Appendix A

Catchment characteristics

Appendix A Catchment characteristics

A.1 Catchment delineation

The catchment delineation was undertaken in ArcGIS using the following data sources:

- NextMap Digital Terrain Model (DTM)
- Ordnance Survey Vector Map line water features

The watercourses within the catchment were "burned" into the DTM by a depth of 2m and the DTM resolution was then reduced from a 5m to 25m resolution using ArcGIS's "aggregate" function. The "aggregate" function was set to select the minimum cell value within the each new 25m grid cell, this approach helps reduce the impact of man-made interventions such as road embankments in addition to avoiding the loss of river channels in narrow gorges of less than 25m width. The ArcGIS "fill sinks" function was then used to remove any remaining sinks prior to assessing flow direction and flow accumulation in order to assess the catchment outline.

A.2 Estimation of median annual flood

The median annual flood has been estimated for all watercourses in the study area with a catchment of greater than 0.5km^2. This has been estimated using the revised median annual flood by catchment descriptors methodology as described in *Improving the FEH Statistical Method* (Kjeldsen et al, 2007). The equation used is presented below:

$$QMED = 8.3062 AREA^{0.8510} 0.1536^{\left(\frac{1000}{SAAR}\right)} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

- Area – the catchment area was estimated using the flow accumulation derived as part of the catchment delineation process
- SAAR – the average annual rainfall was based on the CEH Effective Rainfall data set.
- FARL – index of flood attenuation attributable to reservoirs and lakes, in this case it was assumed that FARL =1.0.
- BFIHOST – base flow index derived using the Hydrology of Soil Types classification.

A.3 Estimation of unit stream power

The unit stream power of all watercourses within the study area with a catchment of greater than 0.5km^2 was assessed based on the following equation:

$$\omega = \frac{\rho g Q S}{w}$$

- ρ - the density of water (1000 kg/m3)

- g - the acceleration due to gravity (9.8m/s)
- Q - discharge rate (in this case QMed was adopted)
- S – channel slope (m/m)
- w – channel width (m). In this instance the channel width was estimated using the relationship between channel width and QMed presented in FEH Vol 3, S5.2. QMed = 0.182 x channel width$^{1.98}$

A.4 Baseline Flood Estimation Single Site statistical analysis

A.4.1 Allan Water at Kinbuck

Name	Allan at Kinbuck		NN 792053
Station ID	37		
National Archive Number	18001		
Catchment Area	161	Sq Km	
Period of Record	1957	-2009	
Gauge Board Zero	93	m AOD	
Bankfull Stage	3.6	m	
Length of Record:	53	Years	
Mean Annual Flood (FSR):	74.3	Cumecs	

National River Flow Archive information:

Station Description

Velocity-area station; stage recorder sited 40m u/s of twin-arch bridge which acts as control at all stages. Gabions installed in 1980 beneath one arch to stabilise control. Steep section contains all floods. Stable rating, well defined throughout full range. Flows are broadly natural. River level protected by SOAEFD.

Catchment Description

River flows through broad flat valley. Lateral tributaries drain steep hillsides. Bedrock predominantly ORS; 85% overlain by superficial deposits. Land use predominantly grassland with some arable and forest.

Factors Affecting Runoff

N: Natural to within 10% at the 95 percentile flow.

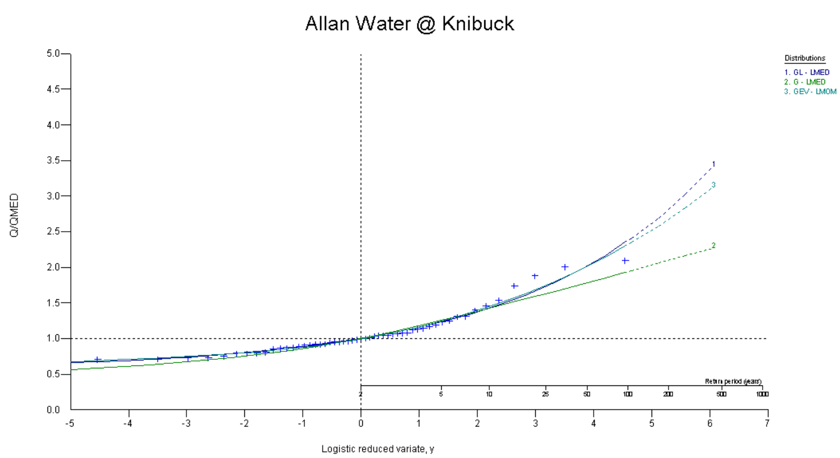

Figure A-1: Comparison of growth curves for a range of distributions

The Single Site Analysis was undertaken using the FEH WIN-FAP software. The GEV-LMON distribution was adopted as it provided the best fit to the observed growth curve.

