Norwich Western Link

Environmental Statement

Chapter 12: Road Drainage and the Water Environment

Appendix 12.2: Flood Risk Assessment

Sub Appendix G: Foxburrow Stream FEH Calculation Record

Author: WSP UK Limited

Document Reference: 3.12.02g

Version Number: 00

Date: March 2024

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Glossary of Abbreviations and Defined Terms

Abbreviation	Definition
AM	Annual Maximum
AREA	Catchment area (km^2)
BFI	Base Flow Index
BFIHOST	Base Flow Index derived using the HOST soil classification
CFMP	Catchment Flood Management Plan
CPRE	Council for the Protection of Rural England
FARL	FEH index of flood attenuation due to reservoirs and lakes
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
HOST	Hydrology of Soil Types
NRFA	National River Flow Archive
POT	Peaks Over a Threshold
QMED	Median Annual Flood (with return period 2 years)
$QMED_{CDs}$	QMED value which has been estimated from catchment descriptors
$QMED_{Adjusted}$	QMED value which has been adjusted by data transfer
$QMED_{Obs}$	Observed QMED value from AMAX flow data
ReFH2	Revitalised Flood Hydrograph method
SAAR	Standard Average Annual Rainfall (mm)

Abbreviation	Definition
SPR	Standard percentage runoff
SPRHOST	Standard percentage runoff derived using the HOST soil classification
Tp(0)	Time to peak of the instantaneous unit hydrograph
URBAN	Flood Studies Report index of fractional urban extent
URBEXT1990	FEH index of fractional urban extent
URBEXT2000	Revised index of urban extent, measured differently from URBEXT1990
WINFAP-FEH	Windows Frequency Analysis Package – used for FEH statistical method

1 Introduction

1.1.1 This document is a supporting document to the Environment Agency's flood estimation guidelines. It provides a record of the calculations and decisions made during flood estimation. It will often be complemented by more general hydrological information given in a project report. The information given here should enable the work to be reproduced in the future. This version of the record is for studies where flood estimates are needed at multiple locations.

2 Method statement

2.1 Overview of requirements for flood estimates

2.1.1 WSP have been commissioned by Norfolk County council to undertake a detailed hydrological assessment of the Foxburrow Stream ordinary watercourse which crosses the proposed location of the Norwich Western Link relief road scheme (NWL). Foxburrow Stream (herein known as FS01) is a small tributary of the River Tud and crosses the NWL at approximately 610515, 313340.

2.1.2 The objective of this hydrological assessment is to provide design inflows for a hydraulic model. The outputs are required to inform the baseline flood risk as well as quantify the impact that the proposed road scheme has on flood risk and the water environment. As such a range of flood events and hydrographs is required. These will include the 5, 10, 20, 30, 50, 100, 200 and 1000 year and the 100yr+44% climate change (CC).

2.2 Overview of catchment

2.2.1 The Foxburrow Stream (FS01) catchment is a small (3.35km^2) lowland catchment situated approximately 10 kilometres due west of Norwich City Centre. The catchment contains a mix of rural, woodland and minor urbanisation landcover types. The ordinary watercourse rises towards the west of the catchment, flowing through two small ponds (minor influence on

FARL value of 0.99), before changing course to flow south-east towards its confluence with the River Tud approximately 2.5 kilometres south-east from the NWL crossing of the ordinary watercourse.

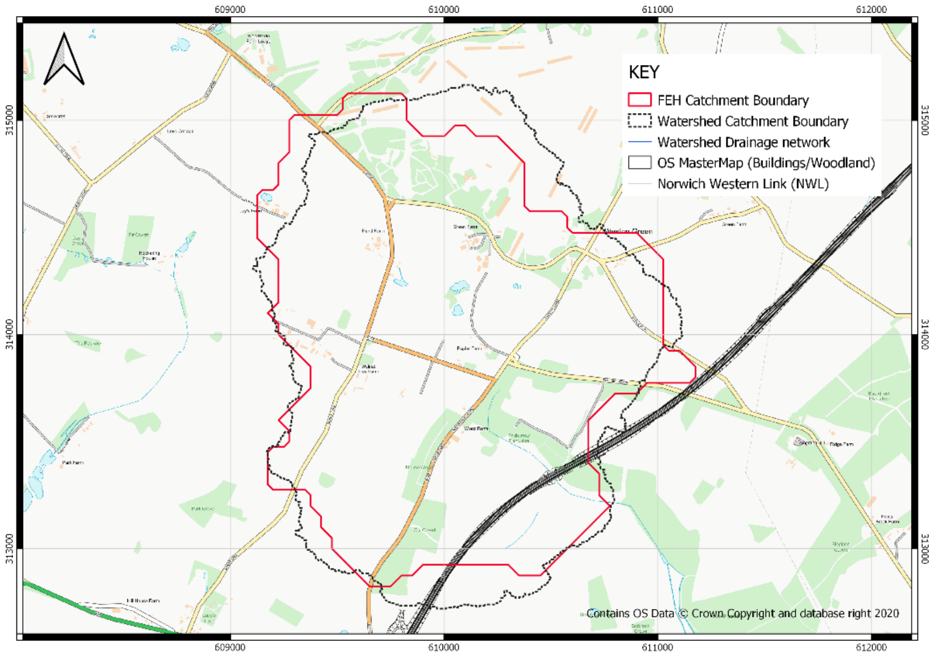
2.2.2 The catchment land cover is predominantly rural (agricultural land) with some woodland in the upper reaches and adjacent to the watercourse. There is some minor suburban landcover associated with RAF Attlebridge within the north-eastern extents of the catchment.

2.2.3 The catchment is flat with an average drainage path slow (DPSBAR) of 16.4m/km. There is a maximum elevation of around 60mAOD (Newyln datum) adjacent to the western catchment boundary. The catchment slopes gradually to around 35mAOD where the NWL crosses the ordinary watercourse and to 33mAOD at the proposed hydraulic model downstream boundary 330m downstream from the NWL crossing.

2.2.4 Online soilscapes mapping (landis.org.uk) shows that the western portion of the catchment is underlain by slightly acid loamy and clayey soils with impeded drainage and freely draining slightly acid soils in the eastern portion. The British Geological Society (BGS) online Geoindex 1:50,000 mapping shows that the catchment is underlain by superficial drift deposits of the Sheringham Cliffs (sand & gravel) and Lowestoft (unsorted diamicton) formations, the drift deposits overly bedrock of the Lewes Nodular, Seaford, Newhaven, Culver and Portsdown formations, all comprising chalk. The soil and geology types underlying the catchment confirm its extremely permeable nature (BFIHOST 0.662).

