LANGHOLM
Flood Protection Scheme

Hydrological Analysis

MAKING COMPLEX EASY

Dumfries & Galloway COUNCIL

Document Control Sheet

Client:	Dumfries and Galloway Council					
Project Title:	Langholm Flood Protection Scheme					
Document Title:	Hydrological Analysis					
Document No:	IBE1511Rp04					
This Document Comprises:	**DCS**	**TOC**	**Text**	**No. of Appendices**	**List of Figures**	**List of Tables**
	1	1	24	2	8	8

Rev.	Status	Author(s)	Reviewed By	Approved By	Office of Origin	Issue Date
D01	Draft	P. Rath	B. Quigley	A. Jackson	Belfast	10/12/2018
D02	Draft	P. Rath	B. Quigley	A. Jackson	Belfast	26/03/2019
F01	Draft	P. Rath	B. Quigley	A. Jackson	Belfast	28/05/2019

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

1 INTRODUCTION

The hydrological analysis for the Langholm Flood Protection Scheme focuses on fluvial flood risk to the town of Langholm, located in Dumfries and Galloway in Southern Scotland. The main source of flood risk arises from the River Esk and its tributary inflows from the Wauchope Water and the Ewes Water. The River Esk can be considered well gauged for the purposes of historical flood analysis and design flood flow estimation having a long term, flood rated hydrometric gauging station located 11km downstream of Langholm. This analysis relates predominantly to this record through the use of statistical methodologies set out in the Flood Estimation Handbook (FEH) (Reed & Robson, 1999). While FEH methods implement robust statistical procedures for flood flow estimation, these have been supplemented with the FEH Revitalised Flood Hydrograph methods (ReFH2) (Kjeldsen, Stewart, Packman, Folwell, & Bayliss, 2005).

1.1 CATCHMENT REVIEW

The River Esk is formed at the junction of the Black Esk, which rises on the northeast slope of Jock's Shoulder, and the White Esk, which rises on the southern slopes of Ettrick Pen. The two headstreams meet in Castle O'er Forest at the southeast corner of Eskdalemuir before continuing as the River Esk through Bentpath and Langholm. The River Esk discharges to the Solway Firth and its principal tributaries within the study area are Megget Water, Wauchope Water and Ewes Water.

The contributing catchment area of the River Esk just downstream of Langholm is approximately 413 km^2. The River Esk catchment is natural and upland; it has mostly impermeable bedrock with approximately two thirds superficial deposits. The land use is predominately rough grazing with more than a third forestry with minimal flood plains. The only main reservoir within the study catchment is the Black Esk Reservoir located in the upper catchment of the Black Esk catchment.

Table 1.1 provides the main catchment descriptors for the subject catchment and sub-catchments catchments that are to be hydrologically assessed in this study (obtained from the FEH CD-ROM v3).

Table 1.1 Summary of Main Catchment Descriptors

Catchment	Area (km^2)	SAAR (mm)	PROPWET	DPSBAR (m/km)	BFIHOST	FARL
River Esk	414.53	1445	0.62	174.0	0.42	0.993
Wauchope Water	40.94	1380	0.6	150.2	0.384	1.0
Ewes Water	79.15	1391	0.6	256.6	0.48	1.0

The Ewes Water is the steepest catchment (indicated by the DPSBAR descriptor) which has the effect of accelerating surface runoff, leading to a more flashy response to rainfall. All three catchments can be described as having average baseflow index values and there is little to no attenuation throughout the catchments (indicated by the FARL descriptor). The main study catchments are shown in Figure 1.1.

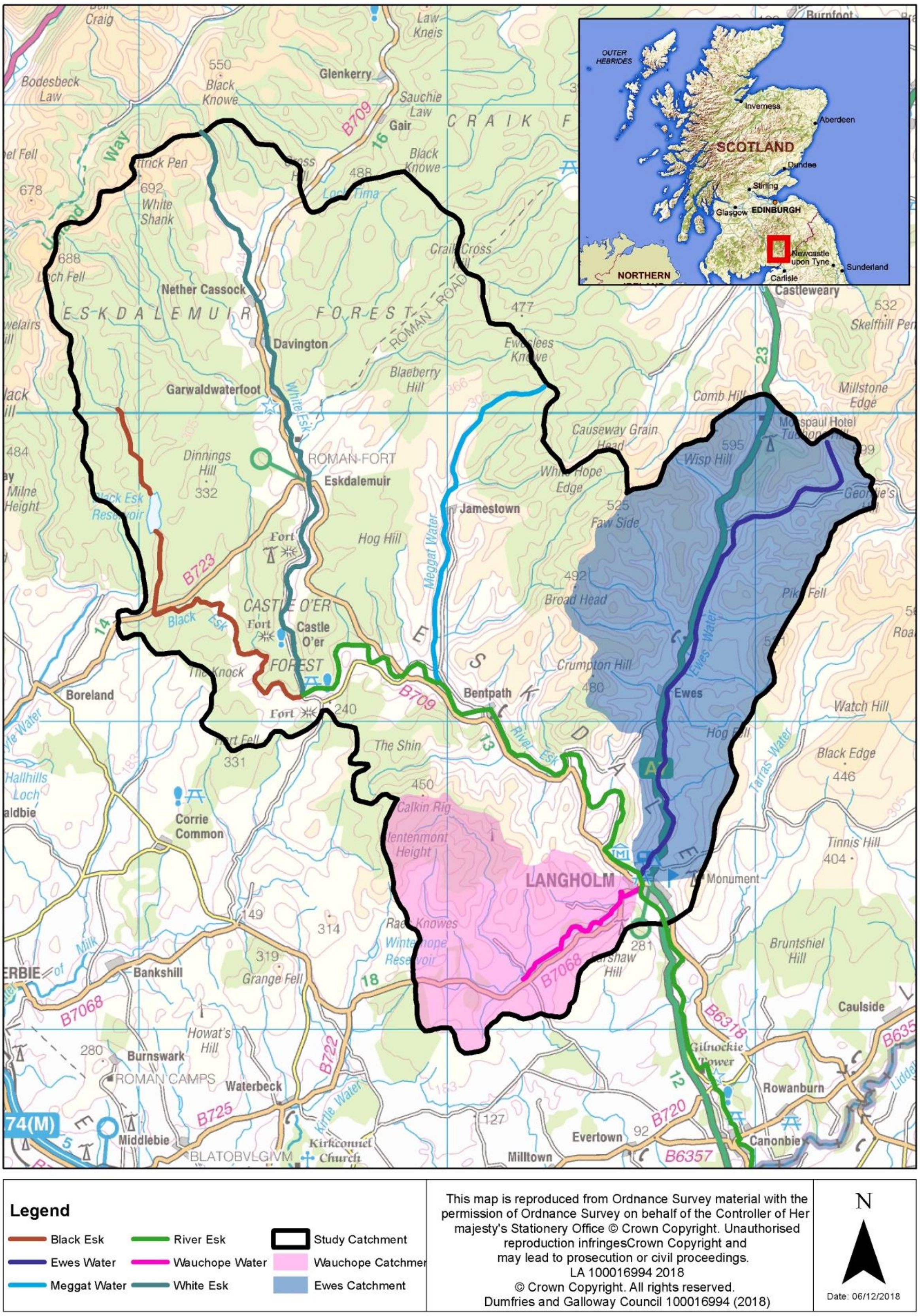


Figure 1.1 Study Catchment(s) and Main Tributaries

1.1.1 Historic Flood Events

As part of this study, RPS reviewed historic flood records in the Langholm area. Sources of information on events include internet searches, community magazines, consideration of SEPA hydrometric data, a review of the Chronology of British Hydrological Events and information provided by Dumfries and Galloway Council. Further information on the calibration/validation data recorded in relation to these events is provided within the hydraulic modelling chapter.