Rank		Date		Stage (m)	Discharge (cumecs)
1	14	DEC	2006	3.675	144.854
2	26	JAN	2008	3.592	138.570
3	16	JAN	1993	3.74	130.01
4	19	NOV	2009	3.342	120.507
5	9	JAN	2005	3.136	106.511
6	1	JAN	1991	3.29	100.83
7	20	OCT	1998	3.22	96.56
8	10	DEC	1994	3.11	90.78
9	31	DEC	1983	3.11	90.5
10	30	JAN	1974	2.98	86.4
11	1	OCT	1985	3.01	85
12	9	AUG	2004	2.754	82.574
13	17	DEC	1966	2.88	80.9
14	28	JUL	1958	2.84	78.8
15	15	NOV	1978	2.83	78.2
16	6	OCT	1990	2.87	77.2
17	9	MAR	1989	2.78	74.7
18	2	NOV	1969	2.76	74.6
19	11	FEB	1962	2.75	74.1
20	28	FEB	1999	2.793	73.343
21	28	FEB	2007	2.58	72.58
22	3	NOV	1979	2.72	72.5
23	7	JAN	1992	2.77	72.3
24	23	JAN	2002	2.76	71.66
25	26	SEP	1981	2.73	70.1
26	21	OCT	1971	2.66	69.5
27	29	NOV	2003	2.518	69.162
28	28	OCT	1996	2.7	68.45
29	29	OCT	2000	2.676	67.46
30	13	JAN	1984	2.66	66.7
31	21	FEB	1995	2.66	66.67
32	17	FEB	1997	2.65	66.13
33	11	DEC	1972	2.59	66
34	11	OCT	1968	2.58	65.5
35	4	DEC	1986	2.61	64.1
36	7	OCT	1977	2.54	63.6
37	10	JAN	1965	2.54	63.6
38	22	FEB	1970	2.53	63.1
39	11	DEC	1961	2.52	62.7
40	26	MAR	1987	2.55	61.5
41	18	APR	1988	2.53	60.4
42	11	FEB	2001	2.527	60.305
43	21	NOV	1963	2.46	59.8
44	19	DEC	1982	2.5	59.1
45	20	JAN	1975	2.37	55.7
46	17	MAY	1976	2.35	54.8
47	27	FEB	1967	2.35	54.8
48	25	DEC	1960	2.350	54.800
49	23	DEC	1980	2.380	51.900
50	11	DEC	1957	2.240	50.500
51	14	SEP	1964	2.260	50.100
52	19	JUN	1973	2.220	49.200
53	17	DEC	1959	2.110	48.800

Table A-1: AMAX data for gauge

A.4.2 Allan Water at Bridge of Allan

Name	Allan at Bridge of Allan		NS 786 980
Station ID	036		
National Archive Number	018005		
Catchment Area	210	Sq Km	
Period of Record	1971	-	
Gauge Board Zero	11.15	m AOD	
Bankfull Stage	3m		
Length of Record:	1930	Years	
Mean Annual Flood:	91	Cumecs	

<u>National River Flow Archive information:</u>

<u>Station Description</u>

Velocity-area station; recorder sited in natural reach with vertical stone wall on rb. Lb steep to 2.6m. Flood rating stable but large boulders make c/m a problem at low flows. As site is within a caravan park the low flow control is susceptible to rearrangement by children. Station useful for obtaining flood data, as flooding frequently occurs in the town of Bridge of Allan.

<u>Catchment description</u>

The Allan Water occupies a broad flat valley with steep lateral tributaries. Bedrock predominantly Old Red Sandstone; ~85% overlain by superficial deposits. Land use grassland with some arable and forest cover.

<u>Factors Affecting Runoff</u>

I: Runoff reduced by industrial and/or agricultural abstraction.