2.2.5 A comparison of the adopted catchment boundary with the FEH catchment boundary is provided below in Figure 2-1.

Figure 2-1 Comparison of catchment boundaries



Flood History

2.2.6 Flood history for the catchment is not well known although this is unsurprising due to the predominantly rural nature of the area. A single incident in Honingham is reported on the BBC regional news website for Norfolk and several others, however this relates to surface water flooding to the A47 road and is away from the catchment of FS01.

2.3 Source of flood peak data

The source of the flood peak data was HiFlows UK version 9. No changes were made to this dataset.

2.4 Gauging stations (flow or level)

2.4.1 There are no gauging stations available outside of standard WINFAP donor sites for the purposes of this study.

2.5 Data available at each flow gauging station

2.5.1 No local gauge data has been analysed for this study.

2.6 Rating equations

2.6.1 No local gauge ratings have been reviewed for this study.

2.7 Other data available and how it has been obtained

2.7.1 Table 2-1 details the other data available for the assessment and how it has been obtained.

Table 2-1 Data availability

Type of data	Data relevant to this study?	Data available?	Source of data	Date obtained	Details
Check flow gaugings (if planned to review ratings)	Yes	No flow gaugings exist.	No data available.	No data available.	No data available.
Historic flood data – give link to historic review if carried out.	A news report relating to surface water flooding on the A47.	Yes	BBC regional news website for Norfolk	30/10/ 2020	As summarised above neither report is relevant to the subject site.
Flow data for events	Yes	No flow data is available as there are no gauges.	No data available.	No data available.	No data available.
Rainfall data for events	No, on the basis there is no observed flood history for this rural watercourse, rainfall data cannot be used to validate design flows.	Yes	https://environment.data.gov.uk/hydrology/explore	Not obtained as cannot be used.	Not applicable
Results from previous studies	Yes	There are no previous studies	Not applicable	Not applicable	Not applicable
Other data or information (e.g. groundwater, tides)	No further data is required to complete the assessment appropriately.	Not applicable	Not applicable	Not applicable	Not applicable

2.8 Initial choice of approach

Table 2-2 Assessment approach

Points to discuss on Approach	Discussion
Is FEH appropriate? (it may not be for very small, heavily urbanised or complex catchments) If not, describe other methods to be used.	The catchment is permeable, so an adjustment will be applied as required to FEH statistical pooling group. ReFH2.3 will be used which is applicable for permeable catchments. Whilst both methods are considered appropriate for the catchment, the statistical method is typically preferred over ReFH2 unless there is data to suggest otherwise.
Outline the conceptual model, addressing questions such as: • Where are the main sites of interest? • What is likely to cause flooding at those locations? (peak flows, flood volumes, combinations of peaks, groundwater, snowmelt, tides…) • Might those locations flood from runoff generated on part of the catchment only, e.g. downstream of a reservoir? • Is there a need to consider temporary debris dams that could collapse?	The potential for the NWL to intercept the ordinary watercourse FS01 and other nearby surface water flow paths is the main driver of flood risk. As the catchment is predominantly rural, there are limited additional existing flood risk receptors. There are no receptors other than farmland downstream of the NWL in the vicinity of the watercourse. The hydraulic model will represent the flow routes and will also include a representation of the NWL watercourse crossings to determine the NWL impact on flood risk. The majority of the FS01 catchment area is upstream from the hydraulic model inflow locations, as such the hydrological model will provide lumped inflows for application at the upstream points of the hydraulic model. Design flows are therefore required at the upstream inflow of FS01.

Points to discuss on Approach	**Discussion**
Any unusual catchment features to take into account? e.g. • highly permeable – avoid ReFH if BFIHOST>0.65, consider permeable catchment adjustment for statistical method if SPRHOST<20% • highly urbanised – avoid standard ReFH if URBEXT1990>0.125; consider FEH Statistical or other alternatives; consider method that can account for differing sewer and topographic catchments • pumped watercourse – consider lowland catchment version of rainfall-runoff method • major reservoir influence (FARL<0.90) – consider flood routing • extensive floodplain storage – consider choice of method carefully	The catchment is highly permeable (BFIHOST19 0.637), FEH statistical pooling group stations will be reviewed and non-flood years removed from the group. ReFH2.3 is suitable for use on highly permeable catchments. The catchment is very flat (DPSBAR 16) and essentially rural ($URBEXT_{2000}$ 0.009) . The DEFRA Magic Map Aquifer Designation Mapping shows that the chalk bedrock is a principal aquifer and the drift deposits are secondary A & B aquifers, both bedrock and drift aquifers extend beyond the topographic catchment boundary of the watercourse. A check of OS 1:50K mapping (Bing Maps) does not highlight any springs within FS01 catchment. This is confirmed by the groundwater levels, discussed in **Chapter 12: Road Drainage and the Water Environment** (Document Reference: 3.12.00) of the Environmental Statement (ES), which confirms that the chalk aquifer is not outcropping in this catchment. These observations indicate that flooding peaks within the catchment are likely to be rainfall event driven rather than groundwater driven.
Initial choice of method(s) and reasons Will the catchment be split into sub catchments? If so, how?	Both the FEH Statistical and ReFH2.3 method have been used for the analysis. Due to the permeable nature of the catchment neither method has been assumed as preferred prior to review of the results. Peak flows will be derived using both the statistical and ReFH2.3 method. The ReFH2.3 hydrograph shape will be adopted for the ungauged catchment. A preferred methodology will be determined upon completion of the assessment.
Source of URBREXT 2000	FEH catchment descriptors.
Software to be used (with version numbers)	WINFAP-FEH v4 ReFH 2.3

3 Locations where flood estimates required

3.1.1 The table below lists the locations of subject sites. The site codes listed below are used in all subsequent tables to save space. The site codes represent the downstream (total) catchment to that point in both cases.

3.2 Summary of subject sites

3.2.1 Flood estimates are calculated at a single location as the catchment is small and a simple assessment of the peak flows at the downstream limit of the model is required.