Table 1.2 lists recorded historic flood events that adversely impacted on the town of Langholm. The most recent notable flood event occurred in December 2015 (Storm Desmond), when the River Esk at Langholm burst its banks leading to inundation of property on George Street.

Table 1.2 Langholm Historic Fluvial Flood Records

Date	Scale or Magnitude	Data Source
1990	A7 at Langholm was closed due to flooding. Buccleuch park flooded.	SEPA
Oct 2005	Street level fluvial flooding occurred in Annandale & Eskdale – Langholm.	BBC News/SEPA
Nov 2009	Record rainfall (an expected maximum of 75mm) prompted rivers to overflow, resulting in numerous road closures.	BBC News
Aug 2012	A number of small watercourses in Langholm flooded in 2012 affecting private properties and the A7 Trunk Road.	SEPA/ Dumfries and Galloway Council.
Dec 2015	The River Esk at Langholm burst its banks and homes within George Street in the town were evacuated by the Police and a care centre was established.	Itv News/ Dumfries and Galloway Council.

1.1.2 Available Hydrometric Data

RPS consulted with SEPA hydrometry and the National River Flow Archive (NRFA) regarding available hydrometric data within the River Esk catchment that could inform design flow estimations. Esk at Canonbie (77002) gauging station was identified which is located approximately 1.2km upstream of the River Esk/Liddel Water confluence. The catchment area at the gauge is approximately 495 km^2 and the study catchment is nested within this area. The Esk at Canonbie (77002) is a valuable source of flow information given the fact that it encompasses the study catchment.

The Esk at Canonbie (77002) peak flow data on the NRFA extends from 1962 to 2015 (hydrological years). Crucially the record period includes the December 2015 flood event. SEPA hydrometry supplied additional flow data allowing the maximum flow recorded in the 2016 hydrological year to be included in the analysis.

2 FLOOD FREQUENCY ANALYSIS

The methods employed in this analysis reflect the current best practice guidance for UK catchments as set out in the FEH. The analysis primarily focuses on the statistical methods grounded in hydrometric data and supplemented with the ReFH2 approach.

The FEH aims to provide clear guidance to practitioners concerned with flood frequency estimation. Much of the relevant information, including catchment descriptors and depiction of catchment boundaries by digital terrain model, is provided in digital format. The procedure introduces and is based on a number of fundamental concepts including the return period (T), index flood (Q_{med}), Annual Maxima (AMAX) and the flood frequency curve. These concepts are defined as follows:

Return Period (T): a measure of the rarity of a flood (or reoccurrence interval). The return period represents the average interval between years containing large floods.

Annual Maxima Series (AMAX): in terms of flood flow hydrology this the maximum recorded flow for each hydrological year on record. A hydrological year spans from 1st October to 30th September.

Index Flood (Q_{med}): can be thought of as a middle sized flood for a particular catchment. The FEH generally adopts the median annual maximum flood, which is the flow expected to be exceeded on average every 2 years. A robust estimate of Q_{med} can be obtained from the AMAX at a given gauge. Ungauged sites require an estimate of Q_{med} using catchment descriptors. These estimates may be adjusted/improved using gauged catchments that are geographically close and/or hydrologically similar to the ungauged subject catchment using FEH methodologies.

Flood Frequency Curve: relates flood size to flood rarity (generally return period). The curve can be fitted to record peak flow data (such as the AMAX) for a range of statistical distributions. This is known as a single site analysis. For ungauged catchments, flood data from a group of hydrologically similar gauged catchments can be amalgamated and used to generate a best estimate flood frequency curve. This is known as the statistical pooling approach. A hybrid approach using the single site analysis and a pooling group of other gauged sites is known as an enhanced single site analysis. The enhanced single site technique is a joint method combining both the ungauged pooling approach and the single site flood frequency curve from the gauged records such that the gauge is given additional weight within the pooling group. An enhanced analysis is only suitable for gauged catchments with data that is suitable for pooling.

2.1 HISTORIC EVENT ANALYSIS

The first step in understanding the flood frequency conditions in relation to the subject catchment and its sub-catchments is the statistical analysis of the single site flood frequency behaviour recorded at Esk at Canonbie (77002) gauging station. This analysis has been carried out in line with the procedures set out in the FEH using the AMAX series records.

2.1.1 Esk at Canonbie (77002)

The Esk at Canonbie (77002) provides 55 consecutive years of peak flow information. The AMAX series for this gauge is presented in Figure 2.1.

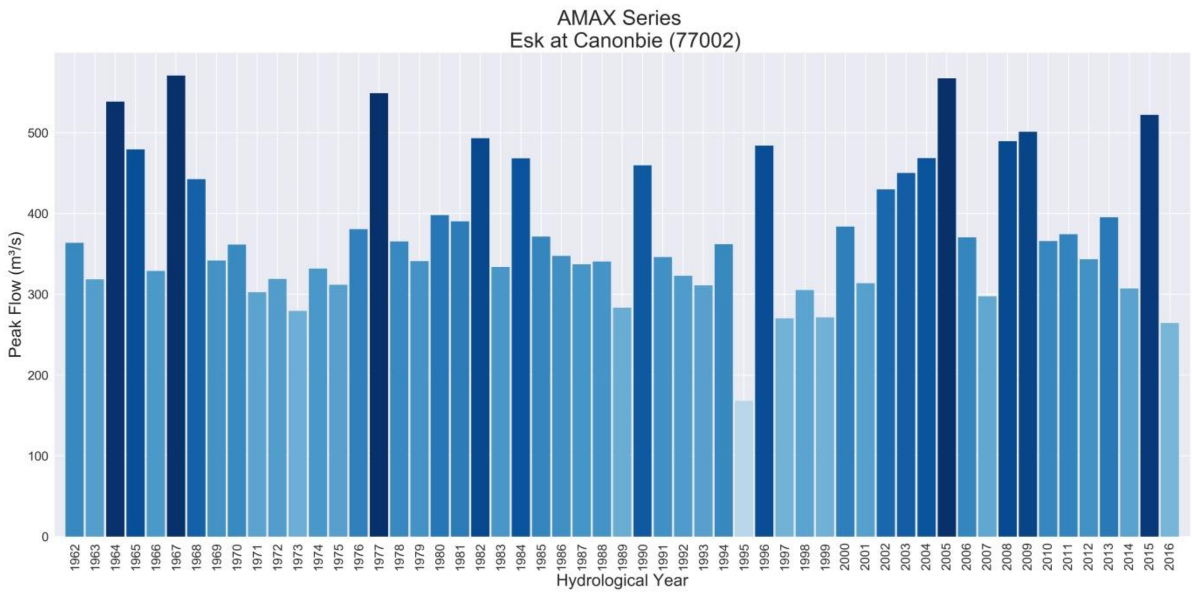


Figure 2.1 AMAX Series for Esk at Canonbie (77002)