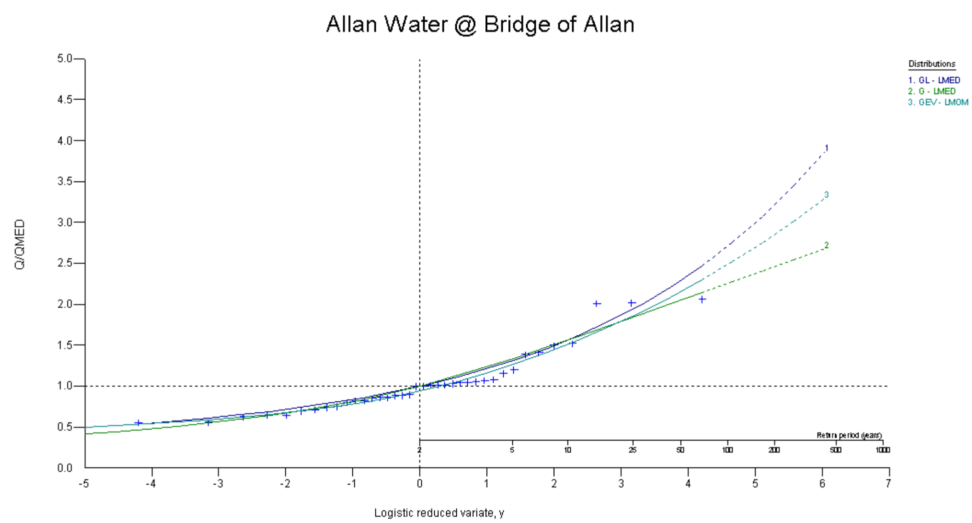

Figure A-2: Comparison of growth curves for a range of distributions

The Single Site Analysis was undertaken using the FEH WIN-FAP software. The GEV-LMOM distribution was adopted as it provided the best fit to the observed growth curve.

Rank		Date		Stage (m)	Discharge (cumecs)
1	14	Dec	2006	2.495	182.27
2	26	JAN	2008	2.475	178.65
3	16	JAN	1993	2.47	177.75
4	10	DEC	1994	2.21	134.65
5	20	OCT	1998	2.196	132.53
6	1	JAN	1991	2.143	124.67
7	10	JAN	2005	2.129	122.64
8	31	DEC	1983	2.01	106.2
9	1	OCT	1985	1.98	102.27
10	28	FEB	1999	1.927	95.54
11	20	FEB	1997	1.92	94.68
12	22	FEB	1995	1.91	93.44
13	28	OCT	1996	1.9	92.34
14	23	JAN	2002	1.898	91.98
15	9	AUG	2004	1.893	91.37
16	8	JAN	1992	1.88	89.81
17	30	JAN	1974	1.88	89.81
18	15	NOV	1978	1.88	89.81
19	6	OCT	1990	1.87	88.61
20	11	SEP	3900	1.868	88.37
21	8	DEC	1979	1.79	79.4
22	4	DEC	1986	1.78	78.29
23	28	FEB	2007	1.778	78.07
24	13	JAN	1984	1.76	76.1
25	26	SEP	1981	1.76	76.1
26	11	FEB	2001	1.751	75.12
27	9	MAR	1989	1.73	72.88
28	21	OCT	1971	1.73	72.88
29	27	MAR	1987	1.71	70.78
30	7	OCT	1977	1.67	66.69
31	26	MAY	1972	1.66	65.68
32	18	APR	1988	1.63	62.74
33	19	DEC	1982	1.62	61.77
34	22	JAN	1975	1.57	57.08
35	23	DEC	1980	1.57	57.08
36	17	MAY	1976	1.55	55.26
37	29	NOV	2003	1.482	49.34
38	19	JUN	1973	1.48	49.18

Table A-2: AMAX data for gauge

A.5 Comparison using other hydrological methods

To assist in putting the hydrological analysis into context three alternative methods have been applied to the Allan Water at Bridge of Allan and Kinbuck.

- Institute of Hydrology, Small Catchments Method (IH124)
- Flood estimation handbook, rainfall-runoff method
- Revitalised flood hydrograph method

These methods have been applied using catchment descriptors extracted directly from the FEH CD v3. The results of the alternative analyses are presented in Table A-3 and Table A-4.