Table 3-1 Site location

Summary Subject	Site Detail
Site code	FS01
Watercourse	Foxburrow Stream
Site	Downstream from NWL01
Easting	610750
Northing	313200
AREA on FEH CD-ROM (km^2)	3.09
Revised AREA if altered	3.35

3.3 Important catchment descriptors at each subject site (incorporating any changes made)

Table 3-2 Important catchment descriptors

Catchment Descriptor	Site Detail
Site code	FS01
FARL	0.991
PROPWET	0.31
BFIHOST19	0.637

Catchment Descriptor	Site Detail
DPLBAR (km)	1.94
DPSBAR (m/km)	16.0
SAAR (mm)	636
SPRHOST	34.94
$URBEXT_{2000}$	0.009
FPEXT	0.15

3.4 Remaining catchment descriptors

Table 3-3 Remaining catchment descriptors

Catchment Descriptor	Site Detail
Site code	FS01
ALTBAR	51
ASPBAR	106
ASPVAR	0.32
FPDBAR	0.70
FPLOC	0.964
LDP	3.3
RMED-1H	11.4
RMED-1D	29
RMED-2D	35.7
URBCONC1990	-999999
URBEXT1990	0.004
URBLOC1990	-999999
URBCONC2000	-999999
URBLOC2000	-999999
C	-0.024
D1	0.30644
D2	0.31286
D3	0.26306
E	0.314
F	2.472

Catchment Descriptor	Site Detail
C(1 km)	-0.024
D1(1 km)	0.3040
D2(1 km)	0.3250
D3(1 km)	0.2570
E(1 km)	0.3140
F(1 km)	2.4750

3.5 Checking catchment descriptors

How the catchment boundary was checked and what were the changes

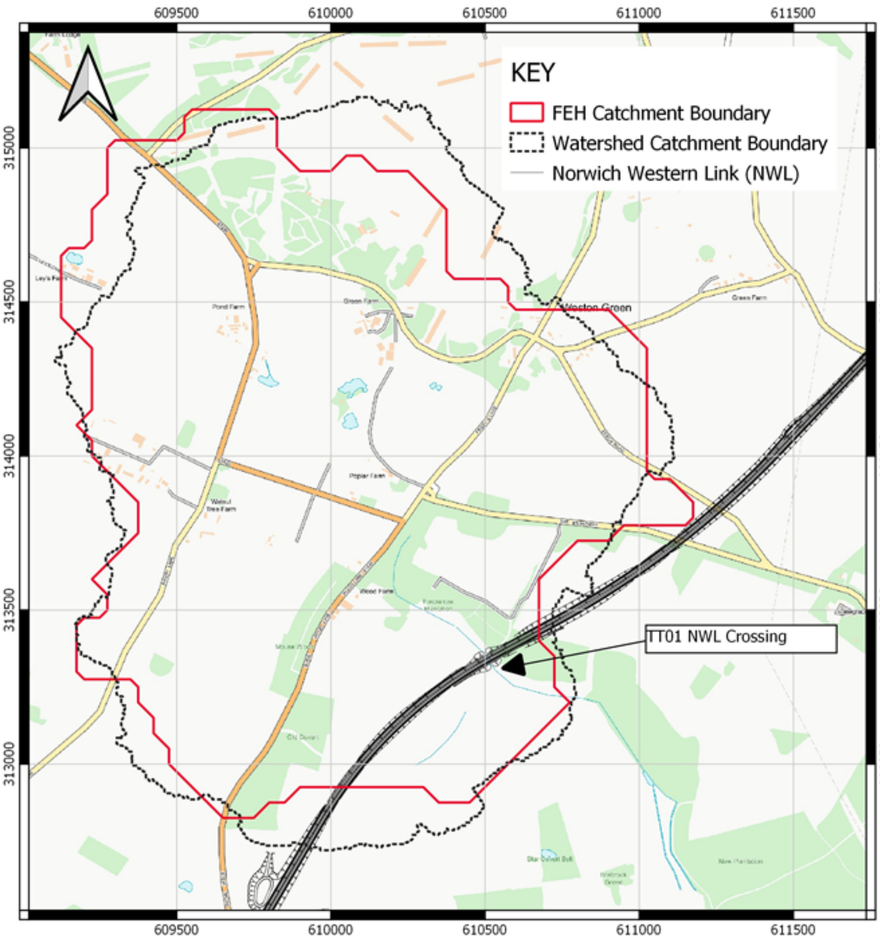
3.5.1 A detailed watershed analysis using LiDAR has been undertaken in GIS software to check the topographic drainage area of FS01. The watershed analysis highlighted differences between the FEH catchment boundaries and the topographic catchment boundaries. 1m LiDAR data, flown in 2015 has been used as a basis for the watershed analysis. It is deemed appropriate to adopt the GIS watershed analysis catchment areas as the more representative of the boundaries, key catchment descriptors have been updated. Since the preparation of this assessment, newer 1m LIDAR data has been flown in 2017. This has been reviewed and the watershed using the 2017 LIDAR is consistent (<0.5% variation) with the watershed from the 2015 data. The following approaches have been adopted to update the catchment descriptors:

- Catchment area has been updated to the GIS watershed analysis value and used to inform all subsequent checks.
- Areas or suburban and urban land cover within the catchment has been measured from freely available OS Open Map Local mapping and used to check or update the $URBEXT_{2000}$ values.
- To check and update FARL, sub-catchments draining to online ponds, the total catchment area (both from watershed analysis) and the pond surface area from OS Open Map Local mapping have been used to update the FARL values if appropriate.

- DPLBAR has been updated using the FEH Handbook Volume 5 equation for new catchment areas.
- DPSBAR has been updated by multiplying the catchment median slope percentage calculated in GIS software by 10, to calculate the value in m/km. The 1m LiDAR DTM has been resampled to a 50m horizontal resolution for this task to provide an approach consistent approach with FEH catchment descriptors.
- As the catchment centroid locations remain broadly like the FEH locations, no updates have been made to FPEXT, SAAR or PROPWET.
- Updates to soil types are discussed separately below.
- Urban drainage network information is not available for either catchment and has not been used within the analysis, however, as the catchments are predominantly rural this is not considered to be a significant limitation.

3.5.2 A comparison of catchment boundaries is presented below.

Figure 3-1 Comparison of catchments



3.5.3 The watershed analysis confirmed that the topographic catchment of FS01 was similar in geometry to the FEH catchment boundary, minor variances were noted around the perimeter and the overall area increased from 3.09km^2 to 3.35km^2. The following changes to key catchment descriptors have been made:

- DPLBAR has been updated from 1.72 to 1.94km.
- The small suburban area (0.146km^2) of RAF Attlebridge to the north has been included within the $URBEXT_{2000}$ calculation and the value was updated from 0 to 0.009.
- There are two small online ponds in the upper reaches of the catchment. A check of LiDAR confirms a drainage ditch from the ponds

and towards Paddy's Lane, the FS01 watercourse emerges downstream from Paddy's Lane and it has therefore been assumed that these ponds are online. The FARL value has been updated from 0.974 to 0.991.

- The DPSBAR value has been updated from has been updated from 17.8 to 16.0m/km.

How other catchment descriptors were checked and what were the changes.