From the AMAX series there are five notable events that occurred in 1964, 1967, 1977, 2005 and 2015. The single site flood frequency curve for the gauging station Esk at Canonbie (77002) has been derived using the AMAX series above (Figure 2.2). This allows each event to be assigned an estimated return period. The Generalised Logistic (GLO) distribution was selected as the distribution which provided the best fit to the data using the L-Median and L Moment techniques.

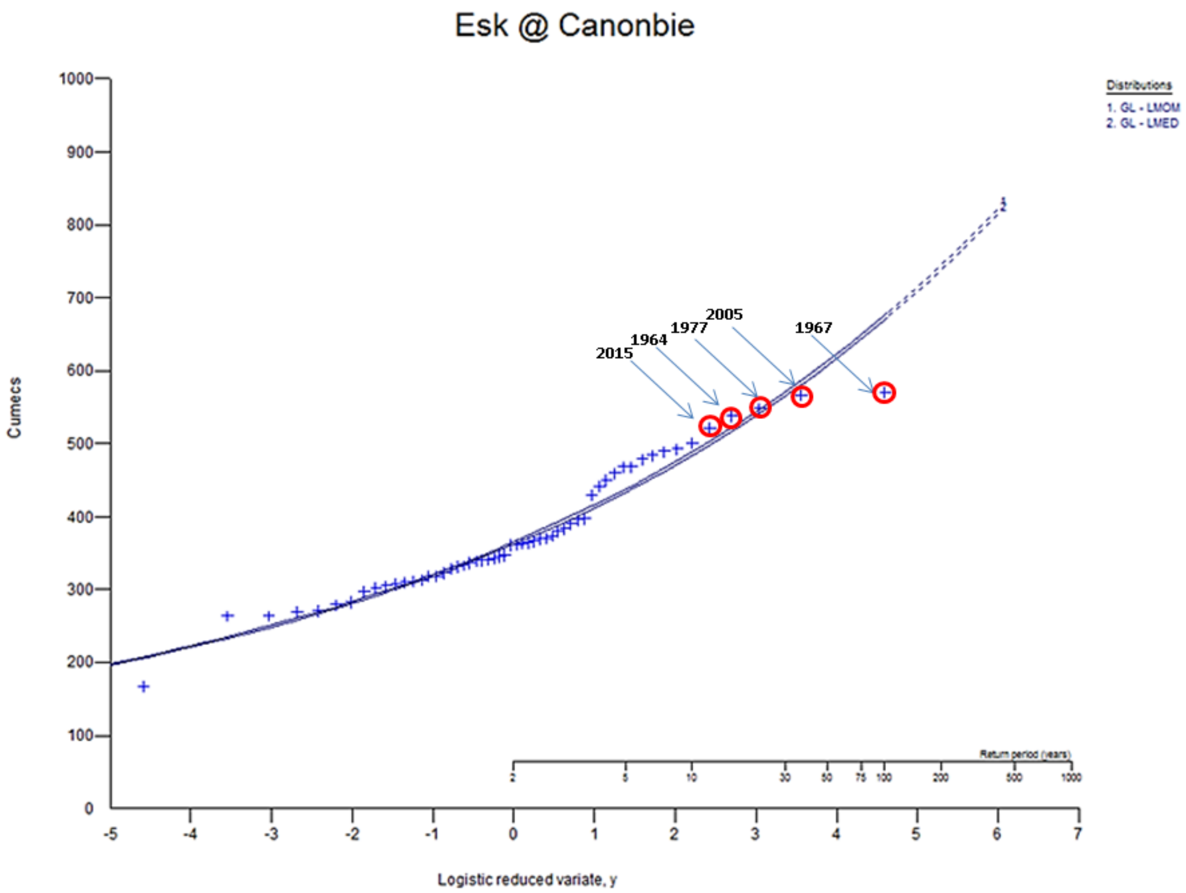


Figure 2.2 Single Site Flood Frequency Curve for Esk at Canonbie (77002)

It can be seen from the flood frequency curve that the events of 1967 and 2005 (in terms of magnitude) are very similar. The events have an estimate return period of approximately 1 in 30 year (3.33% AEP). The top five events are presented in descending order of magnitude in Table 2.1.

Table 2.1 Estimated Return Periods for the five largest AMAX Events

AMAX	Hydrological Year	Event Date	Flow (m^3/s)	Estimated Return Period L-Moments	Estimated Return Period L-Median
AMAX1	1967	09/10/1967	570.798	30	32
AMAX2	2005	12/10/2005	567.346	29	31
AMAX3	1977	31/10/1977	548.934	23	24
AMAX4	1964	06/10/1964	538.677	20	21
AMAX5	2015	05/12/2015	522.225	16	17

2.1.2 Hydrologic Assessment Points and Catchments

A detailed hydrological analysis was undertaken to determine the flood flow hydrographs and peak flows for the following watercourses:

- River Esk
- Wauchope Water
- Ewes Water

Data from a river survey - undertaken to aid in constructing a computational hydraulic model – was used to establish numerous Hydrological Assessment Points (HAPs). They were strategically located at the most upstream and downstream extremities of the model and on any tributaries just before their confluence with the main river channel. Intermediate HAPs were also created along the main channel and tributaries for generating lateral flow contributions. Intermediate HAPs serve as check points along the reaches to ensure that the hydraulic modelling is anchored to the hydrological estimations. The HAP locations are provided in Figure 2.3. The catchment descriptors (obtained from the FEH CD-ROM v3) associated with the HAPs are given in Figure 2.3.