Return period (yrs)	SCS baseline (cumecs)	FEH single site (cumecs)	IH124 (cumecs)	FEH R-R (cumecs)	ReFH (cumecs)
2	47.3	82.7	85.9	86.0	98.6
10	99.2	132.4	134.0	138.2	140.7
50	177.6	189.7	204.8	195.7	182.4
200	277.6	251.0	300.2	250.2	234
500	366.0	299.2	386.1	296.3	280.1

Table A-3: Comparison of the hydrological analysis results for the Allan Water at Bridge of Allan

Return period (yrs)	**SCS baseline (cumecs)**	**FEH single site (cumecs)**	**IH124 (cumecs)**	**FEH R-R (cumecs)**	**ReFH (cumecs)**
2	44.1	68.6	70.3	73.77	86.13
10	91.7	99.9	109.7	119.94	123.83
50	163.2	139.3	167.6	170.63	161.86
200	254.4	185.0	245.7	218.65	208.47
500	377.8	223.2	316.2	259.15	250.43

Table A-4: Comparison of the hydrological analysis results for the Allan Water at Kinbuck

A.6 Hydrological assessment using Soil Conservation Service Runoff Curve Number methodology

A.6.1 Introduction

The Soil Conservation Service's (SCS) Runoff Curve Number hydrological methodology provides a methodology for quantifying the impact of land use change on flood flow generation. The method is reported in Urban Hydrology for Small Watersheds TR-55 (USDA, 1986). Originally the method was developed in order to facilitate the hydrological assessment of urbanising catchments in North America but its principles can be applied in reverse to assess the impact of natural flood management measures. A flow chart of how the methodology has been applied to the Allan Water catchment using GIS has been provided in Figure A-3.

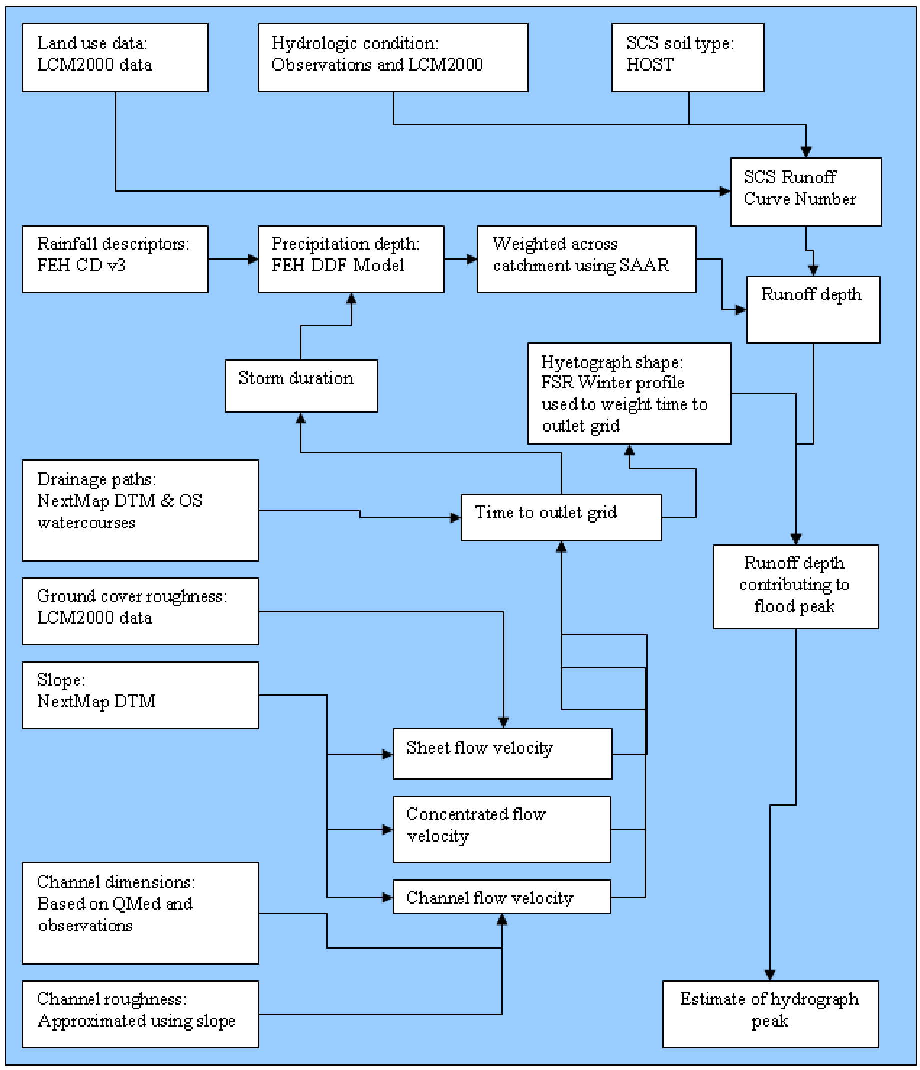

Figure A-3: Flow chart summarising how the SCS Runoff Curve Number hydrology method has been applied to the catchment

