road flooding from culvert beneath Murray Road
Event	July and August
Mechanism	Overland flow onto road that contributed to greater flow to this location via Murray Terrace.
Cause	Culvert and screen blockage. Culvert is partially blocked at downstream end. Screen is in poor condition. Channel upstream is heavily vegetated and poorly maintained.
Impact	Contributed to flooding of Murray Road.
Photos	Sediment on Murray Road due to overtopping  Culvert inlet 

Location	Road flooding at Woodside of Culloden Smallholdings
Event	Uncertain
Mechanism	Channel capacity exceedence and ponding in fields upstream.
Cause	Overgrown channels and banks may have contributed to flooding.
Impact	Resulted in road flooding upstream of Heights of Woodside.
Photos	Flooding diverted back into channel 

Location	SUDS pond overtopping at Heights of Woodside
Event	Uncertain
Mechanism	SUDS pond filled and breached low point leading to flooding over footpath back into channel and towards property on Gean Place.
Cause	Possible insufficient capacity of SUDS and/or blockage.
Impact	Resulted in footpath flooding downstream of Heights of Woodside.
Photos	New SUDS overflow installed following the August flood  

6.4 Evidence of sediment erosion and deposition

3 August	6 Sept
	

3 August	6 Sept
	

2010	3 August
	

3 August	6 Sept

2010	3 August
	

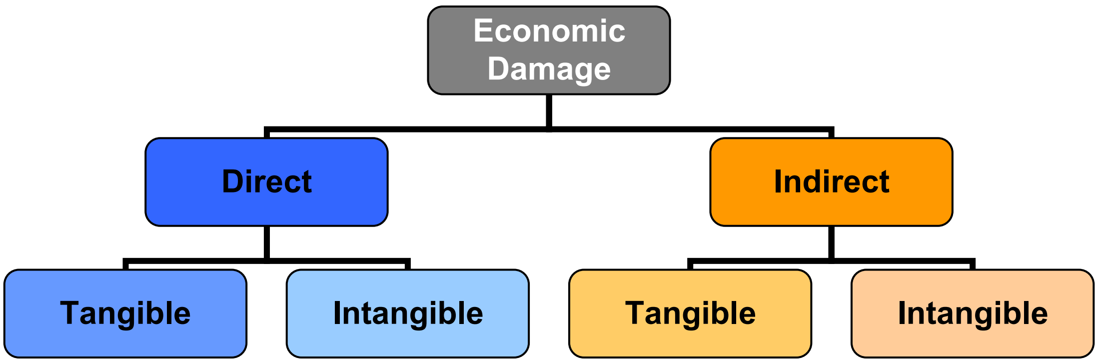
6.5 Flood damage estimates

A number of mainly residential properties were inundated by the recent flooding. A review of the property flood damages as a result of recent flooding can be used to help determine the impact and scale of the flooding and to help quantify the benefits of future works to mitigate the flooding.

Post flood questionnaires taken by the Council along with interviews with homeowners during the site visit and with Highland Council staff have been used to determine property flood depths and flood damages for the recent flooding.

Flood damage assessment can include direct, indirect, tangible and intangible aspects of flooding, as shown in Figure 6-1 below. Direct damages are the most significant in monetary terms, although the MCM and additional research provide additional methodologies, recommendations and estimates to account for the indirect and intangible aspects of flood damage.

Figure 6-1: Components of flood damage



6.5.1 Economic flood damages

Event damages have been calculated for both the July and August flood events. Unfortunately very little evidence and impact of the August flood event was collated by the Council. Flood event data and details on the properties flooded and flood depths were obtained from the following sources:

- Flood questionnaires
- Site visit photographs and discussions with homeowners
- Council GIS and incident reports for the July event.

Flood event damages have been determined using FHRC standard Multi-Coloured Manual (MCM) data. The following assumptions have been made:

- Short duration flooding (less than 12 hours) have been used
- Depth damage curves for properties define by type have been used (information on property age and social group has not been used as the level and quality of the data is not sufficient to make this worthwhile.
- Damage values have been brought up to date to current values using the RPI.
- Intangible health impacts of flooding have been included using the approved proxy value of £200 per household per year (or flood in this case).
- Indirect flood damages excluded from the MCM depth damage curves have been included to account for rental of alternative accommodation (22 weeks @ £90 per week), additional heating costs for drying out (£190) and the additional cost of electricity for running dehumidifiers to accelerate the drying out process (£707 and £1,414 depending on how deep the flooding is).
- The additional costs for emergency services (recommended to be 5.6% of the total damages).

Items excluded from the estimation of flood damages include:

- Cost of car damage (insufficient information available);
- Traffic disruption costs;
- Risk to life;
- Indirect damages to commercial properties; and
- Socio-economic equity.

The depth damage curves available assume that properties are flooded above the property threshold level. These are appropriate and have been used to determine the flood damages for properties inundated above ground floor thresholds as defined by questionnaire responses.

However, many properties in the area affected were not flooded above floor levels, but were flooded below the floor level, with flood waters accessing the property via airbricks. For these property types, the MCM depth damage curves for below threshold levels have been used. The damage associated with this assumes some degree of remedial works is required to dry out the sub-floor level area of the property.

Furthermore, many other properties only observed flooding to gardens, outbuildings, garages and surrounding land. Where no property flooding occurred and only garden and/or garage damages occurred the relevant components of the MCM depth damage curves for a standard residential property have been used to build up a cost for these properties.

6.5.2 Total flood damages

Total cost of flooding has been estimated to be £286,000. This represents the damage that occurred due to the recent floods based on available information. The total damages may be greater than those provided due to low declaration from owners within questionnaires.

A summary of the total estimated flood damages is provided in the table below, with further details and assumptions for each property provided in Appendix E.

Table 6-1: Breakdown of estimated flood damages

Category	Count / flood damage
Total properties flooded above floor levels (based on information from questionnaires)	7
Total properties flooded below floor level (includes the above values)	28
Total properties where only gardens and garages flooded	42
Total properties where only gardens flooded	22
Total direct property flood damage	£224,000
Total drying out costs	£37,000
Total rental accommodation costs	£8,000
Intangible damages	£8,000
Total damages excluding emergency services costs	£277,000
Total damages including emergency services costs	£286,000
Proportion of total for Culloden Burn West	26%
Proportion of total for Smithton Burn	74%

The above estimate of total damages should be noted as an estimate which provides an indicative assessment of the possible damages from the July floods. In some circumstances homeowners may have witnessed higher or lower total costs, additional insurance premiums and other costs associated with the flood response or post flood cleanup/repairs. Furthermore, the social aspects of flooding may far outweigh any economic or tangible aspects that must be considered by the Council in terms of future works to alleviate the flooding.

Based on historic flooding to the two burns, it could be argued that the flooding for this type and scale of event has an approximate frequency of every 10 years. Assuming the same flood damages for a range of return period estimates from 10 years to 500 years would generate an Average Annual Damage (AAD) of £42,900. Based on a 100 year financial period and a present value factor of 29.813, the Present Value damages would be approximately £1.3million. However, assuming a minimum frequency of flooding of 25 years, the estimate of Present Value damages reduces to £600,000.

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