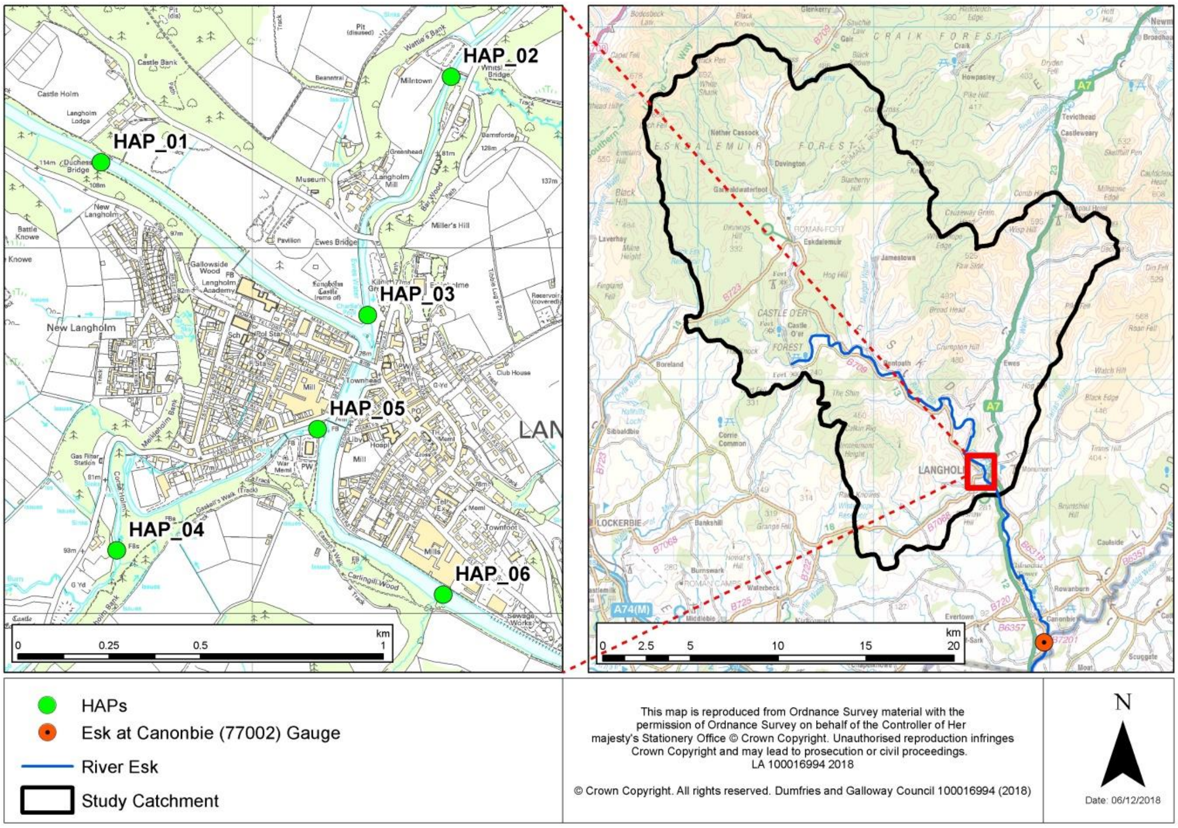


Figure 2.3 Location of Langholm HAPs

Table 2.2 Langholm HAP Catchment Descriptors

HAP	Location*	AREA	SAAR	FARL	BFIHOST	URBEXT2000	SPRHOST
HAP_01	u/s on Esk	290.15	1471	0.99	0.407	0.0004	44.58
HAP_02	u/s Ewes Water	79.15	1391	1	0.481	0	39.66
HAP_03	d/s of Ewes Water	79.46	1391	1	0.48	0	39.73
HAP_04	u/s of Wauchope water	40.94	1379	1	0.386	0.0013	44.97
HAP_05	u/s of Wauchope Water	41.38	1380	1	0.384	0.0001	45.2
HAP_06	d/s Langholm on River Esk	412.72	1446	0.993	0.42	0.0008	43.59
HAP_07	d/s Langholm on River Esk	414.53	1445	0.993	0.42	0.001	43.55

**d/s = downstream, u/s = upstream*

Individual catchments were delineated for all HAPs. Delineating the catchments required the use a terrain processing algorithm (implemented using ArcGIS extension Arc Hydro). Following the terrain processing procedure, the output catchments and boundaries were subject to further validation by superimposing multiple feature layers and raster's including 10k OS background mapping, rivers/streams feature classes, urban drainage networks and high resolution Digital Terrain Models in ArcGIS. This process was undertaken to ensure the catchment areas extracted from the FEH CD-ROM were accurate and to inform whether there should be any amendments to other catchment descriptors. The FEH CD-ROM catchment areas proved to be in line with those that were derived from the terrain processing procedures described above (Table 2.3). As a result, no alterations were considered necessary to the catchment descriptors.

Table 2.3 Revised Catchment Areas

HAP	Coordinate X	Coordinate Y	FEH Area (km^2)	Revised Area (km^2)
HAP_01	326719	597626	290.33	290.15
HAP_02	338419	593650	79.15	79.15
HAP_03	338426	593683	79.59	79.46
HAP_04	331504	583585	40.90	40.94
HAP_05	331459	583576	41.48	41.38
HAP_06	329491	595398	412.72	412.72
HAP_07	329524	595348	414.53	414.53

3 FEH STATISITICAL METHOD

3.1 INDEX FLOOD (Q_{MED})

The relationship between flow and return period is known as the flood frequency curve. A FEH statistical analysis of flood peak data (single or pooled analysis) is a method of flood estimation accepted by the Scottish Environment Protection Agency (SEPA) for determining the flood frequency curve.

3.1.1 Q_{med} Estimation (gauged)

Information available from the NRFA states that the Esk at Canonbie (77002) is suitable for Q_{med} estimation, but not for pooling as there is a lack of confidence in the extreme flow estimation, due to out of bank flow and interaction with the nearby Liddell Water. SEPA provided supporting data quality grades that reinforced the use of this gauge for Q_{med} estimation. Consequently, the observed Q_{med} derived using the full 55 years AMAX series was calculated as 362.131 m^3/s.