A.6.2 Estimation of time to peak

The time to outlet was calculated for the entire catchment on a 25m grid. In order to calculate the time to outlet the surface flow was divided into three classes as recommended by TR55.

- Sheet flow – the slow flow of water through vegetation
- Concentrated flow – the flow of water through normally dry localised topographical troughs
- Channel flow – the flow of water along recognisable watercourses

The TR55 methodology does not include a means of accounting for groundwater flow and only includes a means of assessing surface runoff. Given that natural flood management measures will have little if any impact on groundwater flows this simplification is seen as appropriate.

A.6.2.1 Estimation of sheet flow velocity

The sheet flow velocity was estimated for all cells with an upslope drainage catchment of less than 0.25Ha (2500m^2) using Mannings equation.

The Mannings roughness was varied according to LCM2000 landuse, no account of hydrological condition was made when estimating sheet flow roughness. The adopted roughnesses were based on guidance contained within TR55.

LCM2000 classification	Applied manning's for sheet flow
Broad leaf woodland	0.5
Coniferous woodland	0.5
Arable	0.1
Horticulture	0.1
Improved grassland	0.15
Set-aside grassland	0.2
Neutral grassland	0.2
Calcareous grassland	0.2
Acid grassland	0.2
Bracken	0.5
Dense dwarf shrub heath	0.6
Open dwarf shrub heath	0.5
Bog	0.6
Inland water	0.01
Bare ground	0.05

LCM2000 classification	Applied manning's for sheet flow
Sub-urban	0.02
Urban	0.015
Littoral rock	0.025

Table A-5: Manning's numbers used in the assessment of sheet flow velocity

A.6.2.2 Estimation of shallow concentrated flow velocity

The velocity of shallow concentrated flow was calculated based on slope as recommended in TR55. The TR55 methodology does provide an alternative shallow concentrated flow velocity for urbanised areas however given the relatively insignificant area of the catchment which is urbanised tied to it being close to the catchment outlet and therefore unlikely to contribute to the peak of flood events therefore the rural shallow concentrated flow was applied across the entire study area. The shallow concentrated flow velocity function is summarised in Figure A-4.

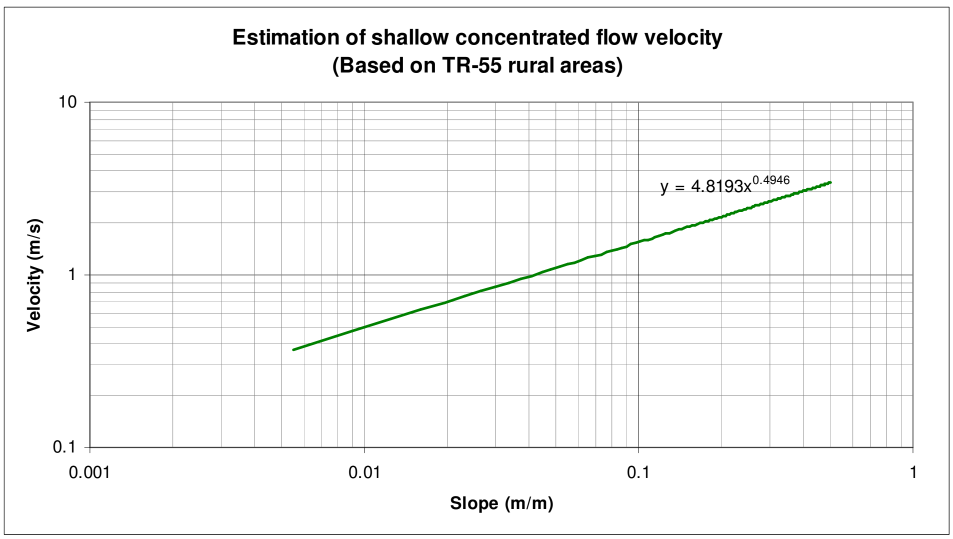

Figure A-4: Summary of the estimation of shallow concentrated flow velocity based on the recommendations of TR55