3.5.4 The geometric changes of the catchment boundary warrants a check on the soil types and associated permeability of the catchment. FS01 has soil and strata types consistent with the permeable nature of the catchment, the following approach has been adopted to check the catchment permeability:

- Soil and strata types have been confirmed using the online Landis Soilscapes Mapping and the British Geological Society (BGS) online Geoindex 1:50,000 mapping.
- The UK 1:250,000 paper soil mapping and Institute of Hydrology (IoH) report No.126 Hydrology of Soil Types (HOST) has been used to determine appropriate HOST classes for soils underlying the individual catchments.
- Table 5.1, FEH Vol 5 has then been used to assign BFIHOST and SPRHOST values and the Griffin et al 2019 paper *"Revising the BFIHOST catchment descriptor to improve UK flood frequency estimates"* for BFIHOST 19 values.

3.5.5 FS01 is underlain by a single soil class 572n comprising proportions of HOST types 5 (37.5%) and 18 (62.5%). The updated SPRHOST and BFIHOST values are 34.94% and 0.662 respectively. The updated BFIHOST19 value is 0.635.

3.5.6 The source of URBEXT was the FEH $URBEXT_{2000}$ (updated to 2020). URBEXT has been updated using Equations 5.18 and 5.19 Kjeldsen (2010).

4 Statistical method

4.1 Search for donor sites for QMED (if applicable)

4.1.1 The top 10 recommended donor sites were consistent for the FS01 catchment. Due to the small AREA of the catchment all recommended donor sites were significantly larger (>10x) the size of the subject catchments. There is an observed trend that all but one 34003 (Bure @ Ingworth) donor sites recommend a reduction in the value of $QMED_{CDs}$ is appropriate.

4.1.2 34005 (Tud @ Cotessey Park) has been selected as the sole donor site, the catchment is hydrologically similar to FS01 and its centroid is the closest proximity to the subject site, with FS01 actually a sub-catchment of 34005. The adjusted QMED value applying just 34005 as a sole donor to FS01 is 0.239m^3/s i.e. almost identical to the value 0.246m^3/s (adopting the top six recommended sites in WINFAP). 34005 reduces the $QMED_{CDs}$ value of FS01 from 0.307 to 0.239m^3/s which is a 22% reduction, however, this reduction is consistent with the observed trend of a reduction in $QMED_{CDs}$ recommended by the donor sites in WINFAP4.

4.1.3 Considering the similarity of the catchments and donor recommendations it is appropriate to adopt 34005 for FS01.

4.1.4 WINFAP Donor Sites for Foxburrow stream (FS01) catchment are shown in the table below.

Table 4-1 Donor Sites

Donor Stations	AREA km^2	BFIHOST	SPRHOST %	SAAR mm	FARL	$URBEXT_{2000}$
34005 (Tud @ Costessey Park)	72.11	0.598	32.65	649	0.973	0.0
34001 (Yare @ Colney)	228.81	0.528	35.34	635	0.971	0.0

Donor Stations	AREA km^2	BFIHOST	SPRHOST %	SAAR mm	FARL	URBEXT$_{2000}$
34003 (Bure @ Ingworth)	161.27	0.778	20.83	669	0.974	0.0
33046 (Thet @ Redbridge)	143.43	0.581	32.23	624	0.946	0.0
33044 (Thet @ Bridgham)	274.99	0.681	25.67	620	0.942	0.0
33019 (Thet @ Melford Bridge)	311.37	0.707	23.94	620	0.932	0.0
33049 (Stanford Water @ Buckenham Tofts)	46.45	0.853	16.31	645	0.915	0.007
33007 (Nar @ Marham)	147.39	0.804	16.57	683	0.926	0.006
33045 (Wittle @ Quidenham)	27.45	0.534	32.27	608	0.974	0.0
33048 (Larling Brook @ Stonebridge)	21.99	0.694	9.61	635	0.907	0.0

4.1.5 Details of the chosen donor sites and QMED adjustment factors are provided in the table below.

Table 4-2 Chosen donor sites

Donor Site Subject	Donor Site Detail
NRFA no.	34005

Donor Site Subject	Donor Site Detail
Reasons for choosing or rejecting	Accepted donor station for this study. It is the closest station to the FS01 catchment, it is close in terms of both geographical distance and has similar characteristics to the subject catchments.
Method (AM or POT)	AM
Adjustment for climatic variation?	No
QMED from flow data (A)	Observed
QMED from catchment descriptors (B)	Rural
Adjustment ratio (A/B)	0.57
Which version of the urban adjustment was used for QMED at donor sites, and why? Note: The guidelines recommend great caution in urban adjustment of QMED on catchments that are also highly permeable (BFIHOST>0.8).	Kjeldsen (2010)

4.2 Overview of estimation of QMED at each subject site

Table 4-3 Estimation of QMED

QMED Estimation Subject	Site QMED Estimation Approach
Site Code	FS01
Method	DT
Initial rural estimate of QMED (m^3/s)	0.31
NRFA numbers for donor sites used (see 4.1)	34005
Distance between centroids dij (km)	5.21

QMED Estimation Subject	**Site QMED Estimation Approach**
Power term, a	0.46
Moderated QMED adjustment factor, $(A/B)^a$	0.77
Weight if more than one donor	Not applicable
Weighted average adjustment factor if more than one donor	Not applicable
Final urban estimate of QMED (m^3/s)	0.24
Are the values of QMED consistent, for example at successive points along the watercourse and at confluences?	Not applicable, downstream point only.
Which version of the urban adjustment was used for QMED, and why?	Kjeldsen (2010)

Table Notes

- Methods: AM – Annual maxima; POT – Peaks over threshold; DT – Data transfer; CD – Catchment descriptors alone.
- When QMED is estimated from POT data, it should also be adjusted for climatic variation. Details should be added.
- When QMED is estimated from catchment descriptors, the revised 2008 equation from Science Report SC050050 **Error! Bookmark not defined.**(Improving the FEH statistical procedures for flood frequency estimation, Science Report:SC050050, Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme (2008)), should be used. If the original FEH equation has been used, say so and give the reason why.

- The guidelines recommend great caution in urban adjustment of QMED on catchments that are also highly permeable (BFIHOST>0.8). The adjustment method used in WINFAP-FEH v3.0.003 is likely to overestimate adjustment factors for such catchments. In this case the only reliable flood estimates are likely to be derived from local flow data.

- The data transfer procedure is from Science Report SC050050. The QMED adjustment factor A/B for each donor site is given in **Table 3.3**. This is moderated using the power term, a, which is a function of the distance between the centroids of the subject catchment and the donor catchment. The final estimate of QMED is $(A/B)^a$ times the initial estimate from catchment descriptors.