3.1.2 Q_{med} Estimation (ungauged)

All seven HAPs established within the study area are ‘ungauged’. Therefore, the estimation of Q_{med} will be made initially with catchment descriptors using the improved FEH regression equation. The equation was developed in 2007 by CEH Wallingford, using higher quality records from the HiFlows-UK dataset and it takes the form:

$$Q_{med} = 8.3062\ AREA^{0.8510}\ 0.1536^{\frac{1000}{SAAR}}\ FARL^{3.4451}\ 0.0460^{BFIHOST^2}$$

Where:

AREA = catchment size (km^2)

SAAR = Standard Average Annual Rainfall (mm/year)

FARL = Flood Attenuation from Lakes and Reservoirs (dimensionless)

BFIHOST = Baseflow Index Hydrology Of Soil Types (dimensionless)

The FEH regression equation is used to derive an estimate of Q_{med} of the catchment in its rural form (i.e. it does not account for increased runoff from impervious surfaces due to urbanisation). The FEH provides guidelines on converting a $Q_{med,\ rural}$ into the $Q_{med,\ urban}$ estimate, taking into account the increased runoff generated by increased area of impervious surfaces. The guidelines recommend applying an urban adjustment to the Q_{med} estimate if the URBEXT2000 catchment descriptor exceeds 0.025 (i.e. 2.5% of catchment area). Urbanisation modifies the natural flood response and therefore

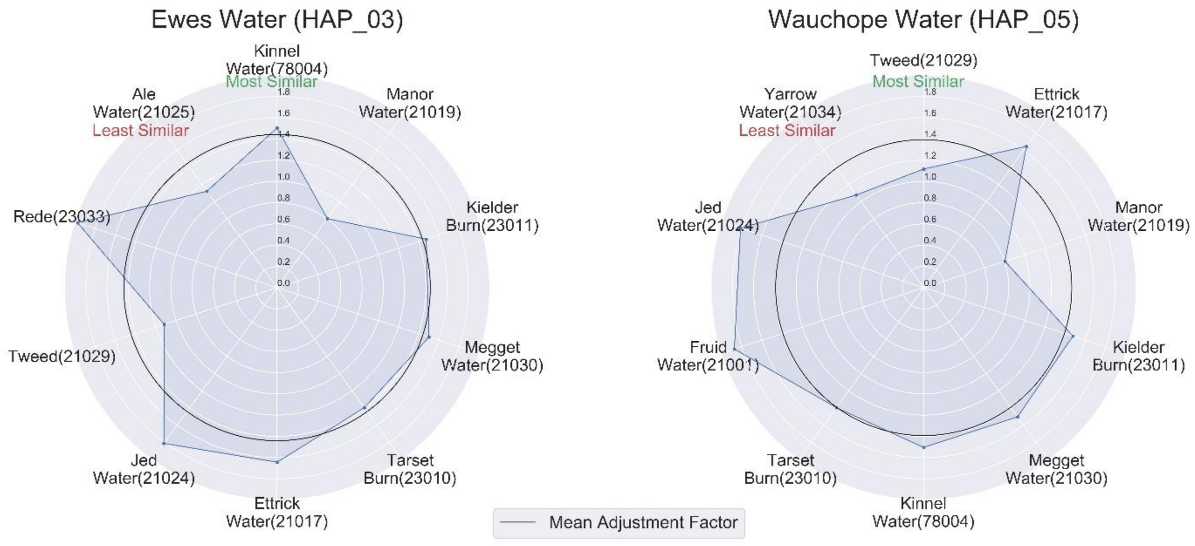
Q_{med} (and the growth curve) should be adjusted for urbanisation. However all of the HAP catchments are either totally rural or only slightly urbanised (maximum URBEXT2000 = 0.0013 at HAP_04).

It is assumed, that any increased runoff generated by urban areas is embodied in the Q_{med} estimate at the Esk at Canonbie (77002) gauge. Therefore, adjustment to Q_{med} accounting for urbanisation is not required; rather a more appropriate method of improving Q_{med} estimates is through the use of donor adjustment. This is a recommended method in the FEH guidelines which aims to improve the accuracy of ungauged Q_{med} estimates by employing data transfer from catchments judged to be hydrologically similar to the target site but for which annual maximum flood data are available. The 'ungauged' rural estimation of Q_{med} at these locations can therefore be brought in line with the observed data at Esk at Canonbie (77002) through the implementation of the FEH donor adjustment methodologies.

3.1.2.1 Donor Adjustment

In essence data transfer tries to account for the proportional error in Q_{med} estimated from catchment descriptors compared with the observed Q_{med} from gauged data. At the Canonbie gauging station the proportional error (taken as the Q_{med} observed/Q_{med} estimated from catchment descriptors) was calculated as 1.40. A method of moderating this adjustment based on geographical distance between centroids could be employed. Applying the geographical moderation term was found to be problematic in this instance. Moving down through the model towards the gauging station it is difficult to resolve the sum of the inflows into the model with the observed Q_{med} value at Esk at Canonbie (77002) without adding lateral inflows which are hydrologically unrealistic. In the interest of maintaining conservative design peak flow estimates, and in line with the guidance on the use of the geographical moderation term from the Flood estimation guidelines, Operation Instruction 197_08, the moderation term has been dropped from this analysis. Therefore, a direct transfer method has been employed, utilising the full adjustment factor of 1.4 to adjust the Q_{med} estimates at the ungauged HAPs.

In order to instil further confidence in subjecting the Q_{med} to a 40% uplift an investigation into 33 other potential donors in the surrounding area (50 km radius) was undertaken. All potential donors were ranked based on a Similarity Distance Measure (SDM) with AREA, SAAR, FARL and FPEXT as the variables. *Note: The hydrological SDM increases in the clockwise direction.*
Figure 3.1 illustrates the top 10 donors for the Ewes and Wauchope Water.



Note: The hydrological SDM increases in the clockwise direction.

Figure 3.1 Potential Donors and Respective Adjustment Factors

For both the Wauchope Water and the Ewes Water the mean adjustment ratio of the top 10 potential donors resulted in values approximately equal to the 1.4. It was therefore concluded that the uplift being applied is justified and supported by other nearby gauging stations.

3.1.2.2 Final FEH Statistical Q_{med} Estimates

The FEH data transfer procedure results in all the ungauged catchments along the modelled watercourse reaches on the Esk receiving an upward adjustment. These Q_{med} estimates are considered to be robust as they are anchored to the observed Q_{med} values at the Esk at Canonbie (77002) gauging station.

Table 3.1 Final Q_{med} Estimates

	HAP_01	HAP_02	HAP_03	HAP_04	HAP_05	HAP_06	HAP_07
$Q_{med, cds}$ (m^3/s)*	168.05	43.72	44.00	31.78	32.25	216.90	217.52
$Q_{med, adj}$ (m^3/s)**	235.72	61.32	61.71	44.57	45.24	304.23	305.09

*Q_{med} estimate directly from catchment descriptors, **Final Q_{med} estimate (adjustment applied).

3.2 GROWTH CURVE DEVELOPMENT

Growth curve development was implemented using WINFAP software (version3) and up-to-date WINFAP files (version 6) downloaded from the NRFA website. The software derives flood growth curves which can be then factored by the Q_{med} estimation to obtain the flood frequency curve. All stations that WINFAP highlighted as being not suitable for pooling were automatically excluded from the analysis. The flood frequency curve allows peak flows to be determined for a range of different return periods.

3.2.1 Flood Frequency Curve Derivation

For ungauged catchments, the FEH statistical method provides a robust procedure for deriving the design flood for any return period by factoring the Q_{med} value. The technique involves pooling a number of gauged sites throughout the UK based on their hydrological similarity. This measure of similarity is calculated using Euclidean distance between several catchment descriptors including AREA, SAAR, FARL and FPEXT (flood plain extents). The sites included in the pooling analysis are predominately rural, resulting in an ‘as-rural’ growth curve. Again, since the catchments are predominantly rural, no adjustment for urbanisation was applied to the growth curves.