A.6.2.3 Estimation of channel flow velocity

The channel flow velocity was calculated for all watercourses with a catchment area of greater than 0.25km^2, this was broadly equal to the point at which watercourses are shown on OS 25k mapping. The analysis was undertaken in ArcGIS on a 25m grid resolution and was conducted using a simplified channel cross-section as shown in Figure A-5. The channel (and floodplain) flow velocity was solved using a simple iterative algorithm within GIS for each grid cell identified as being a watercourse within the catchment.

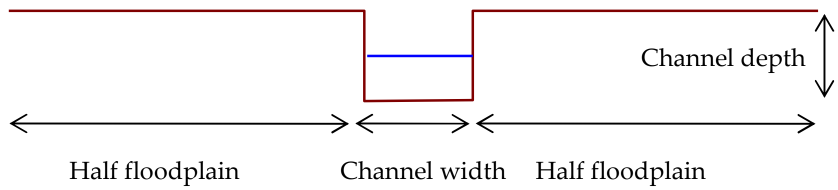

Figure A-5: Schematic of the simplified channel cross-section used in the flow routing model

For the baseline case the floodplain roughness was taken to be 0.04. Floodplain width was taken to be equal to one tenth of the inverse of the channel slope, hence a channel slope of 0.01 was assumed to have a floodplain width of 10m. The relationship between floodplain width and channel slope was based on observations made at representative points across the catchment.

The channel Manning's roughness was estimated for all river channels based on the bed slope. This was completed by estimating the roughness of a number of reaches of known slope across the catchment to generate the relationship shown in Figure A-6. The channel width was based on the previously estimated bankful channel width generated for the stream power analysis.

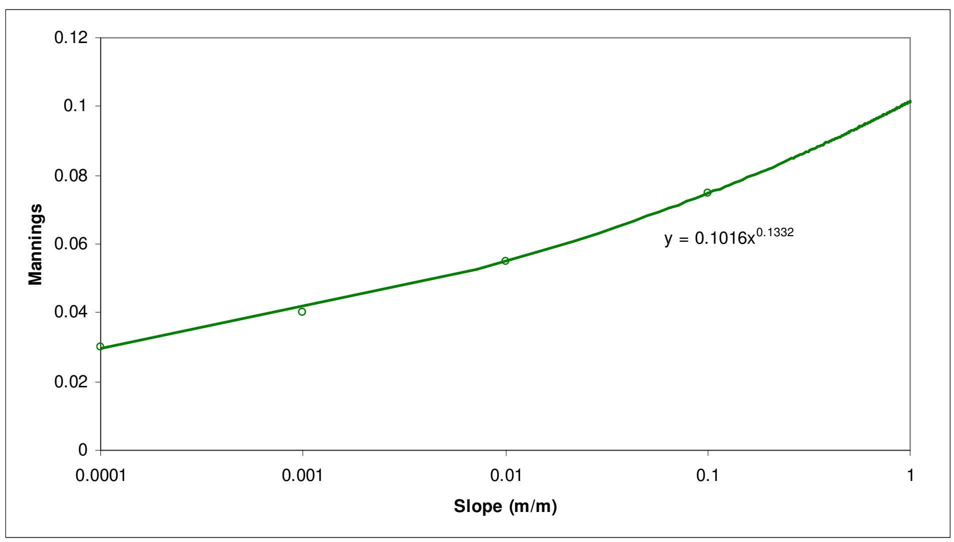

Figure A-6: The adopted relationship between channel slope and channel Manning's roughness

A.6.3 Assignment of runoff curve numbers

Runoff curve numbers were assigned based on landuse and soil type. The existing catchment landuse was assessed using LCM2000 data as shown in Table A-6. The soil type was assigned based on Standard Percentage Runoff from the HOST data using the relationship shown in Table A-7.