- If more than one donor has been used, use multiple rows for the site and give the weights used in the averaging. Record the weighted average adjustment factor in the penultimate column.

4.3 Risk-Based QMED for Extreme Events

4.3.1 The subject catchment (FS01) is noted as being highly permeable. A pooling group growth curve tailored to the site should in theory pick up the potential for increased runoff from the site once the ground becomes saturated. There are limited examples of extreme events on permeable catchments in the overarching pooling group database and furthermore BFIHOST is currently not included in the pooling group equation and so the final pooling group is not wholly comprised of permeable catchments. There is no evidence for the threshold at which these catchments could become saturated, however for design when considering climate change it seems prudent to incorporate an allowance for this eventuality in our risk profile. For this reason a second approach separate to the standard FEH procedures outlined above is recommended for the climate change scenarios.

4.3.2 The River Tud catchment is gauged (34005) and hydrologically similar to the catchments of interest with the notable exception that the permeability of the soils is lower. Using 34005 as a potential donor for the subject site (FS01) and using the increase in $QMED_{CDs}$ predicted when reducing the associated subject site BFIHOST value to the River Tud catchment BFIHOST provides a QMED multiplier that is indicative of a response when catchment permeability is lower. This greater multiplier has been applied when deriving design flows for the 100yr plus climate change and the 1000yr events. That is a revised higher 100yr event is derived onto which the climate change allowances are applied. This provides a simple risk-based approach to the development of design flows that recognises the uncertainty in the catchment without overcomplicating the analysis given the lack of observed data available.

Table 4-4 Risk-based approach

Site code	BFIHOST19	Original $QMED_{adj}$ (m3/s)	BFIHOST Risk-based	$QMED_{adj}$ Risk-based (m3/s)
FS01	0.662	0.24	0.598	0.307

4.4 Derivation of pooling groups

4.4.1 Individual pooling groups were initially generated in WINFAP4 for FS01 catchment, the recommended default groups were identical apart from the last station in the group which for FS01 is 206006 (Annalong @ Recorder). Following review of the default group for FS01 206006 was removed and replaced with 36010 and as such the groups were identical.

4.4.2 Noting the shallow gradient and permeable nature of the subject catchment, there were a limited number of WINFAP4 recommended pooling group sites which were hydrologically similar to the subject sites, and it has been considered appropriate to retain the higher-ranking sites which are otherwise reasonable rather than simply replacing them with sites much further down the list of recommendations which are flatter or more permeable. As such the final pooling group is markedly similar to the default pooling group.

4.4.3 Considering the highly permeable strata and soil types within the subject catchments, the typical approach to FEH statistical pooling group selection of removing highly permeable sites has not been adopted here. Instead highly permeable sites are retained within the group due to their hydrological similarity to the subject sites. Non-flood years i.e. AMAX entries which are less than half of $QMED_{Obs}$ (threshold specified before any entries have been removed) for sites with SPRHOST less than 20 have been rejected from the site for the purposes of the pooling group.

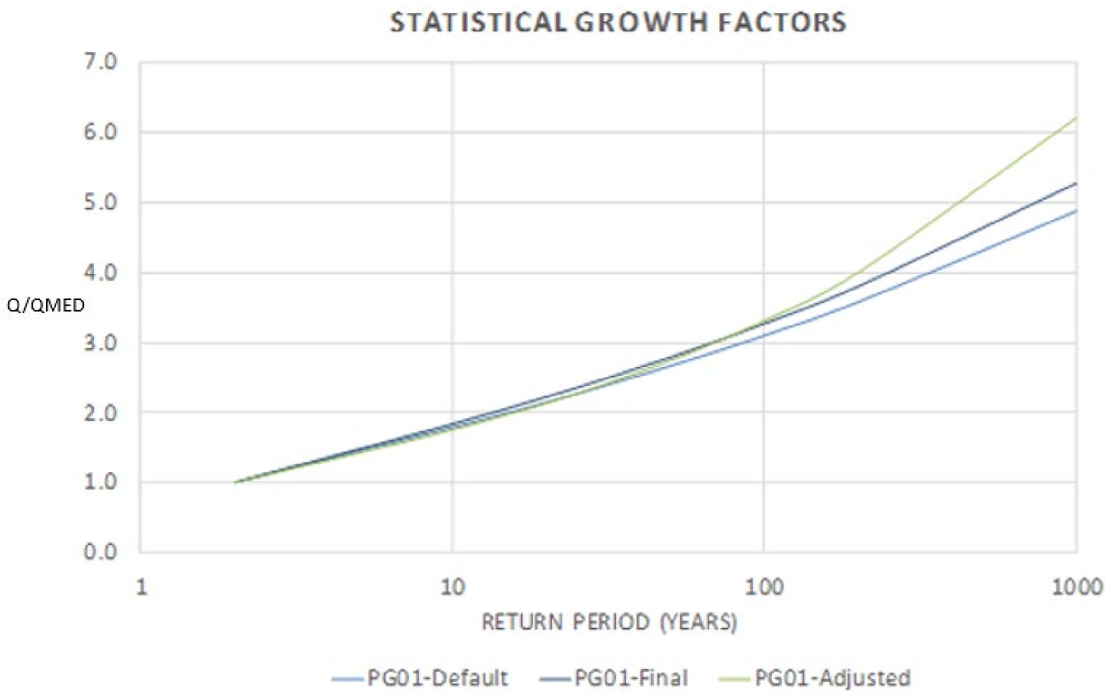
4.4.4 A single pooling group has been derived for the FS01 catchment. The composition of the pooling group is given in the annex. Pooling groups were derived using WINFAP 4.

Table 4-5 Pooling group details

Name of group	**Site code from whose descriptors group was derived**	**Subject site treated as gauged?** (enhanced single site analysis)	**Changes made to default pooling group, with reasons** Note also any sites that were investigated but retained in the group.	**Weighted average L-moments**, L-CV and L-skew, (before urban adjustment)
PG01	FS01	No	The following site was removed due to hydrological dissimilarity to the subject sites: • 206006 – mountainous catchment; extremely steep and high rainfall. The following sites have had non-flood year entries removed from their AMAX records: • 27073 – 2 entries removed, 26016 – 3 entries removed & 44008 – 7 entries removed. The following site was investigated due to missing data years, but retained as only 5 years were missing from a 45-year record: • 44008 The following site was investigated due to having a short record, but not removed as it is a junior station and otherwise reasonable, retaining it has minimal impact on growth curve: • 49005 The following station was added to provide 500yrs of data and due to its similarity to the subject site: • 36010	L-CV: 0.251 L-Skewness: 0.279

4.4.5 The following figure shows the growth curves for the pooling group before and after pooling removal and addition of the pooling group stations and with a permeable adjustment applied (PG01-Adjusted). The pooling group adjustments have increased the growth curve by approximately 5% in the 100yr event. The final growth curve with permeable adjustments applied is also shown.