3.2.2 Pooling Group and Growth Curve Development

While pooling groups can be derived for ungauged catchments, consideration was given to developing growth curves on the River Esk using an ungauged approach and an ‘Enhanced Single Site’ approach for comparison. This goes against the FEH recommendations where the gauged data must be of suitable quality such that it is eligible for pooling, but it was carried out regardless to highlight the effect of the different methods. The comparison of growth curves for the main River Esk catchment is presented in Figure 3.2.

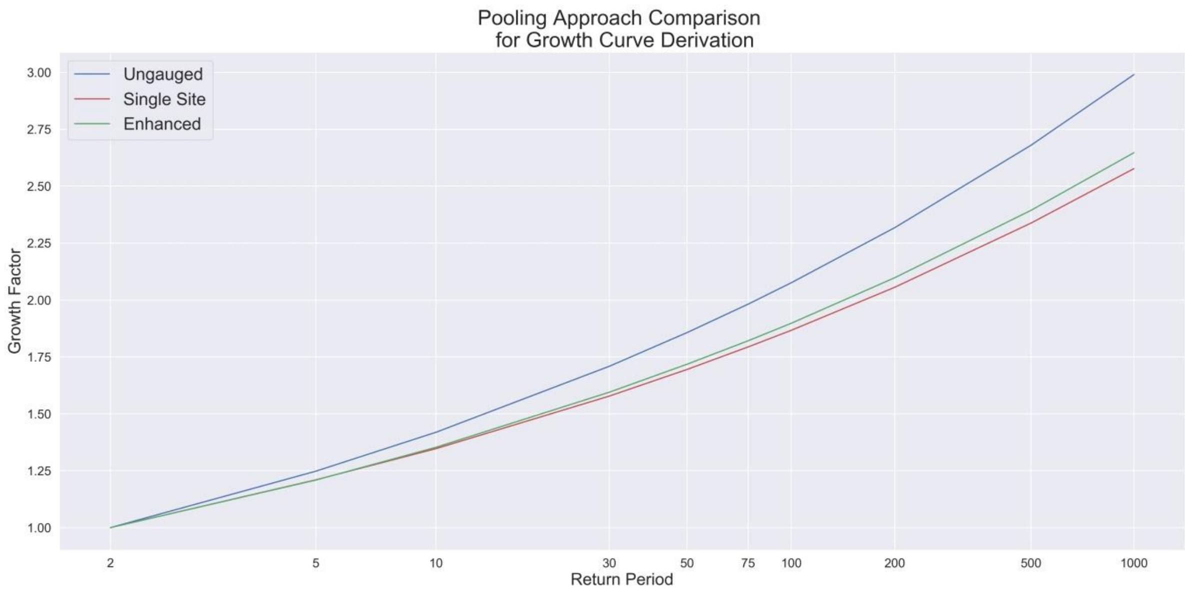


Figure 3.2 Growth Curve Comparison (River Esk Main Channel)

It was observed that the ungauged approach produces the steepest growth curve. Due to the additional weighting of the gauge within its own pooling group, the enhanced single site growth curve is closer to the single site curve. Due to uncertainties in high flow estimations on the River Esk, the ungauged method was used to derive the flood frequency curve for the main River Esk Channel.

Separate pooling groups were constructed for the Ewes Water and Wauchope following a simple ungauged pooling approach. While the Ewes Water is the steeper catchment, it is almost twice as big as the Wauchope Water catchment. As a result, the pooling analysis derived a slightly steeper growth curve for the Wauchope Water. The growth curves derived for these ungauged catchments are presented in Figure 3.3.

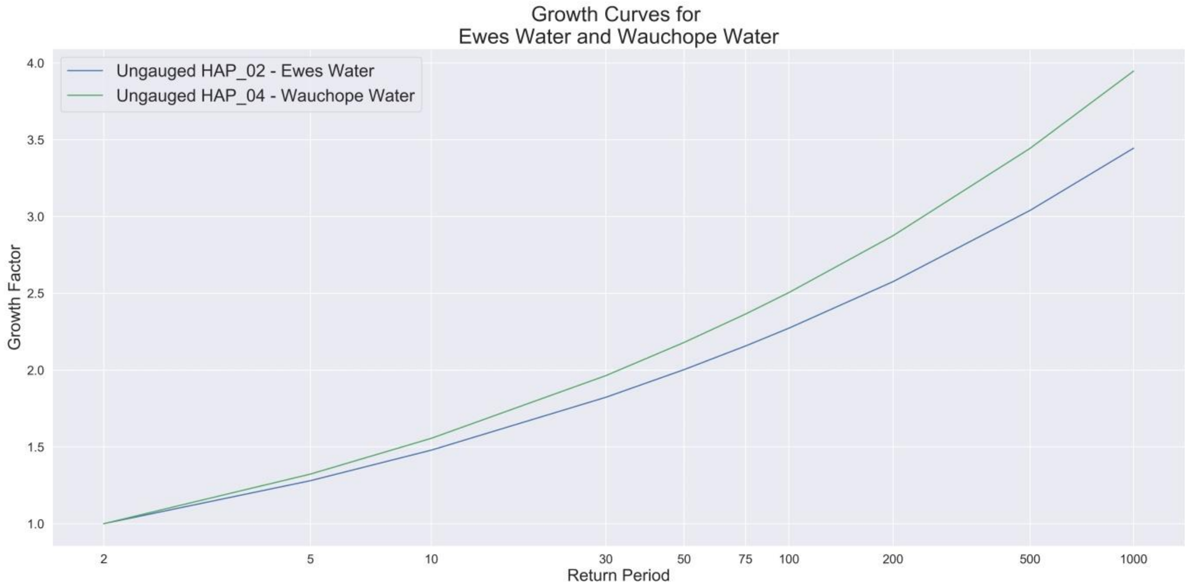


Figure 3.3 Growth Curve Comparison (Ewe and Wauchope Water)

All constructed pooling groups were subject to further review. Sites that had an inadequate record length, chalk catchment, or disparate AMAX distributions were removed from the group. A total combined record length of 500 years was conserved in the pooling groups as recommended under FEH guidelines.

The pooling groups were assessed for homogeneity which indicates how hydrologically similar the pooling group is to the subject catchment. A 'goodness-of-fit' test was undertaken to identify the best fitting distribution. With the exception of the HAP_04 pooling group, the Generalised Extreme Value (GEV) distribution is consistently the better performing distribution. However the GLO growth factors gave higher estimated peak flows for all HAPs. Consequently the GLO distribution was adopted as the preferred flood frequency distribution for the Wauchope Water (HAP_04). The GEV distribution was taken forward for the River Esk and the Ewes Water, owing to the fact that the GEV provided the best fit and will theoretically provide the best flood flow estimates. Details of the initial and modified pooling groups are provided in Appendix A.