LCM2000 code	LCM description	Soil A	Soil B	Soil C	Soil D	SCS description
11	Broad leaf woodland	36	60	73	79	Fair, woods (assumption of storm in winter)
21	Coniferous woodland	36	60	73	79	Fair, woods
41	Arable	74	83	88	90	Good, fallow ground (assumption of storm in winter)
42	Horticulture	74	83	88	90	Good, fallow ground (assumption of storm in winter)
51	Improved grassland	68	79	86	89	Poor, pasture
52	Set-a-side grassland	30	58	71	78	Meadow
61	Neutral grassland	39	61	74	80	Good, pasture
71	Calcareous grassland	39	61	74	80	Good, pasture
81	Acid grassland	39	61	74	80	Good, pasture
91	Bracken	35	56	70	77	Fair, brush
101	Dense dwarf shrub heath	30	48	65	73	Good, brush
102	Open dwarf shrub heath	48	67	77	83	Poor, brush (muirburn)
121	Bog	85	85	85	85	Bespoke (see Figure A-7)
131	Inland water	100	100	100	100	Open water
161	Bare ground	77	86	91	94	Fallow, bare soil
171	Suburban	61	75	83	87	Residential, 1/4 acre plots
172	Urban	89	92	94	95	Urban- Commercial and business
201	Littoral rock	98	98	98	98	Paved parking lots, roofs and driveways

Table A-6: Assignment of runoff curve numbers based on LCM2000 code

Standard Percentage Runoff (HOST)	SCS Soil Class	HOST soil classes
<10%	A	1, 2, 13
10-20%	B	3, 4, 5, 7, 11
20-40%	C	6, 8, 9, 16, 17, 18, 20, 28
>40%	D	10, 12, 14, 15, 19, 21, 22, 23, 24, 25, 26, 27, 29

Table A-7: Summary of the conversion used for HOST soil classes to SCS soil classes

In the absence of a published Curve Number for moorland/bog a runoff curve number of 85 was estimated based on a comparison between the runoff from HOST class 29 using the FEH's Dynamic Percentage Runoff and the runoff generated by a range of SCS Curve Numbers as shown in Figure A-7. It is accepted that Curve Number 85 does not give a good match to the runoff generated by HOST class 29 however the match is acceptable for rainfall depths over 100mm, which is approximately equal to a 1 in 2 year 16 hour rainfall event in the wet upland areas where bog is found in the catchment.

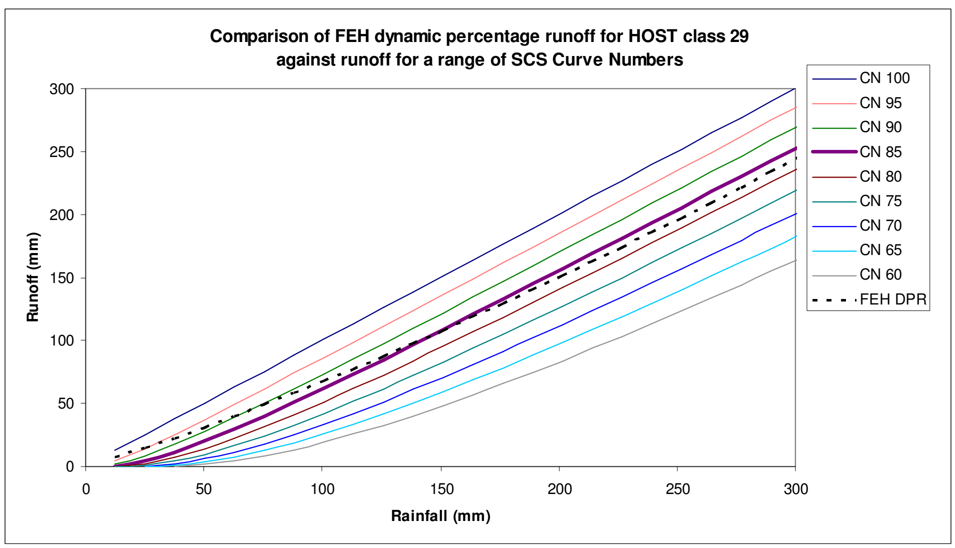

Figure A-7: Comparison of the runoff generated by HOST class 29 using the FEH Dynamic Percentage Runoff and a range of SCS Curve Numbers

A.6.4 Design precipitation event

The design precipitation events were selected using the Flood Estimation Handbook's Depth Duration Frequency (DDF) model. The input parameters for the DDF model were the mean descriptors extracted from the FEH for the entire Allan Water catchment. The average time of concentration for the Allan Water at Bridge of Allan was identified as 8.4hrs, following the recommendations detailed in TR-55 a selection of storm durations around 70% longer than the average time to peak were quantified as detailed in Table A-8.