Figure 4-1 Statistical growth factors



4.5 Derivation of flood growth curves at subject sites

Table 4-6 Pooling group details

Flood Growth Curve Derivation Subject	Flood Growth Curve Derivation Approach
Site code	All sites
Method (SS, P, ESS, J)	P
If P, ESS or J, name of pooling group (4.4)	PG01-Adjusted
Distribution used and reason for choice	Generalised Extreme Value – best fit

Flood Growth Curve Derivation Subject	Flood Growth Curve Derivation Approach
Note any urban adjustment or permeable adjustment	WINFAP v4 urban adjustment (Kjeldsen 2010)
Parameters of distribution (location, scale and shape) after adjustments	Location: 0.871 Scale: 0.343 Shape: -0.165 Bound: -1.209
Growth factor for 100-year return period	3.054

Table Notes

- Methods: SS – Single site; P – Pooled; ESS – Enhanced single site; J – Joint analysis
- A pooling group (or ESS analysis) derived at one gauge can be applied to estimate growth curves at a number of ungauged sites. Each site may have a different urban adjustment, and therefore different growth curve parameters.
- Urban adjustments to growth curves should use the version 3 option in WINFAP-FEH: Kjeldsen (2010).
- Growth curves were derived using the revised procedures from Science Report SC050050 (2008).

4.6 Flood estimates from the statistical method

Table 4-7 Statistical method flood estimates

Return Period (in years)	Flood peak (m^3/s)
2	0.24
5	0.34
10	0.42

Return Period (in years)	**Flood peak (m^3/s)**
20	0.51
30	0.57
50	0.66
75	0.74
100	0.8
200	0.96
1000	1.5
100 (Note 1)	1.02
200 (Note 1)	1.23
1000 (Note 1)	1.90

Note 1: Stats flows with risk based approach. It is proposed this approach is used for the larger events.

5 Revitalised flood hydrograph (ReFH) method

5.1 Parameters for ReFH2 model

5.1.1 Note: If parameters are estimated from catchment descriptors, they are easily reproducible, so it is not essential to enter them in the table.

5.1.2 No flood event analysis has been carried out for this assessment

Table 5-1 ReFH2 parameters

Site code	**Method:** OPT: Optimisation BR: Baseflow recession fitting CD: Catchment descriptors DT: Data transfer (give details)	**Tp (hours)** Time to peak	**C_{max} (mm)** Maximum storage capacity	**BL (hours)** Baseflow lag	**BF0** Baseflow recharge
FS01	CD	4.41	594.52	46.55	0.03

5.2 Trial and Error Design events for ReFH2 method

Table 5-2 Design events

Site code	**Urban or rural**	**Season of design event (summer or winter)**	**Storm duration (hours)**	**Storm duration Interval (hours)**	**100yr Peak Flow**
FS01	Rural	Winter	7.5	0.1	1.25
FS01	Rural	Winter	8.5	0.1	1.27
FS01	**Rural**	**Winter**	**9.5**	0.1	**1.29**
FS01	Rural	Winter	10.5	0.1	1.28

5.2.1 The storm durations are not likely to be changed in the next stage of the study, e.g. by optimisation within a hydraulic model.

5.2.2 For the purposes of the study a simple trial-and-error storm duration analysis has been undertaken in ReFH2.3 to determine the maximum peak flow for a 100yr return period for FS01. A timestep interval of 6mins has been used to capture finer intervals of rainfall than the ReFH2.3 recommended value of 30minutes. The final storm durations selected for FS01 is 9.5hrs. As the study is interested in peak flows at a single location on the watercourse, with the view of a maximising the 100-year peak flow for assessment of flood risk, the storm durations are unlikely to be subject to further review.

5.3 Check of Catchment Storage Estimates in ReFH2

5.3.1 No checks of catchment storage estimates in ReFH2 were required for the FS01 catchment.

5.4 Design Event for ReFH2

5.4.1 The design flows for the ReFH2 approach have been derived assuming a catchment wide flood event. This is assumed to be a winter event with a duration of 9.5 hours for FS01. The full catchment area of FS01 is 3.35km^2 and the resulting catchment wide Aerial Reduction Factor and Seasonal Correction Factors are 0.973 and 0.681 respectively.

Table 5-3 ReFH2 flood peaks

Return Period (in years)	Flood peak (m^3/s)
2	0.36
5	0.5
10	0.62
20	0.75
30	0.85
50	1.01
75	1.16
100	1.27
200	1.58
1000	2.36

6 Discussion and summary of results

6.1 Comparison of results from different methods

6.1.1 This table compares peak flows from the ReFH2 method with those from the FEH Statistical method for two key return periods.

Table 6-1 Comparison of Statistical and ReFH2

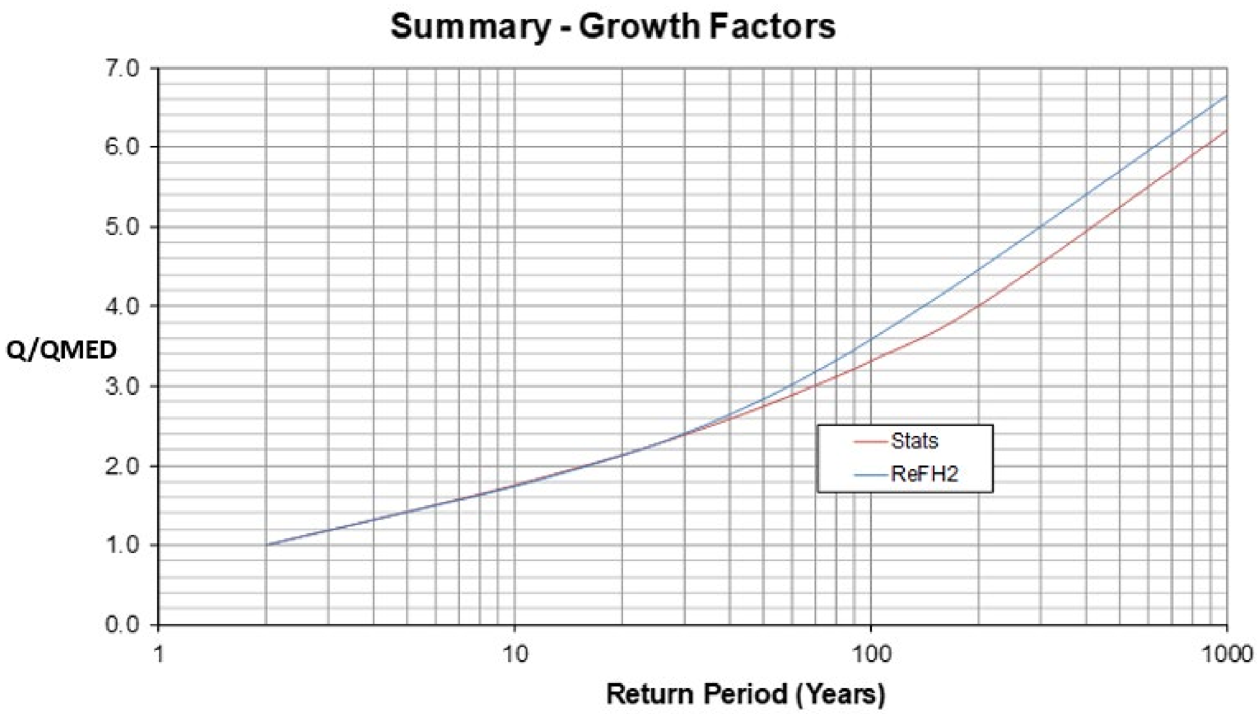
Parameter	Output for 2 year return period	Output for 100 year return period
ReFH2 Peak Flow (m^3/s)	0.36	1.27
Statistical Peak Flow (m^3/s)	0.24	0.8
Ratio (ReFH2/Statistical)	1.5	1.59