3.2.3 Flood Frequency Curves

After deriving growth curves, it is possible to produce the flood frequency curves at each HAP by multiplying Q_{med} by the respective growth curve factors. Three flood frequency curves were developed; one for the main River Esk Channel using the ungauged pooling approach after reviewing other techniques, one for the Ewes Water and one for the Wauchope Water.

3.3 FINALISED FEH STATISTICAL PEAK FLOW ESTIMATES

The flood frequency curves output the estimate flows for each HAP over a range of return periods. These flow estimations are presented in Table 3.2.

Table 3.2 FEH Statistical Peak Flows (m^3/s)

HAP	Q2	Q5	Q10	Q30	Q50	Q75	Q100	Q200	Q500	Q1000
HAP_01	235.72	300.07	342.03	404.02	431.84	453.53	468.85	505.15	552.29	587.41
HAP_02	61.32	80.21	92.90	112.46	121.54	128.71	133.86	146.31	162.93	175.74
HAP_03	61.71	80.72	93.49	113.18	122.31	129.53	134.71	147.24	163.96	176.86
HAP_04	44.57	58.97	69.35	87.54	97.16	105.41	111.65	128.14	153.50	175.92
HAP_05	45.24	59.85	70.39	88.85	98.62	106.99	113.33	130.07	155.81	178.56
HAP_06	304.23	387.29	441.44	521.45	557.35	585.34	605.11	651.97	712.81	758.14
HAP_07	305.09	388.38	442.69	522.92	558.93	586.99	606.82	653.81	714.83	760.28

4 FEH REVITALISED FLOOD HYDROGRAPH

This assessment has also considered the ReFH2 methodology with FEH13 Depth Duration Frequency (DDF) rainfall model, as an alternative for estimating peak flows. This method differs from the statistical approach in that it is a deterministic model and aims to represent the main hydrological processes which occur at a catchment scale. The ReFH2 rainfall-runoff method is one that generates a full design hydrograph based on rainfall. It can be used as it is or in tandem with statistical peak flow methods to scale of the semi dimensional hydrographs to the FEH statistical estimates.

4.1 STORM DURATION AND SEASON

The ReFH2 software initially provides recommended storm duration based on catchment descriptors. However an iterative process is undertaken, whereby the storm duration is modified until the largest peak flow is achieved, and therefore the ‘critical storm duration’ achieved. This was assessed at the most downstream point in the hydrological analysis on each of the three water courses. The chosen storm season is ‘winter’, which is the default, recommended in the FEH for predominately rural catchments. The choice of season is further supported by reviewing the event data recorded at the Esk at Canonbie (77002) which revealed that the vast majority of large flood events appear to occur in the autumn/winter period.

The recommended storm duration in the ReFH2 model was 7 hours and 30 minutes, but an iterative process revealed the critical storm duration to be 9 hours 30 minutes. The critical storm duration was also assessed on the Wauchope (HAP_05) and Ewes Water (HAP_03) and found to be 9 hours 30 mins and 6 hours 30 mins respectively.

4.2 HYDROGRAPH WIDTH COMPARISON

The ReFH method calculates hydrograph shape parameters that determine the shape of the design hydrograph. This is based purely on catchment descriptors. In the absence of a reliable flow gauge in Langholm, a comparison of hydrograph shapes was undertaken between the ReFH outputs and the observed continuous records at Esk at Canonbie (77002). This was to ensure the design hydrographs are truly reflective of the observations at the gauge downstream. Figure 4.1 presents the comparison of observed hydrographs using the last 30 AMAX records with the design hydrograph on the main River Esk channel.

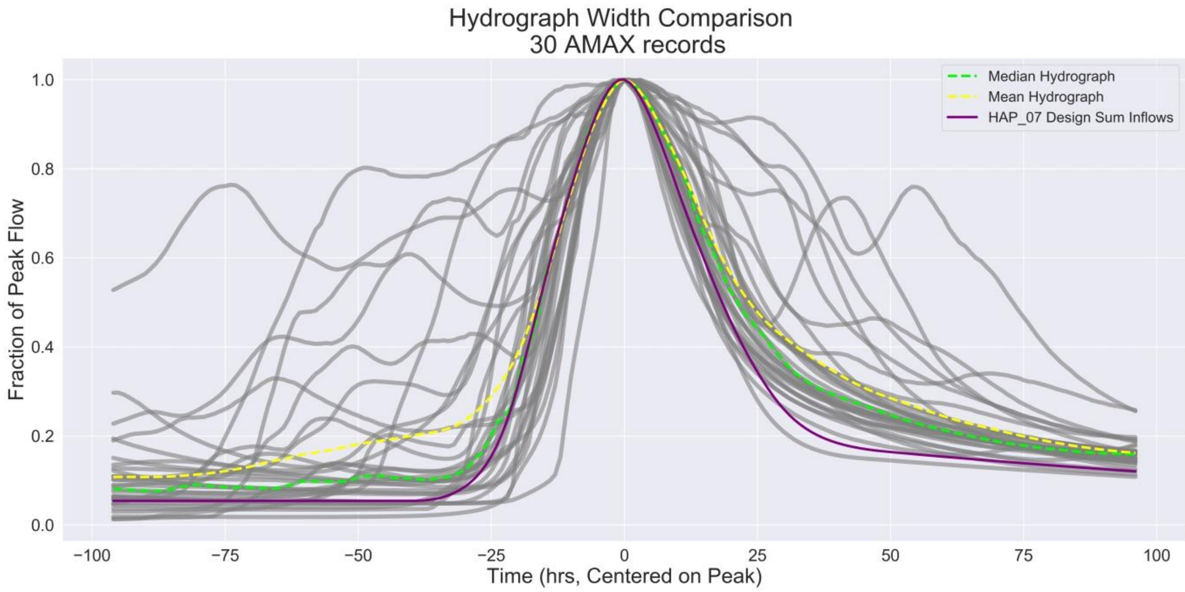


Figure 4.1 Hydrograph Width Comparison (HAP07)

The design hydrograph on the main River Esk channel is slightly narrower than the average hydrographs developed from the 30 AMAX events recorded at Esk at Canonbie (77002) gauge. The rising limb gradient is approximately equal to the observed response. The recession limb tails off a little early in comparison to most observed events, but is well within reasonable tolerance. The time-to-peak (beginning of rising limb to peak) of the design hydrograph is approximately 30hrs, which is also approximated in the historic event averages. Although Esk at Canonbie (77002) is downstream of the study catchment, and in the absence of a reliable flow gauge in Langholm, the design hydrograph on the River Esk main channel was considered an adequate representation of the catchment response to rainfall.