Return period (yrs)	Average rainfall depth (14hr) (mm)	Average rainfall depth (15hr) (mm)	Average rainfall depth (16hr) (mm)	Average rainfall depth (18hr) (mm)
2	35.0	35.9	36.9	38.7
10	51.0	51.0	53.6	56.0
50	71.1	71.1	74.5	77.6
100	81.9	81.9	85.6	89.0
200	94.2	94.2	98.3	102.1
500	113.2	115.7	118.0	122.3

Table A-8: Catchment average rainfall depths for a range of storm durations and rainfall return periods used in the synthesis of flood hydrographs on the Allan Water catchment for the baseline (existing) case

The design rainfall depths were not scaled to account for storm area, with a point rainfall being applied to the whole catchment. For a 216km^2 catchment with a storm duration of 16 hours the Area Reduction Factor could be expected to be in the region of 0.93.

The Flood Studies Report 75% Winter Rainfall Profile was used as a donor hyetograph for the design rainfall events within the catchment. In applying the hyetograph to the catchment it was assumed that the rainfall event commences across the entire catchment at the same time with the rainfall intensity being weighted based on SAAR. The 75% donor hyetograph was included within the assessment using a weighting derived using the time to outlet grid. This weighting was based on the assumption that rain falling on cells with a time to outlet equal to half the storm duration would contribute most to the hydrograph peak, while runoff generated from rain falling on cells with a very short or very long time to outlet would arrive either before or after the flood peak. Effectively this approach is the same as calculating the peak of a unit hydrograph. Figure A-8 provides further information on how the method has been applied. Drawing WBAWPP023 shows the weighting factor calculated for the entire catchment for the 16hr storm which was found to generate the maximum discharge at Bridge of Allan.

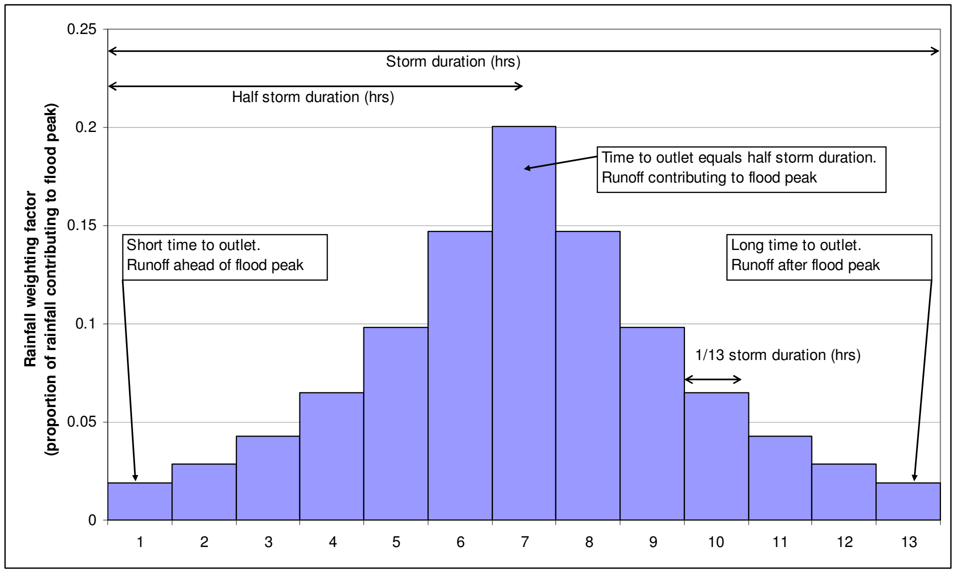

Figure A-8: Summary of the derivation of rainfall weightings based on time to outlet FSR standard winter storm profile

Return period (yrs)	Peak flow at Bridge of Allan (cumecs)			
	14hr storm	15hr storm	16hr storm	18hr storm
2	42.4	44.6	47.3	47.1
10	-	-	99.2	-
50	-	174.0	177.6	172.6
100	-	-	223.1	-
200	-	-	277.6	-
500	-	361.7	366.0	351.6

Table A-9: Estimated flood hydrograph peaks on the Allan Water at Bridge of Allan estimated using the alternative SCS Curve Number methodology for the baseline (existing) case