6.1.2 There is a significant variation between both approaches with the ReFH2.3 method predicting higher flows (50% higher at QMED and 60% higher for the 100yr return period event) throughout the range of return periods for FS01. A comparison of the growth curves, shown below highlights a reasonable agreement between the two approaches indicating that the difference in flows is predominantly associated with the QMED calculation, this is confirmed by the general consistency in the ratios between QMED and the 100yr event.

6.1.3 The agreement in the growth curves above the 100-year is attributed to the permeable adjustments to the statistical growth curve which noticeably increased growth factors for the 1000-year event. Runoff from a 1000-year storm event on the permeable catchments would be expected to be disproportionately higher than return periods up to around 100-year.

6.1.4 FEH statistical is not recommended for long return periods i.e. >150-years so typically the ReFH2.3 method is generally preferred here, however the growth factors from the risk based approach for the statistical method are similar so the statistical data has been used unchanged.

Figure 6-1 Growth factors



6.2 Final choice of method

Choice of method and reasons

6.2.1 The statistical method has been selected as the final choice of method for design peak flows. A risk based approach to the statistical method has been used for the 100 and 1000-year return periods which results in greater flow estimates than the two standard approaches.

6.2.2 There is notable discrepancy between the FEH-statistical and ReFH2.3 peak flows for all return periods but this is predominantly associated with the estimate of QMED. There is significantly greater confidence in the QMED estimates from the FEH-statistical method than the rainfall-runoff generated estimates from ReFH2.3.

6.2.3 A comparison of the specific discharge for the observed QMED value from the donor site and the donor adjusted QMED values for FS01 is provided below. The comparison highlights that the specific discharge estimates from ReFH2.3 are higher than the donor sites observed specific discharge, with the donor adjusted QMED values for FS01 within a much closer and sensible range. ReFH2.3 estimates for FS01 which is encompassed within the overarching donor site catchment are notably more than 2x the specific discharge of the donor site.

Table 6-2 Specific discharge comparison

Location	QMED m^3/s	QMED l/s	Catchment Area Km^2	Catchment Area (ha)	Specific Discharge l/s/ha
34005 Observed	3.105	3105	72.1	7210	0.43
FS01 FEH Stat	0.21	210	3.35	335	0.62
FS01 ReFH2.3	0.36	360	3.35	335	1.07

6.2.4 Considering that the FEH statistical method applies best use of local data and the QMED estimates of specific discharge are within close agreement to the selected donor site, it is considered appropriate to adopt these estimates for all return periods up to the 100-year.

6.2.5 There is uncertainty in runoff for the larger storm events which occur when the subject catchments soil capacity is diminished. To manage the uncertainty, it is proposed to adopt a higher risk-based QMED to derive the longer return period peak flows (100yr + climate change, 200yr and 1000yr). The increased QMED value has been determined by adjusting the BFIHOST value of the subject sites to match the chosen donor and increase the $QMED_{CDs}$ value of the subject sites prior to adjustment, further detail is provided in **Section 3**. The adjustment has been applied to the FEH statistical peak flows. A summary of the updated flows is provided in the table below.

Table 6-3 Summary of updated flows

Subject Catchment	Return Period (Yr)	Peak Flow Default (QMEDadj) m3/s	Peak Flow Risk-based (QMEDadj) m3/s	Also adjusted with ratio method
FS01	100	0.8	1.01	No
FS01	200	0.96	1.54	Yes
FS01	1000	0.96	2.30	Yes

6.3 Assumptions, limitations and uncertainty

Table 6-4 Assumptions limitations and uncertainties

Assumptions, limitations or uncertainty discussion point	Summary of project specific assumptions, limitations or uncertainty associated with the discussion point
List the main assumptions made (specific to this study)	The catchment is highly permeable, adjustments have been made to account for this, but significant uncertainty will remain. The FEH statistical approach is more applicable to return periods 100-years and below but is likely to be underestimating extreme storms. The catchment is ungauged, whilst flow estimates have been scrutinised, some uncertainty remains.

Assumptions, limitations or uncertainty discussion point	**Summary of project specific assumptions, limitations or uncertainty associated with the discussion point**
Discuss any particular limitations, e.g. applying methods outside the range of catchment types or return periods for which they were developed	No known long-term flood history and no available gauged data makes it troublesome to validate the estimates. Low runoff generation due to permeability but limited to knowledge of broad scale soil mapping, uncertainty has been accounted for within the largest peak flows.
Give what information you can on uncertainty in the results – e.g. confidence limits for the QMED estimates using FEH **3** 12.5 or the factorial standard error from Science Report SC050050 (2008).	The 95% confidence intervals for ungauged moderately urbanised catchments using one donor for the 2yr and 100yr events are 0.40-2.51 and 0.34-2.94 times the calculated design flows respectively. These intervals have been derived from the Environment Agency guidance on using local data to reduce uncertainty to reduce flood frequency estimation, 2017 for ungauged catchments.
Comment on the suitability of the results for future studies, e.g. at nearby locations or for different purposes.	This assessment has been completed for the FS01 catchment using standard methods. The assessment should be suitable for future studies on similar catchments within the locality of FS01, however, any future assessment should make use of the best available data at the time.
Give any other comments on the study, for example suggestions for additional work.	No updates for further studies, unless additional gauge data becomes available.