4.3 REFH2 PEAK FLOW ESTIMATES

The peak flow estimates for all return periods simulated in the ReFH2 model are presented in Table 4.1 below:

Table 4.1 ReFH2 Peak Flow Estimates (m^3/s)

HAP	Q2	Q5	Q10	Q30	Q50	Q75	Q100	Q200	Q500	Q1000
HAP_01	173.72	222.39	257.07	316.22	347.37	374.56	395.47	452.72	549.71	640.35
HAP_02	44.56	57.79	67.30	83.67	92.34	99.94	105.79	121.89	149.55	175.57
HAP_03	44.89	57.97	67.36	83.48	92.02	99.50	105.27	121.13	148.19	173.68
HAP_04	32.69	42.07	48.75	60.14	66.14	71.37	75.39	86.39	105.03	122.43
HAP_05	33.11	42.64	49.42	61.00	67.09	72.41	76.50	87.70	106.66	124.37
HAP_06	242.74	311.32	360.29	443.96	488.09	526.66	556.33	637.65	775.69	904.95

HAP	Q2	Q5	Q10	Q30	Q50	Q75	Q100	Q200	Q500	Q1000
HAP_07	242.51	310.96	359.82	443.29	487.31	525.77	555.37	636.47	774.11	902.97

The hydrographs produced by the ReFH2 model can be represented as semi-dimensional. This shape represents the response of the catchment and may be used for scaling to match FEH statistical peak flow estimates (i.e. if the statistical method is chosen as the preferred peak flow estimation method) and later used for input to the computational model.

5 SELECTION OF FLOOD FLOW ESTIMATION TECHNIQUE

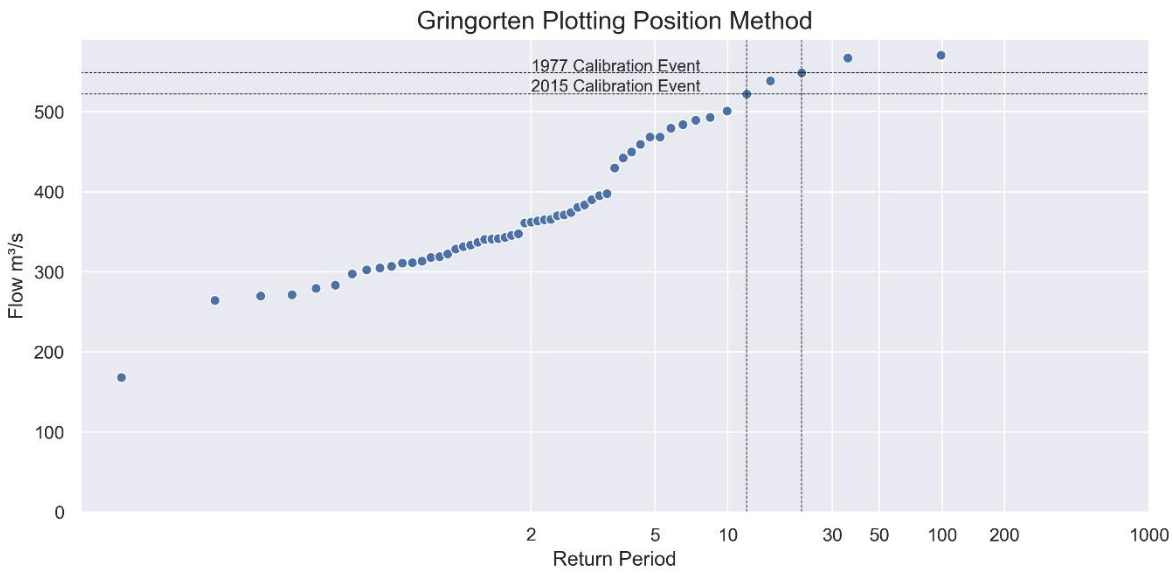
Two methods of flood estimation were employed to provide design peak flow estimates in the Langholm area. Due to the availability of high quality flood flow gauge records available on the River Esk, the statistical method is the preferred methodology for the derivation of peak flood flow estimates at all the HAPs. However the ReFH2 method with the latest FEH 13 DDF rainfall model has been retained for comparison purposes. A review of the FEH statistically based estimates against the ReFH2 derived peak flows found that FEH statistical estimates were consistently greater than ReFH2 estimates. As the statistical method is a more robust method anchored to observed data at the Esk at Canonbie (77002) gauge, and to maintain a precautionary approach to design flow estimation, the FEH based estimates were taken forward to hydraulic modelling. Hydrograph shapes derived from the ReFH2 method were scaled to match the FEH statistically derived peak flows for input to the computational model.

6 LATERAL INFLOW METHOD

Lateral inflows were generated between each of the HAPs for input to the hydraulic model. Pre-modelling checks were undertaken to ensure the sum of inflows at each of the HAPs matched peak flow estimates. Lateral inflows have been calculated using the catchment area ratio to scale the hydrograph at the respective downstream HAP. Point and lateral inflow spreadsheets are provided in Appendix B.

7 POST HYDROLOGY AND MODEL CALIBRATION

Initial hydraulic model calibration results displayed water levels in the Langholm area that were not representative of observed events and outside the accepted tolerance accepted by SEPA. Justifiably, further investigations were undertaken to assess the return period of the calibration events (1977 and 2015) using the Gringorten plotting positions of the recorded AMAX series at the Esk at Canonbie (77002) gauge. Plotting positions specify the positions at which particular data points are to be plotted on the frequency axis. Gringorten plotting positions are commonly used when plotting GEV distributions but have been found also suitable for the GLO distribution also. Unlike using a return period estimate derived from a best fit curve (as is section 2.1.1), the event return period is read directly from the data point.



The method described above results in return period estimates for the 1977 and 2015 event of 1:12yr and 1:21yr respectively. Peak flow estimates were then derived off the design flood frequency curves for these events for hydraulic model calibration.

8 CLIMATE CHANGE PROJECTIONS

UK Climate Projections (UKCP09) predict that future climate change may lead to warmer and drier summers, warmer and wetter winters with less snow, and more extreme temperature and rainfall events. This predicted increase in rainfall leads to predicted increases in river flows and increases in river flooding. In this assessment, RPS will consider the impact as a 44% increase of present day flow rates by the 2080s (high emissions scenario 67th percentile) in line with SEPA guidance note[1].

[1] https://www.sepa.org.uk/media/219653/flood_model_guidance_v2.pdf
Note: at the time of this study, the UKCP18 had not yet been officially released.

9 BIBLIOGRAPHY

Kjeldsen, T. R., Stewart, E. J., Packman, J. C., Folwell, S. S., & Bayliss, A. C. (2005). Revitalisation of the FSR/FEH rainfallrunoff. Environment Agency.

Reed, D. W., & Robson, A. R. (1999). *Flood Estimation Handbook.* Wallingford: Institute of Hydrology.