6.4 Checks

Table 6-5 Assessment checks

Assessment checks discussion points	Summary of project specific outcomes associated with the checks
Are the results consistent, for example at confluences?	Yes
What do the results imply regarding the return periods of floods during the period of record?	As per the historical review, little is known about the long-term flood history of the catchment.
What is the 100-year growth factor? Is this realistic? (The guidance suggests a typical range of 2.1 to 4.0)	Growth factors for the catchment are within appropriate ranges and are as follows: PG01: 3.23
If 1000-year flows have been derived, what is the range of ratios for 1000-year flow over 100-year flow?	The ratios are as follows: PG01: 1.87 These ratios are derived from the final flows which includes adjustment via the ratio method discussed above.
What range of specific runoffs (l/s/ha) do the results equate to? Are there any inconsistencies?	The 100yr specific runoff ranges are: FS01: 2.38 The specific runoff rates are low for the catchment for the 100-year return period, however, checks undertaken on the QMED value provide confidence in the accuracy of the assessment and considering the low relief, moderate rainfall and high permeability of the catchment the low specific runoff is considered representative.

Assessment checks discussion points	Summary of project specific outcomes associated with the checks
How do the results compare with those of other studies? Explain any differences and conclude which results should be preferred.	There are no other results available for comparison.
Are the results compatible with the longer-term flood history?	No details of the long-term flood history have been made available to support this assessment.
Describe any other checks on the results	None.

6.5 Final results

Table 6-6 Final flows

Return Period (in years)	Flood peak (m^3/s)
2	0.24
5	0.24
10	0.34
20	0.42
30	0.51
50	0.57
75	0.66
100	0.80 (note) Unadjusted flood peak
200	0.96 (note) Unadjusted flood peak
1000	1.5 (note) Unadjusted flood peak

Note: This is the unadjusted 100-yr, 200-yr and 1000-yr value. The risk-based 100-yr values to be applied for climate change scenario peak flows are:

Table 6-7 Risk-based values

Return Period (in years)	Flood peak (m^3/s)
100	1.02
200	1.23
1000	1.90
100+44%	1.47

6.5.1 Whilst the permeable adjustments to the pooling group showed a significant increase in predicted flows for the 1000-yr event, the statistical approach is not strictly appropriate at this level. For this reason the risk based values are proposed for use for all events above the 100-yr event.

6.5.2 Flood hydrographs have been derived from ReFH2.3. Further details on the derivation of these is provided in **Section 6.2**. The hydrographs will be provided within a spreadsheet to the hydraulic modeller and/or the reviewing authority if requested.

6.5.3 Sensitivity testing of long storm durations is likely to be undertaken within the associated hydraulic modelling exercise and reported appropriately.

Annex - supporting information

Pooling group composition

List the gauging stations included in each pooling group, and their periods of record.

PG01 Pooling Group (FS01)

Pooling group

Station	Distance	Years of data	AREA	SAAR	FPEXT	FARL	BFIHOST	DPSBAR	Summary	Decision
27073 (Brompton Beck @ Snainton Ings)	1.614	37	8.06	721	0.237	1.00	0.89	47.7	Good matches for BFIHOST, SAAR, FARL and URBEXT. Representative.	Retain
76011 (Coal Burn @ Coalburn)	1.661	42	1.63	1096	0.074	1.00	0.20	47.2	Site is impermeable and not like subject site. However following review it is sensible to retain.	Retain
27051 (Crimple @ Burn Bridge)	2.021	47	8.17	855	0.013	1.00	0.31	62.9	Descriptors are similar to subject site but not perfect, there are few better WINFAP4 recommendations.	Retain
45816 (Haddeo @ Upton)	2.184	26	6.81	1210	0.011	1.00	0.59	81.0	Higher BFIHOST than most of group, representative of sites.	Retain
28033 (Dove @ Hollinsclough)	2.43	44	7.92	1346	0.007	1.00	0.40	166.7	Not very representative of subject site but few better options exist following review.	Retain
26016 (Gypsey Race @ Kirby Grindalythe)	2.551	19	15.85	757	0.030	1.00	0.96	57.2	Ver permeable and low relief, like subject site.	Retain

Station	Distance	Years of data	AREA	SAAR	FPEXT	FARL	BFIHOST	DPSBAR	Summary	Decision
25019 (Leven @ Easby)	2.587	41	15.09	830	0.019	1.00	0.52	128.0	Again, higher relied and lower permeability, but few better WINFAP4 recommendations exist.	Retain
49005 (Bolingey Stream @ Bolingey Cocks Bridge)	2.757	9	16.08	1044	0.023	0.99	0.63	81.4	Fair BFIHOST, representative of subject catchments.	Retain
47022 (Tory Brook @ Newnham Park)	2.835	25	13.43	1403	0.023	0.94	0.43	106.0	Slightly dissimilar to subject sites, however, following review retain.	Retain
25011 (Langdon Beck @ Langdon)	2.878	33	12.79	1463	0.012	1.00	0.24	123.4	Somewhat dissimilar relief to subject site, however upon review better options are lacking.	Retain
25003 (Trout Beck @ Moor House)	2.952	46	11.40	1905	0.041	1.00	0.23	92.0	More impermeable than subject site and more rainfall, but lower in group and again fewer better options are presented by WINFAP4.	Retain
27010 (Hodge Beck @ Bransdale Weir)	2.978	41	18.82	987	0.009	1.00	0.34	149.8	Slightly dissimilar but lower impact in group and better options are not forthcoming.	Retain
71003 (Croasdale Beck @ Croasdale Flume)	3.008	37	10.71	1882	0.016	1.00	0.28	156.0	Low representativeness of subject site but low impact in group and removal does not alter growth curve significantly.	Retain

Station	Distance	Years of data	AREA	SAAR	FPEXT	FARL	BFIHOST	DPSBAR	Summary	Decision
44008 (South Winterbourne @ Winterbourne Steepleton)	3.04	33	20.18	1012	0.015	1.00	0.81	93.8	Good match for the sites it is permeable, high BFIHOST.	Retain
206006 (Annalong @ Recorder)	3.101	48	14.44	1704	0.023	0.98	0.34	270.8	Extremely steep mountainous and high rainfall catchment, impermeable. Collectively misrepresentative of subject sites.	Retain
36010 (Bumpstead Brook @ Broad Green)	3.161	52	27.58	588	0.045	1.00	0.39	34.1	Added as is better match than 206006 to maintain data years.	Retain

Final Design Hydrographs

Final design hydrographs